The Space Qualification Process of the LuGRE GNSS Payload

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***Abstract*—The Italian Space Agency (ASI) and the National Aeronautics and Space Administration (NASA) sponsored the Lunar GNSS Receiver Experiment (LuGRE), an exciting investigation that aims to provide Positioning, Navigation, and Timing (PNT) on the Moon. This paper describes the qualification process implemented to get LuGRE ready to fly in 2024. The payload verification campaign is detailed according to several prototypes and tests at different stages throughout the project. It followed a rigorous process, tailored to the specific requirements of each payload element, ensuring the payload ability to withstand the extreme environmental conditions of the LuGRE mission.**

Keywords—LuGRE, space, qualification, moon, test.

I. Introduction

In the last decades, an increasing interest in space opportunities has attracted both the academic and the industrial worlds. Under the auspices of the New Space Economy, governments and agencies worldwide are ensuring an exciting growth of the space sector, creating an infinite value to society [1]. The development of the Lunar GNSS Receiver Experiment (LuGRE) is a clear example of one of the ambitious challenges embarked by the two space agencies (NASA and ASI) in collaboration with the industry. Indeed, LuGRE is part of NASA's Commercial Lunar Payload Services (CLPS) Task Order 19D, which will fly on Firefly Aerospace's Blue Ghost lunar lander (BGM1) in 2024 for their first mission to the Moon [2]. The payload aims to provide the first GNSS fix at lunar distance.

Qualification tests are essential activities in space projects, performed on components ranging in size from small earth-orbiting scientific payloads to very large lunar-mission spacecraft [3] [4]. Several studies available in literature analyzed the importance of a comprehensive testing campaign to ensure the success of a space mission. At both system [5] and component level [6], the qualification process allows to characterize the system performance in terms of radiation sustainability, structural stability, and mechanical degradation [7].

This paper describes the approach employed for the development, testing, and validation of LuGRE. It dives into details on the complex process that resulted in the space qualification of the payload. After a general overview of its architecture in Chapter II, Chapter III describes the testing standards, model philosophy, and the components testing strategies. Moreover, Chapter IV investigates the verification control methods and approach, leaving the conclusions to Chapter V.

II. Payload Overview

The LuGRE payload has been designed as a robust, low-mass, and power efficient system able to withstand the severe conditions imposed by the mission environment. It consists of:

- A High-Gain Antenna (HGA), optimized for GNSS L1/E1 and L5/E5a bands.
- A Front-End Assembly (FEA), incorporating a Low Noise Amplifier (LNA) and a series of filters to isolate the receiving signals from noise and interferences.
- The QN400-SPACE receiver, Qascom's multi-constellation (GPS/Galileo) and multi-frequency (L1/L5) GNSS receiver, optimized for high-sensitivity acquisition in deep-space applications.
- Coaxial harnesses and cabling connecting all payload elements to each other and to the BGM1 lander.

The development process resulted in a flexible payload, with a total mass of less than 5 kg, able to match the high-level robustness required to endure the system dynamics. Moreover, with a maximum operational power of 14W, LuGRE has been able to meet the power constraints at lander-level. In addition, LuGRE met the Do-no-Harm requirements bounding the project.

The HGA was produced by the US Company Haigh-Farr, as a 3x3 planar passive L-band HGA, operating in the L1/E1 and L5/E5a GNSS bands. It is co-located with the lander X-band antenna on the top deck of the BGM1 lander (see Figure 1) in an Earth-pointed gimbal platform to achieve Earth visibility. Due to the presence of nearby instrumentation, the HGA has been tuned to limit out-of-band interference. Moreover, the antenna gain has been designed for deep space applications, allowing acquisition of GPS and Galileo signals throughout the lander journey to the Moon and once on its surface.

