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Geomatic techniques for the documentation of the Underwater Cultural Heritage

By

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ABSTRACT

Abstract

Underwater Cultural Heritage (UCH) needs to be preserved, documented, and safeguarded due to their intrinsic values. The documentation is a fundamental tool for increasing the resilience of UCH. Therefore, the study, the communication and the protection of this Heritage are supported by many processes and require specific data to be collected, stored, and pre-processed, before performing the actual data processing and quality certification steps that are essentials for the documentation of the Heritage. In addition, these activities involve many disciplines, actors, and stakeholders, leading to the need to establish fruitful collaborations among scientists, professionals, and institutions.

The research presented in this PhD thesis focuses on one of the research fields of **Geomatics**, discussing 3D metric techniques for underwater surveys and addressing the need to document the UCH via a **Photogrammetric approach**, by studying and applying geomatic sensors and methods in real scenarios, with the aim of documenting and promoting the Underwater Cultural Heritage and the Coastal Landscape.

This thesis is targeted to fill some gaps present in the current knowledge of underwater photogrammetry data processing. The core of this research focuses on the study and the design of a workflow to enhance photogrammetric datasets, boosting the performance of the final results (3D models and 2D products) in terms of reliability of the delivered metric and colourimetric data. Specifically, the thesis focuses on the possibility of enhancing **legacy datasets** or any kind of underwater photographic datasets not acquired with the purpose of a photogrammetric reconstruction.

The methodology is developed around 3 main collaborations with national and international universities and provides an establishment of a methodological protocol specifically designed for I) **enhancing sub-optimal datasets** (i.e. exploiting the metric and radiometric content of less-than-ideal image datasets by adopting pre-processing strategies, to achieve acceptable results) II) **restoring colour information** and III) providing a novelty strategy for **georeferentiation in very shallow water** (< 4 m depth). For each use case different solutions are proposed and evaluated and, finally, challenges, success and drawbacks faced during the development of the methodological protocol are applied in the real case of a metric survey of an underwater archaeological excavation site (the late imperial roman wooden wreck of Torre Santa Sabina - Carovigno, Brindisi, Italy).

"There are more ships lying at the bottom of the sea than there are sailing on it."
"Ci sono più navi che giacciono in fondo al mare di quante non vi navighino sopra"

Predrag Matvejević, Mediteranski Brevijar

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Finally, thanks to my mother, my father, my siblings, and my dog; they are placed at the bottom of this list solely because good foundations are always found beneath good buildings.

Guardare le stelle significa vedere la luce che hanno emesso nel passato.
Alcune di esse si sono spente tanti anni fa,
eppure, continuano ancora oggi a brillare nel cielo di notte.

Questa tesi è dedicata alla mia Stella.

Contents

I. Declaration of originality I
II. List of Tables II
III. List of Figures V
IV. List of abbreviations XII
1. Introduction 2
1.1 Research topic 2
1.2 Methodological framework 4
1.2.1. Specific research questions 5
1.2.2. Overview of the academic literature, needs and lack of the current state of the art 6
1.2.3. Objectives, Goals, and contribution of this PhD research 7
1.3 Compliance with international policy framework 9
1.3. *..... 9*
1.3.1. Sustainable Development Goals contributions 9
1.3.2. Interaction with the 2030 Agenda and the related policy frameworks 11
1.4 Structure of the dissertation 12
1.5 Keywords 14
PART I - Theoretical background 16
2. Underwater Cultural Heritage: evolution of the legislative context 18
2.1 International charts and conventions on Underwater Cultural Heritage 18
2.2 The concept of in-situ conservation 22
2.3 Marine Protected Areas 23
2.4 The marine environment and the coastal Landscape 25
2.5 Initiatives to document and promote UCH 28
2.6 An example of political action towards the protection of UCH: The Italian National Superintendency for Underwater Cultural Heritage 31
3. Underwater Cultural Heritage: metric documentation with traditional and Geomatics techniques and methods 34
3.1 Traditional documentation techniques 36
3.2 Underwater photogrammetry 38
3.2.1. Optical and physics issues related to underwater photogrammetry 38
3.2.2. Geometric calibration of the camera 46
3.2.3. Radiometric correction of the images 47
3.3 UAS photogrammetry in very shallow water 48

3.4 Non-image-based techniques 49
3.4.1. Acoustic techniques 49
3.4.2. Other techniques 50
3.5 Positioning at different depths 50
PART II – Methodology, results, and validation 52
4. Processing strategies for enhancing sub-optimal datasets... 54
4.1 Case study: The Mandalay MHT shipwreck 55
4.2 Camera calibration 59
4.2.1. Single- and stereo- camera calibration with fixed baseline 59
4.2.2. Pre- and self- calibration of underwater cameras 61
4.3 Image masking 63
4.4 Image enhancement filters 66
4.5 Simple radiometric correction 70
5. Processing strategies for restoring colour information..... 76
5.1 Case studies: The Green Bay diving site and the and Lady Thetis Shipwreck 77
5.2 Colour correction based on a mathematical model 80
5.2.1. Modelling Absorption and Backscattering 83
5.2.2. Evaluation of the results 87
5.3 Colour correction based on a physical model 91
5.4 Comparative results between the mathematical and the physical methods 98
6. Georeferencing strategies in very shallow waters 102
6.1 Topography contribution in UW photogrammetry 102
6.2 The proposed solution 105
6.2.1. The 5m aluminum pole (PALONE) 105
6.2.2. The conic underwater marker (CONETTO) 108
6.2.3. Tilt compensation smart antenna (Leica GS18 GNSS RTK Rover) 111
6.3 Testing and validation of the proposed solution 112
6.3.1. Accuracy comparison with Total station and stability of the markers over the time 112
6.3.2. Assessment of the tilting compensation and comparison with the Leica AP20 AutoPole 121
7. Torre Santa Sabina: Underwater and Coastal documentation 130
7.1 Coastal Landscape Heritage documentation 134
7.1.1. The Bronze Age settlement 134
7.1.2. UAS data acquisition and processing 135
7.2 Underwater Cultural Heritage documentation 140

7.2.1. Main underwater evidence 140
7.2.2. The Torre Santa Sabina 1 wreck 142
7.2.3. Legacy Underwater data acquisition and processing (2007 survey) 146
7.2.4. Underwater data acquisition and processing (2020 survey) . 148
7.2.5. Comparison with legacy data (2007 and 2020 surveys) 153
7.2.6. Complete excavation and final documentation (2021 survey) 155

8. Suggestions and examples of online dissemination 160

8.1 Multi resolutions 3D model and high resolution orthophoto visualization 161

8.1.1. Porto Cesareo – Multi resolution 3D model visualization 161
8.1.2. Le Cesine – High resolution orthophoto visualization 163

8.2 Extended reality 165
8.3 webGIS 166

PART III – Discussion of results and future visions 170

9. Discussion & Critical considerations 172

9.1 Goals reached by the methodology 172
9.2 Limits to bridge and overcome 175

10. Conclusions and Future perspectives 178

10.1 Final considerations and suggested procedures 179
10.2 Future works and activities 180

Bibliography 184

References 184
My PhD publications 195

Appendix 200

A - International Conventions and Charts 200

Charter for the Protection and Management of the Archaeological Heritage on the Protection and Management of Underwater Cultural Heritage (1990) 200
Charter on the Protection and Management of Underwater Cultural Heritage (1996) 206
Convention on the Protection of the Underwater Cultural Heritage (2001) 211

B – Algorithms and codes 223

LAB colour correction 223
Contrast Limited Automatic Histogram Equalization (CLAHE) 224
Depth maps export (Python) 226
Colour analysis (Matlab) 227

C – Orthophotos and DSM 229

I. Declaration of originality

I Hereby declare that

This PhD thesis entitled "***Geomatic techniques for the documentation of the Underwater Cultural Heritage***" was carried out by me for the degree of Doctor of Philosophy in Architectural and Landscape Heritage (35° cycle), under the guidance and supervision of Professors *Filiberto Chiabrando* (Politecnico di Torino, Italy) and *Rita Auriemma* (Università del Salento, Italy).

The interpretations are based on my reading and understanding of the original texts, and they are not published in this form of books or monographs. The other books, articles, and websites I have used are acknowledged at the respective place in the text. For the present thesis, which I am submitting to the University, no degree or diploma or distinction has been conferred on me before, either in this or any other University.

II. List of Tables

Table 1. Main technical specification of the Nikon Z7 Mirrorless digital camera. 57
Table 2. Description of the *Mandalay* dataset with the number of images acquired from each camera. 58
Table 3. The estimated offset of the SA3 slave camera from the SA2 master camera. 60
Table 4: Values of polynomial radial distortion coefficients and focal length (in pixels) for each of the three camera configurations employed. 62
Table 5. Results after the image alignment and camera self-calibration for the same dataset for images with and without masks. 64
Table 6. Results after the image alignment and camera self-calibration for the same dataset for images with different sizes of circular masks. 65
Table 7. Numbers of detected features for the left and right images of the selected stereo couple for each of the employed image-enhancement filters. 67
Table 8. Numbers of matched features using both FLANN and Robust matching methods for the selected stereo couple for each of the employed image-enhancement filters. 68
Table 9. Numbers of tie-points and reprojection residuals at different quality levels of alignment for each of the employed image-enhancement filters. 69
Table 10. Olympus TG-6 camera main technical specifications. 78
Table 11. The various quantitative metric coefficients for 4 sample images of the Protaras dataset 90
Table 12. The various quantitative metric coefficients for 4 sample images of the Limassol dataset 90
Table 13. Intensity value (RGB) for the eight main colour patches in for the reference colour chart and for the different colour correction methods adopted... 93
Table 14. Euclidean distance (RGB) between the reference colour chart and the different colour correction methods adopted, for the eight main colour patches. .93
Table 15. Euclidean distance (CIELAB) between the reference colour chart and the different colour correction methods adopted, for the eight main colour patches. 96
Table 16. Intensity value (RGB) for the eight main colour patches in for the reference colour chart and for the different colour correction methods adopted (Protaras test site) 98
Table 17. Intensity value (RGB) for the eight main colour patches in for the reference colour chart and for the different colour correction methods adopted (Navis lapidaria). 98

Table 18. Euclidean distance (RGB) between the reference colour chart and the different colour correction methods adopted, for the eight main colour patches (Protaras test site).....99
Table 19. Euclidean distance (RGB) between the reference colour chart and the different colour correction methods adopted, for the eight main colour patches (Navis lapidaria). 99
Table 20. Theoretical planimetric error in case of TS measurement of a prism, for different pole length and different pole tilt whenever the pole is not perfectly perpendicular on the measured point. 104
Table 21. Theoretical altimetric error in case of TS measurement of a prism, for different pole length and different pole tilt whenever the pole is not perfectly perpendicular on the measured point. 104
Table 22. Theoretical plano-planimetric error in case of TS measurement of a prism, for different pole length and different pole tilt whenever the pole is not perfectly perpendicular on the measured point. 105
Table 23. Marker coordinates measure via GNSS (tilt-compensated) – first day. 113
Table 24. Marker coordinates measured via TS – first day. 113
Table 25. Discrepancy between marker coordinates measured via GNSS and TS. 114
Table 26. Marker coordinates measure via GNSS (tilt-compensated) – second day. 114
Table 27. Discrepancy difference between marker coordinates measured via GNSS – first day and second day. 114
Table 28. Comparison between point distances measured via GNSS – first day and second day. 115
Table 29. Marker coordinates measure via GNSS (tilt-compensated). 120
Table 30. Absolute difference between marker coordinates measured via GNSS – first day and second day. Marker 4 has been moved due to a mistake. 120
Table 31. Standard deviations of the measurements of point A coordinates, with AP20 and GS18 (single epoch and 10s acquisition) in steady, and tilting configurations (max 5 gon and max 10 gon). 123
Table 32. Standard deviations of the measurements of point B coordinates, with AP20 and GS18 (single epoch and 10s acquisition) in steady, and tilting configurations (max 5 gon and max 10 gon). 125
Table 33. Standard deviations of the measurements of point C coordinates, with AP20 and GS18 (single epoch and 10s acquisition) in steady, and tilting configurations (max 5 gon and max 10 gon). 127
Table 34. eBee X camera main technical specifications. 136
Table 35. DJI Phantom 4 RTK camera main technical specifications. 137
Table 36. RMS error for GCPs and CPSs referred to the three different approaches followed using the two software. 140
Table 37. Olympus TG-6 camera main technical specifications. 149

Table 38. Characteristics of the photogrammetric dataset collected on the first day of the survey. 151
Table 39. RMS error for GCPs referred to the photogrammetric survey of the stern of the wreck. 151
Table 40. Characteristics of the photogrammetric dataset collected on the second day of the survey. 152
Table 41. Characteristics of the photogrammetric dataset related to the 2007 survey. 153
Table 42. Comparison between direct and photogrammetry survey with both Photomodeler (old) and Metashape (new) approach. Data are referred to a portion of the study of 4,5 m^2. 154
Table 43. For each of the different epochs, the table list the number of images and the RMSE on the GCPs. 156

III. List of Figures

Figure 1. Sustainable Development Goals (SDGs), (UNITED NATIONS, 2016). 11
Figure 2. Workflow of the present thesis and Parts of the document. 12
Figure 3. Graphical abstract representing the main content of each chapter of the thesis. 13
Figure 4. Main convention and charts on the concept of Underwater Cultural Heritage during the last decades. 22
Figure 5. Main conventions, declarations, and guidelines on the definition of Marine Protected Areas. 24
Figure 6. Example of aluminium grid square used for archaeological documentation purposes. 37
Figure 7. The colourful rainbow bands that make up white light get absorbed / attenuated by liquid water at different rates. This graph attempts to approximate how deep certain colours of light penetrate. According to this graph, blue light penetrates deepest, while ultraviolet, red and infrared are rapidly absorbed near the surface. Source: Wikimedia Commons, Author: Tomemorris, License: CC-BY-SA-4.0 40
Figure 8. Backscatter from a strobe near the lens 42
Figure 9. Backscatter can be minimized by moving the strobe away from the lens 42
Figure 10. When a ray of light hits the surface of the water perpendicularly, it penetrates the surface without any problems (a). If the beam is inclined, part of the light is reflected from the surface of the water and only part of it penetrates towards the bottom (b), And when the sun is very low on the horizon, the surface of the sea acts like a mirror and reflects an huge amount of light (c). 43
Figure 11. When cameras are employed underwater, the light passing from the medium interface air-water, undergoes the effects of refraction. The result is a smaller FOV than that obtainable with the same lens used in a terrestrial environment. Source: [66] 45
Figure 12. Comparison between a case with flat port to one with a dome port. Examining the behaviour of the light rays that pass through the glass and the window, it is evident that when they pass perpendicular to the surface, they do not undergo deviations. The shooting angle, and the underwater focal length do not vary. Source: [66] 45
Figure 13. Graphical schema summarising the main step of the different methods proposed to cope with the issues characterising the processed data. 55
Figure 14. *Mandalay* aground on Long Reef, New Year's Day, 1966. (Image courtesy of the Miami Herald). 56

Figure 15. The *SeaArray* V4, a diver-operated tri-camera photogrammetry system employed in this research. In this chapter, the front camera is referred to as SA2, while the rear ones are respectively SA1 (left side) and SA3 (right side)....56
Figure 16. Nikon Z7 with the 14mm Rokion Cine DS Lensing. 57
Figure 17. One of the three calibrated scalebar used for scaling the model. ..57
Figure 18. The *SeaArray* employed in the acquisition phase on the *Mandalay* archaeological site (*Biscayne National Park* – Florida – USA). 58
Figure 19. On the left, the checkerboard pattern detected by the Stereo Camera Calibrator of Matlab; on the right, pattern-centric view of the estimated positions of the SA2-SA3 stereo couples. 60
Figure 20. The calibration panel employed in the acquisition of the dataset (A) and (B) on the left; and the dataset (C) on the right. 61
Figure 21. Radial distortion curves for the three camera configurations: in blue, the configuration (A), in red (B) and in green (C). 62
Figure 22. Comparison of the reprojection errors based on the average values of the residuals, expressed in millimetres, for the datasets (B) and (C) both when self-calibration and pre-calibration are performed. 63
Figure 23. Circular mask adopted; the darker area will not be used during the calibration of the sensor and the feature detection (key-points) and matching (tie-points) steps. 64
Figure 24. Comparison of the image residuals on the SA2 camera after the calibration. On the left, image residuals using the full image; on the right, image residuals cropping out the parts close to the edges of the sensor. 65
Figure 25. Comparison of residuals on different sizes of circular masks. From left to right: 3700x3700 pixels, 4600x4600 pixels and 5500x5500 pixels. 65
Figure 26. The stereo pair selected for testing different enhancement algorithms. In red, the portion of the image, representing the mast step, showed in Figure 27. 66
Figure 27. A portion of the right image (representing the mast step) of the stereo pair represented in figure 7 showing the effect of the applied algorithms on the original images; ImageFilter DETAIL (top left), ImageFilter EDGE ENHANCE (top right), SFS (bottom left) and Wallis (bottom right). 68
Figure 28. On the top, detected features on the left and right image of the selected stereo pair (in blue); on the bottom, features matched by the FLANN method (in green). 69
Figure 29. The employed checkerboard test pattern (50 mm side squares – CamAlign – CHB – SXW – V7.1) before (left) and after (right) the white balancing. The RGB and the luminance histograms are showed on the top right corner both before and after the correction. 71
Figure 30. 3D model (triangulated mesh) of the Mandalay texturized without using white balancing (left) and after the radiometric correction (right). 72
Figure 31. On the left, orthophoto of the *Mandalay* (70% transparency) superimposed over its hillshade DSM in order to make the 3D features more

relevant; On the right, archaeological drawing of the site (Image courtesy of the *National Park Service*). It is possible to notice several differences between the 2020 orthophoto and the archaeological survey (produced several years before).....73
Figure 32. Olympus Stylus TG-6 Tough camera. 78
Figure 33. Sensor and equipment used in the framework of this research.....78
Figure 34. Test site 1 - the Green Bay diving site (Protaras). 79
Figure 35. Test site 2 - the Lady Thetis Shipwreck diving site (Limassol). ...79
Figure 36. The diagram shows the value of the intensity absorption of red, green and blue colour channels (top to bottom), for each of the eight main colour patches (Red, Green, Blue, Cyan, Magenta, Yellow, Black, White), based on camera to object distances for Protaras test site. 81
Figure 37**.** The diagram shows the value of the intensity absorption of red, green and blue colour channels (top to bottom), for each of the eight main colour patches (Red, Green, Blue, Cyan, Magenta, Yellow, Black, White), based on camera to object distances for Limassol test site.....82
Figure 38. For Protaras dataset: from top to bottom is the colour value behaviour for Red, Green and Blue channels as the camera to object distance increases for the white colour patch. 84
Figure 39. For Protaras dataset: from top to bottom is the colour value behaviour for Red, Green and Blue channels as the camera to object distance increases for the black colour patch.....84
Figure 40. Correction results for Protaras Dataset: a) original image, b) LAB, c) CLAHE, d) proposed method (2^{nd} degree polynomial for the back scattering was used and 2^{nd} degree exponential for the absorption).....85
Figure 41. For Limassol dataset: from top to bottom is the colour value behaviour for Red, Green and Blue channels as the camera to object distance increases for the white colour patch. 86
Figure 42. For Limassol dataset: from top to bottom is the colour value behaviour for Red, Green and Blue channels as the camera to object distance increases for the black colour patch.....86
Figure 43. Correction results for Limassol Dataset: a) original image, b) LAB, c) CLAHE, d) proposed method (2nd degree polynomial for the back scattering was used and 2nd degree exponential for the absorption). 87
Figure 44: From Left to right the results provided by our algorithm, LAB, CLAHE, and the original images. Images from Protaras dataset 88
Figure 45: From Left to right the results provided by our algorithm, LAB, CLAHE, and the original images. Images from Limassol dataset.....88
Figure 46. Orthoimages of the Navis Lapidaria of AMP Porto Cesareo, generated using the a) Olympus; b) Xrite; c) LAB and d) Sea-thru colour correction methods. 92
Figure 47. Colour accuracy measurements of the Olympus colour correction method. Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI. 94

Figure 48. Colour accuracy measurements of the Xrite colour correction method. Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI. 94
Figure 49. Colour accuracy measurements of the LAB colour correction method. Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI. 95
Figure 50. Colour accuracy measurements of the Sea-thru colour correction method. Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI. 95
Figure 51. For a) Olympus; b) Xrite; c) LAB and d) Sea-thru colour correction methods, the diagrams shows the measured and reference colours in the CIE 1976 L*a*b* colour space on a chromaticity diagram. Red circles indicate the reference colour. Green circles indicate the measured colour of each colour patch. The chromaticity diagram does not portray the brightness of colour 96
Figure 52. Examples of artifacts due to model quality 97
Figure 53. Examples of artifacts due to inaccurate range maps (ie, edges of the model) 97
Figure 54. Examples of artifacts due to the albedo of manmade objects 97
Figure 55. A brief summary of the main pros and cos of the adopted methods. 99
Figure 56. The theoretical plano-altimetric error (E) resulting from the non-verticality of the pole is function of the length of the pole (P) and the tilting angle to the normal (ε), and it follows the equation (5). 104
Figure 57. The “fishing rod” effect, that occur consequently when the telescopic pole can’t oppose the bending moment generated by the weight of the instrument and the environmental (wind and waves) conditions. As a result, the point to be measured (P) will have the coordinates P_a (or P_b whenever a tilting compensation device is employed). 106
Figure 58. On top: overall view of the four sections composing the PALONE. On the bottom: details of the tip (A) coupling mechanism (B) and topographic “Leica bayonet mount” for prism (C). 106
Figure 59. Different details of the aluminium pole: A) Tip; B) Coupling system of the four sections; C) Steel adapter for topographic prism. 107
Figure 60. Detail of the closing system for jointing the different sections of the plug-in pole 107
Figure 61. Concept of the CONETTO System. On the left: the food boxes that are used for containing the ballast (gravel, sand or lead). On the right: the kitchen funnel that composes the conical part of the CONETTO. 108
Figure 62. Different view of CONETTO n.1 109
Figure 63. On the top: Underwater markers are stacked on top of each other to save space. On the bottom: the bag containing the cones and the lids. 110

Figure 64. Projection of the front view (half left) and cross section (half right) of the CONETTO. The section on the right displays an 8 mm ⌀ threaded bar for employment in sandy environment. 111
Figure 65. The Leica GS18 smart antenna with the Leica CS20 Controller. The measure of the point is registered by a boat operator holding the CS20 controller. 112
Figure 66. On the top: diver operators receive the net containing the CONETTO System from a surface operator. On the bottom: diver operator is ensuring the marker on the seabed surface. 116
Figure 67. A surface operator is holding the pole vertically and steady for performing the GNSS measurement. The verticality is ensured by a movable level bubble. The surface operator has to communicate with a boat or shore operator (depending on the distance of the site) for receiving clearance that the point has been recorded. 117
Figure 68. A diver operator is carefully placing the tip of the pole on the center of the cone vertex, waiting for the surface diver to give clearance to move to the next point. 118
Figure 69. Overall view of the measurement operations; scuba diver operator on the bottom holding the tip of the pole on the center of the cone vertex, and surface operators on the top, ensuring the verticality of the pole and awaiting for confirmation from the boat operator. 119
Figure 70. Leica AP20 AutoPole 121
Figure 71. Relative coordinates plot for point A (0;0) for the test in steady configuration. 123
Figure 72. Relative coordinates plot for point A (0;0) for the test in tilting (max 5 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures. 124
Figure 73. Relative coordinates plot for point A (0;0) for the test in tilting (max 10 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures. 124
Figure 74. Relative coordinates plot for point B (0;0) for the test in steady configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures. 125
Figure 75. Relative coordinates plot for point B (0;0) for the test in tilting (max 5 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures. 126
Figure 76. Relative coordinates plot for point B (0;0) for the test in tilting (max 10 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures. 126
Figure 77. Relative coordinates plot for point C (0;0) for the test in steady configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures. 127

Figure 78. Relative coordinates plot for point C (0;0) for the test in tilting (max 5 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures. 128
Figure 79. Relative coordinates plot for point C (0;0) for the test in tilting (max 10 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.....128
Figure 80. Torre Santa Sabina (Brindisi, Salento, Southern Apulia), Camerini bay.....131
Figure 81. Archaeological maps of the Torre Santa Sabina bay (submerged and semisubmerged contexts) taken from the 2007-2012 excavation documents. 133
Figure 82. Panoramic view of the coastline of Baia dei Camerini, Torre Santa Sabina (Carovigno, Brindisi, IT). 134
Figure 83. Bronze age settlement in the Mezzaluna bay: pole holes 135
Figure 84. The eBee X fixed-wing platform with the SODA 3D camera and the scheme of the camera tilting option.....136
Figure 85. Screenshot of the eMotion flight plan of the surveyed area. 137
Figure 86. Screenshot of the DJI Terra software with the acquired UAS data using the Phantom 4 RTK.....138
Figure 87. UAS orthoimage of the shore of Santa Sabina, with superimposed the topographic vertexes (red triangles) and the GCPs (blue dots) used for the georeferentiation of the photogrammetric flights. 139
Figure 88. UAS orthoimage of the shore of Santa Sabina (eBee X).....140
Figure 89. Submerged blocks.....141
Figure 90. Partially submerged quarries. 141
Figure 91. Mezzaluna bay channel.....142
Figure 92. Torre Santa Sabina 1 wreck. (Photo E. Peluso).....143
Figure 93. Torre Santa Sabina 1 wreck, remains of the deck above two beams. 143
Figure 94. Torre Santa Sabina 1 wreck, view from the bow area: kelson with the mast step, side keelsons, frames and a pillar on the left. 144
Figure 95. Torre Santa Sabina 1 wreck, mast step at the bow. 145
Figure 96. Torre Santa Sabina 1 wreck, North-african Amphora. 145
Figure 97. Torre Santa Sabina 1 wreck, Dressel 30 amphora. 146
Figure 98. Survey operations inside the grid square frame. Source: [136]...147
Figure 99. Direct survey restitution obtained from AutoCAD on the basis of a traditional grid square survey. Source: [136].....147
Figure 100. 3D reconstruction with Cinema 4D. Source: [136] 147
Figure 101. Image acquisition phase during the underwater photogrammetric survey of the Roman shipwreck in Torre Santa Sabina.....149
Figure 102. The image shows the topographical survey operation in Torre Santa Sabina performed to measure the position of the underwater markers.....149
Figure 103. Orthoimage of the stern of the shipwreck, georeferenced using five 10 cm squared checkerboard markers, measured with celerimetric method. 150

Figure 104. Orthoimage of the stern of the shipwreck, generated via free-net adjustment after the archaeological categorization. In red, the portion of the analysis of Figure 11.....151
Figure 105. Comparison between the same portion (1 m^2) of the two dense point clouds generated in the two days of the underwater photogrammetric survey using the two different georeferentiation techniques. 152
Figure 106. On the left, an image of the 2007 dataset before the radiometric correction; on the right, the same image after applying the LAB filter. 154
Figure 107. On the top, drawing of the shipwreck produced via direct survey in 2007; on the center, RGB orthoimages of the two parts of the wreck surveyed in 2007 (right) and 2020 (left); on the bottom, DEMs of the same orthoimages of the two surveys. 155
Figure 108. Ad-hoc self-built pole-holder device created to guarantee centimeter grade georeferentiation. 157
Figure 109. Tripolitanian amphoras' cargo remains. 162
Figure 110. Tripolitan II amphora fragments. 162
Figure 111. Visualization of one of the Porto Cesareo's Tripolitanian amphoras' cargo remains loaded in the 3DHOP interface. 163
Figure 112. Aerial view of the submerged pier in San Giovanni. 164
Figure 113. High resolution ortophoto of the surveyed roman pier uploaded on ARIADNE Visual Media Service 165
Figure 114. The public webGIS CartApulia portal 167
Figure 115. The public webGIS UnderwaterMuseMap portal 167

IV. List of abbreviations

The following abbreviations and acronyms are used in this dissertation:

AI: Artificial Intelligence
BBA: Bundle Block Adjustment
CH: Cultural Heritage
CLAHE: Contrast Limited Automatic Histogram Equalization
COD: Camera to Object Distance
COTS: Commercial Off The Shelf
CP: Check Point
CRP: Close-Range Photogrammetry
CS: Computer Science
DEM: Digital Elevation Model
DPV: Diver Propulsion Vehicle
DSLR: Digital Single-lens Reflex
DSM: Digital Surface Model
DTM: Digital Terrain Model
GCP: Ground Control Point
GI: Geospatial/Geographic Information
GIASS: Gruppo d'Indagine Archeologica Subacquea Sicilia - Sicily Underwater Archaeological Investigation Group
GIS: Geographic Information System
GNSS: Global Navigation Satellite System
GSD: Ground Sample Distance
HE: Horizon Europe
ICUCH: International Committee on the Underwater Cultural Heritage
ICOMOS: International Council on Monuments and Sites
ICP: Iterative Closest Point
ICT: Information and Communication Technologies
IGMI: Istituto Geografico Militare Italiano
IMO: International Maritime Organization)
IUCN: International Union for Conservation of Nature and Natural Resources
KSO: Key Strategic Orientations
LiDAR: Light Detection and Ranging
MIBACT: Ministry of Cultural Heritage and Activities and Tourism
MMS: Mobile Mapping System
MPA: Marine Protected Area
NAVSTAR GPS: NAVigation Satellite Timing And Ranging. Global Positioning System
N-RTK: Network Real-Time Kinematic
OS: Open-Source
PC: Point Cloud
PPK: Post Processing Kinematic
PSSA: Particularly Sensitive Sea Area
RF: Reference System
RMSE: Root-Mean-Square Error
ROI: Region Of Interest
ROV: Remotely Operated Vehicle
RTK: Real-Time Kinematic
SBL: Short Baseline
SDG: Sustainable Development Goal
SfM: Structure from Motion
SFS: Shape From Shading
SIFT: Scale-invariant Feature Transform
SW: Software
TLS: Terrestrial Laser Scanning
TP: Tie Point
TS: Total Station
UAS: Uncrewed Aerial System
UAV: Uncrewed Aerial Vehicle
UCH: Underwater Cultural Heritage
UN: United Nations
UNCLOS: United Nations Convention on the Law of the Sea
UNEP: United Nations Environment Programme
UNESCO: United Nations Educational, Scientific and Cultural Organization

UN-GGIM: United Nations Initiative on Global Geospatial Information Management
USV: Unmanned Surface Vessel
UTM: Universal Transverse Mercator Projection
WebGIS: Web Geographic Information System
UW: Underwater
WGS: World Geodetic System

INTROD

UCTION

1

Chapter 1

1. Introduction

1.1 Research topic

The marine environment has always been of interest to scientists and researchers of various disciplines. With more than 70% of the planet's surface covered by water, the marine space is still largely unexplored in many respects. Over time, the international community has achieved an ever greater awareness of the cultural and historical value of the priceless Heritage that our seas and oceans conceal; in January 1999, it was estimated that there are about three million wrecks on the seabed of our planet [1].

The wreck is comparable to the more generic concept of ruin; therefore, we can consider it a special kind of ruin containing everything on board when the ship sank. As Historical memory of ancient civilization, shipwrecks constitute the actual testimonials of the art and culture of the populations who have travelled and inhabited the coastal territories of the world.

In other words, wrecks are the closest thing to *"time capsules"*, a *"pure"* time of which the French anthropologist Marc Augè also speaks about, *"[...] absent from our world of images, simulacra and reconstructions, from our violent world whose rubble no longer has time to become ruins"* [2].

Underwater Cultural Heritage (UCH) means *"all traces of human existence having a cultural, historical or archaeological character which have been partially or totally underwater, periodically or continuously, for at least 100 years"* [3].

Changes in the coastal line over the centuries (for natural or human reasons), might eventually expose the UCH, voiding the benefit of the anaerobic environment; this kind of Heritage is, in fact, in a context that, on the one hand, is complex and hostile and, on the other hand, allows its preservation.

[2] IEEE edition Style Referencing is used in this dissertation.
[3] References of books, articles and newspapers are reported in the text; website links are in footnotes.
[4] The use of comma as decimal separators (Italian convention) is adopted in the manuscript.

The importance of studying and preserving the UCH is stated in three important international conventions and charters: the 1982 UNCLOS (United Nations Convention on the Law of the Sea)[5], the 1996 ICOMOS (International Council on Monuments and Sites) Charter on the protection and management of Underwater Cultural Heritage[6], and the 2001 UNESCO (United Nations Educational, Scientific and Cultural Organization) Convention on the Protection of the Underwater Cultural Heritage[7]. The 2001 Convention recommends considering first to protect ancient shipwrecks or submerged archaeological sites in situ before considering recovery. In marine archaeology, in fact, many wooden or metallic artefacts are found in a different state of conservation depending on the environment in which they are discovered [4], and their recovery is not always the best strategy for pursuing their preservation and conservation. Therefore, it is more and more important to consider advanced technologies, such as photogrammetry and rapid mapping, for the documentation and the virtualization of underwater CH (Cultural Heritage) not only for dissemination and visualization purposes, but also for the study from domain experts, the reproduction of replicas, the degradation monitoring, and all the wider outcomes subsequent to the metric survey of a CH.

The scientific community's growing interest in surveying and monitoring submerged assets arises from the increasing demand for high-resolution products with metric and colourimetric contents. Although many instrumental and methodological solutions for the documentation, monitoring, and study of the archaeological and cultural heritage, through geomatics techniques, are already available for the terrestrial environment, for the underwater context the challenge is still open. In fact, the high-resolution capability and accurate positioning in these contexts are still hard to achieve.

Among the different metric documentation techniques, photogrammetry in underwater environment is affected by challenges related to the different optical properties of the medium (water), light penetration, visibility and suspension, radiometric issues and environmental drawbacks that make the underwater documentation difficult.

Nevertheless, it is currently possible to speed up and make UCH metric documentation more cost-effective, guaranteeing at the same time safety conditions during underwater operations, thanks to the use of underwater photogrammetry integrating various types of cameras and sensors.

Underwater Cultural Heritage constitutes an invaluable resource that needs acknowledgement and proper treatment to continue offering significant benefits to humankind. However, despite its indisputable value, UCH has been mainly neglected in most marine planning attempts. Lately, however, the opportunities and challenges for UCH have been considerably different [5].

This thesis aims to study, test and compare innovative geomatics technologies and methodologies to provide knowledge, high-resolution metric surveys,

[5] https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf
[6] https://www.icomos.org/charters/underwater_e.pdf
[7] https://unesdoc.unesco.org/ark:/48223/pf0000126065

monitoring for "in situ" preservation and enhancement for UCH at low depths. In particular, the ancient shipwrecks (beached wrecks located at low depth) are the most challenging underwater archaeological evidence concerning their valorisation, documentation, and accessibility. This challenge is mainly due to their position, depth, and vulnerability of the wooden hull, as well as other organic materials of the cargo.

The underwater heritage is currently the privilege of a few professionals: the thesis work aims at proposing, analysing and comparing workflows and tools that can enhance access, fruition, and sharing of archaeological findings and marine landscape through immersive tours and 3D models; this is functional not only to guarantee the aspect of fruition and promotion from the wide public (in compliance with the Convention on the Value of Cultural Heritage for Society [6]), but especially to provide domain experts with 3D models of certified metric and colourimetric quality, useful not only for the study of the UCH but also for the design of conservation and protection measures functional to its preservation. Hence, this work discusses innovative and easy-to-use solutions based on integrated instrumentation; the final purpose is to deliver a detailed description of the operative procedures that are useful in underwater archaeology and scalable to other fields of application.

Thanks to the wideness of scenarios in which this thesis has been developed, the approach results are innovative and replicable.

1.2 Methodological framework

A list of the primary *motivations* for investigating this dissertation topic of documentation of the Underwater Cultural Heritage with Geomatic techniques is presented to clarify the needs and gaps that this research wants to fill in:

- Historical: improving the knowledge and the scientific research of the ancient shipwrecks, milestones of trans-Mediterranean routes from the Bronze age to the Modern age. In this way, it is possible to reconstruct the dense network of maritime connections and movements of men and goods, namely the most fruitful heritage of the Mediterranean, the sea in the middle of the land, the sea of proximity [7].
- Geoarchaeological: fostering the scientific research on the relative sea-level changes and the evolution of coastal landscapes through the study of the beached wrecks as markers of the ancient shoreline.
- Cultural: ensuring the in-situ preservation and protection of the shipwrecks through shared knowledge, following the 2001 UNESCO Convention of the Underwater Cultural Heritage Protection.
- Socio-political: enhancing and making accessible UCH at various depths, otherwise inaccessible and invisible, through digital technologies and the narrative and communicative use of 3D models, extended reality storytelling and animation. The objective responds to a new relationship between community and heritage, a new perception of

heritage, the principles of the Faro Convention (2005): heritage as a common good, a resource for the cultural, spiritual, social, and economic development of communities.

- Technological: testing and discussing non-invasive 3D multi-sensors survey systems with related operative methodologies. This can provide high-resolution surveys and monitoring for a wide range of underwater applications based on image and range measurements as well as positioning systems.
- Needs to document and valorise Underwater Cultural Heritage and Coastal areas to promote cultural identity, also as an effect caused by the pandemic.
- Geomatics techniques and methods support the research in different disciplines and areas of study.
- Problems of interaction between archaeologists and surveyors can find support in the definition of documentation and investigation strategies, thanks to advancements in technologies that provide modern instruments and innovative techniques.
- Need for the definition of standardized data processing strategies to provide reliable high-resolution products (3D models, orthophotos, thematic maps, etc.) in underwater surveying and monitoring.
- Increased comprehensive knowledge and awareness of these archaeological assets, with subsequent "in situ" preservation and control of the underwater archaeological sites.
- Wider accessibility, i.e., bringing heritage to a large public thanks to virtual fruition tools, which can enhance and return the underwater heritage to the community.
- Aside from the aims of metric documentation of the heritage, those techniques can be used also for application not strictly related to UCH, such as monitoring of subsea pipework, offshore platforms, bridge and piers pillars, docks, breakwaters and other similar marine and submarine structures and infrastructures.

1.2.1. Specific research questions

After the above-listed motivations, there are some questions that this dissertation will attempt to answer. They are the following:

Research questions

- What is the degree of metric and colourimetric accuracy required for an adequate survey, functional to the domain experts' point of view?
- Which are the existing main limitations in the integration of geomatics techniques with the archaeological needs?
- How is it possible to exploit UCH legacy data not originally acquired for photogrammetric purposes?

- Which are the adequate methods to survey different UCH at specific depths?
- How to calibrate camera geometry for optimal results in sub-optimal conditions and data?
- How to properly correct image radiometry based on information such as camera to object distance, light absorption and backscattering?
- What are the limits of GNSS positioning and georeferencing in water and how is it possible to exploit existing methods and instruments?
- How can geomatics methods, techniques and instruments help UCH domain experts, such as marine archaeologists, in spreading the knowledge of UCH and allow their valorisation and promotion?
- How to deal with constrains related to the underwater survey?
- Does the current literature provide comprehensive and easy to adopt solutions to address these limits with controlled outcomes and certified results?
- Is there a solution to bridge these gaps?

To answer these questions, an overview of the literature (§ 1.2.2) and an explanation of the objectives of this research (§ 1.2.3) is carried out in the following sections.

1.2.2. Overview of the academic literature, needs and lack of the current state of the art

Underwater exploration is, essentially, interdisciplinary, and thus requires a strong collaboration between researchers in different fields (e.g., geology, biology, archaeology, engineering, geomatics). Due to the remoteness and the limited access of a typical underwater archaeological site, it is crucial to adopt 3D metric techniques for a correct and complete recording of the site itself and all its elements [8]. Geomatics techniques can nowadays provide a wide range of tools and solutions for monitoring and documenting marine assets [9].

The formation and appearance of underwater archaeological sites depend on the chemical-physical characteristics of the submerged environment, the nature of the seabed, the presence, and characteristics of the cargo (if any), post-depositional anthropogenic factors, and any faunal disturbances. Submerged deposits made up of shipwrecks (hull and/or cargo and/or onboard equipment) discussed in this thesis belongs to the category of beached wrecks (within 6 m) and low depth wrecks (within 18 m).

Beached wrecks are sometimes exceptionally preserved thanks to the fast covering process and the "trap effect" (i.e. the capacity of sand and sediments to create a cocoon around the wrecks guaranteeing an anaerobic and semi-insulated environment [10]–[13]); nevertheless, their minimum depth and frequency along the coats present severe issues for the investigation, exposition, and fruition, due to the constant and devastating wave motion that affects wooden and organic remains, if not embedded in an anaerobic environment. Furthermore, their value of

geomorphological indicators for the relative variations of the sea level and the coastal profile is noteworthy, as they are essential markers of the ancient shoreline [14], [15]

Submerged wrecks located at low depth near the coast or offshore are those most exposed to plundering, particularly if they are far from the coast, less subject to monitoring, and are deeply disturbed by the action of trawling or boats used for shellfish fishing, which causes a sort of "ploughing" of the load and the perimeter areas of the hull [16], [17]

The scientific community has fully addressed the increasing demand for high-resolution products with metric and colourimetric content for terrestrial applications; therefore, several commercial solutions and standard procedures are already available nowadays. Conversely, the high-resolution 3D reconstruction, the radiometric correction capability, and the positioning in the underwater context are still open issues. From the geomatics point of view, the presence of the water medium and the related additional drawbacks do not allow scientists to act smoothly as in the terrestrial field.

1.2.2.1 Photogrammetric camera calibration and radiometric correction

Following conventional photogrammetry and computer vision-based algorithms (Structure from Motion approach), image collection and processing still represent a significant open issue in underwater contexts [18]. Photogrammetric methods allow precise mapping of the underwater landscape and a detailed three-dimensional reconstruction of archaeological remains and evidence, useful to evaluate the health state of these findings [19]. Another aspect is the correction of colour variation incurred by the light propagating in water, which can be addressed through image enhancement [20].

1.2.2.2 3D model creation, visualization, and dissemination

As an alternative to direct access, media and virtual techniques can simulate the visiting experience at a distance. It can improve data sharing between scientists and provide diving operators with a measure of responsibility and custodianship, a good solution for the need for supervision and control. 3D annotation online and virtual reality exploration are currently being addressed [21] even on low-performance hardware and limited bandwidth, thanks to emerging technologies based on batched multiresolution and 3D compression [22].

1.2.3. Objectives, Goals, and contribution of this PhD research

Increasing the knowledge is the basis for every act of protection and valorisation of the archaeological and built Heritage; for facing the complex study of the conservation of the underwater Heritage and the coastal Landscape, it is important to develop investigation and survey techniques (such as bathymetry, photogrammetry, and so forth) that requires the integration of several disciplines,

not only for the evaluation of the causes of the submersion, but also for the definition of the important relations between the underwater archaeological remains with the ones on the shore, taking into account the historical and chronological data available, and always considering natural and anthropic factors. The aforementioned objectives go towards efficient and effective protection and valorisation of the Heritage.

An important outcome of an accurate metric survey is the production of thematic maps relative to materials, conservation status, and so forth, with a methodology like the one adopted on the land. The development of appropriate surveys is the basis for scheduling the conservative restoration actions [23]. Such restorations activities must keep in mind that biological colonisations also endanger underwater ruins (in the short term). For this reason, it is important to activate actions towards the initial survey and constant monitoring over time, functional to the conservation of the Heritage.

Over the years, some researches tried to provide a suitable methodology for both satisfying the need of required metric accuracy and the need of fieldwork survey in the archaeological domain. Despite consolidated methodologies and standards exists in terrestrial survey, there are still some gaps and shortcomings in the underwater environment. At first, there is a lack of solutions for providing easy to deploy workflow for expert domains (archaeologists) with no proficiency in Geomatics to conduct further research on the acquired data, for example 3D model inspection, multitemporal analysis of excavated sites and their contents. Moreover, it is crucial to evaluate different strategies on dissemination using tools for 3D model sharing and visualisation, not only for scientists but also the general public.

Aims of the thesis

The present thesis aims to **investigate the different and already-known advanced 3D metric survey techniques for UCH documentation**. By investigating the existing studies and operative standards, the thesis would like to fill the lack of a linear workflow that can be adjusted in order to fit different situations.

This clarification allows the development of the second step of research: the evaluation of different possible strategies to **define a suitable survey method based on the characteristics of the object and its context** (different depth, different sites, different techniques required). It is crucial to consider innovative and new technologies to describe underwater assets and design valorisation and preservation activities accordingly. In this framework, the methodology has been validated by selecting the explicative case studies of the Torre Santa Sabina 1 shipwreck. The work described delivers a feasible methodology that allows mapping and monitoring a wide range of sites. Based on the various applications in the field and using the experience gained from the case study analysis, a set of technical specifications for a 3D underwater archaeological survey can be developed, to be shared with users, stakeholders, and professionals. The thesis will ensure the reproducibility of developed methodologies on the heterogeneity of environments with different light and hydrodynamic conditions, leading to safer, viable, and reproducible monitoring operations.

The technological impact of the thesis is the achievement of high-resolution surveys, both in terms of geometry and colorimetry contents, thanks to the development of workflow capable of overcoming the difficulties related to the marine environment significatively improving current common practices. The final aim is to **metrically and radiometrically document Underwater Cultural Heritage** with the most appropriate methods and techniques and make available the products of the survey in a wider way. In other words, the final objective regards the generation of metrically controlled HBIM of the surveyed objects and sites, and how to make the derived products available correctly and fruitfully widely. The research will contribute to the dissemination of underwater knowledge, enhancing multidisciplinary approaches and scientific collaborations, permitting the definition of new procedures and methods to solve open problems like data visualization to improve high resolution underwater surveys.

For this purpose, the last part of the thesis aims to discuss **possible ways of dissemination and fruition** of the work, both in-situ and remotely (online and offline). The final effort is to improve the visibility of underwater assets by reinforcing cultural values and knowledge transfer. The increased accessibility for those categories of potential visitors, who (for physical, economic, age-related issues or ills) cannot enjoy the direct diving, through Extended Reality tools and online enhanced remote visiting experiences. The strategy will help raise awareness among the citizens about their historical heritage and identity and reach a wider audience. Moreover, the high-resolution documentation and mapping of archaeological evidence also give the chance to enhance and promote the underwater CH and boost a new archaeo-economy based on the marine richness. Innovative monitoring and surveying procedures can promote underwater tourism, which combines in single activity leisure, sport, culture, and ecology, which is very profitable and highly sustainable, and the remote enjoyment of archaeological contexts. The exploitation of 3D reconstruction, remote visits, and virtual explorations serve as tools for managing the cultural-natural heritage of underwater archaeological and MPAs areas from a new perspective (as an ethical obligation), based on the participatory approach of all the local stakeholders.

1.3 Compliance with international policy framework

1.3.1. Sustainable Development Goals contributions

SDGs contribution



This dissertation falls within some of the Sustainable Developments Goals (SDGs)[8] (Figure 1), the core topic of the 2030 Agenda for Sustainable Development (UNITED NATIONS, 2016), defined by the United Nations General Assembly and adopted by all United Nations Member States in 2015. The document *"provides a shared blueprint for peace and prosperity for people and the planet, now and into the future"*. Moreover, the United Nations Member States, UN-GGIM[9], in the

[8] https://sdgs.un.org/goals
[9] https://ggim.un.org/

document *"The Role of Geospatial Information in the Sustainable Development Goals"*, listed and explained the main goals in which GI technologies and methods can effectively help. These thesis aims are related to SDGs 9, 10 and 14. These are:



- SDG 9. *"Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation"*[10]: the technical and technological improvements supported by this thesis will improve industrial sustainability through a smart and more efficient workflow for data acquisition and processing. The tangible feedback projected on the different fields will enhance the resilience of the industrial infrastructure because of the replicability of proposed high-resolution survey/monitoring protocols and their wide deployability and uses. The outcomes and considerations will permit multitemporal quantitative evaluation of UCH and archaeological assets for improving their resilience in submerged environments.



- SDG 10. *"Reduced inequality"*[11]: social innovation focuses on policies and practices for the smart distribution of tourists and visitors in unconventional and well-known cultural destinations, such as the underwater environment. New tourists will have the opportunity to know and virtually visit the underwater heritage improving cultural values, osmosis, and knowledge transfer. The increased availability of virtual visiting experiences will also improve the accessibility of UCH to fragile categories, such as the elderly, disabled people or ill people.



- SDG 14. *"Conserve and sustainably use the oceans, seas, and marine resources for sustainable development"*[12]: the thesis activities looked forward to developing key tools for documenting and managing underwater archaeological and cultural assets, supporting the conservation and restoration of shipwrecks and sites. The effort of the dissemination aspects focuses on giving people the opportunity to know their own identity heritage by supporting the sustainable development of cultural values, based on inclusive and participatory methodologies of companies, organizations, communities, and people, seeking to contribute to their well-being and enabling cooperation based on principles of justice, proximity and distribution of governance and decision.

[10] https://sdgs.un.org/goals/goal9
[11] https://sdgs.un.org/goals/goal10
[12] https://sdgs.un.org/goals/goal14



Figure 1. Sustainable Development Goals (SDGs), (UNITED NATIONS, 2016).

1.3.2. Interaction with the 2030 Agenda and the related policy frameworks

This PhD thesis fits the main topics identified by the Horizon Europe[13] (HE) Mission area *"Healthy oceans, seas, coastal and inland waters"*, with particular focus on Clusters 2 and 4 of the Pillar 2 HE *"Culture, Creativity and Inclusive Society"* and *"Digital, Industry and Space"*; addressing the Key Strategic Orientation for research and innovation KSO1 *"Industrial leadership in key and emerging technologies that work for people"* with innovative solutions and emerging technologies to enhance survey capabilities in the marine environment. The key aim is to combine research and innovation to acquire new knowledge and empower the blue economy by developing technologies and promoting their use in several applications, thus providing tangible impacts from multiple perspectives.

In line with UNESCO's Convention on the Protection of the Underwater Cultural Heritage 2001 [3] and the Faro Convention 2005 [6], we must address our effort to the development of *"models for managing underwater cultural heritage in a way that brings benefits for the sustainable economic development of regions"*, to *"increase the positive image of underwater archaeology and the involvement of the public in the awareness, the protection, and enjoyment of the underwater cultural heritage"*.

This dissertation is in line with the aims of the United Nations Decade of Ocean Science for Sustainable Development [24] which aims to create a network of eminent partners of the Ocean Decade that can lead by example to catalyze support for the Decade through targeted resource mobilization, networking, and influence.

[13] https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en

"In 2017, the United Nations General Assembly proclaimed the United Nations Decade of Ocean Science for Sustainable Development (2021-2030) ('the Ocean Decade'). The vision of the Ocean Decade is 'the science we need for the ocean we want', and it envisages nothing less than a revolution in ocean science that will trigger a step change in humanity's relationship with the ocean. It will bring together scientists, resource providers, governments, business and industry, philanthropic Foundations, UN agencies and many other stakeholders from diverse sectors to generate scientific knowledge and develop the partnerships needed to support a well-functioning, productive, resilient, and sustainable ocean." [14]

1.4 Structure of the dissertation

This research presents a literature review about the main convention and charts on UCH protection and management (*Chapters 2),* and a literature review about the main geomatics methods for the documentation of UCH *(Chapter 3*). After that, the research intends to focus on the lack of a procedure to enhance sub-optimal or legacy data, trying to bridge and overcome the related problems. These gaps will be investigated in-depth, covering different scientific theoretical literature backgrounds to provide an exhaustive overview of the topic of processing strategies, including camera calibration (*Chapter 4*). The analysis will cover applications for efficient generation of 2D products and enable high-resolution 3D models creation. This thesis purposes to contribute in an operative and practice way also to the problem of colour restoration of underwater images, through a comparison of an ad-hoc and existing algorithms and methods based on physical and mathematical models (*Chapter 5*). Another important aspect, concerning georeferentiation issues and solutions in very shallow water is also discussed (*Chapter 6*). The core methodology of this PhD thesis will be applied in a real case study, the underwater archaeological site of Torre Santa Sabina 1 wreck (*Chapter 7*). Hence, combining different methods, it will be possible to perform a complete photogrammetric survey. Finally, this thesis will propose some suggestions for disseminating the generated products among the wide public (*Chapter 8)*. *Chapters 9 and 10* present discussions, critical reflections, conclusions, and possible future developments.

Figure 2 shows the workflow of the thesis and the three distinct parts in which it is divided, while Figure 3 represent a graphical abstract showing the main topic of each chapter of this thesis.



Figure 2. Workflow of the present thesis and Parts of the document.

[14] https://www.oceandecade.org/ocean-decade-alliance/



Figure 3. Graphical abstract representing the main content of each chapter of the thesis.

1.5 Keywords

- Underwater Photogrammetry
- Image Enhancement Methods
- Shipwreck Documentation
- Digital archaeology
- Uncrewed Aerial Systems
- Camera Calibration
- Colour correction
- Underwater positioning
- Geospatial Information (GI)
- Underwater Cultural Heritage (UCH)
- Seascapes Archaeology
- Shallow Depth Surveys
- 3D Model Generation

Part of the work described in the next chapters has been published previously in:

→ **A. Calantropio** [ACDE], F. Chiabrando, B. Seymour, E. Kovacs, E. Lo, and D. Rissolo, 'Image Pre-Processing Strategies for Enhancing Photogrammetric 3d Reconstruction of Underwater Shipwreck Datasets', *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 43B2, pp. 941–948, Aug. 2020, doi: 10.5194/isprs-archives-XLIII-B2-2020-941-2020.

→ **A. Calantropio** [ACDE], D. Rissolo, and E. Kovacs, 'Pre- and self-calibration of underwater cameras for photogrammetric documentation of archaeological sites', in *Proceedings of the ARQUEOLÓGICA 2.0 - 9th International Congress & 3rd GEORES - GEOmatics and pREServation Lemma: Digital Twins for Advanced Cultural Heritage Semantic Digitization.*, pp. 512–514., Valencia, 2021, doi: 10.4995/arqueologica9.2021.13259.

→ M. Vlachos, **A. Calantropio** [ABDE], D. Skarlatos, and F. Chiabrando, 'Modelling colour absorption of underwater images using Sfm-Mvs generated depth maps', *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 43, pp. 959–966, 2022., doi: 10.5194/isprs-archives-XLII-2-225-2018

→ **A. Calantropio** [BCDE], F. Chiabrando, and R. Auriemma, 'Photogrammetric Underwater and UAS surveys of Archaeological Sites: the case study of the roman shipwreck of Torre Santa Sabina', in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Jun. 2021, vol. XLIII-B2-2021, pp. 643–650. doi: 10.5194/isprs-archives-XLIII-B2-2021-643-2021.

→ Auriemma, R., **Calantropio, A.** [BCD], Chiabrando, F., Coluccia, L., Rugge, M., D'Ambrosio, P., Buccolieri, M., & Picciolo, A., 'Underwater archaeological surveys in Salento waters: results and methods', in *FOG special volume: Proceedings of the 6th European Conference on Scientific Diving 2021*, Freiberg, 2021, vol. 58, pp. 96–105.

→ Auriemma, R., Antonazzo, A., **Calantropio, A.** [BCD], Chiabrando, F., Coluccia, L., Leone, D., Maschio, P. F., Turchiano, M., & Volpe, G., 'Shipwrecks stories in a "trap bay": Research and valorization in Torre S. Sabina (Brindisi, Italy)', in *DEGUWA Annual Meeting on Underwater Archaeology IN POSEIDON'S REALM XXVI 'Safety and Waterways'*, 2021, pp. 7–7.

[A] Conceived and designed the analysis [C] Contributed data or analysis tools [E] Wrote the paper
[B] Collected the data [D] Performed the analysis

For this thesis, the above-mentioned research papers have been expanded and completed.

Theoretical background

This section presents the theoretical background about the object of the research: a literature review about the main conventions and charts on UCH protection and management (Chapters 2), and a literature review about the main geomatics methods for the documentation of UCH (Chapter 3).

PART I

2

Chapter 2

2. Underwater Cultural Heritage: evolution of the legislative context

Before investigating the different techniques and methods for surveying underwater assets, it is necessary to clarify the meanings and the evolution of the ***notion of UCH***. To this purpose, some questions that can guide this exploration for a definition are: what is UCH? How can we define it? How has the notion of UCH evolved and developed over the years? A literature investigation based on notions and evolutions of the legislative context on the topic is necessary. In this literature, the main international conventions and charts are considered. The different semantic definitions of UCH have changed over time, and therefore it is necessary to understand the evolution of the concept in the last 70 years. This chapter presents the definition of UCH, and describes the evolution of the concept, along with the definition of Marine Protected Areas, the marine environment, and the coastal Landscape.

2.1 International charts and conventions on Underwater Cultural Heritage

The first recall about Underwater Heritage was done in the UNESCO recommendation of 1956, where the international principles for archaeological excavation (valid also in the marine environment) were defined [25].

When the World Heritage List was established for the first time [26], i.e., the list of sites that represent particularities of exceptional importance from a cultural

or natural point of view, despite the central role of the sea in the spread of cultures and civilizations since the dawn of human history, the first list of World Heritage Sites, drawn up in '78, did not contain any sites with a maritime or submarine location.

One might therefore think that the interest in the underwater Heritage is recent. It became a topic in vogue only after the invention of the first air-breathing device in 1943 by Cousteau and Gagnan [27]. However, the first complex underwater archaeological recovery (without positive outcome) in history dates to 1446 by Leon Battista Alberti. *"His proverbial antiquarian curiosity was pinned on the famous Roman imperial ships that the emperor Caligula had built for his idleness in Lake Nemi and whose memory had never faded."* [28].

UNCLOS 1982

However, awareness of this type of Heritage has remained entirely latent for many centuries. It is necessary to wait until 1982 to see the birth of the first international text [29], which, although it was drafted to outline the laws of the sea, also includes two articles that refer specifically to underwater archaeological sites and historical objects, and provides that the same *"shall be preserved or disposed of for the benefit of mankind as a whole, particular regard being paid to the preferential rights of the State or country"* [29].

Charter of Lausanne 1990

The first specific reference to the submerged Cultural Heritage dates back to the ICOMOS charter of 1990, which defines the archaeological Heritage as "*all vestiges of human existence and consists of places relating to all manifestations of human activity, abandoned structures, and remains of all kinds (including subterranean and underwater sites), together with all the portable cultural material associated with them."* [30].

The attention spans structures and infrastructures, such as ports, harbours, and marine systems. The interest has been growing because of the development of underwater exploration technologies and techniques, which unfortunately opened the road to reavers, with subsequent damage to the Heritage itself. This prompted the European Council to adopt in 1992 the European Convention on the protection of archaeological Heritage, with the recommendation to create archaeological parks for the underwater Heritage [31].

Charter of Sofia 1996

The International Committee on the Underwater Cultural Heritage (ICUCH) was founded in 1991 by ICOMOS Australia to promote international cooperation in the protection and management of underwater cultural heritage and to advise the International Council on Monuments and Sites (ICOMOS) on issues related to underwater cultural heritage around the world[15]. As a supplement to the 1990 charter, in 1996 ICUCH authored the drafts that led to the ratification of the first document on the protection and management of the underwater Heritage, i.e. the Charter on the Protection and Management of the Underwater Cultural Heritage [32]. Hand in hand with the need for knowledge and study, awareness of the importance of this type of Heritage has therefore also developed with respect to the significant risks to which it is subject. Considerable importance is given by the increasing interest, on the part of collectors, of finds that come from the seabed; this

[15] https://icuch.icomos.org/

alarming development is in part linked to recent advances in diving technology and may give rise to forms of looting. The enhancement of the underwater Heritage must in fact deal with the problems of *"protection"* whose solutions are not always easily feasible in a marine context; the action to promote a submerged emergency, if not adequately reasoned (also through awareness programs for the local population), inevitably puts it at risk of depredation.

Declaration of Siracusa 2001

In the declaration of Siracusa, adopted in 2001 at the end of a conference on the cultural Heritage of the Mediterranean Sea, it was outlined that *"The Mediterranean countries have a special responsibility to ensure that the submarine cultural heritage they share is made known and preserved for the benefit of humankind."* [33]

Following the International Conference *"Means for the Protection and Touristic Promotion of the Marine Cultural Heritage in the Mediterranean"*, held in Palermo and Siracusa, Italy, on 8-10 March 2001 [33], the most recent international document on the subject as today is the **2001 UNESCO Convention on the Protection of Underwater Cultural Heritage**.

1St definition of UCH

In this latter document, it is proposed (for the very first time) the first definition of underwater cultural Heritage as *"all traces of human existence having a cultural, historical or archaeological character which have been partially or totally under water, periodically or continuously, for at least 100 years such as: (i) sites, structures, buildings, artefacts and human remains, together with their archaeological and natural context; (ii) vessels, aircraft, other vehicles or any part thereof, their cargo or other contents, together with their archaeological and natural context; and (iii) objects of prehistoric character*" [3].

The Convention sets out basic principles for the protection of underwater cultural Heritage by outlining four main principles:

Convention of Paris 2001

"Obligation to Preserve Underwater Cultural Heritage - States Parties should preserve underwater cultural Heritage and take action accordingly. This does not mean that ratifying States would necessarily have to undertake archaeological excavations; they only have to take measures according to their capabilities. The Convention encourages scientific research and public access.

In Situ Preservation as first option - The in-situ preservation of underwater cultural Heritage (i.e. in its original location on the seafloor) should be considered as the first option before allowing or engaging in any further activities. The recovery of objects may, however, be authorized for the purpose of making a significant contribution to the protection or knowledge of underwater cultural Heritage.

No Commercial Exploitation - The 2001 Convention stipulates that underwater cultural Heritage should not be commercially exploited for trade or speculation, and that it should not be irretrievably dispersed. This regulation is in conformity with the moral principles that already apply to cultural Heritage on land. It is not to be understood as preventing archaeological research or tourist access.

Training and Information Sharing - States Parties shall cooperate and exchange information, promote training in underwater archaeology and promote

public awareness regarding the value and importance of Underwater Cultural Heritage."[16]

Convention of Faro 2005-2011

After the UNESCO's Convention on the Protection of the Underwater Cultural Heritage (2001), the new stage of the current process of reappropriation of the cultural heritage as a common value, "popular" asset, is represented by the Framework Convention on the Value of Cultural Heritage for Society [6], adopted by the Committee of Ministers of the Council of Europe on the 13th October 2005 in Faro, effective since 1st of June 2011 and ratified by Italy on the 23th September 2020 (House of Representatives). The Convention had the merit of defining an innovative and revolutionary concept of Cultural Heritage (CH), intended as the body of resources inherited from the past, identified by the citizens as the reflection and expression of their values, beliefs, knowledge, and traditions in continuous evolution. It recognizes the right of the single citizen and all humanity to benefit from the CH, tempered by the responsibility of respecting it. These principles are the basis for the chain of research, conservation, protection, management and participation, and cultural dialogue, promoting the birth of a sustainable and multicultural social, political, and economic environment. It is a fact that UCH is increasingly required to have a social return beyond the cultural aspect, seeking a positive impact on the economic and social fabric of a community. On the other hand, the European Union guidelines promote Blue Growth and responsible and sustainable tourism linked to the sea and UCH.

Experiencing the past underwater is rapidly becoming an enormous asset in the leisure industry and the "experience economy". This development implies risks and opportunities for the protection as not all the UCH can be enjoyed through direct access for various reasons: position, depth, and safety/integrity of the assets, but also safety and diving capabilities of researchers, citizens, stakeholders and tourists.

This is particularly true for the submerged deposits of shipwrecks (hull and/or cargo and/or onboard equipment). Just those provided of inorganic cargo and at a limited depth can be accessible, but only under favourable conditions of visibility and only to a few divers, that are only a small percentage of the whole community interested in exploring its own past.

Charter of Udine 2016-2022

After 20 years of the Sofia Charter for the Protection and Management of the Underwater Cultural Heritage [32] a summit in Udine drafted an outline of the most recent experiences in the field in the Italian panorama. The discussions and considerations led to a shard proposal, the Udine Chart for the Underwater Archaeology [34]; this document represent the outcome of an intense debate of the scientific community on the UCH and the related challenges to guarantee the development of the research, promoting at the same time, virtuous model of public engagement to the archaeological heritage.

