Digitally Intensive Precision Ranging Subsystem of the Lunar Atmospheric and Dust Environment Explorer's Transponder

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ABSTRACT

The communication subsystem of NASA's Lunar Atmospheric and Dust Environment Explorer (LADEE) makes use of the Space Micro µSTDN, a digitally intensive S-Band transponder. The effects of received radio frequency power, downlink data rate and temperature on transponder's ranging accuracy were investigated. The LADEE flight ranging data is corrected using calibration data taken during thermal vacuum testing of the flight transponder. The root mean square single standard deviation accuracy of the LADEE transponder ranging after calibration for temperature and uplink power is 5.2 ns, which corresponds to a single shot range accuracy of just 78 cm. Since both uplink power and temperature are measured inside the transponder, such post measurement calibration is valid over the entire qualification temperature range (-30 ºC to 65 ºC) and over four orders of magnitude of radio frequency uplink power (-120 dBm - -80 dBm). The root mean square variability of the flight data after calibration is found to be just 2.2 ns.

INTRODUCTION

While satellites in low earth orbit can achieve good knowledge of their orbit with GPS measurements or Doppler measurements, those operating in geosynchronous earth orbit or interplanetary space generally require time of flight ranging measurements in addition to Doppler measurements to accurately ascertain their trajectory. The accuracy with which a satellite's orbit can be determined impacts the amount of fuel used during station keeping maneuvers. Improving the precision of maneuvers often allows mission life to be extended because fewer station housekeeping maneuvers are needed which conserves fuel.

NASA's Lunar Atmospheric and Dust Environment Explorer (LADEE) is a small satellite studying the structure and composition of the thin lunar atmosphere. It's low lunar equatorial orbit requires frequent maneuvers. Without these, LADEE's orbit would decay in a matter of days, resulting in premature impact on the lunar surface. Fortunately, LADEE's guidance and propulsion systems have performed exceptionally well.

The LADEE spacecraft's communication subsystem consisted of two omni-directional antennas, a mediumgain antenna and a single-string transponder, namely Space Micro's Integrated µSTDN Transponder (Figure 1). The Integrated µSTDN Transponder consists of a core transponder containing all the electronics, a diplexer to allow concurrent transmit and receive, an RF switch to select between the omni-directional antennas and a medium gain antenna, and test couplers. The spacecraft's communication subsystem is compatible with NASA's Near Earth Network (NEN), Deep Space Network (DSN) and Space Network (SN).

The performance of the ranging system that is part of LADEE's µSTDN transponder is one of the reasons the mission could be extended for 28 days. This extension, representing a 15% lengthening greatly increases the science data return from the mission. This paper examines the digitally intensive design and state-of-the-art ranging techniques that are used in the LADEE transponder. The transponder combines analog coherence with digital ranging. This best-of-both-worlds approach achieves the accuracy of digital ranging without sacrificing the precise integer ratio of transmit-to-receive frequency that heritage STDN radios have used. Moreover, it does so without breaking the mass, power or cost budget of a small satellite while using exclusively EEE-INST-002 Level 2 EEE parts.

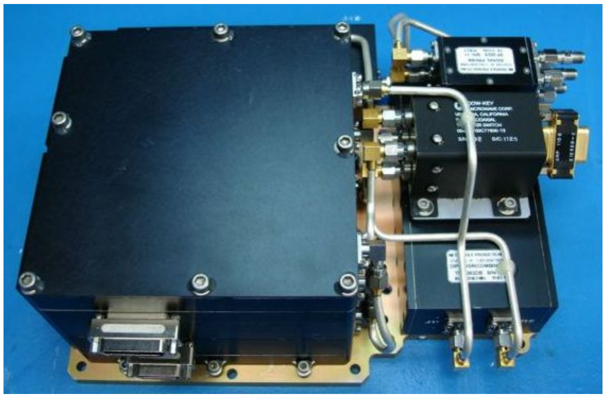

Figure 1: Space Micro's Integrated μSDTN Transponder. The core transponder is on the left. The diplexer, RF switch and test couplers are on the right.

COMMUNICATIONS WAVEFORMS

The PCM/PSK/PM modulation scheme is used for the low data rate uplink. The command (uplink) data is first phase-shift keyed onto a subcarrier which is then phase-modulated onto the uplink carrier.1 Similarly, the low data rate telemetry (downlink) data is phase-shift keyed onto a subcarrier which is then phase-modulated onto the telemetry carrier. When ranging mode is selected, the commanding signal is combined with the ranging channel and then phase-modulated onto the carrier. When coherent mode is selected, the telemetry carrier is frequency locked to the command carrier, thereby allowing Doppler measurements to be performed. The transponder is also capable of directly PSK-modulating the carrier for higher data rates.

