Spacecraft-level Testing and Verification of an X-Band Phased Array

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Abstract—The MESSENGER spacecraft uses an X-band (8.4-GHz) phased array for high-rate downlink communications to meet mission data requirements yet still survive the extreme environment at the planet Mercury. To survive the solar intensity at the planet, the MESSENGER spacecraft uses a sunshade that must remain Sun-pointed; this restricts pointing of the spacecraft. The use of two phased-array antennas alleviates the need for a gimbaled high-gain dish. The RF signal is routed through on-board solid-state power amplifiers that control the phases of the signals fed to the phased arrays, thereby pointing without the need for any moving parts while maintaining a Sun-pointed attitude. Each phased array is composed of eight slotted waveguide sticks.

This paper describes a method for a real-time, fast verification of the steering of the phased array during any phase of spacecraft-level testing (including thermal-vacuum) without the need to free radiate, which is specifically critical to a spacecraft during integration and test. This newly developed and implemented approach does not require near-field probing, in-line couplers, or extra flight mates and de-mates. Once the antennas are integrated onto the spacecraft, schedule constraints force the need for very quick verification methods. The technique described herein quickly samples the phase of the signal at each array element and, in conjunction with subsystem-level measurements, mathematically calculates the radiated antenna pattern. The phases within each array element are measured using innovative loop couplers that may simply be removed once testing is complete. These phases are combined using specifically designed software to calculate the far-field radiated pattern to verify pointing.[1,2]

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1. INTRODUCTION

The Mercury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft was launched on 3 August 2004 from Cape Canaveral Air Force Base. In March 2011, MESSENGER will be the first spacecraft to achieve orbit about Mercury, where it will collect and transmit back to Earth science data for one year [1]. MESSENGER is part of NASA's Discovery Program and was built and is managed by The Johns Hopkins Applied Physics Laboratory (JHU/APL).

At Mercury the solar intensity is up to 11 times the level observed at Earth. To mitigate this stress, MESSENGER uses a fixed ceramic-cloth sunshade that allows the spacecraft body to operate at roughly 25ºC; this sunshade must remain Sun-pointed. Because of this constraint and the geometry of the inner-planet trajectory of MESSENGER, the Earth can be in any direction about the spacecraft, resulting in the need for a high-gain downlink in all directions about the spacecraft.

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To achieve beam pointing in all directions about the spacecraft, two degrees of freedom are needed. One is provided by spacecraft rotation about the spacecraft-Sun axis (thus maintaining the proper pointing of the sunshade). The other is one-dimensional steering of the antenna beam. A traditional gimbaled high-gain dish could accomplish this task; however, this architecture does not meet the thermal and packaging requirements of the MESSENGER spacecraft. These requirements are met with an electronically steered phased-array antenna architecture [2,3].

2. DESCRIPTION OF PHASED-ARRAY SYSTEM

The MESSENGER spacecraft uses two opposing-faced phased arrays for high-gain downlink coverage as shown in Figure 1. Each array is required to scan to ±45º from its respective boresight, but each has the capability of scanning ±60º to support additional coverage if necessary. This one-dimensional scanning, coupled with spacecraft rotation about the spacecraft-Sun line, allows the main beam of the antenna to be steered in all directions.

Each phased array is composed of eight radiating elements, as shown in Figure 2. Each radiating element is a slotted rectangular waveguide with parasitic monopoles to achieve right-hand circular polarization. The array pattern is very narrow in the non-scanning direction of the array (in the *XY* plane). The spacecraft rotation about the spacecraft-Sun line ensures that the Earth remains in this plane. The array scans in its broad beam dimension. This minimizes the amount of pointing loss in the antenna gain caused by phase errors. The scanning resolution of the array is 1º [4].

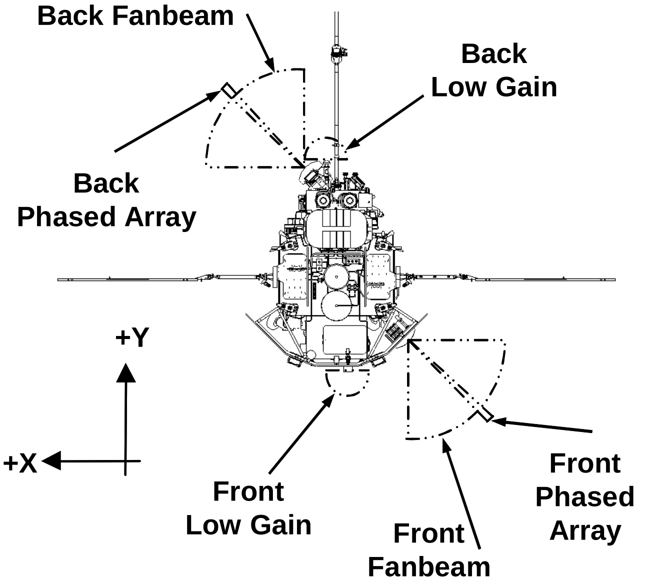


Figure 1. MESSENGER Antenna Coverage.