The 8th and 9th September 2022, a first workshop for updating the Udine Chart took place to ensure the inclusion of the aspects more related to internal waters, i.e.

[16] https://en.unesco.org/underwater-heritage/2001

rivers and lakes and the interaction with the opportunities offered by the development of new remote sensing technologies.

The conventions, charter, and declarations listed above can be summarised as the following Figure 4

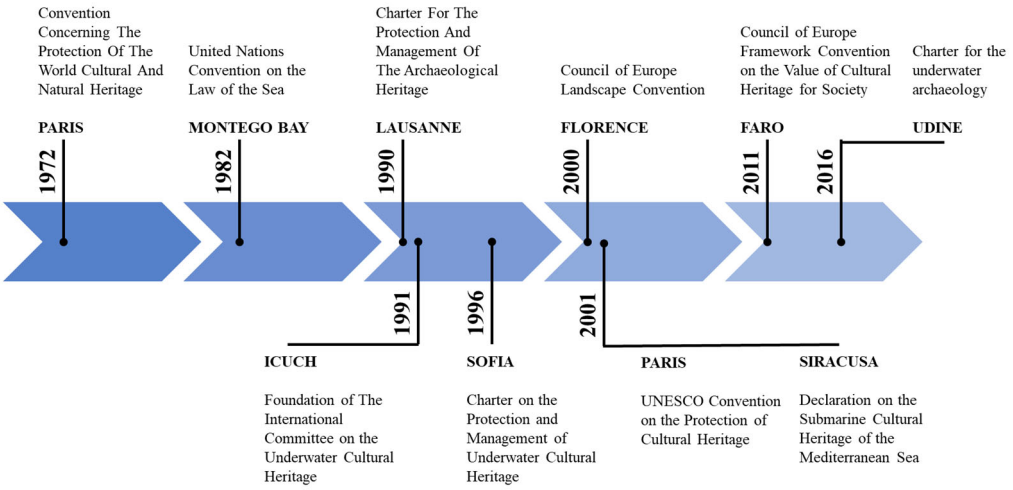


Figure 4. Main convention and charts on the concept of Underwater Cultural Heritage during the last decades.

2.2 The concept of in-situ conservation

The long evolution of the concept of Heritage comes to affect the submarine heritage as well substantially; the latter is therefore not configured as a nineteenth-century statement but as a very recent conquest if we can define it that way. It is noteworthy that in the 2001 Convention on the Protection of the Underwater Cultural Heritage [3], for the first time, **in-situ conservation** is explicitly indicated as the choice to be preferred, also to underline the importance and respect for the historical context of Cultural Heritage and their scientific relevance, recognizing that this Heritage is (under normal circumstances and for some materials) preserved underwater thanks to the low rate of deterioration due to the absence of oxygen. Therefore, recovery from the seabed is not always automatically justified. Moreover, often, in consideration of the state of conservation and the sinking methods, recovery is not always configured as the operation that guarantees maximum preservation and conservation of the asset.

In-situ conservation

For this reason, it is important to consider innovative technologies for documentation and study even by those who do not have the skills or the ability to go underwater. Adopting these technologies cannot ignore the need for historical and archaeological knowledge, which are indispensable for a careful and intelligent application of the technical solutions available today.

In-situ conservation of the underwater archaeological Heritage is a complex operation in terms of methodological approach and operational workflow. This requires a multitude of experts (not only archaeologist and geomatics, but also engineers, chemists) that can integrate the available archaeometric information.

This approach should not be considered as a sum of the different contributes, but rather a complementary coordination towards the improvement of the knowledge of the Heritage.

2.3 Marine Protected Areas

In the last years the conservation and the valorization of the cultural Heritage have been of interest of international agreements, as it is important to protect the cultural value of the in-situ conservation. For the underwater Cultural Heritage the 1992 European Convention on the Protection of the Archaeological Heritage outline the importance of *the creation of "reserve zones" for preservation of evidence to be excavated at a later time*. It is therefore crucial to explain the current system of protection of marine environment starting from the concept of *"Marine Protected Areas"* that aims not only to ensure the protection of the archaeological underwater Heritage but also the starting point for the institution of archaeological parks.

In the '80s of the last century, the IUCN (International Union for Conservation of Nature and Natural Resources) has defined the term *"Marine Protected Area"* as *"Any area of intertidal or subtidal terrain, together with its overlying waters and associated flora, fauna, historical and cultural features, which has been reserved by legislation to protect part or all of the enclosed environment"* [35], [36]. With these definitions, the IUCN intended to protect non only the seabed, but also the water, the flora and fauna and the archaeological remains located above it, ensuring not only the protection of the biodiversity but also the protection of the cultural evidences.

Protected areas are divided into six types, depending on their objectives [37]:

MPAs classifications

Category I – Protected area managed mainly for science or wilderness protection (Strict Nature Reserve/Wilderness Area);
Category II – Protected area managed mainly for ecosystem protection and recreation (National Park);
Category III – Protected area managed mainly for conservation of specific natural features (Natural Monument);
Category IV – Protected area managed mainly for conservation through management intervention (Habitat/Species Management Area);
Category V – Protected area managed mainly for landscape/seascape conservation and recreation (Protected Landscape/Seascape);
Category VI – Protected area managed mainly for the sustainable use of natural ecosystems (Managed Resource Protected Area). (IUCN, 1994)

MPAs are established with the aim of creating an integrated marine-land system of protected environments. The adoption of specific action of protection of the marine environment is even more necessary for the Mediterranean Sea, due to a relevant number of archaeological evidence that are disseminated among; for this reason and *"because of their scientific, aesthetic, historical, archaeological,*

cultural or educational interest" with the aim of safeguard the resources, the natural sites and the cultural Heritage of the Mediterranean sea, with the possibility of identify MPAs for preserving relevant sites, the United Nations Environment Programme (UNEP) Regional Seas Programme proposed a regional convention adopted in 1976 [38] to prevent pollution from different human sources in the Mediterranean sea. The convention was adopted on 1976, updated in 1982 [39] and amended on 1995.

Also the IMO (International Maritime Organization) has established some guidelines for the Identification and Designation of Particularly Sensitive Sea Areas (PSSAs) [40]:

"A PSSA is an area that needs special protection through action by IMO because of its significance for recognised ecological, socio-economic, or scientific attributes where such attributes may be vulnerable to damage by international shipping activities. An application for PSSA designation should contain a proposal for an associated protective measure or measures aimed at preventing, reducing, or eliminating the threat or identified vulnerability. Associated protective measures for PSSAs are limited to actions that are to be, or have been, approved and adopted by IMO, for example, a routeing system such as an area to be avoided.

The guidelines provide advice to IMO Member Governments in the formulation and submission of applications for the designation of PSSAs to ensure that in the process, all interests - those of the coastal State, flag State, and the environmental and shipping communities - are thoroughly considered on the basis of relevant scientific, technical, economic, and environmental information regarding the area at risk of damage from international shipping activities."[17]

The conventions, declarations, and guidelines listed above can be summarised as the following Figure 5.

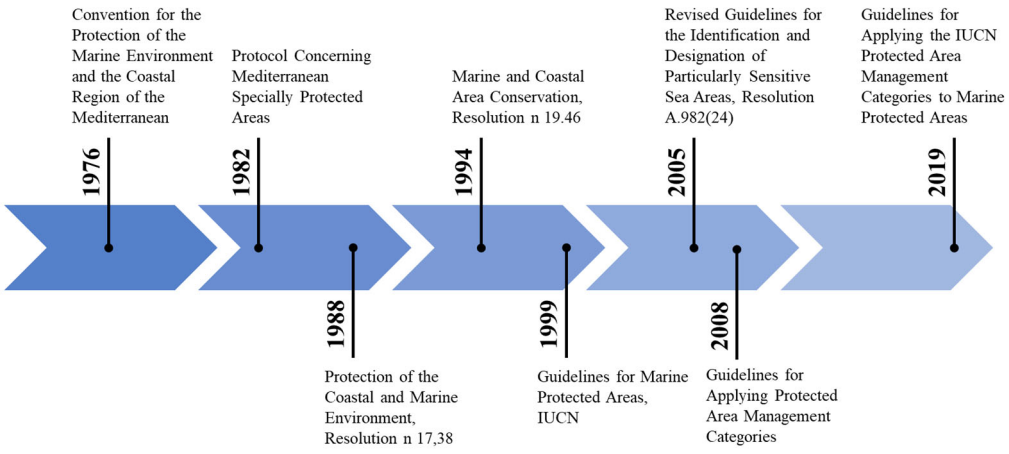


Figure 5. Main conventions, declarations, and guidelines on the definition of Marine Protected Areas.

[17] https://www.imo.org/en/OurWork/Environment/Pages/PSSAs.aspx

2.4 The marine environment and the coastal Landscape

In the above paragraphs, it has been explained the concept of Underwater Cultural Heritage and its evolution in the last 70 years.

There is a strong bond that links the Underwater Cultural Heritage with the cultural identity of the Mediterranean Sea; in fact, the coast of the Mediterranean has been a place for cultural and economic exchanges, whose archaeological traces and remain are the witnesses. Therefore, it is essential to fully understand the problematics of the conservations of these artifacts through proper documentation techniques, deepening theoretical and methodological aspects related to the management of coastal areas, and the integrated preservation of archaeological sites.

The challenges related to the documentation of the coastal landscapes are complex and multifaceted. Some have already been addressed by different means, others lie on uncharted ground, including setting up innovative approaches, using and re-appropriating cultural content to preserve and transmit this invaluable treasure to future generations. The underlying methodological approach to the landscape or, still better, seascapes archaeology, is holistic, contextual, diachronic, and transdisciplinary. The landscape is the "living palimpsest", no longer made up of isolated monuments but of "assets" related to each other, which only if inserted in a "system" and framed within, become comprehensible in all their historical, cultural, and social value.

The progressive emergence of the notion of "environment," which was not existing in the 1948 Italian Constitution, was introduced in Italy by the Franceschini Commission (Commissione d'indagine per la tutela e la valorizzazione del patrimonio storico, archeologico, artistico e del paesaggio, created with the law L. 310 of 1964).

The management and protection of cultural Heritage and of the natural environment encountered various difficulties in Italy following the Second World War, following the emergence of the concept of "cultural heritage" as opposed to the one of "historical-artistic heritage".

The protection of the natural environment has suffered from a series of problems, still not resolved as today, linked to the expression "cultural and environmental heritage," which seems to indicate that the environmental Heritage is not also cultural by definition. As Oreste Ferrari writes, this "may seem like a simple question of terminology, but in reality, it is a substantial question, which has in fact determined different types of behaviour in the protection action." [41].

In Italy, the documentation of archaeological underwater and coastal sites has been, in recent years, an essential subject of different conferences and seminars, as the interest in this kind of Heritage has increased in the last decades. In particular (again in Italy), the numerous and important disastrous events (earthquakes, land exploitation, coastal erosion, landslides, and floods caused by indiscriminate deforestation) have constituted further difficulties that require collective attention and public intervention.

The proceedings of the World Environment Day (Held in Rome on June 5, 1985) subsequently promoted the unequivocal interconnection between the "historical-cultural" environment and the "physical-natural" environment. Thanks to this, the development of diagnostic and monitoring systems has been achieved, which allows documenting, through maps, the factors that increase the vulnerability of cultural Heritage, with particular reference to anthropogenic and environmental phenomena.

The submerged Heritage is closely linked to the marine and coastal Landscape in which it is located; even if at the beginning of the twentieth century, the protection of landscape assets and the notion of "landscape" was legally considered in the same way as that of "things of art" [42], at the beginning of the twenty-first century, since there was a need for a vision broader than the concept, we find a reference to the marine Landscape in the European Landscape Convention, which extended the notion of Landscape to *"the entire territory of the Parties"*, including *"natural, rural, urban and peri-urban areas [...], land, inland water, and marine areas"* [43].

The concept of Landscape and the definition of landscape heritage can be extended also to the coastal areas. The first application of this concept was internationally introduce by Westerdahl as "the whole network of sailing routes, with ports, havens and harbours along the coast, and its related constructions and other remains of human activity, underwater as well as terrestrial" based on this approach, the so defined Landscape should be compared "to its terrestrial counterpart, but not just as an extension of the latter" including also "shipping, shipbuilding and fishing and their respective hinterlands, with nodal points of coast towns and land roads, fords, ferries and inland waterways" [44].

The coastline as a frontline, is something that evolves over the decades and centuries, and it is correct to sustain that every shore with the related marine areas, from the point of view of the knowledge, interpretation and preservation, as expression of the way the man shaped and transformed natural sites to be adapted at his needs, it's part of cultural resources, and specifically architectural and landscape heritage [45].

Analysing the coastline as any other architectural expression, it is possible to define some criteria (conceptual, methodological, and practical) similar to the modern culture of restoration. The main aim to follow is to mediate the socio-economic needs to those of preservation of the coasts, meant as natural and historic-cultural systems and subsystems [23]. Following this approach it is not correct to focus only to the single Heritage, but it is important to understand the relations with the surrounding territories; this imply the creation of paths and itinerary for historical and cultural promotion, inside a new panorama of relations between each of the connected archaeological emergencies, each of them understood on its authenticity and unicity [23].

The topic of the relation of the coastal areas and the duality land-sea has a strong cultural connotation and emblematically represent the symbol of the underwater archaeological Heritage, whose conservation can't preclude the study of the connections with the land. For this specific purpose it remains crucial to develop

new ways of integrating heterogenous data in specific GIS (Geographic Information Systems) that can represent a good starting point for each conservation and valorisation activity for the archaeological Heritage and the landscape heritage.

The concept of protection and valorisation of coastal areas, and the complex relation between sea and land, has a strong cultural value represented by the importance many archaeological findings, whose preservation must be linked with the evaluation of historic and environmental dynamics that are in common with lands above sea level.

Coastal areas have always been a dynamic environment; apart from natural factors, the seashore have been affected (especially in the recent years) by different anthropic factors. The study of Underwater archaeological sites requires to understand and virtually reconstruct the coastline, based on interpretation of both archaeological data and available geomatics, geologic and geophysics data. The integration of data from those disciplines fostered the acquisition of a knowledge also towards the topic of coastal Landscape and archaeology of coastal settlements.

The link between geological phenomenon (proximity to a river, composition of the soil and the rocks) and the presence of archaeological evidence is very important, this is the main reason why it is possible to find archaeological remains also hundred meters inner land from the coastline. In the Mediterranean Sea we have witnessed a retreat of the coastline that caused the submersion of human made artifacts and structures (today those sites vary in depth, between some centimeters up to 3-4 meters).

The study of the sea level and the interpretation of the causes behind the submersion of those archaeological remains are complex; there are several reason such as eustatic sea level change due to changes in either the volume of water in the world's oceans or net changes in the volume of the oceanic basins, vertical tectonic movements, coastal erosion or mineral deposits formed during the accumulation of sediment on the bottom of rivers and other bodies of water. Each of those causes is related to a different way to study how and why the phenomena happened.

The coastline of the Mediterranean Sea for the last 2000 years has been drafted by Antonioli and Leoni [46] based on measured performed on roman pool of imperial period located in the Tyrrhenian Sea. The fact that those structures had strong relations with the sea level allowed to understand useful information about the historical sea level (and therefore coastline) of that period.

Harbours, ports, and pool annexed to roman villas were built in function with the activities related to the sea, and they maintained strong relations between the sea level and the geographical context. The documentation of the relationships between the ports, the cities and the territories is crucial to understand their role in the general maritime politic [47].

The integration of Geomatics, geophysics and archaeological data allows to understand and reconstruct the coastline, as it was in ancient ages, and therefore allows not only the comprehension and the study of the coastal Landscape and to actuate countermeasures for coastal erosion, but also the human impact on the recent phenomenon of climate change. This is helped by the possibility of chronologically classify the archaeological remains located along the shore.

The most recent geo-archaeological studies related to the Mediterranean Sea shows that the main reason for submersion of underwater Heritage is linked to a slow increase of the sea level that caused in the last 2000 years a slightly noticeable regression of the coastline [48]–[50], with some more important tectonical movements (mainly local) such as the case of Campi Flegrei, that caused a more important submersion of several meters below the current sea level [51].

The study of this kind of data is important to define the relations between the submerged archaeological Heritage with the coastline and the land, also considering the period and the context of the sinking, to define connection also useful for valorisation and protection actions.

In an optimal situation, valorisation, and conservation projects of MPAs should aim to contextualise the underwater Heritage in the surrounding framework from and environmental and Landscape point of view. Valorisation and conservation project should also ensure a system of services for enabling the fruition of the Heritage; in this way, the importance is given not only to the conservation but also to the valorisation, keeping a balance between the anthropic risk and the need of promotion and making "visible the invisible". This must be linked with research activities that aims at communicating scientific data in a fast and easy way, not only to scientist but also to the public (not from the point of view of tourist marketing, but for the promotion of the cultural and historical point of view of specific places and regions).

The idea of the coastal Landscape, and the Landscape in general is not the esthetical one of "panoramic view" but rather as the identity of the places, a compresence of nature, culture, history and the assumption of the aesthetic identity of the Landscape as an integration of this three elements [52]

2.5 Initiatives to document and promote UCH

For the present research aim of documenting the Underwater Cultural Heritage it is essential to analyse the existing associations, projects and recent articles related to UCH documentation and preservation. An investigation of existing ideas, discussions and proposals was carried out to support the documentation of these places. This paragraph presents a list of some initiatives aimed to document, preserve, and promote UCH. Below, some Italian examples of "groups and associations", "events", and "paper from newspapers and websites" are presented subdivided into different classes of typology. The following list is by no means exhaustive, but it covers the main areas.

National associations and Administrative Bodies:

- Soprintendenza del Mare della - Regione Siciliana[18]

[18] https://www2.regione.sicilia.it/beniculturali/archeologiasottomarina/

- Soprintendenza Nazionale per il Patrimonio Culturale Subacqueo[19]
- Fondazione Sebastiano Tusa[20]
- AIOSS (Associazione Italiana Operatori Scientifici Subacquei)[21]

International associations and Administrative Bodies:

- ISPRS WG II/9 - Underwater Data Acquisition and Processing[22]
- The ICOMOS International Committee on the Underwater Cultural Heritage (ICUCH)[23]
- UNESCO Underwater Cultural Heritage[24]

International institutes, centers, societies and fundations:

- IKUWA (Internationaler Kongreß für Unterwasserarchäologie)[25]
- Département des recherches archéologiques subaquatiques et sous-marines (Drassm)[26]
- Centre Camille Jullian CNRS bureau d'architecture navale antique[27]
- Arqueologia Nautica y Subacuatica[28]
- Centro de Arqueología Subacuática[29]
- Instituto para la Memoria Arqueológica Naval Hispánica
- National Park Service (NPS) – Submerged Resources Center[30]
- Alexandria Centre for Maritime Archaeology & Underwater Cultural Heritage[31]
- Institute of Nautical Archaeology (INA)[32]
- INA Foundation - Institute of Nautical Archaeology[33]
- INA Turkey Bodrum Research Center[34]
- The Honor Frost Foundation[35]

[19] https://www.beniculturali.it/ente/soprintendenza-nazionale-per-il-patrimonio-culturale-subacqueo

[20] http://www.fondazionesebastianotusa.org

[21] https://www.aioss.it/

[22] https://www2.isprs.org/commissions/comm2/wgs/#wg2-7

[23] https://icuch.icomos.org/

[24] https://en.unesco.org/underwater-heritage

[25] https://www.nauticalarchaeologysociety.org/ikuwa

[26] https://www.culture.gouv.fr/Thematiques/Archeologie/Acteurs-formations/Les-services-de-l-archeologie-au-ministere-de-la-Culture/Le-departement-des-recherches-archeologiques-subaquatiques-et-sous-marines

[27] https://ccj.cnrs.fr/spip.php?article1863

[28] http://arqueologianauticaysubacuatica.uca.es/

[29] https://www.juntadeandalucia.es/organismos/iaph/estructura/centro-arqueologia-subacuatica.html

[30] https://www.nps.gov/orgs/1635/index.htm

[31] http://www.cmauch.org/

[32] https://nauticalarch.org/

[33] https://nauticalarch.org/ina-foundation/

[34] https://nauticalarch.org/bodrum-research-center/

[35] https://honorfrostfoundation.org/

- NAS Nautical Archaeology Society[36]
- Ephorate of Underwater Antiquities[37]
- The Turkish Foundation for Underwater Archaeology (TINA)[38]
- The Leon Recanati Institute for Maritime Studies (RIMS)[39]
- Institut Européen d'Archéologie Sous-Ma¬rine (IEASM) F. Goddio[40]
- Oxford Centre for Maritime Archaeology[41]
- Center for Underwater Archeology of Catalonia (CASC)[42]
- Centre for Maritime Archaeology - University of Southampton[43]
- The German Society for the Promotion of Underwater Archaeology (DEGUWA)[44]
- The Albanian Center for Marine Research[45]
- The department of underwater archaeological studies of The National Heritage Institute (INP) Tunisia[46]
- Centre of Underwaterarchaeology of the Ministry of Culture of Bulgaria[47]
- Institute for the Protection of Cultural Heritage of Slovenia, Ljubljana[48]
- International Center for Underwater Archeology in Zadar[49]
- Croatian Conservation Institute – Underwater Archaeology[50]
- Laboratory of Maritime Archaeology (LabMA), Kotor Montenegro
- AURORA Trust Foundation[51]

Projects, groups, and initiatives:

- Underwater Muse[52]
- Fish&Chips[53]

[36] https://www.nauticalarchaeologysociety.org/
[37] http://www.culture.gov.gr/en/ministry/SitePages/viewyphresia.aspx?iID=1369
[38] https://anamed.ku.edu.tr/en/about/other-offices-in-merkez-han/the-turkish-foundation-for-underwater-archaeology-tina/
[39] https://maritime.haifa.ac.il/
[40] https://www.ieasm.institute/institute.php
[41] https://ocma.web.ox.ac.uk/ocma
[42] http://www.maccasc.cat/Museu-sota-l-aigua
[43] https://www.southampton.ac.uk/archaeology/research/groups/centre_for_maritime_archaeology.page
[44] http://www.deguwa.org/
[45] https://www.facebook.com/albaniamarinecenter
[46] https://www.inp2020.tn/en/inp_tunisie/
[47] http://www.museology.bg/en/museums/i5/center-for-underwater-archaeology.html
[48] https://www.zvkds.si/en/about-us
[49] http://www.icua.hr/en
[50] https://www.h-r-z.hr/en/index.php/djelatnosti/konzerviranje-restauriranje/podvodna-arheologija
[51] https://www.auroratrust.com/about/
[52] https://www.italy-croatia.eu/web/underwatermuse
[53] https://greece-italy.eu/rlb-funded-projects/fishchips/

- BlueMed[54]
- MedDive in the Past[55]
- MUSAS[56]
- AMPHITRITE
- The Pavlopetri Underwater Archaeology Project[57]
- Archeologia Subacquea Speleologia Organizzazione (ASSO)[58]
- SUNRISE Summer School[59]

All these initiatives show how the attention towards the study, the conservation and the promotion of the UCH is nowadays a reality established worldwide. Because the promotion of the marine context and the production of new sustainable plans requires a careful knowledge on the condition, extension, position and metric consistency of the archaeological remains and cultural sites underwater, it is crucial to provide geomatic solutions to accurately document the UCH.

2.6 An example of political action towards the protection of UCH: The Italian National Superintendency for Underwater Cultural Heritage

Due to the need of the need for many skills necessary for the protection, management, and enhancement of the sea and its riches, in recent years, the Sicily Region has equipped itself with structures created with the specific purpose of carrying out research, investigations, recovery, and valorisation of the underwater archaeological Heritage, a pre-eminent sector for the island already in the post-war period. This is how in 1999, the GIASS (Gruppo d'Indagine Archeologica Subacquea Sicilia - Sicily Underwater Archaeological Investigation Group) by Prof. Sebastiano Tusa, who will later become the first superintendent for the Superintendence for the Cultural and Environmental Heritage of the Sea, established by the Sicily region in 2004 [53].

With the establishment of the Superintendency of the Sea, Sicily was (at the time) the very first administrative body in Italy and in Europe that protects, manages, and enhances the culture of the sea. "Sea and culture is a combination that represents for us something inseparable which, in addition to being the daily object of the exciting path of research, knowledge, protection, and enhancement that we practice with professionalism and enthusiasm, can be for the future of this island something more than a tourist slogan. " [28].

[54] https://bluemed.interreg-med.eu/
[55] http://meddiveinthepast.eu/
[56] https://www.progettomusas.eu
[57] https://www.nottingham.ac.uk/pavlopetri/index.aspx
[58] https://asso-net.blogspot.com/
[59] https://www.sunrisesummerschool.com/

Later in 2009, the Italian National Superintendecy of Underwater Cultural Heritage was created. “The National Superintendency for Underwater Cultural Heritage is an office with special autonomy of a non-general managerial level under the Ministry of Culture of Italy. The Superintendency is responsible for the activities of protection, management, and valorisation of national underwater cultural heritage.” [60]

The National Superintendence for Underwater Cultural Heritage, hereinafter "National Superintendency", based in Taranto, oversees the performance of the activities of protection, management and enhancement of the underwater cultural heritage referred to in Article 94 of the Code, as well as the functions attributed to Ministry pursuant to the law of 23 October 2009, n. 157, concerning the ratification and execution of the Convention on the protection of the underwater cultural heritage, adopted in Paris on 2 November 2001. To this end, it liaises with the Superintendencies of Archeology, Fine Arts and Landscape.

In the territory of the Province of Taranto, the superintendent of the National Superintendency also carries out the functions pertaining to the superintendents of Archeology, Fine Arts and Landscape. The superintendent also exercises the functions referred to in article 43, paragraph 4, on state institutes and places of culture present in the same territory, and not assigned to other offices of the Ministry.

The National Superintendence has operational centers at the Archeology, Fine Arts and Landscape Superintendencies with headquarters in Naples and Venice and in the others identified with a subsequent provision.[61]

[60] https://www.coe.int/en/web/cultural-routes/-/national-superintendency-for-underwater-cultural-heritage

[61] https://www.beniculturali.it/ente/soprintendenza-nazionale-per-il-patrimonio-culturale-subacqueo

3

Chapter 3

3. Underwater Cultural Heritage: metric documentation with traditional and Geomatics techniques and methods

Researches have changed the way they interact with and document the Underwater Cultural Heritage, over the decades.

The importance of modern technologies and innovative methods used today for the documentation of the Heritage is not only linked to the ease with which they allow the dissemination among groups of scholars and researchers, but also fundamental for the involvement of the general public. In particular, the study of the submerged Heritage contributes not only to the formation of cultural identity at the local level but also internationally, since most of the wrecks and the loads they carried are located in international contexts, deriving directly from ancient trade routes, for which ships, and their contents can often be located today at a great distance from their context of origin or destination.

Unlike in the past, thanks to these technologies, it was possible to witness the transition from one-way communication (passive for the user) to involve the broad public. The democratisation of knowledge that has introduced the extensive use of the web and social networks is an example of this concept. Today, quoting Giuliano Volpe, we have "graphic reconstructions, virtual processing, multimedia products, 'time machines' and other digital technologies which are just some of the possible tools to tell stories layered in landscapes or enclosed in an artifact, in a clear way,

understandable, compelling, exciting, fun, in order to arose curiosity and even joy, starting with children " [54].

Thanks to the “art bonus” [55], digital technologies have also helped to bridge some important delays in Italy. In fact, in art. 12 paragraph 3 [55], the free reproduction of any cultural property is envisaged. As Giuliano Volpe's reflections also underline, thanks to advances in the field of digital photography and the ever-increasing accessibility of photographic means, it is now possible to "reproduce and make available online many images of archaeological finds, works of art, books, manuscripts, facilitating their knowledge, sharing and consultation, not only among scholars from all over the world but also among ordinary citizens and tourists." [54]

Many problems today can indeed be solved with technological solutions and thanks to the progress of science, but on the condition that the structural and organisational problems, and the cultural points of view that caused them, are not neglected. [56]

The Italian geographer and academic Lucio Gambi also focus on the importance of these tools for the *Istituto per i Beni Artistici, Naturali e Culturali* (the Italian Institute for Cultural and Natural Heritage); if it is true that photographic and cartographic operations cannot, on their own, provide complete documentation apart from the need of choosing "between things to focus on and things to leave in the shade" [57], graphic and photographic documentation remains the necessary condition for the heritage documentation, whether it is a complex of cultural or environmental assets, or in the case of a single asset. The photographic and cartographic reproduction will necessarily have to lead to a research phase, which will include "the historical processing of the materials in order to obtain a more exhaustive picture around each studied theme" [57].

The importance of images in the study of Heritage, today fundamental as the subject of photogrammetric techniques applied for metric and documentary purposes, is not only linked to the advent of photography (and more recently to image-matching algorithms); already between the sixteenth century and the end of the eighteenth there was a need for the study of antiquities comparable to the study of natural sciences, a study "aimed at the same description, controllable and therefore reliable, of its objects" [58] from which the importance illustration, always to make observable and comparable by all scholars "what can happen under the eyes, and what can be represented in images" [59].

Even if an accurate survey is important for underwater archaeology, the survey itself must link the archaeological knowledge to the surveyed geometry. So not only computer science must be involved, but it is always fundamental to insert archaeological knowledge in the process [60].

It is possible to identify three main topics regarding the issues connected to geomatics applications in underwater environments. A first point concerns the generation of the 3D models and the related metric products, which is related to best practices and standards adopted during the acquisition phase (e.g., image overlapping, camera calibration, radiometric correction, integration with data from different sources). A second point is related to the correct georeferentiation of the generated 3D model and the related metric products, due to the difficulty (or

impossibility) of relying on GNSS when underwater. Finally, a third topic is related to dissemination and management: certain visualization platforms offer the possibility of interacting with the model, with the option of generating geometric sections and sharing models in ways that facilitate communication within or between different user groups.

This chapter illustrates the different techniques and methods applied in this thesis for surveying underwaters assets and sites, to clarify the context in which the methodology of the thesis is set.

3.1 Traditional documentation techniques

For surveys in marine environment, it is crucial to ensure the operators have a deep physical knowledge of the site and its environmental conditions (i.e., morphology, depth, currents, visibility and transparency of the water, general condition of the sea, and so forth). The most important factor is, above all, the depth in which the site is located, as this will affect not only the diving time and the safety related issues, but also due to the penetrations of the light spectre at different depths, that will influence the identification of the materials, together with the photographic and photogrammetric acquisitions.

The knowledge phase for an underwater site involves different disciplines, several professionals and specific analysis that might led to the reconstruction of the hypothesis of the sinking, the geologic characteristics of the area, the metric survey of the structures and artefacts, the identifications of materials and the related degradation. This knowledge phase must always be supported by historical-archaeological research, by referring to both antiques and modern sources, especially when related to ancient port structures. Another source of information are paintings, historical pictures, legacy aerial images and postcards, maps, archive data, technical reports, and everything that could help describing the topographic context.

The described approach is important for underwater sites in which the aim of the survey and documentation is to guarantee the in-situ conservation of the heritage.

This preliminary recognition must focus not only on the water body but also to the surrounded environment (both shores and lands). In the specific case of this dissertation, for very shallow water, the use of aerial photography is of fundamental importance, as it not only allows to spot archaeological alignment of structures, but also (in case of very clear and shallow water) the consistency of the findings.

Already acquired aerial data must be interpreted and sometimes manipulated to enhance the contrast, in order to define the consistency and the general topography of the site. If properly used, arial images might be the basis for the subsequent realization of a general planimetric view of the site. Nowadays it is common the use of satellite images or UAS images, depending on the required resolution of the final map to be produced.

The survey campaign is performed in an integrated way, both with direct and indirect investigation techniques. Nowadays it remains crucial to execute an accurate documentation for the subsequent study or valorisation phase.

Before beginning any excavation phase, it is necessary to provide a complete site plan and an accurate photographic documentation; those will be important to decide how to proceed with the excavation.

After delimiting the area and starting with the first phase of excavation, it will be necessary to cover the excavated area with a grid square (Figure 6), this operation is called "site gridding" and allows to divide the excavation area in smaller squares. Each grid square must be linked to the adjacent squares by using pickets that will mark reference points of known coordinates, to be left on position for the entire duration of the excavation.

There are different kind of grid squares; 1x1 m^2, 2x2 m^2 but also bigger or smaller size, up to 0,1 m in the case of detail survey. The structures can be made using PVC or metallic structures that will have to lean directly on the seabed using free-standing devices that will be used also as ballast.

Every corner of the grid square will be marked with an identification plastic label with permanent marker, (i.e., with a letter and a number).

The excavation will follow the same principle of ground excavation, layer by layer, making sure to avoid low visibility conditions caused by the sediment removing and the consequent suspension in the water. If needed, a Sorbonne pump[62] might be used.

It is important to perform a photographic survey of every layer before its removal, and eventually draw any scientific reference that can be worthy of attention.

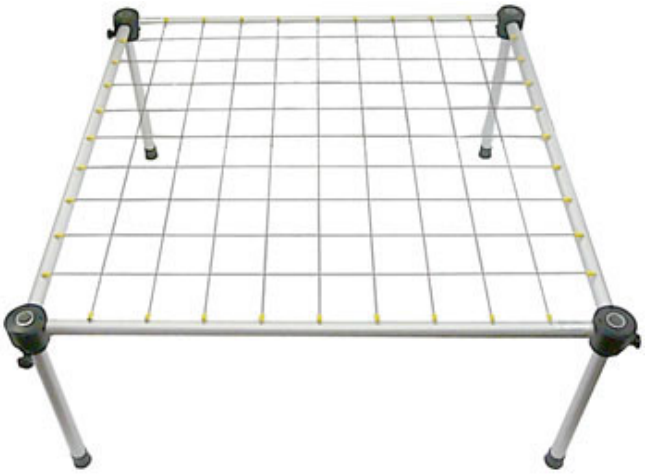


Figure 6. Example of aluminium grid square used for archaeological documentation purposes.[63]

[62] Specific pump used to remove muddy earth on sea or lake bottoms, especially for archaeological prospecting purposes, based on the emulsifier principle.

[63] http://www.brescianisrl.it/newsite/ita/stampa_prodotto.php?stampa=2290

3.2 Underwater photogrammetry

Consistent with emerging documentation requirements, the study of underwater CH via Geomatics employs Photogrammetry, that can be used for the remote or indirect study of inaccessible CH sites by domain experts.

Underwater photogrammetry has become one of the most affordable and adopted methods for the documentation and the 3D reconstruction of submerged archaeological assets. In the digital evolution of Photogrammetry, images are captured to exploit (using computer vision-based procedures such as image matching and Structure From Motion solutions) their intrinsic metric contents.

One of the very first application of photogrammetry in underwater archaeology has been proposed by D. Rebikoff in 1958. The project consisted in the in-situ displacement of a grid square to define the flight path and the acquisition scheme for a pre-planned overlap/sidelap. The grid square, realised with ropes, was provided with knots at specific distances to be recognisable in the images. Diver operator were required to proceed at a constant depth shooting images at each knot [61].

If for small wrecks and contained cargo loads it is possible to easily operate with divers' operators, in case of sites with higher extensions, or bigger wrecks with spreaded out cargo loads it is important to better organize the displacements of markers to be surveyed with different techniques.

Although underwater photogrammetry has become widely adopted, there are still significant unresolved issues – especially those related to the acquisition and the processing phases of underwater imaging – that are worthy of attention. First of all, the documentation itself is not sufficient and must be supported by careful georeferencing strategies of a topographical survey, and its consistency through the use of the same reference system [62]. Moreover, due to the need for generating an accurate virtual 3D replica or twin of the surveyed object or site, it is necessary to address specific issues, such as preserving consistent radiometry, avoiding blurry and low-contrast or over/under-exposed images, and the like. Even if the definition of best practices and standards to be adopted during the acquisition phase appear to be difficult, there is a massive amount of data gathered so far by professionals and the scientific community all over the world that cannot be discarded. The compelling idea is to attempt to achieve the best possible reconstruction results, even from sub-optimal (turbid, blurry, low contrast) datasets or less-than-ideal acquisition geometry. An investigation of different strategies and approaches for balancing the quality of the geometric and the radiometric component of the photogrammetric products, without neglecting their reliability concerning the surveyed object, will be addressed in § 4 and § 5.

3.2.1. Optical and physics issues related to underwater photogrammetry

For submerged Heritage, for which it is necessary to work in the marine environment, the phase of survey is one of the most important (together with the

planning phase), as it is functional to understand not only the current state of the assets, but also to make historical hypothesis and assumptions, as well as defining the successive steps of valorisation. Marine environment and conditions cause specific alterations that requires again the joint collaboration of different scientists in a multidisciplinary approach. A basic knowledge of the physical principles that regulate the transmission of light helps to understand both the optical phenomena and the "countermeasures" to be adopted when performing a photogrammetric survey.

3.2.1.1 The underwater spectrum of light and the selective absorption

An important factor that influences the survey is the depth in which the assets are located: this is related to a degradation in the visible electromagnetic spectrum; and it is an important aspect for the study and the recognition of the materials, both for photographic and photogrammetric purposes.

Sunlight, which we normally consider “white light” is the ensemble of a wide range of shades. These, by limiting to the visible colours, range from red to violet in the following order: red, orange, yellow, green, light blue, blue and violet. Water, like many other substances, absorbs part of the light that passes through it. This absorption is not homogeneous but occurs in a different way, depending on the mass of water crossed by the light, for the various colours. The phenomenon is known, precisely because it occurs in a selective way on the various colours, with the term "selective absorption".

Underwater images are therefore affected by inconsistency in radiometry; due to the optical properties of water. When light propagates in the water, all (but mainly higher wavelengths) colours are affected by a degradation in intensity. This degradation changes, as we mentioned, based on the examined wavelength and mainly in function to the acquisition depth, but also of the camera to object distance, and the water physical characteristics and conditions for a given site at the specific acquisition time frame. Water causes significant attenuation of light while it passes through it, making its intensity exponentially weaker the more it travels [63]. The attenuation of light underwater is frequency-dependent meaning that red light is attenuated over much shorter distances than blue light, as well as the backscattering of blue and green, resulting in a change in the observed colour of an object at different distances from the camera and light source [64].

Objects photographed underwater appear to have a false blue/green tone; this is a result of several effects that are caused due to the water while in the air these effects are not present. Non-absorbed waves come to our eyes basically in two ways: through reflection and transmission. Reflection occurs with opaque objects, when the unabsorbed wavelength is deflected and reaches the observer's eye (or the camera senor); transmission, on the other hand, concerns transparent objects, which absorb some wavelengths and let others pass through them, taking on the colour of the latter. The same phenomenon occurs with the sea. Water absorbs some wavelengths very well (i.e., red, green and yellow) which are then "taken out of the way", preventing us from seeing them. The wavelengths that remain (i.e., blue) are

not absorbed but are passed through the water, allowing us to see the sea of that colour.

Another factor that should not be underestimated is the presence of materials in the water: for example, if we consider the delta of a river, probably the suspended sand and clay particles will give the water a more turbid colour, tending to brown. The presence of phytoplankton is another cause of colour distortion in underwater environments; in fact, it absorbs blue and red, resulting in a reflection of green. In practice, where there is water with phytoplankton, its colour will be more green than blue. This seemingly useless information is extremely important: studying the colour of the ocean allows scientists to assess the distribution and location of phytoplankton worldwide.

Countermeasure: White balance

In digital cameras the "white balance" feature allows the camera to interpret the colours in an appropriate way by eliminating the chromatic dominants due to the light that, instead of white, can be coloured. White balance eliminates this unpleasant effect by returning more natural colours; something that cannot happen using film instead. The advantage of digital images, compared to traditional film photography consists in being able to automatically correct the colours and give them a more similar aspect to the real one. However, there are some limits: the camera can reduce the intensity of a chromatic component, for example blue, if this predominates over the others but certainly cannot create red where it is totally absent.

Countermeasure: Artificial light

This first problem can be partially solved by using the flash. Its white light allows to revive even the dullest colours, but only at a certain distance. What happens with sunlight also happens with flashlight. By saying earlier that colours are absorbed as a function of the amount of water the light passes through, it means that it doesn't matter which direction the light comes from; what matters is the distance the light travels underwater (Figure 7).

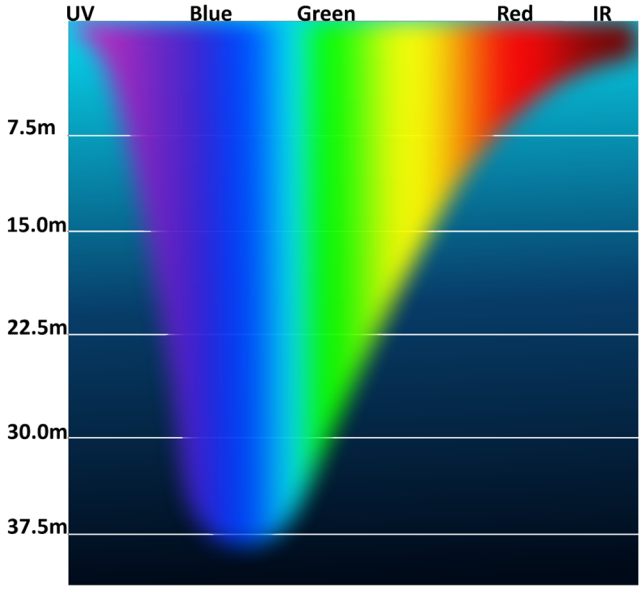


Figure 7. The colourful rainbow bands that make up white light get absorbed / attenuated by liquid water at different rates. This graph attempts to approximate how deep certain

colours of light penetrate. According to this graph, blue light penetrates deepest, while ultraviolet, red and infrared are rapidly absorbed near the surface.
Source: Wikimedia Commons, Author: Tomemorris, License: CC-BY-SA-4.0

Another factor to be considered is the depth of the bottom. If we are in the middle of the ocean, the light will not be able to penetrate for more than a few hundred meters, so - in other words - we will not have any kind of reflection of the bottom and we will see the water of a dark and intense blue. If, on the other hand, we are close to the coast, we will see the water of a brilliant blue-turquoise due in part to the reflection of the seabed. The phenomenon of reflection is described in § 3.2.1.3

3.2.1.2 Diffusion and backscattering

Diffusion is another important phenomenon that must be kept in mind, and it is related to the presence of suspended materials in the water. Micro-organisms, such as plankton, are always present; in tropical areas the period of coral reproduction is characterized by large numbers of eggs dispersed in the water; but the real issue is the sand. Whether raised from the seabed due to rough seas or carried for example by rivers, the sand more than anything else can make an underwater panorama as if it were shrouded in fog. The light, hitting the suspended materials, is reflected in every direction so that everything appears blurred and lacking details. This phenomenon is however always present since the presence of suspended elements in the water is a common factor.

Backscatter or backscattering is usually a diffuse reflection due to scattering and refers to the light from a flash or strobe reflected from the particles in the lens' field of view, causing specks of light to appear in the photo. This gives rise to what are sometimes referred to as orb artifacts. Photo backscatter can result from snowflakes, rain or fog, or, in the specific case, suspension in the water medium. Due to the size limitations of modern compact and ultra-compact cameras, especially digital cameras, the distance between the lenses and the built-in flash has decreased, thereby reducing the angle of reflection of light on the lenses and increasing the likelihood of reflection of the lens. light from normally subvisible particles.

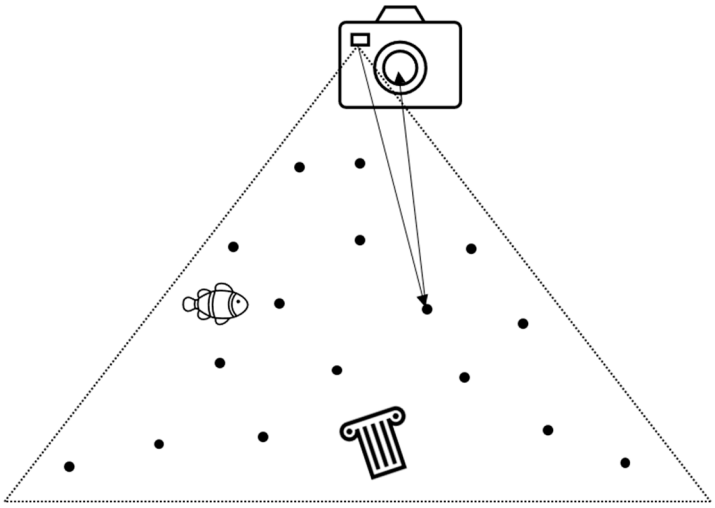


Figure 8. Backscatter from a strobe near the lens

Countermeasure: Strobe direction

Backscatter can be reduced by compensating for the strobing direction of the photo as far away from the corner of the lens as possible. This is normally done by placing the light source high and to one or both sides by placing the strobes on extendable arms. As the light comes from the sides, the reflected light is mainly in the direction of the strobe instead of the camera lens.

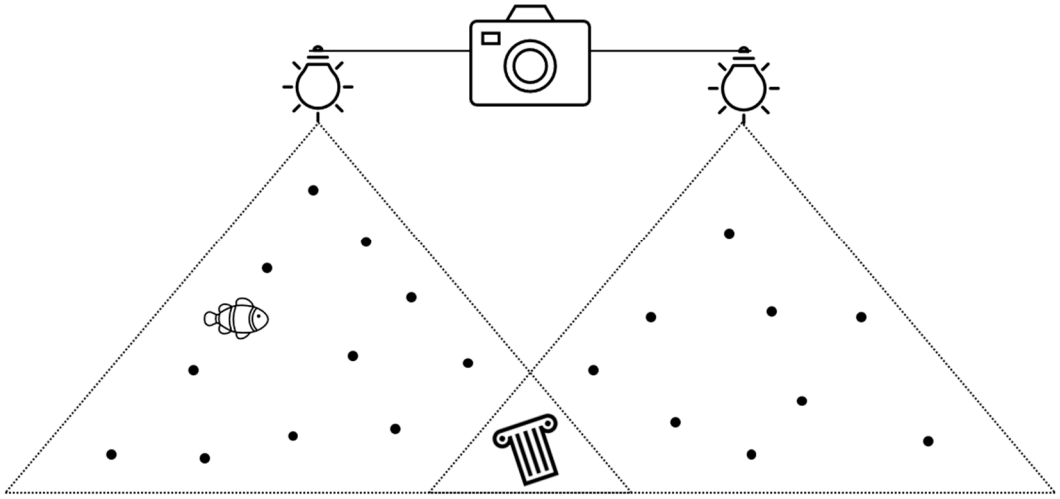


Figure 9. Backscatter can be minimized by moving the strobe away from the lens

Countermeasure: Reduce distance

To overcome the issue of reduction of details and sharpness of distant object, related to diffusion, it is necessary to work at a very short distance, thus photographing the object of interest while being close to it. However, an important fact remains: with normal cases, all lenses increase their focal length, thus reducing the FOV and forcing to shoot from greater distances than would be done on land survey (in order to comply with the required overlap).

3.2.1.3 Reflection and refraction of light in water

Depending on the angle at which the light hits the surface of the water, there will be a greater or lesser part of the light reaching the bottom. If the light comes with a different inclination, only a part of it penetrates towards the bottom while a part is reflected (Figure 10).

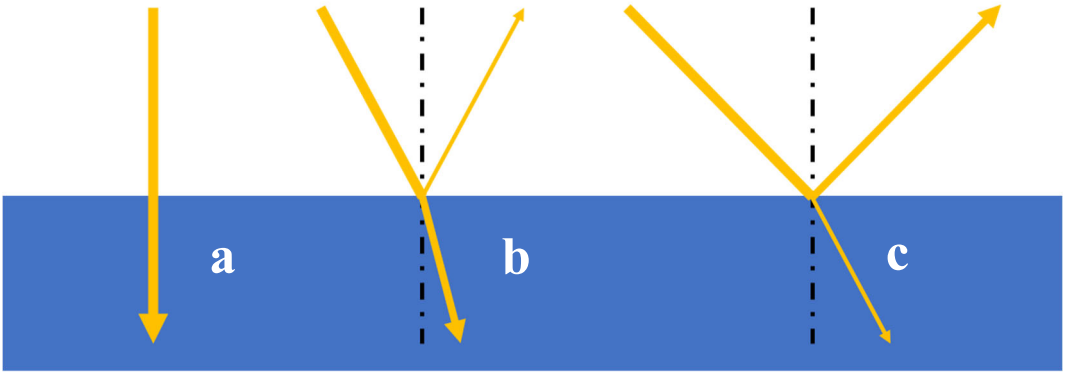


Figure 10. When a ray of light hits the surface of the water perpendicularly, it penetrates the surface without any problems (a). If the beam is inclined, part of the light is reflected from the surface of the water and only part of it penetrates towards the bottom (b), And when the sun is very low on the horizon, the surface of the sea acts like a mirror and reflects an huge amount of light (c).

It should also be noted that the rays of light that reach the surface of the water not vertically, undergo a deviation. In fact, due to the lower speed of light in the water, they tend to change direction approaching the line perpendicular to the surface that passes through the point where the rays hit the surface. If the light rays passing from the air to the water are deflected and their direction becomes closer to the perpendicular, on the contrary, passing from the air to the water there is a deviation from the perpendicular.

The light rays that pass from water to air tend to move away from the perpendicular that passes through the point where the rays hit the surface. The law of refraction, generally known as Snell–Descartes law, governs the deviation undergone by light rays when they pass from a sharp interface between air and water. It is described by the following equation.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

where:
θ_1 = angle of incidence
θ_2 = angle of refraction
n_1 = refractive index of the first medium (approximately 1 for air)
n_2 = refractive index of the second medium (comprised between 1.3330 and 1.3721, depending on the salinity of the water [65]).

It is important to consider that the random effect of the surface ripples generates unpredictable a-priori refractions and therefore not modellable without considering a degree of approximation.

It has been said that objects appear closer; to determine the distance at which they appear (called apparent distance) knowing the real one, the value of this is divided by the refractive index of the medium.

3.2.1.4 Refraction in UW photogrammetry: flat and dome port

The influence of refraction is also felt in underwater photogrammetry; everything, speaking of human sight, appears closer or larger when underwater and in the same way it also happens for the digital and traditional camera. In this case, the most disadvantaged cameras, even if it is possible to implement countermeasures, are the DSLRs.

When the camera is used in a terrestrial environment it has a characteristic shooting angle (FOV) and this does not undergo any variation. The angle is determined by the focal length of the lens. Lenses with a short focal length have a very wide shooting angle. As already mentioned, when the light encounters the water "folds" approaching the perpendicular of the plane that separates the water from the air, that is located, in this case, in correspondence with the glass.

This behaviour will also occur when photographing and will result in a lower shooting angle. Decreasing the shooting angle transforms the behaviour of the lens making it more similar to that of a telephoto lens (Figure 11).

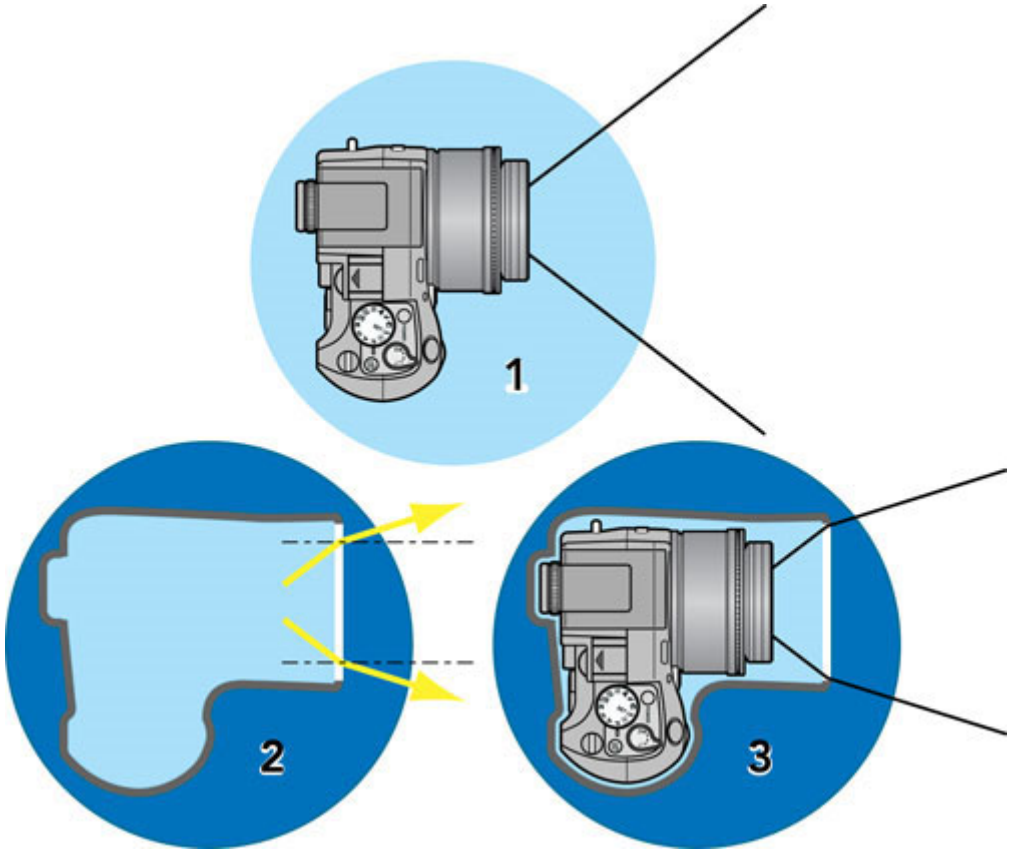


Figure 11. When cameras are employed underwater, the light passing from the medium interface air-water, undergoes the effects of refraction. The result is a smaller FOV than that obtainable with the same lens used in a terrestrial environment. Source: [66]

The "dome port" is an hemispherical porthole [67] that represents a solution for reducing the shooting angle. It is always of great benefit, even if the qualitative improvement is more noticeable compared to a flat port only in combination with pushed wide-angle lenses (Figure 12). It must also be said that each objective corresponds to a very specific type of porthole. Its curvature must be suitable for the focal length of the lens and the center of the sphere of which the port is part must coincide with the optical center of the lens which is not necessarily in correspondence with the outermost lens. It is therefore necessary (at least in theory) a different porthole for each single focal length. In practice, the same port is used for multiple lenses of different focal lengths.

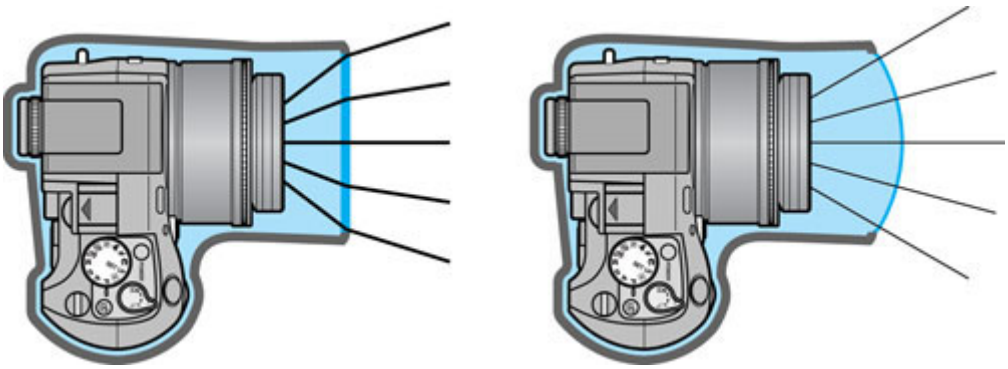


Figure 12. Comparison between a case with flat port to one with a dome port. Examining the behaviour of the light rays that pass through the glass and the window, it is evident that when they pass perpendicular to the surface, they do not undergo deviations. The shooting angle, and the underwater focal length do not vary. Source: [66]

There are glass or acrylic glass portholes on the market, plexiglass with particular optical characteristics, and there are pros and cons for each of the two. Those in crystal (glass) are generally more robust given the hardness of the material. The optical characteristics of the two materials are still excellent but there are differences not only economically but also on a practical level. If the glass portholes are more resistant, the different density between glass and water makes any scratches more evident than with plastic portholes. These materials, in fact, thanks to a density similar to the water, and therefore to a similar optical behaviour, are able to mask those small scratches that can be produced on the external surface with use. It should be considered that the plastic porthole, given the simpler workability, is generally cheaper than the glass ones.

3.2.2. Geometric calibration of the camera

To preserve the metric consistency and to obtain reliable 3D metric products, this process must be followed according to photogrammetric principles that are even more important in underwater photogrammetry. The wide diffusion of low-cost and non-metric sensors requires that some attention be given to proper geometric calibration of the employed optics. Via calibration, it is possible to describe geometric distortions that are observable on final images due to lens materials, shapes and construction characteristics of the cameras and the optics used in the survey operations.

Calibration of digital cameras for photogrammetric purposes is a well-known practice [68] and is an essential preliminary step for a correct 3D object reconstruction. Via camera calibration, it is possible to obtain intrinsic camera parameters (f, cx, cy, k1, k2, k3, k4, b1, b2, p1, p2) that allow for describing the interior orientation and the lens distortion. Knowing these parameters is essential as they can be used for generating images as close as possible to central perspectives, to be used for metric purposes.

The following calibration parameters can be determined:

- f - Focal length.
- cx, cy - Principal point coordinates, i.e., coordinates of lens optical axis intersection with sensor plane.
- b1, b2 - Affinity and non-orthogonality (skew) coefficients.
- k1, k2, k3, k4 - Radial distortion coefficients.
- p1, p2 - Tangential distortion coefficients.

There are, however, different methods and strategies for calibrating digital cameras. The most commonly available photogrammetric suites that use computer vision algorithms allows performing the so-called self-calibration of the camera [69]. In this standard approach, it is possible to reach accuracy improvements up to a factor of 3 [70] compared to a situation where no camera calibration is performed. This approach proved to be effective even in the case of non-metric and non-conventional Low-Cost photogrammetric sensors [71].

In situations where the conditions do not significantly change between the calibration and the survey phases, it is possible to pursue a pre-calibration strategy. In pre-calibration, the camera is calibrated in a controlled environment (using a calibration polygon) or with ad-hoc procedures (employing calibration panels with checkerboard or dot patterns) in order to obtain a set of intrinsic parameters to be used as an initial guess during the self-calibration phase performed before or during the BBA (Bundle Block Adjustment) in a typical photogrammetric workflow.

While the first option is the most common in data acquisition situations, especially in archaeology [72], it is still possible to observe a consistent gain in the accuracy of the survey whenever a robust self-calibration procedure is conducted; when correctly performed this will pay back in lower reprojection errors. This aspect is essential mostly when a photogrammetric survey is conducted in

underwater environments [73], as additional distortions are introduced due to the different refractive indexes of the two mediums (the water and the air), and due to the geometric characteristics of the flat or dome port that could be used [67].

The problem of camera calibration (geometry distortion compensation) in an aquatic environment, considering both the cameras and the underwater cases, will be addressed (§ 4.2) in order to identify the approach that allows for achieving the best results so as to define standardized procedures.

3.2.3. Radiometric correction of the images

For different disciplines, such as (but not only) underwater archaeology and marine biology, domain experts and scientists aim to obtain images with consistent colour compared to the real object of the scenery. These needs fostered the research towards automatic or semi-automatic colour correction methods and algorithms for underwater images, mainly used in pre- or post-processing phases of the photogrammetric process. In other works, many researchers have addressed this issue and have developed algorithms to counter this effect and restore the 'true' colour in Underwater (UW) images [64], [74]–[78].

Various image enhancement and restoration methods have been proposed in the past decades. This section will give an overview of such methods and their relevance to our work.

A topic that has kept scientists engaged over the years is the absorption and scattering coefficients of water. Jerlov classified waters into three distinct oceanic kinds and five unique coastal kinds in 1951[79]. Following Jerlov's contributions, various methodologies aim to determine the inherent optical properties of Jerlov water types [80], [81].

A mathematical model for spectral analysis of water characteristics was proposed in 2014, instead of a colour correction technique in the RGB space [82]. [81] utilized natural water bodies and categorized them to determine the positions of all physically important RGB attenuation coefficients, (used for defining how easily a volume of material can be penetrated by a beam of light - the SI unit of attenuation coefficient is the reciprocal metre [m^{-1}]) for UW imaging. The authors here showcased that the range of wideband attenuation coefficients in the ocean is restricted and demonstrated that the normal transition from wavelength-dependent attenuation $\beta(\lambda)$ to wideband attenuation $\beta(c)$ is more complex than initially was demonstrated by standard image formation models.

[83] suggested a simple fusion-based approach for enhancing UW photos using a single input while blending multiple well-known filters. As the authors support, this method successfully improved UW footage of dynamic situations.

A first proposal for colour correction of UW images by using the $l\alpha\beta$ colour space is presented in [75]. To increase image contrast, chromatic components' distributions are white balanced, and histogram cut-off and stretching of the luminance component are done. Their results show that this pipeline is thriving under the assumption of a grey world and homogeneous lighting of the scene. These assumptions are acceptable only for close-range acquisition in a downward

direction, such as seabed mapping or UW photography and under situations with slight light changes.

[74] proposed an automated method for rectifying colour discrepancy in UW photos gathered from diverse angles while building 3D structure-from-motion derived models. This contribution aimed to image large scale biological environments, which prohibited the use of colour charts due to the sensitivity of marine ecosystems to seabed disturbances. The authors deployed a "gray-world" colour distribution to focus on colour constancy. This means that surface reflectance has a gray-scale distribution that is independent of scene geometry. The same authors in 2016 proposed a formation model for calculating the true colour of scenery taken from an UW automated vehicle with strobes. This methodology required a unique setup of camera and strobes which subsequently allowed for the creation and proposal of a unique image formation model that considered this setup to provide the necessary colour restoration to the images.

[84] modified the current UW image formation model. They derived the physically valid space of backscatter using oceanographic measurements, demonstrating that the wideband coefficients of backscatter differ from those of direct transmission, even though the current model portrays them as the same. As a result, they proposed a revised UW image formation model that takes these deviations into account and validated it using in situ UW experiments. The same authors implemented their work in [78] creating the Sea-thru pipeline for colour reconstruction. While the revised model is physically more accurate, it contains more parameters that make it challenging to use. An easy and fast method based on a mathematical model for restoring the colour information on images captured underwater, will be presented, and compared in §5.2. In §5.3 a colour correction method based on a physical model will be discussed and compared with other automatic or semi-automatic colour correction methods.

3.3 UAS photogrammetry in very shallow water

To plan a correct survey campaign, it is necessary also to understand the topographical situation of the site, not only for an overview of the area but also for understanding relations that links the surrounding territory with the underwater Heritage itself. For land surveys the use of a hybrid approach with the integration of total stations and GNSS equipment remains fundamental.

An important apport for this aim is the use of aerial photography that can be used both for land survey and for shallow water mapping of archaeological evidences. This is important not only to spot the presence of an archaeological implant, but also to better understand the disposition of the structures. Aerial photogrammetry (including especially legacy data) represent the cartographic basis for drafting an overall plan of the site.

For sites that presents assets halfway between water and land, or with emerged and submerged portions, it is specifically important to study relations with the coast and the land, to spot any element that might suggest any sort of continuity or prosecution. Here again the aerial photogrammetry plays an important role to

understand the limits of the archaeological structures both in land and underwater, functional for a better planning of the subsequent surveys.

Another application of UAS in shallow water is to process drones' imagery with Structure from Motion (SfM) and Multi View Stereo (MVS) techniques to provide a low-cost alternative to established shallow seabed mapping techniques. *"Based on known depth observations from bathymetric LiDAR surveys, an SVR model was developed able to estimate more accurately the real depths of point clouds derived from SfM-MVS procedures."* [85]

3.4 Non-image-based techniques

Aside from the specific framework and research field of this thesis (i.e., photogrammetry), there are other non-image-based techniques that are functional to the metric survey of seabed and related archaeological remains. The principal ones are listed below.

