Technology demonstration of the Geodetic Reference Instrument Transponder for Small Satellites (GRITSS)

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ABSTRACT

The Geodetic Reference Instrument Transponder for Small Satellites (GRITSS) introduces a novel geodetic time-of-flight observable to address the problem of site tie bias errors between GNSS and VLBI ground station antennas, thereby improving the realization of the international terrestrial reference frame (ITRF). By enforcing mutual and simultaneous spectral compatibility between GNSS and VLBI observations, GRITSS enables application of intra-technique interferometric processing between ground station antennas. In this way, GNSS and VLBI observations may be tied together at the most fundamental level; their respective electrical points of reference (e.g. phase center and intersection of axes). GRITSS is a development by the University of Massachusetts Lowell and NASA Goddard Space Flight Center that implements the technology necessary to realize this new delay observable. And, through a contracted effort with ISISpace, our instrument will be demonstrated on a CubeSat in low Earth orbit. In our contribution, we will review the importance of the ITRF to space-based Earth science missions, how the GRITSS observable aims to improve the ITRF, and the latest plans for the GRITSS technology flight demonstration.

1 Applicability to Earth Science Measurements

The Terrestrial Reference Frame (TRF) is the foundation for virtually all airborne, space-based, and ground-based Earth observations and is realized as an international standard through the International Terrestrial Reference Frame (ITRF). The importance of maintaining and improving the ITRF is highlighted in two important reports from the US National Academies of Sciences, Engineering, and Medicine: “Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space” [1] and “Evolving the Geodetic Infrastructure to Meet New Scientific Needs” [2]. These reports highlight the importance of maintaining and enhancing the geodetic infrastructure that enable modern geodesy and support all aspects of Earth system observations. In particular, these reports highlight the need to improve the ITRF to enable future sea level measurements that will require an ITRF with an accuracy of 1 mm (decadal scale) with stability at 0.1 mm/year (annual scale). This is a factor of 10-20 beyond current capability. Other areas of NASA’s Earth Surface and Interior focus area will also benefit from an improved ITRF, including studies of global ice mass change and crustal deformation.

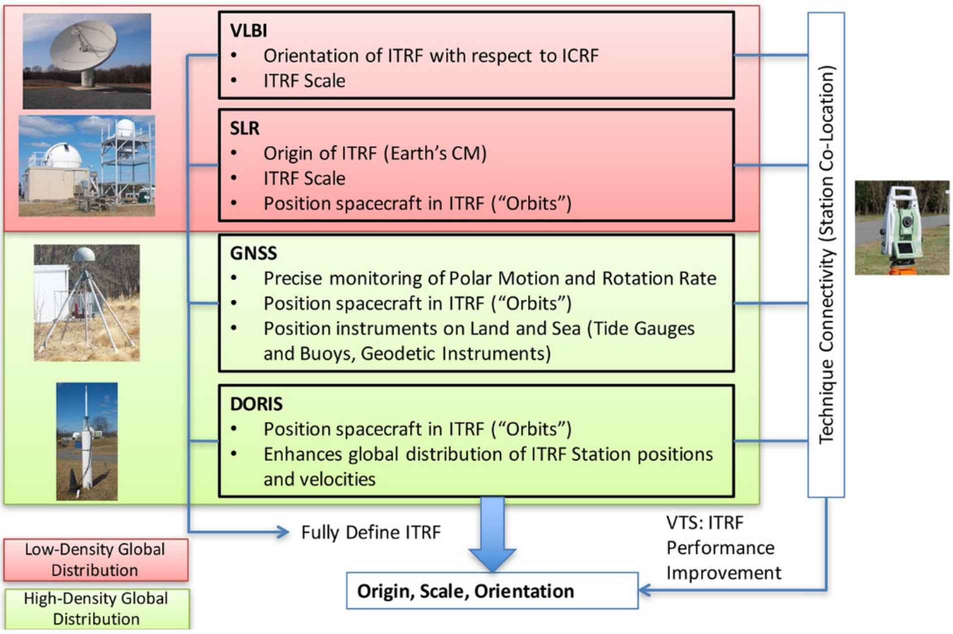


Figure 1: All four geodetic techniques' contributions to the definition of the ITRF.