Figure 1: Firefly BGM1 Lander

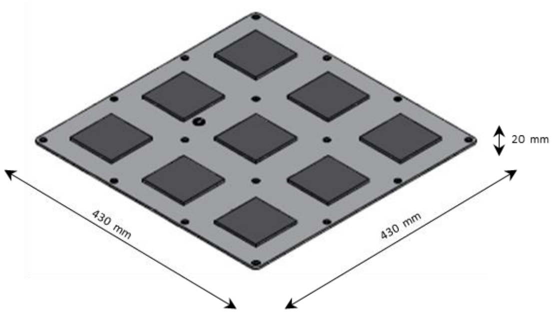

Figure 2: LuGRE HGA Layout

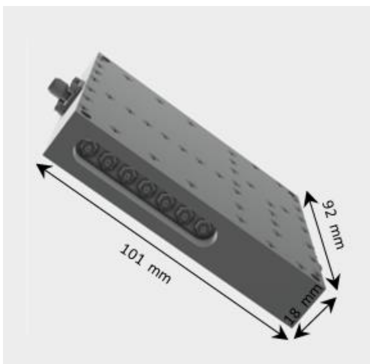

Figure 3:LuGRE LNA Layout

The FEA is mounted under the deck, and it is connected to the antenna through a coaxial harness. It is a dual-frequency device that contains a pre-selection band pass filter (BPF), followed by a Low-Noise Amplifier (LNA) and an equalizer (EQ). The FEA was designed to mitigate the imbalance introduced by the amplification stage. Therefore, the signals impinging the antenna are amplified and filtered throughout the RF chain to provide to the GNSS receiver a stronger and smoother input to acquire.

Figure 4: LuGRE QN400-SPACE GNSS Receiver

Finally, the QN400-SPACE receiver is connected via a coaxial cable with SMA female interface to the FEA. The receiver acquires and tracks GNSS signals and communicates with the lander On-Board Computer (OBC) through a RS422 serial connection via a DB-9 connector.

III. Assembly & Integration

Several challenges played a significant role in the development of the LuGRE payload, in particular the lack of raw materials due to the COVID 19 world crisis [8]—which led to a tremendous delay in the delivery of the various components—and the innate complexity of acquiring and tracking GNSS signals at lunar distances. The Assembly, Integration and Verification (AIV) process has been applied to each level of assembly, from element to system. It covered all activities necessary to ensure that the design fulfils the requirements, with adequate margin, under the operational and environmental conditions.

The verification objectives for the space qualification of the payload focused on:

- Qualifying and accepting both the design and development processes.
- Ensuring that the product was free from workmanship defects and acceptable for use.
- Verifying that the space system was able to fulfill mission requirements.
- Confirming product integrity and performance throughout the project lifecycle.

Moreover, a Design, Verification and Control Matrix (DVCM) tracked the payload development status throughout the project phases to:

- Guarantee systematic traceability of all requirements at each verification stage.
- Monitor the verification process.
- Clarify responsibilities in terms of requirements verification among this project partners.

Each element of the LuGRE payload has been developed in various prototypes to validate the system at various stages throughout the project life cycle, and according to the technology maturity level and heritage of each element. This approach represents a pillar in the realization of this project. Moreover, the process permitted the assessment of the LuGRE system in terms of reliability, functionality, durability, safety, confirming the payload's ability to withstand the extreme mission conditions.

The elements composing the LuGRE payload were validated using:

- An **Engineering Model (EM)**, which is commonly used in the preliminary phase of the system design. At this stage, this model is a partial or complete prototype of the overall system, and it focuses on verifying its performance and technical specifications. In particular, the LuGRE GNSS receiver presented an additional model configuration, the **Engineering Testing Unit (ETU)**. The ETU is not considered a development model, even if flight representative in form and fit. It is conceived only for interface testing, verification of test facilities and GSE. Therefore, it undergoes only functional and interface testing.
- An **Engineering Qualification Model (EQM)**, which is the first model used to demonstrate that the product meets the technical specifications required by the mission. During the EQM phase, the model is subjected to more strenuous qualification levels using simulated environments that are representative of the mission. At this stage, the tightest margins against the design requirements are considered.
- A **Flight Model (FM)**, which is the final model envisioned for the space mission. The FM is built using the same materials and manufacturing processes as the EQM. Even though it undergoes rigorous quality control to prevent reliability regression, it undergoes Acceptance testing where the safety margins are more relaxed than for the EQM model.
- A **Protoflight Model (PFM)**, whose design generally relies on previous heritage. This method is based on building a prototype which is already ready to flight. This model is subject to a rigorous qualification test program that combines elements of both prototype and flight acceptance verification [9] [10].

