Telemetry Recovery and Uplink Commanding of a Spacecraft Prior to Three-Axis Attitude Stabilization

Jonathan R. Bruzzi, J. Robert Jensen, Karl B. Fielhauer, Darryl W. Royster, Dipak K. Srinivasan
The Johns Hopkins University Applied Physics Laboratory
11100 Johns Hopkins Rd.
Laurel, MD 20723-6099
443-778-5398
jonathan.bruzzi@jhuapl.edu

Abstract—After separation from the launch vehicle, a spacecraft's Guidance and Control system typically orients the spacecraft autonomously into a three-axis stabilized attitude for non-spinners. If an anomaly occurs, or if the spacecraft fails to orient itself appropriately, the Mission Operations team will want to observe spacecraft telemetry or may even be required to command the spacecraft before attitude stabilization. Antenna coverage in these cases is critical, since the command and control antenna may be rotating away from the ground station line-of-sight as the spacecraft tumbles. However, activating opposite-pointing hemispherical low-gain antennas on the spacecraft to obtain more complete angular coverage comes at the cost of presenting an interferometric signal to the ground station (or spacecraft receiver, depending on the radio-frequency subsystem configuration) which fluctuates as a function of the relative antenna positions and tumble rate of the spacecraft. Recent programs developed by The Johns Hopkins University Applied Physics Laboratory, specifically MESSENGER and STEREO, have investigated the capability of the Deep Space Network and Universal Space Network receivers to recover telemetry from a tumbling spacecraft at a low orbital altitude. Also investigated was the ability of a tumbling spacecraft utilizing a Small Deep-Space Transponder to register valid uplink commands, even in the presence of a second, closely-spaced uplink frequency, as expected for the two STEREO spacecraft.[1,2]

TABLE OF CONTENTS

[1] 0-7803-9546-8/06/$20.00© 2006 IEEE
[2] IEEEAC paper #1202, Final Version 3, Updated Dec. 20, 2005

1. INTRODUCTION/MOTIVATION

Current NASA requirements stipulate that deep-space missions monitor all critical events and maneuvers, including any propulsive de-tumbling of a spacecraft after separation from the launch vehicle. Furthermore, a particular program may have a secondary goal of being able to command a tumbling spacecraft should the onboard systems fail to autonomously stabilize the spacecraft properly.

Two recent deep-space programs developed and operated by The Johns Hopkins University Applied Physics Laboratory (APL) have investigated the problem of telemetry recovery and/or uplink commanding prior to attitude stabilization: The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, which will be the first spacecraft to achieve Mercury orbit [1, 2], and the Solar-TErestrial RElations Observatory (STEREO) mission, a pair of spacecraft to be launched in tandem and designed to observe the Sun in three dimensions [3, 4]. MESSENGER was launched in August 2004 and achieved successful telemetry recovery during its de-tumble maneuver. STEREO is presently undergoing Integration and Test (I&T), with launch planned for Spring 2006. In addition to the requirement to monitor telemetry during the spacecraft de-tumble events, the STEREO program is carrying the added goal of verifying uplink command capability prior to spacecraft separation and/or three-axis attitude stabilization.

After separation from the third stage of the Delta II launch vehicle, each spacecraft could be spinning as much as 2 rpm (3-σ), as indicated by the launch vehicle manufacturer. Although this spin is mainly a rotation around the axis joining the spacecraft to the launch vehicle, the tumble can evolve to an arbitrary, compound rotation as dictated by the slight imbalance in separation impulse and the inertial moments of the specific spacecraft. The result is a dynamic and arbitrary angle between the boresight of the spacecraft antennas and the observing ground station. The MESSENGER and STEREO spacecraft are each equipped with a set of opposite-facing low-gain antennas (LGAs). If a single LGA is activated (as was done part of the time after MESSENGER's separation), the signal strength at the ground will follow the radiation pattern of the LGA and perhaps drop out completely as the antenna rotates away from the ground station.

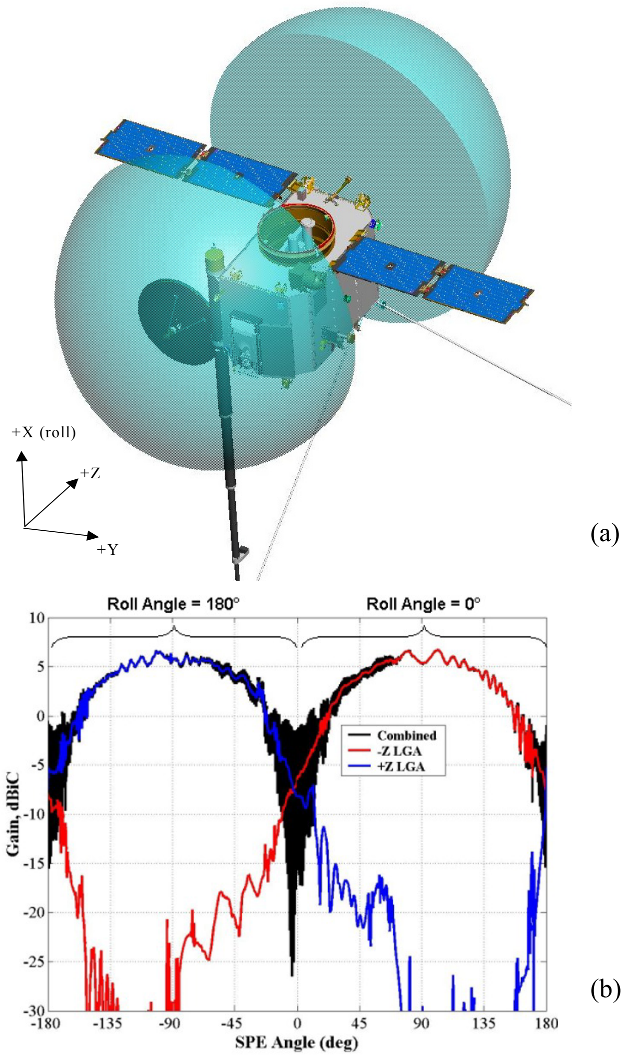


Figure 1 - (a) Depiction of the STEREO LGA coverage and (b) an interferometric pattern resulting from an arrayed configuration.

