THE INNOVATOR CUBESAT MISSION AND THE DEVELOPMENT OF ITS INTERSATELLITE LINK TRANSCEIVER (ISL-T)

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ABSTRACT

The INNOVATOR project (INtersatellite liNk fOr graVity and ATmOspheRic science) is part of Italian Space Agency (ASI)'s ALCOR program, and it is dedicated to in-orbit testing of an innovative payload able to perform very accurate radio science observations in the field of gravity science and atmospheric science. The payload includes an InterSatellite Link Transceiver (ISL-T) for TT&C, ranging and range-rate measurements. The mission will place 2 6U CubeSats in the same low Earth orbit, with a relative distance variable depending on the phase of scientific observations. The two CubeSats will be connected via radio by the ISL-T measurements, allowing gravity and high-altitude atmospheric profiling to validate the performance of the ISL-T itself. Relative ranging and range-rate measurements are essential for precision orbit determination and for a very accurate estimation of all the accelerations acting on the CubeSats. Moreover, the stable Doppler link between them enables atmospheric radio occultations, providing measurements of density, temperature, pressure, and information on the Total Electron Content (TEC). All these elements are of fundamental scientific interest, both around the Earth and around other planets. This paper describes the current status of the INNOVATOR project and the outcomes of the Phase A study.

1 INTRODUCTION AND SCIENTIFIC MOTIVATION

The INNOVATOR project (INtersatellite liNk fOr graVity and ATmOspheRic science) was approved as part of ASI's ALCOR program and aims to in-orbit testing of an innovative payload that allows very accurate radio science observations to enable space experiments in the field of gravity science (determination of planetary masses and gravity fields) and atmospheric science (determination of the properties of neutral and ionized atmospheres). The payload consists of an InterSatellite Link Transceiver (ISL-T) incorporating the following functions: (i) TT&C, (ii) ranging measurements, and (iii) range-rate measurements. For the in-orbit validation, a mission is currently in the definition phase, and this foresees the launch of 2 6U CubeSats, to be placed in the same low

Earth orbit, with a relative distance variable depending on the phase of scientific observations. The two CubeSats will be constantly connected via radio by the ISL-T measurements, allowing gravity and high-altitude atmospheric profiling in low Earth orbit to experiment and validate the performance of the ISL-T itself. Relative ranging and range-rate measurements are fundamental to enabling a precision orbit determination process, which brings, as a by-product, the ability to estimate very accurately all the accelerations acting on the two spacecraft. Furthermore, the presence of a very stable Doppler link between the two satellites allows for atmospheric radio occultations, which directly provide density/temperature/pressure measurements of the portion of the atmosphere included along the line of sight, as well as information on the Total Electron Content (TEC), all quantities of enormous scientific interest both around the Earth and around other planetary bodies.

The motivation for this demonstration mission in LEO lies in the possibility of exploring and investigating in detail the interior and atmospheres of several interesting bodies in the solar system, particularly the so-called "ocean worlds" [1]. To this aim a precision orbit determination process allows a detailed estimation of all the accelerations acting on the spacecraft, thus giving the possibility of estimating the masses and gravitational fields of the planetary body under study, its dynamical properties, and density models for surrounding gases and/or dust. Traditionally, the observable quantities used by scientific experiments to determine planetary gravity fields are obtained through radio tracking of the probes, at frequencies in the microwave range, by a ground antenna (DSN or ESTRACK) [2]. Generating these radio observables requires the probe's onboard antenna to point in the Earth's direction and use an onboard coherent radio transponder. Both of these constraints impact spacecraft resources, including mass, power, and attitude control. For this reason, in recent years different systems have been proposed for radio tracking for the purpose of determining gravity fields. We refer, in particular, to satellite-to-satellite tracking systems, already used for the NASA Gravity Recovery and Climate Experiment (GRACE) [3] and Gravity Recovery and Interior Laboratory (GRAIL) [4] scientific missions.

In recent years, a clear trend has emerged to propose space missions (including deep space exploration and observation) carried out using small satellites (e.g. CubeSats) that can fly as secondary payloads and are released at their destination to perform specific tasks and communicate via the mother probe or directly with the Earth. The added value for planetary science and exploration is twofold: (a) increasing the quality and quantity of primary scientific objectives; (b) enable new observations in potentially hazardous environments with lower-cost platforms [5][6]. By combining the benefits of the satellite-to-satellite tracking (SST) technique, already used in the GRACE and GRAIL missions, with the enabling technologies tested in the field of small missions, it would be extremely useful to have small-sized ISL systems. The requirement is to simultaneously determine the distance and relative velocity (range and range-rate) between different components of a small constellation (two or more smallsats or between a smallsat and the mother probe), but also to provide TT&C services. This concept is currently being implemented only on the ESA Hera mission, where the mother probe will make range and range-rate measurements with two CubeSats (called Juventas and Milani), released near the binary asteroid Didymos [7][8].