The transponder's receiver locks to the residual carrier, subsequently to the command subcarrier and then demodulates the command data. When ranging mode is selected, the transponder strips the ranging channel from the received signal and filters it. The ranging channel is subsequently combined with the telemetry signal and phase modulated onto the telemetry carrier. The relative amount of power in each signal component is determined by the command and ranging (for uplink) or telemetry and ranging (for downlink) modulation indices.2

ARCHITECTURE OF THE SPACE MICRO μSTDN

A basic block diagram of the μSTDN is shown in Figure 2. The RF subsystem amplifies and downconverts the uplink signal to a medium frequency intermediate frequency (IF), which is subsampled by the ADC. Digital filtering, downconversion and downsampling are performed in an FPGA. The carrier and subcarrier are recovered, and command data is demodulated and output. The ranging channel is stripped off and sent to the transmit modulator when turnaround ranging is selected. Because the ranging channel is digitized, it could readily be demodulated to perform regenerative ranging if that is desired. The digital receiver provides uplink RF power, automatic gain control (AGC) and lock detect functions. Telemetry data is encoded, modulated, combined with the ranging channel and upconverted to a medium IF. The signal is then converted to the analog domain, upconverted to RF and amplified. A digitally intensive architecture with medium frequency IF was chosen to make the system highly reconfigurable with FPGA code changes, but without significant redesign of the hardware. This design can address all the common waveforms over the entire SGLS and STDN frequency bands. The chosen architecture has the additional benefit that it does not significantly increase power consumption over a traditional analog design.

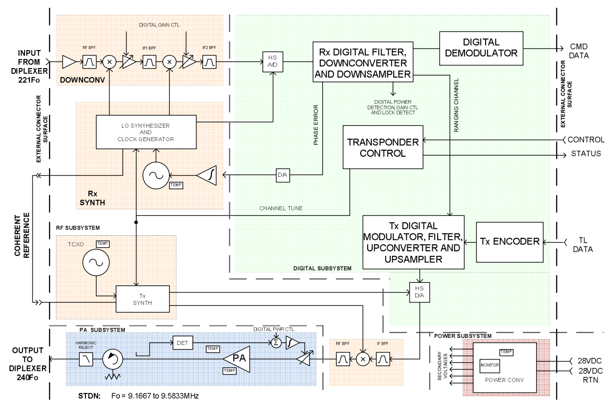

Figure 2: Basic block diagram of the μSTDN

RANGING CHANNEL CALIBRATION

The ranging channel is digitally filtered to be approximately 800 kHz wide. The ranging turnaround function modulates the entire ranging channel, including noise onto the downlink. Ranging channel gain control is achieved by apportioning the ranging channel the correct predetermined modulation index in the transmit modulator.

The absolute delay of the ranging channel through the transponder is the compound delay of the transponder's RF front end, digital processing and the RF back end as well as the delay in the various passive elements in the RF chain such as the diplexer. The delay varies slightly with RF uplink power and temperature. During thermal vacuum (TVAC) testing, the range delay is measured over temperature and uplink power (Figure 3). A calibration model can be derived from this data.

Typically, the variation of the ranging channel delay is required to be less than 25 ns after calibration. As seen in Figure 3, the transponder meets this requirement even without calibration. When calibrating with a third order polynomial function, the root mean square single standard deviation accuracy of the LADEE transponder ranging after calibration for temperature and uplink power is 5.2 ns, which corresponds to a single shot range accuracy of just 78 cm. Since both uplink power and temperature are measured inside the transponder, post measurement calibration is valid over the entire qualification temperature range (-30 ºC to 65 ºC) and over four orders of magnitude of radio frequency uplink power (-120 dBm - -80 dBm).

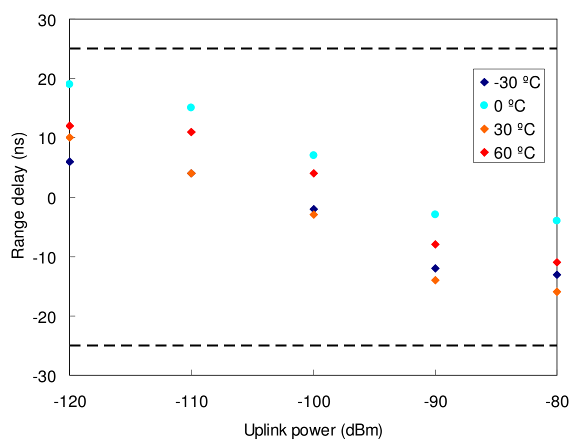

Figure 3: Transponder range delay calibration data

LADEE MISSION RANGING DATA

During the LADEE mission, transponder turnaround ranging was used to update the orbital estimates. Uncalibrated range bias data for a 10-day period of September 2013, during the transfer orbit phase of the mission is shown in Figure 4. With the exception of some points which occur during spacecraft maneuvers, the range bias remains within a ±30 ns band. Nevertheless, there are clear patterns that can be discerned in the data.

