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Building damage assessment scale tailored to remote sensing vertical imagery

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ABSTRACT

Damage assessment from very high resolution (VHR) remote sensing imagery plays a fundamental role in the delineation of the impact caused by catastrophic events. To date internationally accepted standard guidelines on how to assess damages to building using vertical imagery have not yet been developed. This study therefore proposes a building damage scale – and related interpretation guidelines to be operationally adopted as a standard by the main stakeholders – tailored to analyses based on VHR remote sensed vertical imagery. Preliminarily, some of the damage scales used for building damage assessment by the main satellite-based emergency mapping services have been analysed and discussed. A quantitative thematic accuracy analysis based on the open accessible crisis datasets related to the earthquake occurred in Central Italy in August 2016 has been carried out. The results highlight that by using VHR remotely sensed images it is not possible to directly apply damage classification scales addressing slight structural damages (e.g. the lowest grades proposed by EMS-'98). The paper demonstrates that using different damage classes and detailing the interpretation guidelines with operational examples is essential to increase the thematic accuracy of the analysis.

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Natural hazards; remote sensing; damage assessment; building damage scale; vertical imagery; earthquake

Introduction

Natural disasters cause an impressive impact in terms of economic losses, affected people and casualties. The number of catastrophic events has more than doubled globally from 1980 to 2011. From 2012 to 2017 natural disasters caused 84.102 fatalities and approximately 1.058 bn US$ in economic losses worldwide. Geophysical events (earthquakes, tsunamis and volcanic activity) were responsible for almost 18% of the total deaths (Munich, 2018).

In recent years, satellite-based emergency mapping (SEM) activations have seen an increase as a practice to provide quick crisis information after major disasters (Voigt et al., 2016). The rapid mapping of damages after a major catastrophic event is generally exploited to support the emergency response phase. Moreover, several mechanisms have been designed to grant the availability of post-event satellite imagery for the actors involved in the management of natural disasters, enabling the extraction of up-to-date geospatial information. Among others, the Copernicus Emergency Management Service (© European Union, 2012–2018, Copernicus EMS) and the UNITAR's Operational Satellite Applications Programme (UNOSAT) usually provide post-event information very rapidly in case of major disasters. Copernicus EMS provides an initial post-event map in about 12 h after the delivery of exploitable satellite imagery that covers the affected areas.

Current procedures for structures and infrastructures damage severity assessment based on very high resolution (VHR) vertical imagery following natural disasters adopt different types of damage scales.

Following a thorough literature review and according to the authors' operational experience in the emergency mapping domain, four different building damage scales will be described in the following paragraphs, namely:

- the "BAR" approach,
- and the damage scales adopted by three different emergency mapping entities/services:
- UNOSAT,
- Copernicus EMS,
- ZKI.

The "BAR Methodology" (Achkar, Baker, & Raymond, 2018) developed by the Signal Program on Human Security and Technology at Harvard Humanitarian Initiative addresses the assessment of damage to structures caused by wind proposing four classes according to the level of damages to the roof and walls of the building ("Critical Visible Damage",

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"Significant Visible Damage", "Minimal Visible Damage" and "No Visible Damage").

In different mapping products addressing natural disasters, UNOSAT conducts building damage assessment on satellite image adopting a binary classification, i.e. damaged vs no damage (UNITAR UNOSAT, 2015a) (UNITAR UNOSAT, 2016b) (Unosat, 2017) (Unosat, 2018), whereas in case of complex emergencies the building damage is generally categorized in three different classes ("Destroyed", "Severe Damage" and "Moderate Damage") (Unosat, 2015b) (UNITAR UNOSAT, 2016a). UNOSAT damage analysis is particularly focused on damages to educational facilities, health facilities and other critical infrastructures and it is not related to the hazard type.

In its first years, the Rapid Mapping service provided by the Copernicus EMS adopted five different damage classes (also in this case not related to the hazard type) and was originally based on the 1998 European Macroseismic Scale (Grunthal, 1998), as originally proposed in 2010 by UNOSAT, JRC and WorldBank/GFDRR during one of the first examples of operational exploitation of remote sensing imagery in a Post Disaster Needs Assessment (PDNA) framework (UNITAR UNOSAT, 2010). Examples of emergency mapping products adopting the aforementioned building damage scale are available on the Copernicus EMS portal (http://emergency.copernicus.eu/mapping/list-of-activations-rapid), e.g. *Copernicus Emergency Management Service (© 2015 European Union), EMSR137*, *Copernicus Emergency Management Service (© 2016 European Union), EMSR159* and *Copernicus Emergency Management Service (© 2017 European Union), EMSR244*.

The Center for Satellite-based Crisis Information (ZKI), an institution of the German Remote Sensing Data Center (DFD) at the German Aerospace Center (DLR) adopts different building damage classification scales evolving over the time. After the Earthquake in Turkey in 2011, the damaged buildings were categorized in two classes, "Highly damaged" and "Possibly damaged" (Turkey – P08 – Ercis – Damage Assessment Map – Detail – 28 October 2011 Copyright: ZKI/DLR), while during the Typhoon in Philippines in 2013 the damaged buildings were categorized in two different classes "Destroyed/heavily damaged" and "Less than heavily damaged or status unknown" (Philippines – San Remigio (South) – P05 – Situation as of 14 November 2013 – Damage Assessment Map – Detail Copyright: ZKI/DLR).

The overview highlights that a standard damage scale of the damage severity to infrastructures – accepted and adopted by the relevant stakeholders – is currently missing. This lack of standard implies significant operational issues for the end users, both in quickly interpreting the damage information (as they need to analyse the underlying data model, when available) and in comparing analyses carried out by different SEM entities. The crucial role of standards is also stressed by the International Working Group on Satellite Emergency Mapping (IWG-SEM, http://www.iwg-sem.org) that aims to improve the collaboration and communication among the Satellite-based Emergency Mapping (SEM) mechanisms and produces and updates Emergency Mapping guidelines (Voigt et al., 2016). A standard damage assessment scale would address this important issue, allowing SEM mechanisms to provide data in a shared standard, streamlining their exploitation and integration with other data sources by the end users.

In this context, the aim of this work – also based on master degree theses developed at Politecnico di Torino (Cotrufo, 2017) and (Muratore, 2017) – is to increase the rapid mapping effectiveness by developing a building damage scale tailored for analysis based on remote sensing VHR vertical imagery, providing visual interpretation guidelines and relevant examples.

The typical data sources exploited for emergency mapping are analysed and discussed in the first section of the paper. The second section is focused on the adopted methodology which is based on: an evaluation of the thematic accuracy of satellite building damage assessment based on a specific case study (earthquake that struck Central Italy in 2016), the design of the proposed standard building damage scale, the compilation of interpretation guidelines and examples and a complete validation exercise. Lastly, the conclusive session presents the main benefits derived from the adoption of the proposed standard building damage scale (now operationally adopted by the Copernicus EMS during Rapid Mapping activations, e.g. *Copernicus Emergency Management Service (© 2018 European Union), EMSR2693* and *Copernicus Emergency Management Service (© 2017 European Union), EMSR257*).

Satellite-based earthquake mapping: general workflow and main data sources

The main operational steps (and related timeline) of a simplified Rapid Mapping general workflow are shown in Figure 1. To date, standard procedures (Figure 1, red box) for structures and infrastructures damage severity assessment based on post-event VHR vertical imagery following natural disasters is generally carried out adopting a multi-temporal approach comparing baseline data (e.g. imagery captured before the event) to post-event imagery (Xinjian & Yin, 2004).