Alternatively, close-to-omni-directional coverage can be ensured during these times by activating both opposite-facing LGAs in an arrayed fashion (as was done during the MESSENGER de-tumble maneuver and is planned for the STEREO de-tumble maneuvers), as depicted in Figure 1. MESSENGER activated each of its two X-band transponders and radiated the same downlink frequency through two separate LGA paths. STEREO will carry only one X-band transponder but will set its switch configuration to radiate through both LGAs simultaneously. In both mission scenarios, a combined interferometric downlink signal is presented to the ground station. Likewise, an interferometric uplink signal will be presented to the STEREO spacecraft transponder. The downlink and uplink signals will in turn fluctuate and fade as a function of the rotation rate of the spacecraft, with the most drastic effects seen at the overlap of the two antenna patterns at 90° from their respective boresights. The desire to verify that telemetry can be recovered and spacecraft commanding can be achieved during each of the aforementioned situations was the driving force behind these investigations.

2. Initial Testing

Preliminary testing for the STEREO program addressed the ability of a Small Deep-Space Transponder (SDST) to acquire uplink and commanding in a rolling spacecraft environment, i.e., a tumble around the axis that links the spacecraft to the launch vehicle only. An SDST manufactured by Motorola and purchased for the MESSENGER flight program was used, both because it was available and because it was nearly identical to the SDSTs to be used on STEREO. Rolling spacecraft uplinks were modeled as amplitude-modulated signals due to the rotation of the line-of-sight toward or away from antenna boresight, as well as the angle-dependent interferometric radiation patterns applicable to dual active LGA cases.

The first tests simulated a single active LGA on a rolling spacecraft by simply shutting off the uplink signal for various durations corresponding to the time the LGA would be out of view for a given roll rate. Before shutting off the signal, the uplink was locked via an uplink acquisition sweep and swept 10 kHz away from the transponder's best lock frequency (BLF). This was done to simulate the worst-case situation where a non-return-to-BLF sweep would be required to accommodate a very fast tumble, and therefore a very fast acquisition sweep. Once the signal is shut off (i.e., the LGA rolls out of view), the transponder BLF has time to drift back to its natural rest frequency. When the signal is turned back on, however, the uplink frequency may be sufficiently outside the current receiver bandwidth that lock cannot be achieved without re-sweeping. The initial trials showed intuitively what was expected: the higher the roll rate, the better the chance of signal re-acquisition once the LGA rolls back into view. For rolls ≥1 rpm, the transponder always re-locked to the uplink carrier. For slower roll rates, the transponder did not reliably re-lock.

Next, tests addressed the arrayed-LGA scenario, where two LGAs would be active simultaneously. For a rolling spacecraft, the nulling effect that the interference pattern would have on the uplink signal was modeled as a sinusoidal amplitude modulation (AM) with a peak null depth, A_{null}, and a periodic rate, f_{null}. The typical uplink signal was represented as

$$S(t) = \sqrt{2P_T}\sin\left[2\pi f_0 t + \theta_{CMD} m(t)\right]$$

where f_0 is the X-band uplink carrier frequency, θ_{CMD} is the uplink modulation index, and $m(t)$ is the uplink subcarrier, phase-shift-key (PSK) modulated with command link transmission units (CLTUs). After the interference modulation was applied, the input to the SDST was represented as

$$S_{null}(t) = \sqrt{2P_T}\ \left[1 + m_{null} \sin\ (2\pi f_{null} t)\right] \sin\left[2\pi f_0 t + \theta_{CMD} m(t)\right]$$

where m_{null} is the AM modulation index corresponding to A_{null}. Various values for A_{null}, P_T, and f_{null} were used to simulate different tumble scenarios. The test setup is shown in Figure 2.

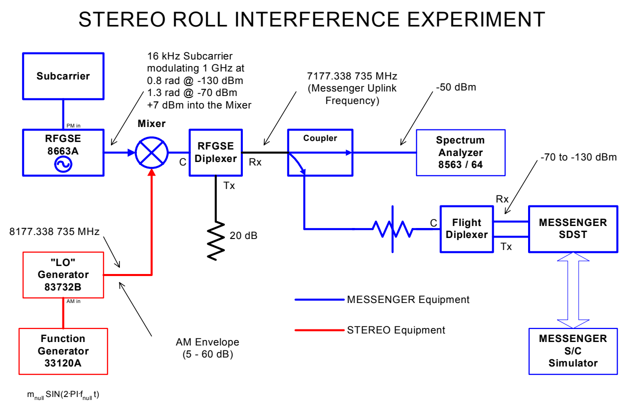


Figure 2 - Rolling spacecraft uplink acquisition experiment.

With peak powers of −70 and −90 dBm at the transponder input, commands were sent to the transponder with applied AM interference. Modulation rates were varied between 1 MHz and 0.2 Hz, and null depths of 40 and 60 dB were created to simulate rolling through the interference pattern. The AM interference was also simulated around the command subcarrier frequency of 16 kHz. In all trials, a bit error rate (BER) of 0 was achieved. These tests demonstrated the ability of the transponder to "ride through" the interference pattern of the arrayed antennas at relatively high power levels, maintaining lock and command capability.

However, at lower peak-power levels, uplink command errors were observed. With peak powers of −130 dBm, 0 BER was achieved for AM frequencies of 5 Hz or higher. At lower frequency AM interference, bit errors were observed. The cause is most likely that at higher AM frequencies, more energy was present in the tracking loop per bit during nulls in the interference pattern. At low AM frequencies, very little energy was present in the loop per bit duration during nulls in the interference pattern. However, in all trials, uplink lock was maintained throughout the applied AM interference. Lowering the peak power even further resulted in a lowering of the frequency at which bit errors began exhibiting themselves.

Uplink acquisition was also attempted during the AM interference for the arrayed LGA configuration. With AM frequencies of 10 Hz or lower, successful uplink acquisition was achieved in all trials. However, with AM interference equal to or greater than 1 kHz, the uplink falsely locked to the AM-generated spur in the uplink frequency spectrum.

