System Development and Spacecraft Testing of the Morehead State University Ground Station

Timothy Pham, Jason Liao. E.J.Wyatt
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA
e-mail: {Tim.Pham, Jason.Liao, E.J.Wyatt}@jpl.nasa.gov

Benjamin Malphrus, Jeffrey Kruth, Robert Kroll,
Michael.Combs, Tobias Gedenk, Sarah Wilczewski,
Jacob Lewis, Alex Roberts, Emily Mattle, Chloe Hart
Space Science Center, Morehead State University
Morehead, Kentucky, USA
e-mail: {b.malphrus, j.kruth, r.kroll, m.combs, tgedenk,
sewilczewski, fjlewis, ajroberts3, ejmattle,
cmhart}@moreheadstate.edu

Abstract— **In support of the Lunar IceCube mission, as well as other CubeSats to be launched on the upcoming NASA Exploration Mission 1, the 21-m ground antenna at the Morehead State University in Kentucky, United States is under development to augment its telemetry, tracking and command capability at X-band (previous capability is limited to S-band). The new system is expected to be operational in 2020. This is the first collaboration between National Aeronautics and Space Administration's Deep Space Network (DSN) and university in ground system development. It will result in a university's tracking station fully compatible with the DSN and thus increase DSN support to mission users with more antenna assets. The new hybrid system architecture combines commercially available RF components, custom-designed microwave feed for Morehead antenna, and specialized DSN digital equipment. Such an approach minimizes the implementation cost, offers learning opportunity for the students to gain experience in system design and implementation, and maximizes system capability and compatibility with the DSN. The ground station at the Morehead State University will handle signal transmission to and reception from spacecraft, and other signal processing functions such as modulation/demodulation, decoding, etc. The backend equipment at the Jet Propulsion Laboratory in Pasadena, California will be responsible for data interface to the mission users. This architecture makes the Morehead antenna appears as one of the DSN antennas. Since early 2018, the 21-m ground system at Morehead has been upgraded with capability to receive spacecraft signal at X-band and process its telemetry and Doppler data. In mid 2019, the Morehead system will be further enhanced with a transmit capability for spacecraft command and ranging. Testing with spacecraft currently in operation such as Osiris Rex, MAVEN and Hayabusa2 is ongoing in an effort to validate system capability and characterize system performance. Preliminary results indicate that the downlink system is functional. They also enable assessment of the Gain-to-System Noise Temperature ratio (G/T) of the Morehead 21-m antenna.**

Keywords - Morehead State antenna; ground system; Lunar IceCube.

I. INTRODUCTION

CubeSats and other small satellites are increasingly used for Earth remote sensing, for science research, and for unique communications activities, all of which have increasing data throughput requirements. In addition, CubeSats are being planned for interplanetary research, with 13 CubeSats slated to fly on the NASA's Exploration Mission-1 (EM-1) in 2020, opening the door for CubeSat and smallsat exploration of the solar system. As these CubeSat missions venture to the distance of the moon and beyond to other bodies within the Solar System, they require a ground tracking system with greater capabilities than previously required for low Earth orbiters. Performance attributes in the ground system such as large antenna, high gain efficiency, operation at higher performing X-band frequency, low noise and low-loss equipment, most efficient forward error correction coding, high transmitting power, etc. become critical to the communications with deep space spacecraft.

Given the expected significant increase in CubeSat missions, beyond what is currently supported by the NASA Deep Space Network (DSN), the NASA Advanced Exploration Systems (AES) Program has been funding an implementation at the Morehead State University to enable its 21-m antenna to support the Lunar IceCube mission, as well as other EM-1 CubeSats. Leveraging on the expertise in deep space communications of the Deep Space Network, a partnership between the Jet Propulsion Laboratory (JPL) in California, United States and the Morehead State University (MSU) in Kentucky, U.S., was established to aid the development of ground station at Morehead, and to develop a strategy that would enhance DSN capabilities by utilizing existing non-NASA assets (i.e., university and non-profit radio astronomy observatories). Our goal is to build a ground station that is capable of deep space communications and tracking, with maximum compatibility with the DSN, and within limited budget. The approach we took is to optimally combine specialized DSN equipment with those available commercially. This hybrid system minimizes

ISBN: 978-1-61208-694-1

development cost; saving the non-recurring engineering cost on signal processing equipment already exist in the DSN. The rest of the system is designed by the Morehead State technical staff and students, from commercially available products; thus, offers a learning opportunity to the students and, at the same time, meeting the low-cost objective.