Radio occultations also provide unique possibilities for determining the physical state, also dependent on time, and the chemical composition of the Earth's and planetary atmospheres. As part of the LEO mission proposed in this project, satellite-to-satellite radio communication allows density, temperature and pressure measurements to be carried out at high altitudes, starting from LEO altitude down to significantly lower altitudes.

In addition to the extraordinary results in the field of gravity science and atmospheric science described above, the ISL measurements would be beneficial to all those missions that require formation flying between satellites with very stringent position and relative velocity control requirements. In particular, the use of a combined topology of two CubeSats would allow the realization of missions for a Distributed Synthetic Aperture Radar (DSAR).

2 SCIENCE NEEDS AND PRELIMINARY CONCEPT OF OPERATIONS

2.1 Reference Mission Scenario

The INNOVATOR mission involves the launch of 2 6U CubeSats, to be placed on the same orbit with a variable relative distance depending on the phase of scientific observations. The main objective is to test in orbit (IOD/IOV) a new scientific instrument that allows very precise radio science observations, in particular in the fields of gravity science and atmospheric science. The payload is an InterSatellite Link Transceiver (ISL-T) that incorporates the following functions (all relating to the two or more satellites of the constellation): (i) TT&C, (ii) ranging measurements, (iii) range-rate measurements. The mission involves two distinct phases. In the first 6 months (Phase I), the two CubeSats will fly at relative distances of around 20km, and the ISL-T system will be used mainly for ranging and range-rate measurements (to estimate the Earth's gravity field, and compare it with the benchmark provided by the GRACE mission). Subsequently (Phase II), the satellites will be moved apart, up to ~5000km, so that the chord of the line of sight between the two satellites reaches the Earth's surface (this configuration is based on the nominal orbit hypothesis of the two CubeSats with altitude of ~500 km). In this second phase, the focus will be on radio occultations, at increasingly lower altitudes, to observe the Earth's atmospheric density/pressure/temperature profiles with excellent spatial and temporal continuity. The orbital maneuvers expected during the operational life of the two satellites can be grouped into 2 main categories: 1. Initial rephasing maneuver between the two satellites immediately after release into orbit, which will bring the two satellites to a relative distance of about 20 km, as required by the mission requirements for Phase I. 2. Rephasing maneuver between Phase I and Phase II, therefore moving from a distance of ~20 km to ~5000 km, to carry out atmospheric occultations.

2.2 Relative CubeSat Dynamics

In Phase I, both CubeSat will fly for 6 months at an identical relative distance of ~20km, required for the gravity science experiments. This relative distance (or, which is the same, relative phase difference $\Delta\varphi$) is obtained via pair of maneuvers. In summary, at a certain time T0 both satellites are commanded with a propulsion maneuver referred to as DV1 and DV2, in the same and opposite direction of the velocity, respectively. This places (i) Sat1 on an eccentric orbit with a larger semimajor axis with respect to the original orbit and (ii) Sat2 on an eccentric orbit with smaller semimajor axis with respect to the original orbit. When the faster satellite Sat2 completes one orbital period along its rephasing eccentric orbit its trajectory is circularized along the original circular operational orbit. Afterwards, when the slower satellite Sat1 completes one orbital period along its rephasing eccentric orbit its trajectory is circularized along the original circular operational orbit. At this point, Sat1 and Sat2 are back on track along the original circular operational orbit, but their phases differ by a phase angle $\Delta\varphi$, and the INNOVATOR Phase I is considered to start, for gravity science observations.

In Phase II, a very similar maneuvering approach to the one illustrated above will be followed to obtain the spacing between 20 km and 5000 km and get to the Radio Occultation science mode. Basically, we simply execute the $\Delta V1$ and $\Delta V2$ propulsion maneuvers to obtain two modified orbits with a different semi-major axis, such in a way that Sat1 and Sat2 will thus be orbiting along two slightly different quasi-circular orbits, and their phase difference will continuously increase, up to the desired distance, without the need for further propelled maneuvers. Our preliminary trajectory design led us to the conclusion that for a complete radio occultation to offer meaningful science results we need to sweep the ~20 km to ~5000 km distance with CubeSat relative velocity in the order of 4 m/s, thus requiring each CubeSat to carry out an initial maneuver of about 2 m/s. However, at the end of each radio occultation observation, we do not stop the relative motion of the two CubeSats, and we will leave the two satellites to continue drifting until the "fast" CubeSat reaches the "slow" CubeSat from behind, and a new radio occultation observation period could start. The 4 m/s value of the relative velocity between CubeSat A and CubeSat B yields the result that a single radio occultation period is covered in ~5 days, and that ~35 days are required for the two CubeSats to realign, so that a new radio occultation period can start. Thus, we conclude that in 200 days (the ~6 months of Phase II), we can carry out 5 full cycles of ~40 days, each including ~5 days of radio occultation observations and ~35 days of satellite free phase drifting.