The ITRF is developed by combining the observations from Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Global Navigation Satellite System (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) stations. Combination of these different measurement techniques is only possible with accurate knowledge of the relative measurement reference points between co-located systems at the observing station, and it is essential in order to take full advantage of the strengths of each technique as outlined in Figure 1. Traditionally, standard surveying techniques have been utilized to co-locate physical reference points (representative of the measurement reference points) within each of the space geodetic measurement techniques but these surveys are limited. The limitation arises because the physical reference points associated with each technique are not strictly tied to the measurement reference point. This is particularly true of the radio-based VLBI, GPS, and DORIS techniques that have measurement reference points (i.e. antenna phase centers and intersection of antenna pointing axes) that vary with azimuth and elevation direction in which the respective technique's source is observed [3,4].

Of the various inter-technique site ties, the VLBI-to-GPS tie is considered the most crucial because the VLBI technique alone provides a link between the ITRF and the fixed/inertial celestial reference frame while the GPS network is by far the most ubiquitous technique. The fusion of VLBI and GPS observations to provide closure between VLBI and GPS derived positions has been investigated in a variety of ways [5,6] but none have directly enabled the VLBI receiver to operate as a stand-alone GPS receiver. Ignoring VLBI/GPS spectral compatibility, the problem arises because the VLBI reflector antenna by design is very directive so it is unable to view multiple GPS satellites simultaneously as required to compute a true GPS-derived position. Conducting traditional VLBI observations of the GPS constellation is further impeded by wavefront curvature that must be corrected in order to reconcile position differences and this technique is not compatible with the standard geodetic VLBI station. In a novel fashion, the Geodetic Reference Instrument Transponder for Small Satellites (GRITSS) establishes compatibility between GPS and VLBI such that the VLBI technique may directly receive the coded information broadcast by the GPS satellite constellation (figure 2) in a stand-alone fashion. Specifically, the GRITSS enables measurement of the delay observable τ_{sv} (figure 2) that when tracked through multiple passes may be used to derive a VLBI position. This position is fundamentally tied to the GPS coded signals and incorporates precision orbit