In Section 2 of this paper, we describe the Morehead ground system architecture that strives for maximum capability with a minimum cost, using the hybrid approach mentioned above. Such an architecture allows the MSU ground system to serve as a node on the Deep Space Network, which could help to offset the tracking load on the DSN for certain class of missions such as CubeSats. In Section 3, we present a nominal operational concept on how the system is expected to operate. Telemetry, tracking and command data flows will be described, along with service management aspects such as the antenna scheduling and generation of predicted Doppler frequencies, antenna pointing, and signal conditions. We highlight key system performance metrics in Section 4. Finally, Section 5 captures some preliminary test results with a few spacecraft currently in operation, such as Osiris Rex, MAVEN and Hayabusa2.

II. SYSTEM ARCHITECTURE

Prior to this implementation effort, which started in 2016, the Morehead State University 21-m antenna has been used to support several educational research picosatellites and nanosatellites such as KySat-1, KySat-2, and the Cosmic X-band Background Nanosat series (CXBN and CXBN-2). The system was also used for short-term capability demonstrations with NASA flight mission such as the Lunar Reconnaissance Orbiter and the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) [1]. Most recently, the system served as the primary ground station for the Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA) mission [2], funded by the Jet Propulsion Laboratory (JPL) in collaboration with the Massachusetts Institute of Technology (MIT). The 21-m antenna, prior to this upgrade, was equipped with a replaceable feed that can support operations at various frequencies in the Radio Frequency (RF), specifically the UHF-band (400- 470 MHz), L-band (1.4 – 1.7 GHz), S-band (2.2 – 2.5 GHz), C-band (4.8 - 5 GHz), X-band (7.0 – 7.8 GHz), and Ku-band (11.2 – 12.7 GHz). Signal reception is available at all these frequency bands and transmission is available at UHF and S-band.

For the EM-1 CubeSat missions, communications between flight and ground systems will be done at X-band to maximize the link performance. The X-band capability will be supported by new equipment (antenna feed, transmitter, receiver, network connections, frequency reference, etc.) and new operational processes (antenna scheduling, spacecraft pointing and doppler prediction, data delivery, etc.) described in this paper. The only thing that is common with the previous S-band and UHF systems is the common infrastructure such as antenna and electrical power. The ground system will have new equipment to transmit signal at 7.1-7.2 GHz and to receive spacecraft signal at 8.4-8.5 GHz. A new X-band antenna feed will need to be developed. On the uplink, a 2-kW transmitter will be deployed, along with the exciter electronics for generation of command and ranging signals. On the downlink, a cryogenic low noise amplifier operating at a very low noise temperature of 11 Kelvins will help to maximize the signal detection. A low-loss DSN-based receiver with its associated telemetry decoding and ranging processors that are optimized for low Signal-to-Noise Ratio (SNR) condition normally seen in deep space communications will also be deployed. These enhancements, relative to capability in previous missions, extend the communications to spacecraft that travel to the Moon and beyond – a 1000 times further than the low Earth orbits.

For past mission support, the MSU ground station could transmit telecommand to spacecraft and receive telemetry data; however, there was no ranging measurement required for the navigation of these nanosatellites. For future missions like the Lunar IceCube, ranging capability is essential in navigating the spacecraft to the moon. Another new challenge is the use of highly efficient error correcting codes, such as Turbo codes, which perform very close to the Shannon limit of the information channel capacity. Unfortunately, there was difficulty in finding commercial products that could support these two functions within available budget. As a result, a hybrid architecture that merges the university-developed hardware with some DSN-developed signal processing components was selected. The university focuses on RF analog components, using commercial parts available from other projects, as well as some newly procured components. The digital portion of the system that process command, telemetry and radiometric (Doppler and ranging) are replica of DSN equipment. This architecture enables the MSU ground station to act as a DSN node of operations since it has the same data interfaces to mission users as other DSN antennas. Since the DSN-provided equipment supports the data interfaces in compliance with the Consultative Committee for Space Data Systems (CCSDS) specifications, the MSU system has an inherent benefit of interoperability with other ground stations worldwide that are CCSDS compliant.