Depending on the stage of the project, the models previously described may be subjected to shock, vibrations, thermo-vacuum, Electromagnetic Interference (EMI) – Electromagnetic Compatibility (EMC), and functional tests. Based on the results of these tests, updates can be applied to the model design and its manufacturing processes.

A. *Standards & Techniques*

The testing and verification process conducted in the LuGRE project was a crucial activity that ensured the correct functionality and performance of the overall payload. To achieve such result, the design, development, and testing of all its elements required a systematic and rigorous approach. LuGRE is a payload developed for ASI under an international agreement between ASI and NASA within NASA's Artemis program [2]. The qualification test campaign was therefore based on the NASA-STD-7000A General Environmental Verification Standard (GEVS) [11], which relates to the MIL-STD-461F standard [12]. In addition, the verification process and the relevant documentation were derived from the standard ECSS-E-ST-10-02C Rev.1 [13].

The GEVS standard is used in NASA - Goddard Space Flight Center (GSFC) projects and has been adapted to produce a LuGRE-specific verification and specification plan that is in line with a Do No Harm approach. The GEVS provides guidelines for environmental verification of space programs involving payloads, subsystems, and components. Moreover, it suggests implementation methods to demonstrate, through testing or analysis, the satisfaction of the project requirements. The standard applies to:

- All space hardware, including interface hardware, developed as part of a GSFC-operated payload, whether developed by GSFC or one of its contractors, another NASA center, or an independent agency [11].
- All space hardware, including interface hardware, developed by GSFC or one of its contractors and provided to another NASA facility or independent agency as part of a payload not operated by GSFC [11].

Besides the environmental campaign, the LuGRE payload underwent an EMI – EMC qualification process. It included tests derived from the NASA-STD-7000A section 2.5 [11], referring to the MIL-STD-461F standard [12]. The EMI-EMC campaign proved the electrical compatibility and Do-No-Harm (DNH) condition of the system with the BGM1 lander interface. It included the following test categories, performed inside an EMI chamber to test common and differential modes, along with turn-on transients [14].

- Radiated Emissions (RE)
- Radiated Susceptibility (RS)
- Conducted Emissions (CE)
- Conducted Susceptibility (CS)

B. *Development Logic*

The current section will provide details on the development, testing and verification processes that each of the LuGRE payload element underwent throughout the project.

1) HGA

The design of the HGA and LNA occurred together in order to enable proper GNSS reception at lunar altitude. The HGA design was based on well-established technology adapted to meet the project's unique requirements and constraints. A PFM approach was chosen to address the limited time available for its development. This required a thorough research for hardware components, whose selection criteria focused on prioritizing available and reliable commercial off-the-shelf (COTS) products. This approach proved to be the most effective in terms of time and resources, minimizing production complexity.

The final product met all project specifications and mission requirements. The HGA was specifically designed to endure the lunar and cislunar environments, with extreme temperatures from -145°C to +125°C, and potential effects of cosmic radiation. Moreover, it was refined to sustain mechanical durability, to operate with a high bandwidth, and show efficient power density in transmission.

A crucial objective in the antenna design process was the maximization of the receiving gain, needed to increase the QN400-SPACE receiver acquisition probability. This proved to be a particularly challenging task given the relatively small physical aperture available on the lander deck (see Figure 1) and the relative lightness and flatness requirements for the antenna's layout (see Figure 2). As the antenna was obtained with a planar array of 9 elements, arranged in a 3 x 3 squared lattice, the element spacing of the array had to be optimized to maintain the gain and reduce both side and back lobes of the antenna pattern.