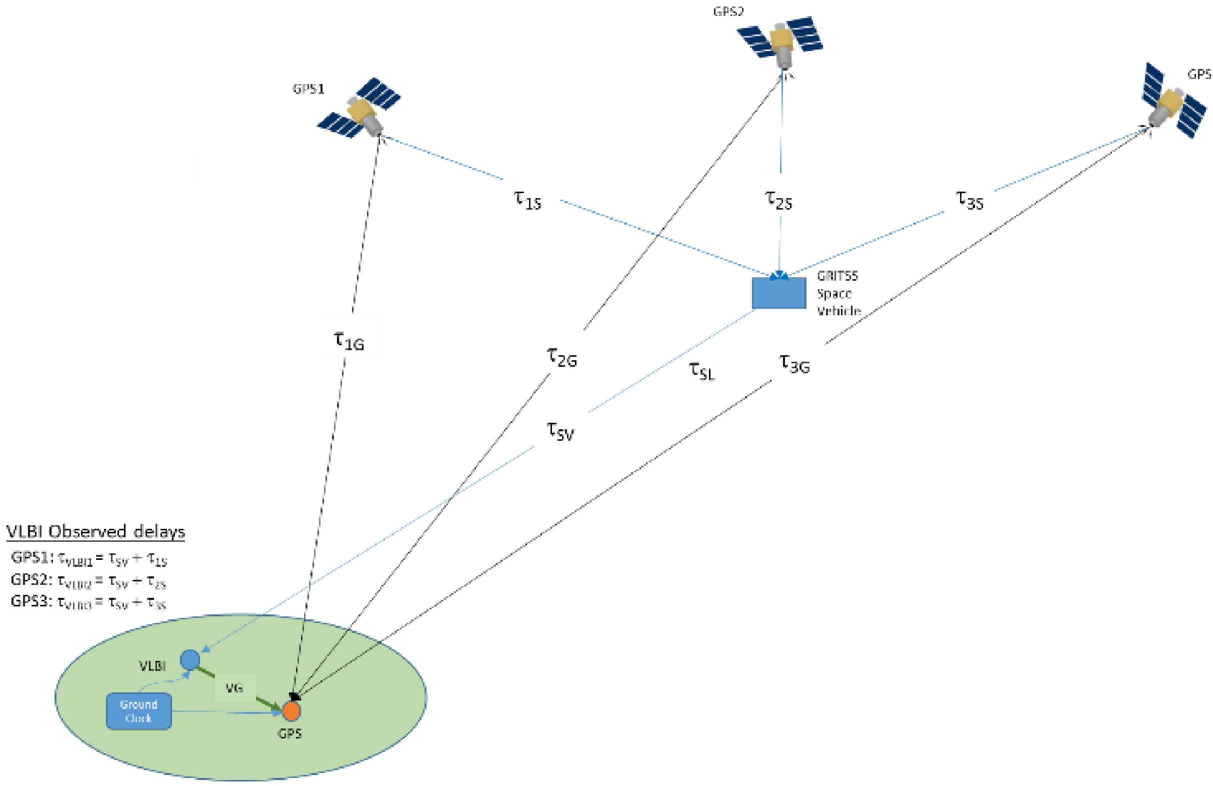


Figure 2: Diagram of the VLBI/GNSS delay observables facilitated by the GRITSS. The data collection geometry outlines the VLBI/GNSS delay observables (τ's), the inter-technique baseline vector *VG* that is defined between the measurement reference points of each technique (not the physical reference point), and their relation to the GNSS constellation. Delay paths in BLUE represent components of the VLBI delay observables, delay paths in BLACK represent components of the GNSS delay observables.

determination (POD) of the spacecraft carrying GRITSS. By enabling the GPS and VLBI techniques to receive a common signal basis, the GRITSS ushers in a new level of accountability between the GPS/VLBI delay observables that is not currently attainable.

Unlike the Geodetic site ties solution offered by other space collocation mission concepts, the GRITSS allows the VLBI station to operate as a pseudo stand-alone GPS receiver so that the requirement to have mutual observability of the spacecraft by multiple VLBI stations is relieved. To achieve mutual observability would add the additional requirement that the GRITSS be in a high enough orbit to be viewable most of the time by multiple VLBI stations (usually separated on continental scales). This requirement significantly increases the cost and complexity of the mission. As such, the GRITSS spacecraft may be flown in a low Earth orbit (LEO) and this is advantageous because it opens up the possibility of using inexpensive CubeSats or other small satellites facilitating implementation of a cost-effective constellation to provide better global coverage and further improving the accuracy of the site ties.

Aside from the site ties solution that is offered by the GRITSS, the instrument also provides the possibility to conduct cross-cutting atmospheric science research by enabling radio occultation experiments through the dog-leg delay path of the VLBI observable shown in Figure 2. In this way, the instrument offers the potential to provide independent measurements of ionospheric and tropospheric delays that can be utilized to enhance the accuracy of these atmospheric data products.

2 Description of Technology

Both the VLBI and GPS techniques are based on radio frequency sensing where the VLBI antenna and receiver are designed to observe in the 2000 - 14000 MHz frequency range while GRITSS supports GPS bands L1 (1575.42 MHz) and L2C (1227.60 MHz). Since both techniques operate in mutually exclusive portions of the radio spectrum, it is not possible to develop a direct tie between these two techniques through co-observation of a single radio source. Furthermore, the VLBI sensor may not simultaneously observe multiple GPS satellites due to its highly directive antenna so that it is not possible to obtain a traditional GPS-derived position with the VLBI antenna. To circumvent the spectral incompatibility and VLBI antenna directionality, the GRITSS introduces a frequency conversion to allow the VLBI station to directly observe the GPS coded signals. As such, the GRITSS relays and upconverts GPS transmissions that are received from its on-board GPS antenna to signals that are broadcast in the operational frequency range of the VLBI ground sensor. A simplified block diagram of the GRITSS space vehicle's transponder architecture is given in Figure 3.

