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Early Communications Testing Between NASA's Deep Space Network and Gateway's Power and Propulsion Element

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Abstract

NASA's Deep Space Network (DSN) is preparing to support the Gateway mission, an international collaboration led by NASA consisting of a lunar outpost hosting humans in orbit around the Moon in a Near Rectilinear Halo Orbit (NRHO). A key element of NASA's Moon to Mars program, Gateway will be constructed incrementally in cislunar space, with its initial component planned for launch in a future NASA mission. The initial component includes a foundational element, the Power and Propulsion Element (PPE) developed by Maxar Space LLC, which will provide the primary communications system for Gateway. PPE will provide high-rate communications between the Gateway, Earth, and the lunar surface (Ref. 1).

In a significant milestone for NASA's Gateway project, Maxar and DSN have successfully tested their advanced communication systems for the first time in summer 2024. These early tests aimed to mitigate risks of major issues during final compatibility testing which will occur just prior to spacecraft shipment. Risk reduction testing was conducted at DSN's Development and Test Facility in Monrovia, California which contains identical signal processing equipment as operational DSN sites (Ref. 2), (Ref. 3) (minus some analog components such as amplifiers). An engineering model of the PPE communication system under test was connected to the test facility through X-band or K-band frequency converters.

The communication system uses a variety of residual carrier or suppressed carrier modes for data transmission defined in the International Communication System Interoperability Standards (ICSIS) (Ref. 4). End-to-end data flow of error-free data was confirmed in the uplink and downlink. Acquisition and tracking performance was evaluated at anticipated signal levels in the cislunar environment. Quality of the pseudo-noise signal used for two-way range measurements of PPE's position was evaluated. This paper will describe the risk reduction test campaign, test results, and forward work to be completed prior to launch.

This risk reduction test comes during a period of increasing use of the Deep Space Network to support crewed missions and underscores the critical role of advanced communication technologies in

achieving NASA's ambitious goals of returning humans to the Moon, exploring Mars, and beyond. Valuable lessons learned and increased partner collaboration are essential to ensure Gateway's success and to usher in a new era of lunar exploration. Such cooperation between partners will be essential to the future success of Gateway and a new era of lunar exploration.

1.0 Introduction

The Power and Propulsion Element (PPE) will provide primary radio links between Earth and Gateway, including continuous communication when crew is present (Ref. 5). In addition to carrying Gateway's traffic, PPE will relay information between Earth and the lunar South Pole – a location whose visibility to Earth makes direct communications challenging. PPE can perform radiometric ranging with NASA's Deep Space Network (DSN) for position determination as well as a number of protocols defined in the International Communication System Interoperability Standards (ICSIS) (Ref. 4) for telemetry and commanding at X-band (7 to 10 GHz). Additionally, Ka-band (22 to 27 GHz) links are used for high-rate data transfer. These communication systems are summarized in Figure 1, along with S-band (2 to 4 GHz) proximity links for visiting vehicles (VVs) provided by another element of Gateway.

The PPE communications system consists of low- and high-gain antennas, analog front ends at X- and Ka-band, and software-defined modems (SDMs) for digital signal processing. Each SDM contains protocol sets implemented on field-programmable gate arrays (FPGAs) to establish direct-to-Earth and lunar surface communications links. On Earth, communications will be supported by NASA's Lunar Exploration Ground Systems (LEGS) ground stations, the European Space Tracking (ESTRACK) network, commercial ground stations, and NASA's Deep Space Network (DSN).

Compatibility testing with the DSN, as well as LEGS and ESTRACK, is scheduled during the final performance test window, which is just prior to spacecraft shipment. NASA and Maxar decided to conduct an early risk reduction test with DSN beginning in May 2024. The goal of this risk reduction testing was to validate key SDM requirements (Ref. 6) and compatibility with the DSN. This risk reduction testing was performed to retire modem-level risks early and to mitigate the need for a retest required by issues found during full compatibility testing, which would likely impact the launch date.

