

Comm for Small Sats: The Lunar Atmosphere and Dust Environment Explorer (LADEE) Communications Subsystem

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ABSTRACT

September 6, 2013 through April 21, 2014 marked the mission lifecycle of the highly successful LADEE (Lunar Atmosphere and Dust Environment Explorer) mission that orbited the moon to gather detailed information about the thin lunar atmosphere. This paper will address the development, risks, and lessons learned regarding the specification, selection, and deployment of LADEE's unique Radio Frequency based communications subsystem and supporting tools. This includes the Electronic Ground Support Equipment (EGSE), test regimes, and RF dynamic link analysis environment developed to meet mission requirements for small, flexible, low cost, high performance, fast turnaround, and reusable spacecraft communication capabilities with easy and reliable application to future similar low cost small satellite missions over widely varying needs for communications and communications system complexity. LADEE communication subsystem key components, architecture, and mission performance will be reviewed toward applicability for future mission planning, design, and utilization.

INTRODUCTION

The LADEE project was a robotic mission that orbited the moon to gather detailed information about the small lunar exosphere, in order to help address long-standing unknowns generated from the Apollo missions and help scientists understand other planetary bodies, as the moon is similar in composition to many other planetary bodies. LADEE was centered around a modular common spacecraft bus designed, developed, built, and tested at NASA's Ames Research Center (shortened to NASA ARC or NASA Ames) near Mountain View, CA in Silicon Valley. NASA Ames also developed and housed the core of the Mission Operations System (MOS) in order to control, manage, and execute the highly successful mission. The payload management, the Science Operations Center (SOC), and overall mission support were provided by NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD. Launch vehicle integration, launch services, and launch operations were managed by NASA's Wallops Flight Facility (WFF), and the LADEE program itself was funded by the NASA Science Mission Directorate, and was managed by the Lunar Quest Program at NASA's Marshall Space Flight Center (MSFC) in Huntsville, AL¹.

LADEE was the first lunar launch out of NASA Wallops Flight Facility and the first mission to use the Minotaur V launch vehicle, launching on September 6, 2013. After three phasing loops, LADEE captured lunar

orbit with three lunar orbit insertion maneuvers. The LADEE mission completed a highly successful 100 days of science after the phasing loops and instrument commissioning, and also completed a successful mission extension including extremely low altitude science (~1-3 km above the lunar terrain), before decommissioning with a controlled impact on the lunar surface on April 17, 2014.

LADEE flew NASA Ames' Modular Common Spacecraft Bus (MCSB) architecture. The idea behind the Modular Common Spacecraft Bus was an innovative way to reduce the amount of non-recurring engineering (NRE) by standardizing modules that could be integrated together to form a spacecraft that could handle essentially any instrument payload or mission, instead of special one-off designs reliant on the payload/mission. As illustrated in Figure 1, it is a flexible design that can allow for legs for landers, or propulsion modules for orbiters. This could drastically reduce the cost and lead-time of spacecraft development - enabling more science missions, more often, and for less cost².



Figure 1 – Modular Approach for Common Spacecraft²

LADEE was made up of a payload module, propulsion module, an extension module, and the bus module. The bus module housed a majority of the spacecraft avionics, including the communication subsystem transponder, medium gain antenna, and one of the omnidirectional lower gain antennas. The spacecraft bus was unregulated in nature, requiring all systems and instruments to be able to tolerate a wide operating voltage range. This was an important factor to the communication subsystem as it had to rely on voltage levels for many discrete controls, including the power amplifier (PA) and its RF (radio frequency) switch.

LADEE hosted and supported three science instruments and one technology demonstration payload. The three science instruments included the Ultraviolet and Visible light Spectrometer (UVS) led by Anthony Colaprete from NASA Ames, the Neutral Mass Spectrometer (NMS) led by Paul Mahaffy from NASA Goddard, and LDEX (Lunar Dust Experiment) led by Mihaly Horanyi from the University of Colorado at Boulder - Laboratory for Atmospheric and Space Physics (LASP). UVS analyzed light signatures of materials it found to determine the composition of the lunar atmosphere. NMS measured variations in the lunar atmosphere over multiple lunar orbits with the moon in different space environments, and LDEX collected and analyzed samples of any lunar dust particles in the thin and fragile atmosphere, to try to answer the question of whether the lunar dust was responsible for the pre-sunrise horizon glow astronauts saw during the Apollo missions³. Even though LADEE has impacted, the work continues to analyze the data from the science instruments in order to answer these questions.

The technology demonstration on LADEE was called the Lunar Laser Communications Demo (LLCD),

which demonstrated the first NASA two-way, high-rate laser communications from lunar orbit. It achieved its mission goals of achieving 20 Mbps uplink and 622 Mbps downlink several times. The LLCD payload was managed by NASA Goddard and management oversight and funding was provided by NASA's Space Communication and Navigation (SCaN) program within NASA's Human Exploration and Operations Mission Directorate (HEOMD). MIT/Lincoln Laboratory designed, integrated, and tested both the flight Lunar Laser Space Terminal (LLST) and the Lunar Laser Ground Terminal (LLGT) at White Sands, NM. Additional ground stations in California and Spain were developed by NASA's Jet Propulsion Laboratory in Pasadena, CA and the European Space Agency, respectively⁴.