To provide the necessary instrumental functionality, a modified version of the GPS receiver flown on the Magnetospheric MultiScale (MMS) mission has been integrated into in the GRITSS. The GPS signals as received by the space vehicle's GPS antenna are digitized by the on-board, custom GPS receiver's ADC. The digitized samples are harnessed so that they may be broadcast to the VLBI station in real time utilizing custom built S and X-band digital data transmitters that have matured to TRL5. Similarly to standard GPS processing, the dual band transmit capability provides compatibility with both legacy and next generation VLBI stations to facilitate correction of the dispersive delay component of the ionosphere from the space vehicle to the VLBI station. Figure 4 provides photos of the prototype hardware that were targeted for the GRITSS.

The QPSK S and X-band digital data transmitters relaying the GRITSS signal both operate at a data rate of 9.216 Mbps at carrier frequencies 3.2 GHz and 10.2 GHz, respectively. This data stream is composed of single bit complex (in-phase/quadrature) samples of L1/L2C bands captured at 2.048 MHz, Additionally, the GPS L1/L2C data samples are interleaved with synchronization symbols that are timed with the space vehicle's on-board time/frequency reference. These synchronization frames provide a means to obtain time-of-flight and Doppler observables of the relayed signal from the space vehicle to the VLBI station (τ_{sv}, Figure 2) and provide a measure of τ_{sv}, independent from the GPS analysis. This is the standard mode of instrument operation that is referred to as GPS-bit mode.

The GRITSS also supports two auxiliary modes of operation mainly to support commissioning exercises. The first serves to configure the instrument to function as a beacon so it operates as a continuous-wave (CW) transmitter (0 bandwidth) at each carrier frequency. This mode facilitates assessment of carrier-to-noise ratio in both transmit bands with standard ground support equipment (e.g. spectrum analyzer). As such, it does not rely on a demodulating the transmission by the GRITSS ground receiver to assess carrier-to-noise ratio (CNR) or other signal stability metrics (e.g. phase noise). While delay measurements in this mode are ambiguous (modulo of the carrier cycle), a Doppler observable may still be extracted. The second auxiliary mode allows the transmitter to broadcast a pseudorandom noise (PRN) sequence and is referred to as PRN mode. The PRN mode simply replaces those GPS bit placeholders in the data framing with deterministic data. Similarly to GPS-bit mode, timing of these PRN data are precisely defined by the instrument's on-board clock. And this mode allows the ground receiver to accrete signal-to-noise ratio (SNR) in the τ_{sv} observable in a much shorter time interval than achievable in the standard GPS bit mode.