Figure 1 shows the new architecture of the Morehead ground station that is being developed. The Mission Operation Center (MOC) interfaces with the Morehead Station ground station via the DSN Deep Space Operation Center (DSOC). Command data could be sent from the MOC directly to the Uplink (UPL) equipment at MSU. Telemetry processing at MSU produces the received telemetry frames, which are then relayed to the Telemetry Tracking Delivery (TTD) at JPL before being delivered to the MOC. The same delivery occurs with radiometric data of Doppler and ranging measurements. The network connection between Morehead State University and the Deep Space Operation Center at JPL is via the NASA

Mission Backbone Network. This network connection has high redundancy and reliability, making it best suited for mission operations. The selected bandwidth of this connection is based on considerations of expected data rate needed for mission support and the annual rental cost. The Lunar IceCube and other EM-1 CubeSats have a maximum data rate under 1 Mbps. A decision was made to set the leased bandwidth at 5 Mbps to provide some flexibility for expanded operational needs.

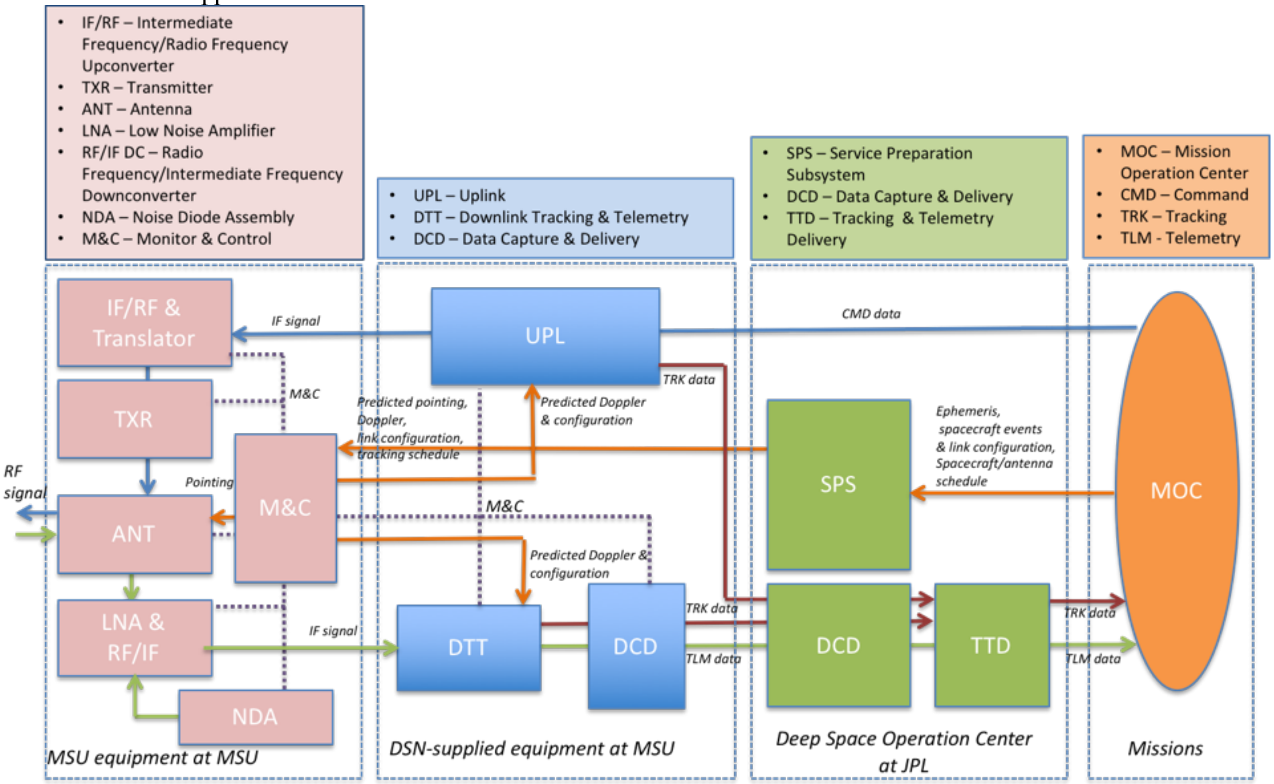

Figure 1. System architecture for the new X-band capability

There is also other ancillary equipment needed for ground station testing, calibration and operation monitoring, besides those used for telecommand and telemetry. The Test Translator with a standard CCSDS transponder ratio of 880/749 is used to convert the uplink signal from a transmitted frequency of ~7.2 GHz to a received signal at ~8.4 GHz. With the Translator loopback, the ranging delay within the ground system can be precisely measured. This station delay is then removed from the ranging measurements observed during spacecraft tracking in order to properly determine the spacecraft range. The loop back capability also enables a partial verification of the uplink and downlink equipment. By configuring the uplink equipment to generate a command data stream, feeding that signal to the downlink equipment, and being able to extract telemetry data, proper operation of uplink signal generation and downlink telemetry processing can be verified.