Since the initial tests of uplink commanding during a tumble showed instances of both success and failure, tests closer to real-life expectations were deemed necessary to increase confidence in the capability of the transponder. Also, the motivation to ensure downlink telemetry recovery during a tumble warranted further investigation.

3. Spacecraft Modeling

A more rigorous investigation was initiated to strengthen the integrity of the tumbling spacecraft signal simulations. To this end, a model of each spacecraft was devised taking into account its specific moments of inertia, as well as the radiation pattern and unique location of each LGA on the spacecraft. In this manner, true-to-flight predicted signal profile examples could be devised specific to each mission. For dual-LGA scenarios, the models also took into account interferometrically induced phase fluctuation, in addition to amplitude fluctuation, as explored earlier.

A different approach was taken to the spacecraft modeling for MESSENGER than for STEREO. The situation for MESSENGER was simpler because there was a single spacecraft and a single launch vehicle separation event. It was assumed for MESSENGER that the motion of the spacecraft would be dominated by the residual third stage de-spin and that this would result in rotation about an axis parallel to the launch vehicle axis at separation. This axis was roughly perpendicular to the line-of-sight to the ground station that was receiving telemetry during the separation event. Therefore, one geometry was considered and only the residual rotation rate was varied. Telemetry from a single antenna and telemetry from the two interfering antennas were both considered.

The MESSENGER spacecraft moments of inertia, after solar panel deployment but prior to deployment of the magnetic boom, are I_{xx} = 449.6, I_{yy} = 432.5, I_{zz} = 533.5 kg-m^2. The rotation is about the x-axis, so these moments imply unstable motion (the rotation axis has the middle moment).

For STEREO, the situation was more complex because there are two separation events: separation of the two, stacked observatories from the third stage and separation of the two observatories from each other. Tumbling between these two events and two sets of separation springs led to the decision to treat the geometry as random. Several simulations of the observatory tumble were performed, and a few were chosen as representative of the various types of antenna motion that could be presented to the ground station.

A further complication was to consider command and telemetry while the observatories were stacked, while they were separated but before solar panel deployment, and while separated with solar panels deployed. Only one of the two observatories was explicitly considered since the two are nearly identical. Moments of inertia were obtained to describe the several configurations of interest to the STEREO separation event. The launch vehicle axis is a stable spin axis for the stacked configuration, but it is unstable for the separated observatories prior to solar panel deployment.

For both MESSENGER and STEREO, polynomial models of the identical antenna patterns were used, as shown in Figure 3. When two LGAs were considered, these patterns were added coherently using the specific location of each LGA. This resulted in an interference pattern, an example of which was previously shown in Figure 1.

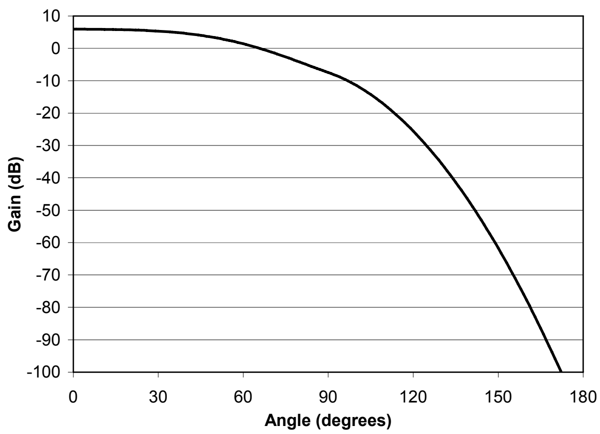


Figure 3 - LGA radiation pattern model.

The motion of the antennas as the spacecraft rotates can be over 2 m along the line-of-sight. This is more than 50 wavelengths and more than 300 radians of carrier phase change. As previously stated, the aim was to simulate this phase fluctuation as part of the investigation. However, the full range of phase change was more than the signal modulation hardware could support, so the phases that resulted from the tumble simulations were high-pass filtered. The assumption was that the receiving station could track the lower-frequency phase variation that occurs when a single antenna dominates the response and that the high-frequency phase changes that occur when the two antennas are interfering presents the greatest challenge to communications during the de-tumble.

4. TUMBLE PROFILE CREATION

Each tumble simulation was the result of time-stepping through the coupled differential equations that describe force-free motion of a rigid body in free space,

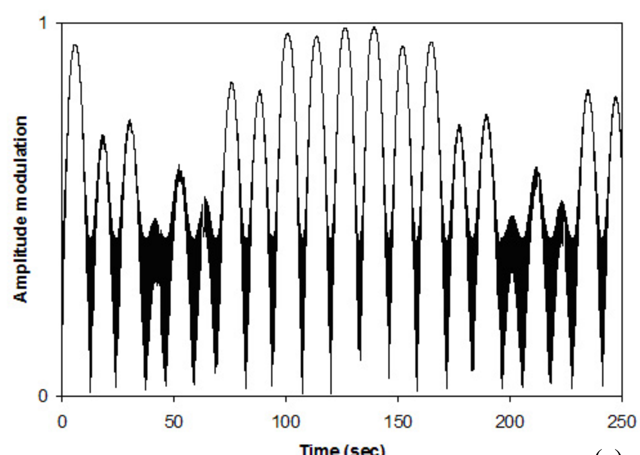
$$\frac{d\omega_x}{dt} = \omega_y \omega_z \left(I_{yy} - I_{zz}\right) / I_{xx}$$

$$\frac{d\omega_y}{dt} = \omega_z \omega_x \left(I_{zz} - I_{xx}\right) / I_{yy}$$

$$\frac{d\omega_z}{dt} = \omega_x \omega_y \left(I_{xx} - I_{yy}\right) / I_{zz}$$

where $\omega_x, \omega_y, \omega_z$ are the rotation rates in the body coordinates and I_{xx}, I_{yy}, I_{zz} are the moments of inertia on the three axes. The axis of rotation moves in the body frame of reference, while the body frame of reference rotates in the ground station coordinate system. Constancy of the total angular momentum was monitored to ensure that numerical errors were not accumulating in the simulations.