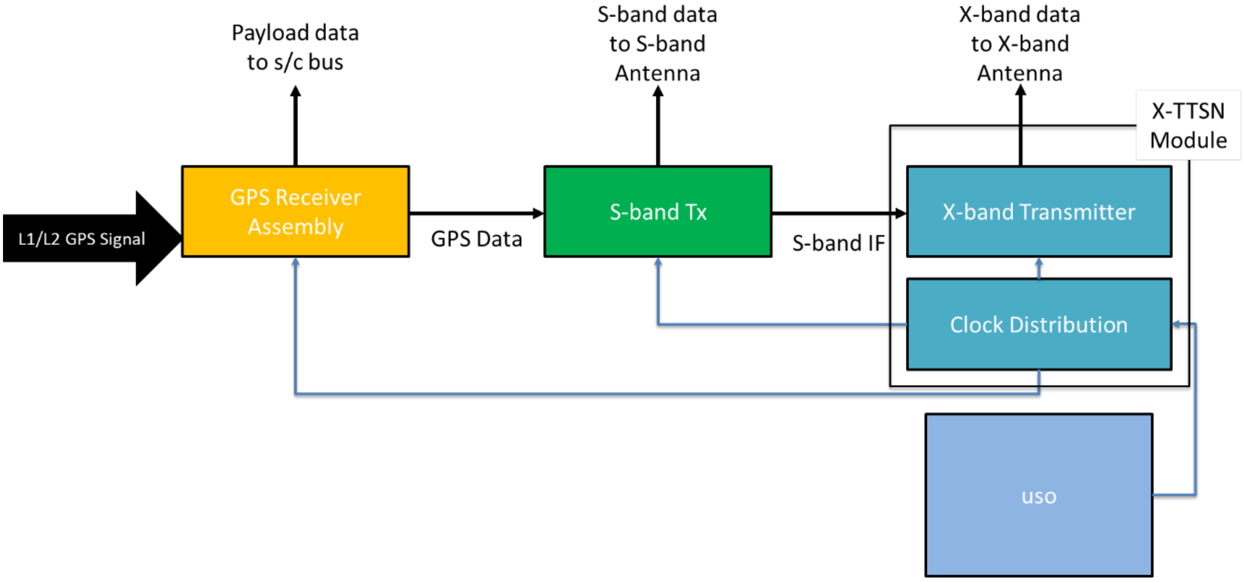
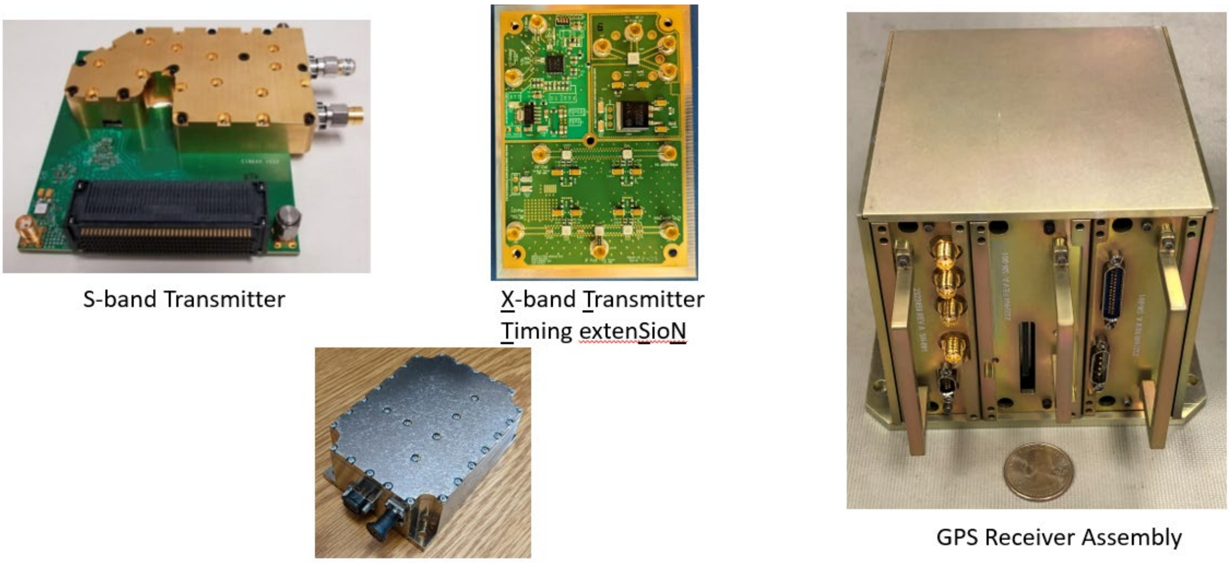


Figure 3: Simplified block diagram of the GRITSS outlining the three custom sub-systems developed for the instrument and the commercial ultra stable oscillator (USO) procured from Wenzel Associates.