The resulting antenna provides more than 14 dBic of gain at boresight and peak sidelobes level of more than 10 dBic. Due to the fluctuations in the HGA's field of view related to the GNSS orbits' dynamics, the main lobe beamwidth was designed as large as possible, allowing the pointing mechanism to sustain a +/- 1 degree of pointing error. Moreover, to be able to receive GNSS signals, the antenna has been designed with a circular polarization (RHCP).

These features complicated the system design, leading to a trade-off on the performances between L1 and L5 frequencies, as well as the balance between polarization purity and efficiency. Another challenge was constituted by the near proximity of a TT&C antenna in X-band on the BGM1 lander's top deck. Hence, a level of isolation has been added, embedding a filter in the antenna feeding network.

2) FEA

The LNA embedded in the FEA was designed by the US company dB Microwave. It is a dual-band high-gain amplifier with a very selective profile around the L1 and L5 bands. Employing custom resonance filters guaranteed a gain above 40 dB at both frequencies with more than 70 dB isolation outside the passband and good roll-off factors. Moreover, higher frequency harmonics and saturation effects related to the TT&C antenna have been mitigated using dedicated filtering.

3) Receiver

The LuGRE QN400-SPACE is an advanced GNSS receiver, designed to provide PNT solutions in outer space. A modular approach has been adopted in its development process to reduce the risks of potential Single Event (SE) effects due to the radiation environment and to increase the reliability of the receiver itself.

The architecture consists of two identical and independent QN400 receiver modules, each subsequently qualified for space applications. Given the mission complexity, a cold redundancy configuration was implemented by the addition of a supervisory board (SB). This board allows selection between the two receiver boards, nominally or based on overcurrent events. Moreover, it monitors the power consumed by the active receiver, providing protection against Single-Event Latch-up (SEL) events.

The flexibility of Qascom GNSS receiver product is derived from the Software Defined Radio (SDR) technology, which has been a well-established knowledge for Qascom for the last several years. The receiver hardware and software configuration utilize previous flight heritage of Qascom's QN400 receiver product on space missions with ASI and NASA [15] [16] [17] [18].

Three different receiver models were involved in the development process of the QN400-SPACE receiver. The first model (EM) was designed to perform the first functional tests and verify the general architecture. The second model (EQM) was used to qualify the receiver for environmental requirements with particularly tight tolerances. Finally, by systematically adjusting the design towards the acceptance stage, the FM has been shaped and it got ready to flight in space. As the final version of the receiver, the FM has a special black paint finish, which is characterized by a high ability to absorb solar radiation. Compared to the EQM model, the FM has been subjected to tests with less stringent tolerances to verify its effectiveness and ensure its full operability.

The testing process on the models was characterized by Test Readiness Reviews (TRR) at the start of each test campaign, as well as Test-Readiness-Boards (TRB), held to assess the relative preliminary results. Subsequently, the model's performance was reviewed in Delivery Review Boards (DRB) to promote the campaign and proceed to the next development or testing phase.

4) Harness

Two separate batches of cabling were prepared, one for qualification and one for flight. The cabling was designed using existing space-qualified coaxial cables. Haigh-Farr, as the antenna supplier company, assembled and tested the cable batches to verify their ability to operate successfully in all mission-critical environments and over their lifetime. As the RF chain is divided in two separate stages by the lander deck, the cables were tested at different relative operating temperatures, as:

- For the harness connecting the HGA to the LNA in the lander top deck, the operative range was -145<T<125°C.
- For the harness connecting the LNA to the GNSS receiver under the deck, the operative range was -35<T<50°C.

IV. Verification

In the context of the LuGRE project, the verification methods varied from testing, review of design (RoD), analysis and inspection, in accordance with the GEVS [11] and ECSS standards [13]. Depending on the stage of the project, the same requirements have been verified using different methods, to allow for a broader comprehension of the system and a more detailed qualification. Moreover, this approach allowed to form a complete assessment of the payload's maturity, ensuring its maximum efficiency and performance reliability during the mission.