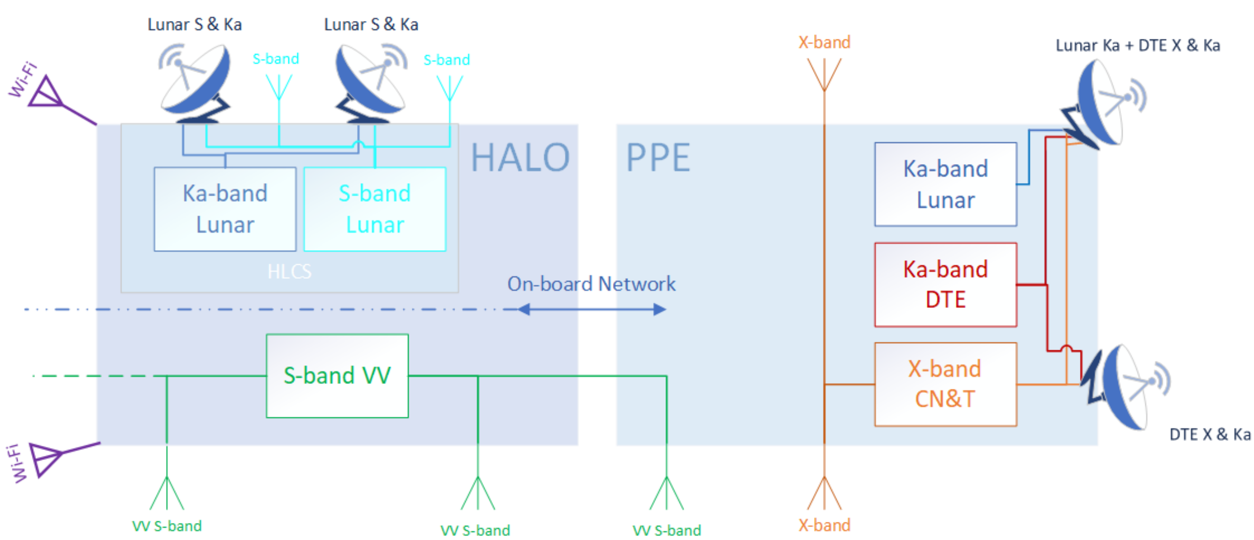

Figure 1.—Overview of Gateway Communication Systems (Ref. 5).

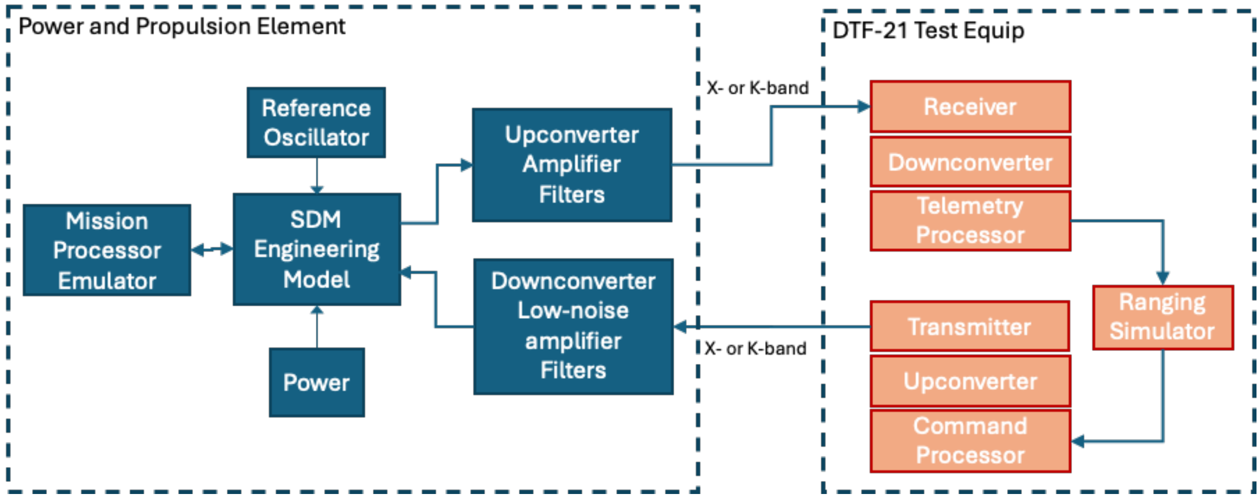

Figure 2.—Simplified Block Diagram of PPE-DSN Risk Reduction Test Configuration.

2.0 Test Setup

The PPE SDM and associated equipment were connected to the DSN Test Facility (DTF-21) in Monrovia, California. DTF-21 provides a testbed using duplicates of the same uplink and downlink equipment maintained at the three DSN sites in Goldstone, California, Madrid, Spain and Canberra, Australia (minus antennas and LNA front-ends) to allow testing of flight equipment or signal processing schemes. A simplified block diagram of the test configuration is shown in Figure 2.