Each simulation was initialized with a spin rate about an axis in the body frame of reference. The initial spin rates were varied between 1/4 and 2 rpm, and for STEREO the initial axis was also varied, as was the spacecraft configuration, as described earlier. At each point in time, the amplitude and phase of the uplink/downlink carrier from each antenna was computed in each of the three cardinal simulation directions. Each direction represented a potential position of the ground station. These amplitudes and phases were added and filtered to obtain the amplitude and phase histories that were then used in the testing program. An example tumble profile is shown in Figure 4.



(a)

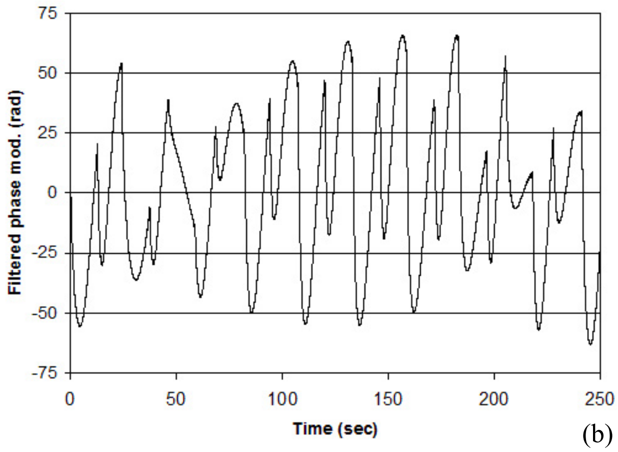


Figure 4 - Example tumble profile for two arrayed LGAs depicting (a) amplitude modulation, and (b) phase (high-pass-filtered) modulation versus time.

Various behaviors were observed in these simulations. In some, a single antenna dominated and only a small amplitude and phase modulation resulted. In others, the two antennas would alternately be pointed directly at the ground station, and large Doppler shifts and intermittent interference effects were observed. In still others, neither antenna was pointed toward the ground station and interference would continue throughout the simulated duration. The motion was always complex and aperiodic.

5. Telemetry Recovery Testing

For telemetry recovery tests, a spacecraft signal simulator was assembled consisting of a vector signal generator (VSG), a compact peripheral component interface (cPCI) digital signal processor/field-programmable gate array (DSP/FPGA) development system, signal conditioning voltage amplifiers, and a controlling laptop computer as shown in Figure 5. The VSG served as the X-band source with the tumble profiles applied to its external modulation inputs by the cPCI high-speed digital-to-analog converters (HS-DACs). Tumble scenarios were commanded via a null Ethernet connection between the laptop and cPCI central processing unit (CPU). Sample turbo-coded (Rate 1/6) downlink telemetry was directly modulated on the carrier via bi-phase, phase-shift keyed pulse-code modulation (Bi-Φ-L, PCM/PSK) using the modulator internal to the VSG. Telemetry consisted of ten continuously cycling 1784-bit short frames at 9.058 kbps for MESSENGER tests and 8920-bit long frames at 30 kbps for STEREO tests.

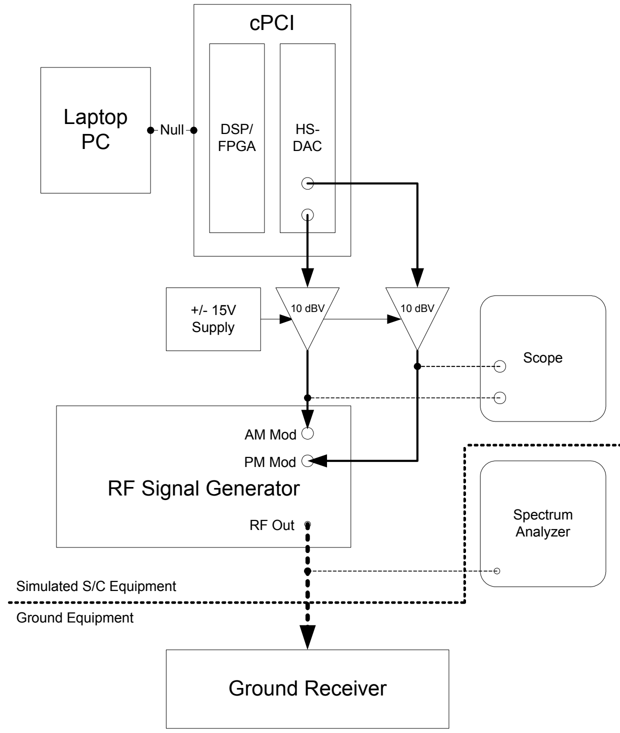


Figure 5 - Test configuration for the tumbling spacecraft simulator telemetry recovery test.

Amplitude and phase modulations simulating the tumble of the spacecraft were applied to the downlink signal according to the individual tumble profiles stored in the cPCI FPGA. The amplitude and phase modulation signals were updated at 48 and 96 Hz, respectively, for MESSENGER and 76 and 152 Hz for STEREO. These rates were chosen to be as high as possible while meeting the data storage constraints of the modulation system. The interference modulation of two LGAs was as high as 12 Hz for the 2-rpm case. There was thus significant change in the interference phase between successive time steps at the points of maximum interference. A higher sample rate would have been desirable, but, if anything, the lower rate should have provided a worse-case situation and should not have biased the test towards a positive result. Since phase fluctuation was believed to have a more deleterious effect on receiver performance, it was updated at the higher rate to improve the integrity of the simulation. For the single LGA cases, where phase modulation was not required, longer-amplitude profiles were tested due to the increased hardware capacity.

Tests were performed initially against a Deep Space Network (DSN) Block V Receiver (BVR) at the DSN Test Facility (DTF-21) in Pasadena, CA. A subset of tests was later repeated at the Universal Space Network (USN) facility in Horsham, PA. Since each of the simulations to be tested considered a spacecraft soon after launch vehicle separation in a near-Earth configuration, the nominal downlink signal power expected at the ground would be relatively strong at the input to the ground receiver. For these tests, nominal signal strength was assumed to be in the vicinity of −90 or

−110 dBm, depending on the mission and the switch configuration. However, depending on the tumble scenario, the signal could have significant fades or, in some cases, complete extinctions. Therefore, the BVR carrier power automatic gain control (AGC) was configured to search over its entire dynamic range of ±50 dBm around the predicted −110 dBm. For stable signals, carrier lock was routinely achieved in 15 s and turbo (telemetry) lock followed 8 s later. Complete test specifics were separately outlined in test plans for MESSENGER [5] and STEREO [6].