This section focuses on the verification of the payload and the methods used to ensure the correct functioning of the overall system.

A. Verification Methods

The system verification methodology is based on two main levels:

- At the element level, the approach includes several test campaigns specifically designed to check the elements alignment with the technical specifications.
- At the payload level, the view expands. It is layered in two levels: the first, involving the engineering and/or qualification models (EM; EQM) of each of the elements (i.e., GNSS receiver, the LNA, and the cabling), the second including flight and/or proto-flight models (PFM, FM) of all payload elements.

In particular, Qascom successfully performed a comprehensive environmental and functional test campaign on the hardware and software of the LuGRE GNSS receiver. The remaining elements of the RF chain, i.e., the HGA, LNA and harness, were supplied and environmentally and functionally tested by the manufacturer Haigh-Farr.

The entire payload underwent functional and interface testing in its flight-like configuration at NASA GSFC facility in Maryland. The aim of this step was to evaluate the overall system in different realistic mission scenarios to identify any criticalities that may arise during the mission. Finally, Firefly Aerospace, as the lander design authority, is responsible for end-to-end testing the payload functionality and interface when integrated with the Lander. The final pre-launch checks will be performed at the Kennedy Space Center (KSC), preparing the system for flight.

B. *Verification Process*

1) *GNSS Receiver*

The verification test campaign of the QN400-SPACE receiver aimed at confirming the satisfaction of its functional requirements, as well as testing its robustness to possible failures relative to the extreme environmental conditions of the LuGRE mission.

The functional verification was performed by testing its behavior in different relevant test scenarios and test cases. Two types of procedures were conceived, as:

- A full functional test procedure (FFT), which verifies the majority of the requirements pertaining to a specific flight software (FSW) release.
- A short functional test procedure (SFT), aimed at confirming the integrity of the device after a specific qualification or acceptance step.

Although the ETU is a representative model in terms of size, hardware, and functionality, it was designed only to test the main interfaces and for limited functional verification. Therefore, it was not subjected to a rigorous qualification campaign.

Both the EQM and FM campaign for the LuGRE receiver was based on a tailored version of the NASA's GEVS 7000A [11]. Figure 5 and Figure 6 present these processes. The plan defined the qualification test guidelines as well as the thermomechanical environment (shock, sinusoidal, random, and TVAC test) and EMC/EMI measurements performed. The acceptance tests included only thermomechanical tests, without shock, assuming less restrictive ranges than those used during the qualification phase, as required by the literature.

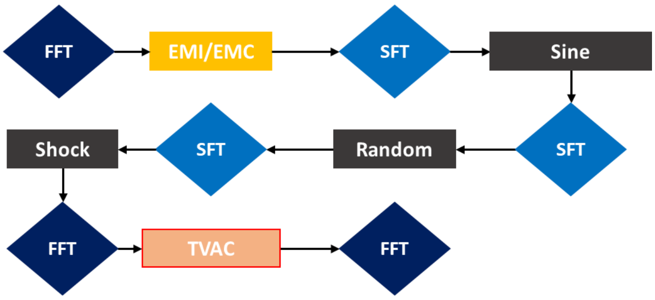

Figure 5:QN400-SPACE EQM Receiver Qualification Test Campaign

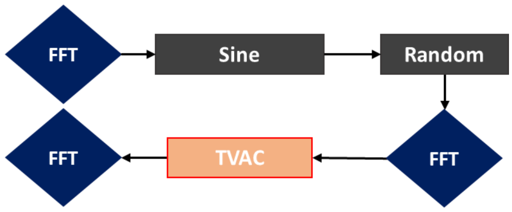

Figure 6: QN400-SPACE FM Receiver & LNA Acceptance Test Campaign

2) *LNA*

The verification of the Low Noise Amplifier (LNA) was performed by dB Microwave and Qascom. This latter was responsible for the functional verification of the LNA during the qualification and acceptance campaign.