As an example, a detail of an 8-hour period on September 15, 2013 is shown in Figure 5. For thermal reasons, the spacecraft is rotated every hour. Consequently, the two antennas take turns being the one pointed towards the ground receiver. During rotation, the signal can be lost as the antenna pattern rotates through a null. Range bias data from the time period during these events has been deleted from Figure 5.

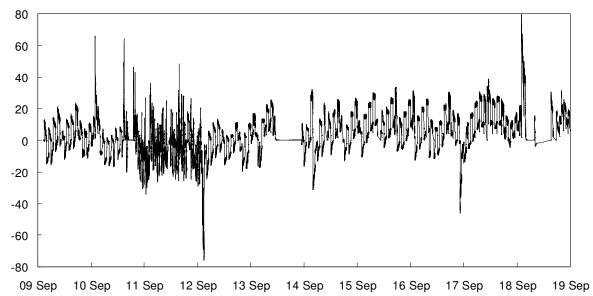

Figure 4: Range bias

As noted above, the transponder's internal status indicators measure temperature and RF uplink power. These values for the same time period are shown in Figure 6. When the transponder is on the sun side of the spacecraft it heats up, and when it is on the other side it cools down. The AGC reading shows how the uplink power varies as the antenna pattern moves relative to the ground receiver.

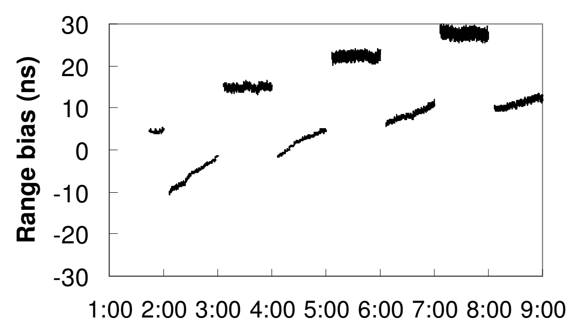

Figure 5: Range bias detail

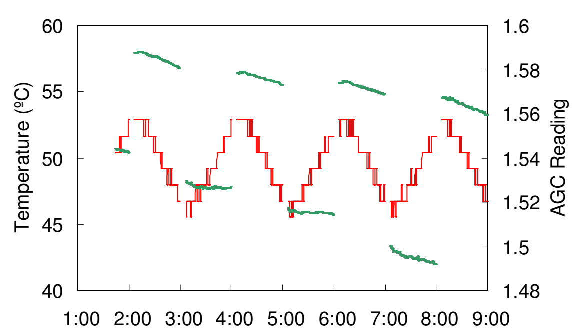

Figure 6: Transponder internal temperature and automatic gain control reading

The two antennas have a known range offset of 16 ns which is mainly the result of the difference in cable length between the antenna and the transponder. The temperature and RF uplink power have been corrected using a simple linear model valid over the temperature and uplink power levels that are observed during flight.

The resulting range bias that has been fully calibrated for antenna, temperature and RF uplink power offsets is shown in Figure 7. The fit line shows the best fit to a second order polynomial. The root mean square estimate of the residue is just 2.2 ns. The residual range bias is the result of systematic drift in ground station time base and orbital motion.

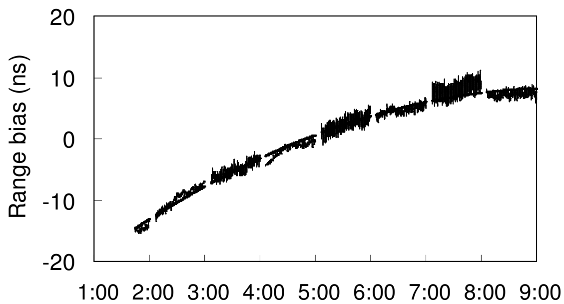

Figure 7: Range bias corrected for antenna, temperature and RF uplink power

Correcting the range data for systematic transponder offsets aids interpretation of the flight data. Systematic range offsets are separated from residual random errors. Systematic range offset sources resulting from spacecraft orientation, data rate and ground station time base offset are identified and quantified.

Acknowledgments

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