Another component that also aids with the monitoring of system performance is the Noise Diode Assembly (NDA). This equipment injects a known noise power into the system at a periodic frequency. By looking at the difference in power levels with and without the added noise, one can determine the noise temperature of the ground system. At MSU, such calibration is expected to be undertaken at the start of the pass, rather than continually through the pass as it is done in the DSN antennas. This is a trade-off for a simpler design in the noise calibration.

III. OPERATIONAL CONCEPT

In this section, we first describe the data interfaces with mission users and their spacecraft. Then, we'll focus on service management aspects of the operations, which include preparation for the tracking pass, as well as equipment monitoring during the pass.

For telemetry processing, as indicated in Figure 1, the signal received at the 21-m antenna is amplified by the cryogenic low noise amplifier and down-converted to an IF frequency around 300 MHz. The signal is then routed from the antenna to the mission control room, about 1 km away, via the fiberoptic link. The IF signal is then fed into an FPGA-based receiver that will digitize, demodulate and decode the signal. The extracted telemetry frames are sent to JPL by the Data Capture and Delivery (DCD) assembly. As the name implies, the DCD also captures and archives the data in short term, giving the option to retransmit the data should the network connection to JPL be temporarily down. At JPL, the telemetry frames are delivered to the mission operation system via an interface compliant with the CCSDS

Space Link Extension (SLE) of Return All Frames or Return Channel Frames. Telemetry frames can also be further processed at JPL into packets or file products under the CCSDS File Delivery Protocol (CFDP), for missions that require this type of product to make it easier for mission operations. However, for Lunar IceCube and other EM-1 CubeSats, the mission interface is at the frame level, under the Return All Frames or Return Channel Frames service.

For radiometric data, the carrier phase and ranging phase measurements of both uplink and downlink are relayed to JPL via the DCD. The information is packed into JPL-specific data format and delivered in real time to mission operation system. The same information can also be packaged in the CCSDS Track Data Message (TDM) format, for maximum interoperability with users who use TDM format. From these data products, the mission navigation team can compute the observed Doppler and ranging, which then helps them with orbit determination for spacecraft navigation

For command data, mission operation system will directly connect to the Uplink equipment at Morehead, using the CCSDS Space Link Extension Forward Command Link Transmission Unit (CLTU) interface specification. This SLE interface also enables user authentication and allows the mission operation team to control the radiation of commands to their spacecraft.

To enable data delivery between mission users and their respective spacecraft, many aspects of service management need to be considered. Service management refers to the antenna scheduling, generation of spacecraft prediction data, equipment monitoring and configuration management. Several service management interfaces are reflected in Figure 2.

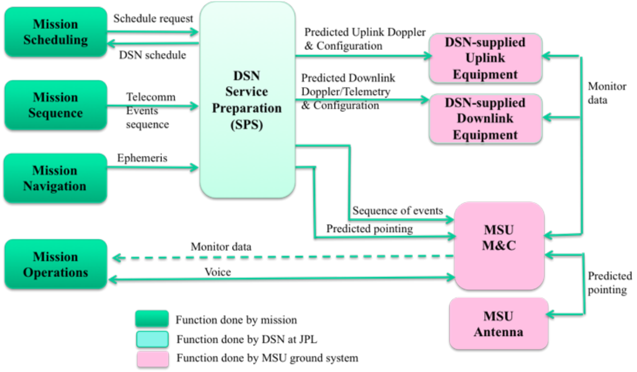

Figure 2. Service management data flow.