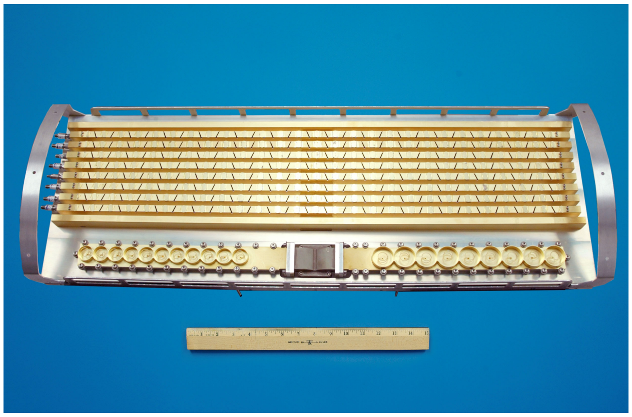


Figure 2. MESSENGER Phased array.

The RF signal is fed to the array as shown in Figure 3. One transponder exciter provides the RF signal source, and that signal is routed to both on-board Solid-State Power Amplifiers (SSPAs). Each SSPA can be in one of four modes: “Distributed Front,” “Distributed Back,” “Lumped,” and off. The distributed modes provide the RF signals necessary for the phased arrays, and the lumped mode provides an RF signal to the fanbeam and low-gain antennas. With both SSPAs in either the “Distributed Front” or “Distributed Back” mode, all eight waveguide sticks of either the front or back phased array are illuminated. If one SSPA was off, however, each phased array can be operated in half-array mode. This mode reduces the effective radiated power by 6 dB, consuming half the power and providing broader beamwidth (3 dB less as a result of half the radiated power, and 3 dB less as a result of half the antenna gain of four radiating elements as opposed to eight).

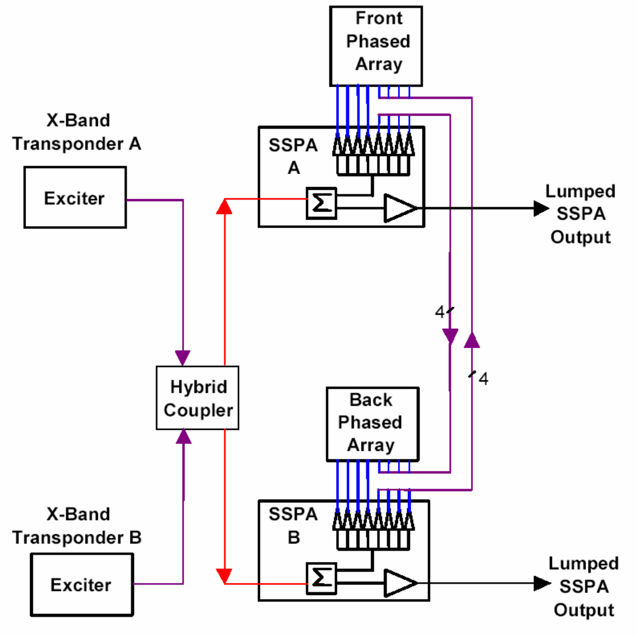


Figure 3. RF Phased-Array Block Diagram.

In the distributed mode, the SSPA splits the incoming RF signal and feeds it through eight "stick" amplifiers. Each stick amplifier consists of a 4-bit X-band phase shifter (22.5º increments) and an amplifier chain. This is where the signal phasing occurs so as to steer the radiated beam. This phase-shifted signal is then routed via coaxial cables to a coax-waveguide adapter (part of each phased-array structure) and then ultimately to each waveguide stick from which the RF power is radiated.

3. SUBSYSTEM-LEVEL TESTING

Individual Antenna Element Testing

Each phased-array antenna is composed of eight radiating sticks of WR-90 waveguide. The antenna sticks are fed from the center of the stick via an H plane Tee and are terminated at both ends with a short circuit. Testing of the antenna began with an initial measurement of the input return loss using a calibrated network analyzer. Because the antenna is relatively narrow band, it was tuned by an adjustment in the short circuit position to improve return loss. Direct measurements of the phased-array antenna gain were made using the JHU/APL indoor Compact Antenna Range. The facility uses a network analyzer in conjunction with a large broadband reflector, broadband feed horn, and RF switch to capture both the horizontally and vertically polarized radiation from an antenna under test (AUT) in an anechoic chamber. A time-gating function is performed using software to eliminate multipath reflections from the measurement. The circularly polarized far-field radiation pattern is computed through post-processing and referenced to a separate measurement of a standard gain horn to determine the absolute gain of the AUT (magnitude and phase) versus mechanical scan angle. This measurement also provided the phase accumulation of signals through each antenna element, $\phi_{antenna}$, used to analytically reconstruct the overall array gain patterns.