A critical aspect of the modular common spacecraft bus covered in this paper is the communications subsystem, which involved several new products and extensions of existing technologies, including a newly designed S-Band transponder and three evolved S-Band antennas – one medium gain and two omnidirectional low gain. The transponder utilized state-of-the-art logic and interfaces developed by Space Micro, Inc. (SMI), and the antennas were custom developed and constructed in collaboration with Carnegie Mellon University, X-5 Systems, and Antenna Development Corporation (AntDevCo).

LADEE COMMUNICATIONS SUBSYSTEM OVERVIEW

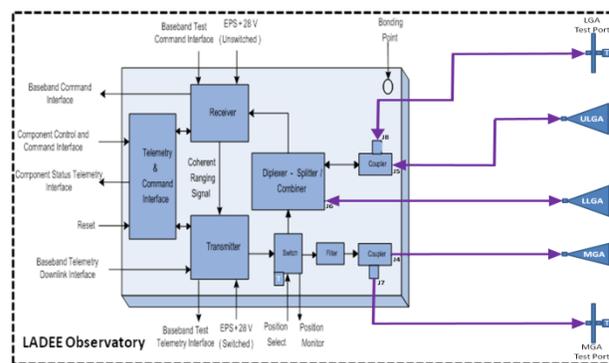


Figure 2 – LADEE S-Band Communications Subsystem Block Diagram

As can be seen in Figure 2 above, the core of the LADEE Telecommunications Subsystem was the S-Band STDN (Space Tracking and Data acquisition Network) compatible transponder core, comprised of a receiver, a transmitter/telemetry/command interface, and related power distribution. The transponder core was supplemented by other RF components, including a transfer switch, bandpass filter, test couplers, an integrated diplexer/splitter-coupler, signal terminators,

and high isolation, semi-rigid interconnect cabling. These components were integrated together onto a single housing baseplate, and connected externally by flexible coaxial cabling to the antennas mounted on the spacecraft. In addition, twisted pair cabling integrated the Electrical Power System (EPS) and Command and Data Handling (C&DH) subsystems with the transponder to comprise the full LADEE Telecommunications Subsystem installation.

The integrated S-Band STDN transponder component assembly comprised the bulk of the Telecommunications Subsystem, and incorporated all active and RF passive devices, with the exception of the antennas and antenna connection cabling, into a single, compact, footprint for mounting and installation as seen below in Figure 3.

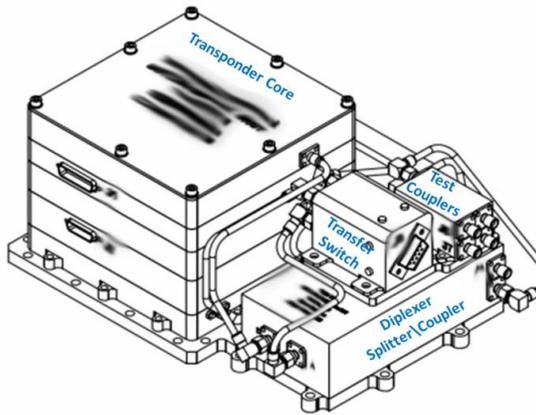


Figure 3 - LADEE S-Band Integrated Transponder Component

The integrated transponder assembly, one of the omnidirectional low gain antennas (Upper LGA, or ULGA), and the directional medium gain antenna (MGA) were mechanically and thermally mounted onto the spacecraft structure on the radiator panel, as seen in Figure 4 and Figure 5. The second omnidirectional low gain antenna (Lower LGA, or LLGA) was mounted on the bottom of the spacecraft opposed to its upper LGA counterpart.

