NavCube3-mini Lunar GNSS Receiver

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BIOGRAPHY

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Luke Thomas has worked as an FPGA design engineer for 24 years. Currently, he is working on the NavCube3-mini GNSS receiver, expanding its capabilities and migrating the algorithms to modern hardware platforms. He also serves as the lead FPGA designer for the (On-orbit Servicing, Assembly, and Manufacturing) OSAM-1 LiDAR. He has a BSEE from Cornell University and an MSEE from Northeastern University.

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Tyler Lee is a software and test engineer supporting NASA Goddard in developing the flight software, ground system, operating system, build system, development environment, and telemetry interfaces for NavCube3-mini.

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ABSTRACT

This paper describes development and testing of NASA Goddard Space Flight Center's new NavCube3-mini (NC3m) spaceborne, weak-signal GNSS receiver, which targets all Earth orbit regimes with special focus on lunar applications. NC3m derives from the ground-breaking Magnetospheric Multiscale (MMS) mission Navigator GPS receiver. The MMS-Navigator (launched 2015) holds a Guinness World Record for highest altitude GPS fix and is currently in a highly elliptic orbit with a 29 Earth radii apogee, nearly half lunar distance. NC3m has reduced size, weight, and power compared to the MMS-Navigator, making it suitable for smallsat applications, and adds multi-frequency and multi-GNSS capabilities, among other improvements. A NC3m engineering test unit was subjected to and successfully completed a comprehensive Technology Readiness Level 6 (system/subsystem model or prototype demonstration in a relevant environment) testing campaign in the second half of 2022. This involved high-fidelity simulations in LEO, GEO, and lunar regimes and full environmental testing, including vibration, thermal vacuum, and electromagnetic compatibility. An overview of the NC3m receiver, the test setup, and a sample of results is presented. The results include predicted performance at high-altitude and in the lunar regime.

I. INTRODUCTION

High-orbit and lunar missions have traditionally relied on ground tracking for navigation. While this approach has been critical for the success of many space missions, ground station resources are inherently limited, and ground-tracking-based navigation solutions are often computed on the ground with significant latency. Recent developments indicate that high-altitude GPS-based navigation provides a promising augmentation or alternative to ground tracking by leveraging existing GNSS infrastructure to enable real-time, on-board, GNSS-based solutions at much higher altitudes than previously achieved. NASA/NOAA's GOES-16 weather satellite, launched in 2016, became the first civilian vehicle to use GPS in geostationary orbit (Winkler et al., 2017), and NASA's Magnetospheric Multiscale Mission (MMS), which launched in 2015 and uses NASA Goddard Space Flight Center's (GSFC) Navigator receiver, operates in highly elliptic orbits with apogees high above the GPS constellation and has claimed the Guinness World Record for highest altitude GPS fix with an altitude of 70,135 km above Earth. MMS has since raised its apogee to over 180,000 km, nearly half the distance to the Moon, and continues to navigate with excellent performance using GPS. Following the success of MMS, the Navigator development team began to investigate the predicted performance of GPS in the lunar regime (Winternitz et al., 2017) and began efforts to develop the next-generation, low size, weight, and power GNSS receiver for all Earth orbit regimes, especially targeting the lunar regime. NavCube3-mini (NC3m) is the culmination of those efforts. The numerous potential advantages of lunar GNSS applications include improvements to on-board, autonomous navigation capabilities, reduced ground support and network loading, and lower operation cost.

These benefits have been broadly recognized, and there has been substantial research and development in this area apart from the work already discussed. The following is a brief and likely incomplete overview. Theoretical lunar GPS/Galileo receiver designs have been simulated and shown promising results (Musumeci et al., 2016), and the use of other constellations, such as BeiDou, has been explored (Ju et al., 2023). Analysis in Guan et al. (2022) shows that multi-GNSS capabilities will substantially benefit high-altitude navigation performance by increasing signal availability and, consequentially, improving geometry. NASA and the Italian Space Agency (ASI) are supporting the Lunar GNSS Receiver Experiment (LuGRE), independent of NC3m, which is scheduled to launch as part of NASA's Commercial Lunar Payload Services program. LuGRE aims to demonstrate GNSS reception in lunar transfer, in lunar orbit, and on the surface of the Moon for a minimum of 12 Earth days (Parker et al., 2022). ESA's Lunar Pathfinder Satellite proposes to use Earth-based GNSS using high sensitivity GNSS receivers (Ventura, 2022). With many new missions targeting the lunar regime, lunar GNSS research and development is expected continue to grow in the near term to support these applications.