3 INNOVATOR PLATFORM

The Innovator Satellite is a CubeSAT 6U platform, in particular 6U XL. To perform the scientific mission and the Intersatellite link, a 3-axis attitude stabilization is used and, in addition, a propulsion system allows the orbit manoeuvres required for both operative mission and de-orbiting phases. Most of the subsystems are COTS items, propulsion and solar panels are customised starting from off-the-shelf items; the customization has to be considered as "minor" maintaining the TRL 7 as design maturity. All units, except the payload, have flight heritage.
The payload, instead, is a custom design, developed in the INNOVATOR project framework, even if the antenna is a COTS one (with flight heritage). The data generated by the payload, are sent to the Ground Station through the satellite S-band link, as for the uplink commands.

The following subsystems and units are included in each INNOVATOR spacecraft:

- 6U XL Structure
- EPS II (4S2P, 84 Wh) + 1 Power Distribution Module
- 2x 3U Deployable Solar Panels
- 1x 6U Body Mounted Solar Panel
- 1x UHF Transceiver
- 1x 2U UHF Antenna footprint
- 1x S-Band Transceiver I
- 1x WideBand S-Band TMTC Antenna
- 1x OBC (with GNSS receiver)
- 1x GNSS Patch Antenna
- ADCS Suite
    - 1x Fine Sun Sensor
    - 1x IR Nadir Sensor
    - 3x magnetorquer
    - 10x coarse Sun Sensors
    - 3-axis deployable magnetometer
    - 3-axis non deployable redundant magnetometer
    - 3x Reaction Wheels
- 1 x Propulsion
- 1 x Payload ISL
- 1x WideBand S-Band Payload Antenna

Figure 1 shows a preliminary subsystem allocation in the satellite, while Table 1 shows the platform main performances.

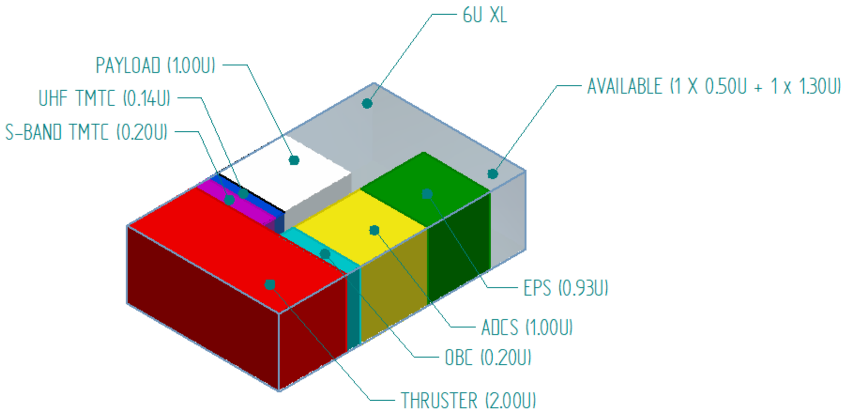

Figure 1. Satellite Volume Budget

Table 1. Platform main performances

Parameter	**Value**
Platform Type	CubeSAT 6U XL
Communication	TX/RX UHF TX/RX S-BAND
ADCS pointing accuracy	< 2°
Propulsion	Electrothermal Propulsion
Propellant Type	Water
DV	~ 50 m/s
Solar Panels	2 x Deployable Solar Panels
Solar Panel Peak Power	45W @ BOL
Battery Pack Capacity	84 Wh
Platform Dry Mass	10.5 Kg
Platform Wet Mass	10.9 Kg

4 INNOVATOR PAYLOAD: THE ISL-T

The InterSatellite Link Transceiver (ISL-T) constitutes the central element of the INNOVATOR project, carrying out the functions of reception, transmission and processing of the signal. The ISL-T devices mounted on board the two CubeSats will share the same hardware platform and differ exclusively in the reception and transmission frequencies, which are configurable by command, as well as the coherence function and those associated with the ranging and range-rate measurements (Doppler).

Table 2 shows the ISL-T parameters.