This paper will summarize the issues uncovered during the risk reduction tests. Many issues uncovered were related to the use of test software to interface with the SDM. These issues will be resolved prior to the full compatibility test when fully verified flight software will be completed. Other issues are related to test configuration, ground software, selection of the modulation indices for nonregenerative ranging, and implementation of the K-band filtering in DSN.

3.0 Completed Testing

3.1 Modulation/Coding Compatibility

A set of modulation, coding, and data rate configurations were defined to cover the most common operational modes. For each mode, we verified demodulator and LDPC decoder lock. In the uplink direction, test data consisted of a short repeating hex string which was verified by inspection. In the downlink, the SDM generates a pseudorandom bit sequence which was post processed to detect errors. Test cases included a limited selection of parameters outlined in the ICSIS unique to PPE's planned modes of operation, most cases involved a sweep of powers to find the point at which the receiver lost lock. Due to time constraints, this was not completed for all modes.

3.2 Codeword Error Rate Test

A long-duration test was executed over approximately 36 h to detect intermittent transmission issues with the SDM which may manifest over long periods of operation. A 1/2-rate coded Offset Quadrature Phase Shift Keying, non-return-to-zero level encoded (OQPSK/NRZ-L) downlink at 200 Msps was chosen. Over 81 million codewords were successfully decoded with zero errors.

3.3 Frequency Sweep

A frequency sweep test was conducted to verify the SDM's ability to acquire a signal offset from the nominal center frequency and track the carrier through motion-induced Doppler shift. First, with no frequency offset power levels from DTF-21 were adjusted to find the minimum signal level at which the modem would acquire. Then the SDM was configured for a frequency offset search range. DTF-21 began the frequency sweep, sweeping down at representative worst-case Doppler rate. The modem acquired and maintained error-free lock for the duration of the test.

4.0 Identified Anomalies

4.1 Ranging Anomalies

PPE uses nonregenerative PN ranging as defined in CCSDS 414.1-B-3 (Ref. 7), (Ref. 8). During the risk reduction testing, upon enabling ranging, the signal-to-noise telemetry received at DTF-21varied beyond expected levels.

Troubleshooting led to conclusion that the command signal was passing through into the ranging downlink. The teams observed that simultaneously running a command uplink to the SDM and a ranging downlink to DTF-21 results in interference on the downlink telemetry signal. When a nonregenerative ranging channel is used, the uplink noise and command signal passes through the ranging channel and become modulated onto the downlink carrier. On PPE, modem filtering is sized to support the bandwidth of the ranging signal, which is wider than the typical command uplink bandwidths. The filtering on the modem is therefore unable to fully separate the command uplink and the ranging uplink signals. The full uplink becomes turned-around on the downlink causing the command signal to degrade both the telemetry downlink and ranging downlink.

To reduce the effects of interference the modulation indices must be optimized on the command, ranging, and telemetry signals. Testing at DTF-21 used a large modulation index for the ranging downlink signal, allowing a large amount of command signal power to pass through to the downlink. Subsequent to testing, the uplink and downlink signals have been modeled to perform this optimization of the modulation indices. Figure 3 shows a basic block diagram of the signal flow in the SDM. Command and