S-band Transmitter

X-band Transmitter Timing extenSioN

Wenzel USO

GPS Receiver Assembly

Figure 4: Photographs of individual hardware sub-systems that constitute the fully assembled GRITSS.

3 In-space Validation of GRITSS Technology

Through sponsorship from the NASA Earth Science Technology Office (ESTO) In-Space Validation of Earth Science Technology (InVEST) program, GRITSS has received funding to carry out an in-space validation of this new technology. In turn, University of Massachusetts Lowell (UML) has put into place a contract with ISISpace in Delft, NL, with support from NASA Goddard Space Flight Center (GSFC), to host GRITSS and provide at a minimum, one year of mission support that is extendable. In addition to hosting GRITSS, the spacecraft will also carry a retroreflector to support tracking by the International Laser Ranging Service. The retroreflector will allow the SGP to tie in the SLR technique into the GRITSS measurements and support POD of the spacecraft. The contract responsibilities of ISISpace include the following:

- Provisioning of a GRITSS-dedicated 12UXL spacecraft
- Electrical power management for the GRITSS payload
- Thermal management of the GRITSS payload
- Customization of command and data handling (C&DH) system
- Customization of a payload data handling system
- Attitude Determination and Control System (ADCS)
- Delivery of GRITSS-dedicated GNSS antenna
- Delivery of GRITSS-dedicated S and X-band transmit antennas
- Secure and manage launch opportunity
- Systems engineering and integration and test support

This mission is classified by NASA as a sub-class D technology demonstration.

3.1 Concept of Operations and Primary Spacecraft Requirements

Currently, ISISpace is targeting a 12UXL vehicle (Figure 5) in LEO at an altitude of 550 km to leverage the wide availability of launch opportunities into this orbit; 6U of this volume is allocated to GRITSS.

A depiction of the mission concept of operation (CONOP) is shown in Figure 6. Following commissioning activities, the spacecraft will commence with mission operations. During operations, the GRITSS will only be active during those periods when there is contact to a VLBI ground station. The current baseline plans to activate GRITSS in contact with the SGP stations in Greenbelt MD (GGAO), Fort Davis, TX (MGO), and Kōkeʻe Park, HI (KPGO). Contact periods to these stations could be as long as approximately eight minutes. Outside of these periods of contact, the GRITSS GPS receiver will continue to track the spacecraft position full time with a clear hemispheric field of view to develop a robust precision orbit solution.

Strict requirements are imposed on the spacecraft to sustain 1 mm-level knowledge in the POD to support the ranging accuracy in the time of flight observable. First, the knowledge requirement on the spacecraft's center-of-mass (CoM) is to be known to better than 0.5 mm. Following deployment and commissioning, the spacecraft is not permitted to incorporate components that move or otherwise shift the spacecraft's CoM (e.g. steerable solar panels, propulsion, etc.) during the course of the mission. The knowledge and stability of the GRITSS receive and transmit antenna phase centers are also critical to POD. To this end, the ADCS pointing stability is required to perform at a level of better than 0.026 degrees in between pointing knowledge updates. And the maximum error in the ADCS pointing knowledge, that is updated at 1 second intervals, is less than 0.1 degrees. It is expected