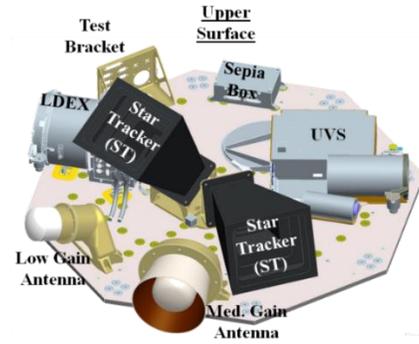


Figure 4 - Radiator Panel Equipment Layout Upper View

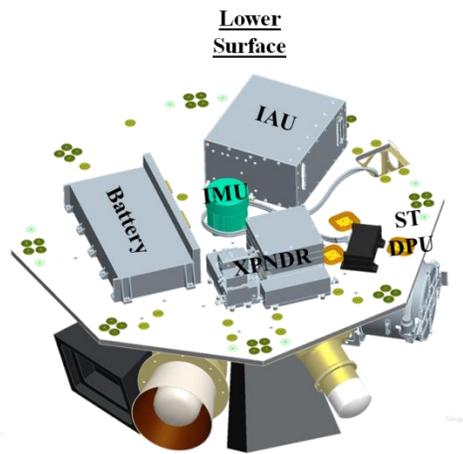


Figure 5 - Radiator Panel Equipment Layout Lower View

All three LADEE antennas were evolved antennas - utilizing a new rapid development, advanced antenna design process based in Darwinian evolutionary algorithms that were initially developed at NASA Ames and are currently being matured and commercialized through Carnegie Mellon University and X-5 Systems. The core research process was flight proven in X-Band on the ST-5 mission, with S-Band variants developed for use on both LADEE and IRIS (Interface Region Imaging Spectrograph, which also launched in 2013 and is continuing to fly). The opposing positioning of the omnidirectional low gain antennas (or “omni’s”) as seen in Figure 6, was designed to provide maximum coverage for the spacecraft in support of all receive operations, and transmit operations when commanded. A commandable RF switch selected between transmission out of both omni’s or directional transmission out of the MGA. The medium gain antenna was transmit only and both omnidirectional low gain antennas were always in receive mode. The opposing and passively coupled LGA configuration contributed, as was anticipated, to multipath effects

briefly described later in this paper, and may be researched in future work.

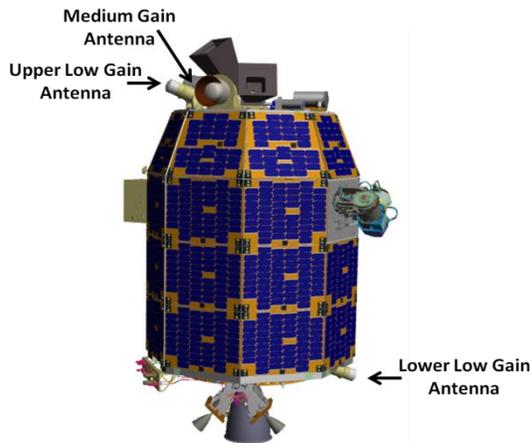
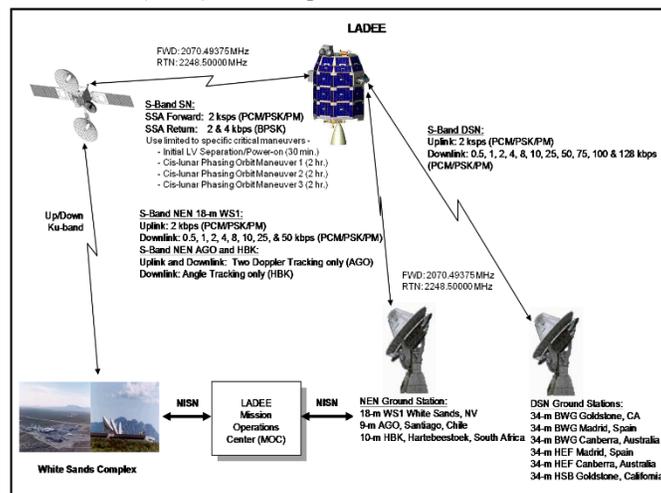


Figure 6 - Antenna Mounting Locations

The LADEE Telecommunications Subsystem supported receiving commands, encoding and transmitting telemetry, provisioning coherent / non-coherent ranging information, and providing tracking data. LADEE communications were operationally bounded by the RF Interface Control Document (RFICD) between LADEE and the SCaN (NASA Space Communications and Navigation office). As illustrated in Figure 7, LADEE communications were required to be fully compatible with Earth-based Near Earth Network (NEN) and Deep Space Network (DSN) ground station resources. LADEE was also compatible with the Space Network (SN) Tracking & Data Relay Satellite System (TDRSS) resources when operated in their legacy S-Band Single Access (SSA) Forward-Return (F-R) mode as also illustrated in .

Figure 7 - LADEE Telecommunications End-to-End Overview



Frequency assignments and spectrum utilization coordination for the Telecommunications Subsystem were provided through the NASA Ames Spectrum Management Office (SMO) consistent with NASA and national procedures for Federal frequency management as described in NPR (NASA Procedural Requirements) 2507-1, NASA Radio Frequency Spectrum

Management Manual, and ISBN 0-16-016464-8, National Telecommunications and Information Administration (NTIA) Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook).

The always-on receiver would acquire the S-band uplink carrier provided in the form of a 2 kbps, BPSK (binary phase shift keying) modulated, 16 KHz sine wave subcarrier. The transponder would demodulate the telecommand and any ranging signals that were present, then output command clock & data to the C&DH subsystem I/O (input/output) interface utilizing a serial, RS-422 level interface.

The transmitter received command selectable unencoded or encoded telemetry and data from the C&DH subsystem I/O interface over a serial, RS-422 interface. Under C&DH Subsystem control and monitoring, the transponder encoded or passed-through the information and phase modulated the S-Band downlink carrier. Telemetry and data could also be applied directly to the carrier in order to be compatible with TDRSS, and was carried as an option throughout the mission that could have been applied to achieve higher data link margins at the expense of tone ranging, if required.