The LNA qualification campaign is presented in Figure 7. It was based on GEVS 7000A [11] and it was specifically tailored to the requirements relative to this element. The LNA was acceptance tested with the GNSS Receiver as shown in Figure 7.

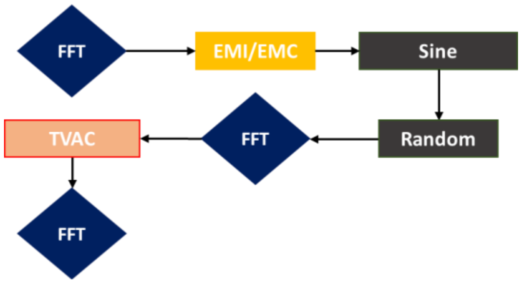

Figure 7:LuGRE LNA Qualification Test Campaign

3) *HGA*

Verification of the HGA involved a series of preliminary tests including unit inspection, VSWR verification, radiation pattern, and polarization purity verification. The HGA protoflight campaign followed the test sequence shown in Figure 8, adapted to the limits and durations defined by the design requirements and NASA GEVS guidelines [11].

The HGA protoflight campaign aimed at assessing its ability to withstand the extreme environmental conditions experienced in the LuGRE mission. Finally, it was subjected to a post-environmental test performance measurement phase.

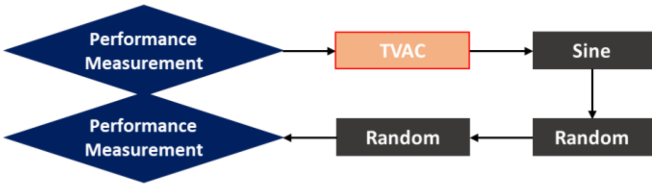

Figure 8: LuGRE HGA Protoflight Test Campaign

4) *Harness*

Finally, the LuGRE harness was also the subject of an extensive qualification campaign. To prevent thermal exhaustion of the harness, two separate batches were tested. The verification approach is described in Figure 9.

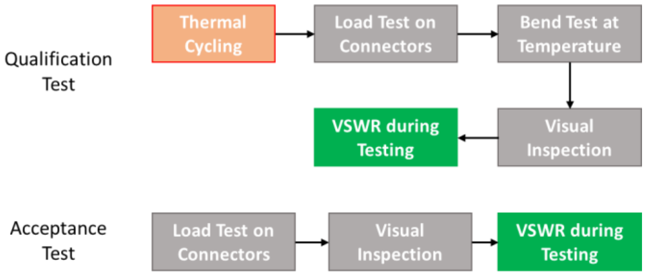

Figure 9: LuGRE Harness Test Campaign

V. Conclusions

The development of the LuGRE payload has been a deeply stimulating project. Undoubtedly, it has been challenged by several factors, such as the spread of the COVID-19 pandemic, the overall design complexity and the number of entities spread around the World involved with various levels of responsibility in the process. Nevertheless, the implemented Assembly, Integration and Verification (AIV) process ensured that the payload fulfilled stringent requirements under all operational and environmental conditions. The verification process implemented, together with the use of multiple prototypes and tests throughout the project lifecycle, enabled to parallelize several concurring activities ensuring all individual elements and the entire payload system to be ready to fly to the Moon.

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References

[1] The European Space Agency (ESA), ESA Space Economy, Available at https://space-economy.esa.int/ , Accessed on 05/24/2023

[2] Parker, J.J., Dovis, F., Anderson, B., Ansalone, L., Ashman, B., Bauer, F.H., D'Amore, G., Facchinetti, C., Fantinato, S., Impresario, G. and McKim, S.A., 2022, January. The lunar gnss receiver experiment (lugre). In Proceedings of the 2022 International Technical Meeting of The Institute of Navigation (pp. 420-437)

[3] The National Aeronautics and Space Administration (NASA), NASA SP-8044, NASA Space Vehicle Design Criteria (Structures) – Qualification Testing, Available at https://ntrs.nasa.gov/api/citations/19710019569/downloads/19710019569.pdf, Accessed on 05/24/2023