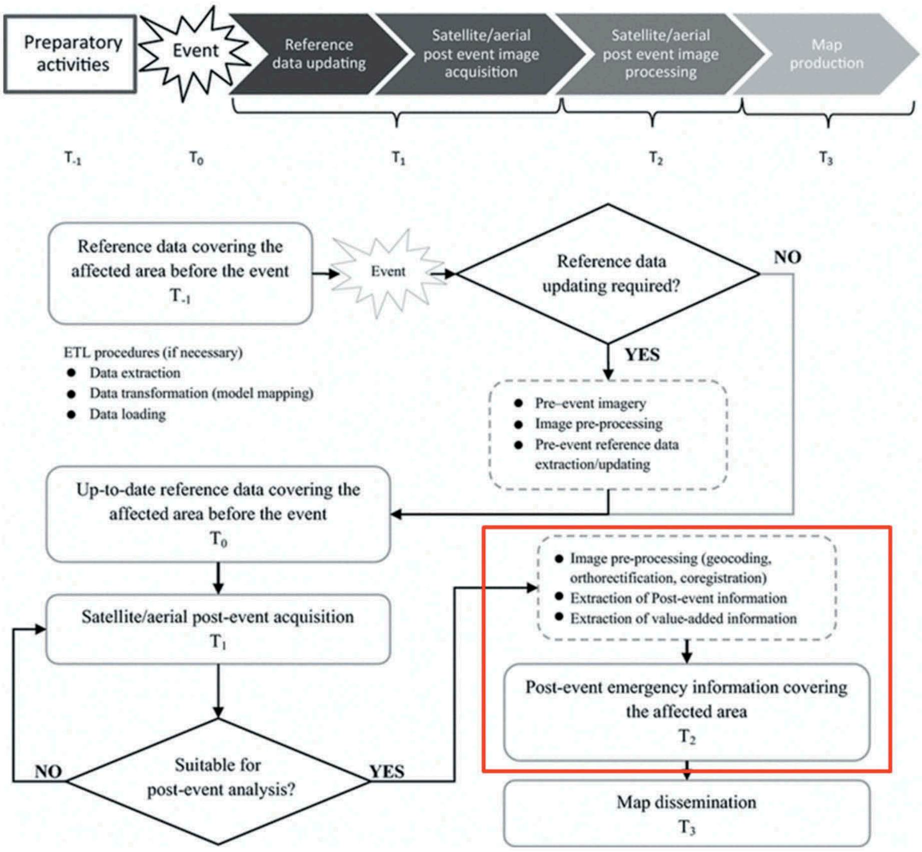

Figure 1. Simplified Rapid Mapping general flow-chart highlighting the main processing steps (crisis information extraction in the red box) and the activity timeline (Ajmar, Boccardo, Disabato, & Giulio Tonolo, 2015)..

As far as earthquakes are concerned, although several semi-automated approaches (including the exploitation of promising deep-learning algorithms) are currently being tested, photo interpretation (Plaza & Al, 2009) is still the most common methodology to rapidly generate earthquake damage assessment as specified in “Rapid Mapping: geomatics role and research opportunities” (Ajmar, Boccardo, Disabato, & Giulio Tonolo, 2015). The same paper also highlights the need to systematically improve the computer-aided photo interpretation (CAPI) both in terms of efficiency and thematic accuracy, to increase the reliability of infrastructure damage assessment information and to improve the timeliness of the crisis information delivery, crucial in rapid mapping. The adopted damage scale and the related interpretation guidelines are clearly impacting on both the aforementioned goals. Another key factor affecting the building damage assessment accuracy and level of detail is the type of remote sensing imagery exploited for the analysis, mainly depending on the platform on which the imaging sensor is installed.

Vertical imagery sources

To provide an overview of the data sources that will be analysed in the cases studies, the different types of vertical imagery and their technical features are described in this section. In the Methodology section, the details (including platform type/name, acquisition date/time, GSD, credits) of each specific dataset exploited for the presented case studies will be provided.

Optical satellite imagery

Satellite platforms allow large areas, potentially with limited or no accessibility due to the event impact, to be sensed and, if required, monitored (Ajmar et al., 2015). The main aspect that influences the effectiveness of a remotely sensed set of imagery in the emergency context is the resolution, mainly the spatial and temporal components. The spatial resolution of satellite images refers to the smallest object size resolvable on ground and it expresses the level of detail reachable by an acquisition system. This is related to the ground sample distance (GSD) that is the nominal dimension of a single side of a square pixel measured in ground units. The spatial resolution plays a fundamental role in the detection of crisis information such as damages to manmade structures, which require VHR imagery to be detected at single feature level.

The temporal resolution or revisiting time of remote sensing systems refers to the time required to acquire new acquisitions over the same area. Virtual constellations (different satellites with similar technical features managed by the same satellite data provider) play an important role in emergency mapping, allowing revisiting time over a specific area of interest to be decreased. Additionally, new sources of datasets e.g. the Planet satellite constellation, can provide satellite images with 3 to 5 m spatial resolution of the entire globe every day (Planet, 2018).

Aerial imagery

Aerial images represent one of the principal datasets used to update existing cartography. Nevertheless, in the emergency mapping context it is also used for damage assessment purposes. The traditional aerial imagery technique offers the possibility to generate products with a very high spatial resolution (GSD ~ 0.1 m) as well as to derive 3D information. Its main drawbacks are i) the time required to deploy the aerial platform (and the related system) in the affected areas (if in-country capacity is not present) and ii) the need to gain proper knowledge of the different regulations to get the permission required to fly from the relevant national aviation authority.

UAV imagery

Unmanned aerial vehicles (UAVs), commonly known as drones, are a component of an unmanned aircraft system (UAS), which include a UAV, a ground-based controller and a system of communications between the two (ICAO, 2011). UAVs are aircrafts without a human pilot aboard and a rapidly upcoming method for remote-sensing data acquisition.

Although UAVs at the beginning were mainly used in military applications, recently several civil applications have emerged, such as safety control, scientific research, and commercial applications. Humanitarian organizations like UAViators promote the use of UAVs for data collection for emergency management and mobilize upon request from aid partners (UAViators, 2018). Other applications of UAVs in the disaster risk reduction domain can be found in (We Robotics, 2018).

High flexibility, low operational costs, small size of the sensors (with GSD down to few centimetres) and UAS increasing use and pre-deployment in several countries, make UAVs suitable for operational applications in emergency mapping (Boccardo, Chiabrando, Dutto, Giulio Tonolo, & Lingua, 2015).

Additionally, initiatives like OpenAerialMap (https://openaerialmap.org/) provide access to a set of openly licensed imagery and map layer services, including UAV imagery, with an increasing coverage at global level. Nevertheless, the flight permission regulation issues described for the aerial imagery applies also to UAV acquisitions.

Vertical imagery technical features

The technical features relevant for building damage assessment of the aforementioned datasets are summarized in Table 1.

Methodology

As highlighted in the Introduction section, the goal of the work was to develop a standard damage scale focused on buildings (as critical structures analysed by the responders to estimate the impact of an event) and tailored to analyses based on VHR vertical imagery acquired by satellite or aerial platforms. To achieve this goal, the methodology detailed in the workflow shown in Figure 2 was applied. It has to be highlighted that the methodology requires a case study to be validated.