The remainder of this paper is organized as follows. First, the NC3m receiver architecture is described at a high level. Next, some description of the NC3m Technology Readiness Level 6 (TRL6) testing methodology is provided, followed by a set of example test results with some discussion. Finally, the paper concludes with a discussion of ongoing work and a brief summary.

II. ARCHITECTURE

The NC3m receiver comprises a GNSS RF card, processor card, low voltage power converter (LVPC), backplane, custom enclosure, and application flight software and firmware. External components (antenna, front end electronics, optional external oscillator) are also required and are mission-dependent *(Figure 1)*. The GNSS RF card provides down-conversion, filtering, and analog-to-digital conversion for received GNSS signals. The LVPC and backplane provide power services and interconnect between the various cards, respectively. The enclosure is constructed from space-grade hardware engineered to survive the harsh stresses of launch and provide protection from space radiation and electromagnetic interference (EMI). Flight software and firmware, hosted on the processor card, implement baseband signal processing of GNSS signals. The fully assembled flight-like Engineering Test Unit (ETU) used for TRL6 testing is shown in *Figure 1*.

While the NC3m system is flexible enough to be integrated with a variety of platforms, the current design is built on NASA's SpaceCube v3.0 mini processor system architecture (Brewer et al., 2020), a cubesat data processing platform that combines the reliability of traditional radiation-hardened (rad-hard) components with the cost and performance benefits of commercial parts. This is accomplished with a hybrid processing approach – a high-performance commercial FPGA is used for data processing, while a separate, rad-hard FPGA functions as supervisor, monitoring for radiation upsets and reconfiguring the commercial part as needed. This approach substantially improves cost to performance ratio compared to using a single, state-of-the-art rad-hard processor and allows for the use of much newer parts, as rad-hard versions often lag by years. The platform is designed to be highly modular in order to support a wide array of missions.

NC3m builds on this platform with the GNSS RF card, which provides a flexible, radiation-hardened solution for down conversion and digitization of GNSS L-band signals. Two independent RF chains allow for the processing of signals with different carrier frequencies, such as the GPS L1 and L2 configuration used in the testing covered in *Section III*. Signals such as GPS L5 and Galileo E5a can also be supported due to the wide receiver bandwidth. Support is included for both on-board and external reference oscillators, and the card can provide power for an external oscillator. A buffered one Pulse Per Second (PPS) signal for timing alignment can also be provided. A GNSS ASIC chipset is used in place of the discrete-component design used

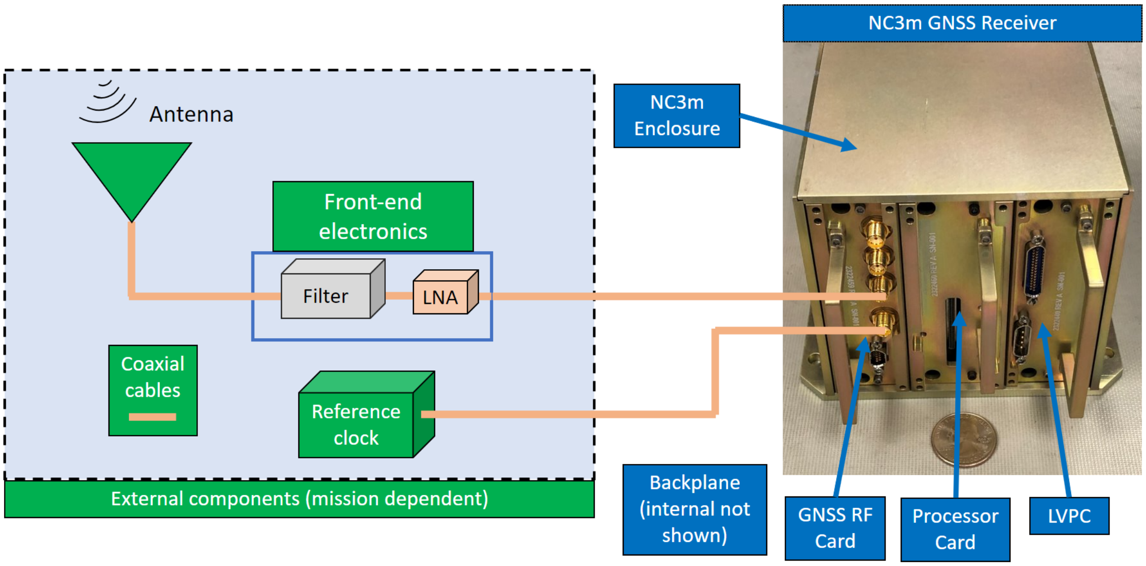

Figure 1: Flight-Like Engineering Test Unit

for MMS-Navigator, contributing to the considerable improvements in size, weight, and power shown in *Table 1*. Additional key differences are highlighted in *Table 2*.