Single LGA Tests

For simulations of a tumbling spacecraft with a single active LGA, both the carrier loop bandwidth and the symbol loop bandwidth were nominally set to 10 Hz. A monitor of the Total Power AGC (measured) was used to track the signal level trend at the receiver while the Total Power (measured) and Carrier Power (measured) were also monitored for actual received signal level. The AGC monitor was helpful in determining when a simulation of an obscured spacecraft signal would start to increase as its LGA rotated back into view, and therefore when to attempt a re-acquisition of the signal. The Total Power and Carrier Power monitors indicated the actual levels of the received signal and provided a visual indication of when the receiver lost lock; however, these monitors were unavailable when the receiver was not in closed-loop lock. Each monitor was updated about once per second.

For slow tumble rates (i.e., 1/4 to 1/2 rpm), a loss of carrier lock required a manual re-acquisition of the signal, using the AGC monitor as a timing guide as to when to initiate the acquisition sequence. Instances of loss of symbol lock or telemetry lock where carrier lock was maintained automatically re-locked as the signal level increased. Faster tumble rates (i.e., 1 to 2 rpm) were more complicated. If carrier was lost and the rate of signal fluctuation was rapid enough, the carrier loop often recovered and re-locked without manual intervention. However, at intermediate tumble rates, signal strength can decrease rapidly, causing loss of carrier lock, yet the signal strength may not recover quickly enough to allow the receiver to reacquire automatically. In these cases, manual reacquisition had to be initiated but had to be precisely timed to acquire when the signal was on an upward trend. If telemetry lock could be achieved at the peak of a signal cycle, some telemetry could be recovered before the eventual decrease in signal caused either loss of telemetry lock again or a complete loss of carrier. The Total Power AGC was essential to recovering telemetry in these instances.

Ultimately, a combination of the AGC and Carrier Power monitors proved useful in determining the optimal time to attempt to acquire the tumbling spacecraft signal so as to recover as much telemetry as possible. Sample screenshots of the AGC and Carrier Power monitors for a 1-rpm, single-LGA test are shown in Figures 6 and 7, respectively. Note the periodic trend exhibited by the AGC monitor and the loss of Carrier Power monitor as the receiver lost carrier lock.

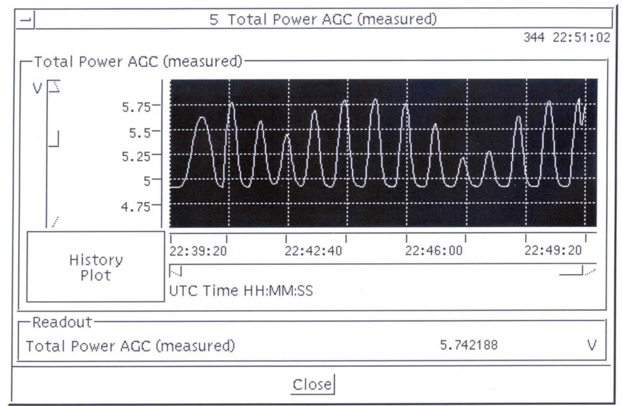


Figure 6 - Sample Total Power AGC monitor: 1-rpm, single-LGA test.

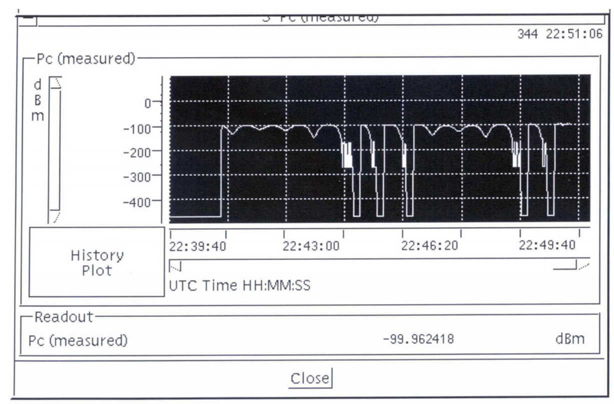


Figure 7 - Sample Carrier Power monitor: 1-rpm, single-LGA test.

Dual LGA Tests

Dual LGA tests simulated the signal generated by the combined interferometric radiation of two active and opposite-facing LGAs as the spacecraft tumbles. As in previous tests, the Total Power AGC and Carrier Power monitors were observed during testing; however, the AGC indicator represented the envelope of the change in signal amplitude since the update rate of the monitor was much slower than the rate of signal fluctuation.

As described above, the dual LGA profiles comprise fast fluctuations in the amplitude and phase of the received spacecraft signal. Although the fast fluctuations caused rapid drops in signal strength, signal recovery occurred very quickly as well. Therefore, although telemetry was lost as the phase of the simulated spacecraft signal underwent very rapid oscillations, carrier lock was rarely lost during any of the dual LGA cases tested. When carrier lock was lost during particularly extreme tumble profiles, the receiver either re-locked automatically or re-locked immediately after a manual command to reacquire. This loss of signal occurred mainly for fast, worst-case tumble profiles demonstrating extended periods of interferometric nulls. The fast phase oscillation of the simulated signal was found to be the dominant cause of loss of turbo lock when compared with modulation of the amplitude oscillations alone.

As a measure of the severity of the tumble profiles tested, turbo frame failures were monitored for each test. As a percentage of total frames received, frame failures were found to increase with tumble rate. It was expected that widening the carrier loop bandwidth would improve the telemetry recovery performance, so each dual LGA test was repeated for a number of carrier loop bandwidths. Symbol loop bandwidth was held constant at 10 Hz. Telemetry performance improved as carrier loop bandwidth increased up to the maximum bandwidth tested of 100 Hz, as shown by the results of the MESSENGER dual LGA tests of Figure 8. The data shown are an average of several trials of each test case.