Phased-Array Antenna Subsystem Testing

To measure the gain of the phased-array antenna without requiring the flight SSPAs, a set of eight 4-bit commercial phase shifters was used. Transmission measurements were made for the eight phase shifters in all 16 phase states. This array of the magnitude and phase measurements was used in generating a look-up table of phase states and corresponding eight-way phase-shifter assembly loss corrections; these tables helped determine the gain of the phased array. The look-up table and loss correction were computed as a function of array electrical scan angle. The phase accumulation of the individual antenna sticks was also measured at boresight and taken into account in creating the optimal look-up table. The above 8-way calibration allows calculation of all radiated antenna parameters, including right- and left-hand circular polarization gains, and gain versus frequency for the 8-element array.

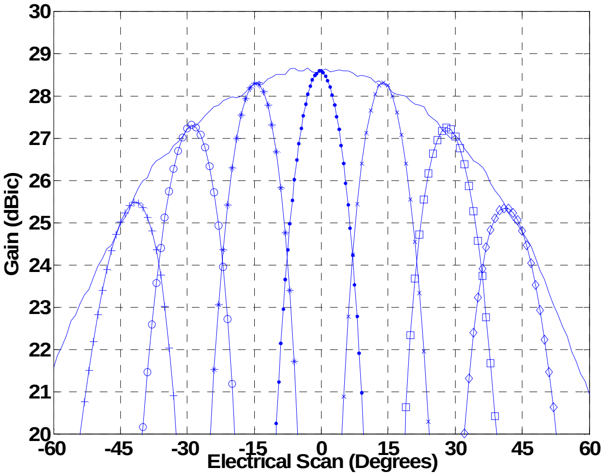


Figure 4. Gain Envelope with Scan Patterns Overlaid.

An additional test method was developed to quickly assess the performance of the phased-array antenna. In this method, the gain was measured by physically rotating the antenna as the beam was electronically scanned in 1° increments from −60° to +60° referenced to the broadside direction. This procedure allowed electrically scanned "gain envelopes" to be determined relatively quickly. This measurement was enabled by synchronizing the compact antenna range software that controls the antenna turntable motor with the phase shifter look-up table index and the network analyzer swept frequency measurement. Figure 4 illustrates the gain envelope pattern superimposed upon gain patterns for several electrical scans or equivalent look-up table indices [5].

4. SPACECRAFT-LEVEL TESTING METHOD

A significant challenge during the spacecraft-level integration and test (I&T) phase of MESSENGER was verifying proper electronic pointing of the phased arrays. A method had to be engineered to measure the pointing of the main beam of the arrays. One way of testing an antenna pattern is by using near-field probing techniques. Near-field techniques eliminate the need for a conventional antenna range by taking measurements in the AUT's near field and using analytical methods to transform these measurements to far-field radiation patterns. Typically for high-gain antenna near-field measurements, a probe antenna is placed a small distance (~3λ) from the AUT and the probe is scanned in a plane at that distance. The amplitude and phase of the received signal at each X and Y coordinate (Z is kept constant) is recorded. The scanning range of the probe must be large enough to capture all the significant energy from the AUT. These measured electric field data are then Fourier transformed into k-space, from which the far-field pattern can ultimately be calculated.

There are some drawbacks to near-field probing. The technical drawbacks include errors introduced by RF reflections, fringe effects, and mechanical errors in scanning the probe. However, the main drawbacks to this method are more practical. During the I&T phase of MESSENGER, the equipment necessary for this technique was unavailable and would have cost too much. Also, in an I&T environment, time is critical; measuring antenna patterns at each scanning angle by sampling the field at all the required points would have taken too long. Furthermore, in order to make measurements in this manner, the spacecraft would have to free-radiate through its high-gain antenna (an obvious safety hazard). Last, there would have been no way to perform this test in a thermal-vacuum chamber.