	Size (in^3)	Mass (kg)	Power (W)
MMS-Navigator	600	6	30
NC3m	100	1.6	13
Improvement	83%	73%	57%

Table 1: SWaP Improvements

	MMS-Navigator	NC3m
Fast Acquisition	X	X
Weak Signal Support (25 dB-Hz)	X	X
GEONS navigation filter	X	X
Reprogrammable FPGA Design		X
Dual Frequency		X
Multi-GNSS		X
Low SWaP		X

Table 2: Key Features

The receiver baseband processing is implemented in custom FPGA firmware and flight software that derives from MMS-Navigator heritage and includes significant updates to support the new hardware platform and capabilities. To effectively service all targeted regimes, NC3m achieves high performance in both strong and weak signal environments. NC3m includes custom signal processing features to enable reliable cold-start (zero a priori knowledge required) acquisition and tracking of signals with carrier-to-noise spectral density (C/N_0) down to 25 dB-Hz, consistent with expected signal strength requirements for many weak-signal applications. Currently, development and testing have been completed for supporting the GPS L1C/A and L2C signals. Development and testing for additional signals is covered in *Section VI*.

NC3m flight software also critically incorporates the Goddard Enhanced Onboard Navigation System (GEONS), an orbit determination filter with substantial spaceflight heritage, including use on MMS-Navigator. GEONS implements an extended Kalman filter to combine an orbital model with intermittent navigation data, allowing for accurate orbit determination even in sparse signal conditions with poor geometry (NASA NTR, 2023).

III. TRL6 TESTING METHODOLOGY

NC3m achieved a critical technology milestone in 2022 after completing testing and passing its TRL6 assessment review. Technology Readiness Level 6 is a key milestone on the TRL technology roadmap used by NASA and other organizations to track technology development. TRL6 is defined as a *system/subsystem model or prototype demonstration in a relevant environment* (NASA, 2020). For NC3m, the TRL6 *prototype* was a flight-like engineering test unit (ETU), and the *relevant environment* was defined as hardware-in-the-loop simulations in representative low Earth orbit (LEO), geostationary Earth orbit (GEO), and lunar (selenocentric) orbits in combination with environmental tests simulating the stresses of launch and the space environment.

The simulation scenarios all used L1 GPS transmitter antenna patterns and a GPS link model carefully calibrated against MMS flight data, similar to the description in Winternitz et al. (2019), though with some updates. For simplicity, and since this testing focused on hardware performance and not precise representation of mission scenarios, the L2 frequency used the same link model as L1, and ionosphere and broadcast ephemeris errors were omitted. The impact of excluding these error sources is relatively minor and well understood. For the LEO and GEO scenarios, simple circular orbit models were used with no maneuvers. The LEO scenario modelled a zenith-pointed GPS patch antenna, while the GEO scenario modelled a small high-gain antenna with approximately 9-10dBi peak gain. The lunar scenario modeled a 12-hour elliptic lunar frozen orbit (ELFO) with south pole apogee coverage. This scenario modelled a 14-16dBi high gain antenna pointed back at the Earth. This allows for full GNSS constellation coverage without stringent pointing constraints and provides adequate gain for good performance from NC3m at lunar distance.

To measure receiver performance, a testing framework and vocabulary to describe it is established. In this paper, **cold start** tests begin with zero a priori information, starting GEONS with a least-squares point solution and large initial uncertainty. **Warm start** tests, on the other hand, begin with substantial information, starting GEONS with converged covariance and uploaded state with representative errors. A high-fidelity GNSS simulator is used to provide RF data from scenarios modeling one of three orbital regimes: **LEO**, **GEO**, or **lunar** orbit. The Comprehensive Performance Test (**CPT**) Suite consists of cold start tests for LEO, GEO, and lunar orbits; warm start tests for GEO and lunar orbits; and an additional set of single channel tests to establish acquisition probability. Some detail on the simulation scenario is provided next.