Table 2. ISL-T parameters

Characteristics	Value/Configuration
Digital interfaces	- CAN BUS (for Telemetry and Commands) - RS422 (for Payload data)
Power supply voltage	(12V-16.8V) or (24V-33.6V)
Uplink	2025 – 2110 MHz or 2200 – 2290 MHz
Downlink	2200 – 2290 MHz or 2025 – 2110 MHz
TX output power	Up to 1.5 W
Compatibility	Form factor PC 104-compatible
Power consumption in typical condition	- RX Only : 12,5 W - Rx + TX : 25 W
Total mass	Less than 978 g
ISL-T Size	1U

4.1 Architecture Overview

The ISL-T architecture is based on the following fundamental elements:

- Polarfire FPGA from Microchip supplied in plastic package (that also embeds the LEON2FT Microprocessor)
- AD9361 RF Transceiver from Analog Device
- Frequency reference: 80 MHz OCXO type RK406NS (RAKON)
- CHA3801 type low-noise amplifier (UMS)
- High power amplifier: SGM6904GPC-S (Sumitono Electric)

Specifically, the ISL-T includes five modules:

- Digital Module (PCB Based) with TT&C Rx section
- TM/TC Module (PCB Based) & Post Regulator section
- S-Band RF Module (RF-on-PCB Based)
  - TT&C Tx section for low power section
- Diplexer Module
  - Pre-select Filter
  - Notch Filter
  - Circulator
- DC/DC Converter Module (PCB based)

The receiver section is based on a single down-conversion stage. The transmitter section is based on the direct synthesis of the S-Band down-link carrier. A S-band vector modulator is then employed to perform the carrier modulation for the TT&C down-link signal. Both functions are accomplished in the digital module by the AD9361 RF transceiver.

In particular, the Digital PCB implements:

- TT&C S-Band LNA front-end
- AD9361 for both S-Band Tx carrier synthesis and vector modulation
- FPGA (MPF500TS from Microchip) for TT&C:
  - TT&C baseband carrier recovery and command demodulation
  - TT&C modulation (including TT&C coherency) is managed by the FPGA that provides in-phase and quadrature modulating signals carrying, depending on the operative mode, either TT&C modulating data (i.e., TM, ranging and/or coherency)

Moreover, the FPGA embeds a Digital Signal Processing (DSP) cores:

  - The TT&C CORE recurring from PLATiNO ASI program in the frame of which TTC&C System-On-Chip has been designed and developed for reprogrammable Microchip FPGA technology.

Figure 2 shows a high-level functional block diagram of the ISL-T with the relevant external interfaces.

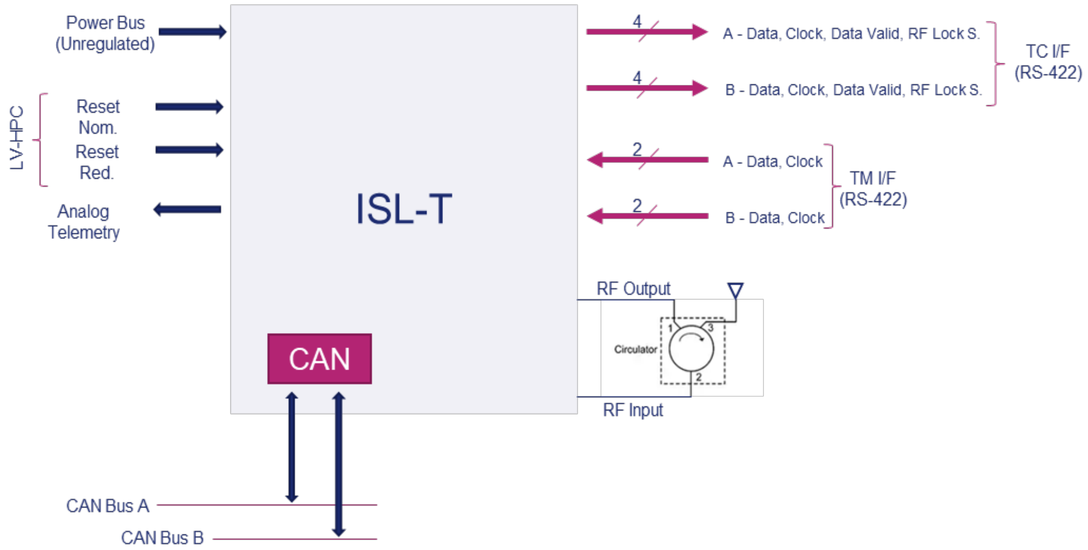

Figure 2. High-level functional block diagram of the ISL-T with the relevant external interfaces

4.2 Main Functions

The ISL-T supports the following main functions:

- Coherent / non-coherent mode
- PN regenerative Ranging
- ESA STD Ranging
- Delta Differential One-way Ranging (DDOR) (OPTION)
- Uplink modulation: PCM/PSK/PM (sine sub-carrier)
- Uplink decoding: BCH, LPDC (128, 64) (OPTION)
- Downlink modulation:
- Symbol rates up to 60 ksps in PCM/PSK/PM modulation format
- Symbol rates from 60 ksps to 1 Msps in PCM(SP-L)/PM modulation format (OPTION)
- Downlink encoding: Concatenated RS(255,223) and convolutional code rate ½, LDPC (2048,1024), Turbo rate ¼ (OPTION)

4.3 Frequency Plan

The ISL-T architecture is characterized by the main features here below:

- All digital carrier recovery loop on the receiving side (Doppler frequency recovery)
- Down-link modulation based on the AD9361 built-in vector modulator (for TT&C)

In the TT&C frequency plan the OCXO frequency is equal to:

$$F_{OCXO} = 80\ MHz \tag{1}$$

while

$$F_1 = \frac{F_{RX}}{221} = \frac{F_{TX}}{240}\ ; (ISL - T\ A) \tag{2}$$

or

$$F_1 = \frac{F_{TX}}{221} = \frac{F_{RX}}{240}\ ;\ (ISL - T\ B) \tag{3}$$

It is worth noticing that while F_1 depends on the selected communication channel, the oscillator frequency, F_{OCXO}, is fixed and as such not strictly related to any specific mission. The reference oscillator provides the 80MHz signal used by both the Digital Module (i.e. FPGA clock) and by the RF Transceiver (AD9361).

5 TECHNICAL BUDGETS

As part of the INNOVATOR Phase A study, a preliminary assessment of the Delta-V, mass, power, and link budgets was performed to support the feasibility of meeting the mission objectives while remaining within the constraints of the 6U hosting platform.
The technical budgets were computed adopting the margin policies specified in [9] that prescribe, among others, a 20% system margin for mass and power. The main outcomes are summarised in the following.

5.1 ΔV Budget

According to INNOVATOR ConOps, the orbital manoeuvres expected during the operational life of the two CubeSats can be grouped into:

a. Phasing manoeuvre at the beginning of the operational Phase I, immediately after release into orbit, which will bring the two satellites to a relative distance between 20 and 50 km.
b. Handover between Phase I and Phase II, placing the two S/C in two circular orbits at slightly different altitudes with a relative orbital speed of 4 m/s.
c. Manoeuvres for collision avoidance.
d. De-orbiting manoeuvre, to comply with a 5 years re-entry guideline as per [10].

The initial altitude assumed for the analysis is 500km, corresponding to a semimajor axis of ≈6871 km. The orbit inclination is ≈97.5°, representative of a Sun-synchronous orbit at the assumed altitude. For estimating collision avoidance and de-orbiting manoeuvres, use has been made of the ESA's DRAMA software tool. The total ΔV budget is ~50 m/s.

5.2 Mass Budget

Table 3 displays a summary mass budget for INNOVATOR, based on the subsystems selected and on the current status of the payload design. The propellant mass is estimated based assuming a specific impulse of 165s, consistently with the selected electrothermal propulsion system.

Table 3. Summary mass budget

Item	Mass Budget	
	Current Estimate	Total with margin
	[kg]	[kg]
Payload	0.965	1.098
Spacecraft	7.145	7.704
Nominal Dry Mass	8.110	8.803
Total Dry with 20% sys. margin	9.732	10.563
Propellant Mass (Isp 165s)	**0.305**	**0.311**
TOTAL WET	**10.037**	**10.874**

5.3 Power Budget

For the mission power budget, a check on the energy balance for the different operative modes was performed, assuming a worst case EOL scenario at the Winter solstice. To this end, the EOL maximum solar arrays generated power is scaled down according to the orbit eclipse duration and of the pointing losses (because of the solar arrays not constantly pointing to the Sun) see Table 4, where the outcome of such a computation for a Dawn-Dusk orbit are shown.

Table 4. Power generation for a Dawn-Dusk SSO

Orbit LTAN	Year period	Orbit period [min]	% Eclipse duration	Pointing loss	EOL max Power [W]	SP Avg Power Out [W]	SP Energy Out [Whr]
06:00	Winter solstice	94.5	24.0%	6.0%	**37.5**	**26.3**	41.4

The total power needed by the S/C subsystems and the payload amounts to ~70W, so appropriate trade-offs in terms of propulsion system and payload duty cycles will need to be carried out to guarantee a neutral energy balance.