To measure the radiated antenna pattern without actually free-radiating, an antenna pattern has to be reconstructed from indirect data. Reconstructing the pattern involves measuring amplitude and phase information from each waveguide stick element of the phased array and mathematically combining the (previously measured) individual stick patterns to form the steered sum pattern. A hat coupler could be placed over the phased array to absorb the RF energy, preventing the spacecraft from free-radiating. There are options for methods to capture the required phase information.

One method is to de-mate the coaxial cable inputs to the waveguide feeds of the phased array. This method provides the phases of the signals at the plane of the antenna feed. These measurements, combined with previously measured phase delays within each waveguide feed, are sufficient to mathematically reconstruct the beam. However, this method also requires an extra mate/de-mate cycle every time an antenna pointing test is required during I&T. Furthermore, the final "flight" mate would be performed well after the spacecraft undergoes environmental testing, which by definition would cancel the validity of the flight mate.

Another possible method to avoid extra mate/de-mate cycles is to use in-line couplers at the coax-to-waveguide adapters. This way, the cables only need to be attached to the (calibrated) coupled port. At the end, these cables need only to be removed and replaced with terminators. The drawback here is that there is the extra mass of the coupler and that a final terminator must be attached that would not have undergone spacecraft-level environmental testing.

The method used on MESSENGER actually samples the signal phases within each waveguide stick as part of an innovative hat-coupler/loop-coupler assembly. This method allows the arrays to operate at full power and radiate as they would in flight, but the spacecraft would not free-radiate any RF energy. Also, no extra flight hardware is necessary, nor any extra mate/de-mate cycles. These signal phases can be mathematically combined in the RF ground support equipment (GSE) to yield the radiated antenna pattern.

5. HAT-COUPLER/LOOP-COUPLER DESIGN

Traditionally, absorptive hat couplers are used during the I&T phase of spacecraft testing. Hat couplers allow the RF system to fully radiate into each antenna port; the radiated power is absorbed by the hat coupler, and an attenuated version is then forwarded to the GSE. This is the standard method of testing antennas with fixed antenna patterns.

With a phased-array antenna, however, simply capturing all the RF radiation and sending a portion of the signal to the GSE does not adequately test the phased-array operation; beam steering cannot be measured with this method. A more complicated system must be used.

For the testing of the MESSENGER phased-array antennas, loop couplers were used to sample the phases of the RF signal within each waveguide stick. These loop couplers measured the internal magnetic field, which is directly related to the radiated RF signal. Each loop coupler was fastened directly to a short circuit plate in one end of a slotted waveguide for test purposes and then removed after testing was complete. This configuration facilitated tests at the spacecraft level by eliminating the need to disconnect and reconnect any RF connections in the system.

A loop coupler consists of a short loop of the inner conductor of a 0.086-inch-diameter semi-rigid coaxial cable that is soldered into a two-hole flange-mount SMA jack connector as shown in Figure 5. The bare end of the cable has a portion of the shield and dielectric removed to expose a length of the center conductor. The center conductor has a hairpin bend in it so that the tip of the center conductor is soldered to the shield of the coax and thus forms a loop. Each short circuit plate of the slotted waveguides has a hole in the center that is large enough for the coaxial cable of the loop coupler to pass through. The length of the coaxial cable is such that the loop is positioned inside the waveguide when the jack connector is screwed securely to the short circuit plate.

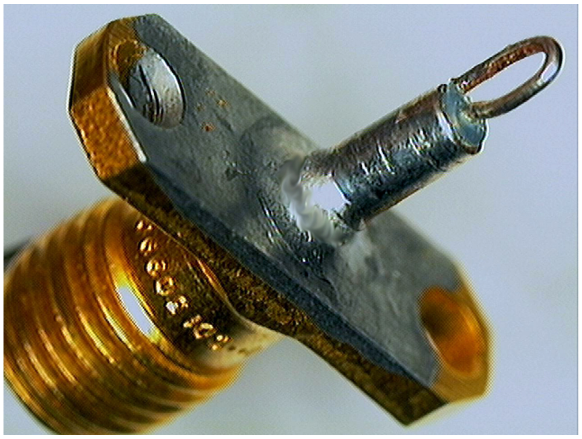


Figure 5. Loop Coupler**.**

The RF electric field inside the waveguide is very small near the short circuit plate, but the RF magnetic field is large. The loop coupler is oriented so that the plane of the loop is orthogonal to the magnetic field lines, thus maximizing the RF magnetic flux captured by the loop. It is the time-varying magnetic flux through the loop that induces a detectable voltage around the loop, and this RF voltage can be monitored on a network analyzer. The phase of the RF voltage signal is related to the phase of the RF field in the waveguide, so the loop couplers provide a way to monitor the phase of the field inside each slotted waveguide element.