The S-Band STDN Transponder system supported both coherent and non-coherent operations. In coherent mode, the downlink frequency would be related to a received uplink frequency by a specified turnaround ratio. In non-coherent mode, the transponder would determine the downlink frequency based on its own internal oscillator. When in coherent mode and ranging tones were applied to the signal from the ground station, the transponder demodulated range tones from the receiver and re-modulated them as part of the downlink carrier to provide range information to the ground. The capability for coherent and ranging operations were critical, as the low orbit requirements and uneven gravity field of the moon made it crucial to have as precise knowledge of LADEE's position as possible.

The receiver was fed from the two Low Gain Antennas, and integrated through a test coupler and a diplexer-

splitter/coupler. The transmitter element of the integrated transponder was coupled into an RF transfer switch that, under C&DH control and monitoring, selected the RF output from the transmitter to be applied to one of two options. The first option was the bandpass filter and RF test coupler to the Medium Gain Antenna (MGA) directly for high data rate downlink. The second option was through the diplexer-splitter/coupler into the two Low Gain Antennas (LGA) for lower rate transmit and all receive functions. One of the LGA paths included a RF Test Coupler for test purposes as well.

The bandpass filter element in the switched transmit channel was included to suppress potential signal components and random noise within the receive bandpass that may be present in the output of the transmitter element. This was for during use of the Medium Gain Antenna for transmit while continuing to receive through the Low Gain Antenna system.

To support operational testing and qualification with minimal impact to the integrated transponder assembly after integration onto the spacecraft, RF test couplers were included in the switched transmit channel and the diplexer output path to the RF splitter/coupler to provide bi-directional testing and monitoring ports. These testing and monitoring ports were extended by flexible coaxial cables to the LADEE radiator panel test bracket upon installation on the spacecraft to facilitate Integration and Test (I&T) operations of the installed telecommunications subsystem. The inclusion of these test couplers were key to testing the subsystem with minimal mates or demates to the flight connections, minimizing risk to flight hardware and increasing flexibility in testing.

General command, control, and telemetry interfaces to coordinate C&DH and TT&C functions related to the integrated transponder assembly's operation and status monitoring interfaces were interfaced, controlled, and monitored with the LADEE C&DH subsystem utilizing serial, RS-422, signal paths and a supporting, register based, command and monitoring syntax. The register based, RS-422 interface was a significant transponder technology improvement for command and status flexibility over the use of previously standard practice of discrete individual relays for commanding, and discrete analog digital outputs for status monitoring. The RS-422 serial interface approach allowed significantly less risk in hardware development with no wire, cabling, routing, or mass penalties for modifying command or status information throughout the development cycle.

The selection control and status monitoring of the RF transfer switch element was provided by direct

connection to the LADEE Integrated Avionics Unit (IAU) and electrical subsystems driving pulsed 28 VDC relays for position selection and monitoring dry contacts for status that were integral parts of the RF switch.

Hardwired safeguards were designed into the integrated transponder. An RS-422 based reset input, requiring specific signal timing for action, was available into the core transponder component and connected to the C&DH subsystem to allow for resetting functions of the transponder core FPGA state machines to a default state should conditions warrant such an action, such as an unresponsive transponder. This function was not used in flight but was extremely valuable during test and troubleshooting of various functions throughout the design, integration, and test lifecycle.

LADEE's receiver was designed to always be receiving, and the transmitter could be commanded on and off. In order to support the receiver, a single unswitched and unfused power feed was required of the spacecraft's Electrical Power System (EPS) to assure the receiver and the ability to receive commands could not be disabled. The transmitter's RF output power amplifier was provisioned with a single switched power feed under control of the C&DH subsystem to provide an operational safeguard against the potential of the communication subsystem becoming stuck in a transmit mode and draining the spacecraft's power system.

Two switched power feeds were required to select the operating position of the RF switch element of the integrated S-Band STDN transponder utilized to route the transmitter output to either the low gain or the medium gain antenna path.

In order to facilitate Flight Software (FSW) development, operational verification, and Integration and Test (I&T) activities not requiring use of the RF demodulation and modulation functions of the transponder, baseband level RS-422 command and telemetry test port capabilities were available on the core transponder. These were used to interface with all of the LADEE testbeds when RF testing was not required and were critical in developing and testing the flight software as the delivery of the transponder was offset from the flight software validation and verification processes.

It should be noted that RF signal test and measurement techniques need to be carefully reviewed, clarified, and defined as part of the requirements and performance validation processes when working with newer RF designs. It should also be noted what raw power digital generation/analysis techniques bring to dynamic RF generation and signal adjustments. This became

particularly evident during LADEE transponder development when a specification confusion arose regarding the methods to be utilized for the setting and validation measurement of the transponder Modulation Index within scope of the performance requirement. The confusion centered around how the manufacturer expected to set and dynamically measure the Modulation Index in the time domain, utilizing the precise digital information available versus how the validation measurement was intended to be validated in the power domain based on customary, commonly accepted industry practice, established before availability of today's more powerful test instruments of observing average power. The result of such a confusion could cause notable differences in the setting made and the resulting validation of that measurement.

INTEGRATION AND TEST, RF TESTBED

The testing regime for the communications subsystem at NASA Ames was developed essentially from scratch in order to meet the requirements of quick but comprehensive small spacecraft testing. The testing facilities now have the ability to test future communications subsystems with only slight modifications, and have already been utilized for in-work cubesatellites and launch vehicle avionics.