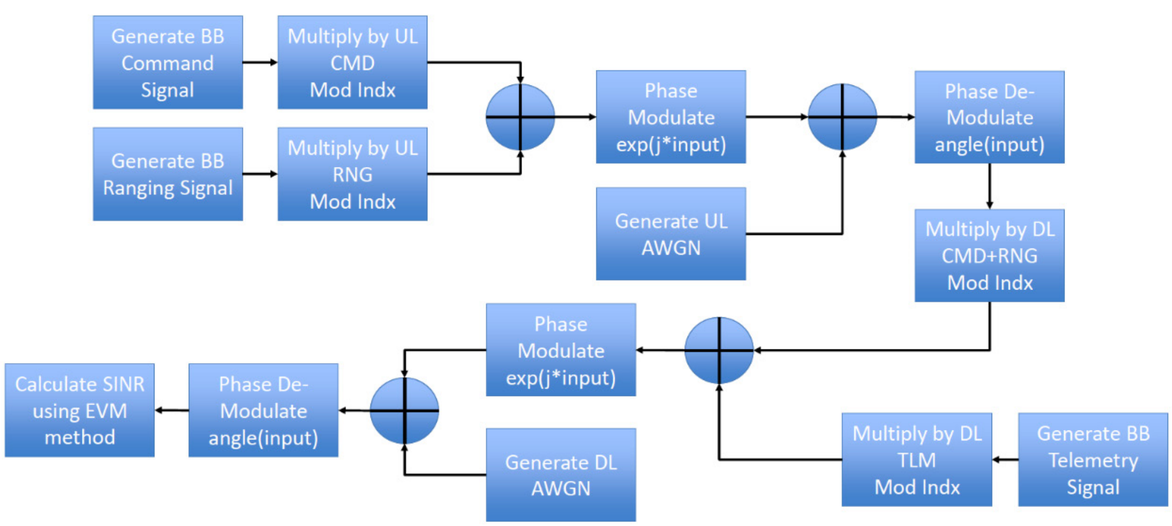

Figure 3.—PN Ranging Optimization Model.

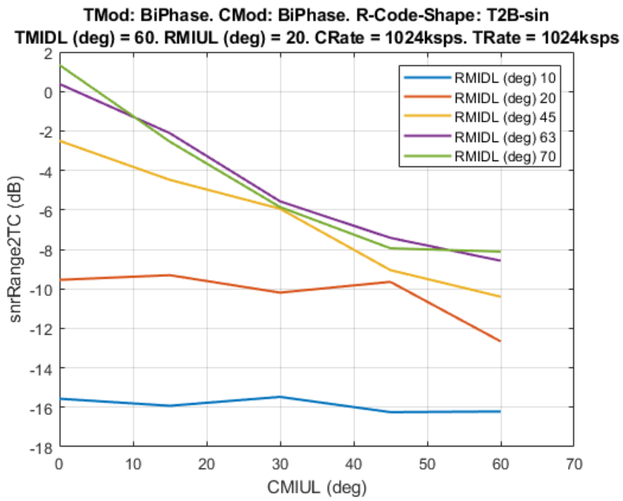

Figure 4.—Signal-to-Interference Power Ratio of the Ranging Downlink-to-Command+Telemetry on Downlink vs. Command Modulation Index Uplink.

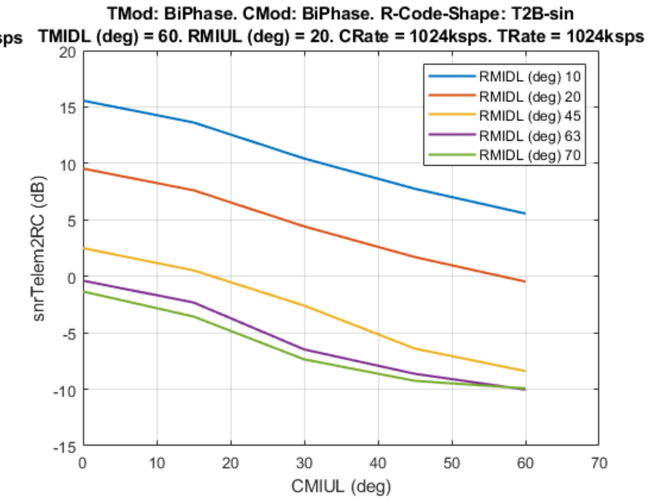

Figure 5.—Signal-to-Interference Power Ratio of the Telemetry Downlink-to-Command+Ranging on the Downlink vs. Command Modulation Index Uplink.

ranging signals are uplinked and demodulated. The sum of the command and ranging is turned-around for the downlink and added to the telemetry signal for reception at the ground.

To reduce the effects of interference we can optimize the modulation indices on the command, ranging, and telemetry signals. Figure 4 and Figure 5 show the results of the simulation. Both figures used a telemetry modulation index (TMIDL) of 60 degrees and an uplink ranging modulation index (RMIUL) of 20 degrees. These were kept constant in the simulation as the interference was primarily due to the command signal leaking into the ranging downlink. Figure 4 shows the power ratio of the Ranging Downlink-to-Command+Telemetry on the downlink (snrRange2TC) versus the command modulation index uplink (CMIUL) at multiple downlink ranging modulation indices (RMIDL). Similarly, Figure 5 shows the power ratio of the Telemetry Downlink-to-Command+Ranging on the downlink (snrTelem2RC) versus the command modulation uplink (CMIUL) at multiple downlink ranging modulation indices (RMIDL).