3.4.1. Acoustic techniques

3.4.1.1 Side scan Sonar

Is a technology that exploit high-frequency (usually between 250 and 1000 kHz) lateral acoustic waves to generate *sonargrams*, i.e., images of the seabed for large area extensions (width 100-300 meters and theoretically unlimited length). The device emits short acoustics impulses towards the seabed; the returning echo can be digitally processed to produce the final image.

3.4.1.2 Sub-bottom profiler

Is a device capable to spot objects underneath the seabed. It is a low frequency sonar (3,5 – 15 kHz), that can penetrate sand and being reflected according to the substrate. With this device and techniques, it is possible to obtain cross sections of the seabed.

3.4.1.3 Multibeam

Multibeam: It is another acoustic device that allows to obtain a high-resolution bathymetric survey. The technology based on multibeam allow to obtain a high amount of data in a narrow time windows. The multibeam is, in fact, capable of measuring different depths at the same time according to its angular setting. The level of resolution is defined by the spacing between signals. Every moment the emitted beam must be correctly placed with respect to the transducer. A drawback of this device is the operative limit close to the coastline.

3.4.2. Other techniques

3.4.2.1 Magnetometer

In some cases, a magnetometer is used in combination with acoustic devices. It is useful for detecting irregularities in the terrestrial magnetic field that might be caused by buried structures or artifacts. Although being a device used mainly for the study of the sediment compositions, it has been widely adopted also in the field of underwater archaeology.

3.4.2.2 LiDAR

"Underwater laser scanners (a form of underwater LiDAR) gather high-resolution optical 3D models instantaneously, without the need for lengthy processing time. Though multibeam sonar and laser line scanners are operationally similar, laser line scanners capture higher resolution data, generating with over 2000 points per line. Sonar and underwater laser scanners can work together however, especially in Defence MCM operations, where sidescan sonar is used to detect possible targets of interest, and then optical sensors are used to identify them. The coverage that sonar provides combined with the resolution that laser scanners achieve enables a complete understanding of wide areas. The high-resolution and consistent data provided by laser scanners is well suited to automatic anomaly detection algorithms – whether that be monitoring pipeline ovality or eventing freespans and anodes."[64]

3.5 Positioning at different depths

As previously mentioned, underwater positioning is a difficult task due to the rapid attenuation of Global Navigation Satellite Systems (GNSS) and radio-frequency signals in the water medium, causing no access to the traditional satellite-based positioning methods. Past and usual approaches to solving the underwater localization problem have employed trilateration via acoustic positioning systems by means of expensive inertial sensors, acoustic beacons in the region of interest, or a combined GNSS approach by a periodic surfacing of the drone. While these methods are useful, their performance is radically limited.

Chapter 6 of this thesis aims at discussing the limits of GNSS positioning and georeferencing in underwater environment and how is it possible to exploit existing methods and new instruments for performing a topographic survey of GCPs and CPs in very shallow waters, for supporting the photogrammetric reconstruction of underwater assets.

[64] https://voyis.com/insight-laser-scanners/

Methodology, results, and validation

Part II is related to evaluation and validation of acquisition strategies related to the documentation of the underwater archaeological and cultural heritage to demonstrate the versatility and suitability of the proposed methodologies and techniques. This part will thus provide technological and methodological tools suitable for giving tangible solutions to the needs of real-world applications. In particular, the establishment of a methodological protocol for the positioning, traditional and 3D documentation, and digital enhancement of the wrecks of ancient boats (remains of wooden hulls and cargos, organic and inorganic) is proposed. This central part of the thesis will also include optimized image processing workflows (based both on photogrammetry and computer vision) to provide high-resolution products, and to visualize and manipulate data for inspection purposes. The proposed strategies require the evaluation and verification of the success of the methodologies and technologies discussed in the previous chapters. The versatility and the suitability of the proposed practices in real case scenarios will have to be also considered in compliance with the operational issues and needs: security and mobility of the divers (underwater archaeologists and technicians), safety and integrity of the archaeological context and findings, underwater operability and data interpretation's needs. During the archaeological survey activities, the proposed techniques must be validated according to the requirements of the experts; particular attention has been paid to the diversification of the selected cases.

The content of this part of the thesis could be summarised in the following different steps:

- Processing strategies for enhancing sub-optimal datasets (§ 4);
- Processing strategies for restoring colour information (§ 5);
- Positioning and georeferencing strategies in very shallow waters (§ 6);
- Application on a case study: Torre Santa Sabina (§ 7);
- Suggestions and examples of online dissemination(§ 8).

PART II

4

Chapter 4

4. Processing strategies for enhancing sub-optimal datasets

Although underwater photogrammetry has become widely adopted, there are still significant unresolved issues that are worthy of attention. This chapter focuses on the 3D model generation of underwater shipwrecks and intends explicitly to address the problem of dealing with sub-optimal datasets. Even if the definition of best practices and standards to be adopted during the acquisition phase appears to be crucial, there is a massive amount of data gathered so far by professionals and the scientific community all over the world that cannot be ignored. The compelling idea is to try to achieve the best reconstruction results, even from sub-optimal or less-than-ideal image datasets. Sub-optimal (or less-than-ideal) datasets can be defined as datasets that lacks the adoption of empirical formulas for project planning acquisition; specifically, with correct block geometry and GCP pattern the measurement accuracy is directly transferred to object space, and planimetric accuracy should be better than height accuracy. Generally speaking, σ_z should not be higher than $3x10^{-4}$ H (average acquisition distance) and σ_{xy} should not exceed the GSD (Ground Sample Distance). Images should not be turbid, blurry or present low contrast, and the whole dataset acquisition should follow the CIPA 3x3 camera rules [86]. A dataset can be defined as "sub-optimal" when it does not meet the above criteria.

This chapter focuses on the investigation of different strategies and approaches for balancing the quality of the photogrammetric products, without neglecting their reliability concerning the surveyed object. The case study of this chapter is the Mandalay MHT, a 34 m long steel-hulled auxiliary schooner that sank in 1966 and now lies in the Biscayne National Park (Florida - USA). The dataset has been

collaborations

UC San Diego

National Park Service
U.S. Department of the Interior

MARINE IMAGING TECHNOLOGIES

provided by the Submerged Resources Center (SRC) of the US National Park Service, in order to develop an experimental image enhancement method functional to the virtualization and visualization of the generated products, as a part of a sustainable, affordable, and reliable method of studying submerged artefacts and sites. The original images have been processed using different image enhancement approaches, and the outputs have been compared and analyzed.

In this chapter, different methods are proposed to solve this issue of dealing with sub-optimal datasets in a comprehensive pre-processing approach (Figure 13). The resulting enhanced images have been processed using different commercial/free software, and the outputs have been compared and analyzed. Those mentioned above can be used in online repositories and for VR and AR tours, providing a sustainable, affordable, and reliable way of studying submerged artefacts and sites.

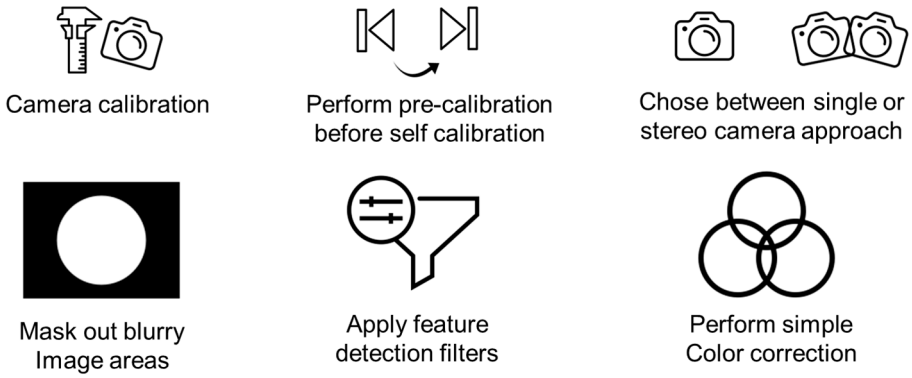


Figure 13. Graphical schema summarising the main step of the different methods proposed to cope with the issues characterising the processed data.

4.1 Case study: The Mandalay MHT shipwreck

The case study of this chapter is *Mandalay MHT* (Figure 14), a 34 m long steel-hulled auxiliary schooner that sank in 1966. *Mandalay* was designed by *John G. Alden Naval Architects, Inc.* and built by *George Lawley & Son, Corp.* in 1928. After being sold in 1931 and renamed *Valor*, it had subsequently five other owners until it was purchased by *Windjammer Cruises, Inc.*, refitted, and renamed as *Mandalay* in 1965, for being used as a luxury cruise ship. The vessel ultimately sank on Long Reef at the end of a 10-day Bahamian cruise, the 1st of January 1966. The *Mandalay* now rests in very shallow water (maximum depth of 6 meters), and it is an outstanding snorkelling underwater site located in *Biscayne National Park* (25º 26.530 N, 80º 7.301 W); *Biscayne* was established as a National Monument in 1968 and designated as a National Park in 1980. The park is dedicated to the public enjoyment and preservation of cultural and natural resources, the protection of a rare combination of terrestrial and undersea life, and the preservation of a scenic subtropical setting[65].

[65] https://www.nps.gov/bisc/learn/historyculture/upload/*Mandalay*.pdf

The data presented in this research have been acquired using the *SeaArray* (Figure 15), a diver operated tri-camera photogrammetric system designed by *Marine Imaging Technologies* in partnership with the *National Park Service Submerged Resources Center*. The current version of the concept (V4) uses three Nikon Z7 Mirrorless digital cameras (Figure 16 and Table 1) to capture 45,7 MP images.



Figure 14. *Mandalay* aground on Long Reef, New Year's Day, 1966. (Image courtesy of the Miami Herald).

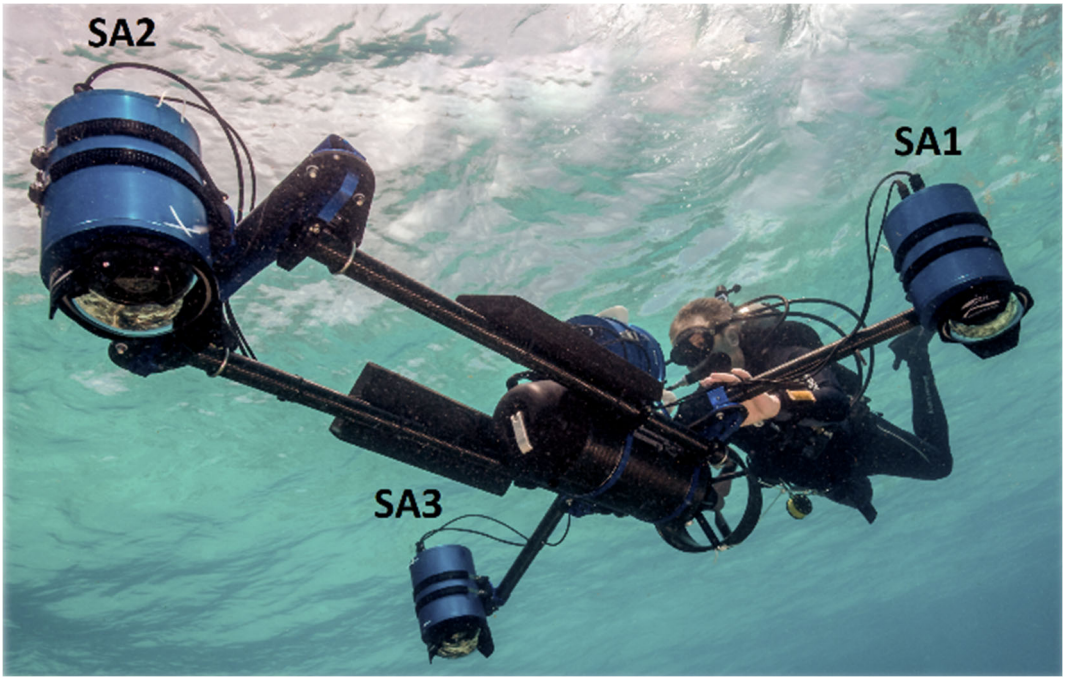


Figure 15. The *SeaArray* V4, a diver-operated tri-camera photogrammetry system employed in this research. In this chapter, the front camera is referred to as SA2, while the rear ones are respectively SA1 (left side) and SA3 (right side).



Figure 16. Nikon Z7 with the 14mm Rokion Cine DS Lensing.

BSI FX-Format sensor [MP]	45,7
On-sensor PDAF	493-Point
Native ISO	64-25.600
Continuous Shooting (Raw & JPG) [FPS]	9
Image processing	Expeed 6
Focal length	14 mm
Pixel Size	4,35µm

Table 1. Main technical specification of the Nikon Z7 Mirrorless digital camera.

Fixed aperture and focus was achieved using a 14mm Rokion Cine DS Lensing; custom housings, chassis and DPV mount were engineered by *Marine Imaging Technologies*. Each camera is always placed in the same relative position during all the acquisitions. The camera housings have been custom designed ad-hoc for the Nikon Z7 mirrorless cameras, with a Nikon FTZ adaptor and a Zen 170 mm glass dome port. Since in a preliminary setup of the system a severe edge softness was noticed, the system was refitted with Zen 230 mm glass dome ports to improve edge sharpness, also converting to a native Z-mount.

For assigning a correct scale to the reconstructed 3D model, a total of 3 scale bars have been used (Figure 17). The length of the two outer calibration target of each scale bar is 0,842 m ± 0,001 m.



Figure 17. One of the three calibrated scalebar used for scaling the model.

The *Mandalay* dataset is composed of a total of 7676 nadiral and oblique images of 8256 x 5504 px, divided as detailed in Table 2. Images were acquired at an average distance of 3 m from the object using the *SeaArray* system (Figure 18).

Camera	*Orientation*	
	Nadiral	*Oblique*
SA1	2385	180
SA2	2347	211
SA3	2356	197
TOTAL	7088	588

Table 2. Description of the *Mandalay* dataset with the number of images acquired from each camera.

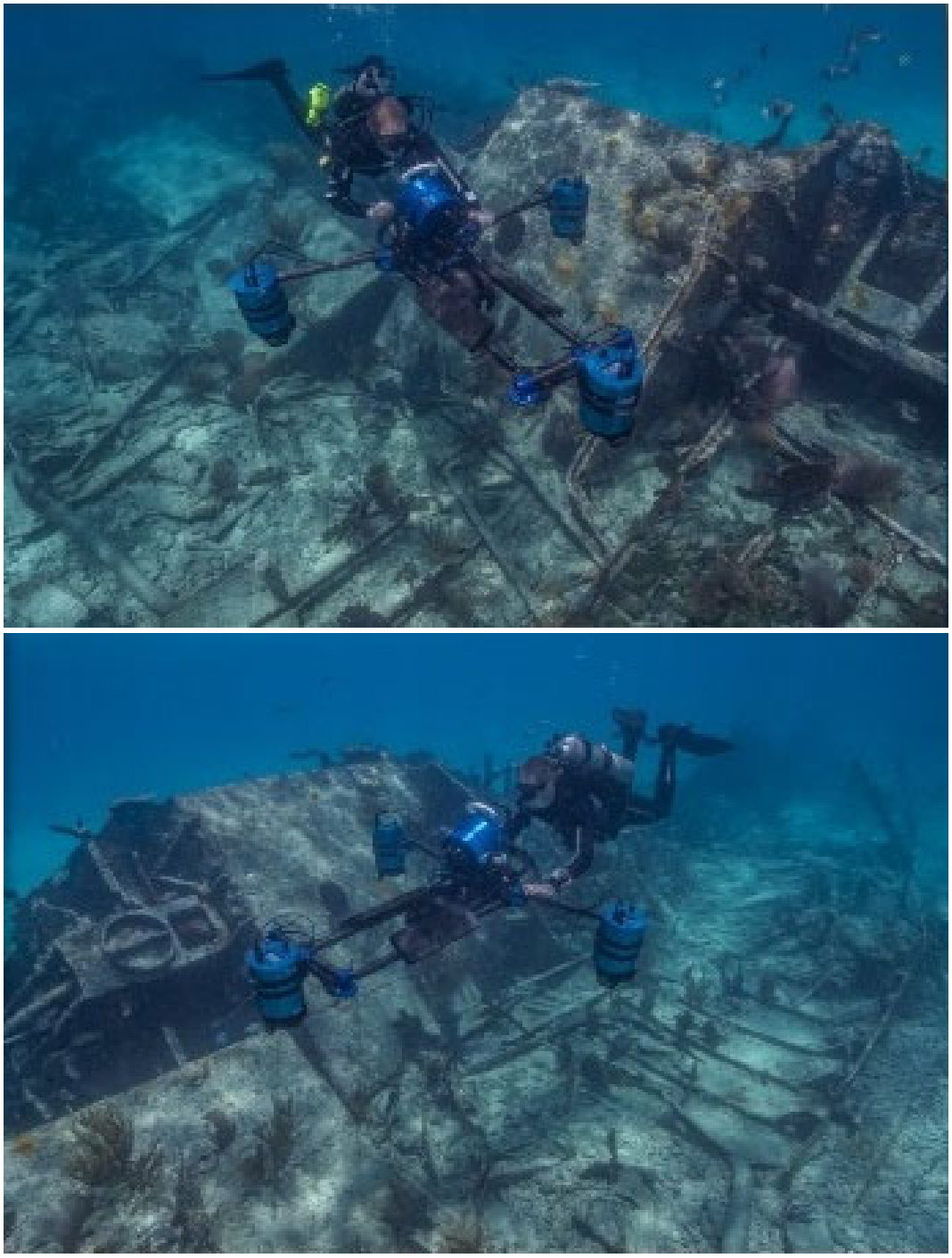


Figure 18. The *SeaArray* employed in the acquisition phase on the *Mandalay* archaeological site (*Biscayne National Park* – Florida – USA).

4.2 Camera calibration

As reported in §3.2.2, camera calibration is essential for the accurate estimation of the image locations and dimensions in the object space [87] also in the case when a local coordinate system is adopted (such as the presented example); in underwater photogrammetry, the effects introduced by the water medium and the camera housings must be seriously considered. During the camera calibration and image orientation step, the coherence of the principal distance must be checked, use a separate calibration certificate for each of the cameras, and omogeneously distribute the scale bars or the measured markers in the recorded scene. If possible, one should perform a pre-calibration out of the water and underwater to compensate for the distortion introduced by the medium. As well, one should keep cameras in the same position during checkerboard and object acquisition in order to avoid change in their external assets.

4.2.1. Single- and stereo- camera calibration with fixed baseline

In this study, a pre-calibration approach has been followed using a 120x65 cm checkerboard test pattern[66], in order to estimate, for each of the cameras, a preliminary set of intrinsics (f, cx, cy, k1, k2, k3, k4, b1, b2, p1, p2) to be used as an approximate values for the subsequent self-calibration to be performed during the BBA (Bundle Block Adjustment). A total of 18 images have been acquired for each camera mounted on the *SeaArray;* this sub-dataset was therefore used to calibrate the employed sensors before the actual processing step.

Another approach was followed using the app Stereo Camera Calibrator of Matlab R2019a[67] in order to estimate, for the master-slave couples of cameras SA2-SA1 and SA2-SA3 the distance to be used as a fixed baseline during the image orientation step (Figure 19). The origin of the coordinate system has been set as the optical center of camera SA2, and the performed stereo calibration of the pair SA2-SA1 and SA2-SA3 provided the relative R (baseline). This procedure, however, led to some sub-optimal results, both since the employed panel was not big enough to be seen from the considered camera couple while shooting simultaneously, both because it is likely that the cameras were not syncronized, and the acquisition of the checkerboard test pattern was made while moving. The estimated offsets of each of the rear cameras (SA1 and SA3, i.e. slaves) from the front one (SA2, i.e. master) has been estimated with an overall RMSE of 7,13 pixels, and thus unacceptable to use the resulting offset values for imposing a fixed, known baseline between each camera pair.

[66] 50 mm squares – CamAlign – CHB – SXW – V7.1
[67] https://it.mathworks.com/products/new_products/release2019a.html

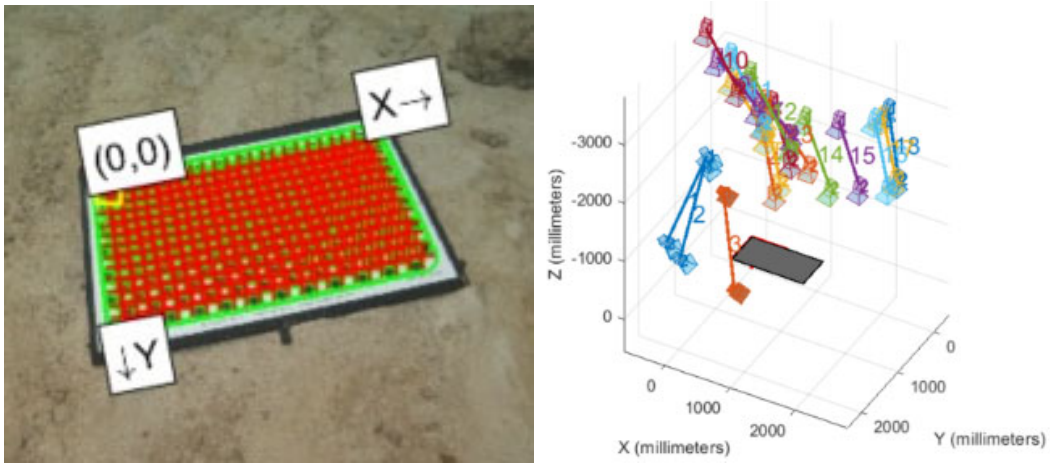


Figure 19. On the left, the checkerboard pattern detected by the Stereo Camera Calibrator of Matlab; on the right, pattern-centric view of the estimated positions of the SA2-SA3 stereo couples.

Another approach has been undertaken via a self-calibration of the same images as a set of rigid camera rig using the software Metashape by Agisoft (version 1.5.2 build 7838 for Windows x64)[68]. The software used the relative position of the slave cameras previously estimated (using the calibration checkerboard), adjusting their positions in order to minimize the reprojection residuals. The variance of the estimated positions, used as a realistic evaluation of the estimation uncertainty of the re-estimated XYZ offset, was too high (Table 3) and therefore the implementation of fixed, known baseline was not adopted in this study.

Slave offset	*Estimated [m]*	*Variance [m^2]*
X [m]	0,859	0,003
Y [m]	1,115	0,004
Z [m]	0,007	0,001

Table 3. The estimated offset of the SA3 slave camera from the SA2 master camera.

The problem related with the inadequacy of this degree of precision find an explanation into the erroneous synchronization of the employed cameras; whenever performing an on-the-go acquisition, if cameras are not properly synchronized, the estimation of the baseline length will vary for each of the acquired stereo pairs, making impossible to consider the baseline a constant know a-priori (which is an essential condition to perform stereo-camera calibration). Therefore, in case it is not possible to properly synchronize stereo cameras, it is advisable to consider them as independent cameras and perform single camera calibration.

[68] https://www.agisoft.com/

4.2.2. Pre- and self- calibration of underwater cameras

This paragraph aims to investigate the pros and cons of pre- and self-calibration approaches when underwater cameras are used in combination with dome ports, both in subaerial and in submerged situations. Three calibration datasets are acquired and compared: the first (A) where the camera is pre-calibrated without any addition (flat or dome ports); the second (B) in which the camera is used in combination with a dome port; and the third (C) where the camera setup has been employed in an underwater environment. For both scenarios (dry and wet), self-calibration and pre-calibration procedures are compared. The evaluation and validation of different camera configurations are presented, and the observable gain in accuracy is discussed.

The material used in this paragraph has been acquired as a courtesy by the Submerged Resources Center (SRC) of the US National Park Service (NPS), and processed, analyzed and discussed by the author of this thesis, and is related to three datasets of images acquired using a Nikon Z7 mirrorless camera (sensor diagonal 43,13 mm; Pixel size 4,34 µm), equipped with a 14 mm Rokinon Cine DS lens. The camera was used in combination with a Zen 230 mm glass dome port, to enhance the quality of images along the edges. This setup has been previously used in combination with other two identical cameras mounted on the SeaArray; a diver operated photogrammetric system designed by Marine Imaging Technologies [18], [88].

The three datasets are composed of images acquired to produce a geometric calibration of the sensors using a calibration checkerboard (Figure 20) of 120x65 cm^2 (with each square 5 cm in size). The acquisitions have been divided into three datasets:

- (A) Camera: Nikon Z7 with 14 mm Rokinon Cine DS lens: 42 images
- (B) Camera + Dome port: As (A) with a zen 230 mm glass dome port: 41 images
- (C) Camera + Dome Port Underwater: Same setup of (B) but employed in underwater condition: 83 images

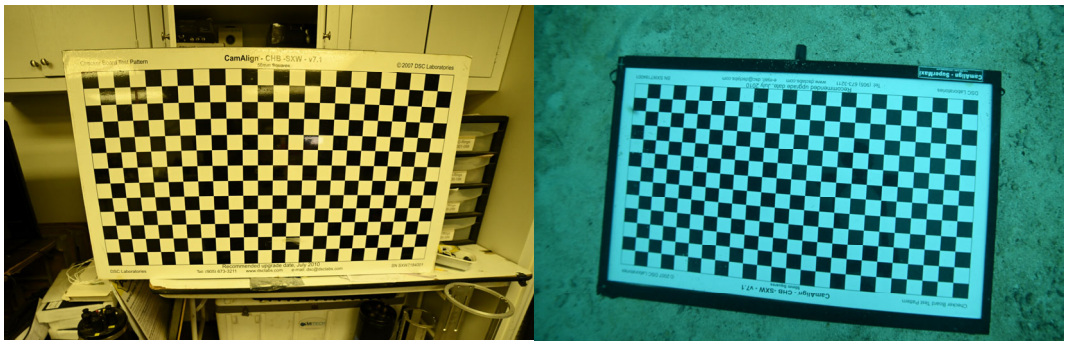


Figure 20. The calibration panel employed in the acquisition of the dataset (A) and (B) on the left; and the dataset (C) on the right.

After the data acquisition (courtesy data from NPS SRC), camera calibration was performed for the three datasets using the Single Camera Calibrator App of the Camera Calibration Toolbox for Matlab [89]. The results of this self-calibration procedure, based on [90], explicitly aimed at obtaining the values of the polynomial radial distortion coefficients, that are summarized in the following Table 4.

Camera Configuration	K_1 *[pix]*	K_2 *[pix]*	K_3 *[pix]*	*f [mm]*
(A) Camera	-0,1257	0,0586	-0,0096	14,47
(B) Camera + dome port	-0,1234	0,0731	-0,0093	14,63
(C) Camera + dome port Underwater	-0,1081	0,0650	-0,0128	15,99

Table 4: Values of polynomial radial distortion coefficients and focal length (in pixels) for each of the three camera configurations employed.

In order to make a more straightforward comparison of the obtained parameters, the curves of the radial distortions have been graphed for the three datasets in the same diagram, as presented in Figure 21. The curves of radial distortion are described as a function of the radial distance from the geometric centre of the sensor (Brown, 1971; Krauss, 1997), as presented in the following equation:

$$\delta r = k_1 \rho^3 + k_2 \rho^5 + k_3 \rho^7$$

where:
ρ = distance from the geometric centre of the sensor
k1, k2, k3 = polynomial coefficients of the radial distortions

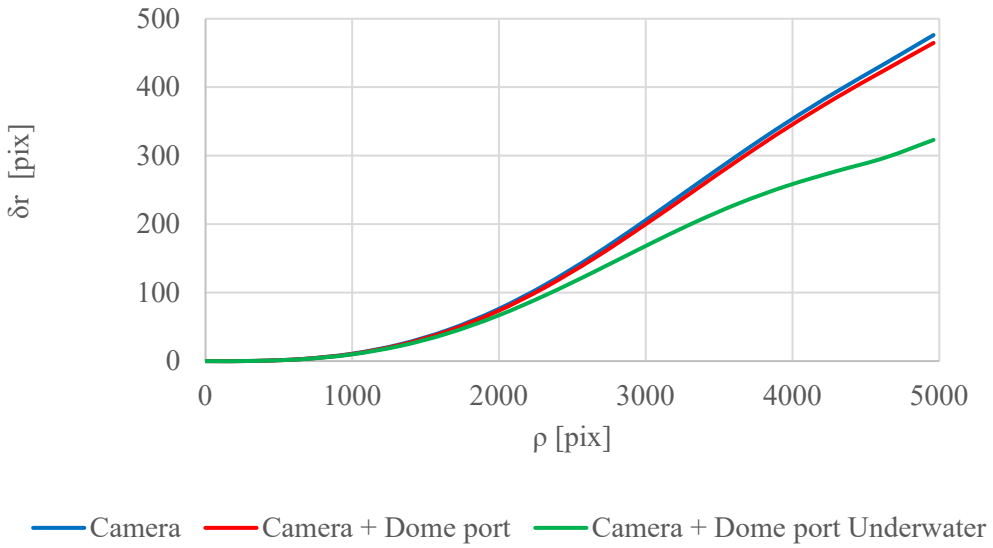


Figure 21. Radial distortion curves for the three camera configurations: in blue, the configuration (A), in red (B) and in green (C).

To also investigate how a pre-calibration approach can positively affect the quality of the survey, pre-calibration has been performed for the dataset (B) and

(C). In doing so, the calibration certificate obtained from the self-calibration of (A) has been used as approximate values for the pre-calibration of (B). Following the same principle, the calibration certificate obtained from the self-calibration of (B) has been used as an initial values for the pre-calibration of (C). The comparison of the reprojection errors when self-calibration or pre-calibration are performed, are shown in the following Figure 22.

In this case, it is possible to observe how the use of a pre-calibration approach can further improve the quality of the survey, reducing the residual reprojection error of the self-calibration in a consistent way. Moreover, is possible to notice how the use of the right camera and lens combinations, specifically designed for underwater survey purposes, are functional to lower the distortion of the images and consequently improve the accuracy of the final 3D products.

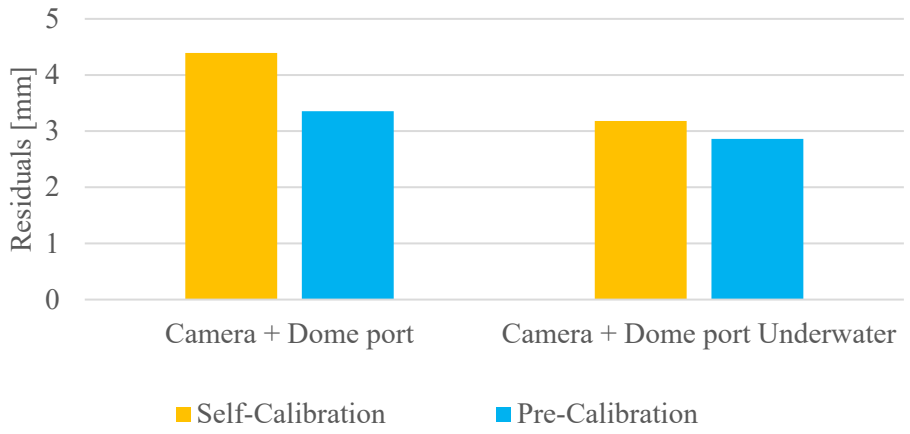


Figure 22. Comparison of the reprojection errors based on the average values of the residuals, expressed in millimetres, for the datasets (B) and (C) both when self-calibration and pre-calibration are performed.

4.3 Image masking

Since distortion at the side of the sensor is high, and because the waterproof housing used, there might be blurring effects on the image edges. Those blurring effects must be avoided because they might reduce the quality of the calibration or increase the reprojection error in some part of the sensor. Reducing the area of the images used for key-point[69] extraction and tie-point[70] detection by masking might be a solution to this issue. This procedure could, however, introduce some problems in regards to the minimum necessary overlap required between images; this was easily solved in the *Mandalay* dataset because of the high redundancy of the acquired data. It is difficult for a scuba diver to follow a pre-defined acquisition trajectory, and operating in an underwater environment might also pose significant hazards especially if complex tasks must be carried out at the same time. For this reason, the presented procedure is a viable solution assuming that acquiring more than the essential number of images might be a way to solve less robust, poorly

[69] point resulting from the feature extraction phase, used for image matching
[70] point resulting from the feature matching phase, used for image orientation

designed, or tricky to achieve acquisition geometries. In this case, before the processing, redundant images must be discarded as unnecessarily increasing the overlap will reduce the baselines, thus reducing the precision of the survey.

At first, all the 7.676 images of the *Mandalay* dataset have been aligned without masking and considering their original size. As a result, only 5.936 on 7.676 images were aligned, with a total amount of 5.359.128 tie-points selected from 6.818.404 key points estracted using SIFT (79% of which used as tie-points in the orientation of the images) and an RMS reprojection error of 1,70 pix. Since the previous image orientation results were not satisfactory, all the images have been masked considering only their central part, with a circle centred at the centre of the image and a diameter of 4600 px as shown in Figure 23. This has been done to avoid area of the sensor with the higher radial distortion (which usually increase proportionally with the distance from the sensor center). Moreover, as dome port with a relatively small radius has been used, the edges of the images resulted slighly blurred due to the virtual image projected behind the limits of the depth of field.

In order to furtherly rationalize processing time, masked images were aligned after being downscaled by a factor of 4. A total of 6.080 on 7.676 images were aligned, with 5.791.409 tie-points of 6.877.323, and an RMS reprojection error of 0,87 pix. The obtained results are summarised in Table 5.

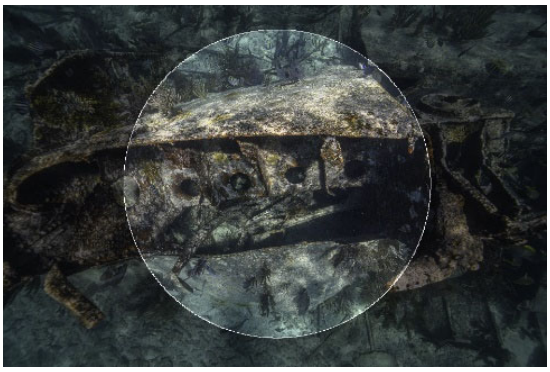


Figure 23. Circular mask adopted; the darker area will not be used during the calibration of the sensor and the feature detection (key-points) and matching (tie-points) steps.

Approach	*No masks*	*Masked*
Quality setting	High[71]	Medium[72]
Images [aligned/total]	**5.936/7.676**	**6.080/7.676**
Tie-points / Key points [%]	40	38
Reprojection RMSE [pix]	**1,70**	**0,87**

Table 5. Results after the image alignment and camera self-calibration for the same dataset for images with and without masks.

The software Metashape by Agisoft has been used (version 1.5.2 build 7838 for Windows x64) setting the key-point limit at 40.000 and the tie-point limit at 10.000.

[71] At High accuracy setting the software works with the photos of the original size.
[72] Medium setting causes image downscaling by factor of 4 (2 times by each side).

Analyzing the results, even if the masked images were downsampled, the total number of aligned images, the number of tie-points and projections was slightly higher than the not-masked dataset, processed at full resolution. It is remarkable to notice also that this approach halved the RMSE reprojection error because the outer part of the sensor with higher residuals was not taken into account (Figure 24).

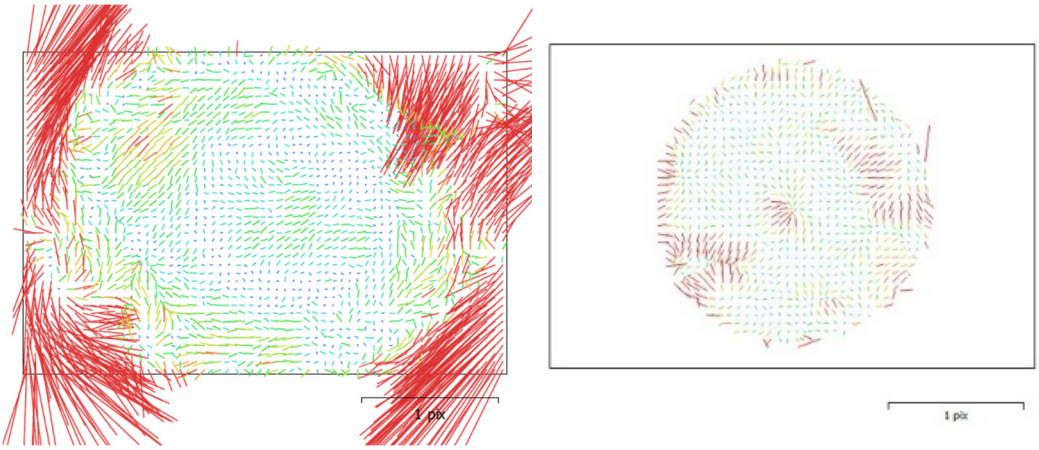


Figure 24. Comparison of the image residuals on the SA2 camera after the calibration. On the left, image residuals using the full image; on the right, image residuals cropping out the parts close to the edges of the sensor.

There is, therefore, a considerable improvement of the alignment phase, at a lower cost in terms of processing time and computing resources. Different sizes of circular masks were tested, smaller as 3700x3700 pixels and bigger as 5500x5500 pixels, leading to very similar or slightly sub-optimal results in comparison to the analyzed one (4600x4600 pixels), that resulted in being the best compromise in terms of the lower areas of the images discarded, the higher number of images aligned, the higher number of tie-points detected and the lower reprojection error, as showed in the following Figure 25 and reported in the following Table 6.

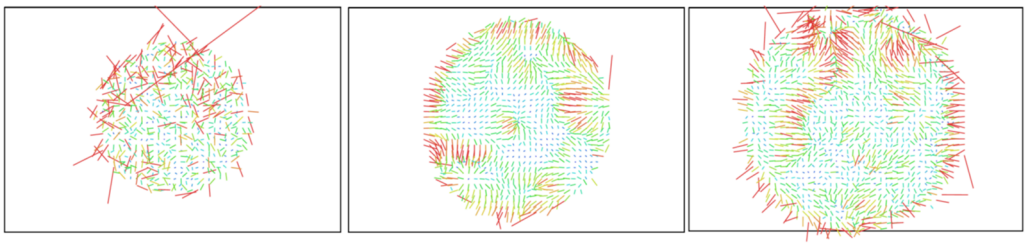


Figure 25. Comparison of residuals on different sizes of circular masks. From left to right: 3700x3700 pixels, 4600x4600 pixels and 5500x5500 pixels.

Size of the mask [pix]	*3700x3700*	*4600x4600*	*5500x5500*
Images [aligned/total]	**3.458/7.676**	**6.080/7.676**	**4.965/7.676**
Tie-points / Key points [%]	41	38	0,42
Reprojection RMSE [pix]	**0.90**	**0,87**	**0.93**

Table 6. Results after the image alignment and camera self-calibration for the same dataset for images with different sizes of circular masks.

4.4 Image enhancement filters

Underwater images are usually affected by lack of contrast, poor visibility, and inconsistency in radiometry. In order to solve this issue, it is possible to run a pre-processing step to use the generated enhanced images only for the tie-point extraction phase. Different enhancement algorithms can improve several aspects of underwater imagery, and some of them have been already benchmarked [91]

Thereafter, different filters have been tested; the first image enhancement method has been applied using the *ImageFilter* module of *Pillow*[73] (*PIL Fork*) in the Python environment. The Python Image-processing library provides various image filters including edge enhancement filters implemented using a convolution of a specific kernel onto the image. The two filters employed in this study were DETAIL and EDGE ENHANCE. A third filter employed was the Wallis filter, an adaptive filter (generalized variance-based image enhancement operator) that applies a spatially invariant operator in order to produce an edge crispening and local contrast enhancement [92]. This filter might be useful in images that present both shadow and bright regions[74].

Another of the filters used, embedded in the MicMac[75] free and open-source photogrammetric suite [93], is the SFS (Shape From Shading) option to augment the tie-point extraction phase. This might be important as, in some cases, it is possible to lose potential information, as the low contrast areas in the images are assimilated to noise and some tie-points cannot be extracted.

For performing the first test, a stereo pair has been selected (Figure 26), then each of the previously described filtered has been applied to both left and right image.



Figure 26. The stereo pair selected for testing different enhancement algorithms. In red, the portion of the image, representing the mast step, showed in Figure 27.

[73] https://github.com/python-pillow/Pillow
[74] https://github.com/eMandanici/ENVI-Wallis-filter
[75] https://github.com/micmacIGN/micmac

The DETAIL and EDGE ENHANCE filters have been applied via a Python script. The Wallis filter has been applied to the selected stereo couple by using GRAPHOS[76] (inteGRAted PHOtogrammetric Suite), an all-purpose free photogrammetric tool based on MicMac, that encloses robust photogrammetric and computer vision algorithms [94], [95] The algorithm has been applied based on five variables, the main ones are contrast[77] and brightness[78] (set to 0,50 and 1,00 respectively), which controls the dynamic range (or amount of enhancement) of an image to fit the target values of mean and standard deviation. The other variables are standard deviation[79], kernel size[80] and average[81] (set to 50, 99 and 127 respectively). The SFS filter has been applied using the software MicMac via the syntax command *TestLib PrepSift*. The effect of the application of the algorithms on the stereo couple can be observed in the following Figure 27.

The effectiveness of the different adopted filters have been tested using the software FME[82] (Feature Matching Evaluation), an open-source tool for the evaluation of different feature detector, descriptor and matching algorithms [95] (Figure 28).

Following the software pipeline, features are first detected both on the left image and the right one using the SIFT (Scale-Invariant Feature Transform) key-point detector and descriptor algorithm [96]. The results of the feature detection are detailed in the following Table 7.

Filter	*Detected features*	
	Left image	*Right image*
Original	75.372	56.208
DETAIL	91.393	67.289
EDGE ENHANCE	169.358	130.290
SFS	296.994	277.718
Wallis	304.185	290.198

Table 7. Numbers of detected features for the left and right images of the selected stereo couple for each of the employed image-enhancement filters.

Then, for matching the features, two approaches were used; a first was performed using the FLANN Matcher[83] (Fast Library for Approximate Nearest Neighbors), that provides a set of algorithms optimized for allowing a fast search of nearest neighbors. Another feature matching method was also tested; the robust matching (based on a brute force approach) that taking the descriptor of one feature in the first set and matching with all other features in the second set using the sum of the absolute value of differences between the descriptor elements. After the

[76] https://github.com/itos3d/GRAPHOS
[77] The parameter which controls the increase or decrease the amount of enhancement (variance gain).
[78] The parameter which controls the degree of brightness forcing.
[79] Target value for the intensity standard deviation in the kernel image.
[80] Size of the convolution kernel, expressed in pixel and linked to the image size.
[81] Target value for the intensity average in the kernel image.
[82] http://tidop.usal.es/software
[83] https://docs.opencv.org/3.4/dc/de5/group__flann.html

matches are computed, they are refined via an LMSE (Least Mean Square Error) approach. Unfortunately for some of the stereo couple (SFS and Wallis), it was not possible to perform the computation; this is due to the fact that the brute force approach performed by the robust matching option will try to match every feature detected on the left image with each single feature detected on the right image; this means 82.480.579.692 matching combinations for the SFS filter and 88.273.878.630 for the Wallis filter, presumably exceeding the computation capability of the program (generating a crash to desktop). The results of the feature matching are summarized in Table 8.

Filter	*Matched features*	
	FLANN	*Robust matching*
Original	332	2.745
DETAIL	313	2.576
EDGE ENHANCE	1.549	2.421
SFS	562	-*
Wallis	1.507	-*

* The number of features to be matched with the brute force approach exceeded the computation capability

Table 8. Numbers of matched features using both FLANN and Robust matching methods for the selected stereo couple for each of the employed image-enhancement filters.

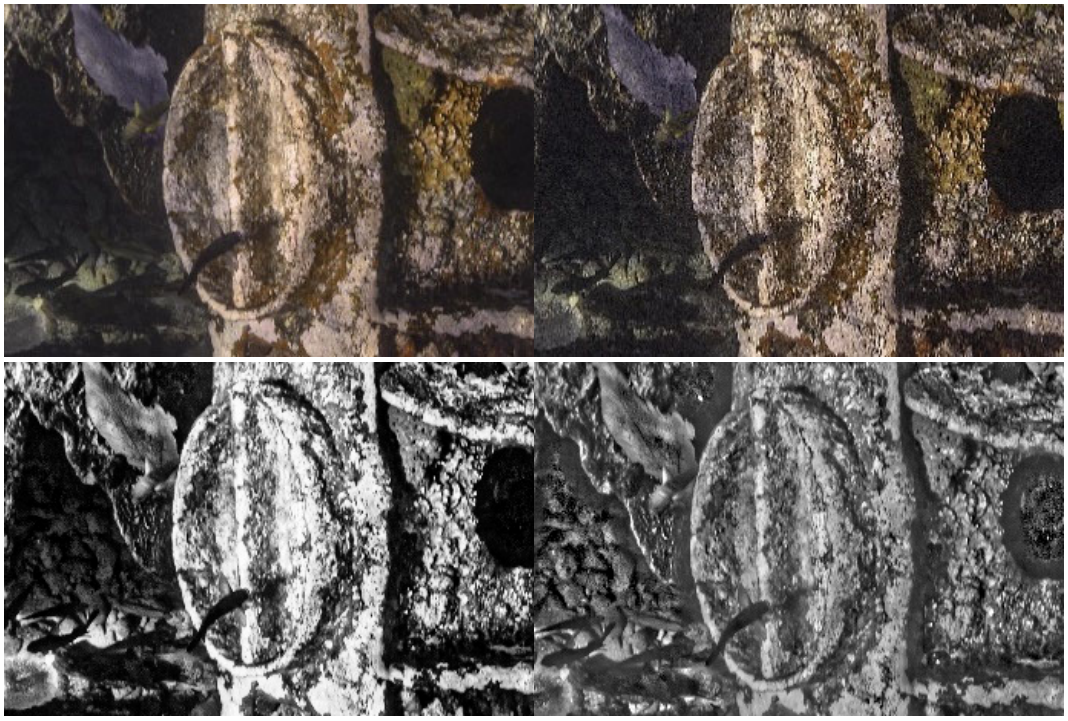


Figure 27. A portion of the right image (representing the mast step) of the stereo pair represented in figure 7 showing the effect of the applied algorithms on the original images; ImageFilter DETAIL (top left), ImageFilter EDGE ENHANCE (top right), SFS (bottom left) and Wallis (bottom right).

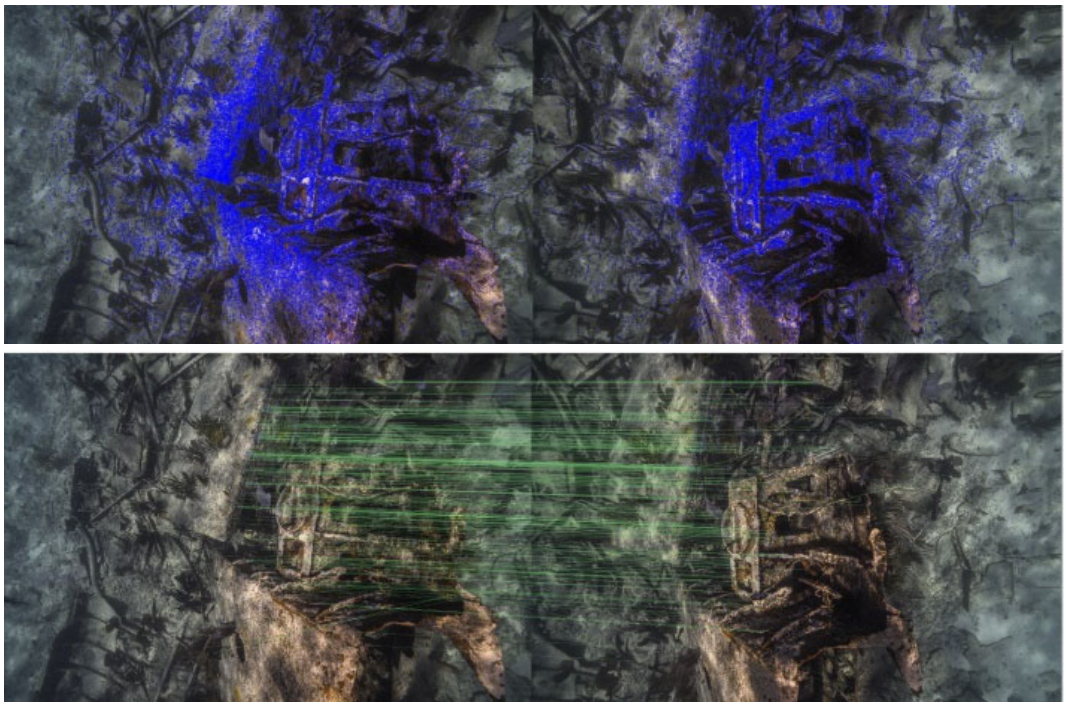


Figure 28. On the top, detected features on the left and right image of the selected stereo pair (in blue); on the bottom, features matched by the FLANN method (in green).

However, this preliminary evaluation lacked a ground truth, making it challenging to evaluate which of the analyzed methods is the best for the selected dataset. As the obtained results might work well only for the selected stereo pairs but might perform differently in a BBA with several pictures involved (pre-processed with the same filter), feature detection, feature matching, and image alignment has been performed with the software Agisoft Metashape for a sub dataset of 32 images of the mast step. The results were reported in the following Table 9.

Filter		*High*[84]	*Medium*[85]	*Low*[86]
Original	*Tie-points*	121,642	39.156	8.426
	Error [pix]	**0,59**	**0,91**	**1,64**
DETAIL	*Tie-points*	109.437	37.097	8.037
	Error [pix]	0,60	0,92	1,79
EDGE ENHANCE	*Tie-points*	84.755	28.828	5.156
	Error [pix]	0,68	1,00	2,18
SFS	*Tie-points*	123.529	49.335	13.528
	Error [pix]	0,65	0,98	1,82
Wallis	*Tie-points*	**140.155**	**52.835**	**14.591**
	Error [pix]	0,67	1,02	1,80

Table 9. Numbers of tie-points and reprojection residuals at different quality levels of alignment for each of the employed image-enhancement filters.

[84] At High accuracy setting the software works with the photos of the original size.
[85] Medium setting causes image downscaling by a factor of 4 (2 times by each side).
[86] With Low accuracy, source files are downscaled by a factor of 16.

As it is possible to observe, at a different level of image downscaling (original size; downscaled by a factor of 4; downscaled by a factor of 16) the Wallis filter performed better in comparison with the other applied filters. While in the case of low-quality alignment there is a consistent gain in the number of tie-points matched (comparing the original images with the same images filtered with Wallis), at higher quality alignment the observed gain is not that relevant. Since the tie-points are matched according to the feature spots detected, it might be useful to upscale source images to localize tie-points more accurately. However a higher number of tie-points does not necessarily correspond to a correct alignment [97]; therefore, filters should be used only when consistent results cannot be obtained due to poor quality of the original images, as they might introduce an undesired level of noise (and a higher reprojection error).

The exploratory considerations done so far will serve for an extensive benchmarking (cloud-to-cloud, density and roughness, analysis), that can be undertaken for an in-depth assessment of the presented filters. There are however some more issues that can interfere with the correct 3D scene reconstruction and should be considered, especially in the case of shallow or very shallow water, such as methods for the removal of caustics [98], which are not addressed in this study.

4.5 Simple radiometric correction

Because underwater images may suffer from severe chromatic aberration, it is crucial to take into account image pre-processing procedures, in order to enhance the quality of generated 2D and 3D products [99]. As it is well known, going deeper, there is a loss of colour associated with the theoretical distance light penetrates underwater, according to its wavelength (As previously discussed in § 3.2.1.1). However, being that the *Mandalay* wreck is, at its deepest point, at 6 m below the surface (with images acquired at about 3 m from the surface), no advanced radiometric correction was performed and the colours were adjusted via white balancing. Images were acquired initially in a RAW format (.NEF) and corrected using the Nikon ViewNX-I[87] software, adjusting the white balance based on the RGB values of a sample white area (5x5 average) selected on the checkerboard (Figure 29).

[87] https://nikonimglib.com/nvnxi/onlinehelp/en/index.html

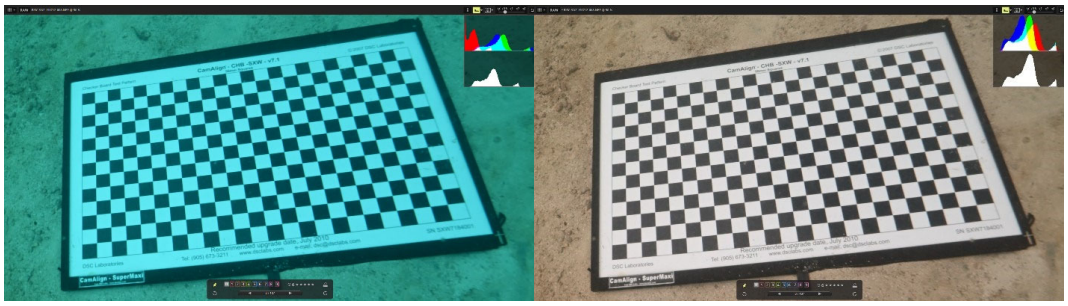


Figure 29. The employed checkerboard test pattern (50 mm side squares – CamAlign – CHB – SXW – V7.1) before (left) and after (right) the white balancing. The RGB and the luminance histograms are showed on the top right corner both before and after the correction.

Although the author of this dissertation is aware that the white colour on the checkerboard cannot be considered "pure white" and may lead to sub-optimal results in the radiometric correction, the acquisition was not meant initially with radiometric correction in mind. As stated in the introduction, this chapter intends to address the problem of dealing with sub-optimal datasets, and so a calibrated neutral white card and a grey card will be used for white balance and exposure setting in future acquisitions. The RAW images have been then batch-corrected in order to apply the white balancing achieved using the checkerboard sub-dataset to the whole scene. 3D model comparison, without and with white balancing, are presented in Figure 30.

The corrected radiometry is also propaedeutic to the generation of orthophotos (Figure 31), that can support a more rigorous production of archaeological documentation. It is important, however, to clarify that this is a simple and straightforward procedure for colour correction, that does not take into account any physical property of the water, neither a mathematical method for modelling colour absorption and backscattering. A more advanced method for colour correction of underwater images is discussed in this thesis, in the next chapter 5.



Figure 30. 3D model (triangulated mesh) of the Mandalay texturized without using white balancing (left) and after the radiometric correction (right).

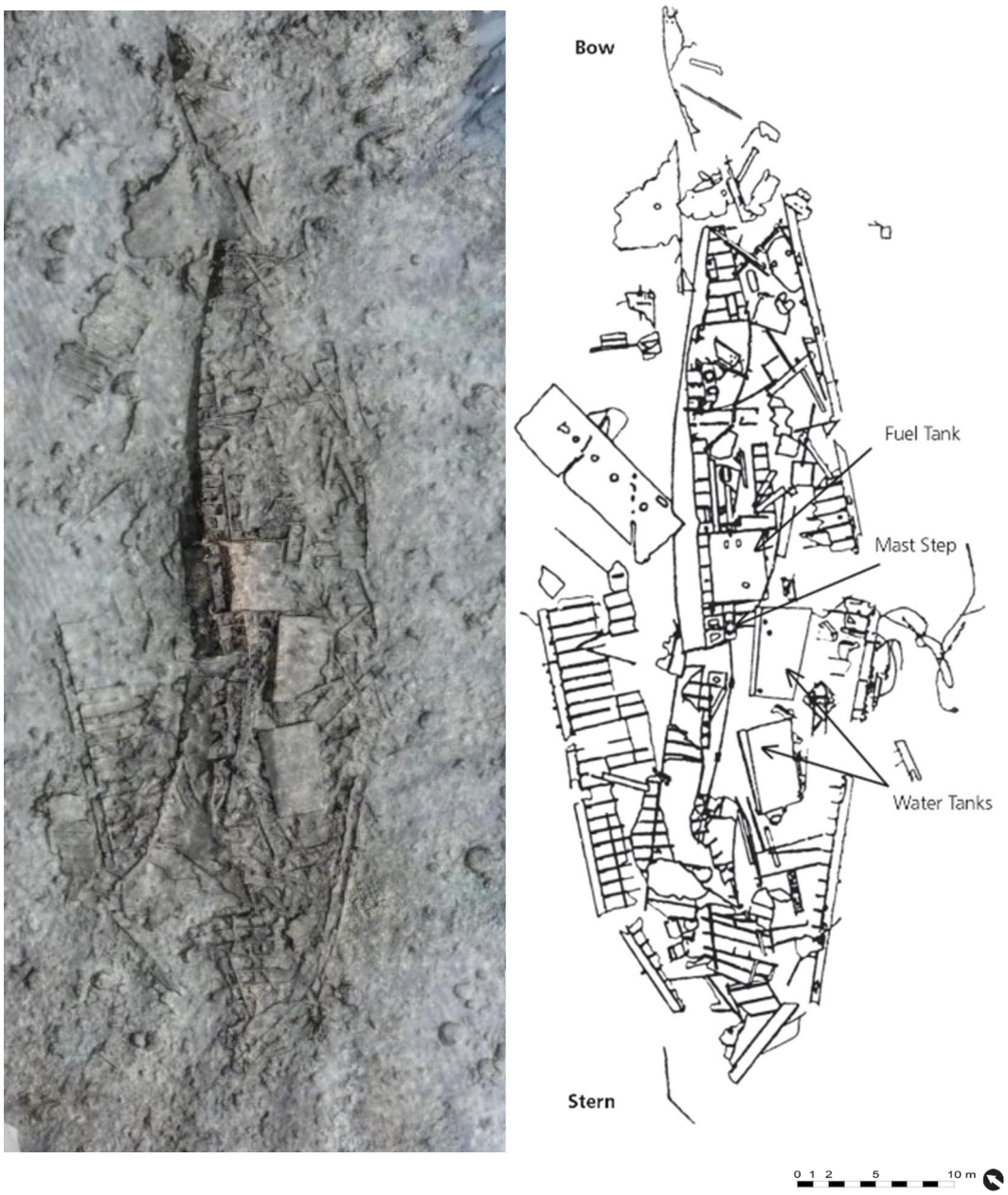


Figure 31. On the left, orthophoto of the *Mandalay* (70% transparency) superimposed over its hillshade DSM in order to make the 3D features more relevant; On the right, archaeological drawing of the site (Image courtesy of the *National Park Service*). It is possible to notice several differences between the 2020 orthophoto and the archaeological survey (produced several years before).

5

Chapter 5

5. Processing strategies for restoring colour information

collaborations

Cyprus University of Technology

Photogrammetric vision lab

The problem of colour correction of underwater images concerns not only surveyors, who primarily use images for photogrammetric purposes, but also archaeologists, marine biologists, and many other domains experts whose aim is to study objects and lifeforms underwater. Different methods exist in the literature; some of them provide outstanding results but works involving physical models that take into account additional information and variables (light conditions, depths, camera to objects distances, water properties) that are not always available or can be measured using expensive equipment or calculated using more complicated models. Some other methods have the advantages of working with basically all kinds of dataset, but without considering any geometric information, therefore applying corrections that work only in very generic conditions that most of the time differs from the real-world applications.

This chapter presents an easy and fast method for restoring the colour information on images captured underwater. The compelling idea is to model light backscattering and absorption variation according to the distance of the surveyed object. This information is always obtainable in photogrammetric datasets, as the model utilizes the scene's 3D geometry by creating and using SfM-MVS generated depth maps, which are crucial for implementing the proposed methodology. The results presented visually and quantitatively are promising since they are an excellent compromise to provide a straightforward and easily adaptable workflow to restore the colour information in underwater images.

As described by Wang et al. [100], UW images always show a green-bluish colour cast, which is driven by different red, green and blue light attenuation ratios [101]. The water properties that control light attenuation of water and thus the scene appearance is dependent on scattering and absorption. Attenuation coefficients

control how the light decays exponentially as a function of the distance that it travels [102]. Pure waters are optically clear mediums with no suspended particles; only the interaction of light with molecules and ions causes light to be absorbed in pure water [103]. Short visible wavelengths, such as blue, are absorbed first, followed by green and then red. As a result, just 1% of the light reaching the water's surface reaches a depth of 100 meters. [104].

All the studies previously mentioned in Chapter 3.2.3 tried to resolve the issue of UW colour attenuation with the use of specific calibrated equipment and a-priori knowledge that occurred from measurements such as reflectance measurements in the surface, measurements for water attenuation coefficients, obtaining image intensity reference values using calibrated colour charts, spectrometers etc. But what happens when this kind of information and equipment is not available or when dealing with archive datasets? Some algorithms exist such as the gray world assumption, LAB Colour Correction (LAB) [75], Contrast Limited Automatic Histogram Equalization (CLAHE) [105], [106], etc in order to correct the colours of UW imagery, all with pros and cons. The biggest disadvantage of these methods is that their performance is heavily dependent on the amount of colour that is present in the scenery, since they assume for the overall scene average colour.

This chapter aims to understand how the intensity of absorbed light for the three RGB channels changes based on the camera to object distance variation. Based on that, a quick and fast method for restoring most of the true colours of the scene will be proposed based on a mathematical model that describes how the colour intensity is absorbed and backscattered, with the final aim of restoring the true information. The model uses the camera to object distance for every pixel of the image that yields this information, in contrast to image enhancement methods like LAB or CLAHE algorithms. The camera to object distances are obtained from SfM-MVS derived depth maps of the images.

5.1 Case studies: The Green Bay diving site and the and Lady Thetis Shipwreck

In the framework of this chapter, a compact underwater camera (Olympus Stylus TG-6 - Figure 32 & Table 10) and a couple of colour calibration charts (ColourChecker® Classic | X-Rite[88]) mounted on a PVC parallelepiped structure have been used (Figure 33).

In order to investigate how different wavelengths, degrade in intensity, two tests have been performed related to acquiring RAW images at varying camera-to-object distance. The test has been carried out by acquiring multiple images of a selected object at a specific depth and performing a photogrammetric acquisition, placing inside the surveyed scene a 40 cm side L-shaped scale bar and the employed structure (without the camera) with the outer calibration chart exposed.

[88] Since the 1st of July 2021, X-Rite Incorporated and Calibrite announced their partnership to transition the X-Rite photo and video portfolio to Calibrite.



Figure 32. Olympus Stylus TG-6 Tough camera.

Resolution [pix]	Focal length [mm]	Pixel size [µm]
4000 x 3000	4,5 mm	1,56

Table 10. Olympus TG-6 camera main technical specifications.

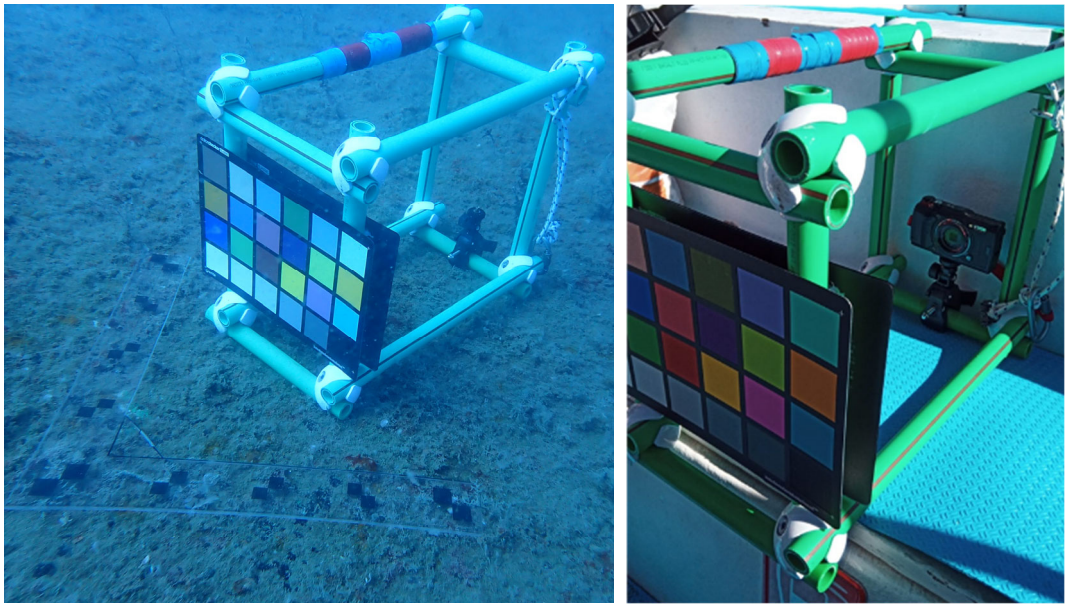


Figure 33. Sensor and equipment used in the framework of this research.