(1) Antenna Scheduling – The MSU antenna is schedulable by the DSN Scheduling. This allows for integrated support on missions, especially those that use both Morehead and DSN antennas. Information on any planned antenna maintenance, or science-related activities such as radio astronomy observations, will be inputted by the MSU team into the DSN schedule to indicate the time when the antenna is not available. The remaining time is open for spacecraft tracking, freely assigned by the DSN Scheduling. Through a web browser or application program interfaces, the operation team at Morehead would be aware of upcoming tracks and make necessary preparation for them.

(2) Signal Predictions – Once a track is scheduled, predictions on the expected Doppler frequency, antenna pointing and signal conditions (e.g., data rates, signal power, coding and modulation scheme, times of signal arrival and exit) are generated by the Service Preparation Subsystem (SPS) at JPL. The required inputs for this processing are spacecraft ephemeris and expected spacecraft communications configuration (e.g., planned data rate, coding/modulation scheme, start and stop time of signal acquisition). They are submitted by the mission operation team for their respective spacecraft. These prediction data products are automatically pulled by the Monitor/Control (M&C) processing at Morehead via a REST (Representative State Transfer) query based on the tracking schedule. The data are then distributed to appropriate equipment at Morehead - predicted pointing go to the antenna controller; expected downlink frequencies with imbedded Doppler and the expected signal conditions are given to the receiver; coding configuration is given to the decoder; uplink frequencies are given to the uplink controller, along with other configuration information necessary for command and ranging signal generation. The sequence of events for a given pass, generated by the SPS, would also indicate the start and stop time of the track, as well as any configuration changes (e.g., date rate) in mid track. With this information, the Monitor & Control at the MSU can automatically configure the equipment for the track and reconfigure the link to accommodate any subsequent changes in mid pass.

(3) Monitor data – Monitor data from all equipment is collected by the MSU M&C and presented to the MSU operators – either an operating staff member or students. Monitor data from the DSN-provided equipment, because of the way it was built to work with the DSN monitor control infrastructure, which is not deployed at Morehead due to implementation constraints, requires a special application program interface to be built to route the data to the MSU M&C. At this point, monitor data is locally stored at the MSU, rather than being routed to the DSOC and subsequently provided to MOC. In the case of anomalous event, monitor data can be extracted and delivered to the mission operation team for post-pass diagnostics.

Voice communications link – The MSU team will be able to exchange information with the DSN operations and mission operation teams via the standard DSN operational voice networks. The voice equipment supplied at MSU is

ISBN: 978-1-61208-694-1

the same as those used in the DSN operations center. Voice-over-internet-protocol data are flown over the same communications link that supports telemetry, command and radiometric data delivery.

IV. SYSTEM PERFORMANCE

Table 1 shows the improvement in the system capability at X-band, before and after this upgrade. By employing a cryogenic low noise amplifier, the system noise temperature is expected to drop by a factor of two, from 215 K to under 100K, yielding a higher signal to noise ratio and making signal detection much easier. Coupled with the use of more complex but highly efficient forward error coding such as Turbo or Low Density Parity Check (LDPC) codes, the system can operate at a much lower signal power threshold, within 1 dB of the Shannon limit of information channel capacity.

TABLE I. PRE AND POST UPGRADE PERFORMANCE

Performance Measure	**Pre-Upgrade**	**Post-Upgrade**
X-Band Frequency Range	7.0 – 7.8 GHz	7.0 – 8.5 GHz
LNA Temperature	70 K	< 20 K
System Noise Temperature	215 K	<100 K
Antenna Gain	62 dBi (@7.7 GHz)	62.7 dBi (@8.4 GHz)
System Noise Spectral Density	-175 dBm/Hz	<-178 dBm/Hz
G/T at 5° Elevation	37.5 dB/K	40.4 dB/K
Time Standard	GPS (40 ns)	Hydrogen maser (1 ns/day)
EIRP	N/A	93.7 dBW
HPBW	0.124 deg	0.115 deg
SLE Compliance	N/A	Yes
CCSDS Compliance	N/A	Yes
Forward Error Coding	Reed Solomon/Convolutional	Reed Solomon/Convolutional, Turbo, Low Density Parity Check
Radiometric	Angle, Doppler	Angle, Doppler, Ranging

The use of the Hydrogen MASER significantly improves the timing accuracy, by an order of magnitude compared to the previous reference to the Global Position System. This in turn improves the accuracy of radiometric data (i.e., reducing the noise in Doppler and ranging measurements), as well as telemetry data time tag.