Test procedures and capabilities were leveraged from previous lunar missions, the Ground Network RF Compatibility test suite, and guidance from NASA Goddard satellite communications engineers. In addition, an RF testbed was built up in-house to test not only the LADEE communications subsystem end to end, but allowed for the flexibility for future small satellite use. It was designed and built to take I/O from multiple sources, including the transponder, multiple antennas, a modem test set, multiple test instruments, and command/telemetry from various Hardware-In-the-Loop (HIL) testbeds. Future work related to the RF testbed includes automation for the testing, which will greatly reduce testing time and staffing burden while increasing completeness and accuracy.



Figure 8 –Hardware Acceptance Configuration

The transponder, antennas, and modem test set were connected by coaxial and power cabling to a consolidated instrument rack containing RF test instruments, isolated system power, automation control capabilities, RF taps, and RF signal switching, as seen in Figure 8. The RF switches were capable of dynamically configuring the RF paths between the device and test instruments for common measurements and proper matching of input and output RF levels between devices. The test system was developed and configured such that it could be operated manually by direct control and display; remotely through an Ethernet connection; or in an automated fashion utilizing a touch screen test controller integral to the system. A simpler version of the interface, addressing proper RF levels, antenna selection, and basic instrumentation test points was also created in order to meet schedule for one of the observatory-level test series. This simpler version, seen below in Figure 9, simply switched between the MGA and LGA options, and had test coupler taps in order to monitor RF power levels and other RF signal characteristics of the uplink and downlink paths.

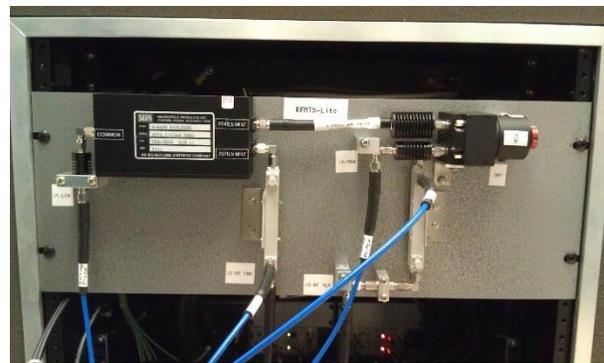


Figure 9 – Simplified RF Power and Level Interface

Two spectrum analyzers were included in the full testbed in order to be able to simultaneously monitor uplink and downlink spectrum, which was critical for both basic monitoring, but also conveniently verifying coherent operations (the transmit frequency shifting with changes in the uplink frequency, which could be commanded by the modem test set). One of the spectrum analyzers was also a vector network analyzer, which was critical for calibrating system losses, cable characteristics, and component performance through both the test system and most importantly, the flight system. This combination of spectrum analyzers and the vector network analyzer is ideal for characterization and monitoring for two-way communications systems.

An RF signal generator with an internal Gaussian white noise generator was included in order to test and verify signal interference requirements and also in order to test the resilience of the communications system to

background noise. Individual frequency counters for uplink and downlink and multichannel RF power meters were included in the system in order to have real time insights into critical RF power levels and system characteristics. Both fixed and variable attenuators were integrated in the system for two reasons: the first reason was to ensure that safe RF levels were being seen both at the flight system and the test system, and the second reason was to test and verify the transponder's ability to lock, track, and receive commands at different signal levels.

This RF testbed, both in simplified and full form, was used for subsystem-level hardware acceptance and test, as well as observatory-level Comprehensive Performance Tests (CPTs), Thermal-VACuum (TVAC) testing, Mission End-To-End Testing, and RF Ground Network Compatibility Testing. The testbed could be commanded by direct connection from the C&DH/FSW HIL's in the LADEE development lab; ITOS (I&T Operating System, the command and telemetry software used by LADEE) workstations in the LADEE High-Bay; NEN, SN, and DSN compatibility test equipment; and remote connection from ITOS workstations in the LADEE Mission Operations Center (MOC), also based at NASA Ames. In addition to use by LADEE, the RF testbed has already been utilized several times by different small satellite and avionics programs, due to its full suite of integrated test instruments and its end-to-end communications testing capability.

During integrated, end-to-end, ground testing prior to flight, an issue had been noted that was attributable to the communication subsystem receiver RF path having to do with loss of data synchronization when certain LADEE data files were uplinked. The root cause was traced to an excessive number of unique consecutive bit patterns in the uncompressed files that violated the performance requirement of the transponder, highlighting the necessity for test-like-you-fly conditions. Without testing-like-you-fly, it is possible this issue may have been overlooked until flight. Through the test-like-you-fly approach this potentially disastrous condition was caught, and the workaround of pre-checking files for these patterns and the use of file compression alleviated the issue prior to flight. A Flight Software patch during the mission extension fixed this problem, and the mission proved its ability to successfully upload files without file compression through the remainder of the mission extension.