In this way, it was possible to obtain depth maps (and therefore the related COD – Camera to Object Distance) for each of the acquired images.

The tests mentioned earlier have been performed in two different sites in Cyprus. Test site 1 (Figure 34) is the Green Bay diving site (Protaras). The test was performed at a maximum depth of 10 m. A photogrammetric acquisition of one of the several stone sculptures located around the diving site was performed. Test site 2 (Figure 35) is the Lady Thetis Shipwreck diving site (Limassol). The test was performed at a maximum depth of 13 m. A photogrammetric acquisition of the shipwreck's upper deck's metal roof was performed.



Figure 34. Test site 1 - the Green Bay diving site (Protaras).



Figure 35. Test site 2 - the Lady Thetis Shipwreck diving site (Limassol).

The eight primary colour patches from the colour chart (cyan, magenta, yellow, red, green, blue, black, white) have been selected. For each channel (red, green, and blue), and based on the change of underwater depth (test A) and of camera-to-object distance (test B), absorption diagrams have been created for the test performed in the two test sites. The intensity value reported on each diagram has been obtained by applying a median filter to a sample area for each patch.

Since UW image acquisition for 3D reconstruction is done exclusively at constant depth with the camera to object distance being the varying constant, it has been decided to focus on a colour correction method utilizing the data collected at the seafloor since they comply with the standard UW image acquisition for 3D reconstruction approach.

For the processing, the RAW images were transformed into 16-bit uncompressed Tiff images in order to process them while keeping the raw information recorded by the camera, undistorted. Multiple tests were done in order

to finalize a proper fitting function to model the colour absorption and the backscattering in UW images. These tests were performed on the data that were suited for photogrammetric 3D reconstruction. In the Protaras site, the dataset contained images of a statue captured in varying distances and angles, while for the 2nd site in Limassol, the dataset contained images of the shipwreck's upper deck's metal roof, suited for photogrammetric 3D reconstruction. The Xrite colour chart was visible alongside the aforementioned scale bar in both datasets.

The two datasets were photogrammetrically processed using Agisoft Metashape to extract the depth maps for the image frames. The 40 cm scale bar was used to bring the 3D models into proper scaling and for the depth maps to provide the proper camera to object distances for each image pixel.

5.2 Colour correction based on a mathematical model

After the photogrammetric processing, the intensity values for the eight primary colour patches of the Xrite colour chart were extracted alongside their respective camera to object distances. This was done for all the images where the colour chart was clearly visible in order to ensure the proper acquisition of the colour intensities. For the intensities, instead of extracting the values given from 1 single pixel on the colour cell, it was decided to extract the median value from a 20 by 20 pixel box inside the colour cell. This ensured that possible noise was neutralized and did not affect the experiment in the later stages. In Figure 36 it is possible to observe that when the camera to object distance increases, the red colour image intensity values of the eight primary Xrite colour patches decays almost exponentially. In contrast the decay is smoother as expected for green and blue. This is also showed when the Limassol site dataset is evaluated (Figure 37).

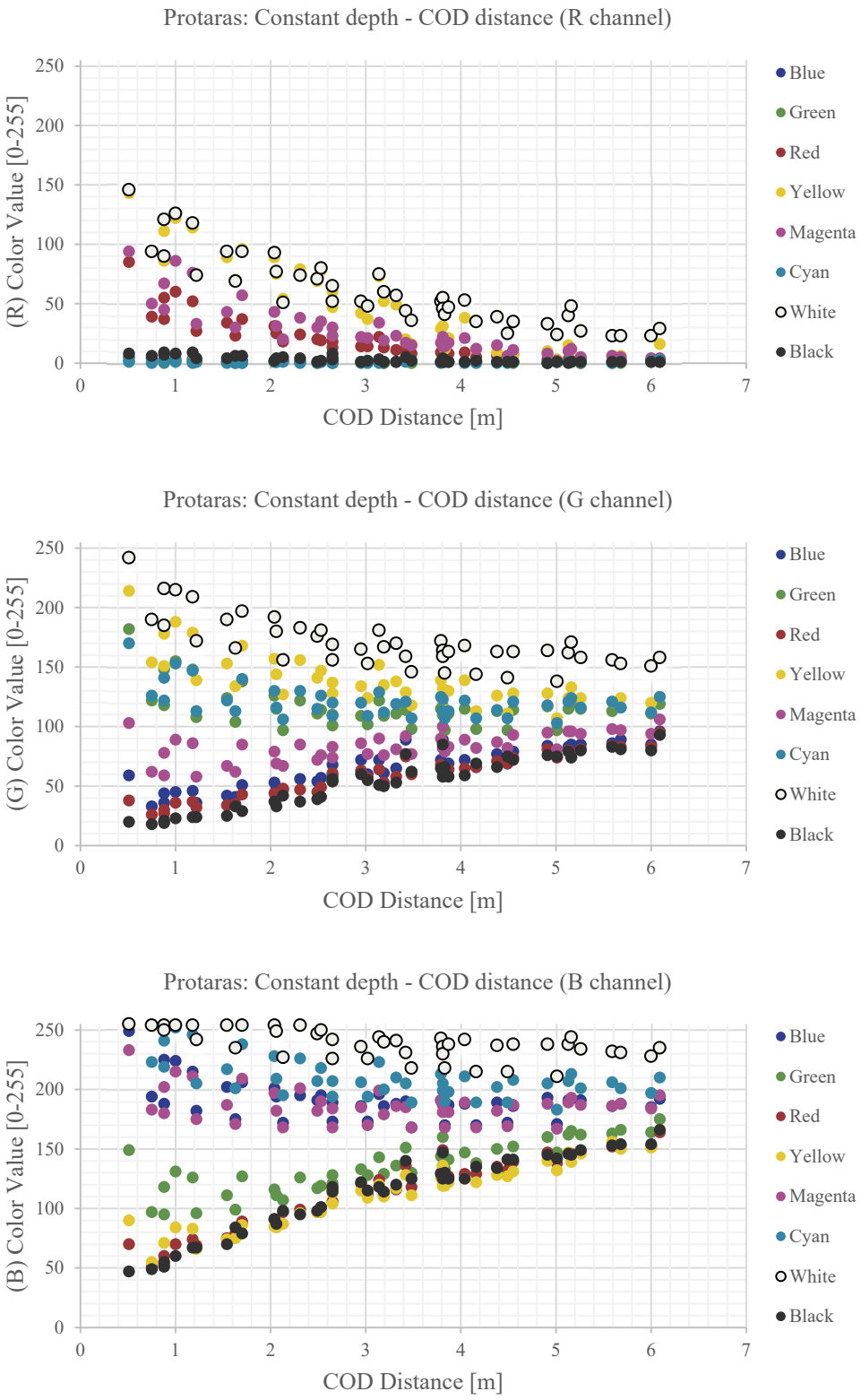


Figure 36. The diagram shows the value of the intensity absorption of red, green and blue colour channels (top to bottom), for each of the eight main colour patches (Red, Green, Blue, Cyan, Magenta, Yellow, Black, White), based on camera to object distances for Protaras test site.

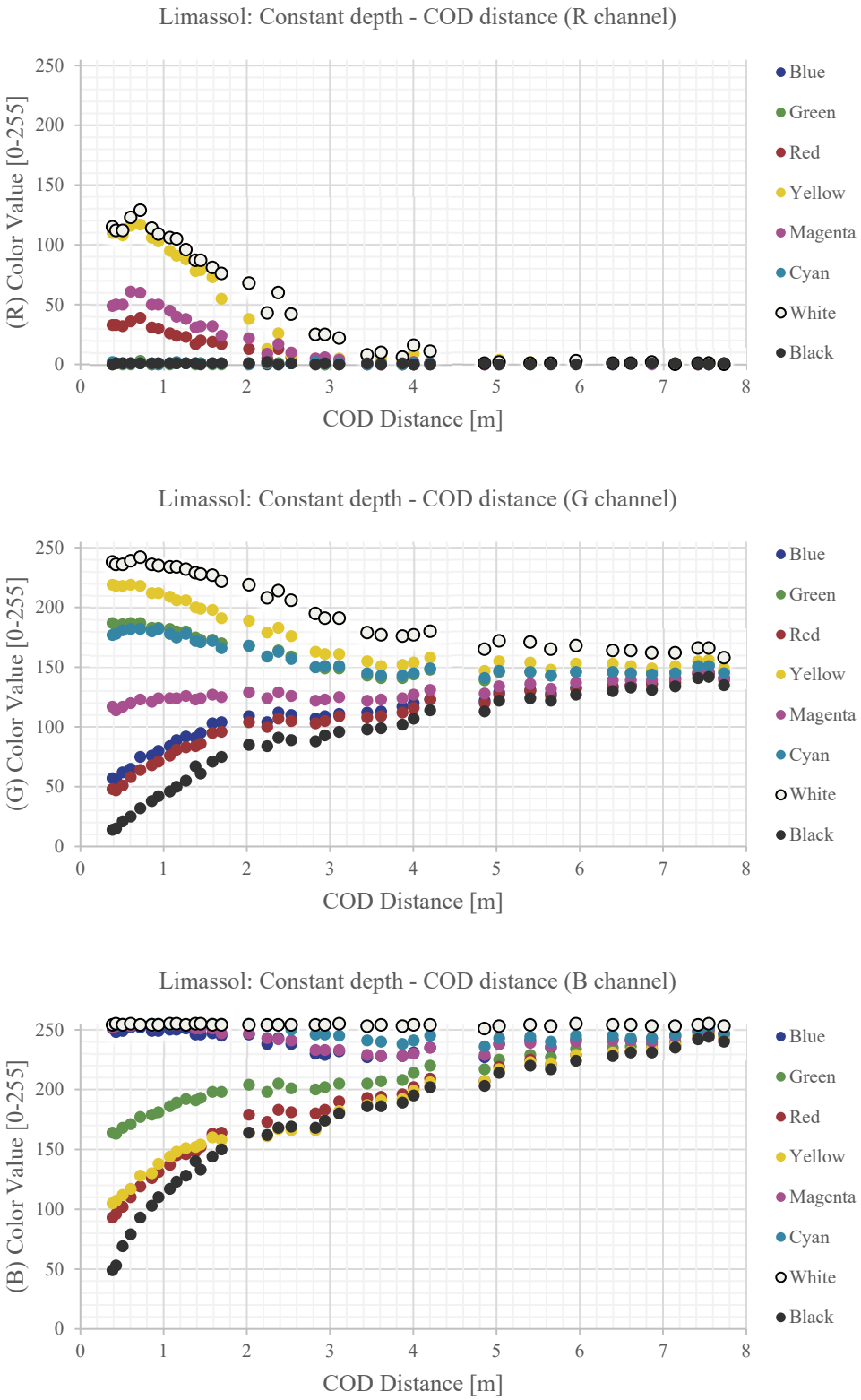


Figure 37**.** The diagram shows the value of the intensity absorption of red, green and blue colour channels (top to bottom), for each of the eight main colour patches (Red, Green, Blue, Cyan, Magenta, Yellow, Black, White), based on camera to object distances for Limassol test site.

5.2.1. Modelling Absorption and Backscattering

Observing the derived graphs (Figure 36 and Figure 37), it is noticeable how different the colour decay is for the various colour patches. For example, it is possible to notice that the colour intensity values of the green and blue patches for their respective channels are decaying based on the camera to object distance. On the other hand, when observing how the black patch behaves, it can be noticed that for green and blue, the values increase. This observation led to breaking down the modelling into two parts. To properly model and correct the colour distortion in the acquired images, the proposed method introduces a model that includes both absorption and backscattering. This idea is also supported by the fact that various image formation models that exist in the literature [64], [78], [84] account for both absorption and backscattering with the latter being an additive element to the former.

Having that in mind, the next step was modelling backscattering and absorption. To do so, data from the two neutral patches, white and black, have been used. More specifically, the colour values based on the camera to object distances of Red, Green and Blue for the white and black colour patches were plotted (Figure 38 and Figure 39). Using linear regression, fitting functions were introduced in order to model the absorption and backscattering.

Having observed the above, multiple tests were implemented to introduce the best fitting function for the data. Multiple fitting functions were tested such us polynomial of various degrees, exponential of 1st and 2nd degree and trigonometric functions. Based on the various tests, the backscattering is best modelled as a 2nd degree polynomial for blue and green where the backscattering for red is negligible thus it can be considered 0. Regarding the absorption, the best fitting function that can be modelled is either a 2nd degree polynomial or a 2nd degree exponential fitting. For both datasets 2nd degree exponential fitting was used for the absorption where 2nd degree polynomial fitting was used for the backscattering since they provided the best visual results. Figure 40 shows the results of the proposed method and the results provided by CLAHE and LAB algorithms.

In Figure 40 LAB and the proposed method show the most visually pleasing results. However, the proposed method provides results only in the areas of the image where there is 3D information or in other words where it has been obtained the camera to object distances. In our method after the colour correction, a white balancing based on the white patch of the colour checker is applied. Although it could be said that LAB gives somewhat of an acceptable result, the problem is that it does not take into consideration any geometric related information. The result may differ significantly if for the same dataset. LAB is applied on multiple images. CLAHE did not manage to improve the colours of the scene. The only noticeable difference is a contrast change.

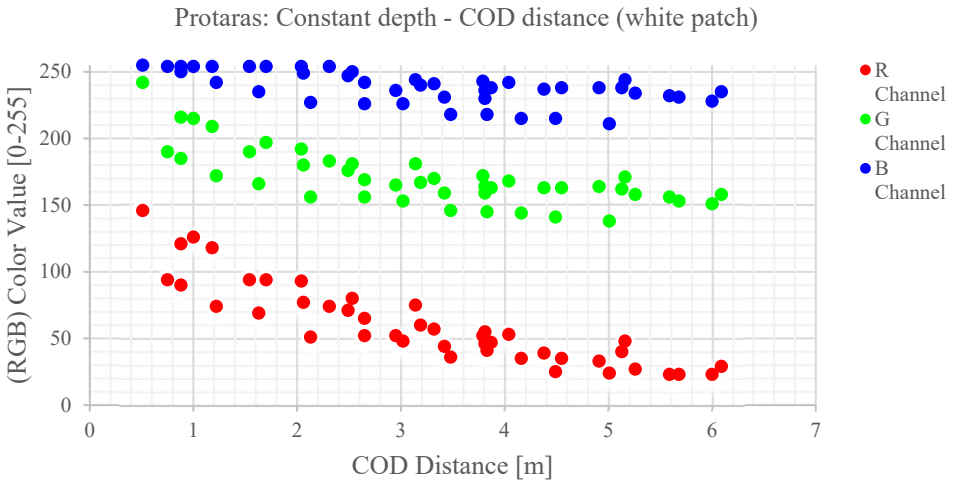


Figure 38. For Protaras dataset: from top to bottom is the colour value behaviour for Red, Green and Blue channels as the camera to object distance increases for the white colour patch.

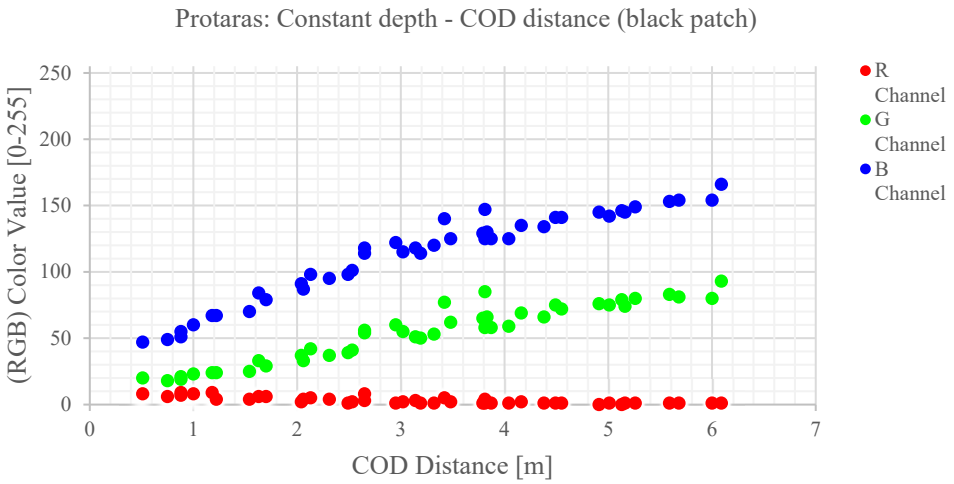


Figure 39. For Protaras dataset: from top to bottom is the colour value behaviour for Red, Green and Blue channels as the camera to object distance increases for the black colour patch.

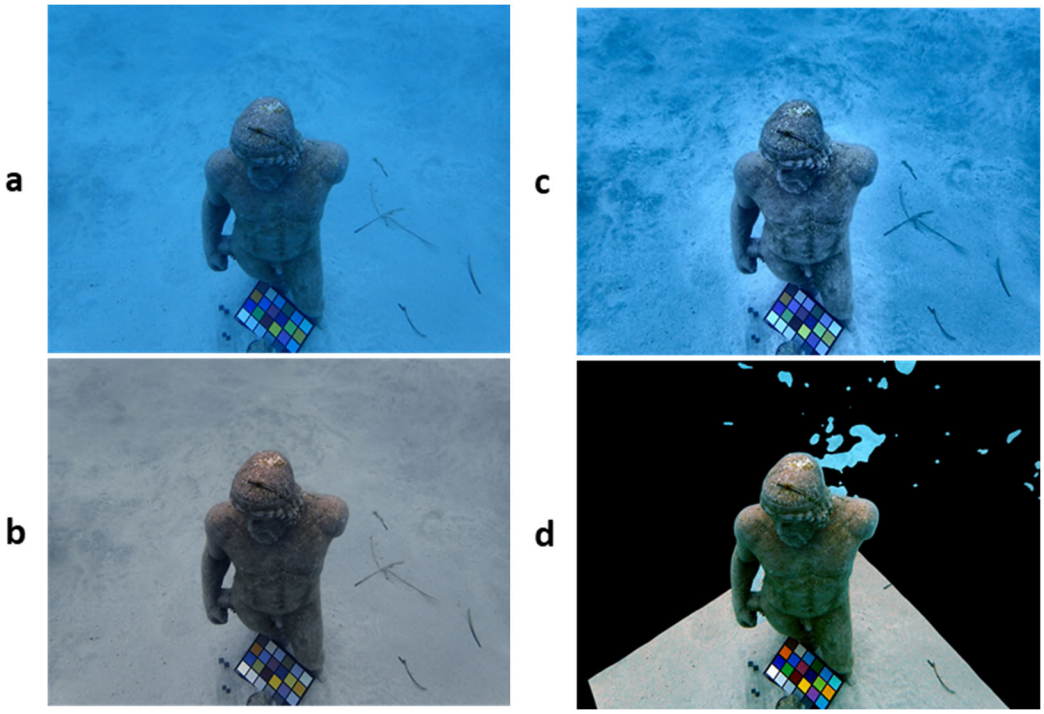


Figure 40. Correction results for Protaras Dataset: a) original image, b) LAB, c) CLAHE, d) proposed method (2nd degree polynomial for the back scattering was used and 2nd degree exponential for the absorption).

The corresponding results for the Limassol dataset are presented in Figure 41, Figure 42 & Figure 43. The behaviour although was expected to be similar, appears to be very different regarding the blue colour absorption on the white patch. Instead of the colour intensity reducing, it can be observed that as the COD changes, the blue intensity stays equal to 1. This can be explained by the shear dominance of blue colour at that particular depth (13-15m) where the dataset was captured.

The modelling for absorption and backscattering remained the same for the Limassol dataset, meaning that backscattering was modelled as a 2nd degree polynomial where absorption was modelled as a 2nd degree exponential function.

Figure 43 shows the results provided by the proposed method, LAB and CLAHE algorithms correction and the original image. Overall, the visual result of LAB and CLAHE is similar to the one provided for Protaras image dataset. Regarding the proposed method, visually the colours of the scene are improved but some noise is present around the poles of the frame. This noise is by-product of the depth map of the image since the SfM-MVS derived models include noise which is transferred into the depth maps.

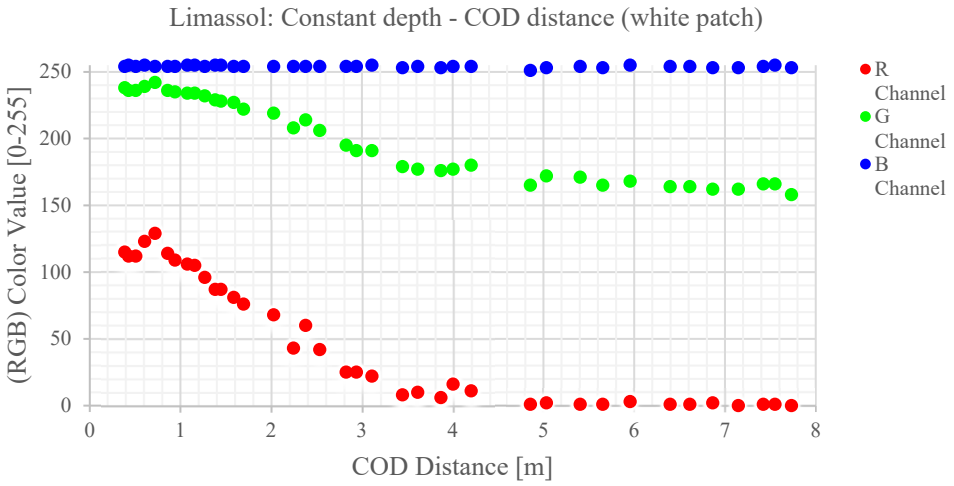


Figure 41. For Limassol dataset: from top to bottom is the colour value behaviour for Red, Green and Blue channels as the camera to object distance increases for the white colour patch.

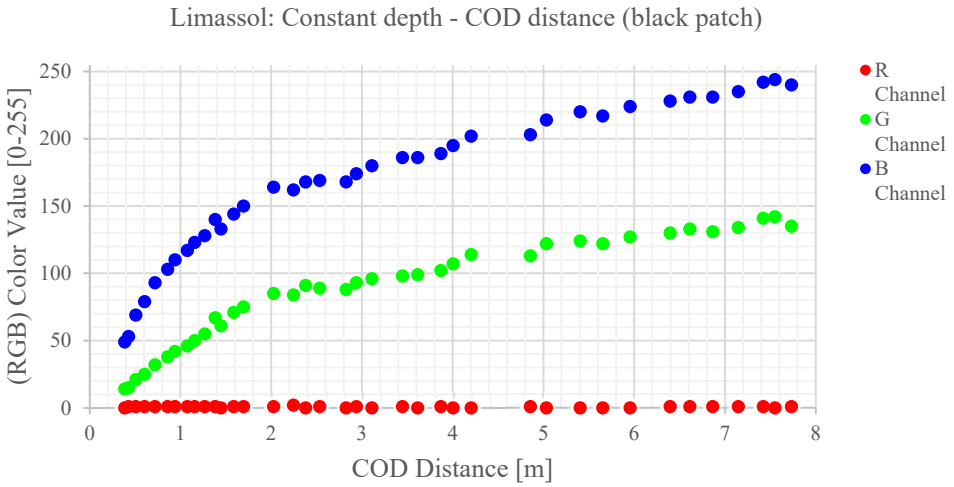


Figure 42. For Limassol dataset: from top to bottom is the colour value behaviour for Red, Green and Blue channels as the camera to object distance increases for the black colour patch.

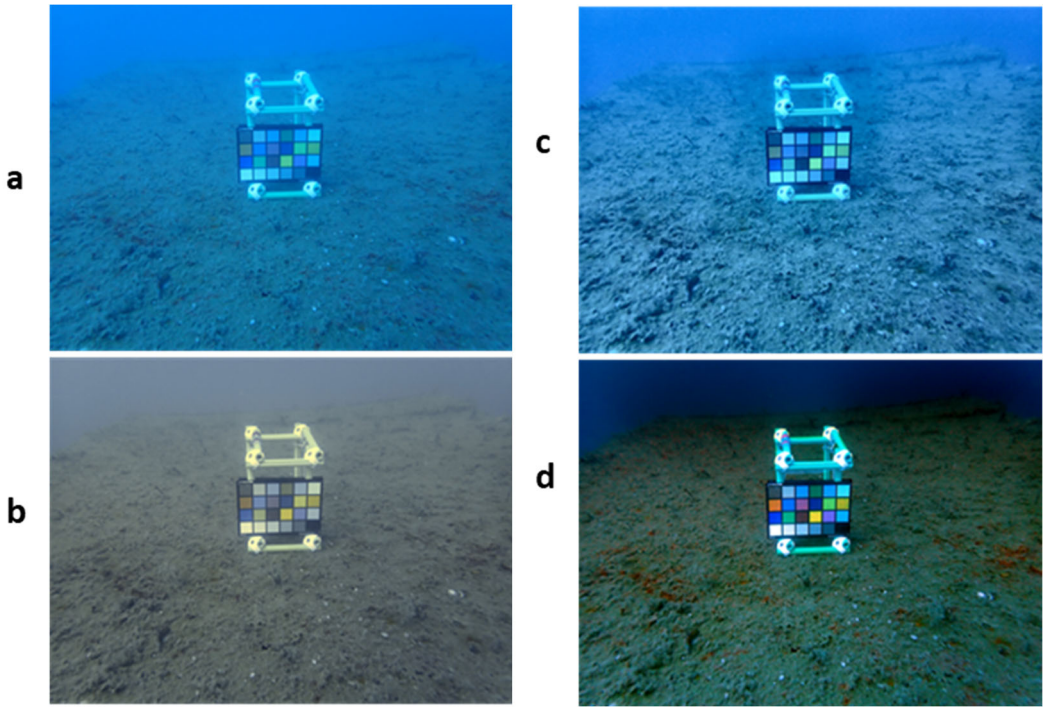


Figure 43. Correction results for Limassol Dataset: a) original image, b) LAB, c) CLAHE, d) proposed method (2nd degree polynomial for the back scattering was used and 2nd degree exponential for the absorption).

5.2.2. Evaluation of the results

Having tested the above on various images, the results vary depending on the images and more specifically, the camera to object distances. In particular, the colour reconstruction suffers more visually in images where the object was further away from the camera. The following figure shows the results of a sample of four images, when the proposed method, LAB and CLAHE colour corrections are applied. Results on the various images are shown in Figure 44 & Figure 45 below. Based on the figures above, the visual result on the produced images differs from image to image. Those differences are primarily due to the camera-to-object distances. From what was evaluated, images taken 3÷5 m away of the objects are shown redder, since the model that is applied, primarily tries to compensate for the lack of red. Since it is distance dependent it can overcompensate in some areas of the image. This effect appears in dark and shadowed areas of the image where the objects appear to have a reddish tone. The results produced for the two datasets differ due to the different environment, depth, seabed characteristics, and water particles. These differences were expected, and the goal was to see and evaluate how impactful the algorithm could be and if the model could restore the missing colour information up to a satisfying degree.

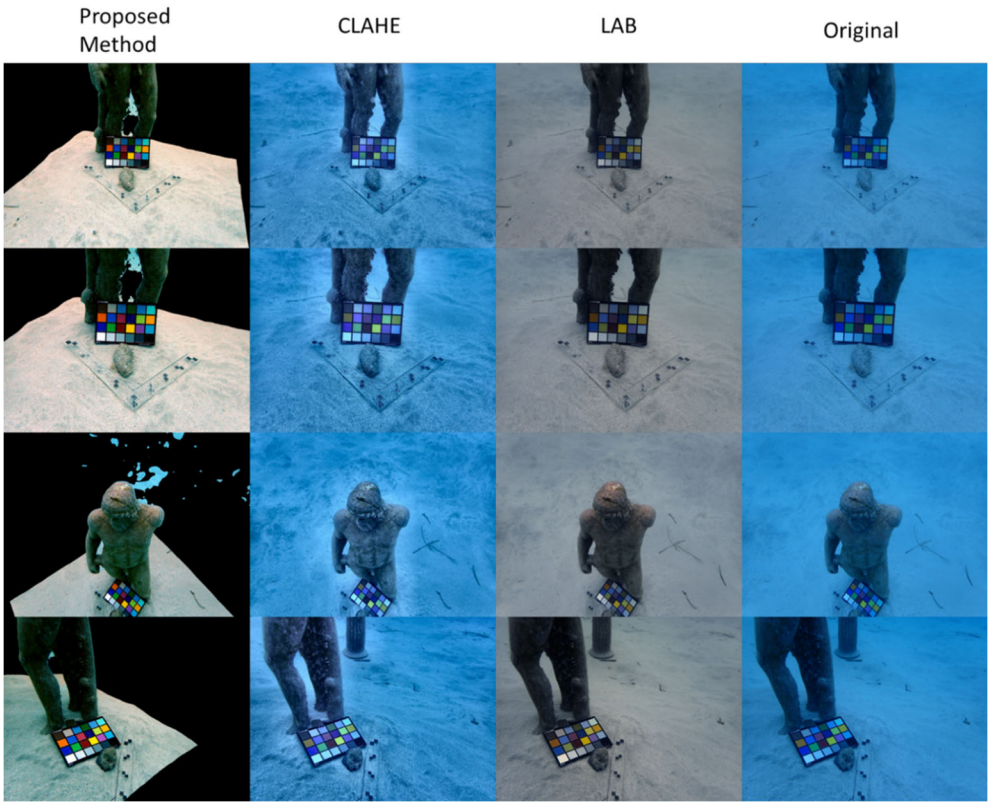


Figure 44: From Left to right the results provided by our algorithm, LAB, CLAHE, and the original images. Images from Protaras dataset

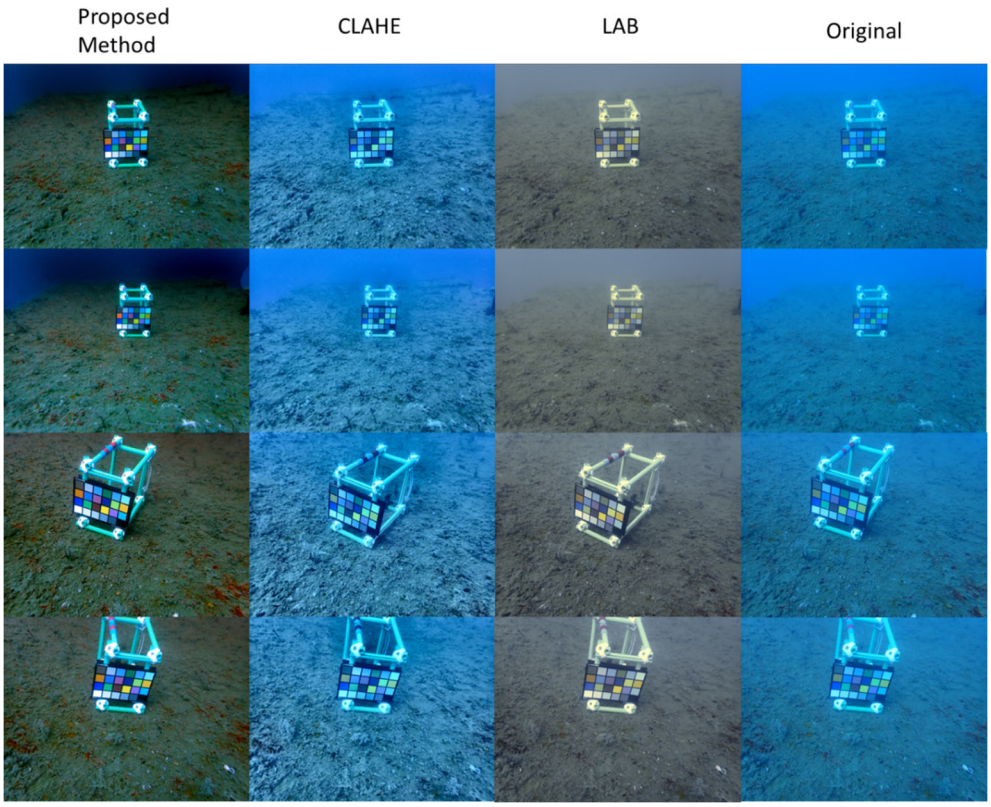


Figure 45: From Left to right the results provided by our algorithm, LAB, CLAHE, and the original images. Images from Limassol dataset

Additionally, compared with the image enhancement algorithms applied to the images (CLAHE & LAB), the proposed model manages to lessen the scene off the fog effect that is caused due to backscattering. This is the major primary benefit of algorithms utilizing scene geometry over common standard enhancement tools. Since there is information about the scene geometry, it can be use in order to compensate and remove backscattering and thus the fog effect on the images. Furthermore, the colour restoration of both CLAHE and LAB fails in both sites due to the lack of enough light on the scene. Such algorithms require a significant amount of light to be present in order to efficiently restore the colour information of UW images and this is usually done using strobes that are mounted on the cameras. In this study was not the case since the goal was the development of an algorithm that can restore the colour of the scene where only natural light is present as it is the case with shallow depths.

As it is demonstrated, the results of the proposed algorithm are visually pleasing and promising, since the applied model in each case managed to restore the majority of the missing colour information of the scene. As expected, it can be observed that the tones of certain colour patches are not fully restored. For example, the red patch is shown to be darker than it is outside of water. This could be considered a reasonable output as it is not possible to restore something that is not present.

To further evaluate the algorithm's performance besides the qualitative results and the visuals of the images, various quantitative metrics were applied for several images to determine the algorithm's effectiveness. These particular images contain the colour patches, but they were not used to fit the model thus they could be used for evaluation later on.

The first measure of the evaluation was the use of the fitting score R^2(Eq1). This is a coefficient used to evaluate a model in cases where a percentage of the dataset is used for training and the rest has been used for testing. This fitting score is mainly used to evaluate ML algorithms but can be used for simple regression models such as the proposed one. The coefficient's best possible score is 1 but it also can be negative [107]. I_{true} is the ground truth colour value of a colour patch for a particular colour channel. In these cases, in an image captured in air (outside the water) has been used to estimate the true values of the colour intensities from the colour patch shown. I_{pred} is the predicted colour value after the implementation of the algorithm in that colour patch. $I_{true.mean}$ is the mean colour value from all 24 patches for a particular colour channel.

Unfortunately, since this metric does not have a fixed coefficient range, it has been decided to modify it to have a more comprehensive range of values. The modified metric ${R^2}_{mod}$ is shown below (Eq2). This modification does not include $I_{true.mean}$ and that allows the coefficient range to change from 0 to 1 with the former being the worst possible value where the latter is the best.

Another metric used for evaluation was metric D. N is the number of colour patches which in our case was 24. This metric is produced by subtracting the minimized sum of squared residuals from 1 as is shown (Eq3) and the best possible value can be 1.

Finally, as an additional evaluation metric, it has been adopted the mean Euclidean distance produced considering all 24 colour patches for all 3 colour channels together (Eq4). For this metric, the closer the value is to 0, the better the evaluation is.

$$R^2 = 1 - \frac{\sum(I_{true} - I_{pred})^2}{\sum(I_{true} - I_{true.mean})^2} \quad (1)$$

$$R^2{}_{mod} = 1 - \frac{\sum(I_{true} - I_{pred})^2}{\sum(I_{true})^2} \quad (2)$$

$$D = 1 - \sqrt{\frac{\sum(I_{true} - I_{pred})^2}{N}} \quad (3)$$

$$EuclD = \frac{\sum\left(\sqrt{(I_{true} - I_{pred})_R^2 + (I_{true} - I_{pred})_G^2 + (I_{true} - I_{pred})_B^2}\right)}{N} \quad (4)$$

The results of these quantitative metrics are shown below in Table 11 and Table 12.

Protaras	*IMGP1*	*IMGP2*	*IMGP3*	*IMGP4*
R^2_{red}	0,36	0,48	0,46	0,71
R^2_{green}	0,79	0,86	0,86	0,65
R^2_{blue}	0,78	0,85	0,85	0,68
$R^2_{mod_red}$	0,84	0,83	0,83	0,90
$R^2_{mod_green}$	0,92	0,96	0,93	0,91
$R^2_{mod_blue}$	0,92	0,95	0,94	0,90
D_{red}	0,78	0,77	0,77	0,83
D_{green}	0,88	0,91	0,89	0,87
D_{blue}	0,87	0,90	0,88	0,85
EuclD	0,27	0,24	0,24	0,26

Table 11. The various quantitative metric coefficients for 4 sample images of the Protaras dataset

Limassol	*IMGL1*	*IMGL2*	*IMGL3*	*IMGL4*
R^2_{red}	-0,52	-0,83	0,15	0,05
R^2_{green}	0,60	0,58	0,77	0,74
R^2_{blue}	0,51	0,51	0,57	0,65
$R^2_{mod_red}$	0,70	0,62	0,84	0,82
$R^2_{mod_green}$	0,96	0,95	0,98	0,98
$R^2_{mod_blue}$	0,97	0,96	0,96	0,97
D_{red}	0,63	0,59	0,73	0,72
D_{green}	0,86	0,85	0,89	0,89
D_{blue}	0,86	0,85	0,85	0,87
EuclD	0,39	0,41	0,30	0,30

Table 12. The various quantitative metric coefficients for 4 sample images of the Limassol dataset

Observing Table 11 and Table 12, it is possible to realize the variation between the values of each metric used as well as their consistency for specific colour channels in almost all the images. For instance, metric R^2 presents the lowest values for almost all the images but especially images that the colour chart is further away from the camera (IMGL1 & IMGL2). Additionally, we observe that all metrics related with the red channel are at their best value for images that the colour chart is closest to the camera (IMGP4 & IMGL4).

Overall, the colour channel that appears to be the least reliably restored based on the metrics, is red which was expected since it is the colour that suffers the most from UW attenuation. Furthermore, the metrics appear overall to be worse for the images of the Limassol dataset. That can indicate the impact of the depth but can also be simply due to the different and thus worse environmental water conditions of the site.

5.3 Colour correction based on a physical model

In the framework of this PhD thesis, it has been interesting to experiment with different colour correction methods for underwater image datasets.

Sea-thru algorithm [78] *"is a physics-based algorithm using the Akkaynak-Treibitz underwater image formation model. It does not use neural networks and was not trained on any dataset. It works without a colour chart, or any information about the optical qualities or depth of the water body."*[89]

The other colour correction method used to be compared with Sea-thru are:

a) The automatic colour correction method performed by the camera used for the acquisition of the images (Olympus Stylus TG-6);
b) The RAW images colour corrected using software DNG ProfileManager[90] of the ColourChecker® Classic | X-Rite
c) The LAB algorithm, which is based on gray-world and uniform illumination assumptions applied in the lαβ space. *"The gray-world assumption is a well-known approach, proposed by Buchsbaum* [108]. *In its simplest version it assumes that the information in the average of each channel of the image is the representative gray level. In other words, the average of the captured image should be gray (achromatic). Colour correction is performed by white balancing of chromatic components (α and β), while the luminance component l is processed to improve the image contrast."* [75]

The dataset is related to the wreck of a Roman *navis lapidaria*, with a cargo of five monumental cipollino marble columns and 1 block from the quarries of Karystos in Evia, Greece, 8.5-8.8 metres long, with a total weight of 78 tons, lies 4.5 meters deep, located in the AMP of Porto Cesareo (Italy). the ship ran aground due to its draft (3 metres) being greater than the depth at the site, considering that sea level was then approximatively 3 m lower than today.

[89] https://www.deryaakkaynak.com/sea-thru
[90] https://www.xrite.com/it-it/service-support/dng_profile_manager

The dataset is composed of 400 raw files and depth maps for 353 of them which have been exported using Agisoft with the v4 script[91]. The processing has been performed using Agisoft Metashape. Before the orthophoto generation, the images have been corrected with Sea-thru and with the above mentioned methods, and four orthophotos have been generated for comparison Figure 46.

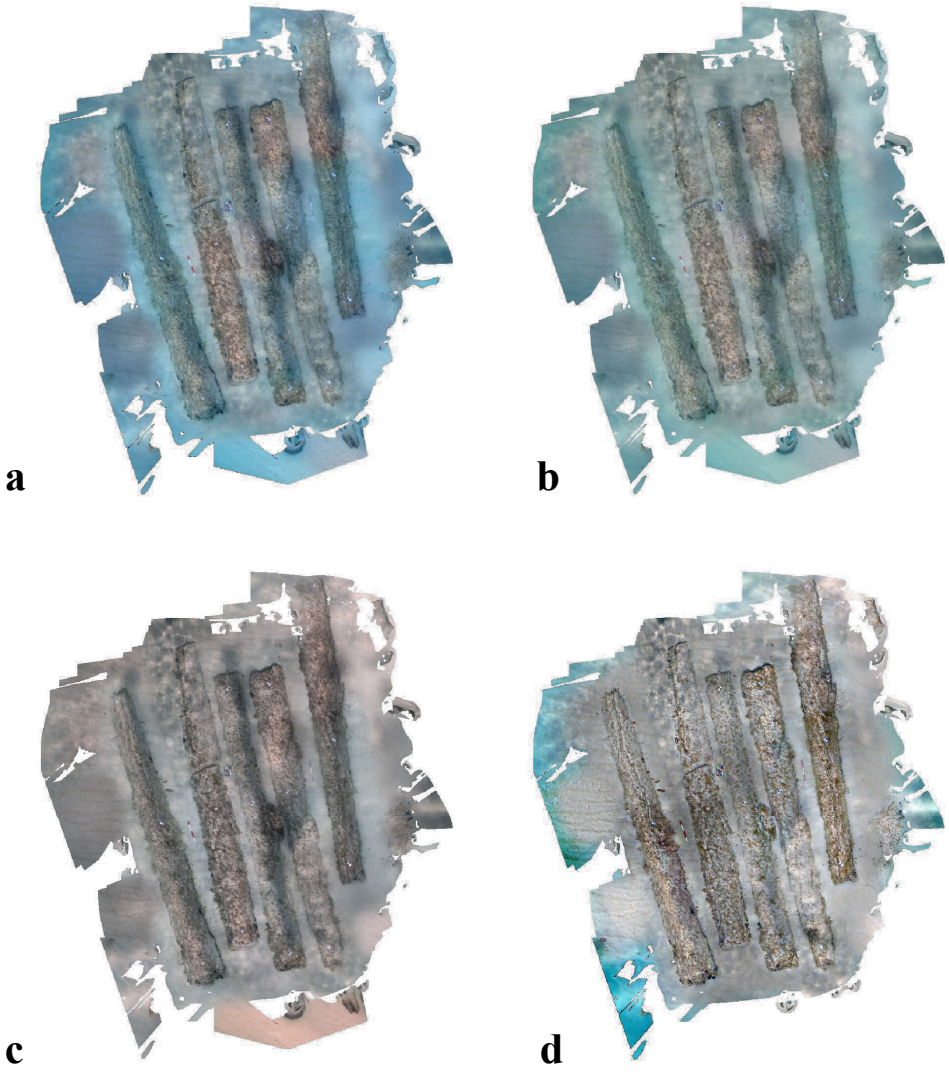


Figure 46. Orthoimages of the Navis Lapidaria of AMP Porto Cesareo, generated using the a) Olympus; b) Xrite; c) LAB and d) Sea-thru colour correction methods.

The eight primary colour patches from the colour chart (cyan, magenta, yellow, red, green, blue, black, white) have been selected. For each channel (red, green, and blue), the intensity value in an RGB space is reported on Table 13.

The comparison of the Euclidean distance in the RGB space, for each of the eight main patch, is reported in Table 14.

[91] https://github.com/dakkaynak/AgisoftScripts

As the RGB colourspace is non-perceptually-uniform, analysis in the CIELAB colour space would make a better perceptually uniform and standardized comparison.

Colour patch		B■	G■	R■	Y■	M■	C■	W□	B■
Reference colour chart	R	51,00	96,00	154,00	226,00	167,00	56,00	241,00	53,00
	G	64,00	146,00	57,00	198,00	80,00	132,00	241,00	53,00
	B	142,00	77,00	59,00	50,00	143,00	163,00	235,00	54,00
Olympus	R	23,35	70,21	149,64	177,85	144,14	28,64	187,97	31,54
	G	97,12	177,87	68,69	199,15	108,72	158,94	232,08	58,44
	B	241,18	145,06	93,71	99,86	190,82	235,89	254,57	88,48
Xrite	R	1,40	86,24	143,79	182,50	143,38	32,65	200,23	47,53
	G	83,62	179,29	88,78	200,93	114,67	149,51	221,11	71,22
	B	210,97	124,73	109,69	88,70	200,49	204,53	242,45	84,47
LAB	R	31,51	118,90	121,23	203,22	142,04	77,35	237,08	43,78
	G	82,29	171,59	60,75	187,73	98,55	157,88	234,98	50,13
	B	176,70	127,86	76,59	92,20	172,63	186,07	247,13	59,27
SeaThru	R	3,66	49,08	165,14	252,91	172,44	1,66	255,00	2,42
	G	22,90	226,53	1,53	249,87	27,44	157,37	255,00	1,83
	B	250,94	51,65	26,16	0,41	226,36	247,28	255,00	12,41

Table 13. Intensity value (RGB) for the eight main colour patches in for the reference colour chart and for the different colour correction methods adopted.

Colour patch		*B*■	*G*■	*R*■	*Y*■	*M*■	*C*■	*W*□	*B*■	$\bar{X}$
Olympus	*EuclD*	0,24	0,18	0,08	0,16	0,14	0,19	0,13	0,09	0,15
Xrite	*EuclD*	0,20	0,13	0,14	0,13	0,16	0,11	0,10	0,08	0,13
LAB	*EuclD*	0,10	0,14	0,08	0,11	0,10	0,09	0,03	0,02	0,09
SeaThru	*EuclD*	0,28	0,22	0,15	0,17	0,22	0,23	0,06	0,19	0,19

Table 14. Euclidean distance (RGB) between the reference colour chart and the different colour correction methods adopted, for the eight main colour patches.

The following Figure 47, Figure 48, Figure 49 and Figure 50 display the colour accuracy measurements for each of the employed methods (Olympus, Xrite, LAB, SeaThru). Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI. Each colour accuracy measurement is displayed as ΔE, the Euclidean distance between measured and reference colours in the CIE 1976 L*a*b* colour space. More accurate colours have a smaller ΔE.

For an alternative representation of the colour accuracy measurements, Figure 51 shows plot the measured and reference colours in the CIE 1976 L*a*b* colour space on a chromaticity diagram. Red circles indicate the reference colour. Green circles indicate the measured colour of each colour patch. The chromaticity diagram does not portray the brightness of colour. "ROIs with a shorter distance between the reference and measurement points have smaller differences in chromaticity, which can contribute to a smaller value of Delta_E. However, brightness also contributes to the value of Delta_E. For example, even though the reference and measurement points for ROI 13 are near each other on the chromaticity diagram, they have a large Delta_E because of their large difference in brightness."[92]

[92] https://it.mathworks.com/help/images/ref/esfrchart.measurecolor.html

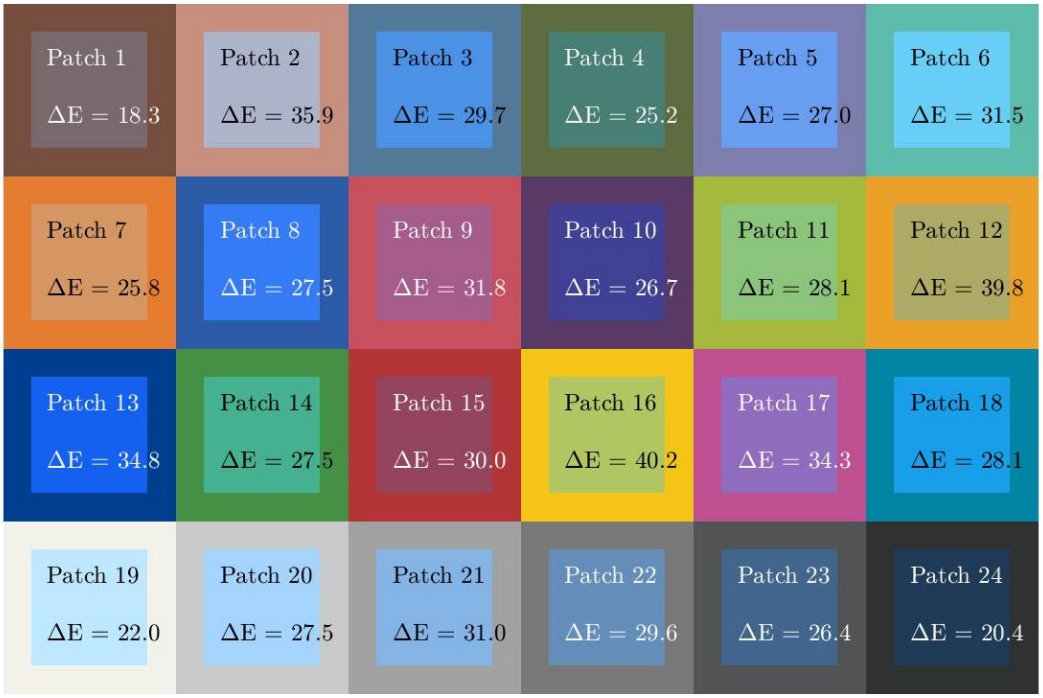


Figure 47. Colour accuracy measurements of the Olympus colour correction method. Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI.

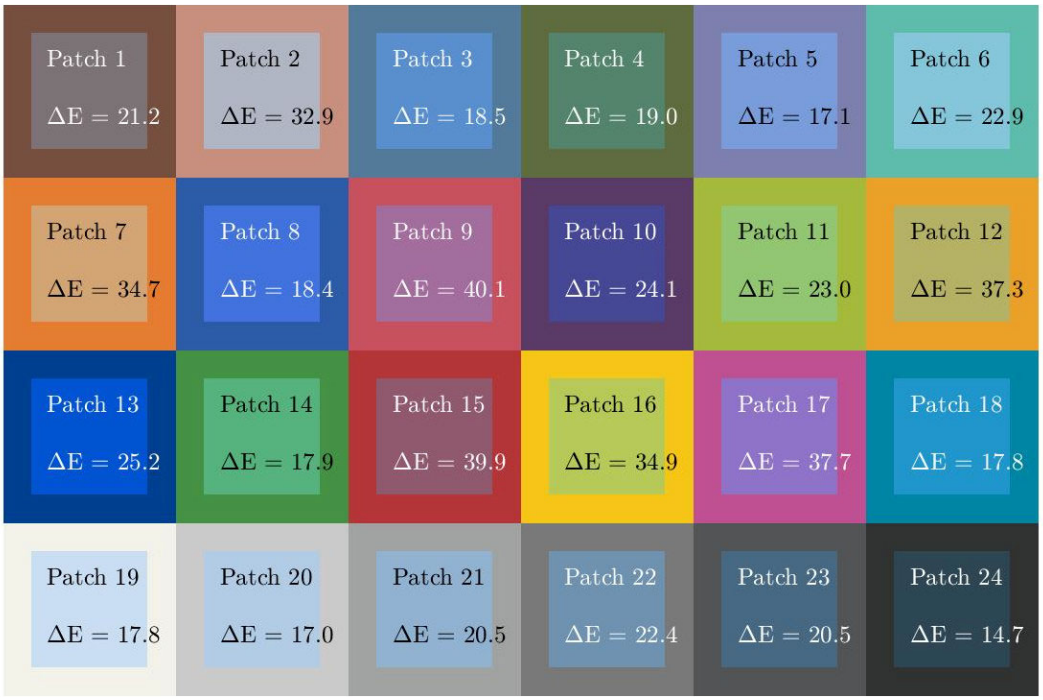


Figure 48. Colour accuracy measurements of the Xrite colour correction method. Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI.

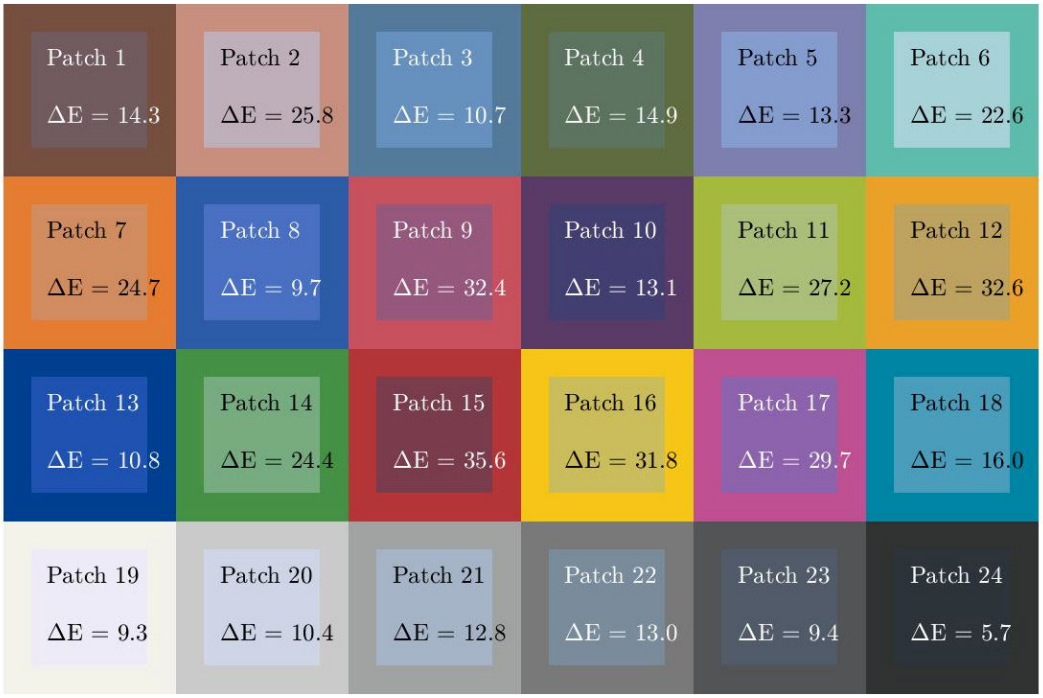


Figure 49. Colour accuracy measurements of the LAB colour correction method. Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI.

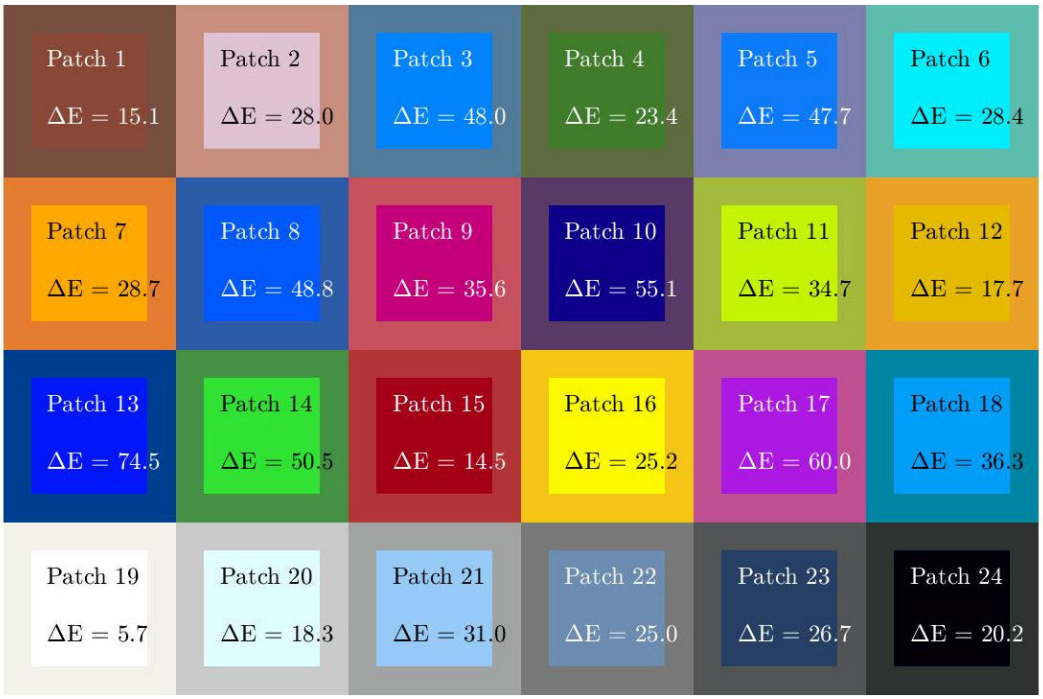


Figure 50. Colour accuracy measurements of the Sea-thru colour correction method. Each square colour patch is the measured colour, and the thick surrounding border is the reference colour for that ROI.

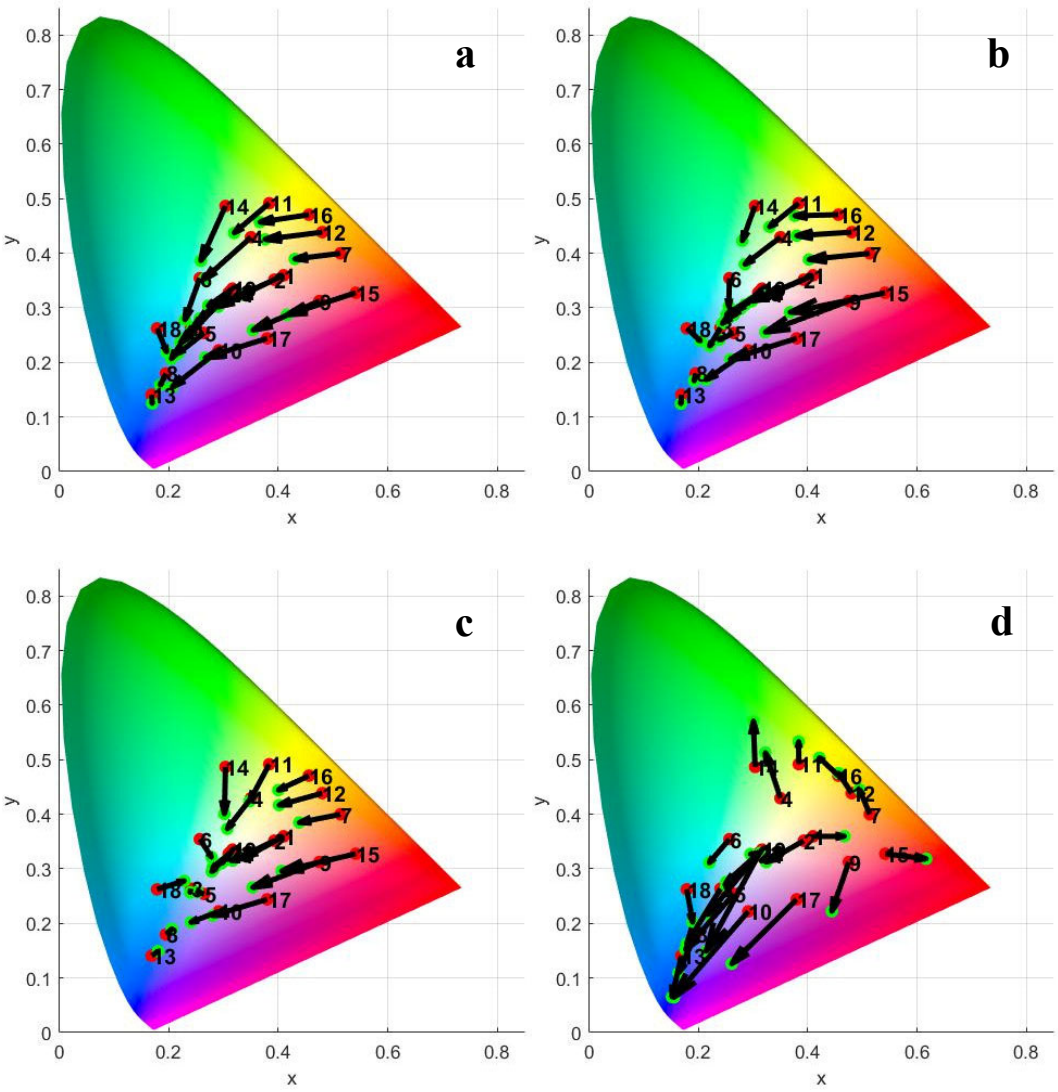


Figure 51. For a) Olympus; b) Xrite; c) LAB and d) Sea-thru colour correction methods, the diagrams shows the measured and reference colours in the CIE 1976 L*a*b* colour space on a chromaticity diagram. Red circles indicate the reference colour. Green circles indicate the measured colour of each colour patch. The chromaticity diagram does not portray the brightness of colour

For the test performed, it is possible to observe how the LAB algorithm performs better both in the comparison in the RGB space and in the CIELAB space. The Olympus and the Xrite colour correction results are comparable, while the Sea-thru is the low performing one in terms of colour restoration for the employed dataset (Table 15).

Colour patch		*B*■	*G*■	*R*■	*Y*■	*M*■	*C*■	*W*□	*B*■	$\bar{X}$
Olympus	Δ*E*	34,77	27,48	29,99	40,23	34,32	28,08	21,98	20,42	29,66
Xrite	Δ*E*	25,23	17,93	39,94	34,93	37,73	17,77	17,80	14,75	25,76
LAB	Δ*E*	10,77	24,44	35,58	31,82	29,69	15,97	9,30	5,67	20,40
SeaThru	Δ*E*	74,53	50,45	14,53	25,21	59,96	36,29	5,73	20,24	35,87

Table 15. Euclidean distance (CIELAB) between the reference colour chart and the different colour correction methods adopted, for the eight main colour patches.

Since the outputs of Sea-thru completely depend on the quality of the depth maps (and therefore the quality of the 3D model), the higher quality the model, the more consistent (and accurate) the resulting colour corrections will be. In this case, it is recommanded to run the 3D model again in Agisoft, using the Sea-thru corrected images, at the highest quality allowed by ones computational resources, clean all artifacts in the model (Figure 52, Figure 53 & Figure 54), export depth maps again, and run Sea-thru again for a better iteration.

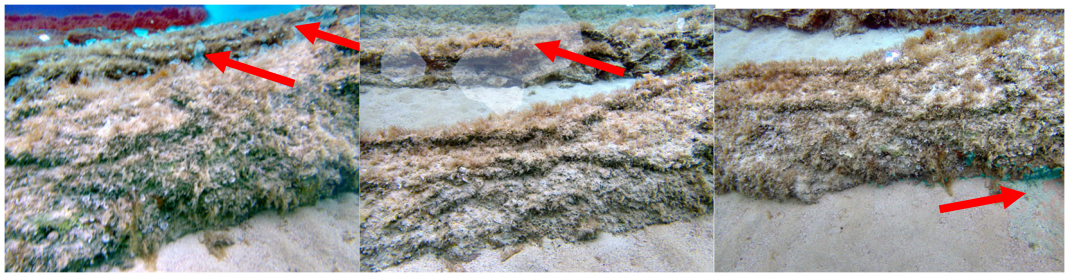


Figure 52. Examples of artifacts due to model quality

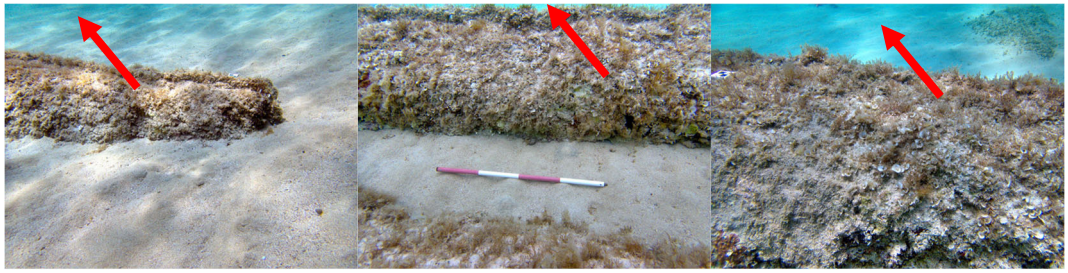


Figure 53. Examples of artifacts due to inaccurate range maps (ie, edges of the model)

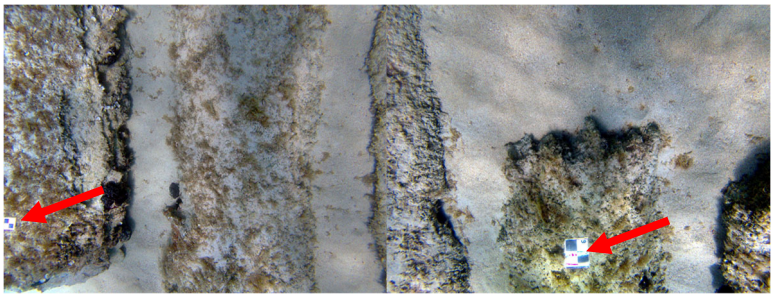


Figure 54. Examples of artifacts due to the albedo of manmade objects

5.4 Comparative results between the mathematical and the physical methods

Since the two colour correction methods described in this chapter were tested in two different experiments, this paragraph aims at quantitatively comparing the results obtained using the mathematical method proposed in §5.2 with the results obtained using the physical method (Sea-thru) discussed in §5.3.