[4] The National Aeronautics and Space Administration (NASA), NASA SP-8045, NASA Space Vehicle Design Criteria (Structures) – Acceptance Testing, Available at https://ntrs.nasa.gov/api/citations/19710021557/downloads/19710021557.pdf, Accessed on 05/24/2023

[5] Sanford, G.E. and Welsh, J.S., 2004. EELV SECONDARY PAYLOAD ADAPTER(ESPA) STATIC QUALIFICATION TESTS. Experimental Techniques, 28(1), pp.34-36.

[6] Rajkowski, T., Saigné, F. and Wang, P.X., 2022. Radiation qualification by means of the system-level testing: Opportunities and limitations. Electronics, 11(3), p.378.

[7] Lee, K.J., Oh, H.U., Jo, M.S. and Kim, D.J., 2012. Verification of Optical Payload CFRP Structure For Satellite Through Analysis And Space Qualification Test. 28TH Int. Congr. Aeronaut. Sci, pp.1-10.

[8] Frieske, B. and Stieler, S., 2022. The "Semiconductor Crisis" as a Result of the COVID-19 Pandemic and Impacts on the Automotive Industry and Its Supply Chains. World Electric Vehicle Journal, 13(10), p.189

[9] Coan, M.R., Hirshorn, S.R. and Moreland, R., 2015. Internal NASA Study: NASAs Protoflight Research Initiative (No. KSC-E-DAA-TN25195). Aerospace Research Central

[10] NASA Technical Standards System (NTTS), Payload Test Requirements - NASA-STD-7002, NASA, 06/06/2018, Available at https://standards.nasa.gov/standard/NASA/NASA-STD-7002, Accessed on 05/24//2023

[11] NASA Technical Standards System (NTTS), General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects, GSFC-STD-7000, Version 04/28/2021, Available at https://standards.nasa.gov/standard/GSFC/GSFC-STD-7000, Accessed on 05/30/2023

[12] NASA Technical Standards System (NTTS), Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, MIL-STD-461, Version 12/11/2015, Available at https://standards.nasa.gov/standard/NASA/MIL-STD-461, Accessed on 05/30/2023

[13] European Cooperation for Space Standardization, ECSS-E-ST-10-02C Rev.1 – Verification, Version 01/02/2018), Available at https://ecss.nl/standard/ecss-e-st-10-02c-rev-1-verification-1-february-2018/, Accessed on 05/30/2023

[14] Mallette, L.A. and Adams, R., 2011. Introduction to EMI/EMC test requirements for space applications. IEEE Aerospace and Electronic Systems Magazine, 26(6), pp.24-29

[15] Longo, R., Bartolucci, M., Longhi, F., Bergamin, M., Fantinato, S., Pozzobon, O., Miller, J.J., Valencia, L., Magnuson, E., De Leon, P. and Flaherty, B., 2020, September. GARHEO Flight Experiment to Test GPS-Galileo Interoperability to Support Launchers and Space Missions. In Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020) (pp. 1301-1317)

[16] Croissant, K., Jenkins, G., McKnight, R., Peters, B.C., Ugazio, S. and van Graas, F., 2021, January. Bobcat-1, the Ohio University CubeSat: preliminary data analysis. In Proceedings of the 2021 International Technical Meeting of The Institute of Navigation (pp. 625-636)

[17] Ugazio, S., Arnett, Z., McKnight, R. and Peters, B.C., 2023, January. Receiver-Specific GNSS Inter-System Bias in Low Earth Orbit. In Proceedings of the 2023 International Technical Meeting of The Institute of Navigation (pp. 831-843)

[18] Enderle, W., Schönemann, E., Gini, F., Otten, M., Giordano, P., Miller, J., Sands, O.S., Chelmins, D. and Pozzobon, O., 2019, September. The joint ESA/NASA Galileo/GPS Receiver Onboard the ISS–The GARISS Project. In Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019) (pp. 1147-1156)