The main workflow steps are briefly described:

Step 1 – All the relevant data and images referred to the activation *Copernicus Emergency Management Service (© 2016 European Union), EMSR177* – selected as case study – were harvested and analysed.

Step 2 – An independent damage assessment was derived from the available post-event aerial image and considered as the Ground Truth (as detailed in the section "Ground Truth generation"). The Ground Truth was generated without any time restrictions to define the possible limitations of rapid mapping activities where time constraints play an important role.

Step 3 – The outputs representing the damaged buildings generated by Copernicus EMS were validated by comparing them to the Ground Truth. Thus, the main quality metrics were calculated (Producer, User and Overall accuracy).

Table 1. Advantages and disadvantages of airborne data versus space-borne data for building damage assessment.

	Space-borne multispectral scanner	Airborne	UAV multirotor and fixed wing
Ground Sample Distance (m)	0.3 – 0.5	0.05 – 0.1	0.05 – 0.1
Delivery Time after Data Request (days)	~ 1.5	> ~ 2*	> ~ 2*
Revisit Interval	Daily	Upon request	Upon request
Swath Width (km)	13 – 20	10**	~ 0.5**
Cloud/haze Influence	High	Medium	Low

* depending on in-country capacity and other logistic issues (including national regulations)
** depending on flight height

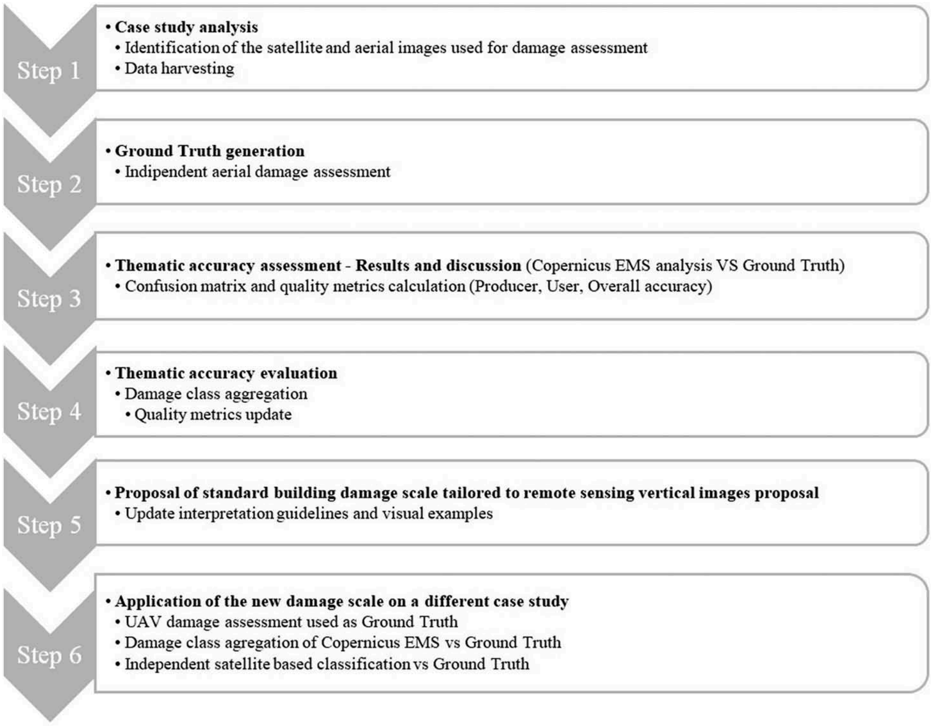

Figure 2. Methodology workflow - Building damage scale evaluation.

Step 4 – To identify the critical damage classes through the evaluation of the accuracy metrics, the following tests were carried out:

- Aggregation of the Copernicus EMS damage scale classes;
- Comparison of the aggregated classes to the Ground Truth;
- Calculation of the aggregated classes quality metrics (Producer, User and Overall accuracy) as per the previous step.

Step 5 – The results of the test led to the proposed of a standard building damage scale tailored to remote sensing vertical images accompanied by a detailed interpretation guideline and visual examples.

Step 6 – For evaluation purposes the proposed damage scale was adopted in a different Copernicus EMS Rapid Mapping activation (used as validation case study), exploiting as Ground Truth an independent building damage assessment based on UAV post-event imagery. Once again, Copernicus EMS damage classes were aggregated and then their thematic accuracy evaluated. Moreover, using the same post-event satellite image as Copernicus EMS, an independent satellite-based damage assessment was performed adopting the proposed standard building damage scale to evaluate its fitness for purpose. Lastly, it was possible to compare the results from the damage assessment from Copernicus EMS and the independent damage assessment (both based on satellite imagery).

Step 1 – case study analysis

On 24 August 2016 at 03:36:32 local time (01:36 UTC), an earthquake, measuring 6.2 on the moment magnitude scale, hit Central Italy in an area near the borders of the Umbria, Lazio, Abruzzo and Marche region. Its epicentre was close to Accumoli, with its hypocentre at a depth of 4 ± 1 km, approximately 45 km north of L'Aquila and 75 km southeast of Perugia (INGV, 2017). The official figures of the Protezione Civile report that the earthquake caused the death of 297 people: 11 in Accumoli, 49 in Arquata del Tronto and 234 in Amatrice. In addition to the loss of human lives, widespread destruction of cultural heritage was also reported.

Identification of the satellite and aerial images used for damage assessment and data harvesting

As Copernicus EMS was the most active SEM mechanism during the Italian Earthquake events in 2016, the information and damage assessment generated in *Copernicus Emergency Management Service (© 2016* European Union), EMSR177 was analysed in the first part. Initially the vector files of the satellite-based damage assessment performed over AOI08 Accumoli [EMSR177] Accumoli: Grading Map, Monitoring 1 and AOI10 AmatriceWest [EMSR177] Amatrice West: Grading Map, Monitoring 1 were downloaded and the towns of Illica, Casale, Saletta, San Lorenzo e Flaviano and Accumoli (highlighted in red in Figure 3) were analysed.

Copernicus EMS provides different types and formats of vector files related to reference and crisis