As the two methods were applied in different test sites, in order to perform a quantitative comparison, the results obtained using the LAB colour correction method in both scenarios have been taken as a common ground truth, as it is the method that quantitatively outperforms all other methods analysed in this thesis (being the one that minimize the mean Euclidean distance among all the analysed colour patches in every analysed scenario).

For this comparison, the eight primary colour patches from the colour chart (cyan, magenta, yellow, red, green, blue, black, white) have been selected. For each channel (red, green, and blue), the intensity value in an RGB space is reported on Table 16 (for the Protaras test site) and Table 17 (for the Navis lapidaria site).

The comparison of the Euclidean distance in the RGB space, for each of the eight main patch, is reported in Table 18 (for the Protaras test site) Table 19 (for the Navis lapidaria site).

Colour patch		B■	G■	R■	Y■	M■	C■	W□	B■
Reference colour chart	R	51,00	96,00	154,00	226,00	167,00	56,00	241,00	53,00
	G	64,00	146,00	57,00	198,00	80,00	132,00	241,00	53,00
	B	142,00	77,00	59,00	50,00	143,00	163,00	235,00	54,00
LAB	R	36,74	130,06	61,43	206,95	119,23	139,73	254,09	23,81
	G	72,76	148,17	28,56	174,46	104,52	168,92	236,54	30,91
	B	152,52	85,89	42,25	35,75	160,40	189,09	196,70	48,03
Proposed method	R	1,92	0,13	91,12	254,70	113,33	0,01	253,35	8,14
	G	17,47	143,46	11,38	196,39	59,06	149,66	252,73	5,92
	B	164,40	40,93	4,47	1,01	154,69	198,59	253,20	5,30

Table 16. Intensity value (RGB) for the eight main colour patches in for the reference colour chart and for the different colour correction methods adopted (Protaras test site).

Colour patch		B■	G■	R■	Y■	M■	C■	W□	B■
Reference colour chart	R	51,00	96,00	154,00	226,00	167,00	56,00	241,00	53,00
	G	64,00	146,00	57,00	198,00	80,00	132,00	241,00	53,00
	B	142,00	77,00	59,00	50,00	143,00	163,00	235,00	54,00
LAB	R	31,51	118,90	121,23	203,22	142,04	77,35	237,08	43,78
	G	82,29	171,59	60,75	187,73	98,55	157,88	234,98	50,13
	B	176,70	127,86	76,59	92,20	172,63	186,07	247,13	59,27
SeaThru	R	3,66	49,08	165,14	252,91	172,44	1,66	255,00	2,42
	G	22,90	226,53	1,53	249,87	27,44	157,37	255,00	1,83
	B	250,94	51,65	26,16	0,41	226,36	247,28	255,00	12,41

Table 17. Intensity value (RGB) for the eight main colour patches in for the reference colour chart and for the different colour correction methods adopted (Navis lapidaria).

Colour patch		*B*■	*G*■	*R*■	*Y*■	*M*■	*C*■	*W*□	*B*■	$\bar{X}$
LAB	*EuclD*	0,04	0,08	0,22	0,08	0,13	0,22	0,09	0,08	0,12
Proposed method	*EuclD*	0,16	0,23	0,21	0,13	0,13	0,16	0,06	0,18	0,16

Table 18. Euclidean distance (RGB) between the reference colour chart and the different colour correction methods adopted, for the eight main colour patches (Protaras test site).

Colour patch		*B*■	*G*■	*R*■	*Y*■	*M*■	*C*■	*W*□	*B*■	$\bar{X}$
LAB	*EuclD*	0,10	0,14	0,08	0,11	0,10	0,09	0,03	0,02	0,09
Sea-thru	*EuclD*	0,28	0,22	0,15	0,17	0,22	0,23	0,06	0,19	0,19

Table 19. Euclidean distance (RGB) between the reference colour chart and the different colour correction methods adopted, for the eight main colour patches (Navis lapidaria).

Considering the resulting $\bar{X}$ of both experiments, it is possible to observe how the proposed mathematical method slightly outperform the Sea-thru physical method, having the resulting $\bar{X}$ closer to the LAB's one (previously assumed as a ground truth).

A more complete and accurate quantitative comparison among these methods would be desirable by performing the same analysis on a common test site (using the chart reference value as a ground truth).

Figure 55 provides a graphical representation summarising the main pros and cos of the employed methods.

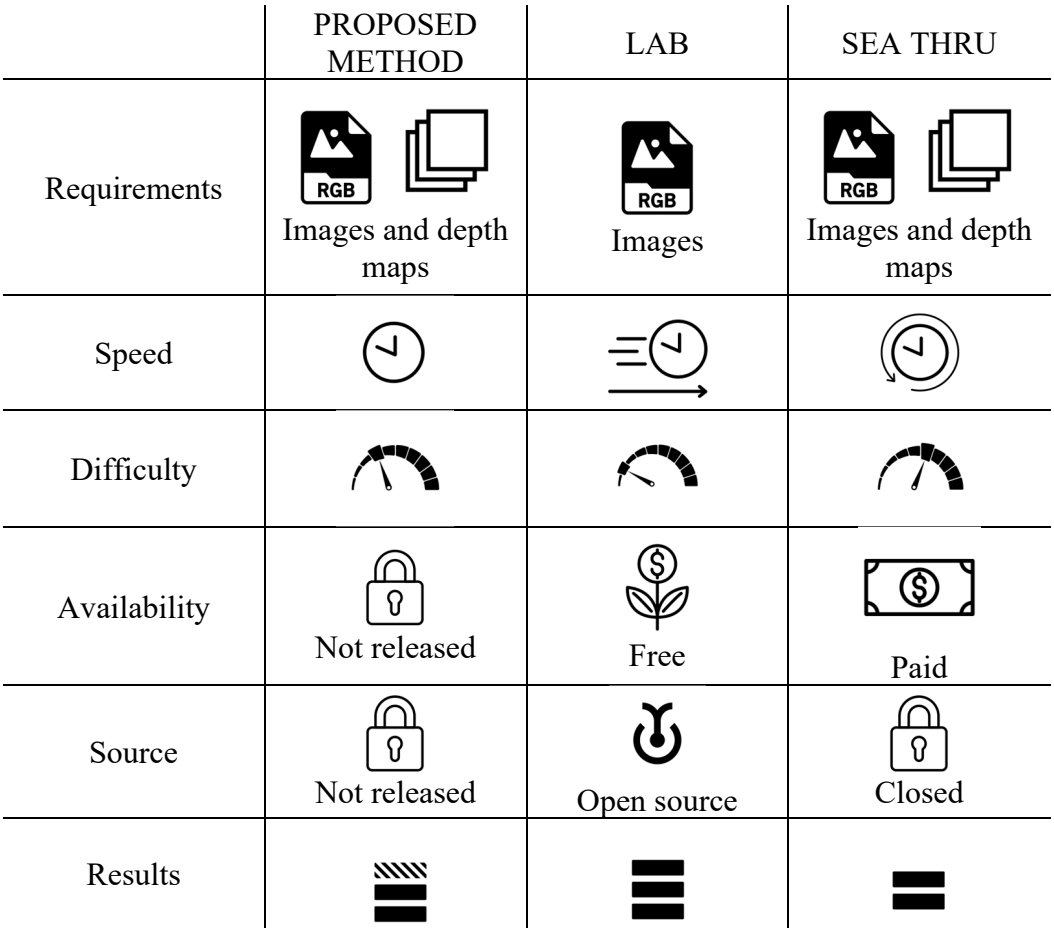


Figure 55. A brief summary of the main pros and cos of the adopted methods.

6

Chapter 6

6. Georeferencing strategies in very shallow waters

This chapter aims at discussing the limits of positioning and georeferencing techniques in underwater environment, and how is it possible to exploit existing methods and new instruments for performing an accurate topographic survey of GCPs in very shallow waters (within 6 m), useful to support the photogrammetric reconstruction of underwater assets.

6.1 Topography contribution in UW photogrammetry

The photogrammetric documentation of UCH assets is an important step for the study of the submerged heritage, but it might not be sufficient alone if not supported by a careful choice of georeferencing strategies for the topographic survey, together with the consistency in the delivery phase through the use of a common reference system among all the generated products [62].

Some traditional archaeological excavation campaigns relied only on the use of scalebars or approximate topographic measurements (especially in UW); if it has been proved that the use of scalebars in photogrammetric recording during archaeological fieldworks are essentials for assigning a correct scale to the generated 3D models and 2D products [109], relying only on them will lead to a lack of absolute georeferentiation, that is crucial whenever the need of multitemporal documentation or merging data from different sources and instruments arises.

Traditional topographic techniques, unfortunately, doesn't work well or are not applicable underwater "as they are", and some considerations have to be made in order to be applied on UW survey, rather than land survey.

If, on one hand, GNSS signal doesn't work underwater, topographic surveys by mean of side shot measures from total station can be used only in proximity of the shore, and in reasonable depths related to the employed pole length.

In recent years, the development of underwater communication and position devices based on acoustic signals [110] have fostered the industrial application of some niche devices; unfortunately, those devices nowadays have accuracies[93] that are compatible with navigation purposes, but are not applicable for the survey of accurate localization of GCPs or CPs underwater, where centimetric accuracies are expected. To overcome the problem of underwater positioning, some recent studies presents the use of a pressure sensor for the accurate scaling and levelling in underwater photogrammetry [111], while other methods suggest the accurate and permanent installation of Ground Control Points (GCPs) for allowing a robust reference frame for the georeferentiation of images blocks [112].

In the literature of topographic surveys in archaeological excavation, it is very common to find a topographic approach consisting in the use of trilateration method performed via tape measures. The average error resulting by this process is usually about 5 cm [113] which is acceptable considering that it is very difficult to obtain correct linear measures with measuring tape on variable distances.

In the case of very shallow water, it is possible to reduce the errors on the reference points by measuring the coordinates of the GCPs via TS (total station) side shot acquisitions from the shore. Scuba diver operators will have to handle the prism to make it vertical before the TS measurements. This system, however, usually lack in accuracy that is directly proportional to the tilting angle of the pole and its length (Figure 56).

It is, in fact, very difficult due to the length of the pole, the meteorological and marine condition, to handle the pole vertically. The employment of this system without appropriate countermeasures will lead to weaker results, compared to traditional trilateration.

The theoretical error on the measures is expressed in the formula (5) and it is mainly related to the planimetric component (6) while the vertical component (7), although still noticeable for longer poles and bigger tilt angles, is one level of magnitude smaller than the planimetric one (Table 20, Table 21 and Table 22).

$$E = \sqrt[2]{{e_{xy}}^2 + {e_z}^2} \tag{5}$$

$$e_{xy} = P \sin \varepsilon \tag{6}$$

$$e_z = P\,(1 - \cos \varepsilon) \tag{7}$$

[93] https://www.waterlinked.com/hubfs/Product_Assets/UGPS_G2/W-MK-21025-1_G2.pdf

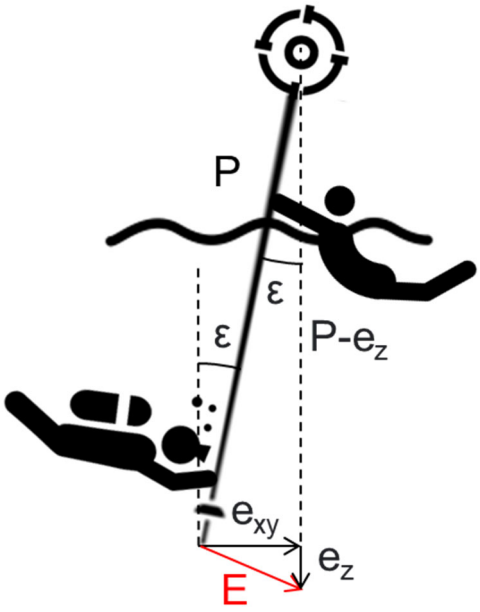


Figure 56. The theoretical plano-altimetric error (E) resulting from the non-verticality of the pole is function of the length of the pole (P) and the tilting angle to the normal (ε), and it follows the equation (5).

E_{xy}		Pole length [m]						
		2,00	2,50	3,00	3,50	4,00	4,50	5,00
Pole tilt [°]	0	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	2	0,070	0,087	0,105	0,122	0,140	0,157	0,174
	4	0,140	0,174	0,209	0,244	0,279	0,314	0,349
	6	0,209	0,261	0,314	0,366	0,418	0,470	0,523
	8	0,278	0,348	0,418	0,487	0,557	0,626	0,696
	10	0,347	0,434	0,521	0,608	0,695	0,781	0,868

Table 20. Theoretical planimetric error in case of TS measurement of a prism, for different pole length and different pole tilt whenever the pole is not perfectly perpendicular on the measured point.

E_z		Pole length [m]						
		2,00	2,50	3,00	3,50	4,00	4,50	5,00
Pole tilt [°]	0,00	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	2,00	0,001	0,002	0,002	0,002	0,002	0,003	0,003
	4,00	0,005	0,006	0,007	0,009	0,010	0,011	0,012
	6,00	0,011	0,014	0,016	0,019	0,022	0,025	0,027
	8,00	0,019	0,024	0,029	0,034	0,039	0,044	0,049
	10,00	0,030	0,038	0,046	0,053	0,061	0,068	0,076

Table 21. Theoretical altimetric error in case of TS measurement of a prism, for different pole length and different pole tilt whenever the pole is not perfectly perpendicular on the measured point.

E		Pole length [m]						
		2,00	2,50	3,00	3,50	4,00	4,50	5,00
Pole tilt [°]	0,00	0,000	0,000	0,000	0,000	0,000	0,000	0,000
	2,00	0,070	0,087	0,105	0,122	0,140	0,157	0,175
	4,00	0,140	0,174	0,209	0,244	0,279	0,314	0,349
	6,00	0,209	0,262	0,314	0,366	0,419	0,471	0,523
	8,00	0,279	0,349	0,419	0,488	0,558	0,628	0,698
	10,00	0,349	0,436	0,523	0,610	0,697	0,784	0,872

Table 22. Theoretical plano-planimetric error in case of TS measurement of a prism, for different pole length and different pole tilt whenever the pole is not perfectly perpendicular on the measured point.

The following chapter propose an easy to adopt and accurate method for the topographic measurement reference points in very shallow water by means of GNSS measurements.

6.2 The proposed solution

In the framework of this thesis, it has been experimented the possibility of measuring the coordinates of GCPs by using a GNSS N-RTK device (i.e., Leica GS18 or similar) when operating in very shallow water environments. For the specific UW use and given the need to adopt materials suitable with the marine environment, a 5m aluminum pole has been self-built (§ 6), together with a set of lightweight and portable conic markers (§ 6.2.2) that are described in the following paragraphs.

6.2.1. The 5m aluminum pole (PALONE)

PALONE (Pole of ALuminum fOr mariNe Environment applications) is a self-built aluminum pole for topographic use in marine environment. Most topographic poles on the market does not reach the length of 5 m, which is a good length compromise when operating in very shallow water. Moreover, some 5 m length poles available on the market are telescopic, with this comes the disadvantage of having an undesired “fishing rod” effect (Figure 57) due to the reduced diameter of the last sections, and due to the momentum generated by the mass attached to the end of the pole that, together with marine and environmental condition (wind and sea waves), might invalidate the measurement process. In addition, they have a fixed rather than a movable bubble level that is required due to the fact that the operator will usually check the verticality of the pole at the water surface.

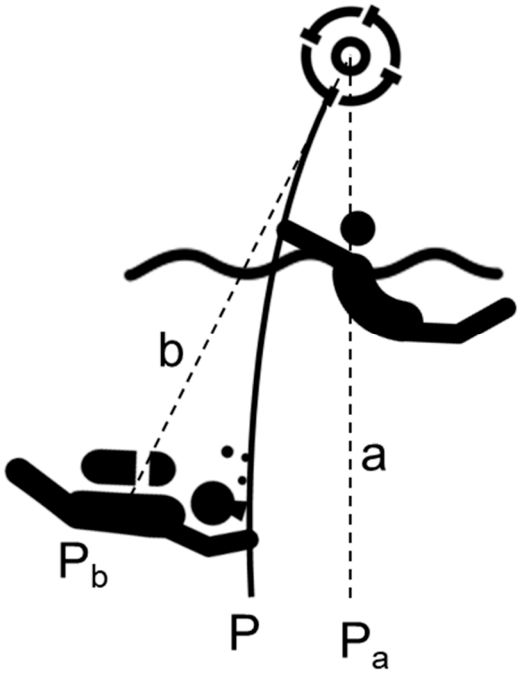


Figure 57. The "fishing rod" effect, that occur consequently when the telescopic pole can't oppose the bending moment generated by the weight of the instrument and the environmental (wind and waves) conditions. As a result, the point to be measured (P) will have the coordinates P_a (or P_b whenever a tilting compensation device is employed).

The PALONE self-built topographic pole is composed by 4 calibrated sections (Figure 58), connected by a plug-and-socket connection system (Figure 59), secured together using a set of Inox fastening clips (Figure 60).

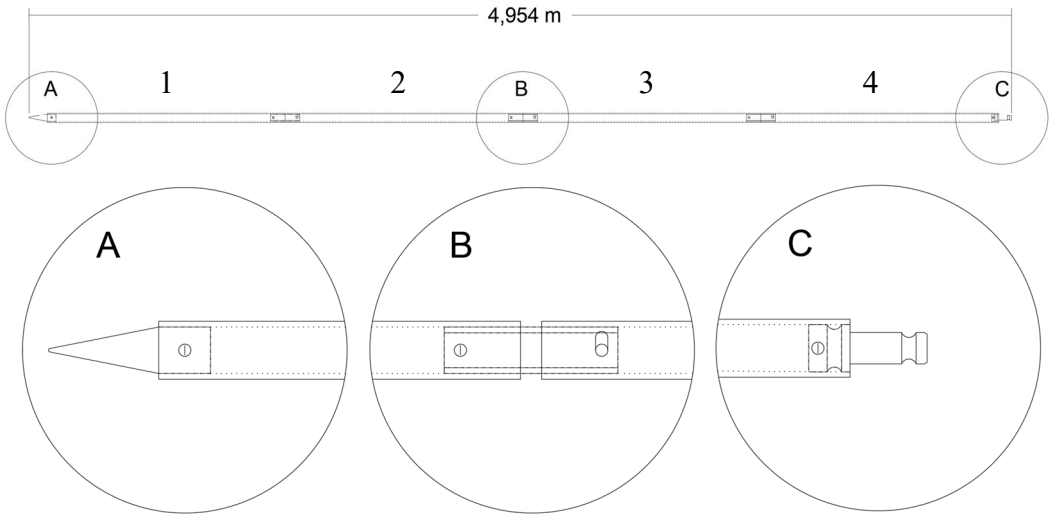


Figure 58. On top: overall view of the four sections composing the PALONE. On the bottom: details of the tip (A) coupling mechanism (B) and topographic "Leica bayonet mount" for prism (C).

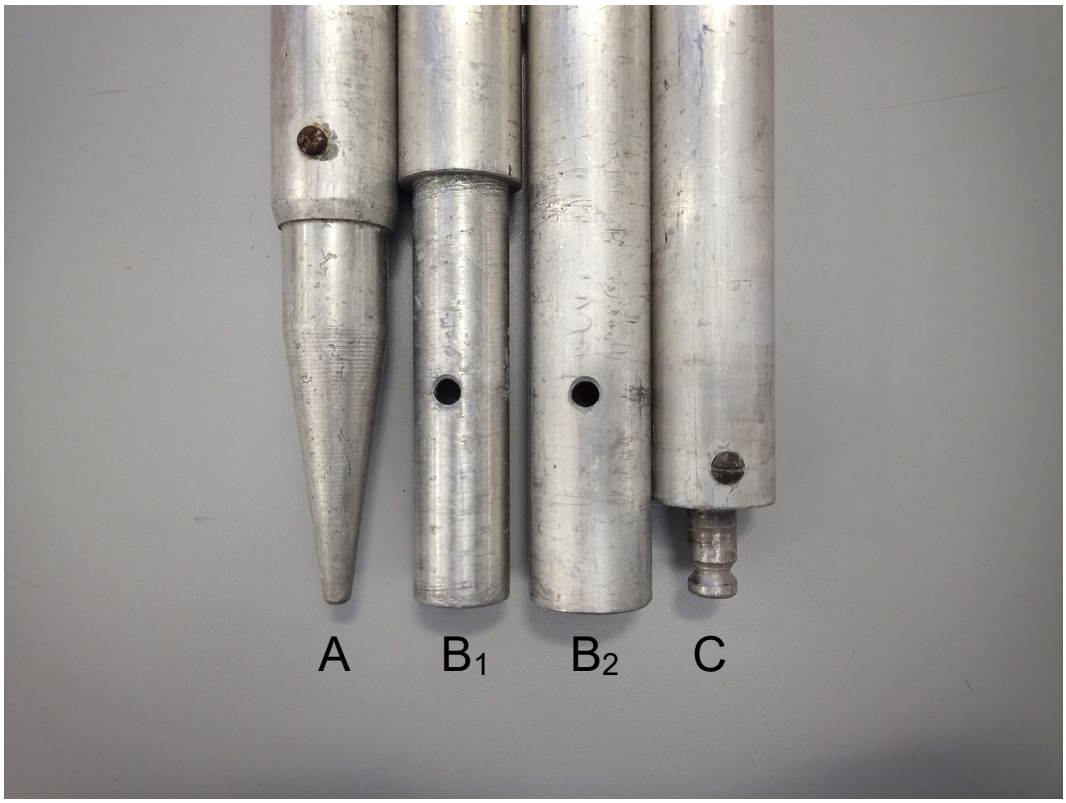


Figure 59. Different details of the aluminium pole: A) Tip; B) Coupling system of the four sections; C) Steel adapter for topographic prism.

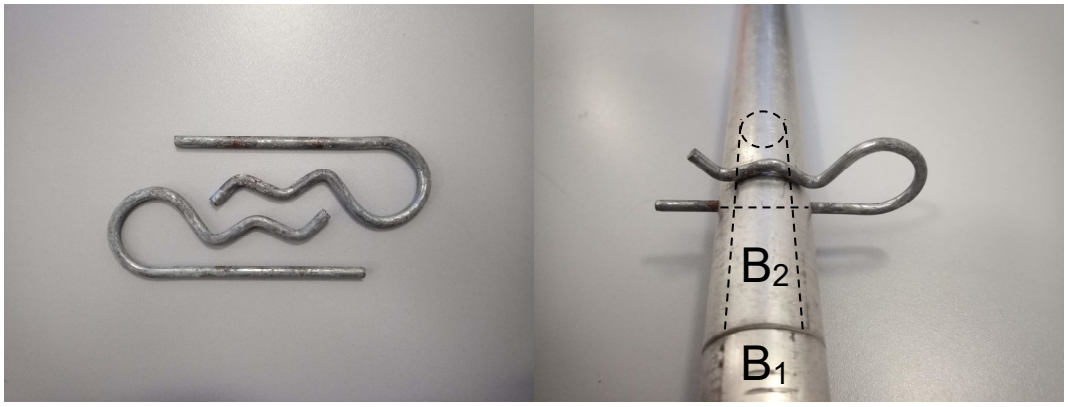


Figure 60. Detail of the closing system for jointing the different sections of the plug-in pole

A couple of bubble levels with a coaxial mount can be placed close both to the tip and at the level of the water surface, where the two operators will ensure the perpendicularity of the pole on the point to be measured.

6.2.2. The conic underwater marker (CONETTO)

CONETTO (CONical marker for undErwaTer Topographic Operations) is a self-built plastic marker for topographic use in underwater environment.

The concept behind its design is related to the geometric shape of a cone, that allows sands and other debris in water to sly down without occlude the view of the center of the point (the tip of the cone).

It has been self-built by assembling a plastic food container with an kitchen funnel (Figure 61), the funnel is riveted on the food box and the corresponding inner circle is cut off from the plastic of the food container (Figure 62), this ensures the stackability and therefore the portability of the cones (Figure 63).

It can be used both on rocky and sandy seabeds; it will be sufficient to fill it inside with sand or gravel retrieved directly on site before starting the survey; this will be also cost-efficient in case the cones have to be shipped or carried for long travels. For the use in sandy environment, it is possible to exploit an additional 40 mm length rod that can be inserted inside the cone and secured by using bolts and nuts (Figure 64). A 8 mm column nut completes the top of the cone, allowing the easy placement of the pole tip.



Figure 61. Concept of the CONETTO System. On the left: the food boxes that are used for containing the ballast (gravel, sand or lead). On the right: the kitchen funnel that composes the conical part of the CONETTO.



Figure 62. Different view of CONETTO n.1



Figure 63. On the top: Underwater markers are stacked on top of each other to save space. On the bottom: the bag containing the cones and the lids.

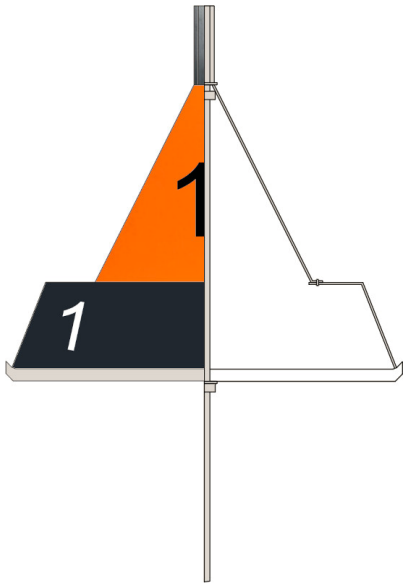


Figure 64. Projection of the front view (half left) and cross section (half right) of the CONETTO. The section on the right displays an 8 mm ⌀ threaded bar for employment in sandy environment.

6.2.3. Tilt compensation smart antenna (Leica GS18 GNSS RTK Rover)

In order to reduce the plano-altimetric error introduced by TS measurements when the pole is not perfectly levelled (Figure 56), and to work independently from the shore proximity, it is possible to employ GNSS receivers that can compensate the tilting errors; in the framework of this thesis, a Leica GS18 (Figure 65) has been employed[94].

The device is provided with a tilting compensation option that can estimate and compensate the tilting angle of the pole via an accelerometer, and the tilting direction using a IMU (this way being immune to magnetic disturbances that affect tilting direction, like similar systems based on compass) [114].

This will ensure that the systematic error introduced by the not levelled pole will be mitigated, as an independent study has showed that the Leica GS18 *"can operate at tilt angles above 30° whilst maintaining a three-dimensional accuracy (3D CQ) of less than 20mm"* [115].

It can be used both in RTK with a base-rover configuration, or with a Network RTK (such as ITALPOS – HxGN SmartNet[95]). However, it is important to consider that in case of the N-RTK mode, survey operators will have to ensure that the surveyed points are located inside the network, otherwise the measurements will suffer lack of accuracy caused by extrapolation outside the network. Whenever it is not possible to operate within the network boundaries, it is strongly advised to work in RTK mode, coupling another GNSS antenna via radio to be used as a base in proximity of the shore.

[94] https://leica-geosystems.com/en-us/products/gnss-systems/smart-antennas/leica-gs18
[95] https://hxgnsmartnet.com/en-us/



Figure 65. The Leica GS18 smart antenna with the Leica CS20 Controller. The measure of the point is registered by a boat operator holding the CS20 controller.

6.3 Testing and validation of the proposed solution

The following paragraphs are related to the test and validation of the proposed solution; in 6.3 the accuracy of the GS18 mounted on the self-built pole is discussed by comparing a set of 9 GCPs measured with both GNSS N-RTK tilt compensation antenna and with TS. Another analysis performed is related to the stability of the conical markers over time, as they have been measured again the day after to look for their stability i.e., change of position on the seabed related to strong current or other factors. In 6.3.2 an assessment of the tilting compensated GNSS receiver has been performed by comparison with the Leica AP20 AutoPole[96], a new instrument by Hexagon Leica composed by a 360 Leica prism mounted on top of a 2,40 m (max) telescopic pole. The system provides a device that communicate to the TS the height of the pole, moreover it streams to the TS the tilt angle and direction for real time compensation of the acquired topographic measures, performed by the automatic recognition, locking and tracking of the 360 prism.

6.3.1. Accuracy comparison with Total station and stability of the markers over the time

The test described in this paragraph has been performed during the Team DiRecT 2022 expedition in the Isola della Coluccia[97], in northern Sardinia. Here the procedure of employment of the CONETTO system has been tested for the very first time.

[96] https://leica-geosystems.com/en-us/products/total-stations/ap20-autopole
[97] https://poliflash.polito.it/studenti_polito/il_team_direct_in_missione_sull_isola_di_culuccia

The procedure is composed by the following steps:

1) The conical markers are placed all around the area of the survey (Figure 66).
2) The position of the markers is measured with the solution proposed in 6.2 (Figure 67, Figure 68 and Figure 69).
3) The photogrammetric survey is performed right after the marker's coordinates are measured.

On the first day of the survey, marker coordinates have been measured with both GNSS (Table 23) and TS (Table 24).

ID	Est [m]	Nord [m]	Elev [m]	σ Est [m]	σ Nord [m]	σ Elev [m]	Tilt [gon]	Tilt Max [gon]
F1	524721,800	4562310,608	-2,675	0,009	0,011	0,024	5,026	11,390
F2	524717,034	4562311,041	-2,488	0,009	0,010	0,022	5,628	13,333
F3	524714,269	4562311,040	-2,336	0,008	0,010	0,022	7,597	7,638
F4	524716,333	4562309,871	-2,415	0,009	0,010	0,023	0,100	6,440
F5	524719,113	4562311,693	-2,564	0,008	0,010	0,022	2,544	6,538
F6	524719,579	4562310,032	-2,539	0,010	0,012	0,029	2,898	2,898
F7	524722,456	4562312,153	-2,755	0,008	0,010	0,022	4,190	4,190
F8	524720,621	4562308,778	-2,507	0,009	0,010	0,023	4,186	5,750
F9	524724,349	4562310,070	-2,811	0,008	0,010	0,022	3,760	6,684

Table 23. Marker coordinates measure via GNSS (tilt-compensated) – first day.

ID	Est [m]	Nord [m]	Elev [m]
TS1	524721,693	4562310,969	-2,770
TS2	524717,044	4562311,249	-2,560
TS3	524714,273	4562311,298	-2,398
TS4	524716,951	4562310,427	-2,552
TS5	524719,365	4562311,854	-2,626
TS6	524719,789	4562310,096	-2,597
TS7	524722,684	4562312,412	-2,812
TS8	524720,835	4562308,815	-2,569
TS9	524724,871	4562310,167	-2,871

Table 24. Marker coordinates measured via TS – first day.

The coordinates were inserted in Agisoft Metashape (version 1.8.5), in correspondence to the markers, in order to check their position. The GSD of the photogrammetric survey was 0,5 mm/pix. The RMSE resulted by the processing is 0,020 m for the coordinates acquired with the GNSS (tilt-compensated) while it is 0,299 m for the coordinates acquired with the TS. The absolute difference of the coordinates is reported in the following Table 25. This behaviour is expected as the side shot TS measurements suffer the planoaltimetric error previously described (5).

ID	Δ Est [m]	Δ Nord [m]	Δ Elev [m]
F1-TS1	0,107	-0,361	0,095
F2-TS2	-0,010	-0,208	0,072
F3-TS3	-0,004	-0,258	0,062
F4-TS4	-0,618	-0,556	0,137
F5-TS5	-0,252	-0,162	0,062
F6-TS6	-0,210	-0,064	0,058
F7-TS7	-0,228	-0,259	0,057
F8-TS8	-0,215	-0,037	0,062
F9-TS9	-0,522	-0,097	0,060

Table 25. Discrepancy between marker coordinates measured via GNSS and TS.

Another analysis performed is related to the stability of the conical markers i.e., change of position on the seabed related to strong current or other factors, such as flora and/or fauna disturbance, or externa human interactions (vessels or bathers not related with the survey operations). Therefore, the markers have been re-measured again with the GNSS N-RTK approach in the following day, leaving them on the seabed overnight (Table 26). The next Table 27, shows the difference of coordinates of all the nine measured GCPs.

ID	Est [m]	Nord [m]	Elev [m]	σ Est [m]	σ Nord [m]	σ Elev [m]	Tilt [gon]	Tilt Max [gon]
S1	524721,804	4562310,635	-2,689	0,013	0,015	0,033	2,512	4,571
S2	524717,082	4562311,091	-2,486	0,013	0,014	0,032	2,944	3,842
S3	524714,305	4562311,094	-2,346	0,014	0,017	0,038	7,817	7,817
S4	524716,349	4562309,891	-2,411	0,013	0,014	0,034	3,116	3,394
S5	524719,129	4562311,703	-2,596	0,014	0,015	0,034	5,043	5,400
S6	524719,620	4562310,105	-2,569	0,013	0,014	0,035	1,795	4,365
S7	524722,385	4562312,189	-2,749	0,010	0,011	0,020	2,536	3,868
S8	524720,625	4562308,745	-2,514	0,012	0,014	0,031	0,952	2,174
S9	524724,322	4562310,054	-2,800	0,012	0,014	0,030	4,871	5,357

Table 26. Marker coordinates measure via GNSS (tilt-compensated) – second day.

ID	Δ Est [m]	Δ Nord [m]	Δ Elev [m]
F1-S1	-0,003	-0,028	0,014
F2-S2	-0,049	-0,050	-0,002
F3-S3	-0,036	-0,054	0,010
F4-S4	-0,017	-0,019	-0,004
F5-S5	-0,016	-0,011	0,032
F6-S6	-0,041	-0,073	0,030
F7-S7	0,071	-0,035	-0,006
F8-S8	-0,005	0,034	0,007
F9-S9	0,027	0,016	-0,011

Table 27. Discrepancy difference between marker coordinates measured via GNSS – first day and second day.

Observing the table, it is possible to notice how the difference between marker coordinates measured in the first and the second day is relatively low and difficult to analyse as it coexists with the planimetric error of 2-3 cm and altimetric error of 3-4 cm of the N-RTK survey.

In order to compensate the GNSS systematisms, a comparison between point distances has been performed, as reported in the following Table 28.

Distance	***[m]***	***Distance***	***[m]***	***Distance difference***	***[m]***
D F1-2	4,790	D S1-2	4,746	Δ F-S 1-2	0,043
D F2-3	2,768	D S2-3	2,733	Δ F-S 2-3	0,036
D F3-4	2,372	D S3-4	2,378	Δ F-S 3-4	0,005
D F4-5	3,327	D S4-5	3,348	Δ F-S 4-5	0,021
D F5-6	1,724	D S5-6	1,666	Δ F-S 5-6	0,058
D F6-7	3,581	D S6-7	3,545	Δ F-S 6-7	0,036
D F7-8	3,850	D S7-8	3,877	Δ F-S 7-8	0,027
D F8-9	3,958	D S8-9	3,926	Δ F-S 8-9	0,031

Table 28. Comparison between point distances measured via GNSS – first day and second day.

The coordinates were inserted in Agisoft Metashape (version 1.8.5), in correspondence to the markers, in order to check their position. The GSD of the photogrammetric survey was 0,5 mm/pix. The RMSE resulted by the processing is 0,024 m, which is acceptable for the needs of the survey.

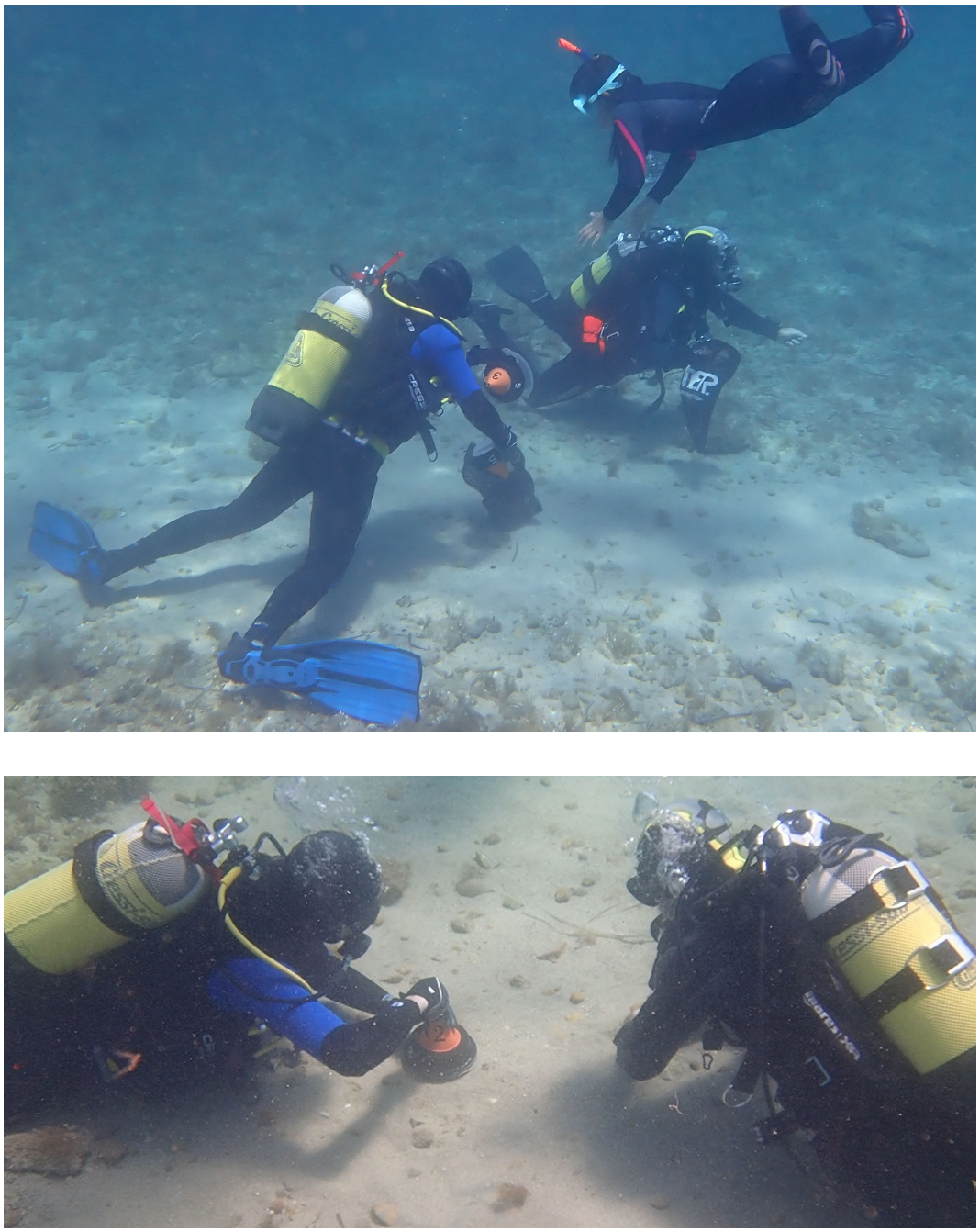


Figure 66. On the top: diver operators receive the net containing the CONETTO System from a surface operator. On the bottom: diver operator is ensuring the marker on the seabed surface.

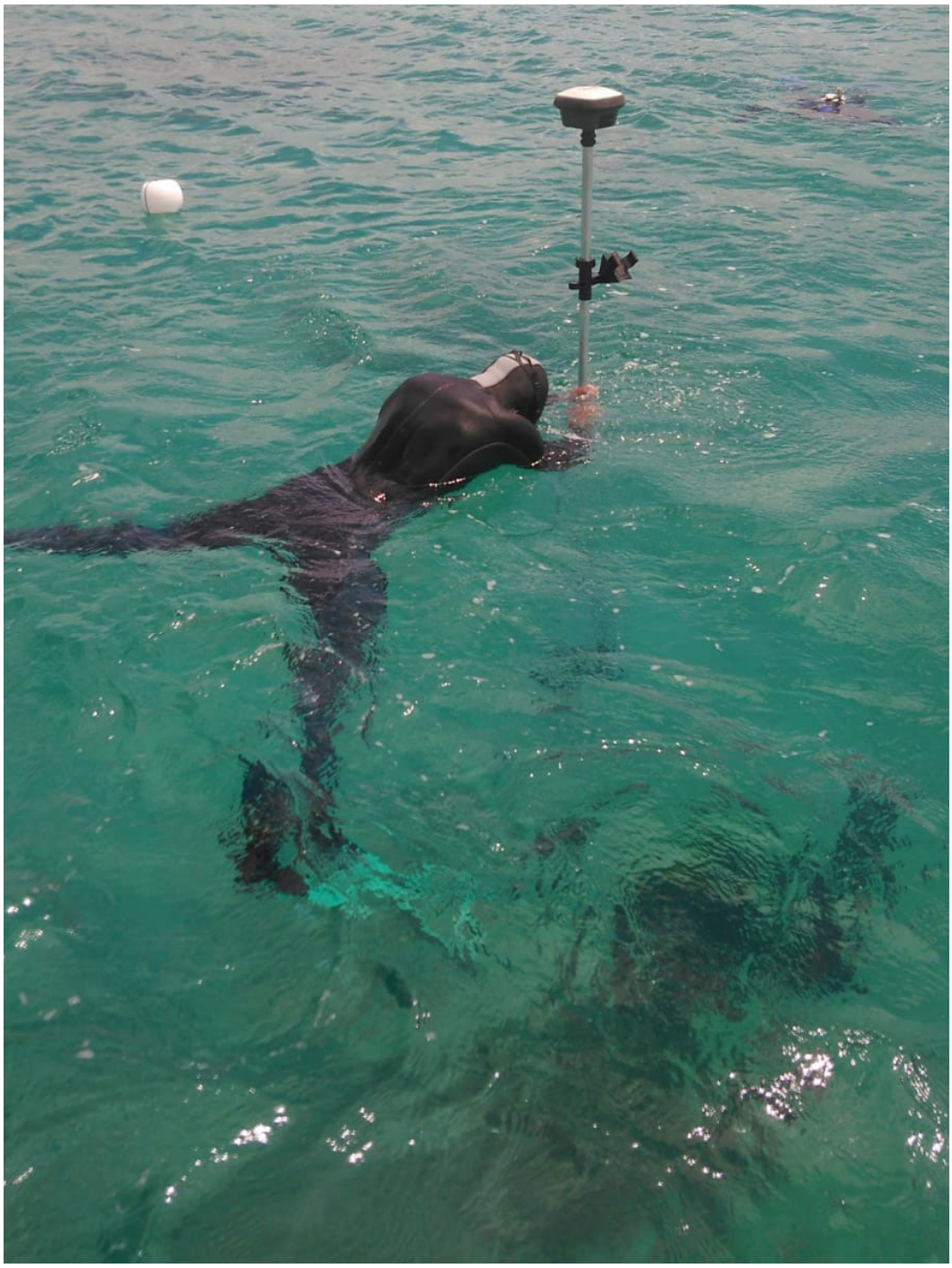


Figure 67. A surface operator is holding the pole vertically and steady for performing the GNSS measurement. The verticality is ensured by a movable level bubble. The surface operator has to communicate with a boat or shore operator (depending on the distance of the site) for receiving clearance that the point has been recorded.



Figure 68. A diver operator is carefully placing the tip of the pole on the center of the cone vertex, waiting for the surface diver to give clearance to move to the next point.



Figure 69. Overall view of the measurement operations; scuba diver operator on the bottom holding the tip of the pole on the center of the cone vertex, and surface operators on the top, ensuring the verticality of the pole and awaiting for confirmation from the boat operator.

The same test has been performed in Marina di Ragusa (Table 29) during the 1st edition of the SUNRISE Summer School[98]. The results this time were less accurate as it was registered that the markers did not remain on the same place (Table 30). This error was most probably related to a gross error caused by a miscommunication between the diving operator (tip of the pole) and the surface operator (surface bubble); the coordinates have been measured when the tip of the pole was on the side of the cone and not ready on the centre. Further employments of this technique will have to ensure codified communication between the diving, the boat, and the surface operators to avoid such kind of gross errors.

ID	Est [m]	Nord [m]	Elev [m]	σ Est [m]	σ Nord [m]	σ Elev [m]	Tilt [gon]	Tilt Max [gon]
F1	455772,781	4071157,649	-3,944	0,013	0,014	0,028	3,007	8,090
F2	455772,357	4071158,497	-4,023	0,014	0,014	0,027	3,864	11,741
F3	455773,669	4071158,874	-3,686	0,013	0,014	0,026	3,723	8,803
F4	455770,883	4071159,048	-3,420	0,013	0,016	0,028	8,342	8,799
F5	455769,564	4071159,560	-3,672	0,014	0,014	0,030	5,043	8,118
F6	455767,801	4071159,476	-3,969	0,014	0,014	0,029	5,132	7,327
F7	455769,084	4071161,570	-4,140	0,012	0,013	0,024	2,497	3,980
F8	455770,509	4071162,954	-4,165	0,013	0,013	0,023	5,289	6,195
F9	455771,268	4071160,333	-3,653	0,012	0,014	0,026	6,912	7,915
S1	455772,649	4071157,769	-3,735	0,019	0,018	0,030	13,051	17,023
S2	455772,319	4071158,438	-3,981	0,018	0,020	0,020	12,701	12,701
S3	455773,745	4071158,734	-3,642	0,027	0,016	0,026	16,632	16,632
S4	455770,217	4071159,201	-3,595	0,020	0,022	0,024	17,766	17,766
S5	455769,699	4071159,458	-3,595	0,018	0,023	0,021	19,106	20,645
S6	455767,820	4071159,449	-3,906	0,017	0,015	0,024	10,464	12,727
S7	455769,055	4071161,549	-4,087	0,015	0,017	0,029	5,519	10,253
S8	455770,470	4071162,935	-4,110	0,012	0,014	0,020	3,461	5,968
S9	455771,164	4071160,379	-3,608	0,011	0,014	0,015	7,654	15,225

Table 29. Marker coordinates measure via GNSS (tilt-compensated).

ID	Δ Est [m]	Δ Nord [m]	Δ Elev [m]
F1-S1	0,132	-0,120	-0,209
F2-S2	0,038	0,060	-0,042
F3-S3	-0,077	0,140	-0,044
F4-S4	0,666	-0,153	0,175
F5-S5	-0,135	0,103	-0,077
F6-S6	-0,018	0,028	-0,063
F7-S7	0,030	0,021	-0,053
F8-S8	0,039	0,019	-0,055
F9-S9	0,104	-0,047	-0,045

Table 30. Absolute difference between marker coordinates measured via GNSS – first day and second day. Marker 4 has been moved due to a mistake.

[98] https://poliflash.polito.it/studenti_polito/conclusa_la_prima_edizione_della_summer_school_sunrise_in_sicilia

6.3.2. Assessment of the tilting compensation and comparison with the Leica AP20 AutoPole

The test described in this paragraph has been performed to compare the accuracy obtainable from the Leica GS18 with the Leica AP20 AutoPole.

"GS18 T Smart Antenna was a primary factor leading to the creation of the AP20. The GS18 T has overcome the levelling constraint of GNSS poles and provided a proven technology suitable for integration into the total station environment. Merging this capability with other concepts to automatically detect height changes of the pole and eliminate manual searches, the AP20 was developed as a comprehensive solution." [116].

AP20 AutoPole (Figure 70) is a new instrument by Hexagon Leica composed by a 360 Leica prism mounted on top of a 2,40 m (max) telescopic pole. The system provides a device that communicate to the TS the exact height of the pole, moreover it streams to the TS the tilt angle and direction for real time compensation of the acquired topographic measures, performed by the automatic recognition, locking and tracking of the 360 prism.



Figure 70. Leica AP20 AutoPole

"The whole measurement chain is based on reliable sensor input instead of manual levelling constraints. IMU technology is used within the AP20 to determine the 3D pole alignment in space. Similar to the Leica GS18 T [114]*, an IMU based on industrial grade, microelectron-mechanical systems (MEMS) include a three-axis accelerometer and a three-axis gyroscope to precisely measure acceleration and angular velocity. These observations, together with continuous target positions from the total station, are provided to a customised inertial navigation system (INS) integrated into the AP20. The INS algorithm mathematically rotates and integrates the IMU measurements into the coordinate system of the total station and determines the attitude of the pole and its associated quality measure"* [116].

The test has been carried out by following the steps below:

1. The identification of a set of points (A, B and C) of known coordinates.
2. Each point is measured a dozen time with:
    a. Three configurations:
        i. Pole is tilted but steady.
        ii. Pole is tilting simulating operative conditions in water (max 5 gon).
        iii. Pole is tilting simulating operative conditions in water (max 10 gon).
    b. And with three instrument settings:
        i. AP20 tilt compensation ON
        ii. GS18 (N-RKT) tilt compensation ON single epoch.
        iii. GS18 (N-RTK) tilt compensation ON 10s acquisition.

The aim of the performed test was to check the standard deviations and the coordinate residuals for the set of coordinates of each point (A, B and C) measured with the three different instrument settings and the three different configurations to simulate operative conditions of UW survey.

The detailed results of the test are showed in the following tables and images. It is possible to observe that for AP20 measures, for all the three points in the three different configurations the results are comparable in terms of standard deviations and coordinate residuals. When it comes for GS18, it is noticeable how the steady configuration results better in terms of measure accuracy, with lower standard deviations and residuals (measures are more accurate and less dispersed), while 10s acquisitions do provide a significant gain in accuracy only for the z component.

The obtained results are very good, especially compared not only to the traditional techniques but also to the analogue land survey case.

Test type	Instrument	σ_x [m]	σ_y [m]	σ_z [m]
Steady	AP20	0,002	0,003	0,002
	GS18	0,007	0,011	0,020
	GS18 (10s)	0,005	0,015	0,020
Tilt max 5 gon	AP20	0,002	0,001	0,000
	GS18	0,004	0,003	0,008
	GS18 (10s)	0,005	0,005	0,007
Tilt max 10 gon	AP20	0,003	0,005	0,001
	GS18	0,004	0,005	0,013
	GS18 (10s)	0,007	0,008	0,010

Table 31. Standard deviations of the measurements of point A coordinates, with AP20 and GS18 (single epoch and 10s acquisition) in steady, and tilting configurations (max 5 gon and max 10 gon).

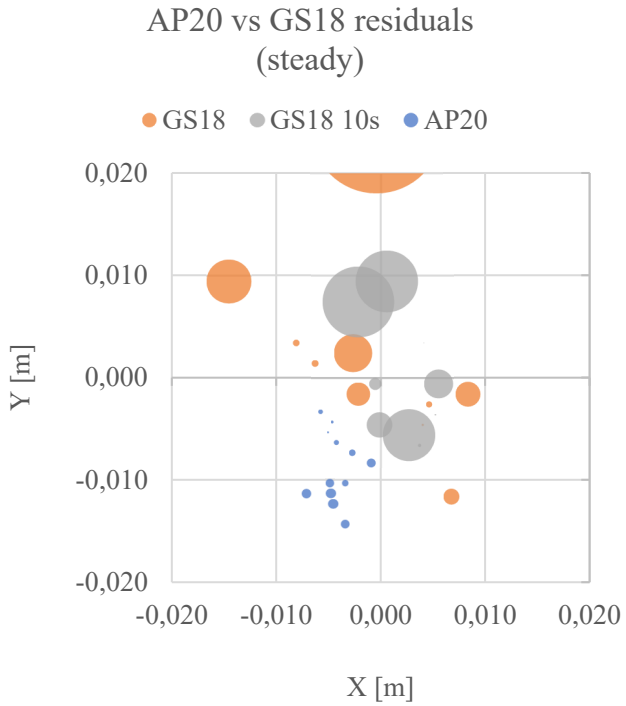


Figure 71. Relative coordinates plot for point A (0;0) for the test in steady configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

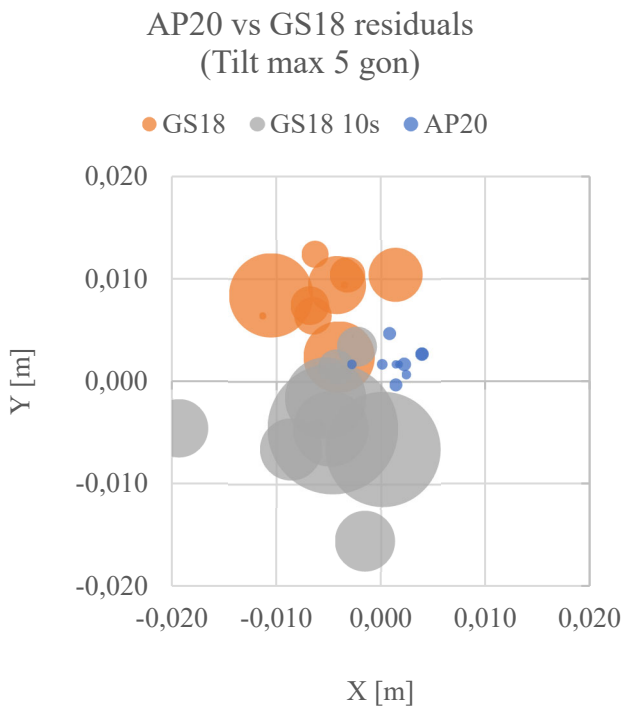


Figure 72. Relative coordinates plot for point A (0;0) for the test in tilting (max 5 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

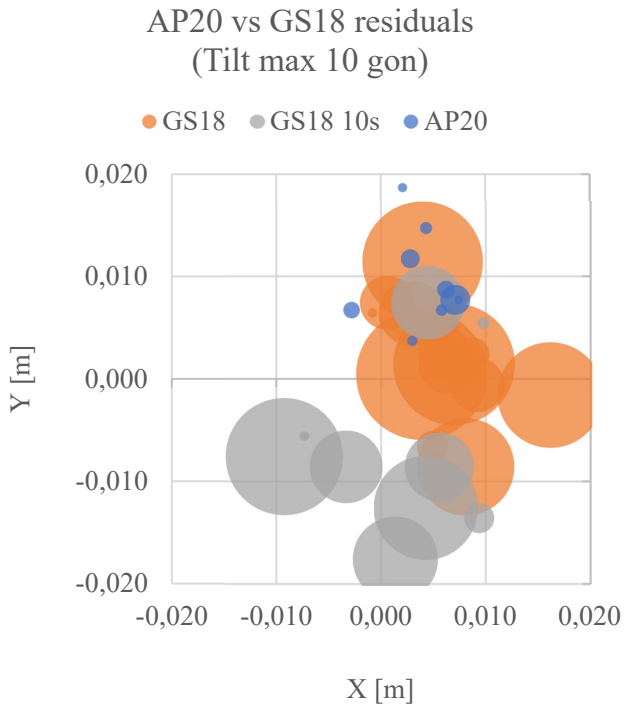


Figure 73. Relative coordinates plot for point A (0;0) for the test in tilting (max 10 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

Test type	Instrument	σ_x [m]	σ_y [m]	σ_z [m]
Steady	AP20	0,003	0,004	0,001
	GS18	0,003	0,004	0,006
	GS18 (10s)	0,005	0,006	0,005
Tilt max 5 gon	AP20	0,003	0,004	0,001
	GS18	0,007	0,004	0,008
	GS18 (10s)	0,003	0,006	0,005
Tilt max 10 gon	AP20	0,002	0,002	0,000
	GS18	0,004	0,008	0,005
	GS18 (10s)	0,004	0,005	0,005

Table 32. Standard deviations of the measurements of point B coordinates, with AP20 and GS18 (single epoch and 10s acquisition) in steady, and tilting configurations (max 5 gon and max 10 gon).

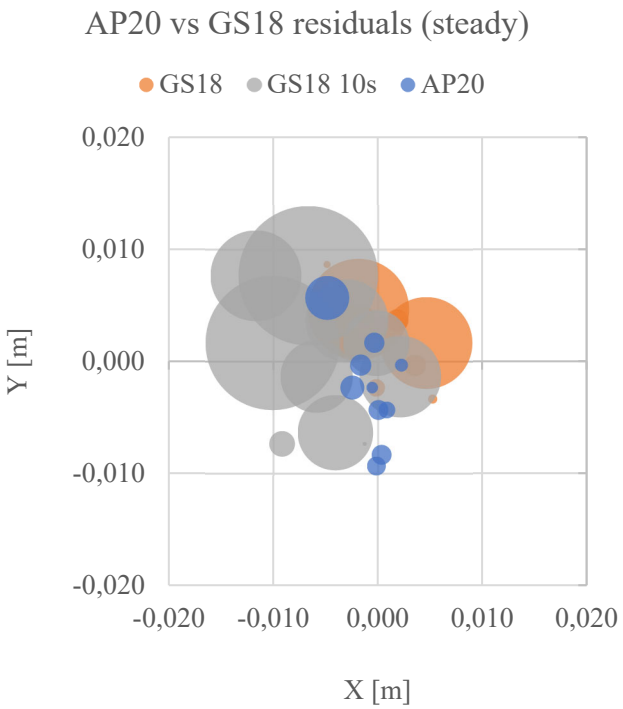


Figure 74. Relative coordinates plot for point B (0;0) for the test in steady configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

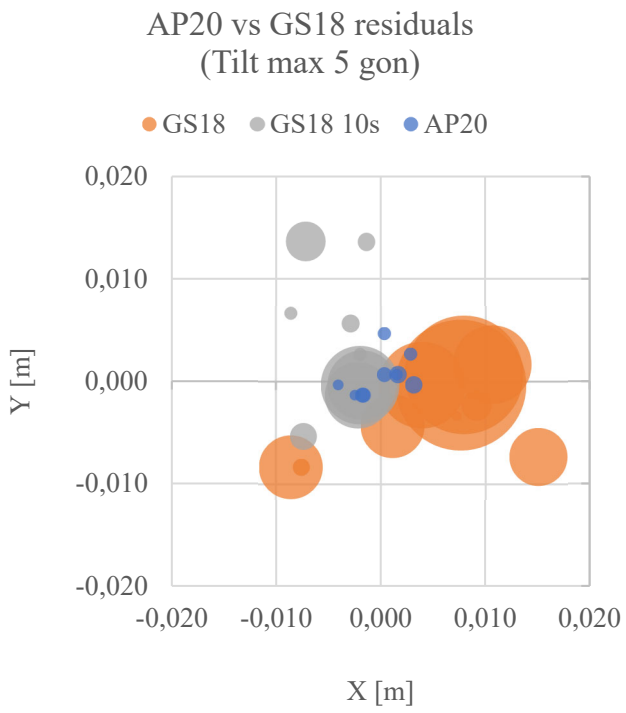


Figure 75. Relative coordinates plot for point B (0;0) for the test in tilting (max 5 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

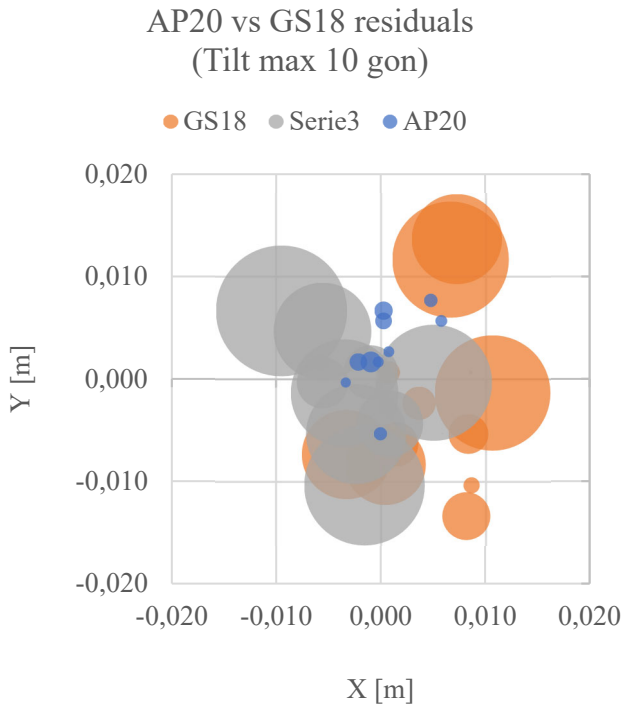


Figure 76. Relative coordinates plot for point B (0;0) for the test in tilting (max 10 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

Test type	Instrument	σ_x [m]	σ_y [m]	σ_z [m]
Steady	AP20	0,004	0,002	0,001
	GS18	0,005	0,004	0,007
	GS18 (10s)	0,004	0,007	0,005
Tilt max 5 gon	AP20	0,004	0,002	0,001
	GS18	0,004	0,005	0,005
	GS18 (10s)	0,005	0,004	0,006
Tilt max 10 gon	AP20	0,002	0,003	0,001
	GS18	0,006	0,006	0,010
	GS18 (10s)	0,005	0,006	0,006

Table 33. Standard deviations of the measurements of point C coordinates, with AP20 and GS18 (single epoch and 10s acquisition) in steady, and tilting configurations (max 5 gon and max 10 gon).

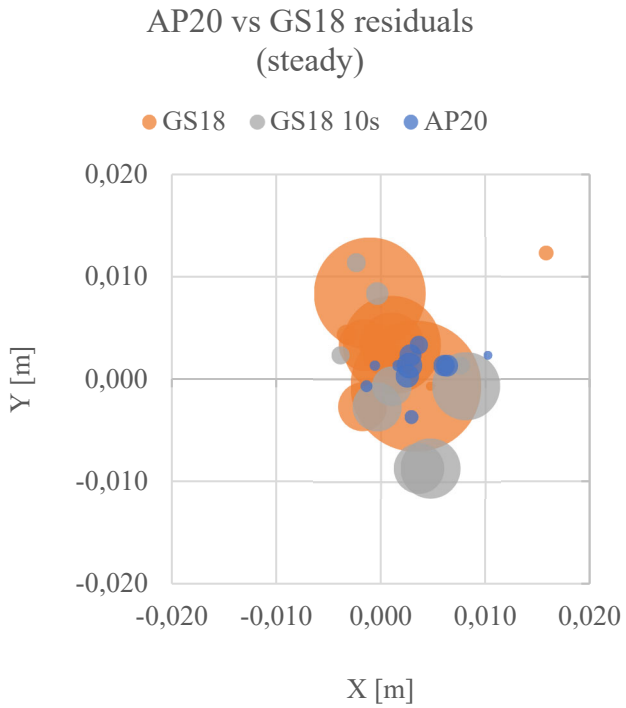


Figure 77. Relative coordinates plot for point C (0;0) for the test in steady configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

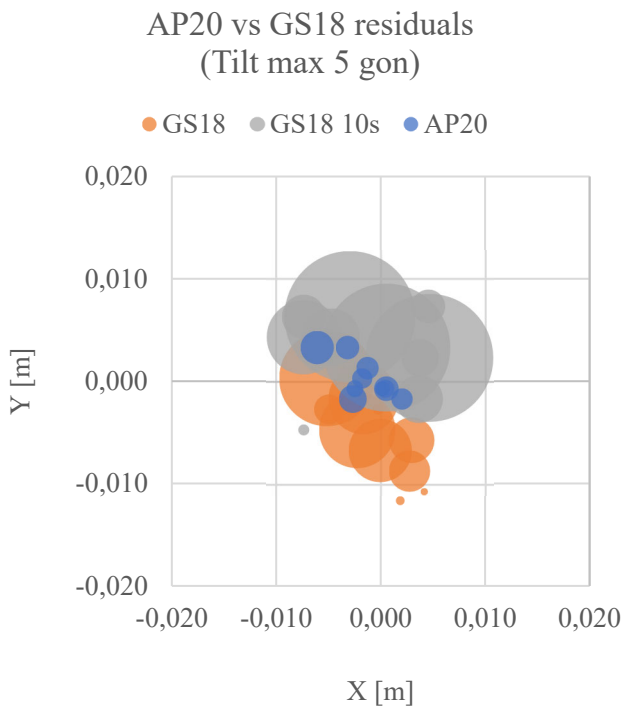


Figure 78. Relative coordinates plot for point C (0;0) for the test in tilting (max 5 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

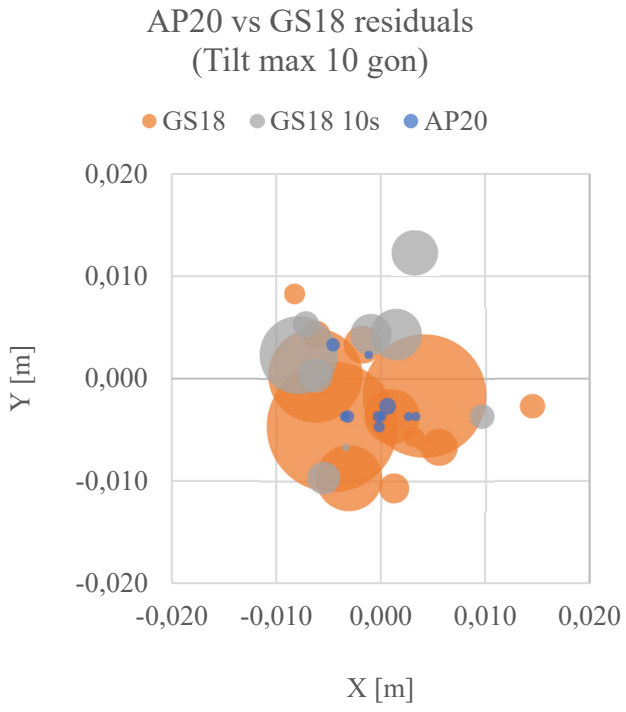


Figure 79. Relative coordinates plot for point C (0;0) for the test in tilting (max 10 gon) configuration. X and Y are the planimetric residuals, while the radius of the point indicates the altimetric residual for each set of measures.