DYNAMIC LINK ANALYSIS TOOL (DLAT)

In parallel to the hardware test facility development, a Dynamic Link Analysis Tool (DLAT) using STK and MATLAB was developed in order to dynamically

predict link budgets/margins (forward and return for both medium gain and low gain antennas) throughout the LADEE mission. This new tool provides the ability to dynamically assess link budgets and margins over time, distance, attitude, and relationships between the spacecraft and ground station resources as an aid in planning for every point in a mission for multiple assets, not just a static link budget for the worst case scenario. DLAT is pre-configured with required earth station (DSN, NEN, etc) and SN asset performance information that is easily updatable as ground networks are updated. DLAT ingests many parameters in order to create a point-by-point link budget for each specified time increment during the time period of the attitude/ephemeris file, parameters include: a spacecraft model, specific performance parameters of the spacecraft communications system, antenna patterns, attitude and ephemeris files into STK, and user-defined parameters (such as data rate, antenna, and mode) into MATLAB and Excel. If an attitude file is not available or undefined, DLAT can also generate custom or general attitude profiles for all modes, in order to provide a characteristic link budget which was and is helpful during all planning stages.

This has proven great utility for LADEE planning, assessment, and real time operational awareness as we operated LADEE around the moon, performing DLAT analyses during every planning cycle and oftentimes in real-time during staffed shifts. The LADEE Mission Planning and Sequencing (MPS) and science teams could then utilize predicted margin when available with little risk to the link. This resulted in our ability to perform maneuver and science data downloads at much higher rates than originally predicted in the worst-case scenario, greatly increasing efficiency and allowing the science and spacecraft engineering teams to download much more data than originally anticipated. The ability to reliably predict the link margin allowed for more overall science data to be taken, and for spacecraft issues to be diagnosed much faster. DLAT should provide the same utility for future missions, allowing them to dynamically evaluate link margins over extended periods on a case-by-case basis throughout their mission lifespan.

FLIGHT SYSTEM PERFORMANCE

The LADEE communications subsystem performed reliably and consistently throughout all phases of the mission; over all modes of mission power, mechanical, and thermal environments experienced and data rates attempted, without hardware or firmware incident or significant performance anomaly.

The communications subsystem - through a combination of factors - including overall, aggregated,

subsystem performance, and primary use of more powerful and more sensitive DSN 34 meter stations for telemetry and commanding than the designed-for NEN 18 meter station, performed flawlessly with significant uplink/commanding and downlink/telemetry margins as was anticipated by the equipment and signal conditions. Downlink data margins were consistently much higher than minimum requirements, even at the maximum 128kbps (unencoded) data rate licensed. Uplink data margins were similarly high, especially when maximum station uplink power was used to assure the command path.

There were no operationally significant unanticipated or unforeseen behaviors of the communication subsystem hardware and firmware. However, there were in-flight signal path behaviors attributable to known and empirically quantified RF phenomenon such as increased solar flux and anticipated multipath RF signal phenomenon near acquisition- and loss-of-earth views. These factors had to be tracked and qualified dynamically for the specific operating conditions and orientations the spacecraft was flown in to aid the Real Time Operations team in real-time activity execution planning.

As indicated, the communications subsystem performed consistently and well during all phases of the mission. The LADEE-developed Dynamic Link Analysis Tool (DLAT) application was used throughout all stages and phases of the mission, including system design and the entire flight, to accurately model spacecraft communications performance during flight and maneuvers. The DLAT tool was found consistently to be very close to actual empirical data and timing through all phases of the mission, and was an indispensable tool for communications planning and modeling.

During the LADEE Commissioning phase, limited empirical antenna pattern qualification tests were executed that indicated a slight shift in the actual antenna gain patterns versus the modeled interferometry patterns calculated using modeling tools and DLAT. However, this did not significantly impact mission communication prediction and performance - due in large part to the significant communication margins enjoyed throughout the mission.

During design and pre-flight development, the communications subsystem was specified and modeled against a “nominal worst case” RF environment scenario that would assure minimum performance requirements could be met most of the time during the mission. This conservative design environment approach, coupled with pushing for all elements of the communication subsystem to perform at or better than their nominal requirements, provided a communications

subsystem that overall met or slightly exceeded nominal system requirements.

Throughout flight, the primary indicators of actual link performance were the DSN earth station received (downlink) RF power, symbol signal-to-noise ratio (SSNR), and the LADEE received (uplink) RF signal level with compensations applied for system power and temperature status. These values tracked well and reliably with minor variations from the slight shift known to exist in the antenna pattern calculated versus empirically verified.

Through keeping track of this type of data over different observatory orientations and modes typically used, the Real Time Operations team was rapidly able to quantify and anticipate reliable initial acquisition and upcoming loss of signal conditions affecting nominal operations, and correct for these under various spacecraft orientations and orbits.

The communications subsystem carried several accepted pre-launch potential risks with the integrated transponder and the genetically evolved S-Band antennas being new designs without flight heritage. Performance and reliability of these components were monitored throughout the mission, as was the potential for phase shift and signal interference occurring between the passively coupled low gain receive/transmit antennas mounted on opposite sides of the spacecraft. These risks, to the extent they could be monitored or measured, were unrealized with all aspects of the communication subsystem performing well and reliably throughout the entirety of the mission and its modes.