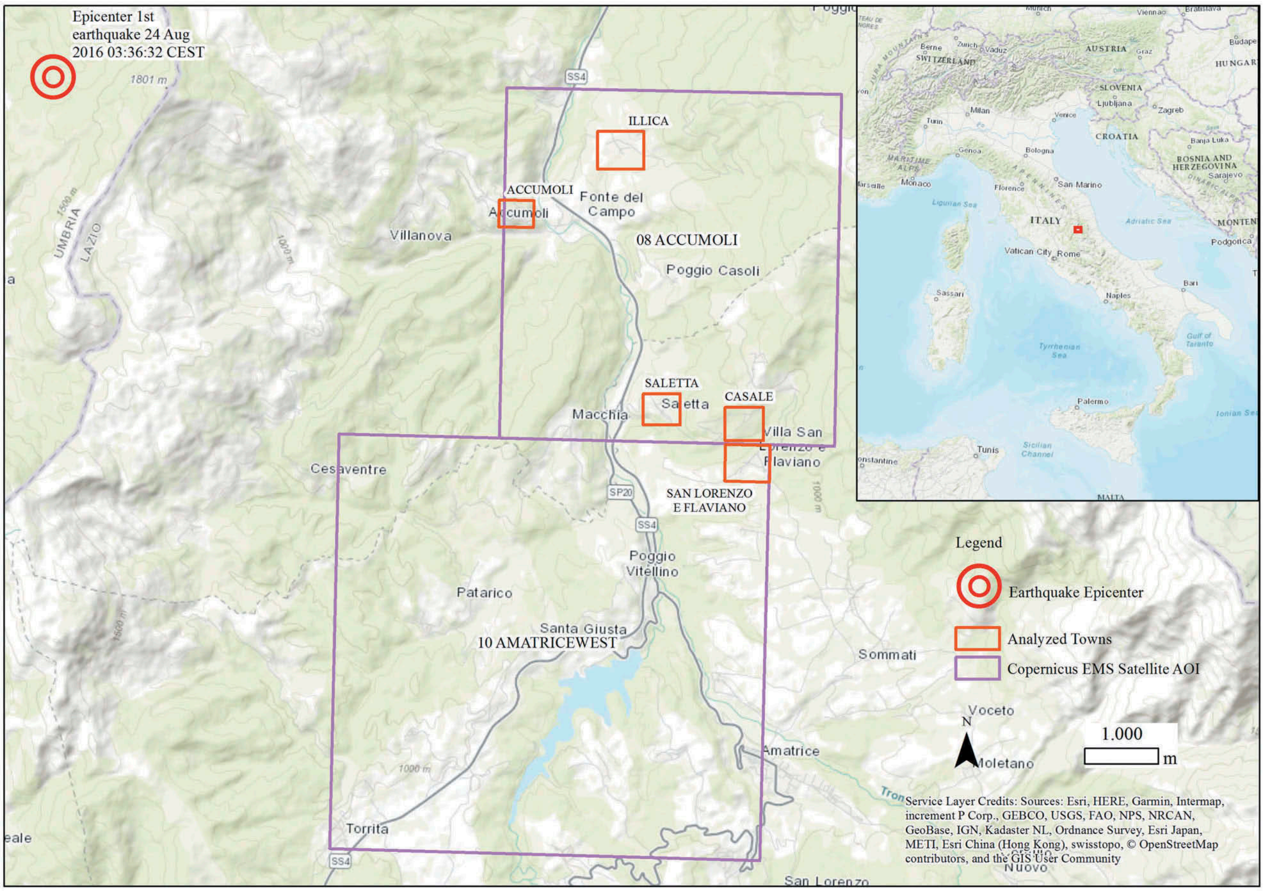

Figure 3. Overview of the Copernicus EMS [EMSR177] Amatrice West: Grading Map, Monitoring 1 [EMSR177] Accumoli: Grading Map, Monitoring 1 areas (purples boxes) and the analysed target areas (orange boxes).

data. From the vector zip package only the shapefile that represents the footprints of each building located in the areas of interest and including information on a satellite-based assessment of the building damages was analyzed. The damage scale uses five levels: Completely Destroyed, Highly Damaged, Moderately Damaged, Negligible to Slight Damage and Not Affected.

In Figure 4, as illustrative and informative purposes, the building footprints of Saletta's area of interest are displayed in a traffic light color code according to the damage scale class.

From the vector metadata it emerged that Copernicus EMS's satellite damage assessment was based on the comparison between:

- Pre-event image: Orthophoto 0.2 m © 2014 CONSORZIO TeA (formed by e-GEOS S.p.A. – CGR S.p.A. – Aerodata Italia srl).
- Post-event image: WorldView-2 © Digitalglobe, Inc. (2016), (acquired on 25/08/2016 09:45 UTC, GSD 0.5 m, approx. 0% cloud coverage, 34° off-nadir angle), provided under Copernicus by the European Union, ESA and European Space Imaging.

Step 2 – ground truth generation

A ground truth is required to assess the accuracy of a classification dataset and is one of the input required to calculate the confusion matrix (Table 2), a table that shows correspondence between the results of a classification process and reference data. It is usually used as the quantitative method of characterizing the thematic accuracy of a dataset, defined as the proportion of agreement between a thematic map and reference data assumed to be correct "Ground Truth".

The diagonal of confusion matrix table lists the number of features that are classified into the correct ground truth class.

Three different metrics are usually calculated to assess the thematic accuracy (Congalton & Green, 1999): Overall accuracy (i.e. the ratio between the sum of the number of buildings correctly classified and the total number of buildings in the area of interest), Producer's accuracy (P.A., i.e. how often real features on the ground are correctly shown on the classified map) and User's accuracy (U.A., i.e. how often the class on the map will actually be present on the ground).

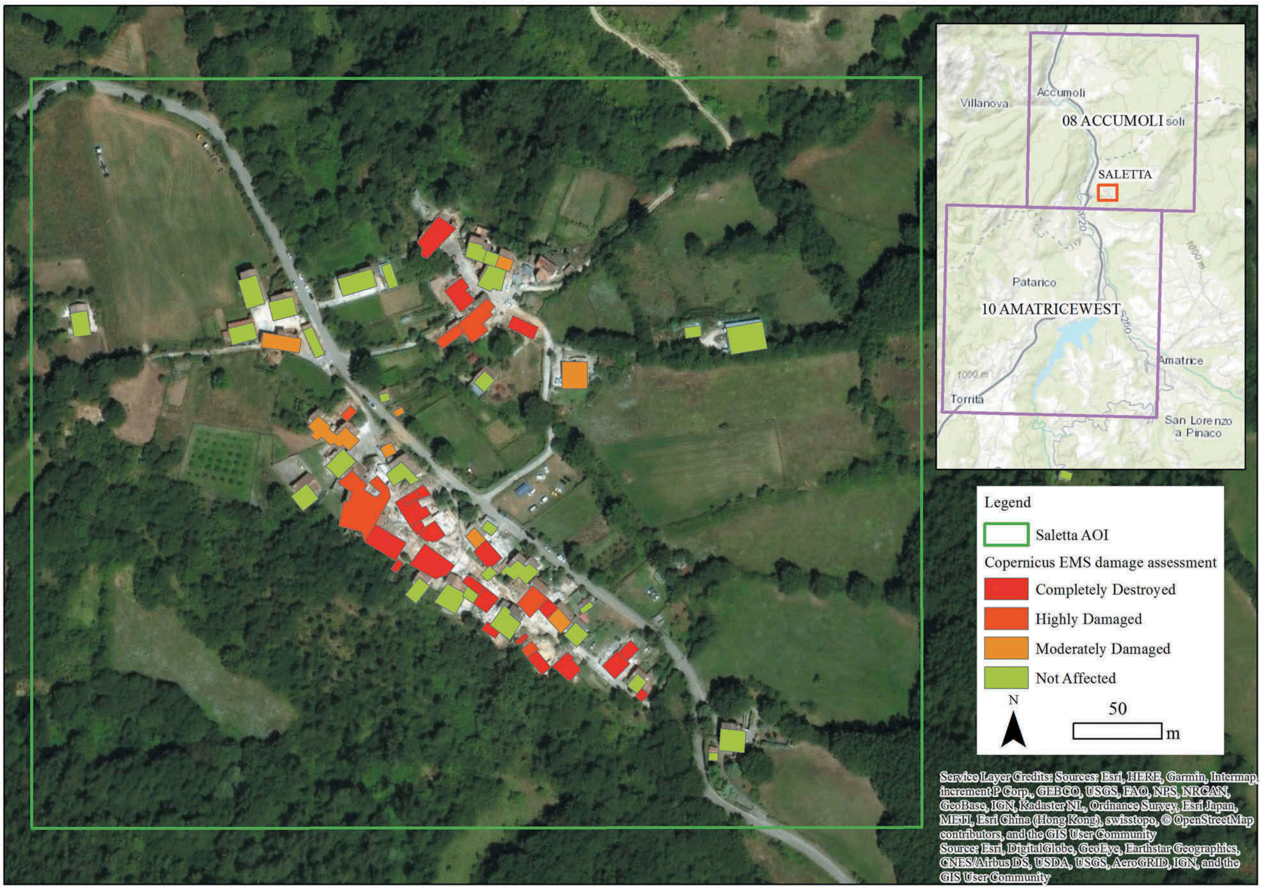

Figure 4. The building footprints over Saletta extracted from [EMSR177] Accumoli: Grading Map, Monitoring 1.