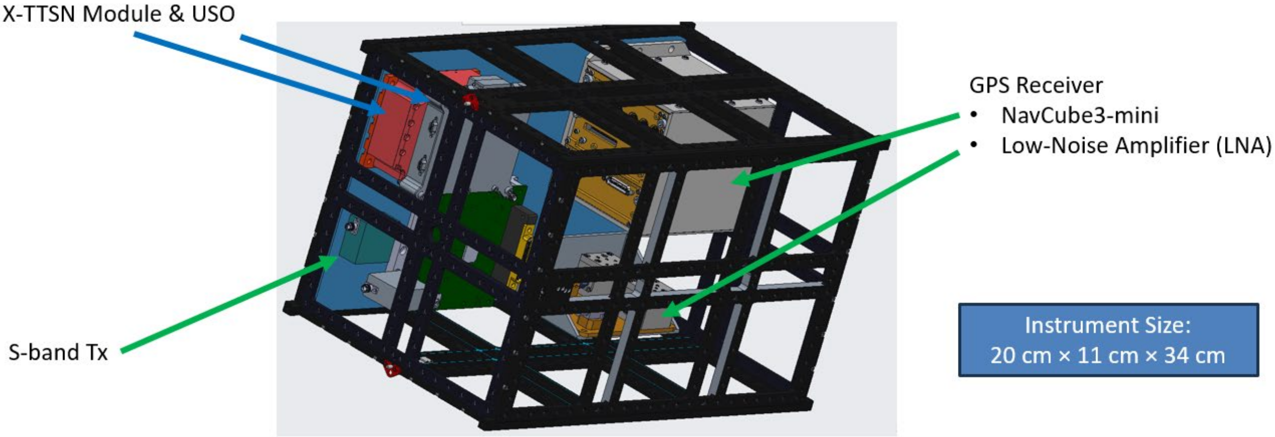


Figure 5: Notional layout of the GRITSS within the 12UXL CubeSat; the GRITSS is allocated 6U of the total volume.

that two orthogonally facing star trackers will be necessary to maintain pointing knowledge at all times during events that may leave a single tracker inoperable (e.g. sun blinding).

As POD also relies on the GPS observations, the L1/L2C GNSS antenna will be rigidly affixed to the zenith facing side of the spacecraft to maximize the field of view to the GPS constellation; the phase patterns of the antenna will be measured as integrated on the spacecraft. To avoid occlusion of the GPS constellation by the Earth's limb, spacecraft pointing maneuvers are restricted to 20 degrees relative to the zenith direction. This CONOP challenges the ability for the spacecraft to generate power through deliberate pointing of the spacecraft solar panels at the Sun, resulting in a need for dual deployable solar panels to provide adequate power for payload operations.

Further challenging the power demand is the thermal management requirement imposed on the spacecraft design. Because GRITSS is targeting picosecond level of knowledge in the instrument's transponder delay, a +/- 1 degree thermal stability requirement has been imposed on the thermal management system. This level of stability is necessary in order for the transponder delay to be calibrated in ground processing using telemetry conveying data from an array of temperature sensors distributed throughout the instrument. A precision calibration of the instrument will be carried out in thermal vacuum chamber testing prior to launch. And this thermal calibration will characterize that delay from the GNSS antenna to the S and X-band transmit antennas over a range of operational temperatures.

The GRITSS payload's S and X-band antennas will be rigidly mounted opposing the GNSS antenna on the nadir facing side of the spacecraft. Identically to the GNSS antenna's zenith off-point restriction, the ADCS will contain the S and X-band antenna off-pointing to 20 degrees with respect to nadir. This pointing restriction prohibits the ADCS from actively training the transmit antennas on the ground station. Hence, relatively low gain transmit antennas are necessary to ensure contact to the VLBI ground station can be achieved with adequate link margin to the VLBI receiver. Furthermore, the transmit antennas' axial ratio (circular polarization quality) are required to be no greater than 3 dB over the field of view to the VLBI station to meet the link budget. Like the GNSS antenna, phase pattern measurements of both S and X-band antennas will be characterized to support the phase center knowledge requirement.