Two significant features being added to the system with this upgrade are the ability to uplink at X-band and to conduct ranging. For ranging measurements, both DSN-specific sequential ranging [3] and pseudo-noise ranging [4] are supported. A full CCSDS-compliant pseudo-noise ranging is expected to be available in 2019.

V. SPACECRAFT TESTING

Because the collecting aperture of the 21-m antenna at Morehead is about 40% that of the 34-m antennas in the DSN, and the system noise temperature is about 4 times higher, there is about 10 dB difference in the received G/T. Thus, only a subset of X-band missions currently supported by the DSN that have sufficiently large link margin, above 10 dB, can be tracked by the Morehead antenna on a non-interfering basis, i.e., without requiring spacecraft to make any change in its downlink data rate. MAVEN, a Mars orbiter currently at low data rate of 23 symbols/s, provides a perfect opportunity for Morehead antenna to track it and be able to decode telemetry data. Osiris-Rex and Hayabusa2 signals, due to the use of higher data rate, leave little link margin to allow decoder lock up. Thus, Morehead tracking of Osiris Rex and Hayabusa2 can achieve carrier demodulation and symbol synchronization, but would not be able to decode the telemetry data.

Figure 3 shows the received carrier SNR (Pc/No) and symbol SNR (SSNR) from Hayabusa2 at both Morehead 21-m (designated as Deep Space Station DSS-17) and DSN 34-m antenna (DSS-25 at Goldstone, California). Both measurements indicate a G/T difference of 11.3 dB.

For Osiris Rex, Figure 4 shows a difference of 10.3 dB between the two sites (Morehead DSS-17 and Goldstone DSS-24), based on PcNo measurements.

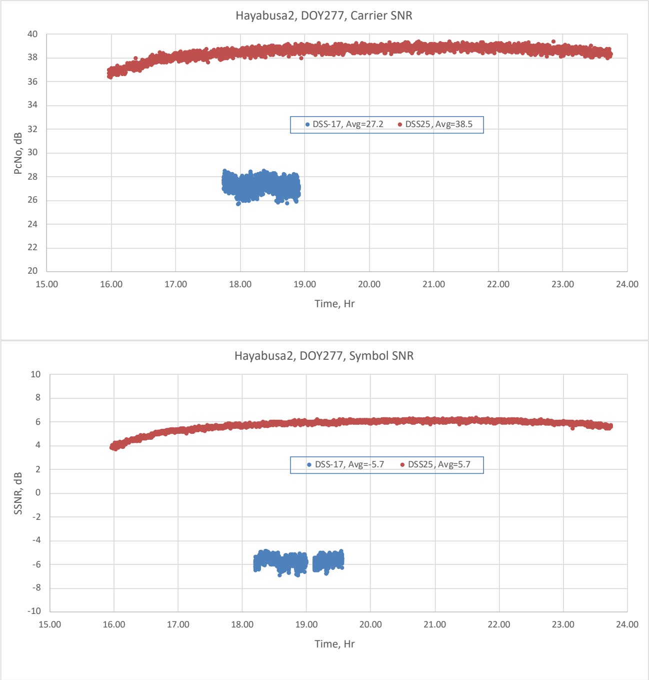

Figure 3. Hayabusa-2 Carrier and symbol SNR

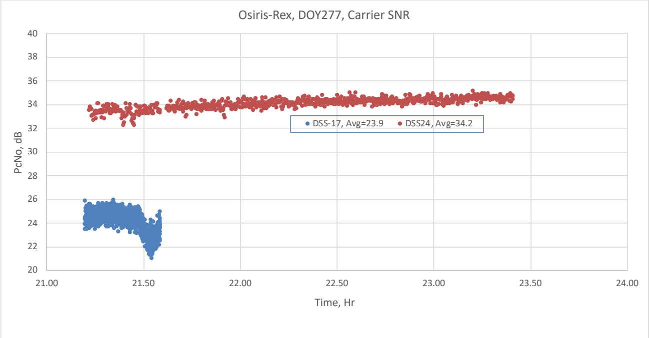

Figure 4. Osiris Carrier SNR

Similarly, Figure 5 shows measurement with MAVEN spacecraft. The PcNo difference was about 11.0 dB; however, due to unknown cause, we were not able to achieve subcarrier lock at Morehead station. As a result, the symbol synchronization suffered excessive degradation, resulted in a 17 dB difference between Morehead and DSN antennas.