Environmental testing was conducted according to the Goddard Environmental Verification Standard (GSFC-STD-7000B, 2021) and consisted of 3-axis random vibration testing to simulate the stress of launch, thermal vacuum testing to simulate the space environment, and electromagnetic interference testing to identify vulnerabilities and monitor for emissions. Before subjecting the receiver to these tests, a baseline CPT was conducted under normal lab conditions. Multiple CPTs were conducted throughout environmental testing and after its completion for comparison to this baseline.

IV. PERFORMANCE RESULTS

NC3m has shown strong performance results in its TRL6 LEO *(Figures 2-4)*, GEO *(Figures 5-7)*, and lunar *(Figures 8-10)* simulations. The receiver surpassed the target number of satellite vehicles (NSVs) tracked in all regimes.[1] Even in the most challenging test, lunar cold start, NC3m tracked numerous signals below 25 dB-Hz, as is evident in *Figure 8*, where the number of signals tracked is shown to be consistently higher than both the target and the total number of visible signals above 25 dB-Hz, indicating that the receiver is tracking signals below this threshold. This is also shown clearly in the C/N_0 histogram *Figure 3*, which gives the number of minutes for which signals were tracked at various carrier-to-noise densities[2]. Examination of the C/N_0 histograms shows that the majority of tracked signals in the GEO and lunar regimes are below 35 dB-Hz, which serves as a rough delineation between transmitter main and side lobe signals. In the LEO regime, all signals are above this level, as only main lobe signals are visible. Example GEONS solution errors for each case are also provided along with an associated approximate upper bound.[3] Root mean squared errors (RMSE) of position and velocity estimates from test runs are given in *Table 3*.[4] These RMSE calculations use data starting after a settling period to account for the initial transience of cold start tests.[5]

[1]Successful performance was defined as tracking the target NSVs during 90% of operation, excluding the startup period. The NSVs tracked target is shown as a dashed line in the included plots and was defined as 75% of the lesser of the total number of visible signals above 25 dB-Hz and 12 (the number of tracking channels implemented). In other words, the target was either 75% of qualified visible signals or 9.

[2]"NC3m tracked signals" occasionally exceeds "True visible signals" in the C/N_0 histograms. This is because the "NC3m tracked signals" statistic is derived from the receiver's estimate of C/N_0, which is not necessarily identical to the truth data, and also because truth observations are generated at a higher rate than receiver observations, leading to a difference in resolution between the two.

[3]Trace marked "Approx. upper bound" is given by 3 times the square root of the sum of the position or velocity error covariance diagonal elements.

[4]Position and velocity estimate errors used to calculate RMSE are the RSS errors in space, equivalent to the total error magnitude. The RSS errors in space are squared and averaged over time, and the square root is taken to get the RMSE.

[5]For lunar and LEO test cases, the settling period is one orbit, and the RMSE calculation takes place over a period of one orbit. For GEO, the settling period is 4 hours, and the RMSE calculation takes place over the subsequent 20 hours. This is a consequence of the 24-hour length of the tests conducted, which includes only one GEO orbit.

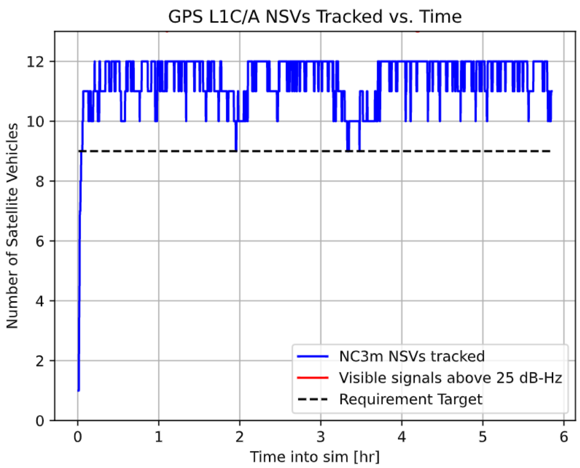

Figure 2: Example LEO Cold Start - NSVs Tracked
Note: Visible signals above 25 dB-Hz are off the scale of this chart, and the receiver implements 12 channels.