Generally, there were no particularly systemic communications issues associated with the LADEE flight communications subsystem in flight. The subsystem performed better than expected due to the “nominal worst case” RF environment scenario used throughout the development and performance planning cycle; the overall, aggregated, subsystem performance; and primary use of more powerful and more sensitive DSN 34m stations for telemetry and commanding than the 18m NEN station originally designed for.

The upkeep, use, and continued development and expansion of the Dynamic Link Analysis Tool (DLAT), and the communications resource tools feeding into it, is a critically important aspect of the LADEE mission technology transfer that can contribute significantly to the success, reliability, and efficiency of future small spacecraft mission concept, development planning, modeling, and operations activities.

LESSONS LEARNED

Given that most of the LADEE communications subsystem did not have flight heritage and the antennas were newly designed specifically for S-Band, many lessons were learned, and are captured below.

Integrated Transponder Specification as Technical and Schedule Risk Reduction

Originally the LADEE communication system integration was to have NASA Ames responsible for the engineering, execution, and integration of the RF passive "glue" components between the contracted transponder and contracted antenna components (such as the diplexer/splitter/coupler, bandpass filter, etc). This approach placed significant technical, schedule, compatibility, integration, and performance risk directly on the government communications team that was not staffed, equipped, or funded to meet the requirements on the schedule available. Therefore, an "Integrated Transponder" component was specified based on a government-provided baseline approach and performance specification. This specification included transponder manufacturer responsibility for selection, procurement, mechanical, and electrical integration of the RF passive components and packaging to meet the government performance and space specifications as a system. The transponder manufacturer was then able to optimize the transponder system design, performance, and system packaging, while minimizing the number of mechanical and electrical interfaces. Without this integrated approach, component footprint, cabling complexity, performance compatibility risk, mechanical, electrical, and system performance qualification overhead would have overwhelmed the flight schedule.

Therefore, an "integrated" transponder performance specification approach should be considered when the design criteria and complexity make sense to enhance the transponder manufacturer's ability to implement and qualify a coherent, "drop-in" design fully optimized for a communications system.

Risk Mitigation with Small/New Vendors

Another significant lesson learned, applicable especially when working with small vendors with finite depth of staff and resources, is that it is critical to understand how your project is going to flow with those before and after to minimize the potential for competition for required resources. LADEE experienced this as the project ended up almost competing with another project for the vendor's resources as the timelines converged on top of each other. Be aware of what is happening around your project with the contractor, and what mitigations are in

place to minimize the multiple programs from needing the same resources at the same time due to delays in your, or other, programs.

There is No Pure COTS Transponder

Related to schedule, with few exceptions mostly in simpler cubesatellite type transponders, there can be no assumption of a true Commercial Off the Shelf (COTS) transponder product being readily available for delivery. Allowing sufficient time in the delivery schedule to address this risk is critical.

For LADEE, it was determined by an industry survey of potential spacecraft transponder manufacturers that a flight transponder could be delivered within a minimum 12-14 months allowing for minimal technical issues and schedule impacts. Based on that knowledge, the LADEE schedule requirements, and the knowledge that many of the potential vendors had existing designs available, 12-14 months was proposed for the delivery of the LADEE transponder. The LADEE transponder delivery then became a critical path item technical issues, implementation challenges, delays due to flight part quality control issues, flight qualified parts, and flight qualified part availabilities aggregated beyond the minimal schedule reserve and material lead times available in such an aggressive development schedule. An informal follow-on survey was conducted of recent space mission transponder procurements versus actual deliveries that concluded 12-14 months is indeed fairly aggressive and that actual delivery dates, even with longer lead times, regularly went past the contracted due date.

Additionally, especially for existing designs, slight performance modifications, such as operational frequency changes or optimizations, analysis and potential adjustments to the original design resulting from changes or obsolescence in qualified flight parts, or materials, and the long lead times associated with flight qualified parts availabilities make even COTS and "build to existing print" transponder procurements a performance and schedule risk that must be carefully considered for adequate lead time.

With smaller companies, especially new to doing business with non-commercial entities such as NASA, there can be a notable learning curve and discontinuity between how they have handled the customer interface, quality assurance, monitoring, and non-conformances with their commercial customers previously, and what is required within scope of their NASA contract, that must be recognized, assessed, understood and allowed for as schedule risks to mitigate.

Overall, depending on the status, complexities, technical maturity of the transponder design, and the familiarity of the company with your business processes, assume no less than 18 months optimistically, and up to 36 months, generally for a transponder delivery of LADEE's size after award. Be aware of where and how the contractor has placed schedule discretion, and how it is impacted over the course of the contract. Watch for potential single point failures related to critical personnel, processes, and materials. Assure adequate and timely incoming quality inspection of all materials are properly performed.

Logic Simulators and Vendor-Built EGSE Can Mitigate Technical and Schedule Risk

Another effort that mitigated schedule impacts to the project was the provisioning for a transponder Logic Simulator and a comprehensive Electronic Ground Support Equipment (EGSE) Transponder Test Set. These two items significantly enhanced interface development, testing, and training activities, as well as reduced reliance on other subsystem resources to perform end-to-end testing and acceptance of the transponder.