Table 2. Confusion matrix table.

		Damage Assessment				
		Not Affected	Moderately Damaged	Highly Damaged	Completely Destroyed	Total
Ground Truth	Not Affected	$\mathbf{i_{1,1}}$	$i_{1,2}$	$i_{1,3}$	$i_{1,4}$	Tot 1
	Moderately Damaged	$i_{2,1}$	$\mathbf{i_{2,2}}$			
	Highly Damaged	$i_{3,1}$		$\mathbf{i_{3,3}}$		
	Completely Destroyed	$i_{4,1}$			$\mathbf{i_{4,4}}$	
	Total	Tot 2				**Total**
	Class	Omission error	Commission error	P.A.	U.A.	
	Not Affected	100%- P.A.	100%- U.A.	$i_{1,1}$/Tot 1	$i_{1,1}$/Tot 2	
	Moderately Damaged					
	Highly Damaged					
	Completely Destroyed					
	Overall Accuracy	**($i_{1,1}$+ $i_{2,2}$+ $i_{3,3}$+ $i_{4,4}$)/ Total**				

Independent aerial damage assessment

Exploiting the availability of VHR post-event aerial imagery, a level of damage, using the same damage scale adopted by Copernicus EMS for EMSR177 was assigned to each single building and the related damage was described in an ad-hoc attribute field. Specifically, the analysis was carried out on the aerial images listed below:

- Pre-event image: Orthophoto 0.2 m © 2014 CONSORZIO TeA (formed by e-GEOS S.p.A. – CGR S.p.A. – Aerodata Italia srl).
- Post-event image: Aerial data © European Commission (acquired on 25/08/2016, GSD 0.1 m, 0 % cloud coverage) provided under Copernicus by CGR, Compagnia Generale Ripreseaeree (S.P.A.).

The visual image interpretation was based on the observation of: i) tone variations, which allowed to distinguish between different features; ii) shape variations, irregular building shape indicated structural building damage almost every time; iii) shadows, which may support the photo interpretation being a proxy of structure elevation. The result of this assessment was considered as Ground Truth for the analysed case study, thanks to the higher GSD of the aerial image and the absence of time constraints for the analysis.

Step 3 – thematic accuracy assessment – results and discussion

The accuracy of Rapid Mapping analyses based on VHR satellite images carried out by Copernicus EMS was evaluated calculating the confusion matrices for each dataset/area. As already mentioned in the previous section (Independent aerial damage assessment), the results obtained by the Independent aerial damage assessment were considered as Ground Truth data.

The confusion matrixes and the related quality metrics related to the five examined areas are shown in Table 3.

It is observed that intermediate damage classes are those characterized by the largest discrepancies and lowest values, as confirmed by P.A. and U.A. in the confusion matrixes (A) (B) (C). P.A. values vary between a minimum of 6% (P.A. of Class Highly Damaged area C) and a maximum of 50% (P.A. of Class Moderately Damaged area C). U.A. values vary between a minimum of 9% (U.A. of Class Moderately Damaged area A) and a maximum of 25% (U.A. of Class Moderately Damaged area B).

In the matrixes (D) and (E) the P.A. and the U.A. do not follow the same patterns as per matrixes (A), (B), (C) due to: i) high percentage of not affected buildings; ii) high number of damaged buildings erroneously classified as not affected by the Copernicus EMS classification (Figure 5). The latter issue is also influenced by the intrinsic limitations of 0.5 m satellite imagery and the tight time constraint (few hours after post-event imagery availability) imposed by rapid mapping.

The average overall accuracy is ~ 60%, value in line with the expected performance of photo interpretation of damages to buildings based on VHR satellite imagery (Corbane, Carrion, Lemoine, & Broglia, 2011).

Step 4 – Thematic accuracy evaluation

The obtained results permitted to identify the damage classes that lead to more discrepancies; specifically, the accuracy metrics of intermediate classes (Negligible to slight damage, Moderately Damaged and Highly Damaged) were significantly lower than in the other 2 classes (Not Affected and Completely Destroyed). Therefore, it was decided to perform a test by aggregating the aforementioned intermediate classes in a new class "Damaged" to evaluate the impact on accuracy metrics. The results are visible in Table 4.

As expected P.A. and U.A. values of the aggregated Damaged class have increased, specifically:

- P.A. is in the range from 35% (P.A. area A) to 62% (P.A. area B)
- U.A. is in the range from 29% (U.A. area A) to 57% (U.A. area B)

Furthermore, a general increase of the overall accuracy is observed after the aggregation, i.e. from 57% to 63% (area A), from 60% to 69% (area B) and from 51% to 62% (area C). The outcomes confirm that intermediate classes are the ones affected by higher interpretation uncertainty.

Contrariwise, the P.A., U.A. and overall accuracy of the areas of Accumoli (D) and San Lorenzo e Flaviano (E) are not influenced by the aggregation, due to the aforementioned Copernicus EMS classification issues.

The results confirm the need to redefine also the damage interpretation guidelines, shifting from a structural damage (EMS-'98 like) to damage (and damage proxies) visible on VHR vertical imagery.

Imagery spatial resolution and viewing angle are the two key factors to be taken into account in developing the damage scale proposal; in fact vertical imagery, i.e. almost null off-nadir angles, does not allow the facades of the buildings to be analysed or cracks and failure in walls to be detected.

Step 5 – Proposal of standard building damage scale tailored to remote sensing vertical imagery

According to the outcomes of the thematic accuracy evaluation, a new standard damage scale to be used for building damage assessment tailored to remote sensing vertical imagery is proposed in Figure 6, defining 4 damage classes.

- Destroyed: assigned to structures that are totally or largely collapsed (> 50%). This category shall be assigned also when only a portion of the building has collapsed to the ground floor. In these cases, the original building structure is no longer distinguishable.
- Damaged: it shall be used when post satellite imagery is available and includes:
  - Major visible damages, which shall be assigned to structures with part of the roof collapsed and serious failure of walls;
  - Minor visible damage level, i.e. buildings with a largely intact roof characterized by presence of partial damage (collapse of chimneys or detach of roof tiles) or surrounded by large debris/rubble or sand deposit.

The separation between Minor and Major Damage grades can be used only when imagery with a GSD of approximately 0.1 m is available (typical for aerial and UAV imagery).