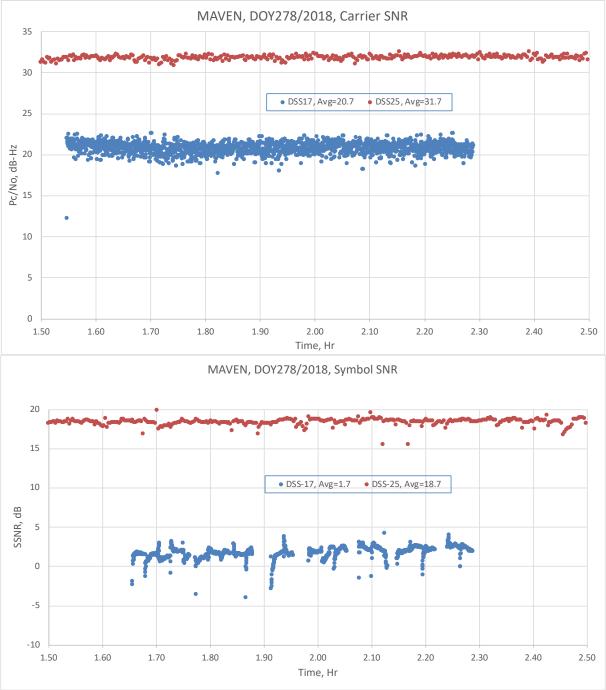

Figure 5. MAVEN Carrier and symbol SNR

Given the difficulty with achieving subcarrier lock and symbol synchronization with Osiris-Rex and MAVEN, we plan to repeat these tests in the near future to collect more data on the performance and to demonstrate a complete data processing all the way to telemetry frame decoding. We also plan to conduct testing with MarCO spacecraft [5], with support from the mission to reduce the data rate down to the level appropriate for the Morehead antenna for a full decoding.

One may notice that in all three tests, the data segment of Morehead was much shorter than the DSN track. This is due to limited test time available, because of ongoing support to the Asteria mission.

VI. CONCLUSION

In summary, this paper describes a tracking ground station being developed at the Morehead State University that optimally combines commercial products and specialized equipment developed for the Deep Space Network. The hybrid architecture will result in a low-cost implementation, with maximum interoperability with DSN antennas and compliance with the CCSDS specifications. Upon completion of the upgrade, the Morehead 21-m antenna system will have full operational telemetry, tracking and command capability at X-band. The system can help to offset some of DSN tracking load in time of heavy demand and is particularly applicable to future CubeSat missions due to the university's strong involvement with CubeSat communities. The system is undergoing testing with spacecraft currently in operation. Preliminary results show the system is functional with successful carrier demodulation and symbol synchronization for spacecraft under test. The G/T measurement indicated Morehead antenna is 10.3 – 11.3 dB lower than that of the DSN 34-m antenna; however more tests will be required to establish more accurate performance and to ensure that we can successful decode telemetry frame from Maven as expected from the link analysis.

ACKNOWLEDGMENT

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Special thanks to J. Yang at JPL for technical assistance with signal acquisition, and to W. Chen and G. Hewitt at Peraton Corporation for assistance with antenna scheduling.

REFERENCES

[1] B. Malphrus, "University SmallSat Programs and Technical Issues", Keck Institute for Space Studies Workshop on New Approaches to Lunar Ice Detection and Mapping, July 2013, http://kiss.caltech.edu/workshops/lunar_ice/presentations1/malphrus2.pdf, retrieved February, 2019.

[2] M. Smith, et al., "On-Orbit Results and Lessons Learned from the ASTERIA Space Telescope Mission", 32th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2018, https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4067&context=smallsat, retrieved February, 2019.

[3] P. Kinman, Sequential Ranging, 810-005, Rev. E, Telecommunications Link Design Handbook, https://deepspace.jpl.nasa.gov/files/810-005/203/203C.pdf, retrieved February, 2019.

[4] P. Kinman, Pseudo-noise and Regenerative Ranging, 810-005, Rev. E, Telecommunications Link Design Handbook, https://deepspace.jpl.nasa.gov/files/810-005/214/214A.pdf, retrieved February, 2019.

[5] Mars CubeSat One, Jet Propulsion Laboratory CubeSat, https://www.jpl.nasa.gov/cubesat/missions/marco.php, retrieved February, 2019.