5.4 Link Budget

The space-to-ground link is ensured thanks to the onboard S-band and a UHF transponder and a Ground Station Network, while the inter-satellite link is guaranteed by the ISL payloads onboard the two CubeSats, operating in S-band. Both the space-to-ground and inter-satellite link compatibility have been checked for having a positive margin (~4dB for the Downlink UHF, ~11dB for the Uplink UHF, ~14dB for the Downlink S-band, and ~13dB for the Uplink S-band). For the space-to-ground link, sample ground stations from the Leaf Space network have been considered for each operative band.

6 GROUND SEGMENT

The peculiarity of INNOVATOR's mission concept involves the introduction of requirements for the management of the pair of satellites in formation (i.e., of a constellation in general) that are potentially dimensional for the ground system dedicated to mission control, which will have to operate collaboratively, sharing database, operations plan and even some resources such as the antenna network for example. The design of INNOVATOR's ground segment (GS) is therefore strongly oriented by the needs of radio science (gravity and atmospheric) applications, the operation of which assumes a key role from an IOD/IOV perspective. Both requirements and preliminary specifications necessarily will be identified and subjected to trade-offs having as the ultimate goal the full operability, including by the science user, of ISL payloads in flight.
Therefore, in the definition of the components, functionalities were identified that evolve the core components of existing systems to reuse by favoring systems and services of the "*aaS" or "anything as a Service" type. Preference has been given to those ground segment application solutions, from the ground station network, and mission control up to scientific data processing and distribution, that allow the integration and development of a modular, flexible, and interoperable system, to make INNOVATOR fully compatible with the Ground Segment as a Service (GSaaS) concept. With this in mind, it is possible to anticipate several requirements that the GS of the INNOVATOR mission will need to ensure to allow access to a global network of ground stations and the use of a Mission Control System (MCS) that guarantees:

- Delivery of telecommands and procedures to satellite platforms
- Delivery of payload data to the scientific user
- Telemetry management from platforms
- Binary data exchange
- Orbit prediction

- Contact time scheduling, booking, and time-of-use optimization
- Integration with ground station networks worldwide

The assessment and further declination of the above requirements mainly involve two subsystems such as the Ground Station System (or GSS=Ground Station System) and the Mission Control Center (MCC), which can be considered as integrated as presented in the high-level architecture in Figure 3.

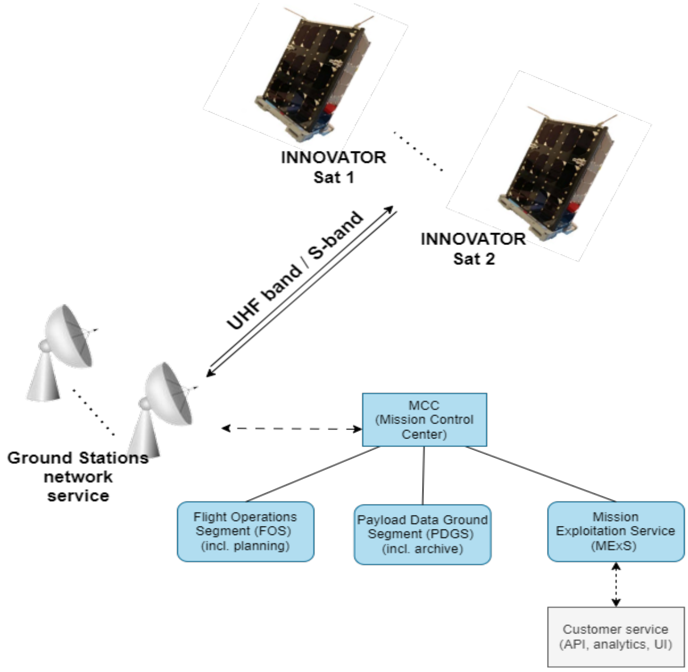

Figure 3. Ground Station System and Mission Control Centre architecture

being:

- A Mission Control Center (MCC), constituted by:
  - A Flight Operations Segment (FOS) - responsible for all flight operations of both the INNOVATOR spacecraft, including monitoring & control, flight dynamics, and planning for both spacecraft and payloads i. via the execution of all platform activities, and commanding of the payload schedules; ii. via the interface towards external GSN service providers.
  - A Payload Data Ground Segment (PDGS) - where payload/science data are processed from L0 (raw format) to higher-level products, to support the gravity and atmospheric data analysis;
    i. A Performance Assessment Segment (PAS) - responsible for validation, quality control, and end-to-end system performance assessment;
  - The INNOVATOR Mission Exploitation Services provide complementary access to INNOVATOR data and/or specific data products or distribution channels. These collaborative elements are designed to enhance the exploitation of INNOVATOR missions in various domains. They contribute specialized solutions to optimize the utilization of INNOVATOR's mission data. It is composed by:
    i. Data dissemination Segment: consisting of a mission exploitation platform aimed at providing users (including mission managers at consortium and Agency levels) a unique access point to retrieve INNOVATOR's science;
- A Ground Stations Network (GSN) - to communicate with the spacecraft, transmitting commands, receiving scientific data and status information, and establish/book downlink/uplink windows opportunities.