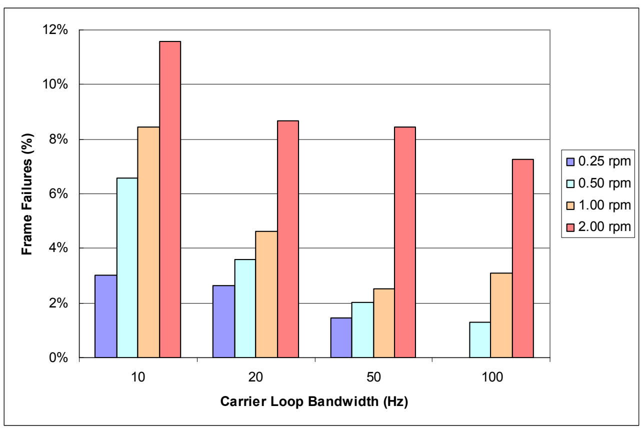


Figure 8 - MESSENGER dual LGA telemetry performance.

Specific to the STEREO program, additional tests were performed where the tumbling spacecraft signal at the ground receiver was in the presence of a second closely-spaced downlink frequency, representing the opposite STEREO observatory's downlink. Tests including the interference signal showed no appreciable difference in telemetry recovery performance as compared with the tests excluding the second downlink signal.

6. UPLINK COMMAND TESTING

For uplink acquisition and commanding tests, the tumbling signal simulator used for telemetry recovery tests was interfaced with a PSG signal generator used in one of the STEREO Ground Support Equipment (GSE) racks. A cycling CLTU command was applied to a 16-kHz subcarrier via non-return-to-zero (NRZ-L) symbols at 2 kbps and modulated onto a 1-GHz carrier (PSK) using the STEREO Spacecraft Simulator Rack. This carrier was then mixed with the tumbling radio-frequency (RF) signal to create the effective tumbling uplink signal at 7 GHz. Toward the goal of performing these tests in the simulated presence of the opposite STEREO observatory's uplink signal, the other STEREO GSE rack was used in conjunction with the MESSENGER Spacecraft Simulator Rack to create a second non-tumbling uplink signal in similar fashion. Both uplink signals were presented to one of the flight transponders through the use of a power combiner, as shown in Figure 9.

Uplink tests performed at APL were intended to measure the ability of the flight transponder of a tumbling STEREO observatory to acquire a sweeping uplink signal and successfully register a cycling CLTU. The tests were performed for a single observatory with its solar panels stowed and with its solar panels deployed for tumble rates of 1/4, 1/2, 1, and 2 rpm and various initial conditions. A continuous interferometric pattern case was also tested as a worst-case scenario, and a non-tumbling test was performed as a control. All the tests were performed at a high (−68 dBm) and low (−100 dBm) power level in the presence of CLTU interference, representing the opposite observatory's uplink signal. Acquisition was attempted using sweep rates of 1300 and 320 Hz/s, with the center of the sweep occurring at a signal peak for the 1300-Hz/s rate and at a signal null for the 320- Hz/s rate. Figure 10 is an example of a tumbling amplitude profile showing the uplink acquisition timing used for a 320-Hz/s sweep (t_{320}) and for a 1300-Hz/s sweep (t_{1300}).

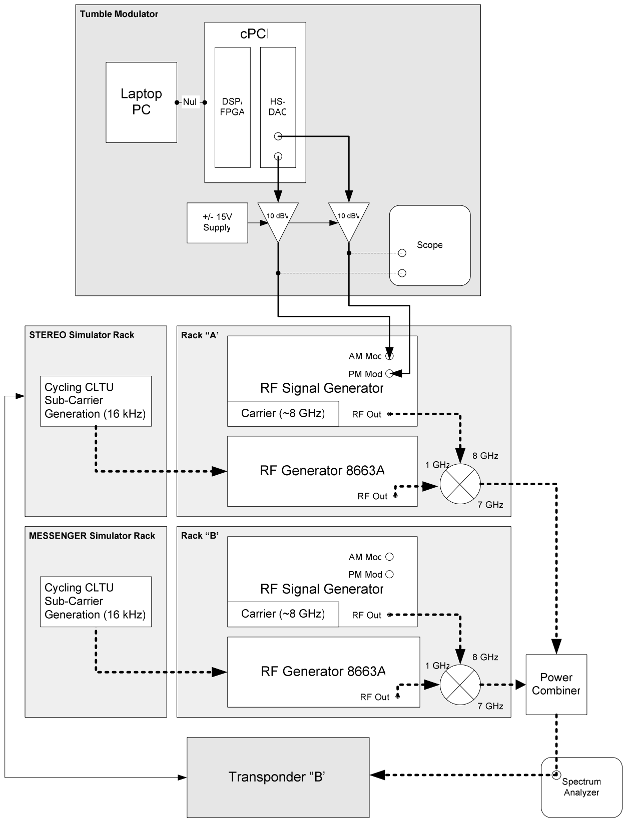


Figure 9 - Tumbling spacecraft simulator uplink command test configuration.

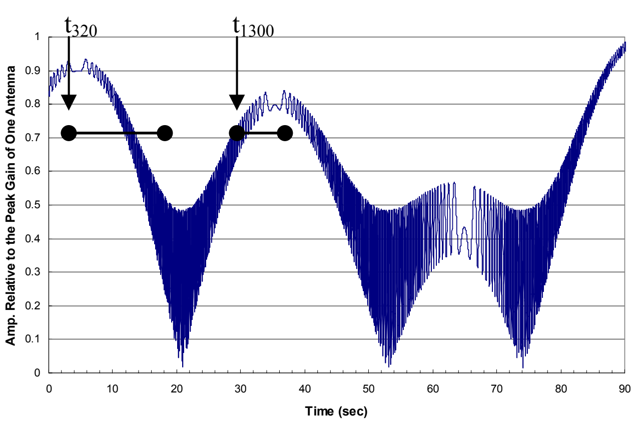


Figure 10 - Tumbling spacecraft uplink acquisition sweep timing example.

The uplink test procedure involved first determining where the center of the sweep should occur, based on the tumble profile and sweep rate to be tested. Once the "center of sweep" time was determined, the "start of sweep" time was determined by subtracting half the full sweep time for the given sweep rate. Full sweep times for sweep rates of 1300 and 320 Hz/s were 11 and 44 s, respectively. The start of sweep time was then used as the point when the uplink frequency sweep would be initiated, relative to the start of the tumble profile. For each test, the success of the acquisition sweep was determined by monitoring the uplink lock indicator and manually checking the data received by the STEREO spacecraft simulator for uncorrupted CLTUs.