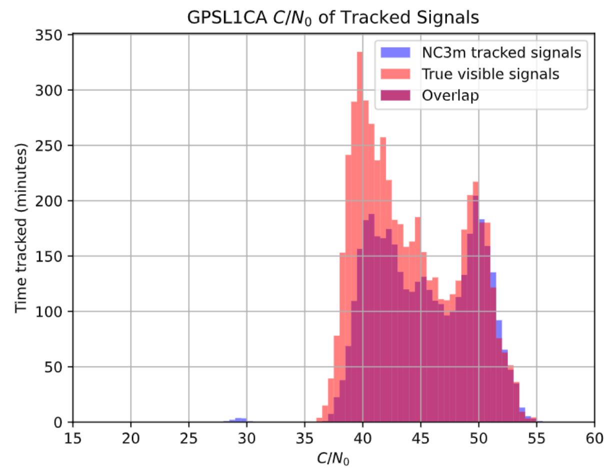

Figure 3: Example LEO Cold Start - C/N0 Histogram

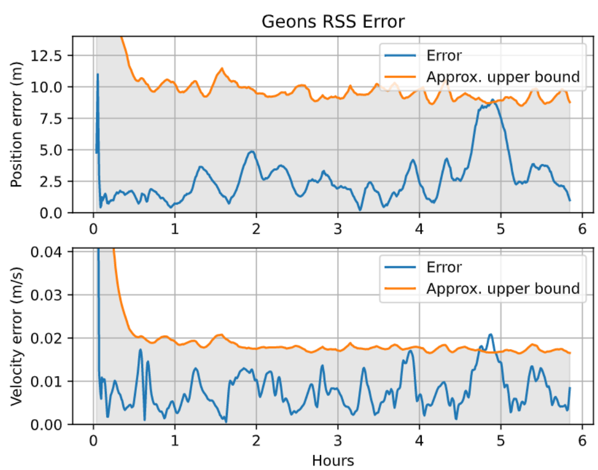

Figure 4: Example LEO Cold Start - GEONS Solution Error

	Position RMSE	Velocity RMSE
LEO	2.40m	8.3mm/s
GEO	4.94m	0.6mm/s
Lunar	24.2m	4.7mm/s