7

Chapter 7

7. Torre Santa Sabina: Underwater and Coastal documentation

collaborations

The 2020 and 2021 underwater archaeological research in the inlet of Torre Santa Sabina - Baia dei Camerini (Municipality of Carovigno, Brindisi, Italy) represented the pilot intervention of the Interreg Italia-Croatia UnderwaterMuse project, which aims to enhance and make accessible the huge underwater heritage of the areas involved through the creation of submerged archaeological parks and the narrative and communicative use of the virtual reality. The Puglia Region - Department of Tourism, Economics of Culture and Valorization of the Territory, partner of the UnderwaterMuse project, launching this research aimed at valorisation, has involved the three regional Universities thanks to an agreement. During the 2020 and 2021 campaign, different survey activities were carried out using several techniques and methodology to produce the area's multi-scale documentation.

Thanks to the collaboration with the Politecnico di Torino, the entire stretch of coast was mapped with UASs (Uncrewed Aerial Systems) photogrammetric flights to reconstruct the coastal landscape in various phases, starting from the Bronze Age. A targeted intervention was carried out on the Roman wreck of the imperial age, beached and abandoned at the ancient shore and now submerged due to the relative rise in sea level. Furthermore, an underwater photogrammetric survey carried out by expert scuba divers has been achieved in the wreck's aft area (2020) as a preliminary study for the complete excavation performed in the following year (2021).

Torre Santa Sabina is located on the Adriatic coast 26 km north of Brindisi (Figure 80). In the Archaic period the site was a landing place connected with the

Messapian settlement of *Κάρβινα* /Karbina (Carovigno), destroyed by Taras in the first quarter of the 5th century BC [117]. Underwater finds have confirmed that the little harbour was very lively from the late Archaic to the Hellenistic period; it was used as a subsidiary stop along the coastal seafaring (cabotage) route by ships coming from the Aegean area, Greece and the Illyrian coast and sailing towards the northern part of the Adriatic Sea.

Torre Santa Sabina probably acted also as a gateway of trans-Adriatic routes involving the redistribution of imports to Messapian settlements in the hinterland. Activity at the harbour seems increasing in the Late Republican period, when Torre Santa Sabina became an auxiliary landing for ships coming from the East, which sailed up the eastern Adriatic coast and then descended to the safe harbour of Brindisi.

The proximity of the harbour to a road network of a certain importance (as indicated by the *via Traiana*), to the major urban centre of *Brundisium*/Brindisi and production centers such as Apani and Giancola, underscores its significant role [118]–[123].The decline of Apani and Giancola in the second half of the 1st century BC coincided with the decline of the harbour, but Torre Santa Sabina continued to function as a subsidiary, minor harbour for the hinterland even after this moment, albeit on a drastically reduced scale.



Figure 80. Torre Santa Sabina (Brindisi, Salento, Southern Apulia), Camerini bay.

The first investigation phase of the area began in 1972 and continued until 1983, leading to the recovery of a large amount of pottery, mainly amphorae (more than 11,000 fragments and complete items), ranging in date from the Archaic to the Medieval periods [124]–[126]. By the mid-1980s interest in the site began to wane. Since the early 2000s, the exceptional informative potential of the Torre Santa Sabina contexts has led the Underwater Archaeology team of the Salento University

to resume work at the site. In collaboration with the Superintendency for the Archaeological Heritage of Taranto and the Brindisi Museum, the Salento University working group has initiated a reassessment of the evidence produced by the investigations of the 1970s and 1980s and created the first-ever general inventory of the finds.

This project has produced excellent results, allowing a deeper understanding of the evidence preserved in the bay and the physical and spatial relations between the artefacts; at the same time, it has clarified the chronology of the occupation phases of the site, revealing periods of more and less intense use. This re-assessment was an essential prerequisite for the start of new investigations, which have been conducted from 2007 using new strategies, methodologies and techniques in compliance with the holistic approach of the seascape's archaeology. New excavations had to address issues still subject to debate, including the role played by the site over the centuries with respect to the changes that can be observed in the morphology of the bay (perhaps a channel harbour in origin), the causes of the wrecks and, finally, the relationship between the archaeological finds (especially pottery) and the identified cargoes.

Consequently, new stratigraphic excavation has been carried out from 2007 until 2012 by the Underwater Archaeology team of the Salento University, Department of Cultural Heritage, in collaboration with Province of Brindisi and Municipality of Carovigno, under the direction of Rita Auriemma (Figure 81).

During the seasons 2020–2021 the underwater archaeological researches were resumed as pilot intervention of the Interreg Italia-Croatia UnderwaterMuse project, which aims to enhance and make accessible the huge underwater heritage of the areas involved through the creation of submerged archaeological parks and the narrative and communicative use of virtual reality [127]. Puglia Region – Department of Tourism, Economy of Culture and Valorisation of the Territory, partner of the UnderwaterMuse project, launching these researches aimed at valorisation, has involved the three regional Universities (Foggia, Bari and Salento) thanks to an agreement. Subsequently, also the Polytechnic University of Turin and the Central Institute for the Restoration of the Ministry of Culture supported the pilot intervention with their competences.

This chapter is related to the photogrammetric survey of the late-imperial era roman shipwreck, located in Baia dei Camerini, Torre Santa Sabina (BR), Italy, and its surrounding territories. An integrated topographic and photogrammetric UAS survey has been conducted in this framework, combined with an underwater close-range photogrammetric survey. The activities of the geomatics survey presented in this chapter aim to provide reliable support for the spatial contextualization and the georeferentiation of the different data acquired during the 2020 archaeological excavation campaign of the shipwreck of Torre Santa Sabina and its surroundings (Figure 82).

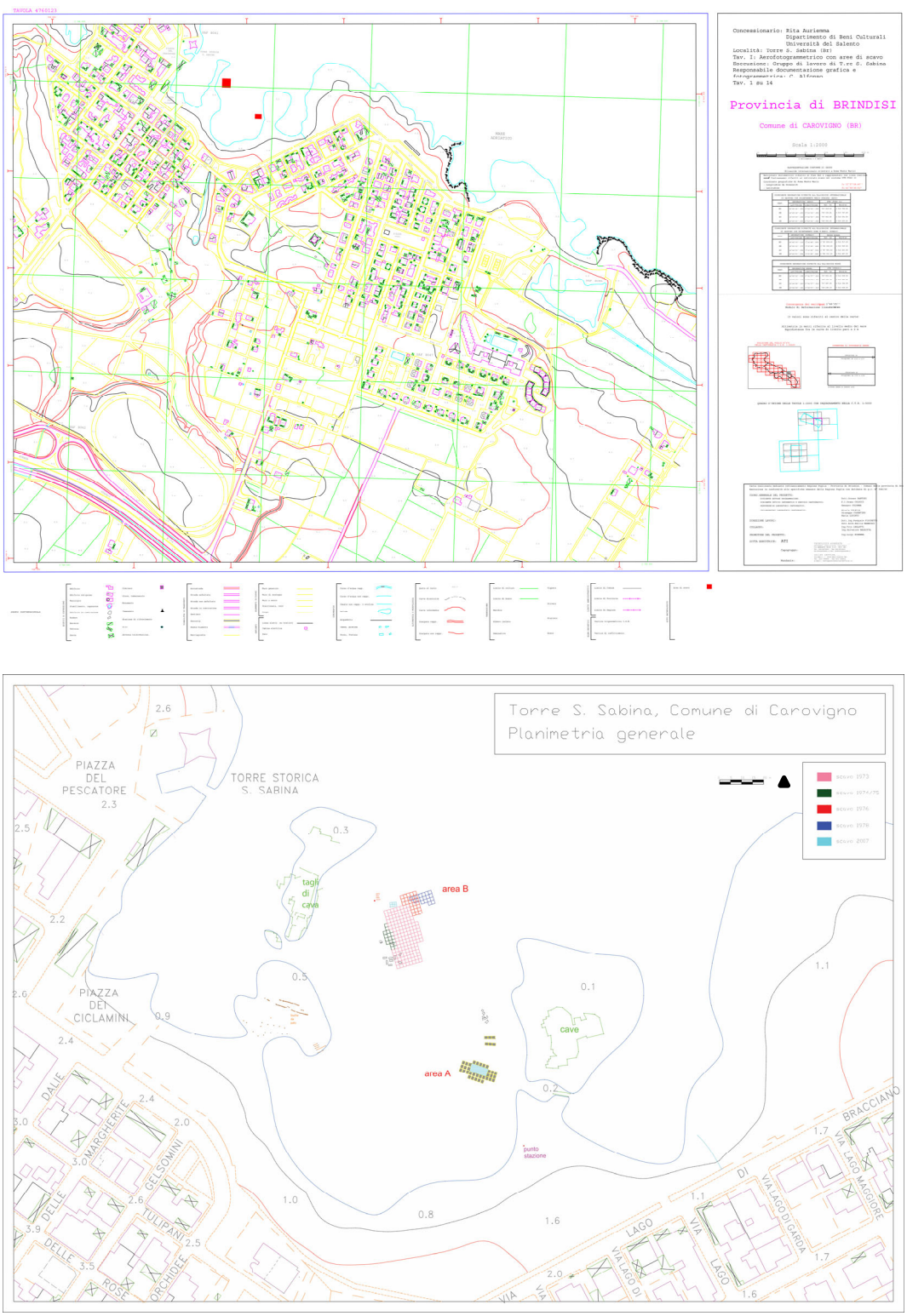


Figure 81. Archaeological maps of the Torre Santa Sabina bay (submerged and semisubmerged contexts) taken from the 2007-2012 excavation documents.

This investigation campaign is in continuity with the previous researches of the UniSalento project *"L'Approdo Ritrovato"* (from 2007 to 2012). However, it marks an important novelty: Torre Santa Sabina becomes the scenario of a pilot intervention of the international UnderwaterMuse project, which aims to enhance and make accessible the vast underwater heritage of the areas involved, otherwise

invisible or reserved for a few, through the creation of submerged archaeological parks and the narrative and communicative use of virtual reality.

Torre Santa Sabina is also the site of a well-preserved shipwreck found on the seabed of Baia dei Camerini in the 1970s; it is related to a Roman ship dated back between the end of the 3rd and the beginning of the 4th century AD. The ship's hull, which is still on the seabed, was over 20 meters long and relatively heavy in tonnage. There is no doubt that this wreck is one of the most interesting in the Mediterranean Sea, according to its exceptional state of conservation that allows understanding the details of the construction technique [124].



Figure 82. Panoramic view of the coastline of Baia dei Camerini, Torre Santa Sabina (Carovigno, Brindisi, IT).

The area of the survey is represented by the shore portion related to Baia dei Camerini, Baia della Mezzaluna, and the south-eastern part of the Baia dell'Isoletta, located in Santa Sabina (BR)

Two main survey activities were carried out in the wreck area and the connected surrounding to integrate aerial and underwater data [128]. First of all, a complete multi-scale UAS survey has been carried out using the possibility offered by the on-board GNSS that allows the direct georeferencing approach: using RTK (Real-Time Kinematik) or PPK (Post-Processing Kinematic) solutions. Furthermore, a second activity concerned the underwater survey of the aft area of the roman shipwreck via close-range photogrammetry has been achieved.

7.1 Coastal Landscape Heritage documentation

7.1.1. The Bronze Age settlement

The Bronze Age settlement in Torre Santa Sabina is currently suspected by numerous traces scattered along the coast, particularly pertinent to post holes dug into the rock. In some cases, it is possible to recognize the trend of some alignments,

perhaps palisades, as in the outcrops affecting the rocks west of the Bay of Camerini; in others, such as those on the eastern side of the Mezzaluna bay, relating to huts (Figure 83). These traces are followed up to the western edge of the settlement, covering a seafront of over 700 m. Where the rock is progressively covered by earthy deposits, it coincides with the original archaeological level, preserved in various stretches of the coast, including the islet of the Mezzaluna.

Numerous potteries from the Middle and Late Bronze Age is recovered from these deposits, especially impasto, but also fragments of Aegean-type figuline pottery from the 13th century BC.

These testimonies, combined with those ascertained archaeologically starting from the end of the 60s of the last century (suffice to recall the large burial mound with 25 pit tombs also containing vascular equipment of the Mycenaean type [129]), trace the physiognomy of a large coastal settlement, multi-layered, which already from the middle of the second millennium BC was an important maritime landing place between the settlements of Torre Guaceto and Egnazia. Obviously, the site also played a strategic role for the rich hinterland, a few centuries later occupied by the Messapian city of Carbina. In this context, a complete photogrammetric acquisition of UAS was performed, which will be a fundamental tool for the topographical classification and the study of all known protohistoric evidence.



Figure 83. Bronze age settlement in the Mezzaluna bay: pole holes

7.1.2. UAS data acquisition and processing

During the 2020, campaign before the underwater acquisitions to define the coastal landscape, a complete multi-scale UAS image acquisition has been carried out starting from Baia dei Camerini up to the Baia dell'Isoletta. The aims of the acquisition were related to the archaeologists' need to obtain high-resolution maps useful for improving the possibility of founding traces or signals connected to undiscovered hidden villages. Another aspect was connected to obtaining large-scale reference support for adding all the information related to the shipwreck surveyed during previous archaeological campaigns.

According to those objectives and to testing different solutions, two platforms were selected. All the area was covered using the platforms Phantom 4 RTK by DJI and the eBee X by Sense Fly equipped with the S.O.D.A. 3D camera. The S.O.D.A. 3D camera has a resolution of 20 MP with a sensor size of 13.2 x 8.8 mm and a focal length of 10.6 mm (Table 34).

Resolution [pix]	Focal length [mm]	Pixel size [µm]
5472 x 3648	10,6 mm	2,4

Table 34. eBee X camera main technical specifications.

The eBee X is the latest fixed-wing platform developed by SenseFly[99] with a wingspan of 1.16 m and a weight of 1.4 Kg. The UAS is equipped with a high-quality dual-frequency GNSS that could work in RTK (Real-Time Kinematic) or PPK (Post Processing Kinematic). The platform could load several sensors in the visible and non-visible spectrum with different characteristics; the most exciting sensor for 3D mapping purpose is without any doubt the new S.O.D.A. 3D, which allows capturing 3 images (1 nadir and 2 obliques) along the flight path changing the camera orientation during flight (Figure 84).



Figure 84. The eBee X fixed-wing platform with the SODA 3D camera and the scheme of the camera tilting option.

In the surveyed area, 3 flights with an elevation of around 130 m, that mean a Ground Sample Distance (GSD) of 3 cm, were performed to cover all the area (Figure 85), from Baia dei Camerini to Baia dell'Isoletta. For the data acquisition, the eMotion software has been employed; the sidelap was set up at 60 % and the overlap at 80 %. According to the previous test reported in [130], the first flight was performed only with nadir acquisition. On the other hand, the second and the third flight were carried out using the possibility of acquiring oblique images employing the camera's tilting option. The second and the third flights were designed with the same paths but in opposite directions. Using the proposed approach, the nadir view's quality (mainly the overlap) is maintained (according to the dedicated flight), not always guaranteed using the tilting option.

[99] www.sensefly.com

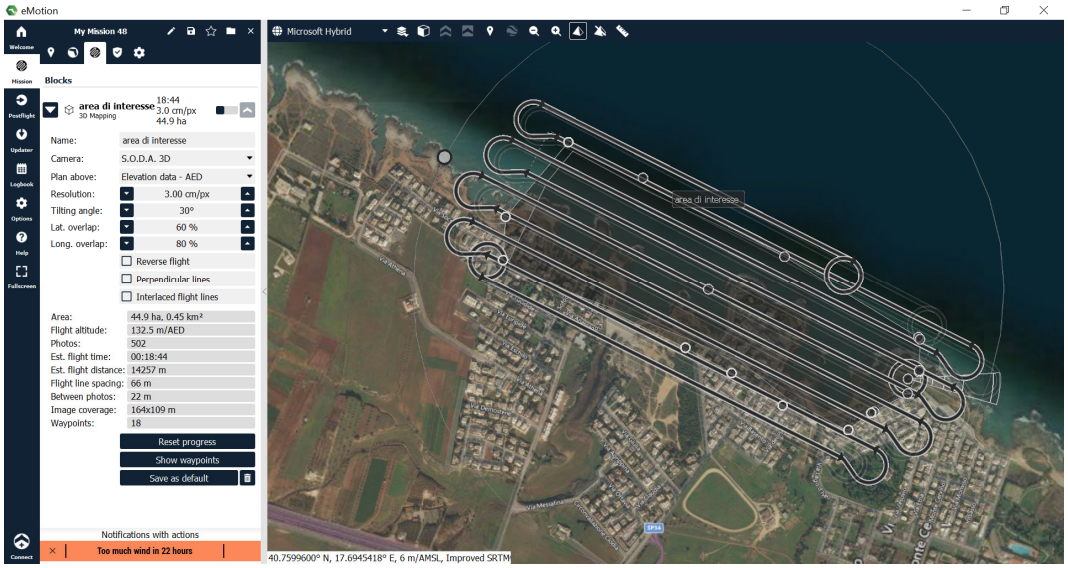


Figure 85. Screenshot of the eMotion flight plan of the surveyed area.

During the flight acquisition, the PPK option was selected. Using this option is possible to acquire and store in the memory card of the drone the RAW GNSS data during the flight and post-process it using data provided by a reference station on the ground.

The PPK processing was achieved using eMotion which can handle the georeferencing and prepare the images required for the next steps. The process is fully automatic, but some parameters need to be accurately checked to understand the obtained accuracy. The workflow combines GNSS UAS acquired data with the GNSS data of the reference station on the ground; the cartographic coordinates of the ground station need to be manually inserted in the software with some other information such as the antenna type and height from the ground vertex. The next step is the processing, where the software can re-estimate the camera poses according to the GNSS data; in the analyzed area, the precision after the post-processing was 4,5 cm (σ).

The same area was overflown with the Phantom 4 RTK multi-rotor platform. This UAS is equipped with a 1" CMOS camera with a mechanical shutter (8,8 mm of focal length) that can acquire images in different configurations thanks to the 3-axis gimbal system (Table 35).

The images were collected at an elevation of 50 m (GSD of 1,36 cm) with a sidelap of 60 % and overlap of 80 %. Six different flights (Figure 86) were carried out, in order to acquire six blocks that, as a whole, can entirely cover the area of interest. The blocks have been created to guarantee safe flight operation, having always more than half battery capacity left at the end of each flight. Only nadir images were captured in the surveyed area.

Resolution [pix]	Focal length [mm]	Pixel size [µm]
5472 x 3648	8,8 mm	2,4

Table 35. DJI Phantom 4 RTK camera main technical specifications.

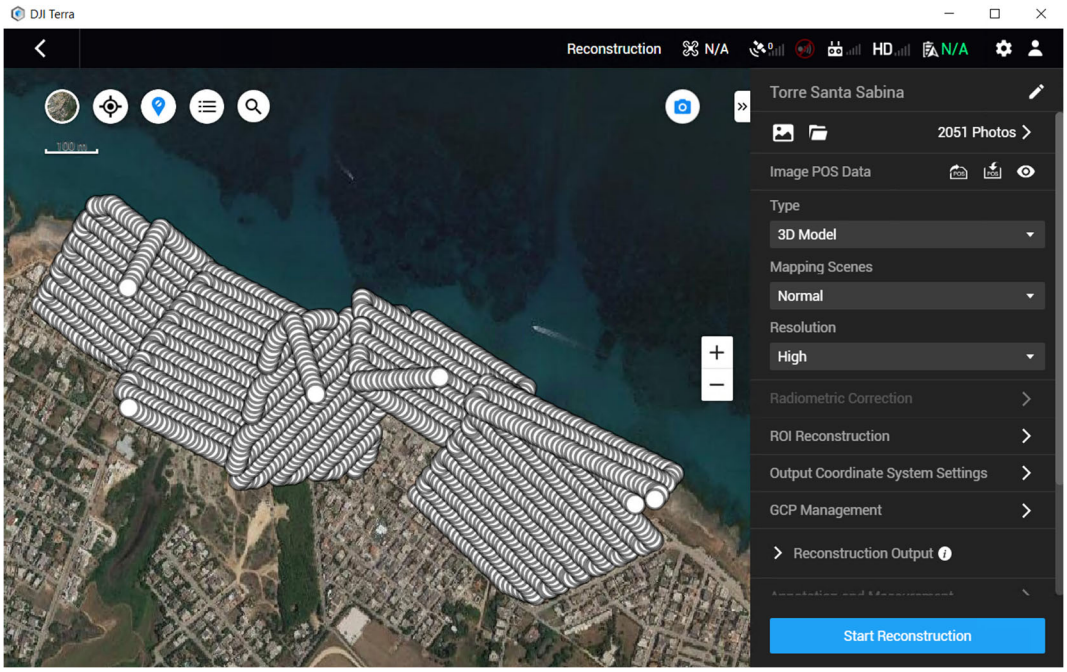


Figure 86. Screenshot of the DJI Terra software with the acquired UAS data using the Phantom 4 RTK.

The original aim was to document the land following the traditional photogrammetric pipeline and extract 3D information of the seabed using an approach like the one reported in [85] as an application of UAS in shallow water to process drones imagery with Structure from Motion (SfM) and Multi View Stereo (MVS) techniques in order to provide a low-cost alternative to established shallow seabed mapping techniques. Unfortunately, due to the sea's condition, extremely rough during the flight days, it was impossible to extract any 3D data of the seabed using the UAS images despite the area being characterized by very shallow water. The flights achieved using the Phantom 4 RTK was carried out adopting the solution known as NRTK (Network Real-Time Kinematic) using an active connection of the platform to a GNSS permanent network: HxGM smartnet service from Hexagon[100]. Following this approach, the GNSS correction is transmitted via GSM to the platform and applied in real-time to the acquired images. The geotag precision using this approach is usually in the range of 3-4 cm, comparable with the one achievable with a PPK solution.

As usual, before the flights, since the main objective from the Geomatics point of view is to evaluate the geometric accuracy of the generated outputs, some points (42) were placed and measured on the field to have a set of points usable as GCPs (Ground Control Points) and/or CPs (Check Points) (Figure 87). The points' survey was carried out using an NRTK approach that allows obtaining the 3D coordinates of the measured markers with an average accuracy of about 2 cm. In the area of Torre Santa Sabina, both natural (e.g., natural and artificial features clearly visible from the acquired images) and artificial markers (0.4 x 0. 4 m panels) were

[100] https://hxgnsmartnet.com/

employed. This part of the survey was carried out using a couple of Leica GNSS receivers (GS14 and GS18 models). Moreover, a GNSS network with4 vertexes were measured using static observation (1 hour for each baseline, sample rate 5 sec). The network was defined and adjusted using the software LGO (Leica Geo Office) thanks to 3 permanent GNSS stations (Brindisi, Conversano and Taranto) of the Hexagon network, allowing to obtain the differentially corrected coordinates of the measured points. The raw data, measured by total station, have been processed starting from the vertex's coordinates using MicroSurvey StarNet 7. All the coordinates are expressed in UTM WGS 84 – 33N and geodetic elevation, estimated using the IGMI grids via ConveRgo[101], a software for coordinates transformation in the new geodetic reference system, defined on the 10/11/2011 with the Italian decree *"Adozione del Sistema di riferimento geodetico nazionale"*[102]. The photogrammetric data were processed using SfM software (DJI Terra and Pix4D) to obtain the traditional output (3D models and orthoimages) useful for the Underwater Muse project's different researchers (Figure 88). Three different approaches were followed; in a first approach (A), all the measured points were considered as CPs; in a second approach (B), all the measured points were used as GCPs; in a third approach (C), all the points were marked as CPs, except for 5 points used as GCPs (highlighted in yellow in figure 5). As it is possible to observe from the following Table 36, the results validate the capability of performing a survey-grade accuracy for both platforms. Using a well-distributed set of GCPs (as in approach C) allows lowering the RMSE of GCPs and CPs further; camera calibration has been performed following a self-calibration approach during the image orientation phase.



Figure 87. UAS orthoimage of the shore of Santa Sabina, with superimposed the topographic vertexes (red triangles) and the GCPs (blue dots) used for the georeferentiation of the photogrammetric flights.

[101] https://www.cisis.it/?page_id=3214
[102] https://www.gazzettaufficiale.it/eli/id/2012/02/27/12A01799/sg

Approach	Software	RMS Error [cm]					
		GCPs			CPs		
		X	Y	Z	X	Y	Z
(A) 42 CPs	PIX4D	n/a	n/a	n/a	2,3	2,9	2,7
	DJI Terra	n/a	n/a	n/a	2,1	2,6	3,1
(B) 42 GCPs	PIX4D	1,5	1,7	1,5	n/a	n/a	n/a
	DJI Terra	1,1	1,2	0,9	n/a	n/a	n/a
(C) 5 GCPs and 37 CPs	PIX4D	1,4	0,7	0,7	1,8	2,5	2,3
	DJI Terra	1,3	0,7	0,6	1,7	2,3	2,9

Table 36. RMS error for GCPs and CPSs referred to the three different approaches followed using the two software.



Figure 88. UAS orthoimage of the shore of Santa Sabina (eBee X).

7.2 Underwater Cultural Heritage documentation

7.2.1. Main underwater evidence

This millenary landing place and its seabed preserved the remains of cargoes and wooden hulls of at least five wrecks that broke against its cliffs or beached. Worthy of note are partly submerged blocks (Figure 89), originating from the nearby quarries and visible along both ridges of the central cove of Torre Santa Sabina, at a depth of 0.80/1.00 m (Figure 90), and a channel with the vault partially preserved, now flooded by the sea in the final stretch (Figure 91).

This evidence, together with the two close beached wrecks (Torre Santa Sabina 1 and 2), indicate a rising of the sea level during the last 2500 years over 2 m [15], [131]. Unfortunately, the wooden remains of Torre Santa Sabina 2 wreck, of Roman Imperial age (calibrated C14 date: AD 50 – 250, with 95.4% probability), despite the covering system of sand, sandbags, and cement slabs, were nearly completely devasted by the environmental energy.



Figure 89. Submerged blocks





Figure 90. Partially submerged quarries.



Figure 91. Mezzaluna bay channel.

7.2.2. The Torre Santa Sabina 1 wreck

The main case study of this chapter is the wreck of the Roman Imperial Age Torre Santa Sabina 1 (late 3rd to early 4th century AD), beached and abandoned at the ancient shore and now submerged due to the relative rise in sea level, a relevant marker of the seascape evolution. It lies at a depth of just 2.8 m in the Camerini inlet, a few meters from the shore, protected by the same imposing covering system as the other wreck, that in this case ensured the preservation of the hull (Figure 92).

This wreck, embedded in the sand and a thick layer (mat) of degraded vegetable materials, is exceptionally well-preserved: it has yielded a few stanchions, deck beams and remains of overdeck beams, as well is presumed remains of the hatch, elements only rarely preserved in wrecks (Figure 93 and Figure 94). For ships of the Roman Imperial Period found in the sea, the only known parallel is the Anse des Laurons wreck in France [132], [133]. The keel is over 14 m long, and the keelson, with T cross section, rests on two small side keelsons, as usual in ships of this period.

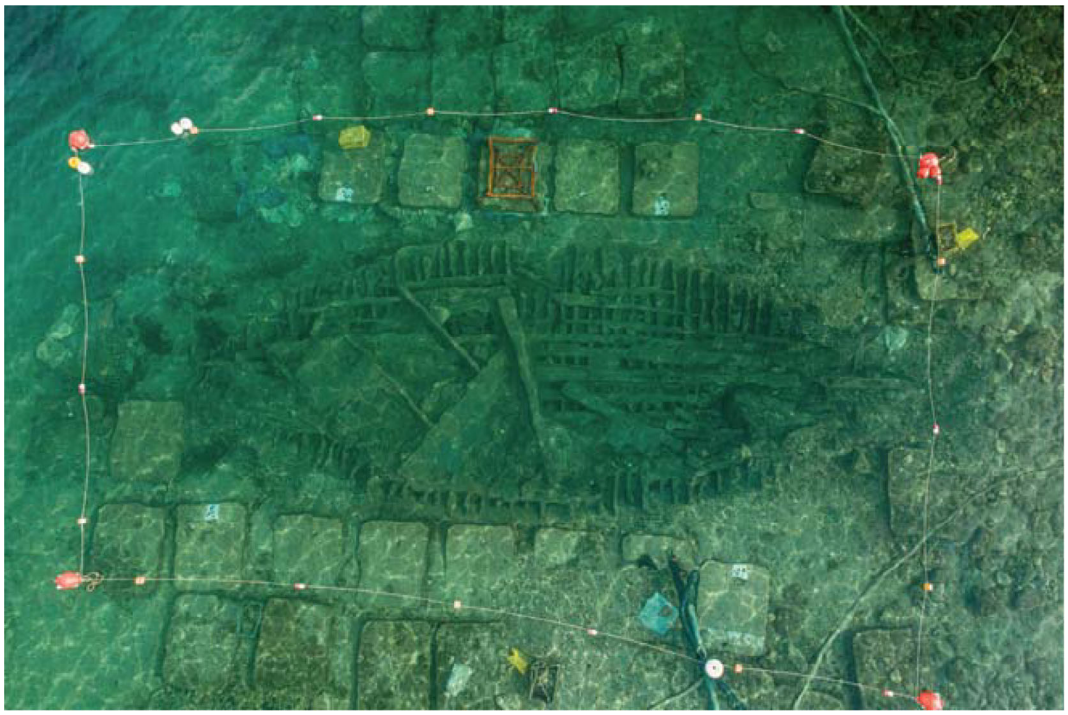


Figure 92. Torre Santa Sabina 1 wreck. (Photo E. Peluso)



Figure 93. Torre Santa Sabina 1 wreck, remains of the deck above two beams.



Figure 94. Torre Santa Sabina 1 wreck, view from the bow area: kelson with the mast step, side keelsons, frames and a pillar on the left.

The keelson shows the rectangular step for the main mast, while a mast step at the bow attests the presence of a fore mast (Figure 95). The framework includes 51 alternating half-frames and floor timbers; the planking is preserved slightly over the round of the bilge (13 planks on the port and 14 on the starboard side). Some repair interventions with patch tenons appear in the planking. The building features suggest that it was a 25–30 m long merchant ship that came from the Tunisian coast and transported wine or fish products from the North African provinces, maybe to Brindisi or another important Adriatic port. Unlike what usually appears in beached wrecks, the ex cavations brought to light ampho rae, both intact and fragmentary, primarily produced in Africa Pro consularis (today's northern Tunisia) (Figure 96).

The amphorae were coated with pitch on the interior and belong to a transitional type between Africana IID ('africana grande' or 'classica') and Bonifay III, variant A (type 27). Their contents could have been fish sauces (*salsamenta*) or wine [134], [135]. The cargo includes also other North African products, as Dressel 30 (Figure 97) and globular containers. Noteworthy is the presence of various items in organic materials – hawsers, ropes, baskets, leather objects – and food remains, both faunal and botanical, found in the pump well.



Figure 95. Torre Santa Sabina 1 wreck, mast step at the bow.



Figure 96. Torre Santa Sabina 1 wreck, North-african Amphora.



Figure 97. Torre Santa Sabina 1 wreck, Dressel 30 amphora.

7.2.3. Legacy Underwater data acquisition and processing (2007 survey)

The area of Santa Sabina has been interested by archaeological excavation since 1973 (Area B). The first known excavation of the Torre Santa Sabina 1 wreck (Area A) dates back in 2007; two survey methodologies were employed; a traditional approach with grid square and a non-conventional photogrammetric survey.

The traditional approach with grid square (1,5 x 3 m sliding frame) has been based on a preliminary draft of the wreck, based on proximate nadir photographs. Subsequently a series of points to be measured have been identified and obtained using the movable pointer of the grid square, with the subsequent restitution on AutoCAD (Figure 99).

The non-conventional photogrammetric application has been performed using a Nikon D50 non-metric camera and the software Photomodeler. After following four main steps (calibration, acquisition, internal orientation, and plotting) it has been possible to obtain the very first rudimental (although innovative for that time 3D model of the wreck. The so obtained 3D model has been later exported in CINEMA 4D for a better visualization (Figure 100).



Figure 98. Survey operations inside the grid square frame. Source: [136]

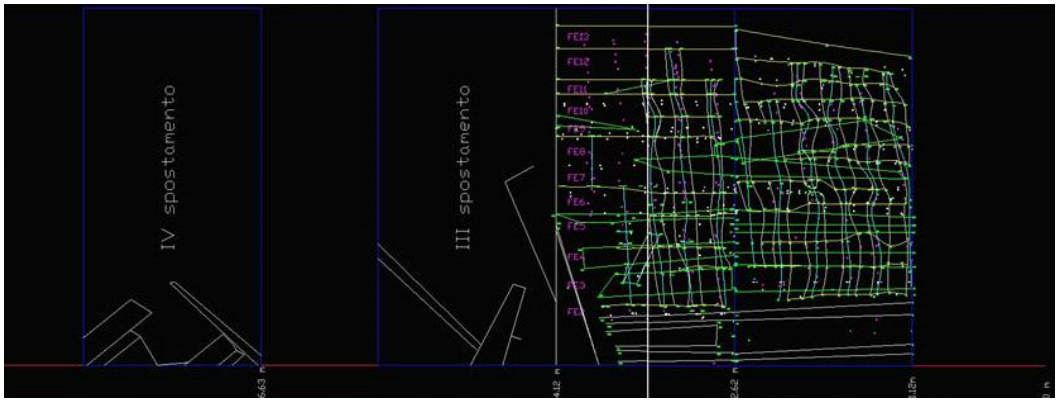


Figure 99. Direct survey restitution obtained from AutoCAD on the basis of a traditional grid square survey. Source: [136]



Figure 100. 3D reconstruction with Cinema 4D. Source: [136]

The direct survey with cartesian coordinates (grid square) suffer the following errors:

1. Systematics: due to the important wave motion in low depths, compromising the verticality of the cursor (plumb line) and therefore affecting the reading in x and y and, minimally, z coordinates.
2. Accidentals: due to the employment of different diving operators with different level of knowledge, skills and and sensibility.

On the other hand, the non-conventional photogrammetric survey provided better and faster results, avoiding the installation of the grid square, reducing the dive times, and allowing for a more comprehensive 3D reconstruction. It is worthy to note that, at that time, it was impossible to operate a photogrammetric survey without relying on a traditional survey techniques, as rudimental non-conventional photogrammetric approaches (compared to the modern ones of nowadays) presented an higher amount of shadow areas (non-reconstructed areas) that had to be integrated using the data deriving from the traditional survey.

The 2007 survey campaign of Torre Santa Sabina confirmed that it was not possible to use only one survey methodology to reach a fully understanding of the site, that had to be merged with the knowledge of an expert domain (underwater archaeologist). [136]

7.2.4. Underwater data acquisition and processing (2020 survey)

Photogrammetric underwater data collection has been performed in two days in September 2020 and focused on the stern of the roman shipwreck survey. The underwater photogrammetric acquisition (Figure 101) has been performed using an Olympus Tough TG-6 digital camera (Table 37) following different acquisition schemas (nadir and oblique) useful for obtaining a complete 3D and 2D documentation. The employed camera can operate without underwater housing at a maximum depth of 15 m; thus, no additional housing has been used during the acquisition phase. This also allowed to reduce image residuals systematic patterns that are usually detected when dome ports are used [137]. The camera also integrates an underwater mode that performs an on-the-fly radiometric adjustment. Given also the very shallow depth on which the survey took place (< 3 m), the data was processed using the automatic colour correction method performed by the camera used for the acquisition of the images (Olympus Stulus TG-6), as already presented in § 5.3. The use of pre-processing algorithms, such as LAB, is in fact justifyed only when colourimetric distortion is problematic and can't be solved otherwise, as in the cases of legacy data or lower depths.

According to the position of the wreck (depth of about 3 m) before the image acquisition, some markers were placed on the seabed and measured using via a topographic approach using a 4 m long pole and a prism, measured via TS (total

station) side shot acquisitions from the shore (Figure 102). Two scuba divers handled the prism to make it vertical before the TS measurements.

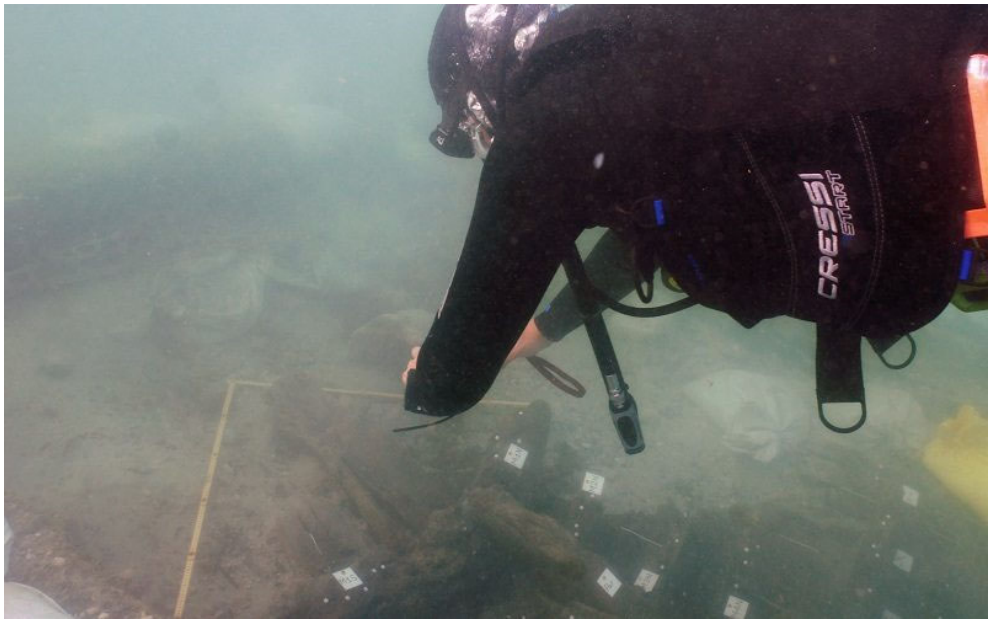


Figure 101. Image acquisition phase during the underwater photogrammetric survey of the Roman shipwreck in Torre Santa Sabina.

Resolution [pix]	Focal length [mm]	Pixel size [µm]
4000 x 3000	4,5 mm	1,56

Table 37. Olympus TG-6 camera main technical specifications.



Figure 102. The image shows the topographical survey operation in Torre Santa Sabina performed to measure the position of the underwater markers.

The measurement of the points' coordinates via this method was affected by errors due to the uneven verticality of the pole caused by the wind and the sea waves. This has been taken into account during the evaluation of the survey accuracy, as a higher RMSE on the measured GCPs is expected.

To evaluate the reliability of an easy and fast survey technique, part of this work focused on assessing the quality of a photogrammetric 3D model generated via a free-net adjustment approach (followed by assigning a scale based on known distances). The 3D model developed following this method has been compared with those generated employing the previously surveyed set of GCPs.

The underwater photogrammetric datasets were processed using the software Agisoft Metashape 1.6.5. The first dataset was composed of images acquired during the first day of the photogrammetric survey. Following the software's operative workflow, at first, images have been oriented. A set of 5 previously measured GCPs has been used to provide correct georeferentiation to the survey; at the end, dense point clouds, DEM, and orthoimages have been generated (Figure 103).

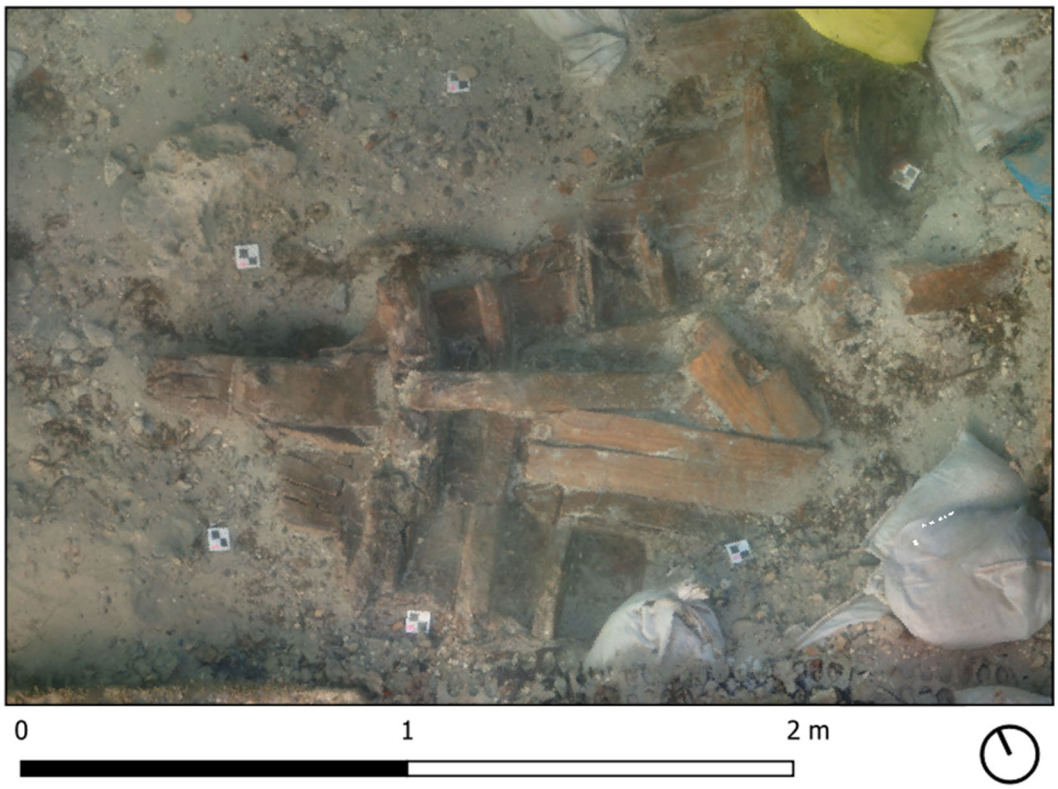


Figure 103. Orthoimage of the stern of the shipwreck, georeferenced using five 10 cm squared checkerboard markers, measured with celerimetric method.

In this case, since no pre-calibration procedure was followed, camera calibration has been performed following a self-calibration approach during the image alignment phase. The characteristics related to this first dataset are reported in Table 38, while the GCPs RMS errors are reported in Table 39.

Total images	343	Oriented images	336
Average acquisition distance [m]	0,83	Tie points	335.584
GSD [mm/pix]	0,2	Projections	937.136
Surveyed area [m^2]	4,5	Reprojection error [pix]	1,42

Table 38. Characteristics of the photogrammetric dataset collected on the first day of the survey.

	RMS error [cm]				
Number of GCPs	X	Y	Z	XY	XYZ
5	1,8	1,6	2,4	2,4	3,5

Table 39. RMS error for GCPs referred to the photogrammetric survey of the stern of the wreck.

The second dataset was composed of images acquired during the second day of the photogrammetric survey. Here before the survey, a necessary archaeological procedure was applied for the characterization of the shipwreck via an operation that allowed to mark clearly the most significant elements of the wreck using small portions of coloured electrical cables, some thumbtacks "push-pin" and plastic cards. Push-pin were also used to indicate where wooden nails were previously located (Figure 104). The same operative workflow of the first dataset has been used. However, this time the 3D model has been generated via a free-net adjustment, assigning a scale to the model via a least-squares adjustment on two scale bars placed in the surveyed scene. In this case, the camera calibration certificate of the previous dataset has been used to provide an initial estimation of the camera's internal parameters. The characteristics related to this second dataset are reported in Table 40.

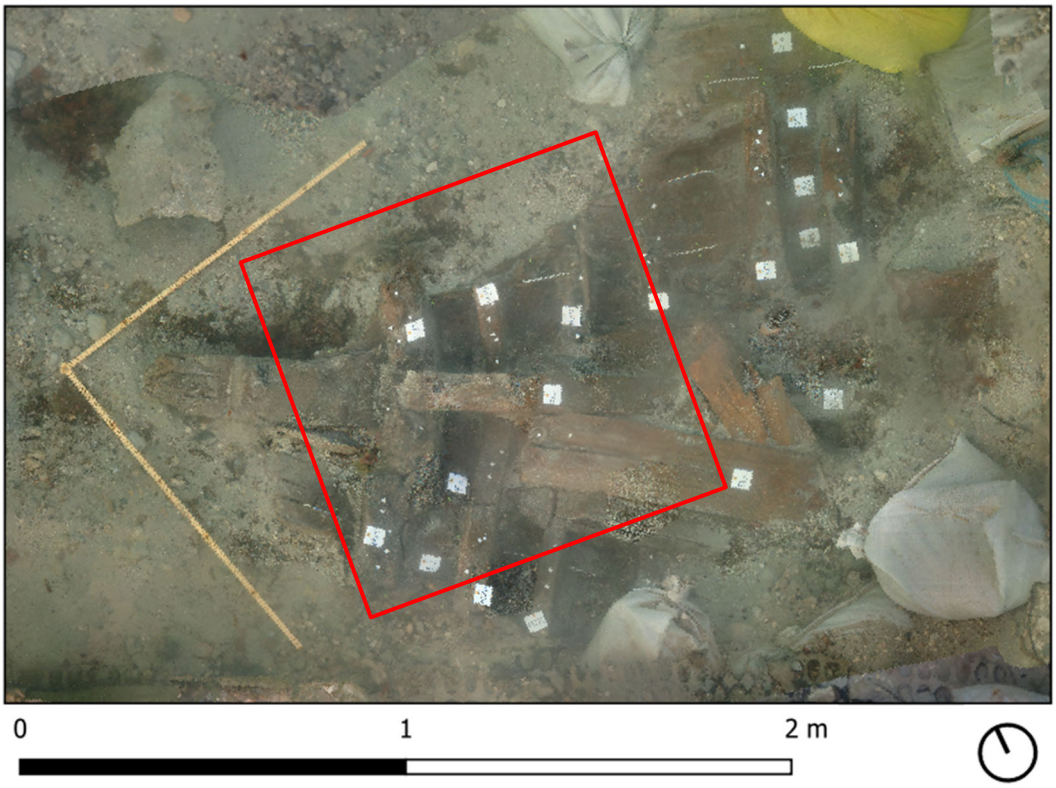


Figure 104. Orthoimage of the stern of the shipwreck, generated via free-net adjustment after the archaeological categorization. In red, the portion of the analysis of Figure 11.

Total images	284	Oriented images	279
Average acquisition distance [m]	0,78	Tie points	218,594
GSD [mm/pix]	0,2	Projections	634,527
Surveyed area [m^2]	4,5	Reprojection error [pix]	1,7

Table 40. Characteristics of the photogrammetric dataset collected on the second day of the survey.

To evaluate the quality of the two 3D models, the same portion (1 m^2) of the two models has been compared, performing a rigid roto-translation (without changing the scale of the models). For point clouds management and analysis, the commercial software Leica Cyclone 3DR[103] has been used; the two clouds have been aligned using the best fit option of the above-mentioned software, allowing for a registration using the ICP (Iterative Closest Point) algorithm. This resulted in an average error of 2,8 mm and a standard deviation of 3,5 mm. It has been therefore performed a C2C (Cloud to Cloud) comparison (Figure 105).

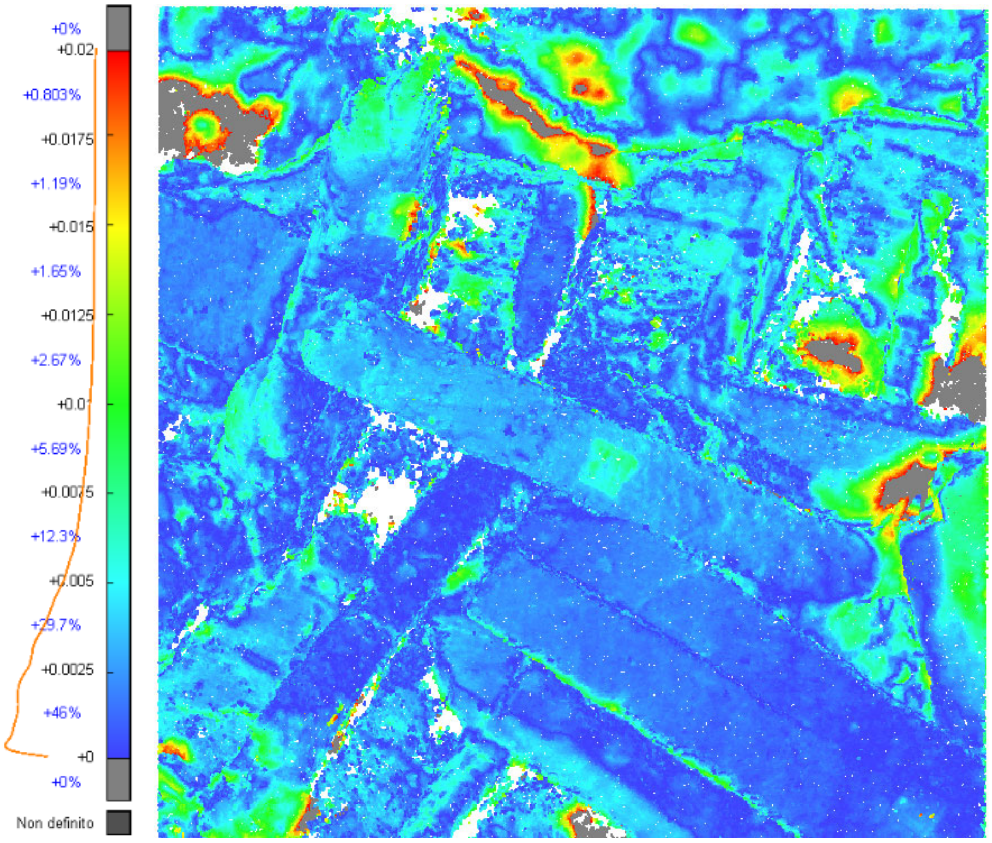


Figure 105. Comparison between the same portion (1 m^2) of the two dense point clouds generated in the two days of the underwater photogrammetric survey using the two different georeferentiation techniques.

[103] https://leica-geosystems.com/en-us/products/laser-scanners/software/leica-cyclone/leica-cyclone-3dr

The max value of detectable deviation has been imposed at 2 cm (predicted accuracy of the method). Even if these methods provide an accurate value of the local deviation between the two models, it is essential to clarify that this value is often overestimated since the algorithm calculates the distance value among a couple of points of the two point clouds that are relatively closest to each other (nearest neighbour distance). This value is always higher than the minimum distance obtained if both models were infinitely dense. Moreover, only positive differences do not show systematic errors.

It is possible to observe that the deviation between the two models is less than 1 cm for 94% of the points. Moreover, the parts of the models with higher discrepancy are mainly related to the seabed and to sands accumulation that likely was moved between the two excavation phases of the two days. The use of this technique has some limits because the survey is performed in a relative reference system. This means that it is impossible to put the derived products in relation to each other or prior/subsequent survey. Moreover, in the case of higher surface extension of the survey, it will be required to place additional and more extended scale bars, as error propagation will likely increase whenever more extended photogrammetric blocks are scaled using relatively small reference scale bars. However, this technique remains crucial in surveys performed at higher depts, where longer poles are not usable, and the georeferentiation has to be performed employing other methods and instruments, such as SBL (Short baseline) acoustic positioning systems.

7.2.5. Comparison with legacy data (2007 and 2020 surveys)

Given the importance of legacy data, it was interesting to compare data obtained and processing techniques followed in the 2020 acquisition campaign with a previous survey campaign performed in 2007 [136]. Images of the 2007 excavation campaign dataset were captured using a Nikon D50 (3008 x 2000 pixels) with underwater housing. The dataset composition is showed in the following Table 41.

Number of images	Focal length [mm]	Acquisition
74	18	Nadiral
79	24	Nadiral
321	35	Oblique

Table 41. Characteristics of the photogrammetric dataset related to the 2007 survey.

Since the acquired images suffered a severe chromatic aberration [138], a radiometric pre-processing has been performed (Figure 106) using the LAB filter, already presented in § 5.2.

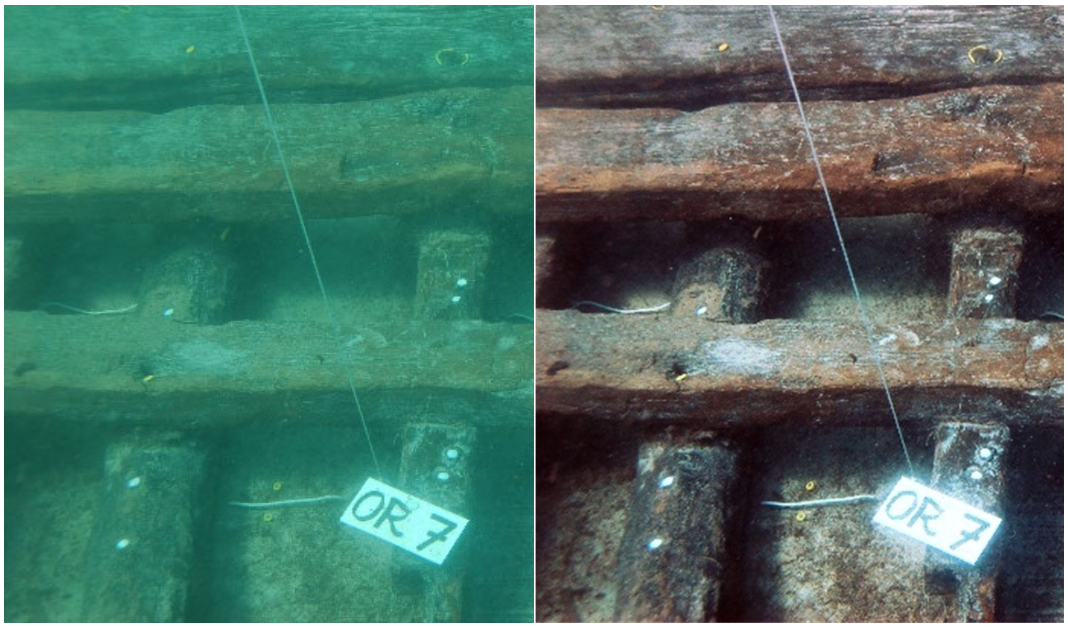


Figure 106. On the left, an image of the 2007 dataset before the radiometric correction; on the right, the same image after applying the LAB filter.

Because absolute georeferentiation data was not available, the operative workflow previously described (generation of a 3D model via a free-net adjustment) has been followed, assigning a scale to the model via a least-squares adjustment on six measures obtained exploiting the metric rulers attached to the archaeological grid square [139], placed in the scene for performing the direct survey. To compare and relate the 2007 and the 2020 survey (Table 42), it was necessary to manually connect the two orthoimages on the same reference system, exploiting a small overlapping part. This made it possible to produce a comprehensive orthomosaic and a DEM (Figure 107) to facilitate the shipwreck shape and extension's comprehension and plan future surveys and eventual recovery operations.

	Direct survey	*Photogrammetric survey*	
		Photomodeler	*Metashape*
Acquisition time [h]	9:00	0:30	0:30
Operators	2	1	1
Processing time [h]	11:00[1]	20:00[2]	1:00[2]
Repr. Error [cm]	± 8	± 1	± 0,05
Georef. Error [cm]	n/a	n/a	3,5

[1] Only referred to the production of drawings
[2] Steps required for the 3D model generation

Table 42. Comparison between direct and photogrammetry survey with both Photomodeler (old) and Metashape (new) approach. Data are referred to a portion of the study of 4,5 m^2.

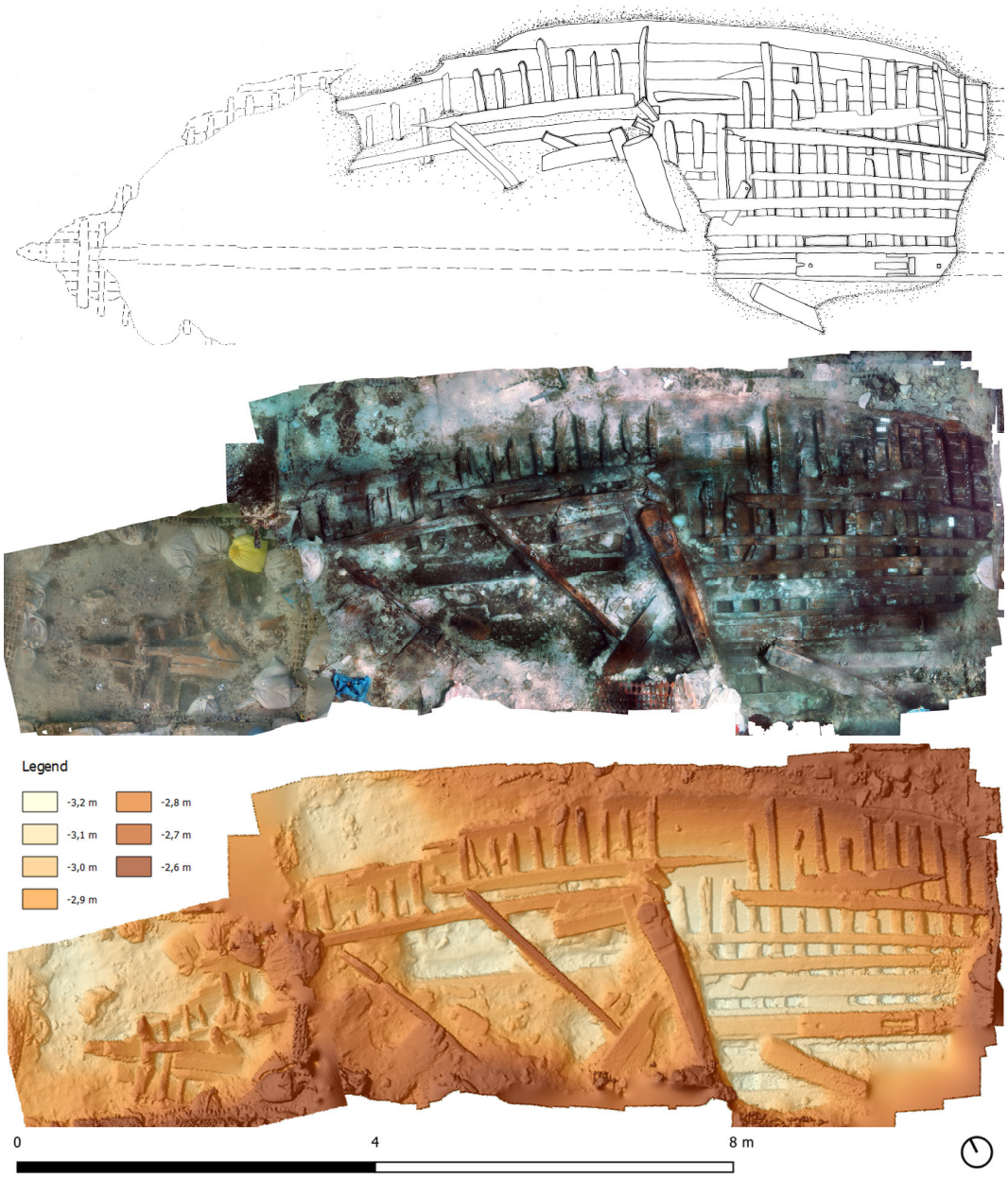


Figure 107. On the top, drawing of the shipwreck produced via direct survey in 2007; on the center, RGB orthoimages of the two parts of the wreck surveyed in 2007 (right) and 2020 (left); on the bottom, DEMs of the same orthoimages of the two surveys.

7.2.6. Complete excavation and final documentation (2021 survey)

In the 2021 archaeological intervention, the entire hull was thoroughly documented by photogrammetric techniques to register the day-by-day results and to obtain a complete 3D model. Photogrammetric underwater techniques have been used in combination with a preliminary topographic survey, needed for the definition of a local reference system. The survey has been conducted with different optical sensors (underwater cameras and action cameras) for the definition of a complete and trustworthy 3D model of the wreck. Since the survey has been performed in shallow water conditions, geometric camera calibration and

radiometric image correction have been performed prior to the data processing phase.

As the main documentation objective was the multitemporal analysis of the excavation phases, and there wasn't any GNSS antenna available on site capable of automatic tilt compensation, it was decided to test an alternative solution to CONETTO and PALONE systems, presented in § 6 and § 6.2.2 respectively.

A permanent set of 6 codified GCPs have been installed, in order to put in relation all the different acquisitions with each other's. For this purpose, an ad-hoc device has been created to guarantee a centimetric grade georeferentiation (Figure 108).

A stiff pole was installed in the center of a movable frame, ensuring that once the pole is levelled it is not affected by tilting errors induced by the environmental conditions, as discussed in §6. This system allows the measurement of the point coordinates using a Total Station and a prism, overcoming both the limits of TS lacking a tilting compensation device, and the limits posed by the accuracy of GNSS RTK acquisition, as already discussed in § 6.3. The system can provide higer accuracies than CONETTO and PALONE, with the drawback of being more time consuming to deploy.

A total of 6 complete multitemporal epochs have been acquired and processed using Agisoft Metashape, adopting the main camera calibration and radiometric correction techniques already discussed in §4 and §5. The RMSE of the different epochs are reported in the following Table 43.

The Appendix C – Orthophotos and DSM, at page 229 of this manuscripts includes the full set of othophotos generated for the purpose of the multitemporal documentation of the excavation site, together with the DSM used both as a delivery product for the archaeological team for the definition of cross section of the wreck, both for assessing a simple change detection analysis by comparing subsequent epochs.

Date of acquisition	Number of images	RMSE on the GCPs
14/09/2021	523	0.010
16/09/2021	444	0.012
18/09/2021	224	0.008
26/09/2021	509	0.009
27/09/2021	549	0.013
28/09/2021	1146	0.012

Table 43. For each of the different epochs, the table list the number of images and the RMSE on the GCPs.