Flight Software, Integration and Test, Mission Operations, and not-to-mention the Communications Subsystem teams require as much time as possible with the communications subsystem for familiarity, interface testing, and troubleshooting. Since transponders are generally long lead time items, they are usually not available until late in the development cycle for interfacing to C&DH, power systems, and MOS (Mission Operations System) system simulators. A Logic Simulator - a transponder core with just the core system logic and power supply sections - was added to the scope of the basic contract to provide C&DH, MOS, and EPS subsystems access to realistically responding and operating logical interfaces. This unit was used for interface and flight software development and testing, as well as MOS training development, while the full transponder was still under construction.

The Logic Simulator allowed development and maturing of the external interfaces (C&DH and Power), and development of I&T and MOS test/exercise scripts while the transponder was still in development, which proved especially valuable as the transponder delivery schedule delayed. Importantly, provisions were also included in the contract for the Logic Simulator unit to have the FPGA programming, as well as the hardware, and electrical interfaces updated at critical times in the transponder development cycle in keeping with the actual logic and interface development.

The LADEE transponder contract also included delivery of an Electronic Ground Support Equipment (EGSE) interface suitable to power and test all operational interfaces and functions of the delivered transponder, including convenient bypass test capabilities for the interfaces. The EGSE significantly improved and simplified the checkout and acceptance testing of the delivered transponders by providing all necessary external interfaces. The EGSE was also under the total control of the communication subsystem team to use in conjunction with the RF test instruments for isolated end-to-end testing not impacting development or resource schedules of other disciplines.

EGSE capable of powering and providing all necessary external interfaces for exercising the transponder should be considered in procurement of transponders. A limited functionality Transponder Logic Simulator should also be considered when lead time is short to provide access to the basic functionality and interfaces by other activities.

Pre-Release and/or Pre-Acceptance Compatibility Testing with Ground Networks

Pre-Release and/or Pre-Acceptance Compatibility testing with Earth Station providers should be included in the scope of any transponder contract deliverable, especially when any new or modified transponder design is generated, to reduce and properly place technical and performance risk.

As LADEE was using a new low-cost transponder design, Pre-Release and Pre-Acceptance testing with NEN and DSN were arranged in addition to the standard Observatory Level Compatibility Tests, with transponder manufacturer support for all these tests negotiated within the contract scope. Pre-Compatibility testing helped define the manufacturer's functional test criteria, familiarize them and the Earth Station providers with the hardware, and quantified the readiness of the design for release and use. This was invaluable to catch issues early with RF leakage, ranging functionality, and performance characteristics of the initial design in time to allow design adjustments and application of mitigations. Waiting until Observatory level RF Compatibility testing after a transponder has been accepted and integrated on the spacecraft does not allow adequate opportunity to catch and correct issues with the transponder and its compatibility with the Earth Station providers.

A compatibility test of the completed engineering unit before the final design acceptance allows opportunity for corrections and adjustments early in the timeline, with time for recovery. The Pre-Acceptance RF Compatibility test allows for a final check to see that

any previous deficiencies identified in the preliminary RF compatibility test were fully addressed while no new issues have arisen before the government takes official delivery of the transponder. Therefore, scheduling Pre-Release and Pre-Acceptance compatibility testing with NEN and DSN should be considered as a risk mitigation especially when any new or modified transponder design is generated, to reduce and properly place technical and performance risk.

Clear Communications of the Specifications and Measurement Methods

When developing new performance specifications and requirements, it is critical to assure the performance and acceptance measurement processes and criteria are clearly communicated and consistent with the measurement expectation with no assumptions. With current improvements in RF measurement and signal generation capabilities and accuracy, versus what was possible when many basic RF test and measurement requirements and processes were initially established, confusions can be avoided by not making assumptions regarding how even common calibrations and measurements are expected to be performed. LADEE had an instance occur in development where the Performance Specification did not distinctly define how a common RF test procedure used within NASA was expected to be performed. Differences in measurement techniques between what can be achieved with today's instruments and techniques versus common industry standard practices resulted in an unnecessary confusion and delay. It is important to be sensitive, especially when working with newer digital signal processing based systems measurements that the measurement methodologies are clearly identified even if older analog measurement techniques are assumed to be clearly established.

CONCLUSION

In light of and learning from the Lessons Learned, the LADEE Communications subsystem operated successfully with minor issues and significant margin during the full duration of the LADEE mission: September 2013 through April 2014. As the subsystem contained many new and/or never before-flown elements, the LADEE communication subsystem paved the way for future small satellite communication subsystems in terms of newer, more powerful, flexible, shorter lead time, and lower cost transponder and antenna system designs and technologies suitable for the new generation of lower cost, shorter lead time, higher risk, small spacecraft missions.

The combination of LADEE's proven communications subsystem architecture, testing regime, operations tools,

lessons learned, and approach to leverage these assets to reduce redundant investments in basic RF test instrumentation and test processes, including mission communications development and design is an invaluable point of reference for the diversity of communication subsystem performance and complexities future small satellite and spacecraft missions can expect to encounter.

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