Table 3: Example Solution RMSE - Cold Start

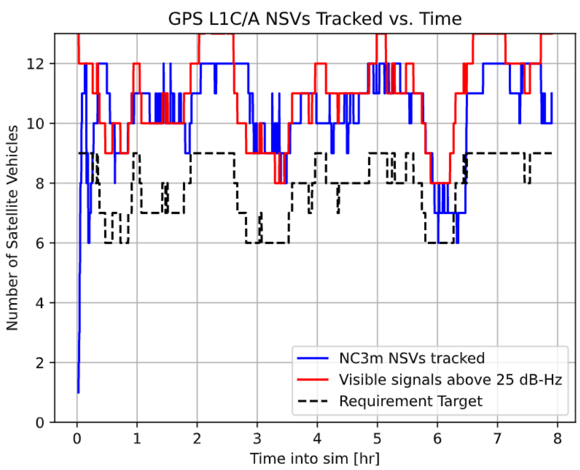

Figure 5: Example GEO Cold Start - NSVs Tracked

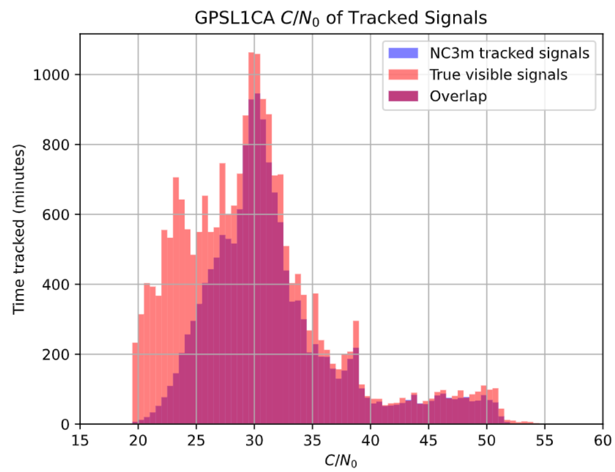

Figure 6: Example GEO Cold Start - C/N_0 Histogram

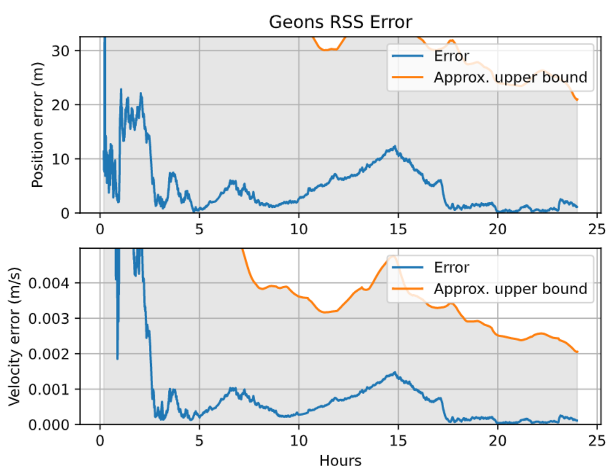

Figure 7: Example GEO Cold Start - GEONS Solution Error

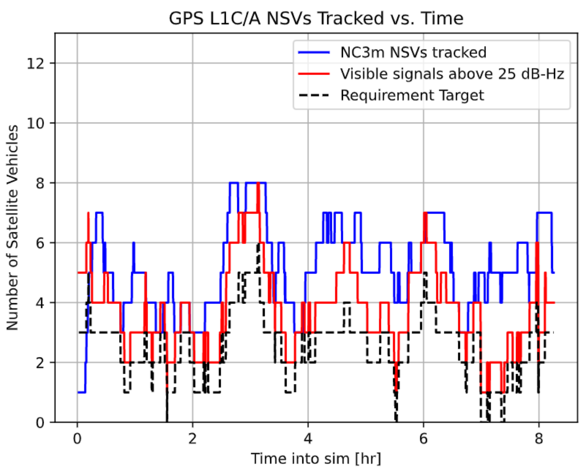

Figure 8: Example Lunar Cold Start - NSVs Tracked

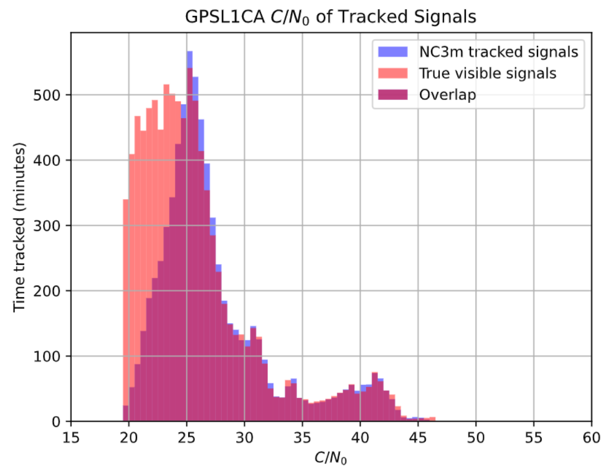

Figure 9: Example Lunar Cold Start - C/N0 Histogram

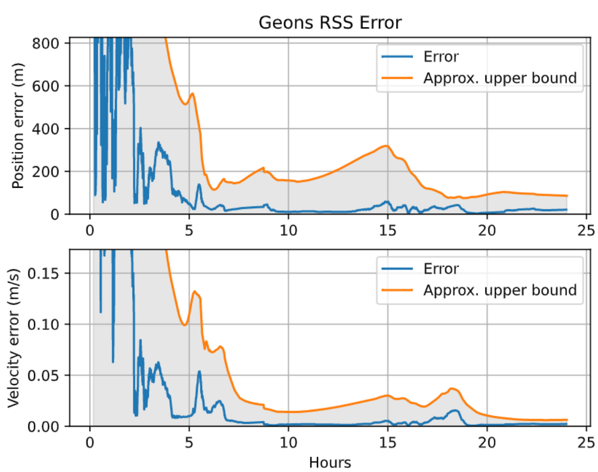

Figure 10: Example Lunar Cold Start - GEONS Solution Error

V. ENVIRONMENTAL TESTING

To simulate the stresses of launch, the NC3m receiver was subjected to 3-axis random vibration testing and frequency response analysis. As the receiver will not be powered during launch, it was not powered during these tests. Analysis of inertial measurements taken during vibration testing gave results well within operational requirements specified by GEVS. A CPT conducted afterwards confirmed no degradation in performance.

A thorough space-environment simulation was conducted using a thermal vacuum (TVAC) chamber to reduce pressure below 10^{-5} Torr and create temperature swings testing operation from -25 to 50C and survival from -30 to 55C. CPTs were conducted at both high and low operational temperature plateaus, and tests were run to monitor performance during temperature transitions. Tests demonstrated performance results in line with the baseline. The receiver was also evaluated for electromagnetic emissions and susceptibilities and found to pass all related GEVS requirements.