The calculation attempts at estimating the signal-to-interference-plus-noise-ratio (SINR) between a desired signal s_i and the superposition of interfering (including various possible noise/distortion components) signals s_n, $n = j_1, \dots, j_M$. The notion of "ideal" in the calculation below refers to the "expected" contribution of the desired signal s_i in the total signal s_T. The signal-to-interference power ratio is defined as follows

$$SINR_{i/\sum j_1,\dots,j_M} = 10 \times log_{10}\left(\frac{\overline{\left|s_{i,Ref}\right|^2}}{\overline{\left|s_{Res} - s_{i,Ref}\right|^2}}\right)$$

$$s_{Res} = s_T - \sum_{n \neq j_1,\dots,j_M} s_{n,ideal}$$

$$s_{i,Ref} = s_{i,ideal}$$

where $\overline{(\cdot)}$ denotes the time average of the enclosed argument and $|\cdot|$ denotes the absolute value (magnitude) of the encoded complex-valued quantity.

A low ranging modulation index combined with a command modulation index as low as practicable can eliminate the interference on the telemetry signal. A low ranging index does provide a low signal power at the ground but can be accounted for with a large integration time at the receiver for a large processing gain.

4.2 DTF Implementation of Square-Root-Raised-Cosine (SRRC) Pulse Shape Filtering

During testing with Offset Quadrature Phase Shift Keying (OQPSK) modulation unexpected Low Density Parity Check (LDPC) corrections were observed at nominal power level and PPE could not acquire the uplink from DTF-21 at expected power levels. It was determined that the issue with acquisition is due to the OQPSK filtering implemented in DTF-21. Subsequent testing showed that the issues manifested only when SRRC was enabled. FPGA DSP processing of SRRC is the suspected root of the issue. This issue is under active investigation at DSN.

4.3 SpaceWire Collisions

Data transfer between the SDM and the remainder of the command and data handling subsystem occurs over a SpaceWire bus. Outgoing bytes of user data are sent over this bus to be modulated and transmitted. Likewise, received data is passed from the SDM. Additionally, the SpaceWire connection carries configuration commands and modem telemetry for performance monitoring of the SDM itself. These metrics (e.g., demodulator lock indicators, automatic gain control values, LDPC decoder status) were used heavily in risk reduction testing. Software on the other end of the SpaceWire bus was tasked with demultiplexing this user data and status information. As mission software was on a separate development cycle from the SDM firmware, only a prototype build was available to support testing at DTF-21. Occasionally this software failed to properly sort the received data. These collisions increased in frequency at higher data rates making it difficult to gain real-time insights as to the modem's operation. A configuration in the SDM allowed the user data flow to be disabled, leaving only the telemetry. Testing continued with this workaround.

4.4 Signal Leakage

DTF-21 includes an RF-shielded room for isolating devices under test. At X-band, signals from the facility's modulators and demodulators are carried across the building over coaxial cable and into the screen room through cable glands. The room's seal is complete with a large door which was initially left open during testing for convenience.

Typically, signals are attenuated at DTF-21's modulators such that they reach the unit under test at comparable levels to what the spacecraft would see on orbit (after calibrating for fixed cable loss). However, in the beginning of risk reduction testing it was desired to record captured signals from DTF-21 for later playback and continued testing. This necessitated attenuating the signal outside the screen room after the strong signal was coupled into the recording device.

Initially, uplink tests were producing far higher error rates than expected given the input signal levels. The team repeated the tests with the screen room door closed and found performance in-line with expectations. We believe the strong signal from outside the screen room was coupling into the receiver chain. This leakage was strong enough to distort the weak signal and cause errors. After this discovery the attenuation stage was also moved back to its original location in a different part of the building. No further issues were encountered.

5.0 Discussion

The risk reduction test campaign verified SDM compatibility with the DSN in many modes which will be critical to successful communications for Gateway. Equally important, testing uncovered issues allowing sufficient lead time for their identification and correction. Though none of the problems described in Section 4.0 are insurmountable, discovery during a pre-ship compatibility test could have impacted the mission's launch schedule.

A less tangible, though highly valuable, contribution of this testing was greater common understanding between DSN, Maxar, and the Gateway program in terms of space communications. To cite one example, an important DSN test is the characterization of a best lock frequency – an offset applied at DSN to its transmit signals at which the spacecraft's receiver is most sensitive (Ref. 9). PPE's receiver is more complex than typical deep space probes and performs internal frequency sweeping. For this design, the concept of a single best lock frequency is not applicable. Arriving at the conclusion to delete this test from the plan required engineers from each organization to understand the design and typical operations of one another's systems. Deep collaboration of this type will be critical for the highly complex mission of establishing permanent human presence in and around the Moon.

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