- Possibly Damaged: it shall be used for buildings whose interpretation is uncertain, due to lower image quality (e.g. shadow or degraded

Table 3. Confusion matrixes related to the areas of Saletta(A), Casale(B), Illica(C), Accumoli(D), San Lorenzo e Flaviano(E). Copernicus EMS damage assessment vs Independent aerial damage assessment.

		Copernicus Satellite Damage Assessment				
		Not Affected	Moderately Damaged	Highly Damaged	Completely Destroyed	Total
A) SALETTA						
Independent Aerial Damage Assessment	Not Affected	17	4	0	0	21
	Moderately Damaged	8	1	2	0	11
	Highly Damaged	3	2	1	0	6
	Completely Destroyed	1	4	7	22	34
	Total	29	11	10	22	72
	Class	Omission error	Commission error	P.A.	U.A.	
	Not Affected	19%	41%	81%	59%	
	Moderately Damaged	91%	91%	9%	9%	
	Highly Damaged	83%	90%	17%	10%	
	Completely Destroyed	35%	0%	65%	100%	
	Overall Accuracy	57%				
B) CASALE						
Independent Aerial Damage Assessment	Not Affected	11	2	1	3	17
	Moderately Damaged	3	2	2	0	7
	Highly Damaged	0	3	1	2	6
	Completely Destroyed	3	1	2	19	25
	Total	17	8	6	24	55
	Class	Omission error	Commission error	P.A.	U.A.	
	Not Affected	35%	35%	65%	65%	
	Moderately Damaged	71%	75%	29%	25%	
	Highly Damaged	83%	83%	17%	17%	
	Completely Destroyed	24%	21%	76%	79%	
	Overall Accuracy	60%				
C) ILLICA						
Independent Aerial Damage Assessment	Not Affected	22	5	6	0	33
	Moderately Damaged	6	6	0	0	12
	Highly Damaged	6	12	2	11	31
	Completely Destroyed	1	6	2	27	36
	Total	35	29	10	38	112
	Class	Omission error	Commission error	P.A.	U.A.	
	Not Affected	33%	37%	67%	63%	
	Moderately Damaged	50%	79%	50%	21%	
	Highly Damaged	94%	80%	6%	20%	
	Completely Destroyed	25%	29%	75%	71%	
	Overall Accuracy	51%				
D) ACCUMOLI						
Independent Aerial Damage Assessment	Not Affected	114	0	0	0	114
	Moderately Damaged	23	0	0	0	23
	Highly Damaged	13	0	1	0	14
	Completely Destroyed	2	0	0	0	2
	Total	152	0	1	0	153
	Class	Omission error	Commission error	P.A.	U.A.	
	Not Affected	0%	25%	100%	75%	
	Moderately Damaged	100%	not applicable	0%	not applicable	
	Highly Damaged	93%	0%	7%	100%	

(*Continued*)

resolution due to high off-nadir angle) or to the presence of possible damage proxies like small traces of debris/rubble or sand deposit around the building. This class attribution can be given by inferring the state of the building from surrounding features. In flooding it could be traces of water currents leading up to and then leaving a building or set of buildings.

Table 3. (Continued).

		Copernicus Satellite Damage Assessment					
		Not Affected	Moderately Damaged	Highly Damaged	Completely Destroyed		Total
	Completely Destroyed	100%	not applicable	0%	not applicable		
	Overall Accuracy	75%					
		Not Affected	Negligible to slight damage	Moderately Damaged	Highly Damaged	Completely Destroyed	
E) SAN LORENZO E FLAVIANO Independent Aerial Damage Assessment	Not Affected	67	0	0	2	0	69
	Negligible to slight damage	0	0	0	0	0	0
	Moderately Damaged	18	0	2	1	0	21
	Highly Damaged	20	0	0	5	0	25
	Completely Destroyed	12	1	0	9	0	22
	Total	117	1	2	17	0	137
	Class	Omission error	Commission error	P.A.	U.A.		
	Not Affected	3%	43%	97%	57%		
	Negligible to slight damage	not applicable	100%	not applicable	0%		
	Moderately Damaged	90%	0%	10%	100%		
	Highly Damaged	80%	71%	20%	29%		
	Completely Destroyed	100%	not applicable	0%	not	applicable	
	Overall Accuracy	54%					

Point 61 (Accumoli): 13°14'55.492"E 42°41'39.48"N WGS-84

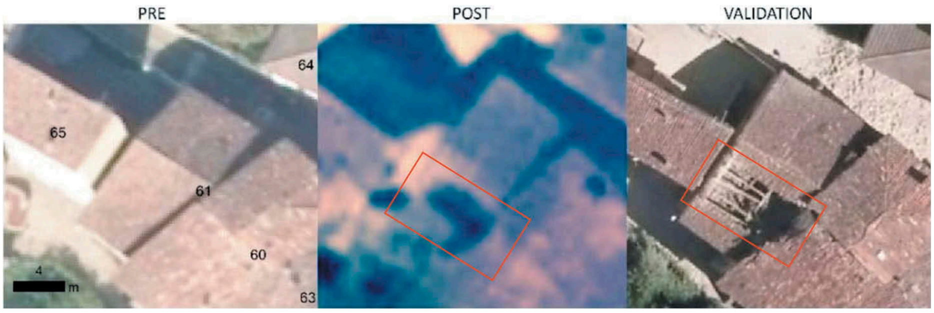

Figure 5. PRE: Accumoli pre aerial event image (GSD 0,2 m), POST: Accumoli post satellite event image (WV-2 sensor - GSD 0,5 m), VALIDATION: Accumoli post aerial event image (GSD 0,1 m).

- No Visible Damage: it shall be assigned to the structures that appear to have complete structural integrity, i.e. when the walls remain standing and the roof is virtually undamaged. It is important to remark that this class don't exclude the presence of structural damages, i.e. the building may anyway have suffered damages that can not be assessed from vertical satellite imagery regardless of is spatial resolution.

Step 6 – Application of the new damage scale on a different case study

The proposed building damage scale was validated as per Step 6 of the workflow shown in Figure 2. It was decided to apply the new building damage scale to assess the earthquake's impact on Pescara del Tronto, another town affected by the seismic event in Central Italy.

Ground truth generation: independent UAV damage assessment

The Ground Truth data were identified by performing a UAV-based damage assessment based on the comparison between the images listed below.

- Pre-event image: Orthophoto 0.2 m © 2014 CONSORZIO TeA (formed by e-GEOS S.p.A. – CGR S.p.A. – Aerodata Italia srl).
- Post-event image: UAV 0.7 m Team Direct (Disaster RECovery Team) of Politecnico of Turin (acquired and processed on 07/09/2016).

The UAV damage assessment in Figure 7 revealed that 18 structures showed no visible damage, 6 structures were classified as Possibly Damaged, 67 structures were damaged (40 structures suffered minor visible damage and 27 structures major visible damage) and 123 structures were destroyed.

Table 4. Confusion Matrixes related to the areas of Saletta(A), Casale(B), Illica(C), Accumoli(D), San Lorenzo e Flaviano(E). Copernicus EMS damage assessment ((aggregation of classes Negligible to slight damage, Moderately Damaged and Highly Damaged to "Damage") vs Independent aerial damage assessment.