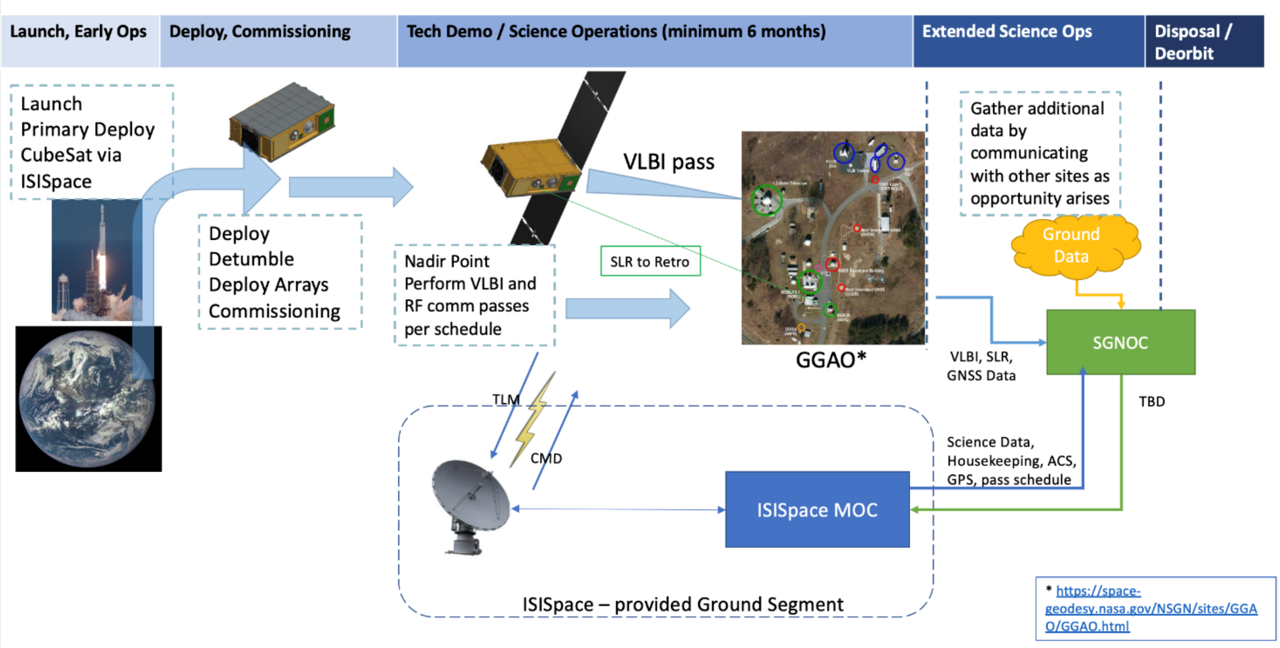


Figure 6: Diagram outlining the GRITSS concept of operations illustrating the flow of data from the instrument observations and ISISpace telemetry to the Space Geodesy Network Operations Center (SGNOC). The ISISpace Mission Operations Center (MOC) coordinates C&DH transactions to the GRITSS-carrying spacecraft and the ground observing station contact schedule flowing from the SGNOC.

3.2 Project Status

Through funding by the NASA ESTO Advanced Component Technology program, the three custom GRITSS sub-systems (GPS receiver assembly, S-band transmitter, and X-TTSN module) were matured to TRL5 in 2022. Shortly thereafter, the instrument was considered for a flight opportunity through InVEST to validate the technique beyond the limited realism that is achievable in the laboratory environment. Subsequently, the GRITSS space flight payload design completed its preliminary review in July 2023. In the following September, the GRITSS in-space technology demonstration project with ISISpace was initiated and is on track to its critical design review in August 2024. Launch is targeted for the Fall of 2025.

4 Summary

The Geodetic Reference Instrument Transponder for Small Satellites has been developed with the objective of resolving intra-technique position biases between GPS/GNSS and VLBI geodetic observations. Early-stage concept studies of the GRITSS technique were carried out, supporting the novel observable that GRITSS will provide through the low-level technology maturation. The support that NASA's ESTO has provided through the Advanced Component Technology program further elevated the technology to TRL5. And follow-on funding through InVEST with a successful demonstration in our sub-class D mission, is expected to advance the maturity of the instrument to TRL7. Beyond this in-space technology demonstration, we anticipate that GRITSS will become part of the space geodesy infrastructure constellation in a long-term, higher class mission through other partnerships.

5 REFERENCES

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