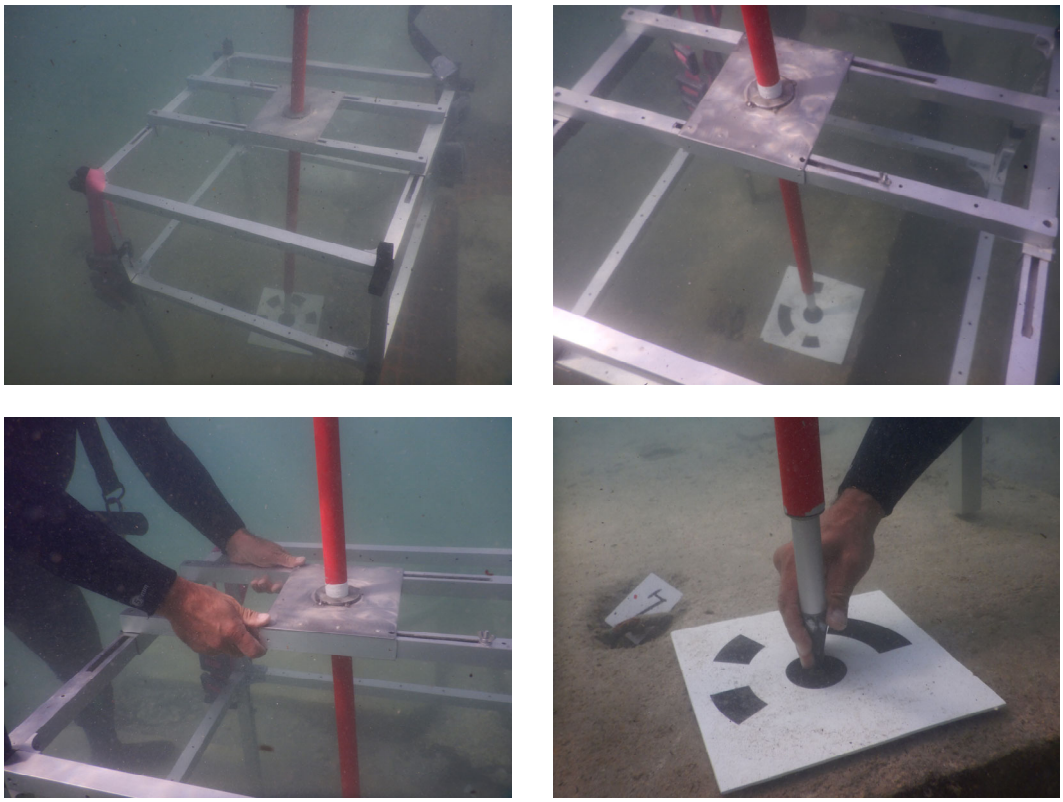


Figure 108. Ad-hoc self-built pole-holder device created to guarantee centimeter grade georeferentiation.

8

Chapter 8

8. Suggestions and examples of online dissemination

This chapter is related to some suggestions on dissemination of the photogrammetric process final products (3D models and orthoimages) and take as case study other activities performed in collaboration with the Underwater archaeology group of UNISALENTO.

The activities reported in this chapter have been conducted in the Adriatic Sea, in the "Le Cesine" Natural Reserve, that led to the identification of a big pier from the Augustan period. Other activities were performed on the Ionian Sea, furthermore, in Porto Cesareo Marine Protected Area, where new evidence has been added to the numerous ones already known, such as some spectacular formations composed uniquely by cemented sherds of Tripolitanian amphorae (2nd cent. AD). This evidence seems to be significant markers of sea-level changes and the evolution of the seascape.

All these sites have shared characteristics that make it possible to highlight a series of aspects that are of interest for the reconstruction of the ancient environment and above all the variations in sea level since antiquity.

In methodological terms, the research conducted in the areas followed a holistic, contextual, diachronic, and transdisciplinary approach to the archaeology of landscapes, or rather seascapes, in this case, coastal and underwater. The primary objective of this systemic vision is to tell the story of social groups in changing landscapes, recording their discontinuities, formative processes, and identity.

For this specific purpose, smart dissemination applications and techniques have proven to be particularly effective in the CH domain, as they allow the discovery of details that are sometimes invisible to the naked eye or not easily accessible such as the Underwater Cultural Heritage analysed in this thesis.

The dissemination approaches discussed in this paragraph puts people at the centre and includes interactive experiences for visitors, researchers or citizens interested in the submerged heritage. It is crucial to focus on the inclusion of different categories of participants (leave no one behind) who would often be ignored or marginalized (people with disabilities, etc.).

Two possibilities of online dissemination for high quality textured 3D models and high resolution orthophotos are proposed.

Finally, the Extended Reality (XR), which has successfully transitioned from the laboratory environment to mainstream technologies available to almost everyone, will be discussed. This set of technologies, together with the most traditional webGIS creation and along with recent advancements in the 3D reconstruction of CH, has the potential to deliver compelling experiences to the final users.

8.1 Multi resolutions 3D model and high resolution orthophoto visualization

The view-dependent resolution of the model (multiresolution) allows minimizing requirements in terms of GPU computational power, RAM usage, and bandwidth, while allowing the visualization of large models at their full resolution on a wide range of devices. This technique can be coupled with volumetric annotations for scientific analysis and presentation enrichment. The submerged sites are explorable only by a small fraction of the population and represent, to date, one of the less accessible environments. Immersive navigation experiences democratize the fruition of this priceless submerged cultural and natural heritage and represent a valuable learning and dissemination practice. Ideal solutions are deployed for museum kiosks and web fruition via mobile or desktop devices.

8.1.1. Porto Cesareo – Multi resolution 3D model visualization

In the waters around Porto Cesareo, submerged and semi-submerged archaeological evidence has recently been un-covered by preliminary surveys carried out in close collaboration with the management of the local Marine Protected Area. The surveys have added new evidence to the numerous discoveries already made [140].

In the sea area called “La Pierta”, which is the broad bay between Torre Chianca (to the south) and Torre Lapillo (to the north), at 600 to 800 m from the coast and at a depth of 3.5 to 4.5 m, on a rocky platform marked to the east – on the landward side – by a steep descent to a depth of 5.5 - 6 m, what was previously assumed to be rock formations have recently been revealed by Mino Buccolieri (the coordinator of the Environmental Education Center of the Municipality of Porto Cesareo) to be extensive concretions of fragments of amphorae - handles, bottoms, rims and walls. These are cemented both to each other and to rocky outcrops on the seabed, which, due to environmental erosion, in six cases have acquired a distinctive morphology,

reminiscent of gigantic mushrooms, with a reduced base and elongated “hats” (Figure 109).

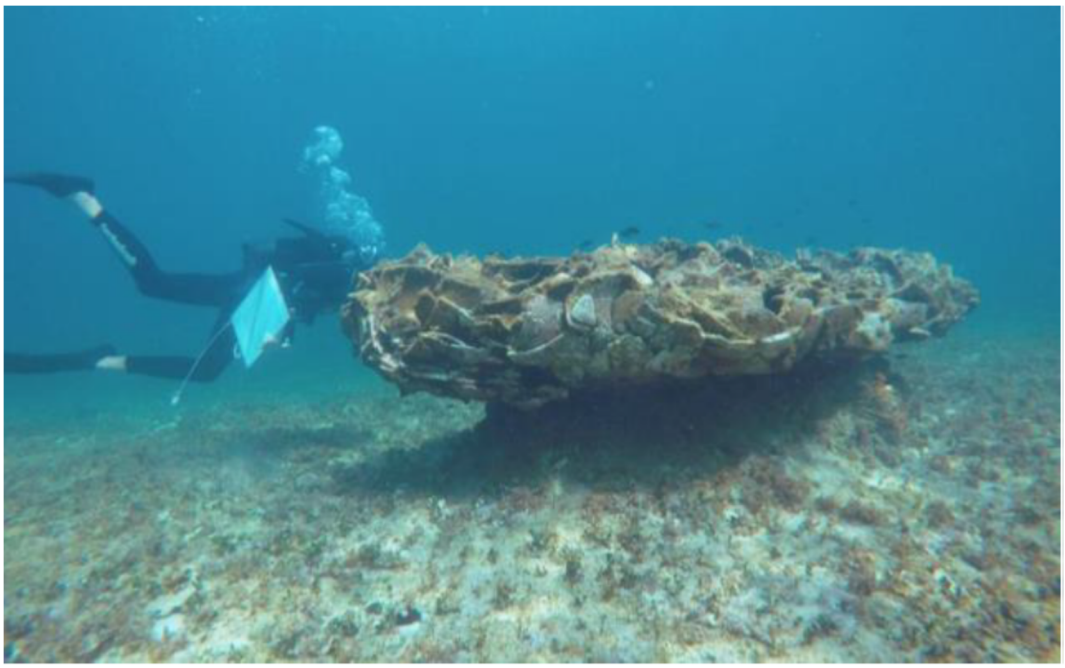


Figure 109. Tripolitanian amphoras’ cargo remains.

The fragments are all of North African amphorae from the province of Tripolitania, classified as Tripolitan II (Figure 110). Their homogeneity confirms that they belong to single ship’s cargo. The Porto Cesareo specimens do not seem to have been dumped. They include no other types of amphorae or vessel, whether common or valuable.

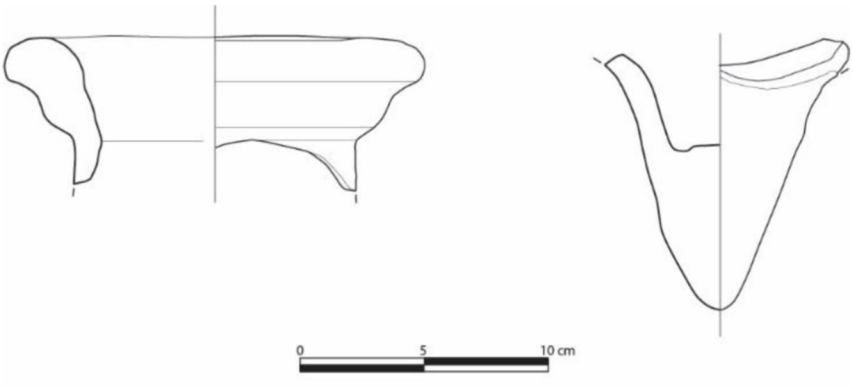


Figure 110. Tripolitan II amphora fragments.

The remains are therefore attributable to a homogeneous cargo of considerable volume, given the number of fragments and the extent of the seabed affected. It therefore appears to have been a “direct” shipment from the place of production to the place of consumption: a “supertanker” travelling fully loaded with a “wholesale” shipment, probably headed east, towards the ports of the eastern

Mediterranean, whose voyage was tragically cut short along the Ionian coastal route between Crotone and Capo Iapigio.

Talking about dissemination possibilities, an application based on the models so far obtained by the 2021 survey campaign was prepared to offer a virtual visit through 3D HOP (3D Heritage Online Presenter), an open-source software package for the creation of interactive Web presentations of high-resolution 3D models, oriented to the Cultural Heritage field [22] (Figure 111). 3DHOP allowed the creation of an integrated interactive visualization of the photogrammetric based 3D models so far generated, embedding all of them directly inside a standard web page based on HTML and JavaScript components. Thanks to the integrated multi-resolution 3D model management, the user can visualize the models from a personal computer without the use of specific software or hardware.

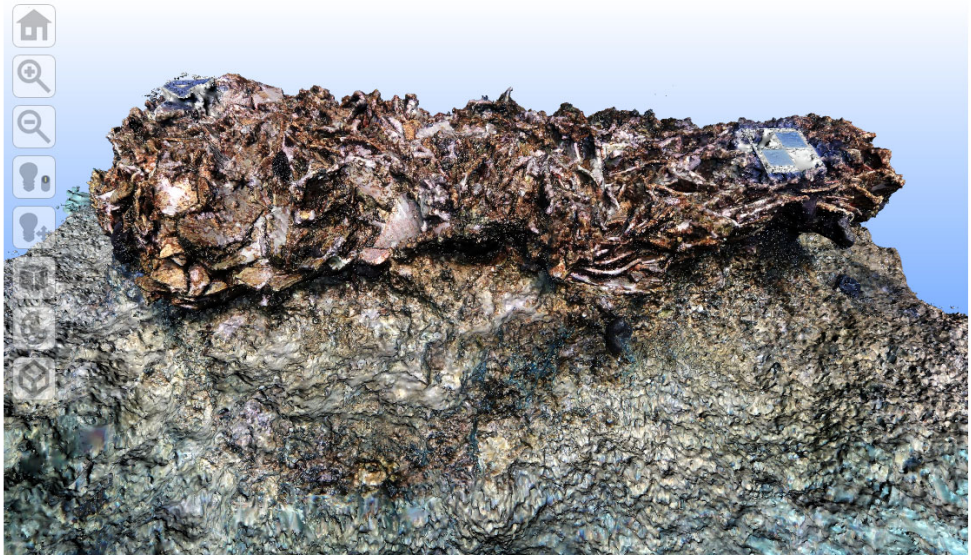


Figure 111. Visualization of one of the Porto Cesareo's Tripolitanian amphoras' cargo remains loaded in the 3DHOP interface.

8.1.2. Le Cesine – High resolution orthophoto visualization

A recent underwater and terrestrial survey in the coastal area coinciding with "Le Cesine" Nature Reserve has allowed the identification of further archaeological evidence, which enriches the previous knowledge of the area. It is worth noting the discovery in 2020 of a submerged port structure of the Roman period, probably a pier, in the locality of San Giovanni, which offers a much more complex view of the ancient port of Lupiae.

The pier has been built using the typical technique of landing stages in the Adriatic and other areas of the Mediterranean, especially eastern, with caissons: two parallel walls built with large parallelepiped blocks of local stone, the space between them filled with irregular stones, sometimes reinforced with internal partitions for the distribution of forces.

This structure begins about 15 m away from the shore and 65 m south-east of the outlet channel; it is bordered by two external curtains of large blocks and stretches east/north-east for about one hundred meters (Figure 112). The pier is

about 8 m wide and the overall length, in this preliminary investigation phase, seems to be 100 m (83 m visible); the foundation rows of the two parallel alignments that make up the curtains are composed of large parallelepiped blocks (1.50 x 0.65 cm) which are laid end-to-end along the entire length of the pier.

The depth of the blocks at the (assumed) start of the pier is less than one meter, while at the head it reaches 4.0 m. It is therefore an important marker of sea-level variation, considering a relative rise since the pier's construction of about 2 m, the draft of ancient ships being compatible with the remaining 2 meters.



Figure 112. Aerial view of the submerged pier in San Giovanni.

Talking about dissemination possibilities, a comprehensive high resolution orthophoto of the surveyed Roman Figure 113 pier has been uploaded on the ARIADNE Visual Media Service [141]. "*Most of the images produced nowadays are very high-resolution. High-resolution images are now a commodity resource, with the impressive evolution of digital photography (just to mention a single example, a recent off-the-shelf smartphone provides a 41 Mpixel camera). When high- or huge-resolution images are available, the visualization on the web can be difficult, due to the amount of data that have to be transmitted before the web browser would be able to present visually something. This is because the browser has to receive the entire file before visualizing it. Another important and critical issue could be the necessity to protect the data, avoiding sending the full resolution image as a single file to a remote host. This service converts a high-resolution image (uploaded using standard image formats) into a multi-resolution version, enabling progressive transmission and rendering it by means of a web visualization page."*[104]

[104] https://visual.ariadne-infrastructure.eu/info/img

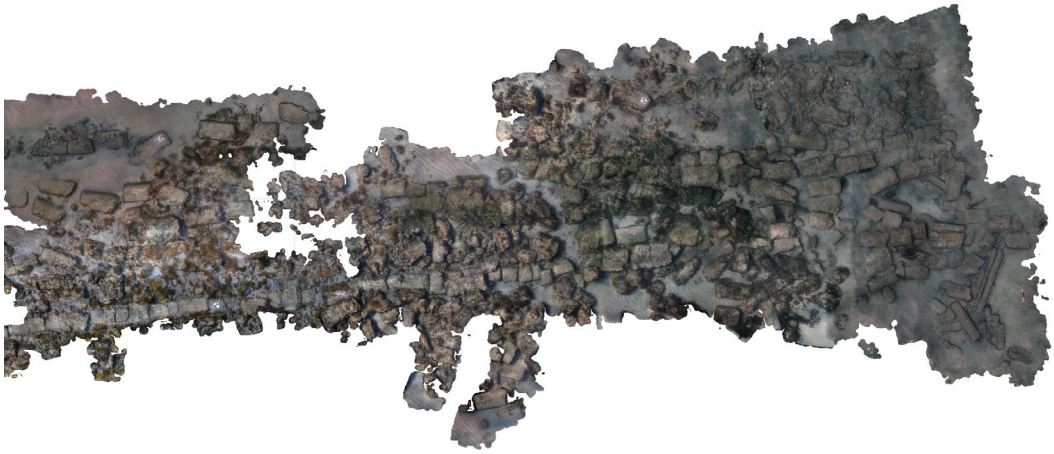


Figure 113. High resolution ortophoto of the surveyed roman pier uploaded on ARIADNE Visual Media Service

8.2 Extended reality

The application of virtual reality, augmented and mixed reality can be exploited to provide 3D reconstructions and immersive virtual tours capable of enabling digital fruition and storytelling of shipwrecks and sites, making them accessible and enjoyable by a wider audience and not only by a few divers. It is also important to provide access to unreachable underwater CH not only to scientists and researchers but also to the wider public, by using immersive technologies and virtual visits [142]. The growing number of applications in underwater photogrammetry in recent years allows one to virtually reconstruct the seafloor, shipwrecks, submerged structures and infrastructures, and therefore enables the study of marine environments and their submerged contents without divers or vehicles in the water. These reconstructions could be exploited in Museums, Marine Protected Areas (MPA) visiting centres and all the regional networks of the places of culture, through headsets (e.g., OculusQ, Geolens or other devices and touch screens) also directly online. At the same time, extended reality techniques might allow responding to the need for dissemination and study (not only to specialists but also to a larger audience) with the final aim of creating immersive tours and 3D reconstructions. The possibility offered by XR can provide to the final user ad-hoc platforms and tools (both online/offline and on-site/remotely). The compelling idea is to create applications usable "at home" and "on the field" to improve the knowledge and the dissemination of underwater environments. The applications can be deployed at two main levels: one related to the expert users such as scuba divers, researchers, and technicians, who are able to visualize the models directly in the underwater environment via mobile devices, and one related to other citizens, able to visualize the underwater environment on the ground via mobile or desktop devices.

8.3 webGIS

The interdisciplinary study, which foresees the synergistic work of various specialists, aims to redesign the ancient physiognomy of the landscapes in the various phases and to understand the forms and ways of the population, which have evolved over the centuries, transforming themselves together with the landscape itself.

"Global archaeology does not aim so much at a global understanding of archaeological traces, probably destined to remain illusory, but rather at the globality of the approach, that is, at the collection of those "sets of information", which the different sources, archaeological and otherwise, they make available to answer, each according to their own possibilities, the historian's questions" [143]

The main tool of the landscapes/seascape's archaeology is the webGIS, which allows for permanently available knowledge, updated over time, of each individual cultural asset. It thus represents a form of objectification of CH: it is the place of "certification" and even of the existence of cultural assets; in fact, cultural assets "do not exist" if they are not catalogued. The creation of the webGIS means gathering all the already available information related to the sites at various depths in an analysed area, and performing a data harmonization in a holistic and systemic perspective of a network of relationships, in accordance with the methodology of landscapes/seascapes archaeology. In this framework, creating a webGIS can be useful to gather information on different sites and locate them. Bibliographical and archival documentation, aerial images, scattered archaeological data, archaeological surveys, oral information and news will also be of great help, as well as the study of winds and currents: everything will help to focus on routes sailed by cargo ships already in ancient times.

webGIS, public and georeferenced for the virtual exploration of ancient shipwrecks can also include voice, text, images, and animations, responding to the need to describe this "invisible" heritage to an ever-increasing number of people. It is important to propose a webGIS in an interactive, user-friendly, and easily readable way, even by a non-technical public, to promote underwater sites with accessibility standards. A successful approach will require directly link information sheets with images, videos, documents, and 3D models of the underwater sites.

An example is The Underwater Archaeological Map of Southern Puglia (CartApulia). Developed on the ArcGIS platform with the support of ESRI Italia, partner of the project, the Cultural Heritage Department of the University of Salento, the contribution of CUIS (Consorzio Universitrio Interprovinciale Salentino) and in concert with the Protection Bodies and the Ministry for Cultural Heritage and Activities the informative version of the *Forma Maris Antiqui* consists of about 650 archaeological and underwater finds, including wrecks, hypothetical wrecks, areas of clay fragments, isolated finds, structures, identified along the coast of southern Puglia (Figure 114).

Another example is the University Ca' Foscari Venice has realized a web platform (Figure 115) that contains underwater archaeological sites in Friuli-Venezia Giulia, Veneto, Puglia region and Spalato (Croatia). The public webGIS

UnderwaterMuseMap portal[105] allows virtual exploration of the sites via vocal information, text, images and animations, answering to the need of making visible an "invisible" heritage. The map is an effective informative tool for displaying the touristic offer and it is promoted at a transnational, national and local level, ensuring the sustainability and its transferability after its realization.

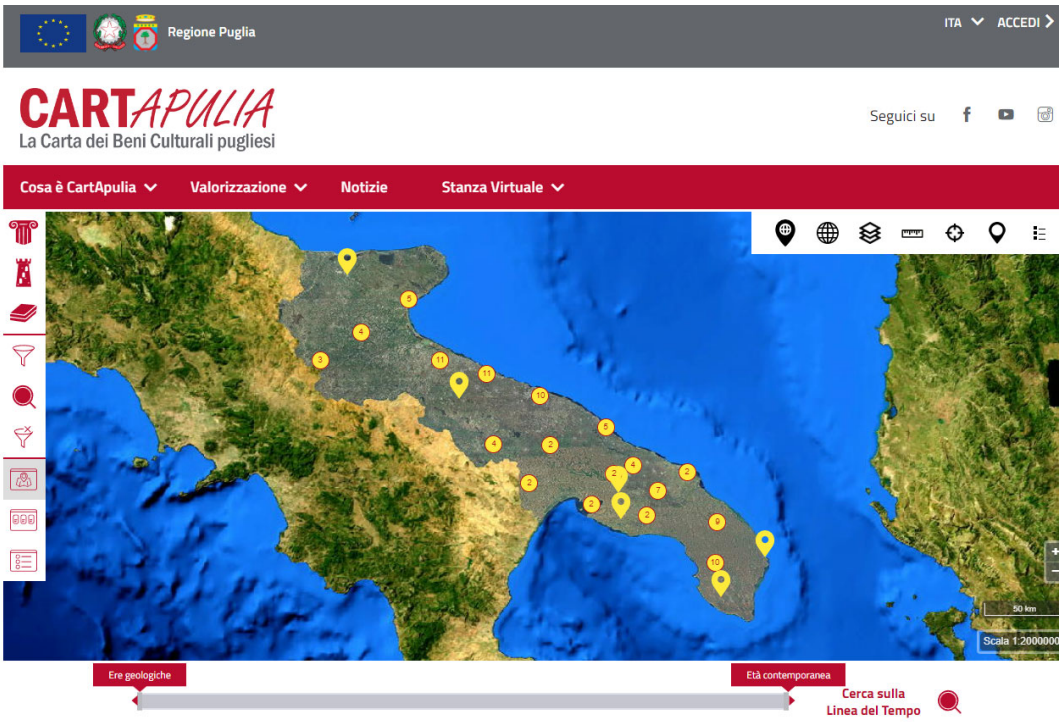


Figure 114. The public webGIS CartApulia portal



Figure 115. The public webGIS UnderwaterMuseMap portal

[105] http://mizar.unive.it/underwatermusemap

Discussion of results and future visions

Part III focuses on discussions of obtained results and critical considerations of practical implications. Some conclusions and future perspectives are reported to reuse the methods and the knowledge carried out in this thesis.

PART III

9

Chapter 9

9. Discussion & Critical considerations

This brief chapter aims to underline the goals achieved by the present research. Moreover, it wants to highlight why and how the study is ambitious and innovative. The methodology is replicable, reusable, and extendable for further studies and domains. As explained in the first chapters, this thesis is in the Underwater Cultural Heritage domain, particularly in the area of archaeological sites of shipwrecks in shallow waters. As geomatics techniques and methods support the research in different disciplines, this approach wants to help various stakeholders (citizens, researchers, policymakers, etc.) to valorize and promote the UCH.

This chapter presents a list of critical considerations and reflections (all connected to each other) on the work done for this PhD thesis. Goals, technologies, and innovations developed also underline possible new solutions and future outcomes (explained in the next chapter, Conclusions and Future perspectives).

9.1 Goals reached by the methodology

In the last years, we assisted in the significant growth of photogrammetry applications in underwater environments. This methodology allows us to document, reconstruct and restore the surveyed underwater assets virtually [144] and make them accessible remotely (not only to the broad public but also to specialists across the globe). Those aspects are crucial since underwater cultural sites are, for their intrinsic nature, among the most difficult-to-reach heritage. The difficulty of operating in water environments derives from the operator's reduced stay time on the site and environmental conditions that might affect the survey (such as light condition, turbidity of the water, etc.), reducing its overall quality. For improving the study of the documented cultural heritage artifacts and sites, it is decisive to

adopt the correct photogrammetric principles to achieve 3D metric products consistent and coherent with the survey's real object. Geomatics provides sensors and techniques that allow scientists and professionals to efficiently record, process, and present data related to underwater archaeological sites. These techniques' potentialities and problems have already been addressed in the past [145]; however, new emerging sensors and applications denote the need to continue investigating and evaluating different approaches. The adoption of low-cost sensors is becoming more common in recent days [146], and the possibility of processing and quickly obtain photogrammetric point clouds cannot be separated from the need for high metric accuracy, which is necessary for a trustworthy survey in cultural heritage documentation [147]. As such, multi-image photogrammetry has proven to be an affordable methodology, supporting underwater archaeological activities with reliable results [148].

Before this study, the possibility of enhancing sub-optimal datasets, and exploit legacy data had been considered and developed only in part ([21], [149], [150]). Moreover, none of these approaches presented a comprehensive way to deal with problems related in the processing of imagery data not acquired for photogrammetric purposes.

More specifically, this thesis aimed at:

- Setting of standardized procedures and guidelines to suitable design and effectively perform the collection of accurate and high-resolution metric data in underwater surveying and monitoring, both from the imagery and the related positioning point of view.

- Definition of strategies for enhancing photogrammetric 3D reconstruction of underwater sites, thus exploiting the metric and radiometric content of less-than-ideal image datasets by adopting pre-processing strategies, to achieve acceptable results also from legacy photographic documentation (non-photogrammetric datasets).

- Setting of different workflow pipelines for 3D data processing: design and test strategies for capture high-resolution images (both in terms of geometric, colourimetric, and spectral contents) and metric information for surveying and monitoring in underwater scenarios.

Concerning the importance of the geometric calibration of a camera in underwater photogrammetric surveys for archaeological purposes, in Chapter 4 it has been showed how the adoption of pre-processing, pre-calibration, image masking, image enhancement filters and radiometric correction strategies could increase survey trustworthiness, coherence and accuracy, reducing the reprojection errors. Moreover, the chapter presented an overall analysis of several aspects of pre-processing strategies, proposing different approaches for enhancing photogrammetric 3D reconstruction of underwater shipwreck datasets. The *Mandalay* dataset was, together with other *Biscayne* datasets, derived from an early iteration of the *SeaArray* multi-camera photogrammetry system; the results obtained and showed in the thesis reflect therefore the outcomes of one of the first deployment of the system and might not represent its actual state of development.

In chapter 5 it has been presented a fast method for restoring the colour information on images captured underwater. The model utilizes the scenes 3D geometry with the creation and use of SfM-MVS generated depth maps which is crucial for implementing the proposed methodology. The results presented visually and quantitatively are promising, since no other algorithm can be implemented in such a straightforward manner to restore the colour information as it avoids the need of obtaining physical data regarding the property of the water and/or the site condition (whose collection is often costly and time consuming). Of course, more accurate algorithms that utilize the scene's geometry exist in the literature. However, the disadvantage is that they need additional information regarding the physical water properties that can be measured using expensive equipment or calculated using more complicated physical models. It must be specified that the model cannot be reused for different datasets meaning that for every new dataset, the presence of colour charts is mandatory to fit the model and evaluate it. Furthermore, different datasets are affected by different light and water conditions which makes the reusability of the model not ideal. Additionally, the model needs 3D information in order to work. The algorithm is not a simple image enhancement, but a 3D based image colour restoration algorithm.

The main result of the activities presented in Chapter 7 lies in the definition of a wide-ranging survey methodology that integrates and updates the previous documentation with the help of new documentation tools and technologies, allowing archaeologists and other researchers to carry out their activities in the framework of verified and updated metric supports.

Concerning the photogrammetric survey performed using UAS, it was possible to document the sites and their immediate surroundings thanks to the generation of metric products (orthophotos, digital surface models, and 3D models) obtained via photogrammetric techniques based on SfM (Structure From Motion) algorithms.

During the UAS data processing, a quality evaluation of the direct photogrammetric approach using the two platforms was carried out and accurately assessed. The proposed georeferentiation method showed that it is possible to obtain good results with a standalone PPK approach, even without any measured GCPs.

An essential part of the activities carried out in the underwater environment was the photogrammetric acquisition of the stern of the Roman wreck of Torre Santa Sabina, which allowed the experimentation of survey techniques to be used in the later campaign. It was also possible to integrate the new data with those of the survey conducted 14 years before this study.

The results presented show that modern photogrammetric algorithms can provide a valid alternative to direct investigations in the documentation of the excavation phases of archaeological sites.

The use of digital photogrammetry techniques applied to the archaeological survey of underwater sites can constantly speed up survey operations without neglecting the quality and reliability of the data collected. The implementation of these procedures also provides better conditions for the operators' involved thanks to the reduction of the total immersion time.

9.2 Limits to bridge and overcome

Finally, there are many "open" aspects and limits to bridge and overcome for every ongoing and innovative research.

One of those limits is related to the end of the survey campaign, when during the integration of both direct and indirect survey data, it is crucial to gather and structure all the information in a way that can be understood and managed not only by geomatics, but also by domains' experts (archaeologist, marine biologists, etc.)

Underwater cameras and dome ports, specifically made for marine environments, are essential for lowering geometric errors related to the presence of two mediums, that might affect the reconstruction results. Future research could be aimed at deepening these aspects in order to link each survey scenario and conditions with the opportune set of camera, lens and dome port.

The author experienced some successes, but also some setbacks with the camera array used in Chapter 4. One of the possible configurations to test in the future will be to tilt some of the cameras in order to achieve a convergent/oblique multi-camera configuration, in addition to the nadiral asset of the master camera, for a better 3D model reconstruction. The correct estimation of known baselines between cameras will also help to improve the geometric correctness of the 3D models, that up until now relies only on the scale assignment using calibrated scale bars. Different consideration must be taken into account in order to apply this procedure in the future, such as ensuring that the cameras are synchronous, comparing calibration in water and outside water, keeping the variance as low as possible (at least of one order of magnitude), and evaluating if the *SeaArray* structure can be considered rigid enough to impose fixed baselines. The checkerboard employed was not large enough due to the 14 mm focal length lens used. Optimal conditions would require calibrating the cameras at the same acquisition distance of the object to be surveyed (which is typically 2-4 meters off the bottom). This issue revealed the need for a large calibration grid. It appears however necessary to assign to the model not only a correct scale but also a coherent georeferentiation; future studies should be devoted to the experimentation of underwater positioning systems, and different calibration procedures will have to undergo further tests, both in and outside water.

The work presented in chapter 5 to restore colour image information only utilized a 2nd degree polynomial fitting for the backscattering and a 2^{nd} degree exponential fitting for the absorption as they provided the best visual results for these particular datasets. That does not mean that these are the only fitting functions that can be used. The fitting can be modified to provide the best possible results depending on the dataset.

Concerning the procedures applied in the real case scenario discussed in chapter 7, critical aspects of applying the employed methodologies are mainly related to the preliminary assessment of the camera calibration and GCPs acquisitions.

Carrying out the survey in very shallow waters provides advantages from the logistic perspective and some drawbacks in the GCPs measurement via traditional topographic methods. These aspects have been assessed and furtherly refined given

the subsequent 2021 survey campaign, in which there has been the possibility to extend the survey to the whole extent of the shipwreck for comprehensive documentation of the archaeological site.

"If we knew what it was we were doing, it would not be called research, would it?"
"Se avessimo saputo cosa stavamo facendo non l'avremmo chiamata ricerca, giusto?"

Albert Einstein

10

Chapter 10

10. Conclusions and Future perspectives

The concept of Heritage is often linked to the one of conservation. The Oxford English Dictionary defines *"Heritage"* as *"property that is or may be inherited; an inheritance. "*; *"valued things such as historic buildings that have been passed down from previous generations"* and *"relating to things of historical or cultural value that are worthy of preservation"* [151].

It is important to emphasise that conservation is not the only strategy to be adopted, even in these contexts. As also recalled by Carlo Federici, one of the most excellent experts in the conservation of documentary material: *"Having established that we have to pass on to posterity the Cultural Heritage that we have inherited from our fathers, I would like to point out that we – as posterity - deserve the enjoyment of those testimonies of the past"* [152]. For this reason, and above all because of the intrinsic difficulty of fruition that derives from in-situ conservation (especially in the underwater Heritage), the ability to know how to plan interventions properly is of crucial importance for the enhancement and promotion that allow the use of the Heritage, without endangering the Heritage itself.

The founding principles of the Faro Convention [6] place the idea of Heritage as a common good, as a resource for well-being and social cohesion; it therefore appears a priority to enhance and make accessible the submerged Heritage to everybody, since by its nature it is not *"handy"* and is in some respects *"invisible"* but it can be rediscovered and made visible also thanks to the creation not only of submerged archaeological parks and itineraries for divers but also through the use of suggestive and evocative tools such as virtual reality and augmented reality, which allow the involvement and use by a wider audience.

Underwater objects and heritage need to be also studied by non-diving experts (historians, architects, chemical engineers, preservationists). Because conservation

in situ is often the only option, there is a growing need for documenting and mapping archaeological evidence of Underwater CH, such as shipwreck sites of different ages and also submerged coastal villages or cargoes of architectural construction materials that sank during transportation.

However, the marine environment should not be considered as an ultimate limit from a technical point of view; The cooperation between the government can overcome the difficulties, research institutions and universities, the allocation of a proper amount of funding and the establishment of training programmes for highly qualified personnel, will be able to fill the gaps between terrestrial and marine surveys.

This research aimed to develop a critical approach to provide methodologies and tools for underwater archaeological heritage documentation and fruition by the whole society. From the analysis of the state-of-the-art, it is clear that direct access and fruition of underwater wrecks is limited to a few cases and a few people. We need to reverse the perspective: besides bringing people to heritage, we should bring heritage to people using digital technologies.

The investigated aspects concern the definition of a procedure to enhance photogrammetric dataset that are sub-optimal or less-than ideal. Moreover, an in-depth study on the topic of geometric camera calibration and radiometric colour correction has been carried out, considering the different methods available in the literature. The thesis described the experience derived from application on the case study of the Torre Santa Sabina 1 wreck (Chapter §7). The several experimental chapter (§4 §5 and §6) developed before the case study constitute the rationale for a knowledge base (meant as the essential material for creating a repository of manuals, procedures, policies, best practices, reusable designs and code, etc) in the documentation of underwater cultural heritage, particularly on wrecks located in shallow water. The dissertation answered the main aim of designing a replicable procedure for conducting survey of UCH with geomatic techniques and methods in very shallow waters. Moreover, the methodology pointed to extended 3D model narrative and communicative use, referring to every kind of virtual-augmented-mixed reality, that can help the promotion and fruition of UCH, also remotely.

Some final consideration with a summary of the suggested acquisition practices and processing strategies are described in the next session, while possible activities and work to be carried out in the future are reported at the end of this chapter.

10.1 Final considerations and suggested procedures

- Before starting the survey, especially in vary shallow water scenarios, it might be useful to delimitate the area of the survey, both on the seabed with lanyard but also on the sea surface with appropriate buoy.
- When using markers underwater, it is better to avoid using white or shiny metal objects. These objects have, in fact, albedos that completely stand out against natural backgrounds and create artifacts in the context of colour reconstruction. Best is to use matte gray-ish markers, or the conical markers presented in this thesis.

- When acquiring images for a mosaic in the water, the operator should try not to make sharp turns. In other words, it is best to ensure that each image in the entire sequence is smoothly and generously connected with the next one. Otherwise, sharp turns will produce poor orientation outputs. While for images in air it is not so much of a problem, in an underwater setting the attenuation coefficient (which is responsible for the distortion of colours in the images) changes with imaging angle, and the relative angle between the sun and the camera. So, images that sharply change directions will have visibly different distortions, that even the modern photogrammetric software seems to handle that poorly.
- When making an underwater mosaic, it is better to cover at least an extra 10%-15% of the surveyed area, in all directions, outside of one's region of interest. This is needed because the edges of a model in photogrammetric software (such as Agisoft Metashape) usually have the least accurate registration, and in turn, result in colour correction artifacts around the edges. So, it is better to make a mosaic for a wider area than ones region of interest.
- For full image resolution depth maps in Agisoft, it is advisable to run alignment at high settings, then run gradual selection and eliminate the most inaccurate tie-points vigorously; dense cloud can be run at low image resolution, but Mesh should be generated in order to exploit the majority of the points of the dense cloud, and high number of faces. If there are floating artifacts after the mesh, it is strongly recommended to run gradual selection again and remove them. In the case of forward-facing scenes where blue water is showing, carefully mask them out and leave them out of the initial image orientation.
- As already discussed in the previous chapter, camera pre- and self-calibration are strongly advisable to obtain the best image orientation possible with the available data.
- Concerning the survey of GCPs, whenever it is not possible to operate within the network boundaries, it is strongly advised to work in RTK mode, coupling another GNSS antenna via radio to be used as a base in proximity of the shore.

10.2 Future works and activities

There are many open aspects and limits to bridge and overcome for the valorization, conservation, and promotion of the UCH. Below, a list of some possibilities of this thesis progress is reported. All points are related and connected to each other, and they could be further developed together in community and multidisciplinary projects:

- Analyzing the state-of-the-art and subsequent identification and cataloguing of the shipwrecks lying on the seabed to implement the

contents of ad-hoc webGIS and point out other possible case studies. Cataloguing of all the shipwrecks sites in the Mediterranean areas at various depths, considering their characteristics, location, lying conditions, preservation status, visible elements of the cargo, hull and onboard equipment, but also environmental conditions, in order to provide a picture as complete as possible of the "potential" of the site. Performing a data harmonization in a holistic and systemic perspective of a network of relationships, in accordance with the methodology of landscapes/seascapes archaeology; in this framework, creating a webGIS will be useful to gather information on different sites and locate them. The organization and the architecture of the web GIS will be conceived in accordance with a hierarchization of information not only internal (historic-archaeological-nautical) but also external, referred, for example, to the operational potential.

- Transferring the thesis core messages through a series of awareness-raising activities targeted to a general audience and strategic stakeholders at local, national and international levels. Sharing experiences and best practices by carrying out networking activities with similar initiatives.
- The definition of a proper methodology to exploit a web-based, mobile device-oriented XR application that allows users to experience Cultural Heritage in a new and interactive way; the user should be provided with XR experience, helpful additional information and suggestions to discover the UCH, and interact with the assets in a playful, gamified way.
- The introduction of pipelines to synthesize deep sea images using existing real world RGB-D benchmarks, in order to fill the lack of image datasets dedicated to deep sea vision evaluation [153].
- Development of scientific and technological solutions necessary to create an innovative measuring system of high-resolution data, both in terms of involved sensors and data processing procedures to overcome the specific problems related to the presence of the water medium. This could be a photogrammetric measuring system based on high-resolution digital cameras and acoustic sensors.
- The positioning solution proposed in this thesis could be further compared with lower-cost alternatives; data fusion and integration for underwater positioning can merge different self-built systems and consumer-grade sensors (optical, doppler velocity log, acoustic SBL, sonar, multibeam), along with the underwater geodetic network implementation: stable installations, accurate and redundant reference measurements, definition of technical procedures to acquire and process data. Data fusion from different sensors (visual and acoustics) will allow the archaeologists to respond to the needs of mapping, documenting, and exploiting the submerged archaeological cultural

heritage without neglecting the need of an accurate and affordable positioning system.

- Development of prototypes of ROVs and USVs for data acquisition, and the related algorithm optimization for improving the survey capabilities and navigation both underwater and on the water surface. The compelling idea is to try to exploit and develop a hybrid positioning approach, based both on the possibility of tracking the ROV using doppler sensors mounted on the ROV and using GNSS data retrieved from the USV. These additional techniques allow to increase the content of achievable information and, at the same time, to reduce the measurement errors due to environmental conditions (such as the presence of suspension and flare), which decrease the image quality and, therefore, sensibly reduce the accuracy and precision of the 3D model derived by the underwater surveying.

Other possible works can be born from the described methodology. This study and its applications are an exemplary replicable method. The hope is to spread this developed knowledge across different experts to generate new research and practical projects by ***sharing knowledge*** and working together with an ***interdisciplinary approach***.

The amount of data collected in the framework of this thesis will constitute the documentary basis on which to set future lines of research, allowing an organic vision of the problems and interpretative criticalities inherent in the historical reconstruction of this territory. It is an approach to documentation that wants to be global and contextually dynamic, that is, open to the revision and integration of data and the re-elaboration of the same.

The investigations in the coming years should further enrich our knowledge and contribute to the historical reconstruction of the Mediterranean region, but in general will provide fundamental data to understand the long process of interaction between man and the natural environment, in a landscape, i.e., the coastal landscape, constantly evolving.

"Science, my lad, is made up of mistakes,
but they are mistakes which it is useful to make,
because they lead little by little to the truth."
"La scienza, ragazzo mio, è fatta di errori,
ma di errori che è bene commettere,
perché un poco alla volta portano alla verità."

Jules Verne, A Journey to the Center of the Earth

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Appendix

A - International Conventions and Charts

This Appendix reports a list of the main international conventions and charts on the topic of the protection and management of the UCH, already discussed in Chapter 2.

Charter for the Protection and Management of the Archaeological Heritage on the Protection and Management of Underwater Cultural Heritage (1990)

ICOMOS

INTRODUCTION

It is widely recognised that a knowledge and understanding of the origins and development of human societies is of fundamental importance to humanity in identifying its cultural and social roots.

The archaeological heritage constitutes the basic record of past human activities. Its protection and proper management is therefore essential to enable archaeologists and other scholars to study and interpret it on behalf of and for the benefit of present and future generations.

The protection of this heritage cannot be based upon the application of archaeological techniques alone. It requires a wider basis of professional and scientific knowledge and skills. Some elements of the archaeological heritage are components of architectural structures and in such cases must be protected in accordance with the criteria for the protection of such structures laid down in the 1966 Venice Charter on the Conservation and Restoration of Monuments and Sites. Other elements of the archaeological heritage constitute part of the living traditions of indigenous peoples, and for such sites and monuments the participation of local cultural groups is essential for their protection and preservation.

For these and other reasons the protection of the archaeological heritage must be based upon effective collaboration between professionals from many disciplines. It also requires the co-operation of government authorities, academic researchers, private or public enterprise, and the general public. This charter therefore lays down principles relating to the different aspects of archaeological heritage management. These include the responsibilities of public authorities and legislators, principles relating to the professional performance of the processes of inventorisation, survey, excavation, documentation, research, maintenance, conservation, preservation, reconstruction, information, presentation, public access and use of the heritage, and

the qualification of professionals involved in the protection of the archaeological heritage.
The charter has been inspired by the success of the Venice Charter as guidelines and source of ideas for policies and practice of governments as well as scholars and professionals.
The charter has to reflect very basic principles and guidelines with global validity. For this reason it cannot take into account the specific problems and possibilities of regions or countries. The charter should therefore be supplemented at regional and national levels by further principles and guidelines for these needs.

Article 1 - Definition And Introduction
The "archaeological heritage" is that part of the material heritage in respect of which archaeological methods provide primary information. It comprises all vestiges of human existence and consists of places relating to all manifestations of human activity, abandoned structures, and remains of all kinds (including subterranean and underwater sites), together with all the portable cultural material associated with them.

Article 2. - Integrated Protection Policies
The archaeological heritage is a fragile and non-renewable cultural resource. Land use must therefore be controlled and developed in order to minimise the destruction of the archaeological heritage.
Policies for the protection of the archaeological heritage should constitute an integral component of policies relating to land use, development, and planning as well as of cultural, environmental and educational policies. The policies for the protection of the archaeological heritage should be kept under continual review, so that they stay up to date. The creation of archaeological reserves should form part of such policies.
The protection of the archaeological heritage should be integrated into planning policies at international, national, regional and local levels.
Active participation by the general public must form part of policies for the protection of the archaeological heritage. This is essential where the heritage of indigenous peoples is involved. Participation must be based upon access to the knowledge necessary for decision-making. The provision of information to the general public is therefore an important element in integrated protection.

Article 3. - Legislation And Economy
The protection of the archaeological heritage should be considered as a moral obligation upon all human beings; it is also a collective public responsibility. This obligation must be acknowledged through relevant legislation and the provision of adequate funds for the supporting programmes necessary for effective heritage management.
The archaeological heritage is common to all human society and it should therefore be the duty of every country to ensure that adequate funds are available for its protection.

Legislation should afford protection to the archaeological heritage that is appropriate to the needs, history, and traditions of each country and region, providing for in situ protection and research needs.
Legislation should be based on the concept of the archaeological heritage as the heritage of all humanity and of groups of peoples, and not restricted to any individual person or nation.
Legislation should forbid the destruction, degradation or alteration through changes of any archaeological site or monument or to their surroundings without the consent of the relevant archaeological authority.
Legislation should in principle require full archaeological investigation and documentation in cases where the destruction of the archaeological heritage is authorised.
Legislation should require, and make provision for, the proper maintenance, management and conservation of the archaeological heritage. Adequate legal sanctions should be prescribed in respect of violations of archaeological heritage legislation.
If legislation affords protection only to those elements of the archaeological heritage which are registered in a selective statutory inventory, provision should be made for the temporary protection of unprotected or newly discovered sites and monuments until an archaeological evaluation can be carried out.
Development projects constitute one of the greatest physical threats to the archaeological heritage. A duty for developers to ensure that archaeological heritage impact studies are carried out before development schemes are implemented, should therefore be embodied in appropriate legislation, with a stipulation that the costs of such studies are to be included in project costs. The principle should also be established in legislation that development schemes should be designed in such a way as to minimise their impact upon the archaeological heritage.

Article 4. - Survey
The protection of the archaeological heritage must be based upon the fullest possible knowledge of its extent and nature. General survey of archaeological resources is therefore an essential working tool in developing strategies for the protection of the archaeological heritage. Consequently, archaeological survey should be a basic obligation in the protection and management of the archaeological heritage.
At the same time, inventories constitute primary resource databases for scientific study and research. The compilation of inventories should therefore be regarded as a continuous, dynamic process. It follows that inventories should comprise information at various levels of significance and reliability, since even superficial knowledge can form the starting point for protectional measures.

Article 5. - Investigation

Archaeological knowledge is based principally on the scientific investigation of the archaeological heritage. Such investigation embraces the whole range of methods from non-destructive techniques through sampling to total excavation.

It must be an overriding principle that the gathering of information about the archaeological heritage should not destroy any more archaeological evidence than is necessary for the protectional or scientific objectives of the investigation. Non-destructive techniques, aerial and ground survey, and sampling should therefore be encouraged wherever possible, in preference to total excavation.

As excavation always implies the necessity of making a selection of evidence to be documented and preserved at the cost of losing other information and possibly even the total destruction of the monument, a decision to excavate should only be taken after thorough consideration.

Excavation should be carried out on sites and monuments threatened by development, land-use change, looting, or natural deterioration.

In exceptional cases, unthreatened sites may be excavated to elucidate research problems or to interpret them more effectively for the purpose of presenting them to the public. In such cases excavation must be preceded by thorough scientific evaluation of the significance of the site. Excavation should be partial, leaving a portion undisturbed for future research.

A report conforming to an agreed standard should be made available to the scientific community and should be incorporated in the relevant inventory within a reasonable period after the conclusion of the excavation.

Excavations should be conducted in accordance with the principles embodied in the 1956 UNESCO Recommendations on International Principles Applicable to Archaeological Excavations and with agreed international and national professional standards.

Article 6. - Maintenance And Conservation

The overall objective of archaeological heritage management should be the preservation of monuments and sites in situ, including proper long-term conservation and curation of all related records and collections etc. Any transfer of elements of the heritage to new locations represents a violation of the principle of preserving the heritage in its original context. This principle stresses the need for proper maintenance, conservation and management. It also asserts the principle that the archaeological heritage should not be exposed by excavation or left exposed after excavation if provision for its proper maintenance and management after excavation cannot be guaranteed.

Local commitment and participation should be actively sought and encouraged as a means of promoting the maintenance of the archaeological heritage. This principle is especially important when dealing with the heritage of indigenous peoples or local cultural groups. In some cases it may be appropriate to entrust responsibility for the protection and management of sites and monuments to indigenous peoples.

Owing to the inevitable limitations of available resources, active maintenance will have to be carried out on a selective basis. It should therefore be applied to a sample

of the diversity of sites and monuments, based upon a scientific assessment of their significance and representative character, and not confined to the more notable and visually attractive monuments.
The relevant principles of the 1956 UNESCO Recommendations should be applied in respect of the maintenance and conservation of the archaeological heritage.

Article 7. - Presentation, Information, Reconstruction
The presentation of the archaeological heritage to the general public is an essential method of promoting an understanding of the origins and development of modern societies. At the same time it is the most important means of promoting an understanding of the need for its protection.
Presentation and information should be conceived as a popular interpretation of the current state of knowledge, and it must therefore be revised frequently. It should take account of the multifaceted approaches to an understanding of the past.
Reconstructions serve two important functions: experimental research and interpretation. They should, however, be carried out with great caution, so as to avoid disturbing any surviving archaeological evidence, and they should take account of evidence from all sources in order to achieve authenticity. Where possible and appropriate, reconstructions should not be built immediately on the archaeological remains, and should be identifiable as such.

Article 8. - Professional Qualifications
High academic standards in many different disciplines are essential in the management of the archaeological heritage. The training of an adequate number of qualified professionals in the relevant fields of expertise should therefore be an important objective for the educational policies in every country. The need to develop expertise in certain highly specialised fields calls for international co-operation. Standards of professional training and professional conduct should be established and maintained.
The objective of academic archaeological training should take account of the shift in conservation policies from excavation to in situ preservation. It should also take into account the fact that the study of the history of indigenous peoples is as important in preserving and understanding the archaeological heritage as the study of outstanding monuments and sites.
The protection of the archaeological heritage is a process of continuous dynamic development. Time should therefore be made available to professionals working in this field to enable them to update their knowledge. Postgraduate training programmes should be developed with special emphasis on the protection and management of the archaeological heritage.

Article 9. - International Co-Operation
The archaeological heritage is the common heritage of all humanity. International co-operation is therefore essential in developing and maintaining standards in its management.

There is an urgent need to create international mechanisms for the exchange of information and experience among professionals dealing with archaeological heritage management. This requires the organisation of conferences, seminars, workshops, etc. at global as well as regional levels, and the establishment of regional centres for postgraduate studies. ICOMOS, through its specialised groups, should promote this aspect in its medium- and long-term planning.

International exchanges of professional staff should also be developed as a means of raising standards of archaeological heritage management.

Technical assistance programmes in the field of archaeological heritage management should be developed under the auspices of ICOMOS.

Charter on the Protection and Management of Underwater Cultural Heritage (1996)

ICOMOS

INTRODUCTION

This Charter is intended to encourage the protection and management of underwater cultural heritage in inland and inshore waters, in shallow seas and in the deep oceans. It focuses on the specific attributes and circumstances of cultural heritage under water and should be understood as a supplement to the ICOMOS Charter for the Protection and Management of Archaeological Heritage, 1990. The 1990 Charter defines the "archaeological heritage" as that part of the material heritage in respect of which archaeological methods provide primary information, comprising all vestiges of human existence and consisting of places relating to all manifestations of human activity, abandoned structures, and remains of all kinds, together with all the portable cultural material associated with them. For the purposes of this Charter underwater cultural heritage is understood to mean the archaeological heritage which is in, or has been removed from, an underwater environment. It includes submerged sites and structures, wreck-sites and wreckage and their archaeological and natural context.

By its very character the underwater cultural heritage is an international resource. A large part of the underwater cultural heritage is located in an international setting and derives from international trade and communication in which ships and their contents are lost at a distance from their origin or destination.

Archaeology is concerned with environmental conservation; in the language of resource management, underwater cultural heritage is both finite and non-renewable. If underwater cultural heritage is to contribute to our appreciation of the environment in the future, then we have to take individual and collective responsibility in the present for ensuring its continued survival.

Archaeology is a public activity; everybody is entitled to draw upon the past in informing their own lives, and every effort to curtail knowledge of the past is an infringement of personal autonomy. Underwater cultural heritage contributes to the formation of identity and can be important to people's sense of community. If managed sensitively, underwater cultural heritage can play a positive role in the promotion of recreation and tourism.

Archaeology is driven by research, it adds to knowledge of the diversity of human culture through the ages and it provides new and challenging ideas about life in the past. Such knowledge and ideas contribute to understanding life today and, thereby, to anticipating future challenges.

Many marine activities, which are themselves beneficial and desirable, can have unfortunate consequences for underwater cultural heritage if their effects are not foreseen.

Underwater cultural heritage may be threatened by construction work that alters the shore and seabed or alters the flow of current, sediment and pollutants. Underwater cultural heritage may also be threatened by insensitive exploitation of living and

non-living resources. Furthermore, inappropriate forms of access and the incremental impact of removing "souvenirs" can have a deleterious effect.
Many of these threats can be removed or substantially reduced by early consultation with archaeologists and by implementing mitigatory projects. This Charter is intended to assist in bringing a high standard of archaeological expertise to bear on such threats to underwater cultural heritage in a prompt and efficient manner.
Underwater cultural heritage is also threatened by activities that are wholly undesirable because they are intended to profit few at the expense of many. Commercial exploitation of underwater cultural heritage for trade or speculation is fundamentally incompatible with the protection and management of the heritage. This Charter is intended to ensure that all investigations are explicit in their aims, methodology and anticipated results so that the intention of each project is transparent to all.

Article 1 - Fundamental Principles
The preservation of underwater cultural heritage in situ should be considered as a first option.
Public access should be encouraged.
Non-destructive techniques, non-intrusive survey and sampling should be encouraged in preference to excavation.
Investigation must not adversely impact the underwater cultural heritage more than is necessary for the mitigatory or research objectives of the project.
Investigation must avoid unnecessary disturbance of human remains or venerated sites.
Investigation must be accompanied by adequate documentation.

Article 2 - Project Design
Prior to investigation a project must be prepared, taking into account:

- the mitigatory or research objectives of the project;
- the methodology to be used and the techniques to be employed;
- anticipated funding;
- the time-table for completing the project;
- the composition, qualifications, responsibility and experience of the investigating team;
- material conservation;
- site management and maintenance;
- arrangements for collaboration with museums and other institutions;
- documentation;
- health and safety;
- report preparation;
- deposition of archives, including underwater cultural heritage removed during investigation;
- dissemination, including public participation.

The project design should be revised and amended as necessary.

Investigation must be carried out in accordance with the project design. The project design should be made available to the archaeological community.

Article 3 - Funding
Adequate funds must be assured in advance of investigation to complete all stages of the project design including conservation, report preparation and dissemination. The project design should include contingency plans that will ensure conservation of underwater cultural heritage and supporting documentation in the event of any interruption in anticipated funding.
Project funding must not require the sale of underwater cultural heritage or the use of any strategy that will cause underwater cultural heritage and supporting documentation to be irretrievably dispersed.

Article 4 - Time-table
Adequate time must be assured in advance of investigation to complete all stages of the project design including conservation, report preparation and dissemination. The project design should include contingency plans that will ensure conservation of underwater cultural heritage and supporting documentation in the event of any interruption in anticipated timings.

Article 5- Research objectives, methodology and techniques
Research objectives and the details of the methodology and techniques to be employed must be set down in the project design. The methodology should accord with the research objectives of the investigation and the techniques employed must be as unintrusive as possible.
Post-fieldwork analysis of artefacts and documentation is integral to all investigation; adequate provision for this analysis must be made in the project design.

Article 6 - Qualifications, responsibility and experience
All persons on the investigating team must be suitably qualified and experienced for their project roles. They must be fully briefed and understand the work required.
All intrusive investigations of underwater cultural heritage will only be undertaken under the direction and control of a named underwater archaeologist with recognised qualifications and experience appropriate to the investigation.

Article 7 - Preliminary investigation
All intrusive investigations of underwater cultural heritage must be preceded and informed by a site assessment that evaluates the vulnerability, significance and potential of the site.
The site assessment must encompass background studies of available historical and archaeological evidence, the archaeological and environmental characteristics of the site and the consequences of the intrusion for the long term stability of the area affected by investigations.

Article 8 - Documentation
All investigation must be thoroughly documented in accordance with current professional standards of archaeological documentation.
Documentation must provide a comprehensive record of the site, which includes the provenance of underwater cultural heritage moved or removed in the course of investigation, field notes, plans and drawings, photographs and records in other media.

Article 9 - Material conservation
The material conservation programme must provide for treatment of archaeological remains during investigation, in transit and in the long term.
Material conservation must be carried out in accordance with current professional standards.

Article 10 - Site management and maintenance
A programme of site management must be prepared, detailing measures for protecting and managing in situ underwater cultural heritage in the course of an upon termination of fieldwork. The programme should include public information, reasonable provision for site stabilisation, monitoring and protection against interference. Public access to in situ underwater cultural heritage should be promoted, except where access is incompatible with protection and management.

Article 11 - Health and safety
The health and safety of the investigating team and third parties is paramount. All persons on the investigating team must work according to a safety policy that satisfies relevant statutory and professional requirements and is set out in the project design.

Article 12 - Reporting
Interim reports should be made available according to a time-table set out in the project design, and deposited in relevant public records.
Reports should include:

- an account of the objectives;
- an account of the methodology and techniques employed;
- an account of the results achieved;
- recommendations concerning future research, site management and curation of underwater cultural heritage removed during the investigation.

Article 13 - Curation
The project archive, which includes underwater cultural heritage removed during investigation and a copy of all supporting documentation, must be deposited in an institution that can provide for public access and permanent curation of the archive.
Arrangements for deposition of the archive should be agreed before investigation

commences, and should be set out in the project design. The archive should be prepared in accordance with current professional standards.
The scientific integrity of the project archive must be assured; deposition in a number of institutions must not preclude reassembly to allow further research. Underwater cultural heritage is not to be traded as items of commercial value.

Article 14 - Dissemination
Public awareness of the results of investigations and the significance of underwater cultural heritage should be promoted through popular presentation in a range of media. Access to such presentations by a wide audience should not be prejudiced by high charges.
Co-operation with local communities and groups is to be encouraged, as is co-operation with communities and groups that are particularly associated with the underwater cultural heritage concerned. It is desirable that investigations proceed with the consent and endorsement of such communities and groups.
The investigation team will seek to involve communities and interest groups in investigations to the extent that such involvement is compatible with protection and management. Where practical, the investigation team should provide opportunities for the public to develop archaeological skills through training and education.
Collaboration with museums and other institutions is to be encouraged. Provision for visits, research and reports by collaborating institutions should be made in advance of investigation.
A final synthesis of the investigation must be made available as soon as possible, having regard to the complexity of the research, and deposited in relevant public records.

Article 15 - International co-operation
International co-operation is essential for protection and management of underwater cultural heritage and should be promoted in the interests of high standards of investigation and research. International co-operation should be encouraged in order to make effective use of archaeologists and other professionals who are specialised in investigations of underwater cultural heritage. Programmes for exchange of professionals should be considered as a means of disseminating best practice.

Convention on the Protection of the Underwater Cultural Heritage (2001)

The Protection of the Underwater Cultural Heritage

Article 1 – Definitions

For the purposes of this Convention:

1. (a) "Underwater cultural heritage" means all traces of human existence having a cultural, historical or archaeological character which have been partially or totally under water, periodically or continuously, for at least 100 years such as:

(i) sites, structures, buildings, artefacts and human remains, together with their archaeological and natural context;

(ii) vessels, aircraft, other vehicles or any part thereof, their cargo or other contents, together with their archaeological and natural context; and

(iii) objects of prehistoric character.

(b) Pipelines and cables placed on the seabed shall not be considered as underwater cultural heritage.

(c) Installations other than pipelines and cables, placed on the seabed and still in use, shall not be considered as underwater cultural heritage.

2. (a) "States Parties" means States which have consented to be bound by this Convention and for which this Convention is in force.

(b) This Convention applies mutatis mutandis to those territories referred to in Article 26, paragraph 2(b), which become Parties to this Convention in accordance with the conditions set out in that paragraph, and to that extent "States Parties" refers to those territories.

3. "UNESCO" means the United Nations Educational, Scientific and Cultural Organization.

4. "Director-General" means the Director-General of UNESCO.

5. "Area" means the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction.

6. "Activities directed at underwater cultural heritage" means activities having underwater cultural heritage as their primary object and which may, directly or indirectly, physically disturb or otherwise damage underwater cultural heritage.

7. "Activities incidentally affecting underwater cultural heritage" means activities which, despite not having underwater cultural heritage as their primary object or one of their objects, may physically disturb or otherwise damage underwater cultural heritage.

8. "State vessels and aircraft" means warships, and other vessels or aircraft that were owned or operated by a State and used, at the time of sinking, only for government non-commercial purposes, that are identified as such and that meet the definition of underwater cultural heritage.

9. "Rules" means the Rules concerning activities directed at underwater cultural heritage, as referred to in Article 33 of this Convention.

Article 2 – Objectives and general principles

1. This Convention aims to ensure and strengthen the protection of underwater cultural heritage.
2. States Parties shall cooperate in the protection of underwater cultural heritage.
3. States Parties shall preserve underwater cultural heritage for the benefit of humanity in conformity with the provisions of this Convention.
4. States Parties shall, individually or jointly as appropriate, take all appropriate measures in conformity with this Convention and with international law that are necessary to protect underwater cultural heritage, using for this purpose the best practicable means at their disposal and in accordance with their capabilities.
5. The preservation in situ of underwater cultural heritage shall be considered as the first option before allowing or engaging in any activities directed at this heritage.
6. Recovered underwater cultural heritage shall be deposited, conserved and managed in a manner that ensures its long-term preservation.
7. Underwater cultural heritage shall not be commercially exploited.
8. Consistent with State practice and international law, including the United Nations Convention on the Law of the Sea, nothing in this Convention shall be interpreted as modifying the rules of international law and State practice pertaining to sovereign immunities, nor any State's rights with respect to its State vessels and aircraft.
9. States Parties shall ensure that proper respect is given to all human remains located in maritime waters.
10. Responsible non-intrusive access to observe or document in situ underwater cultural heritage shall be encouraged to create public awareness, appreciation, and protection of the heritage except where such access is incompatible with its protection and management.
11. No act or activity undertaken on the basis of this Convention shall constitute grounds for claiming, contending or disputing any claim to national sovereignty or jurisdiction.

Article 3 – Relationship between this Convention and the United Nations Convention on the Law of the Sea

Nothing in this Convention shall prejudice the rights, jurisdiction and duties of States under international law, including the United Nations Convention on the Law of the Sea. This Convention shall be interpreted and applied in the context of and in a manner consistent with international law, including the United Nations Convention on the Law of the Sea.

Article 4 – Relationship to law of salvage and law of finds

Any activity relating to underwater cultural heritage to which this Convention applies shall not be subject to the law of salvage or law of finds, unless it:
(a) is authorized by the competent authorities, and
(b) is in full conformity with this Convention, and

(c) ensures that any recovery of the underwater cultural heritage achieves its maximum protection.

Article 5 – Activities incidentally affecting underwater cultural heritage
Each State Party shall use the best practicable means at its disposal to prevent or mitigate any adverse effects that might arise from activities under its jurisdiction incidentally affecting underwater cultural heritage.