Having defined these activities, one of the hallmarks of MCC is being able to manage several processes regarding these key aspects:

- A baseline for mission planning: planning and execution processes in terms of plan validation, Space2Ground/Ground2space contacts, Operations Feasibility, and Execution monitoring of Mission Operations.
- Baseline for science data processing chains: Payload (science) data generation processes, to produce final products starting from payload data
- Baseline for science data provisioning services: mission exploitation processes in terms of 1) User interface; 2) Service Orchestration; 3) Data Repository/storage 4) Data Processing; 5) Data Visualization/Presentation

7 EXPECTED PERFORMANCE OF THE INNOVATOR LEO MISSION

7.1 Atmospheric Science Simulations

Radio occultation experiments are a remote sensing technique used to sound the atmospheres of planets and moons to infer their characteristics. The aim is to obtain vertical profiles of the physical properties of the neutral atmosphere (e.g., density, pressure, and temperature) and ionosphere (e.g., the electron number density). For this purpose, radio occultations take advantage of the frequency shift brought on by refraction when a radio signal passes through the atmospheric medium.
A radio occultation event occurs when a radio link is established between a receiving and a transmitting antenna. In the case described in this paper, both the antennas are on board two spacecraft that initially cover the same orbit around the Earth at an altitude of ~500 km. We assume the spacecraft have initially a relative distance in the order of 20 km. Thus, the distance between the two spacecraft is gradually increased (using suitable orbital manoeuvres) such that the radio ray path traverses deeper and deeper layers of Earth's atmosphere, down to the point where the signal path is tangent to the Earth surface and the distance between the two spacecraft reaches values of about 5000 km. We report here the main result of the INNOVATOR Phase II, which consists of the plot shown in

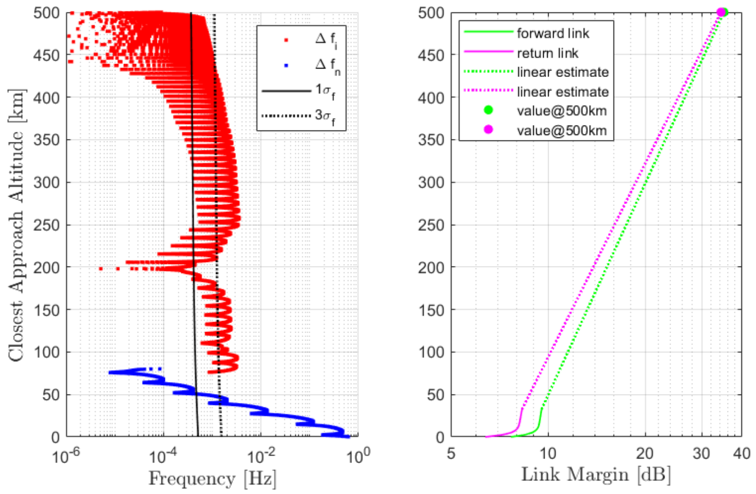

Figure 4. Observability of the Earth's ionosphere and troposphere in Phase II of the INNOVATOR mission

In Figure 4 the expected frequency shift on the radio link, due to the ionosphere (red) and troposphere (blue), is compared to the total uncertainty (black line) on the radio link itself. The plots in Figure 4 demonstrate that the frequency shift is higher than the $3\sigma_f$ uncertainty for large altitude ranges: between 200 and 430 km (that is, inside the upper ionosphere), in the range 80-180 km (the lower ionosphere), and below 50 km (when the signal is crossing the lower neutral atmosphere). In addition, Figure 4 shows that in the altitude ranges in which the frequency shift due to the atmospheric refraction is higher than the measurement uncertainty (see left panel), the link margin is positive (see right panel). Note that the link margin has been evaluated in the altitude range between 0 and 30 km (solid lines), and when the closest approach altitude is 500 km. In the altitude interval between 30 and 500 km, the dotted lines represent a linear estimate of the link margin. Further analysis will be required during the Phase B study to obtain a better estimate for this altitude range.

7.2 Gravity Science Simulations

As introduced in Section 1, the gravity field of a celestial body can be estimated through the Orbit Determination (OD) process of one or multiple S/C that orbit the body. When radiometric observations are employed for the measurement of a gravity field, the conducted radio science experiment also becomes a gravity science experiment. The level of accuracy of the gravitational field estimate mainly depends on the geometry of the S/C trajectory and the characteristics of the acquired observations (e.g., noise level, acquisition duty cycle, etc.).