Both uplink frequency sweep procedures resulted in successful frequency lock and CLTU reception of the flight transponder for all uplink tests performed. However, sweeps at 1300 Hz/s required a precise knowledge of the tumble period. Some tests showed that the transponder could occasionally miss the sweeping uplink at the center frequency but then lock to the uplink as it continued the sweep. Misalignment of the sweep center frequency with the peak of the tumbling uplink signal on the order of 1 or 2 s could result in the failure of the transponder to lock at all.

Sweeps at 320 Hz/s did not require a precise knowledge of the tumble period. On the contrary, the tests proved that the center of the sweep could even occur during a deep null in the tumbling uplink signal and the transponder would still successfully lock and receive valid CLTUs. Therefore, an uplink frequency sweep could be arbitrarily initiated at a sweep rate of 320 Hz/s to achieve successful acquisition. For both sweep procedures, after transponder lock of the uplink signal, the spacecraft simulator successfully registered many CLTUs.

7. MESSENGER FLIGHT DATA

After MESSENGER launch, flight data were extracted from the DSN to determine what, if any, residual tumble was induced due to the separation from the third stage of the launch vehicle. For this mission, the third stage was a Thiokol Star 48B used to de-spin the MESSENGER spacecraft from 60 rpm to ±2 rpm (3-σ), as stated earlier. Figure 11 shows the carrier power-to-noise ratio (Pc/No) as a function of time for the Block-V Receiver (BVR) used by the DSN at the Beam-Waveguide (BWG) Station in Canberra, Australia (DSS-34). The highly varying Pc/No, on the order of 4 orders of magnitude, represents residual tumble of the MESSENGER spacecraft at separation. A constant Pc/No would have indicated the spacecraft was in a low- or no-tumble state. Through observation of the carrier data of Figure 11 and knowledge that the tumble was roughly about the z-axis of the spacecraft, it was estimated that the residual tumble was about 0.28 rpm from the time of separation until the de-tumble maneuver. This estimate agrees with the tumble rate of 0.29 rpm recorded by spacecraft telemetry.

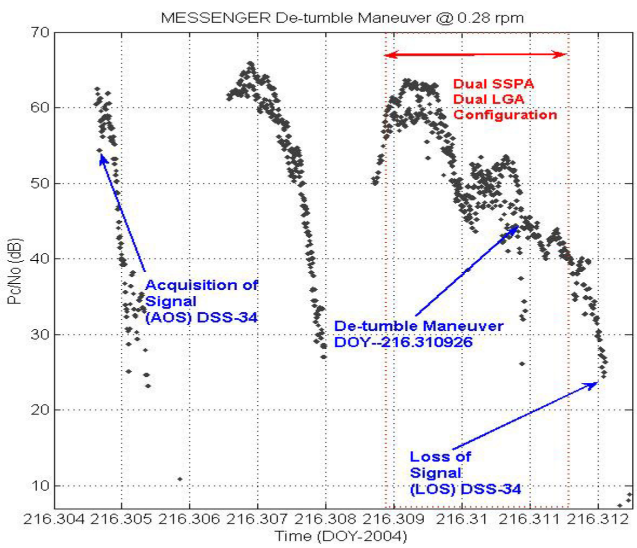


Figure 11 - Tumbling MESSENGER spacecraft Pc/No at critical de-tumble event.

To remove the residual tumble, the spacecraft's Guidance and Control (G&C) subsystem was programmed to attempt to de-tumble using the spacecraft's four reaction wheels. If the tumble rate was too high, then the propulsion system was armed and would fire thrusters to remove the residual tumble. To view this critical event the spacecraft's solid-state power amplifiers (SSPAs) and LGAs were configured strategically to allow the ground station to capture telemetry and downlink carrier power. No intervention of the ground controller was enacted to perform the de-tumble maneuver; all spacecraft action was fully autonomous.

The spacecraft's SSPA was turned on at the detection of separation and routed to a single LGA. Due to the residual tumble and lack of 3-axis attitude control until Day-of-Year (DOY) 216.31, the carrier signal power varied with time. On the ground, the carrier loop bandwidth was opened to 100 Hz. Carrier lock was repeatedly obtained near the peak of the LGA pattern and was successively lost as the LGA rotated out of view of the ground station. Just prior to DOY 216.31, another LGA-SSPA combination was brought on line to provide nearly two full hemispheres of coverage about the expected tumble axis. No matter the orientation of the spacecraft, with both SSPAs powered and routed to LGAs on opposing sides of the spacecraft the critical event would be in constant view of the DSN, albeit through an interferometric downlink pattern. Both SSPAs and LGAs were turned on approximately 2 minutes before the maneuver to allow the DSN to achieve lock and remained on for 1 minute after the maneuver to collect data.

As can be seen from Figure 11, the DSN remained in lock during the de-tumble event during the time both SSPAs and LGAs were transmitting. After the maneuver, the second SSPA and LGA combination were turned off and the spacecraft resumed normal operations with a single SSPA and the carrier loop bandwidth reduced to 5 Hz. As expected, carrier power roll-off due to single LGA coverage was observed toward the end of the DSN track as the spacecraft traveled out of view of the ground station.

8. CONCLUSIONS/RECOMMENDATIONS

The tests performed highlighted a number of steps to ensure successful telemetry recovery and uplink commanding of a tumbling spacecraft after launch vehicle separation. When a single LGA is active, observation of the total power AGC can aid considerably in maximizing telemetry recovery. Timing the acquisition attempts to coincide with a rise in signal level can maximize the amount of telemetry collected. Additionally, with two active LGAs providing close to omni-directional coverage, opening the carrier loop bandwidth of the receiver (tested up to 200 Hz) can significantly increase the amount of telemetry recovered at all expected tumble rates. No negative effect on single LGA performance was observed from opening the carrier loop bandwidth. Therefore, if no requirement exists, carrier loop bandwidth should be widened as much as possible for first acquisition and narrowed once the spacecraft successfully de-tumbles and the downlink signal stabilizes.