		Copernicus Satellite Damage Assessment			
		Not Affected	Damaged	Completely Destroyed	Total
A) SALETTA					
Independent Aerial Damage Assessment	Not Affected	17	4	0	21
	Damaged	11	6	0	17
	Completely Destroyed	1	11	22	34
	Total	29	21	22	72
	Class	Omission error	Commission error	P.A.	U.A.
	Not Affected	19%	41%	81%	59%
	Damaged	65%	71%	35%	29%
	Completely Destroyed	35%	0%	65%	100%
	Overall Accuracy	63%			
B) CASALE					
Independent Aerial Damage Assessment	Not Affected	11	3	3	17
	Damaged	3	8	2	13
	Completely Destroyed	3	3	19	25
	Total	17	14	24	55
	Class	Omission error	Commission error	P.A.	U.A.
	Not Affected	35%	35%	65%	65%
	Damaged	38%	43%	62%	57%
	Completely Destroyed	24%	21%	76%	79%
	Overall Accuracy	69%			
C) ILLICA					
Independent Aerial Damage Assessment	Not Affected	22	11	0	33
	Damaged	12	20	11	43
	Completely Destroyed	1	8	27	36
	Total	35	39	38	112
	Class	Omission error	Commission error	P.A.	U.A.
	Not Affected	33%	37%	67%	63%
	Moderately Damaged	53%	49%	47%	51%
	Completely Destroyed	25%	29%	75%	71%
	Overall Accuracy	62%			
D) ACCUMOLI					
Independent Aerial Damage Assessment	Not Affected	114	0	0	114
	Damaged	36	1	0	37
	Completely Destroyed	2	0	0	2
	Total	152	1	0	153
	Class	Omission error	Commission error	P.A.	U.A.
	Not Affected	0%	25%	100%	75%
	Damaged	97%	0%	3%	100%
	Completely Destroyed	100%	not applicable	0%	not applicable
	Overall Accuracy	75%			
E) SAN LORENZO E FLAVIANO					
Independent Aerial Damage Assessment	Not Affected	67	2	0	69
	Damaged	38	8	0	46
	Completely Destroyed	12	10	0	22
	Total	117	20	0	137
	Class	Omission error	Commission error	P.A.	U.A.
	Not Affected	3%	43%	97%	57%
	Damaged	83%	60%	17%	40%
	Completely Destroyed	100%	not applicable	0%	not applicable
	Overall Accuracy	55%			

Damage class aggregation of copernicus EMS vs ground truth

The Copernicus EMS damage assessment was downloaded from the [EMSR177] Grisciano Grading Map, Monitoring 1. The downloaded datasets were based on the analysis of the images listed below.

- Pre-event image: Orthophoto 0.2 m © 2014 CONSORZIO TeA (formed by e-GEOS S.p.A. – CGR S.p.A. – Aerodata Italia srl).
- Post-event image: WorldView-2 © Digitalglobe, Inc. (2016), (acquired on 25/08/2016 09:45 UTC, GSD 0.5 m, approx. 0 % cloud coverage, 34° off-nadir angle), provided under Copernicus by the European Union, ESA and European Space Imaging.

Preliminary, the damage classes were aggregated to enable the comparison of the Copernicus EMS results with the Ground Truth. The adopted class aggregation is visible in Table 5.

The accuracy assessment was performed using a confusion matrix as per the previous analysis.

Like in the previous analysis conducted by Copernicus EMS, the overall accuracy is about 60%, even aggregating the critical damage classes. This

Damage Grade	Description of the related Damage	PRE Event Aerial (0.1m < GSD < 0.3m)	POST-Event imagery and brief Interpretation Guidelines: POST Event Satellite (0.3m < GSD < 0.5m)	POST Event Aerial (0.1m < GSD < 0.3m)	POST Event UAV (GSD < 0.1m)
Destroyed	Total collapse; collapse of part of the building (>50%); building structure not distinguishable (the walls have been destroyed or collapsed).		Building structure not distinguishable.	Total collapse of the building.	Total collapse of the building.
Damaged "Major" and "Minor" shall be used only when Aerial/UAV imagery (GSD<0.3 m) is available. Only "Damaged" grade when using Satellite imagery.	**Major**: Partial collapse of the roof; serious failure of walls (Tip: black spots on the rooftop suggest collapse of part of the roof).		Only "Damaged" grade when using Satellite imagery. Black spots on the rooftop suggest collapse of part of the roof.	Partial collapse of the roof.	Partial collapse of the roof
	Minor: The roof remains largely intact, but presents partial damage (Tip: white spots on the rooftop suggest tiles' lack or displacement and collapse of chimneys). Presence of damage proxies like large debris/rubble or sand deposit around the building.		The structure appears intact; large debris deposit on the ground.	Roof tiles detach. The structure appears intact; large debris deposit	Collapse of chimneys, roof tiles detach. The structure appears intact; large debris deposit
Possibly Damaged	Uncertain interpretation due to image quality (e.g. shadow or degraded resolution due to high off-nadir angle). Presence of possible damage proxies like small traces of debris/rubble or sand deposit around building. Building surrounded by damaged/destroyed buildings.		Small traces of debris deposit on the ground.	Small traces of debris deposit on the ground.	Small traces of debris deposit on the ground.
No Visible Damage	The structure appears to have complete structural integrity; the walls remain standing; the roof is virtually undamaged. **The building may anyway suffered damages that can not be assessed from vertical satellite imagery (from no to slight structural damage).**		The structure appears intact.	The structure appears intact.	The structure appears intact.

Figure 6. Proposed Building Damage Scale tailored to remote sensing vertical imagery.