Article 6 – Bilateral, regional or other multilateral agreements
1. States Parties are encouraged to enter into bilateral, regional or other multilateral agreements or develop existing agreements, for the preservation of underwater cultural heritage. All such agreements shall be in full conformity with the provisions of this Convention and shall not dilute its universal character. States may, in such agreements, adopt rules and regulations which would ensure better protection of underwater cultural heritage than those adopted in this Convention.
2. The Parties to such bilateral, regional or other multilateral agreements may invite States with a verifiable link, especially a cultural, historical or archaeological link, to the underwater cultural heritage concerned to join such agreements.
3. This Convention shall not alter the rights and obligations of States Parties regarding the protection of sunken vessels, arising from other bilateral, regional or other multilateral agreements concluded before its adoption, and, in particular, those that are in conformity with the purposes of this Convention.

Article 7 – Underwater cultural heritage in internal waters, archipelagic waters and territorial sea
1. States Parties, in the exercise of their sovereignty, have the exclusive right to regulate and authorize activities directed at underwater cultural heritage in their internal waters, archipelagic waters and territorial sea.
2. Without prejudice to other international agreements and rules of international law regarding the protection of underwater cultural heritage, States Parties shall require that the Rules be applied to activities directed at underwater cultural heritage in their internal waters, archipelagic waters and territorial sea.
3. Within their archipelagic waters and territorial sea, in the exercise of their sovereignty and in recognition of general practice among States, States Parties, with a view to cooperating on the best methods of protecting State vessels and aircraft, should inform the flag State Party to this Convention and, if applicable, other States with a verifiable link, especially a cultural, historical or archaeological link, with respect to the discovery of such identifiable State vessels and aircraft.

Article 8 – Underwater cultural heritage in the contiguous zone
Without prejudice to and in addition to Articles 9 and 10, and in accordance with Article 303, paragraph 2, of the United Nations Convention on the Law of the Sea, States Parties may regulate and authorize activities directed at underwater cultural heritage within their contiguous zone. In so doing, they shall require that the Rules be applied.

Article 9 – Reporting and notification in the exclusive economic zone and on the continental shelf

1. All States Parties have a responsibility to protect underwater cultural heritage in the exclusive economic zone and on the continental shelf in conformity with this Convention.

Accordingly:

(a) a State Party shall require that when its national, or a vessel flying its flag, discovers or intends to engage in activities directed at underwater cultural heritage located in its exclusive economic zone or on its continental shelf, the national or the master of the vessel shall report such discovery or activity to it;

(b) in the exclusive economic zone or on the continental shelf of another State Party:

(i) States Parties shall require the national or the master of the vessel to report such discovery or activity to them and to that other State Party;

(ii) alternatively, a State Party shall require the national or master of the vessel to report such discovery or activity to it and shall ensure the rapid and effective transmission of such reports to all other States Parties.

2. On depositing its instrument of ratification, acceptance, approval or accession, a State Party shall declare the manner in which reports will be transmitted under paragraph 1(b) of this Article.

3. A State Party shall notify the Director-General of discoveries or activities reported to it under paragraph 1 of this Article.

4. The Director-General shall promptly make available to all States Parties any information notified to him under paragraph 3 of this Article.

5. Any State Party may declare to the State Party in whose exclusive economic zone or on whose continental shelf the underwater cultural heritage is located its interest in being consulted on how to ensure the effective protection of that underwater cultural heritage. Such declaration shall be based on a verifiable link, especially a cultural, historical or archaeological link, to the underwater cultural heritage concerned.

Article 10 – Protection of underwater cultural heritage in the exclusive economic zone and on the continental shelf

1. No authorization shall be granted for an activity directed at underwater cultural heritage located in the exclusive economic zone or on the continental shelf except in conformity with the provisions of this Article.

2. A State Party in whose exclusive economic zone or on whose continental shelf underwater cultural heritage is located has the right to prohibit or authorize any activity directed at such heritage to prevent interference with its sovereign rights or jurisdiction as provided for by international law including the United Nations Convention on the Law of the Sea.

3. Where there is a discovery of underwater cultural heritage or it is intended that activity shall be directed at underwater cultural heritage in a State Party's exclusive economic zone or on its continental shelf, that State Party shall:

(a) consult all other States Parties which have declared an interest under Article 9, paragraph 5, on how best to protect the underwater cultural heritage;
(b) coordinate such consultations as "Coordinating State", unless it expressly declares that it does not wish to do so, in which case the States Parties which have declared an interest under Article 9, paragraph 5, shall appoint a Coordinating State.
4. Without prejudice to the duty of all States Parties to protect underwater cultural heritage by way of all practicable measures taken in accordance with international law to prevent immediate danger to the underwater cultural heritage, including looting, the Coordinating State may take all practicable measures, and/or issue any necessary authorizations in conformity with this Convention and, if necessary prior to consultations, to prevent any immediate danger to the underwater cultural heritage, whether arising from human activities or any other cause, including looting. In taking such measures assistance may be requested from other States Parties.
5. The Coordinating State:
(a) shall implement measures of protection which have been agreed by the consulting States, which include the Coordinating State, unless the consulting States, which include the Coordinating State, agree that another State Party shall implement those measures;
(b) shall issue all necessary authorizations for such agreed measures in conformity with the Rules, unless the consulting States, which include the Coordinating State, agree that another State Party shall issue those authorizations;
(c) may conduct any necessary preliminary research on the underwater cultural heritage and shall issue all necessary authorizations therefore, and shall promptly inform the Director-General of the results, who in turn will make such information promptly available to other States Parties.
6. In coordinating consultations, taking measures, conducting preliminary research and/or issuing authorizations pursuant to this Article, the Coordinating State shall act on behalf of the States Parties as a whole and not in its own interest. Any such action shall not in itself constitute a basis for the assertion of any preferential or jurisdictional rights not provided for in international law, including the United Nations Convention on the Law of the Sea.
7. Subject to the provisions of paragraphs 2 and 4 of this Article, no activity directed at State vessels and aircraft shall be conducted without the agreement of the flag State and the collaboration of the Coordinating State.

Article 11 – Reporting and notification in the Area
1. States Parties have a responsibility to protect underwater cultural heritage in the Area in conformity with this Convention and Article 149 of the United Nations Convention on the Law of the Sea. Accordingly when a national, or a vessel flying the flag of a State Party, discovers or intends to engage in activities directed at underwater cultural heritage located in the Area, that State Party shall require its national, or the master of the vessel, to report such discovery or activity to it.
2. States Parties shall notify the Director-General and the Secretary-General of the International Seabed Authority of such discoveries or activities reported to them.

3. The Director-General shall promptly make available to all States Parties any such information supplied by States Parties.
4. Any State Party may declare to the Director-General its interest in being consulted on how to ensure the effective protection of that underwater cultural heritage. Such declaration shall be based on a verifiable link to the underwater cultural heritage concerned, particular regard being paid to the preferential rights of States of cultural, historical or archaeological origin.

Article 12 – Protection of underwater cultural heritage in the Area
1. No authorization shall be granted for any activity directed at underwater cultural heritage located in the Area except in conformity with the provisions of this Article.
2. The Director-General shall invite all States Parties which have declared an interest under Article 11, paragraph 4, to consult on how best to protect the underwater cultural heritage, and to appoint a State Party to coordinate such consultations as the "Coordinating State". The Director-General shall also invite the International Seabed Authority to participate in such consultations.
3. All States Parties may take all practicable measures in conformity with this Convention, if necessary prior to consultations, to prevent any immediate danger to the underwater cultural heritage, whether arising from human activity or any other cause including looting.
4. The Coordinating State shall:
(a) implement measures of protection which have been agreed by the consulting States, which include the Coordinating State, unless the consulting States, which include the Coordinating State, agree that another State Party shall implement those measures; and
(b) issue all necessary authorizations for such agreed measures, in conformity with this Convention, unless the consulting States, which include the Coordinating State, agree that another State Party shall issue those authorizations.
5. The Coordinating State may conduct any necessary preliminary research on the underwater cultural heritage and shall issue all necessary authorizations therefor, and shall promptly inform the Director-General of the results, who in turn shall make such information available to other States Parties.
6. In coordinating consultations, taking measures, conducting preliminary research, and/or issuing authorizations pursuant to this Article, the Coordinating State shall act for the benefit of humanity as a whole, on behalf of all States Parties. Particular regard shall be paid to the preferential rights of States of cultural, historical or archaeological origin in respect of the underwater cultural heritage concerned.
7. No State Party shall undertake or authorize activities directed at State vessels and aircraft in the Area without the consent of the flag State.

Article 13 – Sovereign immunity
Warships and other government ships or military aircraft with sovereign immunity, operated for non-commercial purposes, undertaking their normal mode of operations, and not engaged in activities directed at underwater cultural heritage, shall not be obliged to report discoveries of underwater cultural heritage under

Articles 9, 10, 11 and 12 of this Convention. However States Parties shall ensure, by the adoption of appropriate measures not impairing the operations or operational capabilities of their warships or other government ships or military aircraft with sovereign immunity operated for non-commercial purposes, that they comply, as far as is reasonable and practicable, with Articles 9, 10, 11 and 12 of this Convention.

Article 14 – Control of entry into the territory, dealing and possession
States Parties shall take measures to prevent the entry into their territory, the dealing in, or the possession of, underwater cultural heritage illicitly exported and/or recovered, where recovery was contrary to this Convention.

Article 15 – Non-use of areas under the jurisdiction of States Parties
States Parties shall take measures to prohibit the use of their territory, including their maritime ports, as well as artificial islands, installations and structures under their exclusive jurisdiction or control, in support of any activity directed at underwater cultural heritage which is not in conformity with this Convention.

Article 16 – Measures relating to nationals and vessels
States Parties shall take all practicable measures to ensure that their nationals and vessels flying their flag do not engage in any activity directed at underwater cultural heritage in a manner not in conformity with this Convention.

Article 17 – Sanctions
1. Each State Party shall impose sanctions for violations of measures it has taken to implement this Convention.
2. Sanctions applicable in respect of violations shall be adequate in severity to be effective in securing compliance with this Convention and to discourage violations wherever they occur and shall deprive offenders of the benefit deriving from their illegal activities.
3. States Parties shall cooperate to ensure enforcement of sanctions imposed under this Article.

Article 18 – Seizure and disposition of underwater cultural heritage
1. Each State Party shall take measures providing for the seizure of underwater cultural heritage in its territory that has been recovered in a manner not in conformity with this Convention.
2. Each State Party shall record, protect and take all reasonable measures to stabilize underwater cultural heritage seized under this Convention.
3. Each State Party shall notify the Director-General and any other State with a verifiable link, especially a cultural, historical or archaeological link, to the underwater cultural heritage concerned of any seizure of underwater cultural heritage that it has made under this Convention.
4. A State Party which has seized underwater cultural heritage shall ensure that its disposition be for the public benefit, taking into account the need for conservation

and research; the need for reassembly of a dispersed collection; the need for public access, exhibition and education; and the interests of any State with a verifiable link, especially a cultural, historical or archaeological link, in respect of the underwater cultural heritage concerned.

Article 19 – Cooperation and information-sharing

1. States Parties shall cooperate and assist each other in the protection and management of underwater cultural heritage under this Convention, including, where practicable, collaborating in the investigation, excavation, documentation, conservation, study and presentation of such heritage.
2. To the extent compatible with the purposes of this Convention, each State Party undertakes to share information with other States Parties concerning underwater cultural heritage, including discovery of heritage, location of heritage, heritage excavated or recovered contrary to this Convention or otherwise in violation of international law, pertinent scientific methodology and technology, and legal developments relating to such heritage.
3. Information shared between States Parties, or between UNESCO and States Parties, regarding the discovery or location of underwater cultural heritage shall, to the extent compatible with their national legislation, be kept confidential and reserved to competent authorities of States Parties as long as the disclosure of such information might endanger or otherwise put at risk the preservation of such underwater cultural heritage.
4. Each State Party shall take all practicable measures to disseminate information, including where feasible through appropriate international databases, about underwater cultural heritage excavated or recovered contrary to this Convention or otherwise in violation of international law.

Article 20 – Public awareness

Each State Party shall take all practicable measures to raise public awareness regarding the value and significance of underwater cultural heritage and the importance of protecting it under this Convention.

Article 21 – Training in underwater archaeology

States Parties shall cooperate in the provision of training in underwater archaeology, in techniques for the conservation of underwater cultural heritage and, on agreed terms, in the transfer of technology relating to underwater cultural heritage.

Article 22 – Competent authorities

1. In order to ensure the proper implementation of this Convention, States Parties shall establish competent authorities or reinforce the existing ones where appropriate, with the aim of providing for the establishment, maintenance and updating of an inventory of underwater cultural heritage, the effective protection, conservation, presentation and management of underwater cultural heritage, as well as research and education.

2. States Parties shall communicate to the Director-General the names and addresses of their competent authorities relating to underwater cultural heritage.

Article 23 – Meetings of States Parties

1. The Director-General shall convene a Meeting of States Parties within one year of the entry into force of this Convention and thereafter at least once every two years. At the request of a majority of States Parties, the Director-General shall convene an Extraordinary Meeting of States Parties.
2. The Meeting of States Parties shall decide on its functions and responsibilities.
3. The Meeting of States Parties shall adopt its own Rules of Procedure.
4. The Meeting of States Parties may establish a Scientific and Technical Advisory Body composed of experts nominated by the States Parties with due regard to the principle of equitable geographical distribution and the desirability of a gender balance.
5. The Scientific and Technical Advisory Body shall appropriately assist the Meeting of States Parties in questions of a scientific or technical nature regarding the implementation of the Rules.

Article 24 – Secretariat for this Convention

1. The Director-General shall be responsible for the functions of the Secretariat for this Convention.
2. The duties of the Secretariat shall include:
(a) organizing Meetings of States Parties as provided for in Article 23, paragraph 1; and
(b) assisting States Parties in implementing the decisions of the Meetings of States Parties.

Article 25 – Peaceful settlement of disputes

1. Any dispute between two or more States Parties concerning the interpretation or application of this Convention shall be subject to negotiations in good faith or other peaceful means of settlement of their own choice.
2. If those negotiations do not settle the dispute within a reasonable period of time, it may be submitted to UNESCO for mediation, by agreement between the States Parties concerned.
3. If mediation is not undertaken or if there is no settlement by mediation, the provisions relating to the settlement of disputes set out in Part XV of the United Nations Convention on the Law of the Sea apply mutatis mutandis to any dispute between States Parties to this Convention concerning the interpretation or application of this Convention, whether or not they are also Parties to the United Nations Convention on the Law of the Sea.
4. Any procedure chosen by a State Party to this Convention and to the United Nations Convention on the Law of the Sea pursuant to Article 287 of the latter shall apply to the settlement of disputes under this Article, unless that State Party, when ratifying, accepting, approving or acceding to this Convention, or at any time thereafter, chooses another procedure pursuant to Article 287 for the purpose of the settlement of disputes arising out of this Convention.

5. A State Party to this Convention which is not a Party to the United Nations Convention on the Law of the Sea, when ratifying, accepting, approving or acceding to this Convention or at any time thereafter shall be free to choose, by means of a written declaration, one or more of the means set out in Article 287, paragraph 1, of the United Nations Convention on the Law of the Sea for the purpose of settlement of disputes under this Article. Article 287 shall apply to such a declaration, as well as to any dispute to which such State is party, which is not covered by a declaration in force. For the purpose of conciliation and arbitration, in accordance with Annexes V and VII of the United Nations Convention on the Law of the Sea, such State shall be entitled to nominate conciliators and arbitrators to be included in the lists referred to in Annex V, Article 2, and Annex VII, Article 2, for the settlement of disputes arising out of this Convention.

Article 26 – Ratification, acceptance, approval or accession

1. This Convention shall be subject to ratification, acceptance or approval by Member States of UNESCO.
2. This Convention shall be subject to accession:
(a) by States that are not members of UNESCO but are members of the United Nations or of a specialized agency within the United Nations system or of the International Atomic Energy Agency, as well as by States Parties to the Statute of the International Court of Justice and any other State invited to accede to this Convention by the General Conference of UNESCO;
(b) by territories which enjoy full internal self-government, recognized as such by the United Nations, but have not attained full independence in accordance with General Assembly resolution 1514 (XV) and which have competence over the matters governed by this Convention, including the competence to enter into treaties in respect of those matters.
3. The instruments of ratification, acceptance, approval or accession shall be deposited with the Director-General.

Article 27 – Entry into force

This Convention shall enter into force three months after the date of the deposit of the twentieth instrument referred to in Article 26, but solely with respect to the twenty States or territories that have so deposited their instruments. It shall enter into force for each other State or territory three months after the date on which that State or territory has deposited its instrument.

Article 28 – Declaration as to inland waters

When ratifying, accepting, approving or acceding to this Convention or at any time thereafter, any State or territory may declare that the Rules shall apply to inland waters not of a maritime character.

Article 29 – Limitations to geographical scope

At the time of ratifying, accepting, approving or acceding to this Convention, a State or territory may make a declaration to the depositary that this Convention shall

not be applicable to specific parts of its territory, internal waters, archipelagic waters or territorial sea, and shall identify therein the reasons for such declaration. Such State shall, to the extent practicable and as quickly as possible, promote conditions under which this Convention will apply to the areas specified in its declaration, and to that end shall also withdraw its declaration in whole or in part as soon as that has been achieved.

Article 30 – Reservations

With the exception of Article 29, no reservations may be made to this Convention.

Article 31 – Amendments

1. A State Party may, by written communication addressed to the Director-General, propose amendments to this Convention. The Director-General shall circulate such communication to all States Parties. If, within six months from the date of the circulation of the communication, not less than one half of the States Parties reply favourably to the request, the Director-General shall present such proposal to the next Meeting of States Parties for discussion and possible adoption.
2. Amendments shall be adopted by a two-thirds majority of States Parties present and voting.
3. Once adopted, amendments to this Convention shall be subject to ratification, acceptance, approval or accession by the States Parties.
4. Amendments shall enter into force, but solely with respect to the States Parties that have ratified, accepted, approved or acceded to them, three months after the deposit of the instruments referred to in paragraph 3 of this Article by two thirds of the States Parties. Thereafter, for each State or territory that ratifies, accepts, approves or accedes to it, the amendment shall enter into force three months after the date of deposit by that Party of its instrument of ratification, acceptance, approval or accession.
5. A State or territory which becomes a Party to this Convention after the entry into force of amendments in conformity with paragraph 4 of this Article shall, failing an expression of different intention by that State or territory, be considered:
(a) as a Party to this Convention as so amended; and
(b) as a Party to the unamended Convention in relation to any State Party not bound by the amendment.

Article 32 – Denunciation

1. A State Party may, by written notification addressed to the Director-General, denounce this Convention.
2. The denunciation shall take effect twelve months after the date of receipt of the notification, unless the notification specifies a later date.
3. The denunciation shall not in any way affect the duty of any State Party to fulfil any obligation embodied in this Convention to which it would be subject under international law independently of this Convention.

Article 33 – The Rules
The Rules annexed to this Convention form an integral part of it and, unless expressly provided otherwise, a reference to this Convention includes a reference to the Rules.

Article 34 – Registration with the United Nations
In conformity with Article 102 of the Charter of the United Nations, this Convention shall be registered with the Secretariat of the United Nations at the request of the Director-General.

Article 35 – Authoritative texts
This Convention has been drawn up in Arabic, Chinese, English, French, Russian and Spanish, the six texts being equally authoritative.

B – Algorithms and codes

This Appendix reports the description of the main algorithms and codes used in the framework of this PhD thesis.

LAB colour correction

This is an excerpt from the scientific paper *"Bianco, G., Muzzupappa, M., Bruno, F., Garcia, R., and Neumann, L.: A NEW COLOR CORRECTION METHOD FOR UNDERWATER IMAGING, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-5/W5, 25–32, https://doi.org/10.5194/isprsarchives-XL-5-W5-25-2015, 2015."*

The proposed method aims to perform a color correction that closely mimics the performance of the visual system. For this reason we have chosen to adopt a perceptual color space as we described below. The $l\alpha\beta$ color space has been proposed by Ruderman et al. (1998) studying the human eye perception of natural images. It is composed of a luminance component l (achromatic) and two opponent color components α and β, as in the human color visual mechanism. Until now this color space has been only used for color transfer applications. In particular, Reynard et al. (2001) have showed that it can be used for hue correction, presenting the results obtained to correct an image with uniform illumination, under red, tungsten, and blue illuminants. Therefore color correction by using this color space is not yet deeply investigated, especially in underwater imaging.

Here, we describe $l\alpha\beta$ space following the transformations matrices suggested in (Reynard et al., 2001), that we have reported in Appendix for the reader's convenience. The several steps to convert RGB coordinates in $l\alpha\beta$ space are reported in the flow-chart of Figure 3. First of all, RGB image has to be corrected by the non linearity (gamma correction), to work with linear RGB coordinates. This step is very important and necessary to pass to the next: conversion in the XYZ tristimulus values. This conversion is achieved by multiplying the linear RGB coordinates $f_i(m,n)$ with $T_{xyz,ij}$ matrix, where the i and j are the matrix indeces in according to the Einstein notation:

$$x_j(m,n) = T_{xyz,ij}\, f_i(m,n) \tag{3}$$

where x_j is the vector of coordinates in XYZ space and (m,n) are the pixel coordinates. From this device-independent XYZ space, we convert the image to LMS space ($l_j(m,n)$ vector) using the $T_{lms,ij}$ matrix:

$$l_j(m,n) = T_{lms,ij}\, x_i(m,n) \tag{4}$$

Now, we transform the data in logarithmic space:

$$l_{log,j}(m,n) = \log l_i(m,n) \tag{5}$$

and finally we can proceed to decorrelate these axes as suggested by Ruderman et al. (1998), by using Principal Components Analysis (PCA), that means multiply $l_{log,j}(m,n)$ vector by the decorrelation matrix $T_{pca,ij}$:

$$l_{l\alpha\beta,j}(m,n) = T_{pca,ij}\, l_{log,i}(m,n) \tag{6}$$

Thus, we have obtained the vector coordinates $l_{l\alpha\beta,j}(m,n)$ of image in $l\alpha\beta$ space. The three resulting principal axes are orthogonal, and it is found that the first axis l represents an achromatic channel, while the second (α) and the third (β) channels are chromatic yellow-blue and red-green opponent channels:

- *luminance* : Achromatic $\propto (r+g+b)$
- α : Yellow-blue $\propto (r+g-b)$
- β : Red-green $\propto (r-g)$

Hence, in this space the color components are decoupled from the luminance, that is, the brightness level of the scene. The $l\alpha\beta$ is a perceptual color space, that is, based on the response functions of the cones in the retina of the eye, because it is derived by the perceptual color space LMS (Long, Medium, Short) mostly used in psychometric research.

In this section we describe the color correction method that we propose for underwater imaging. The method is based on the assumptions of gray world and uniform illumination of the scene, as explained in the previous section. Thus, we formulate the Eq. 2 in $l\alpha\beta$ space. Let us express the RGB color coordinates $f_i(m,n)$ in the LMS space ($l_i(m,n)$) as:

$$l_i(m,n) = D_{ij} \cdot f_j(m,n); \tag{7}$$

where D_{ij} is the transformation matrix obtained as product of the two transformation matrices $D_{ij} = T_{xyz,ij} \cdot T_{lms,ij}$. Expressing the terms of Eq. 2 in LMS space in according to Eq. 7 and computing the logarithm of both sides of the Eq. 2, we have:

$$\log l_i^*(m,n) = \log \frac{l_i(m,n)}{\overline{l_i}}; \tag{8}$$

where $l^*_{lms,i}(m,n)$ are the corrected coordinates in LMS space of $f_i^*(m,n)$, $l_{lms,i}(m,n)$ are the coordinates of $f_i(m,n)$ and $\overline{l_i}$ its average in according to gray-world assumption. Applying the logarithm quotient rule and multiplying by the $T_{pca,ij}$ matrix, we obtain:

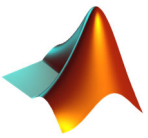
$$T_{pca,ij} \log l_i^*(m,n) = T_{pca,ij} \log l_i(m,n) - T_{pca,ij} \log \overline{l}_i; \tag{9}$$

Each term in this equation is similar to Eq. 6, that states the coordinates conversion in the $l\alpha\beta$ space. Thus, we have obtained the desired expression of Eq. 2 in $l\alpha\beta$ coordinates:

$$l^*_{l\alpha\beta,i}(m,n) = l_{l\alpha\beta,i}(m,n) - \overline{l}_{l\alpha\beta,i}; \tag{10}$$

where $l^*_{l\alpha\beta,i}(m,n)$ are the corrected coordinates, $l_{l\alpha\beta,i}(m,n)$ the component of RGB image and $\overline{l}_{l\alpha\beta,i}$ its average. In order to correct color casts of an image the α and β components ($i \in \{2,3\}$) must be changed, as suggested in (Reynard et al., 2001), while the luminance component remains unchanged, at least regarding the translation of the mean, but it will be elaborated in a different way, to improve the contrast image, as described in the next section. After color correction processing we must transfer the result back to RGB to display it by applying the inverse operations. It has to be noted that the white point ($\{1, 1, 1\}$ in RGB space) has $\{0, 0, 0\}$ coordinates in $l\alpha\beta$ space. This means that the method performs a shift of α and β components respect to the coordinates $\{0, 0\}$, putting the distributions of these coordinates around the white point. Correcting image casts respect to the white point in this space seems to be more realistic respect to adjust the distributions of color channels around a gray point as in RGB space. We can conclude that the gray-world assumption is transformed in a "white-world" assumption in the $l\alpha\beta$ space.

Contrast Limited Automatic Histogram Equalization (CLAHE)



```
%{
Author: Prajesh Jhumkhawala
%}

function[]=CLAHE(filename)
%{
    This is an adaptation to the original histogram equalization
method.
    This approach was suggested by Stephen M. Pizer, R. Eugene
Johnston, James P. Ericksen,
    Bonnie C. Yankaskas, Keith E. Muller in the paper Contrast-
Limited Adaptive Histogram Equalization:
    Speed and Effectiveness
(http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=109340&url=
http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3
D109340).

%}

close all;
%Reading the image, resizing the image and then converting it to
gray-scale
img=imread(filename);
resized_image=imresize(img,[512 512]);
img_gray=0.21*resized_image(:,:,1) + 0.72*resized_image(:,:,2) +
0.07*resized_image(:,:,3);
imshow(img_gray);
title('Gray image');

img_pad=double(padarray(img_gray,[8 8],'symmetric')); %Padding the
image
figure;
[row,col]=size(img_pad); %Storing the row and column number of the
padded image
clip_limit=0.1; %Setting the clip limit
eqcount=zeros(row,col);
y_size=1;
x_size=1;
while(y_size<col)
    %Calculating the pixel count for every conextual area
    for x=x_size:x_size+16;
        for y=y_size:y_size+16;
            eqcount(x,y)=0;
            for i=x_size:x_size+16;
                for j=y_size:y_size+16;
                    if img_pad(i,j)==img_pad(x,y)
                        eqcount(x,y)=eqcount(x,y) + 1;
                    end
                end
            end
        end
    end
    if x_size==1;
        x_size=x_size+15;
    else
        x_size=x_size+16;
    end
    if x_size>=row
        x_size=1;
        if y_size==1;
```

```
            y_size=y_size+15;
        else
            y_size=y_size+16;
        end
    end
end
output=(zeros(row,row));
y_size=1;
x_size=1;
while(y_size<col)
    %Calculating the various values for the computing CLAHE
    for x=x_size:x_size+16;
        for y=y_size:y_size+16;
            cliptotal=0;
            partialrank=0;
            for i=x_size:x_size+16;
                for j=y_size:y_size+16;
                    if eqcount(i,j) > clip_limit
                        incr=clip_limit/eqcount(i,j);
                    else
                        incr=1;
                    end
                    cliptotal=cliptotal+(1-incr);
                    if img_pad(x,y) >= img_pad(i,j)
                        partialrank = partialrank + incr;
                    end
                end
            end
            redistr = (cliptotal / (16*16)) * img_pad(x,y);
            output(x,y) = partialrank + redistr;
        end
    end
    if x_size==1;
        x_size=x_size+15;
    else
        x_size=x_size+16;
    end
    if x_size==row
        x_size=1;
        if y_size==1;
            y_size=y_size+15;
        else
            y_size=y_size+16;
        end
    end
end
    u=uint8(output);
    imshow(u);
    title('CLAHE');
end
```

Depth maps export (Python)



```
# This script exports a SCALED DENSE depth map, after MESH stage
has been completed, and a scale has been entered.
# If no scale is entered, depth maps have relative scale.
# Exported depth maps are the same size as the original images in
the chunk, but compressed. This level of compression does not
affect the accuracy needed for colour correciton.
# Derya Akkaynak

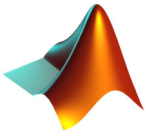
import Metashape

# Select active chunk
chunk = Metashape.app.document.chunk

# Is the model scaled? If not assign scale of 1
if chunk.transform.scale is None:
    scale = 1
else:
    scale = chunk.transform.scale

# Export depth maps for all aligned cameras in chunk
for camera in chunk.cameras:
    # First check if the camera is aligned
    if camera.transform:
        depth = chunk.model.renderDepth(camera.transform,
camera.sensor.calibration)
        depth = depth * scale
        depth = depth.convert(" ","F16")
        compr = Metashape.ImageCompression()
        compr.tiff_compression =
Metashape.ImageCompression().TiffCompressionDeflate
        # Remember to update this path according to your folders
        depth.save("/Users/deryaakkaynak/Desktop/depth" +
camera.label + ".tif", compression = compr)
```

Colour analysis (Matlab)



```
% This script allows measuring colour reproduction in a MATLAB
environment using an Xrite test chart
% Alessio Calantropio

% Select an image in wich the ColourChecker appears
I = imread("imagename.jpg");

% Display the image and manually select the four corners for
locating the colour chart
imshow(I)
title("Captured Image of ColourChecker Chart")
text(size(I,2),size(I,1)+15,"Chart courtesy of Calibrite", ...
    "FontSize",10,"HorizontalAlignment","right")
blackPoint = drawpoint;
whitePoint = drawpoint;
darkSkinPoint = drawpoint;
bluishGreenPoint = drawpoint;
cornerPoints = [blackPoint.Position;
    whitePoint.Position;
    darkSkinPoint.Position;
    bluishGreenPoint.Position];

% Use the points to create 24 ROIs from wich extract colour
information, then display in a chart
chart = colourChecker(I,"RegistrationPoints",cornerPoints);
displayChart(chart)
colourTable = measureColour(chart)
figure
displayColourPatch(colourTable)

% Batch apply the above to all the images contained in a folder,
saving the colour information for each image in a separate .txt
file to be later analysed
% Specify the folder where the files live.
myFolder = 'E:\PATH';
% Check to make sure that folder actually exists.  Warn user if it
doesn't.
if ~isfolder(myFolder)
    errorMessage = sprintf('Error: The following folder does not
exist:\n%s\nPlease specify a new folder.', myFolder);
    uiwait(warndlg(errorMessage));
    myFolder = uigetdir(); % Ask for a new one.
    if myFolder == 0
         % User clicked Cancel
         return;
    end
end
% Get a list of all files in the folder with the desired file name
pattern.
filePattern = fullfile(myFolder, '*.jpg'); % Change to whatever
pattern you need.
theFiles = dir(filePattern);
for k = 1 : length(theFiles)
    baseFileName = theFiles(k).name;
    fullFileName = fullfile(theFiles(k).folder, baseFileName);
    fprintf(1, 'Now reading %s\n', fullFileName);
    % Now do whatever you want with this file name,
   I = imread(fullFileName);
imshow(I)
chart = colourChecker(I,"RegistrationPoints",cornerPoints);
```

```
displayChart(chart)
colourTable = measureColour(chart)
writetable(colourTable,fullFileName + ".txt",'Delimiter',' ')

end
```

C – Orthophotos and DSM

This Appendix reports a collection of ortophotos, DSM and GIS analysis performed in the framework of this thesis.

Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 14/09/2021 – ***Orthophoto***

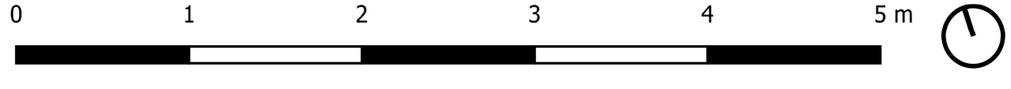


0 1 2 3 4 5 m

Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 16/09/2021 – ***Orthophoto***





Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 18/09/2021 – ***Orthophoto***



Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 26/09/2021 – ***Orthophoto***



0 1 2 3 4 5 m

Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 27/09/2021 – ***Orthophoto***



0 1 2 3 4 5 m

Appendix C

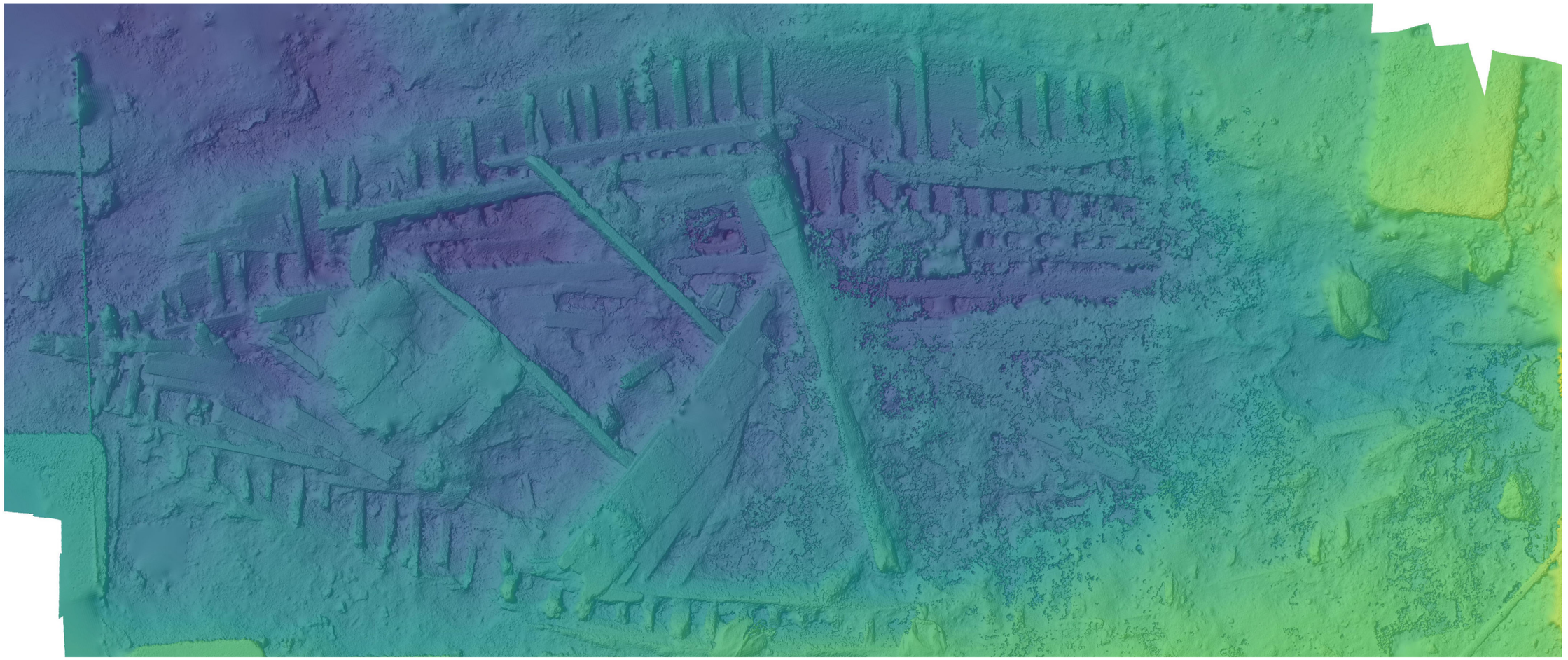
Orthophotos and DSM // Torre Santa Sabina I – 28/09/2021 – ***Orthophoto***



0 1 2 3 4 5 m

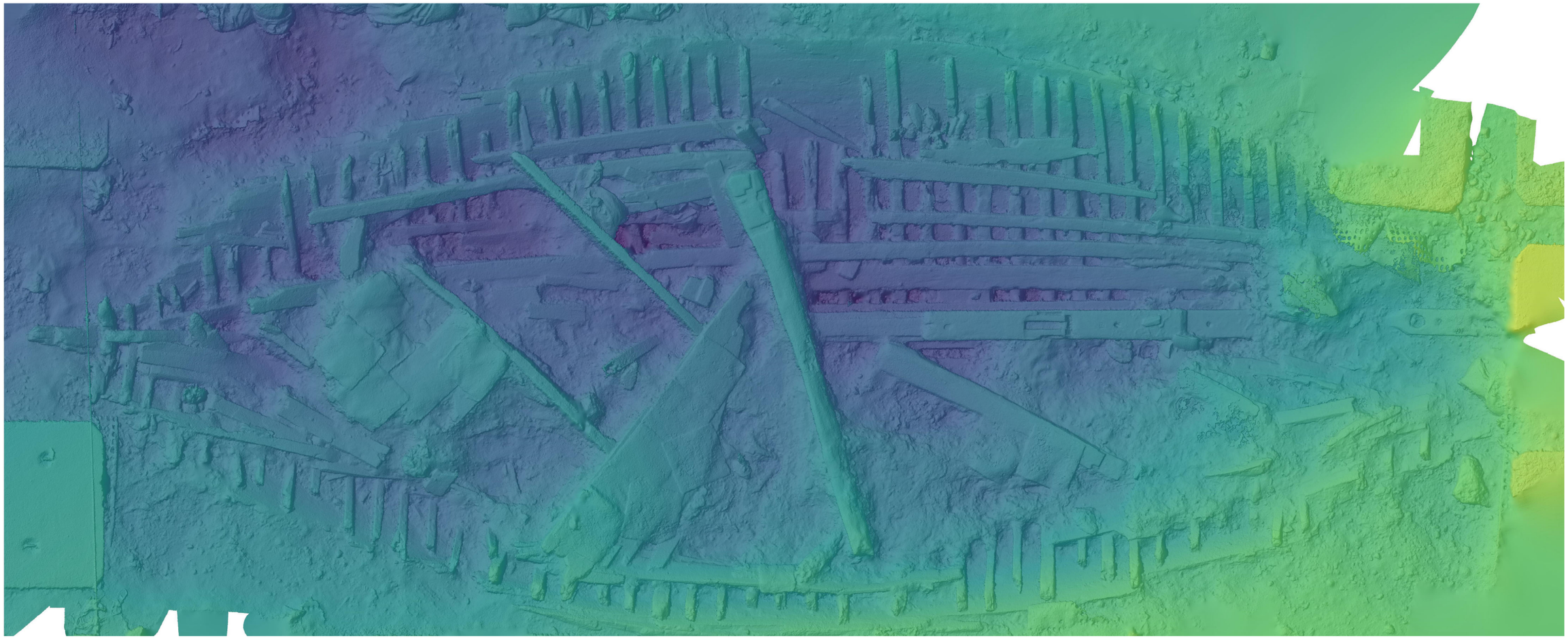
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 14/09/2021 – ***DSM***



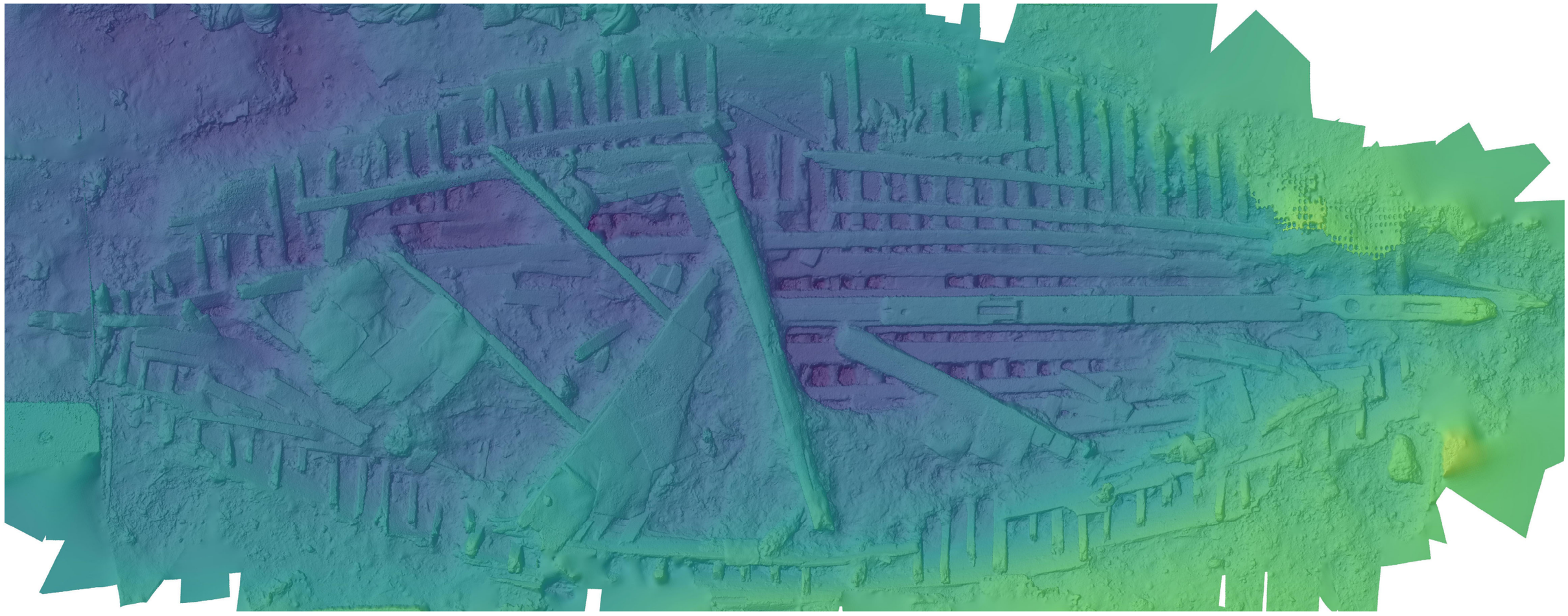
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 16/09/2021 – ***DSM***



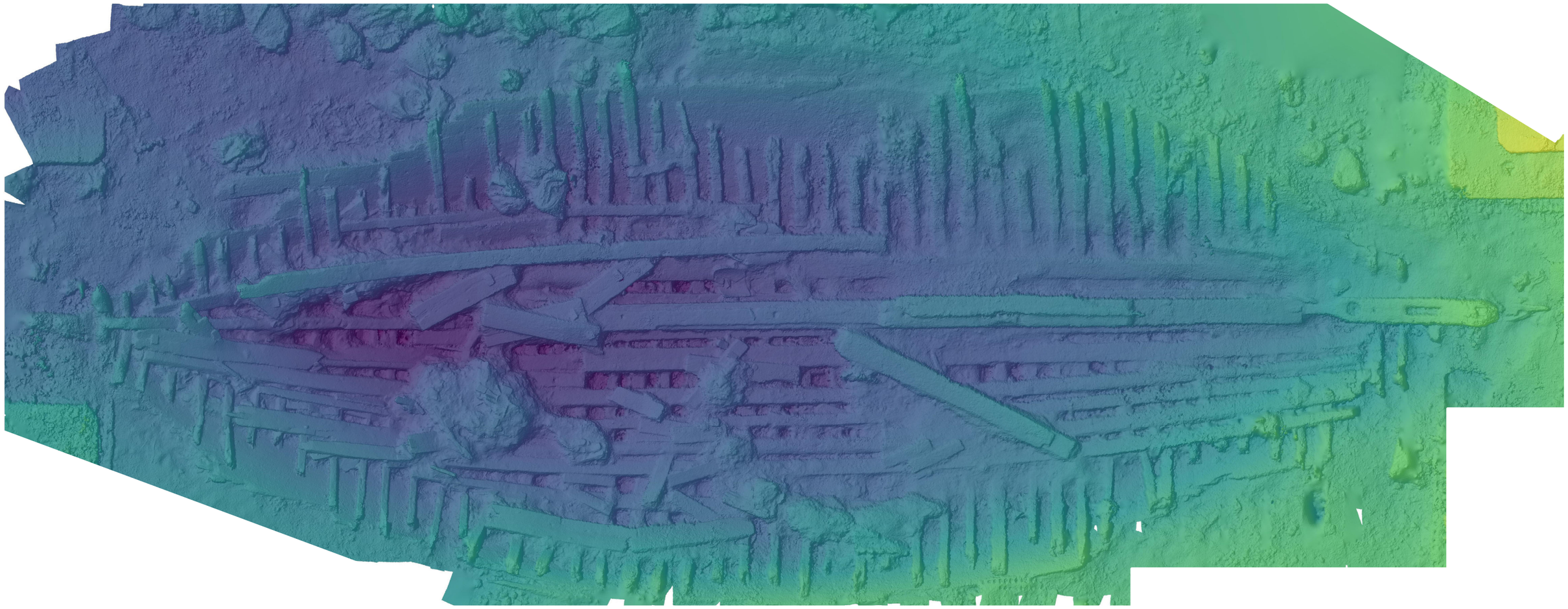
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 18/09/2021 – ***DSM***



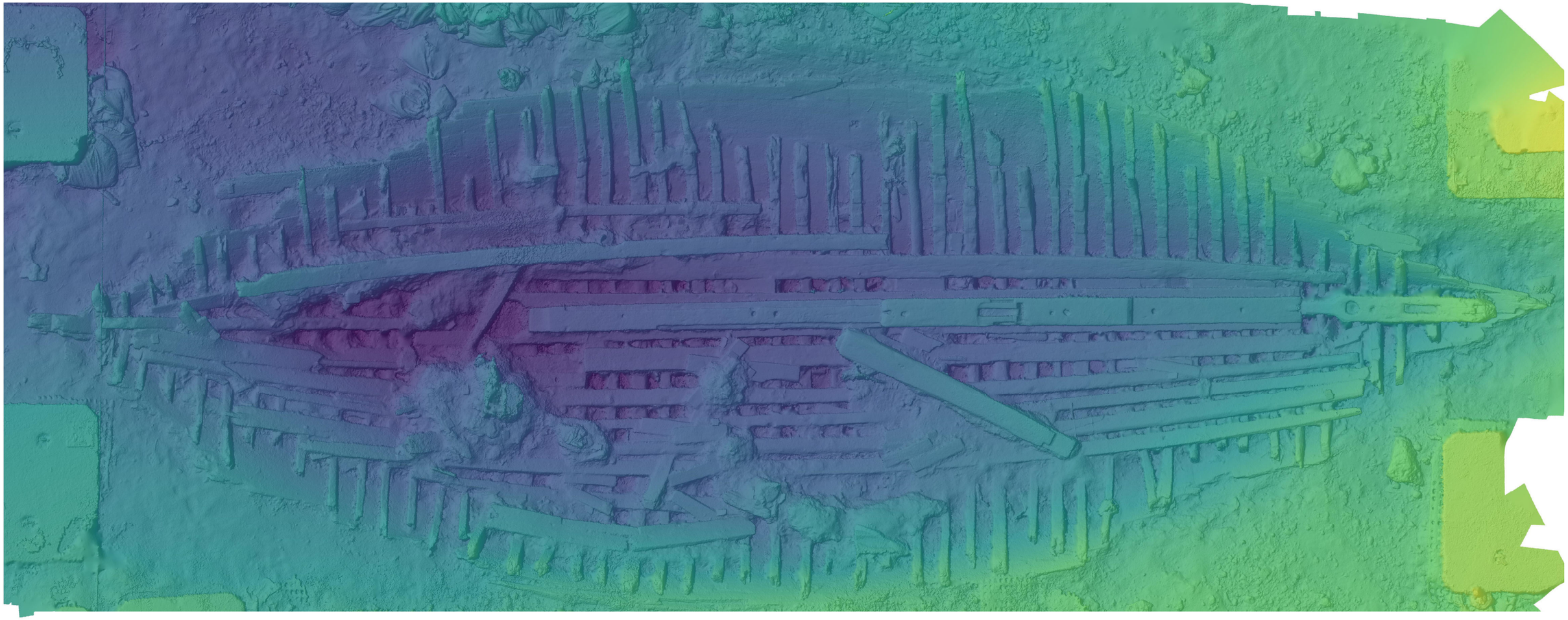
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 26/09/2021 – ***DSM***



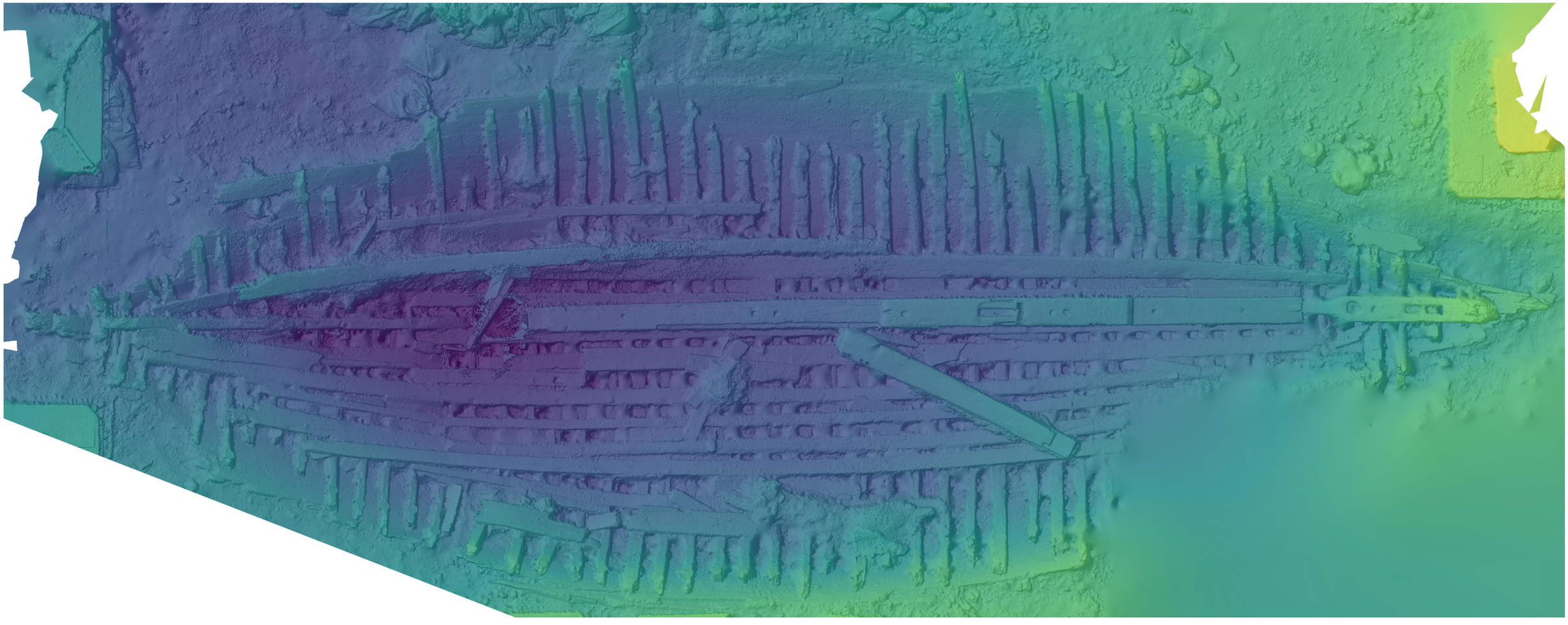
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 27/09/2021 – ***DSM***



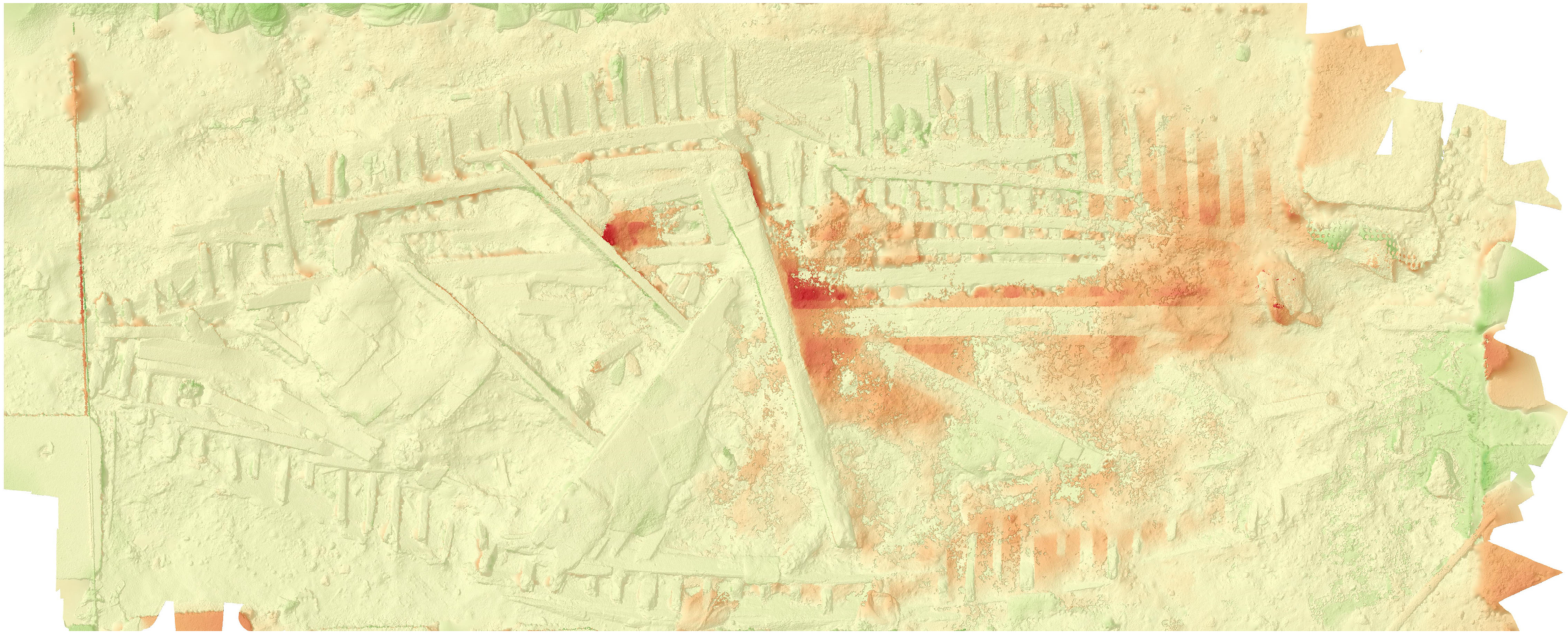
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 28/09/2021 – ***DSM***



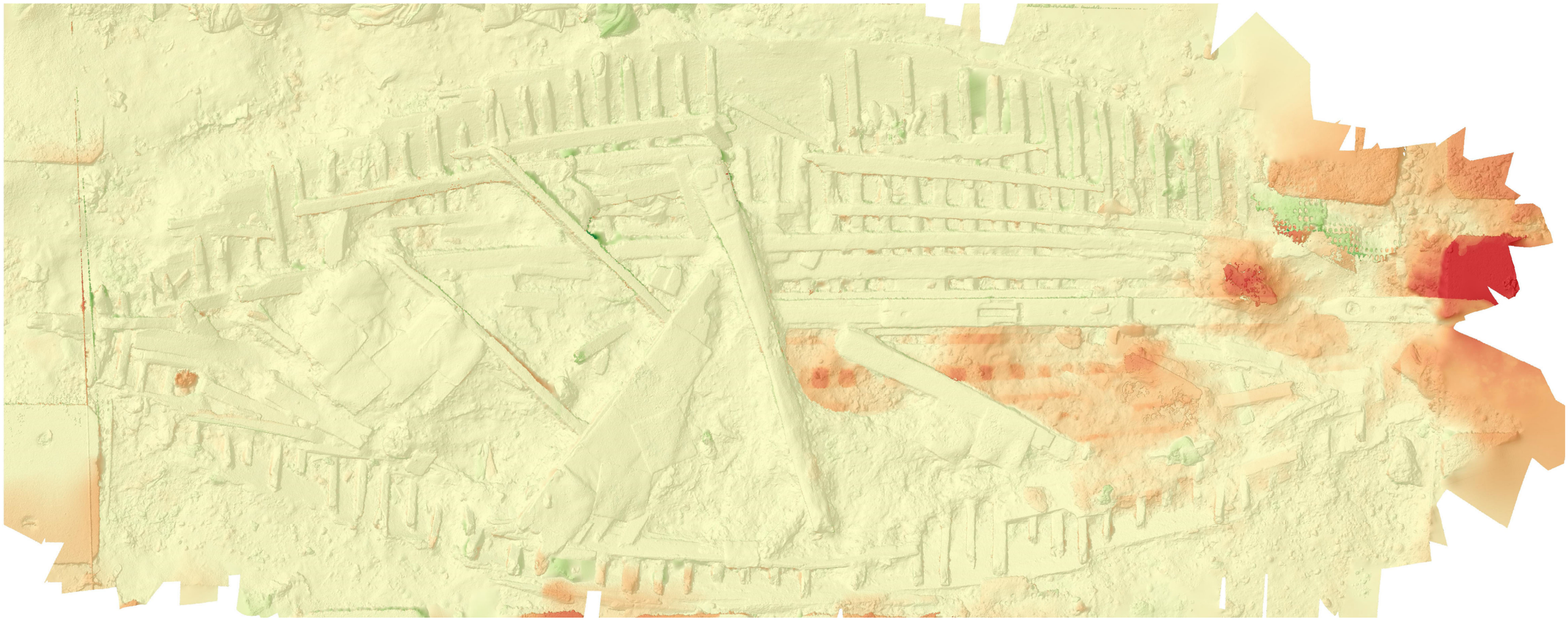
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 14-16/09/2021 – ***C2C Comparison***



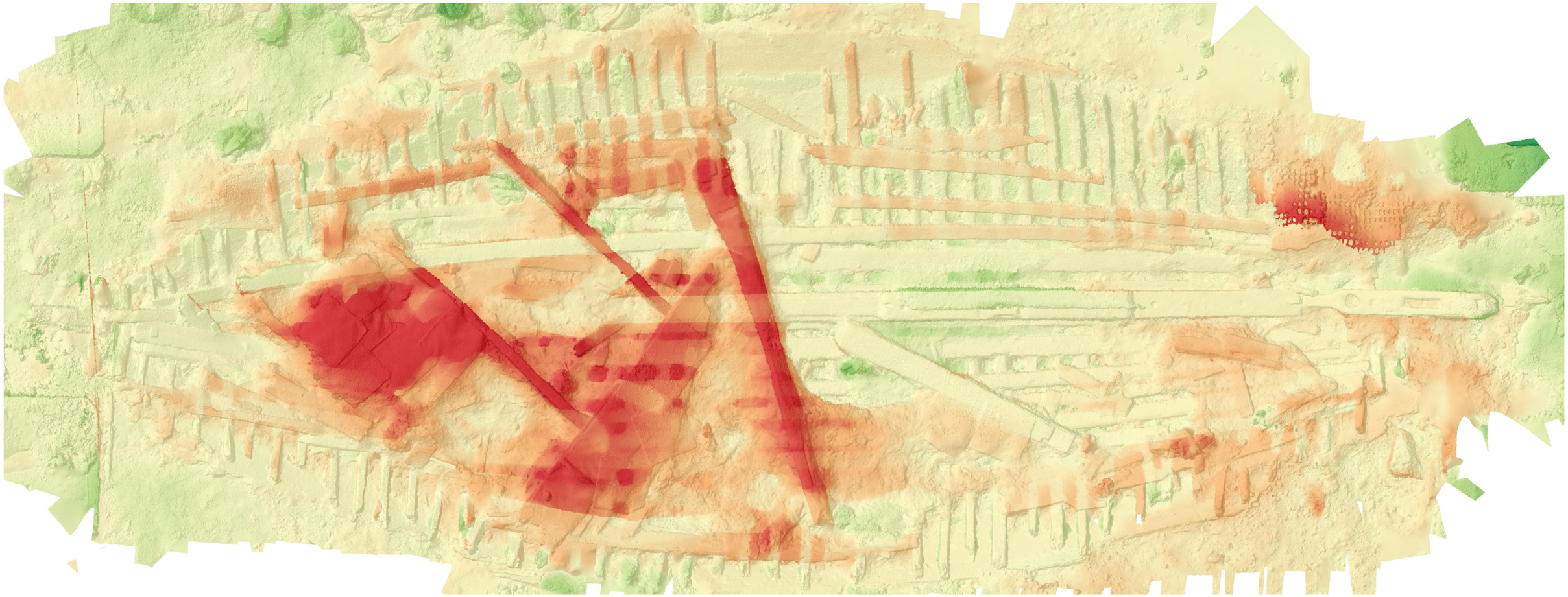
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 16-18/09/2021 – ***C2C Comparison***



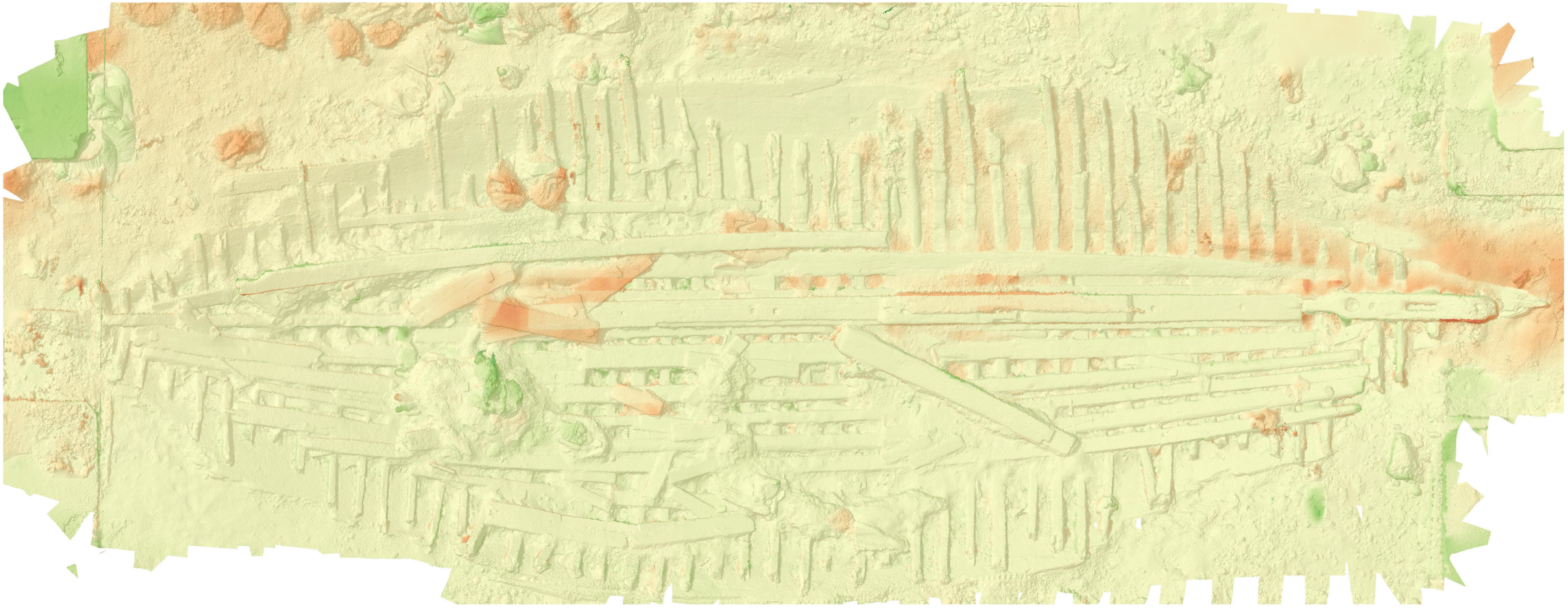
Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 18-26/09/2021 – ***C2C Comparison***



Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 26-27/09/2021 – ***C2C Comparison***



Appendix C

Orthophotos and DSM // Torre Santa Sabina I – 27-28/09/2021 – ***C2C Comparison***