The main gravity science expected results of the INNOVATOR Phase I consists in the plot shown in Figure 5, which proves that the RMS of the uncertainties estimated by INNOVATOR is smaller than the simulated Earth's gravity field up to about degree 110. This is a confirmation that INNOVATOR would be capable of observing and fully estimating the Earth's gravity field up to degree 110. The plot also shows that the RMS of INNOVATOR is larger than the RMS of GRACE by approximately four orders of magnitude at lower degrees (1 to 30) while at the higher degrees (30 to 125) the difference tends to decrease by up to two orders of magnitude. This says that, under the described assumptions, the INNOVATOR estimate would not be as accurate as the GRACE estimate. The analyses that will be carried out in the next Phases of this project will allow us to consolidate the actual maximum degree that can be estimated with INNOVATOR, thus offering a complete comparison with the GRACE mission.

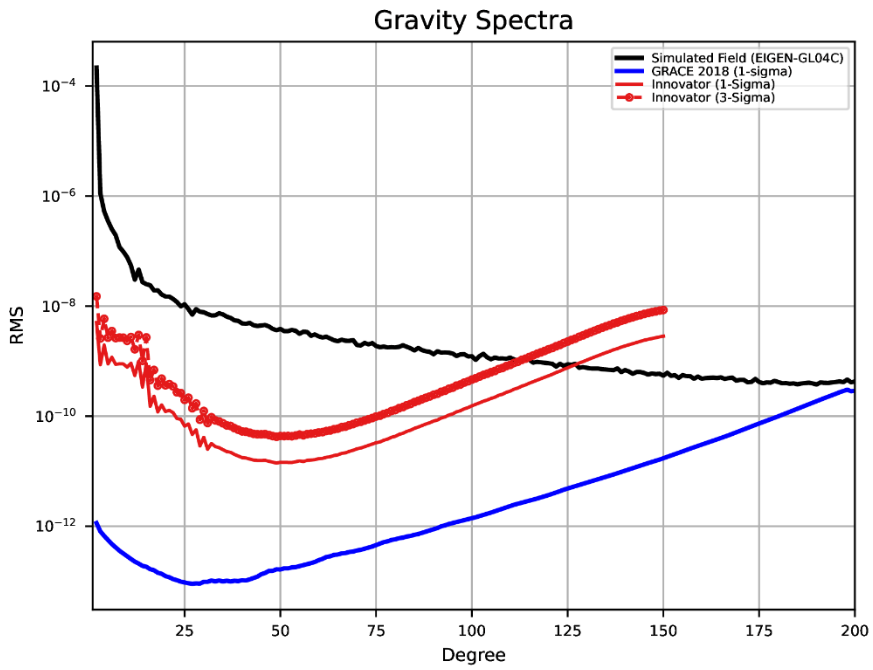

Figure 5. Comparison of the RMS of the INNOVATOR simulated estimation with the actual RMS of GRACE estimated uncertainties. The black line identifies the RMS of the Earth's gravity field model EIGEN-GL04C [11]

8 CONCLUSIONS

The INNOVATOR project is designed to test an innovative payload that can perform accurate radio science observations in the fields of gravity and atmospheric science. The payload comprises an InterSatellite Link Transceiver (ISL-T) for TT&C, ranging, and range-rate measurements, crucial for precise orbit determination and accurate estimation of all gravitational and non-gravitational accelerations acting on the two spacecraft. Additionally, the Doppler link between them enables atmospheric radio occultations. The chosen platform for INNOVATOR is a CubeSAT 6U XL and to achieve the scientific mission and Intersatellite link, the spacecraft uses a 3-axis attitude stabilization and a propulsion system for orbit maneuvers, required for both the operative mission and de-orbiting phases. In addition, the ISL-T devices mounted on board the two CubeSats will share the same hardware platform and differ exclusively in the reception and transmission frequencies, which are configurable by command, as well as the coherence function and those associated with the ranging and range-rate measurements (Doppler). Furthermore, an initial evaluation was carried out to assess the Delta-V, mass, power, and link budgets. The purpose of this assessment was to determine the feasibility of fulfilling the mission objectives while staying within the limitations of the 6U platform. In order to correctly size the ISL-T system, in terms of transmission power, gain of the RX/TX antennas, etc., the orbital geometry of the two CubeSats has been studied in both Phases of the mission. It is clear that the most demanding one is Phase II, in particular at the end of the long rephasing phase when the two CubeSats will be at a relative distance of ~5000 km, needed to obtain an Earth grazing RF beam. The next step will be a Phase B study, where deeper analysis will be conducted in order to refine the already promising outcomes we obtained so far from every point of view.

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