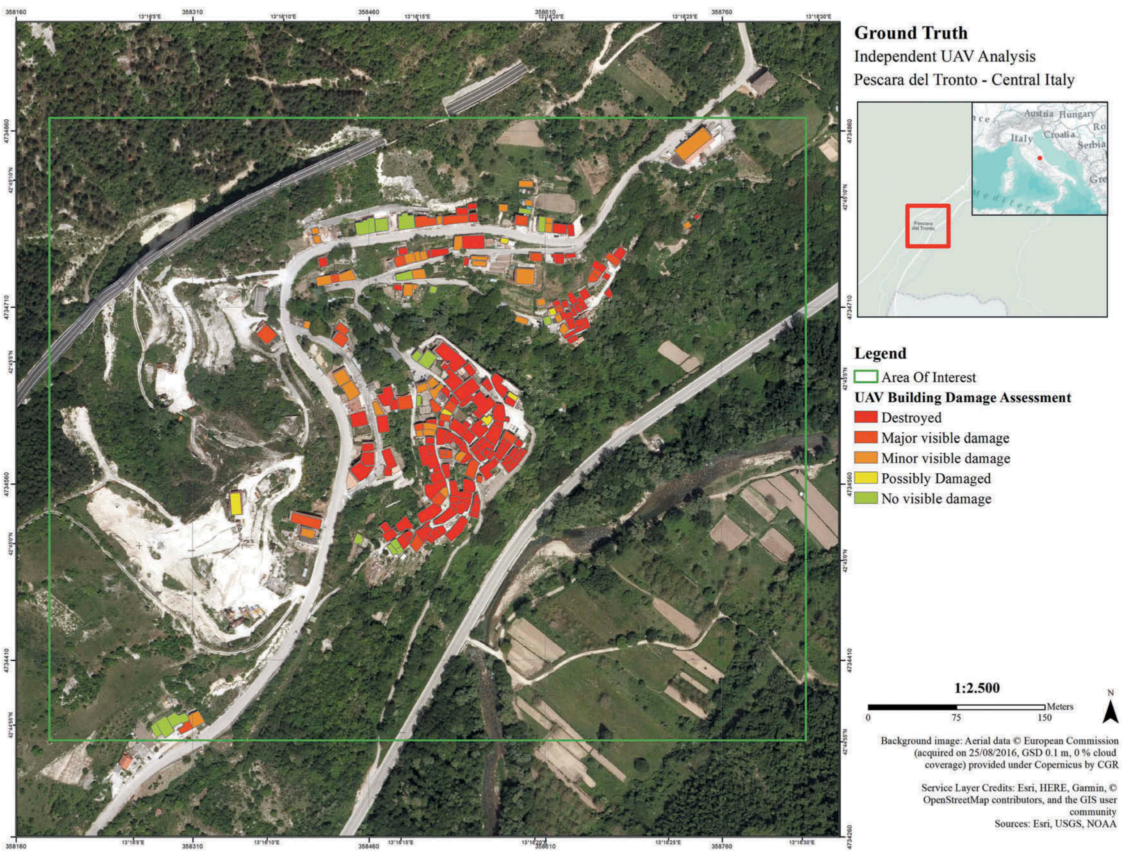

Figure 7. Building damage assessment (used as Ground Truth) of Pescara del Tronto and based on UAV imagery.

Table 5. Correspondence of Copernicus EMS Damage classes to the Proposed Building Damage Scale classes (for comparison purposes).

Copernicus EMS Damage classes	Proposed Building Damage Scale classes
Not Affected	No Visible Damage
Negligible to Slight Damage	Possibly Damaged
Moderately Damaged	Damaged
Highly Damaged	
Destroyed	Destroyed

result is due to the interpretation uncertainty of the intermediate classes as confirmed by the low P.A. (Possibly Damaged 0%, Damaged 15%) and U.A. values (Possibly Damaged 0%, Damaged 45%) of Table 6. This result confirm once again that also different interpretation guidelines should be developed and adopted.

Independent classification vs ground truth

The last validation is based on the generation of a new satellite-based damage assessment adopting the Proposed Building Damage Scale and the related interpretation guidelines (detailed in Figure 6) without time constraints. The images for the analysis are the same used by Copernicus EMS and listed in the previous section. The results were therefore compared to the Ground Truth generated from the UAV analysis. The accuracy assessment results are summarised in the Confusion Matrix shown in Table 7.

The P.A. reports high values for the classes No visible damage (100%), Possibly Damaged (83%) and Destroyed (98%) and a 46% for the Damaged class. The U.A. reports high values for the classes Damaged (94%) and Destroyed (100%). The No visible damage class has 42% accuracy and the Possibly Damaged class reports 28%. As expected the accuracy is lowest in the Possibly Damaged class. This is plausible, and depending on the characteristics of the satellite image, principally the spatial resolution (lower than the UAV spatial resolution used to extract the Ground Truth) and the atmospheric conditions (haze) which mostly affected the CAPI.

Nevertheless, the overall accuracy is 81%, i.e. an increase of about 20% with respect to the Copernicus EMS damage assessment.

Conclusions

The current lack of a standard building damage scale accepted and adopted by satellite emergency mapping entities at international level impacts on the emergency response phase. More specifically, it jeopardises the exploitation of emergency mapping products by the end users, especially when they need a comprehensive overview of the impact of the event over large areas, by means of:

- comparing and integrating analyses carried out by different SEM mechanisms over the same area;
- aggregating analyses covering different areas.

The evaluation of the thematic accuracy of a satellite-based building damage assessment generated by an operational emergency mapping service after the 2016 Italian earthquake highlighted that building damage assessments based on remote sensing vertical imagery are affected by intrinsic limitations, mainly related to the post-event imagery viewing angle and resolution.

In particular, it was demonstrated that damage scales based on structural damages (e.g. EMS- ’98 like) without specific visual interpretation guidelines are not suitable for analysis based on vertical imagery and limited (> 0.3 m) spatial resolution, especially when assessing the intermediate damage classes (from slight to moderate damages).

To cope with the aforementioned issues and according to the outcomes of the thematic accuracy assessment, a new building damage scale tailored to remote sensing vertical imagery and focused on visible damages (and damage proxies) was developed, including visual interpretation guidelines and examples based on imagery acquired by different platform (satellite, aerial and UAV) and characterised by different spatial resolution categories.

Table 6. Confusion Matrix related to the area of Pescara del Tronto. Copernicus EMS satellite damage assessment vs independent UAV damage assessment.

		Copernicus Satellite Damage Assessment				
PESCARA DEL TRONTO		No visible damage	Possibly Damaged	Damaged	Destroyed	Total
Independent UAV Damage Assessment	No Visible Damage	15	0	3	0	18
	Possibly Damaged	3	0	1	2	6
	Damaged	45	0	10	12	67
	Destroyed	10	0	8	103	121
	Total	73	0	22	117	212
	Class	Omission error	Commission error	P.A.	U.A.	
	No Visible Damage	17%	79%	83%	21%	
	Possibly Damaged	100%	0%	0%	0%	
	Damaged	85%	55%	15%	45%	
	Destroyed	15%	12%	85%	88%	
	Overall Accuracy	60%				

Table 7. Confusion Matrix related to the area of Pescara del Tronto. Independent satellite damage assessment vs independent UAV damage assessment.

		Independent Satellite Damage Assessment				
PESCARA DEL TRONTO		No visible damage	Possibly Damaged	Damaged	Destroyed	Total
Independent UAV Damage Assessment	No Visible Damage	18	0	0	0	18
	Possibly Damaged	1	5	0	0	6
	Damaged	24	12	31	0	67
	Destroyed	0	1	2	120	123
	Total	43	18	33	120	214
	Class	Omission error	Commission error	P.A.	U.A.	
	No Visible Damage	0%	58%	100%	42%	
	Possibly Damaged	17%	72%	83%	28%	
	Damaged	54%	6%	46%	94%	
	Destroyed	2%	0%	98%	100%	
	Overall Accuracy	81%				

The proposed damage scale, consisting of 4 classes (Destroyed, Damaged, Possibly Damaged and No visible damage) and not related to specific event types, was evaluated and tested on a different case study, demonstrating to enable a more robust and accurate analysis as well as a streamlined visual interpretation during the damage assessment phase. This simplified damage scale overlaps also with guidelines for classification of dwellings during field surveys proposed by the World Bank (The World Bank, 2003) as highlighted in (Meier, 2015).

The proposed building damage scale is currently adopted as a standard by the Copernicus EMS Rapid Mapping service when assessing damages to buildings for the grading maps of *Copernicus Emergency Management Service (© 2017* European Union), EMSR257, *Copernicus Emergency Management Service (© 2017* European Union), EMSR260 and *Copernicus Emergency Management Service (© 2018* European Union), EMSR269.

Additionally, the building damage scale was proposed also to IWG-SEM and it is currently under review by its members in the framework of the IWG-SEM Emergency Mapping Guidelines initiative.

Future work should focus on the adoption of the proposed scale using different data sources, including VHR satellite imagery with high off nadir angles (> 40°) and different azimuth angles as well as oblique aerial imagery, with the goal to analyse also building facades, thus overcoming the main limitations of vertical imagery.

The integration with georeferenced imagery acquired at street level (e.g. crowdsourced information acquired and shared through Mapillary) could also be tested for both validation and calibration purposes.

Disclosure statement

No potential conflict of interest was reported by the authors.

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