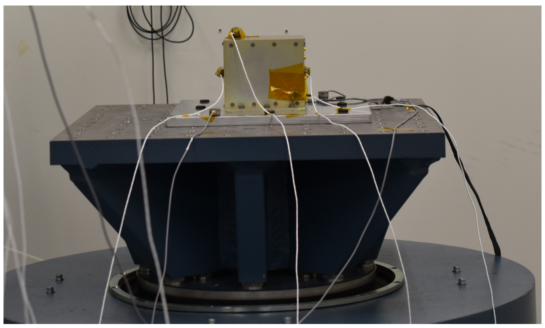

Figure 11: Vibration Testing

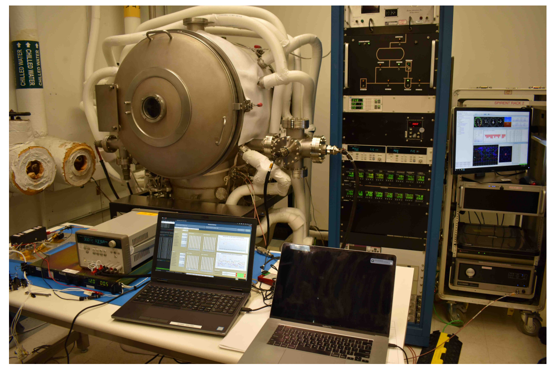

Figure 12: Thermal Vacuum Testing

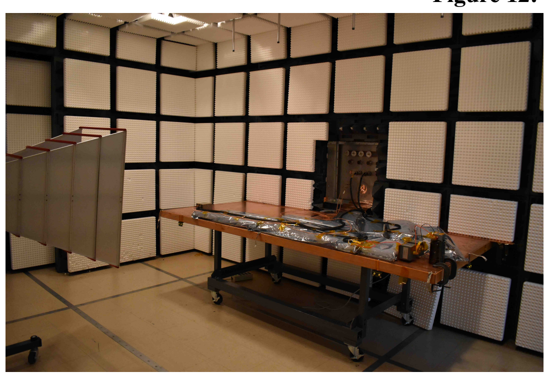

Figure 13: EMI Testing

After completing all environmental testing, a final CPT was conducted in lab conditions to verify that performance had not been affected. Once again, strong performance was demonstrated by all metrics. No substantial change was observed in terms of NSVs tracked or solution error, confirming NC3m's robustness to the environments of launch and space operation.

VI. ONGOING WORK

NC3m has multiple prospective missions. A customized version of the receiver, focusing on enabling precise orbit determination for a LEO geodetic application and interfacing with an S/X-band transmitter, will fly on the Geodetic Reference Instrument Transponder for Small Satellites (GRITSS), an in-development NASA mission. NC3m can also be incorporated into the Lunar Communications Relay and Navigation System (LCRNS), intended to support lunar communications and navigation for NASA Artemis missions and other lunar orbiting and lunar surface users.

Although only GPS L1C/A and L2C signals were processed during TRL6 testing, GPS L5 tracking is now fully supported and has shown promising results. Additionally, Galileo E1 support has been developed and is currently beginning integration and testing, and E5a support is also in development. When all signals are brought online, NC3m will be able to simultaneously process L1C/A, L5, E1, and E1a by utilizing GPS-Galileo interoperability and the receiver's dual-frequency architecture.

VII. SUMMARY

This paper introduces the NavCube3-mini (NC3m) space GNSS receiver that targets all Earth orbit regimes and especially lunar orbits and cis-lunar space. NC3m derives from the Navigator GPS receiver which is currently navigating the Magnetospheric Multiscale mission (MMS) in elliptic orbits reaching nearly half the distance to the Moon. The paper describes the basic architecture of NC3m and its extensive and successful TRL6 test campaign, completed in 2022. This test campaign demonstrated a NC3m engineering test unit (ETU) in simulated LEO, GEO, and lunar orbits and relevant vibration, thermal vacuum, and EMI environments. The results predict that NC3m can provide excellent performance in all these regimes, including lunar orbit. With low SWaP, high performance, and multi-frequency capabilities, NC3m is a mature TRL6 technology ready to support the next generation of challenging GNSS applications. This receiver aims to push the limits of GNSS applications, expanding the range of operability to the Moon and offering enhanced, real-time, on-board navigation as an alternative or as an augmentation to traditional ground-based tracking techniques.

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