With a single active LGA, uplink acquisition sweeps should be performed as quickly as possible as the downlink signal level is observed to rise. Knowledge of the tumble periodicity through observation of the non-coherent downlink AGC also aids in optimizing timing of uplink sweep initiation. Alternatively, if two LGAs are activated, uplink sweeps should be performed at a relatively slow rate. This ensures that the transponder can "catch" the uplink frequency as it sweeps by the transponder's rest frequency, even if an interferometric fade occurs at the same instant (i.e., the sweeping frequency is still within the reach bandwidth of the transponder when the signal recovers from an interferometric fade). The slow sweep rate also allows similar recovery from fades after initial sweep lock but before completion of the frequency sweep. Once acquisition is achieved, CLTUs should be consistently registered by the transponder.

REFERENCES

[1] Vaughn, R. M., J. C. Leary, R. F. Conde, G. Dakermanji, C. J. Ercol, K. B. Fielhauer, D. G. Grant, T. J. Hartka, T. A. Hill, S. E. Jaskulek, J. V. McAdams, M. A. Mirantes, D. F. Persons, and D. K. Srinivasan, "Return to Mercury: The MESSENGER Spacecraft and Mission," *2006 IEEE Aerospace Conference Proceedings,* Paper #1562, 15 pp., Big Sky, MT, March 4–11, 2006.

[2] MESSENGER Mission Web Site: http://messenger.jhuapl.edu/

[3] Morring, Jr., Frank, "Solar Studies," *Aviation Week & Space Technology,* pp. 62-64, September 5, 2005.

[4] STEREO Mission Web Site: http://stereo.jhuapl.edu/

[5] Bruzzi, J. R., *MESSENGER DSN Test Plan for Telemetry Recovery from Tumbling Spacecraft*, DSN Test Plan (DTF-21), November 20, 2003.

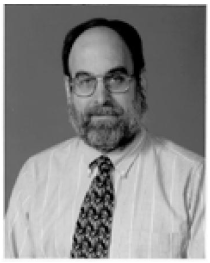
[6] Bruzzi, J. R., *STEREO Tumbling Spacecraft RF System Test Procedure (Non-Hazardous Procedure),* APL Drawing #7381-9362, November 29, 2004.

ACKNOWLEDGMENTS

The MESSENGER mission is sponsored by the NASA Science Mission Directorate as part of its Discovery Program. The STEREO mission is the third Solar Terrestrial Probes mission, sponsored by the NASA Science Mission Directorate and managed by NASA/GSFC. The authors wish to thank Dave Grant and Ed Reynolds, program managers of MESSENGER and STEREO, respectively, for their support of this work. We also thank Kate Reynolds, Lloyd Ellis, Matt Angert, Judi VonMehlem, and Bob Stilwell for their contributions to this work, as well as the teams of individuals who assisted with this test effort at DTF-21, DSN, the Jet Propulsion Laboratory, and the USN in Horsham, PA.

BIOGRAPHIES

Jonathan R. Bruzzi *is a member of the Associate Professional Staff in the Space Department RF Engineering Group at The Johns Hopkins University Applied Physics Laboratory (APL). He received his B.S.E in electrical engineering in 1999 and his M.S.E. in electrical engineering in 2000, both from the University of Pennsylvania. Mr. Bruzzi joined the APL Space Department in 2000, specializing in antennas, electromagnetics, and optical communications. He has since acted as lead investigator for the MESSENGER and STEREO tumble testing, lead engineer for the MESSENGER low-gain antennas, co-investigator of the group's spacecraft optical communications development effort, and designer of flight electromagnetic hardware and phased-array calibration routines.*



J. Robert Jensen *earned a B.A. at Cornell College, Mt. Vernon, Iowa, in 1973 and a Ph.D. in Physical Chemistry at the University of Wisconsin, Madison, in 1978. Since 1978 he has been at APL (since 1989 as a member of the Space Department), where he has participated in several space programs including TOPEX, MSX, NEAR, CONTOUR, and New Horizons. His work has focused on spacecraft communications and navigation, new techniques and methods for satellite and airborne radar altimetry, and a variety of space radar applications.*

Karl B. Fielhauer *is currently the lead engineer responsible for the MESSENGER RF communication system. He is also the supervisor of the RF Systems Engineering Section of the RF Engineering Group at APL. He received a B.S. in 1985 from Lawrence Technological University in Southfield, Michigan, and an M.S.E.E. in 2002 from The Johns Hopkins University in Baltimore, Maryland. Before joining APL, Mr. Fielhauer worked for the Department of Defense and Litton's Amecom Division in College Park, Maryland. Since joining the APL Space Department in 1997, he has focused primarily on the design and development of digital hardware for the TIMED and CONTOUR missions and their ground support equipment. Mr. Fielhauer was previously the Lead RF Communications Engineer on the CONTOUR mission and is a member of IEEE.*

Darryl W. Royster *is a member of the Senior Professional Staff in the RF Engineering Group at APL. He is the lead RF Integration and Test Engineer for the STEREO spacecraft and was responsible for the MESSENGER compatibility testing with the Deep Space Network and the data collection of the MESSENGER phased array during integration. Before joining the APL Space Department in 2001, Mr. Royster designed commercial land mobile radio products for Ericsson, Inc. (formerly General Electric Land Mobile Radio), from 1987 to 2001 and for Motorola paging division from 1984 to 1987. He received his B.S. and M.S. in electrical engineering from Virginia Polytechnic Institute and State University in 1982 and 1984, respectively.*

Dipak K. Srinivasan *is a member of the Senior Professional Staff in the RF Engineering Group of the APL Space Department. He received his B.S. and M. Eng. in electrical engineering in 1999 and 2000 in electrical engineering from Cornell University, and an M.S. in applied physics from The Johns Hopkins University in 2003. Mr. Srinivasan joined the APL Space Department in 2000, where he was the lead RF Integration and Test Engineer for the CONTOUR and MESSENGER spacecraft and is currently an RF telecomm analyst for the MESSENGER project and lead system verification engineer for the New Horizons project.*