One loop coupler was placed at the end of each waveguide stick of each MESSENGER phased array. A semi-rigid RF cable was connected to each SMA jack, feeding an 8-way RF switch. The switch was thermal-vacuum (TV) rated for the temperatures expected within the TV chamber used during spacecraft testing. The switch position was commanded by the GSE selecting the RF signal from one of the waveguide sticks; this signal was routed back to the GSE for measurement. The semi-rigid cable for stick 1 of each array also had an additional 10-dB coupler attached prior to the switch. This coupler provided a reference signal for the GSE against which to compare signal phases.

6. TEST EXECUTION AND GSE DESCRIPTION

The goal of the spacecraft-level testing of the array is to calibrate the phased-array system and confirm proper pointing of the antenna beam. Proper operation is verified by mathematically reconstructing the antenna beam based on the radiated phases at each stick. The radiated phase can be calculated as the sum of two transmission measurements. Referring to the block diagram of Figure 6, the two measurements are (1) the relative phases at the coax-to-waveguide feeds, ϕ_{coax} (measured at the spacecraft level), and (2) the antenna element phase accumulation, $\phi_{antenna}$ (measured on the compact antenna range). The amplitude information for the individual antenna element patterns was taken from subsystem-level measurements. Using ϕ_{coax} and the previously measured element patterns, the phased-array antenna gain patterns were reconstructed using the following complex summation:

$$A(\theta) = \sum_{N=1}^{4,8} E_N(\theta) \cdot e^{j\phi_{coax\,N}} \;, \tag{1}$$

where θ is the angle from the antenna normal vector, E represents the individual element patterns (which include the individual radiated phase delay of each element, $\phi_{antenna}$), and A represents the complete half (N = 4) or full (N = 8) array pattern. As a matter of convenience, the reconstructed pattern was plotted in real time to give the integration engineer a validation of the commanded scan position. An example of the pattern reconstruction software is shown in Figure 7.

To measure the relative phase of the eight channels at the fully integrated level (with an X-band transponder), an HP 8410 network analyzer was used in the RF GSE because it allowed an external reference signal. An eight-way PIN diode switch was connected between the eight loop couplers and the test port of the network analyzer. The PIN diode switch provided a highly repeatable connection of the eight individual paths and, because of its very fast switching speed, permitted a fast assessment of phased-array system performance. The coupled port of the directional coupler in the path of channel 1 provides the reference signal needed for the network analyzer.

The initial calibration of the RF GSE and loop-coupler phase included measuring the phases presented to the coax-to-waveguide feeds with all the phase shifters in the SSPAs set to their zero-state, $\phi_{coax}\big|_{\phi_{shifter}=0}$. These phases were measured by connecting the network analyzer to the end of each cable feeding each coax-to-waveguide feed of each antenna element while referenced to a common stick feed. The results were normalized providing $\phi_{coax}\big|_{\phi_{shifter}=0}$, which described the relative phases delivered to a particular phased array when the phase shifters were zeroed. These results proved to be repeatable to within 13º (about half of a least-significant-bit). After this initial calibration, the final flight connections were made between the coax cables and the coax-to-waveguide feeds, preventing any future direct phase measurements at the ϕ_{coax} reference plane.

After this flight connection was completed, the RF GSE could measure only the relative phases sampled from the loop couplers for each stick, ϕ_{meas}. Referring to Figure 6, ϕ_{meas} is directly related to the desired antenna pattern, ϕ_{rad}, by a constant set of phases for the RF GSE. So, a second calibration was performed during each set of phased-array tests to quantify the RF GSE phases.

The second calibration related ϕ_{meas} to ϕ_{coax}. ϕ_{meas} was also measured by the RF GSE with all the phase shifters set to the zero state, $\phi_{meas}\big|_{\phi_{shifter}=0}$, denoted $\phi_{0\text{-}state}$, allowing a transfer function between ϕ_{coax} and ϕ_{meas} to be determined. With a known transfer function between ϕ_{coax} and ϕ_{meas} as well as knowledge of $\phi_{antenna}$, the desired antenna pattern could be mathematically calculated from ϕ_{meas} for any array pointing via $\phi_{shifter}$.

In addition to defining the RF GSE phase, $\phi_{0\text{-}state}$ also provided a reference for repeatability of the system. Since $\phi_{0\text{-}state}$ measured the relative phase at the output of the entire system (both the spacecraft and RF GSE), any variations in $\phi_{0\text{-}state}$ reflected a change in one of the spacecraft or RF GSE stages. $\phi_{0\text{-}state}$ was also normalized to remove the effect of typical variations that occurred as a result of changes in GSE cabling during I&T after the eight-way switch. But any

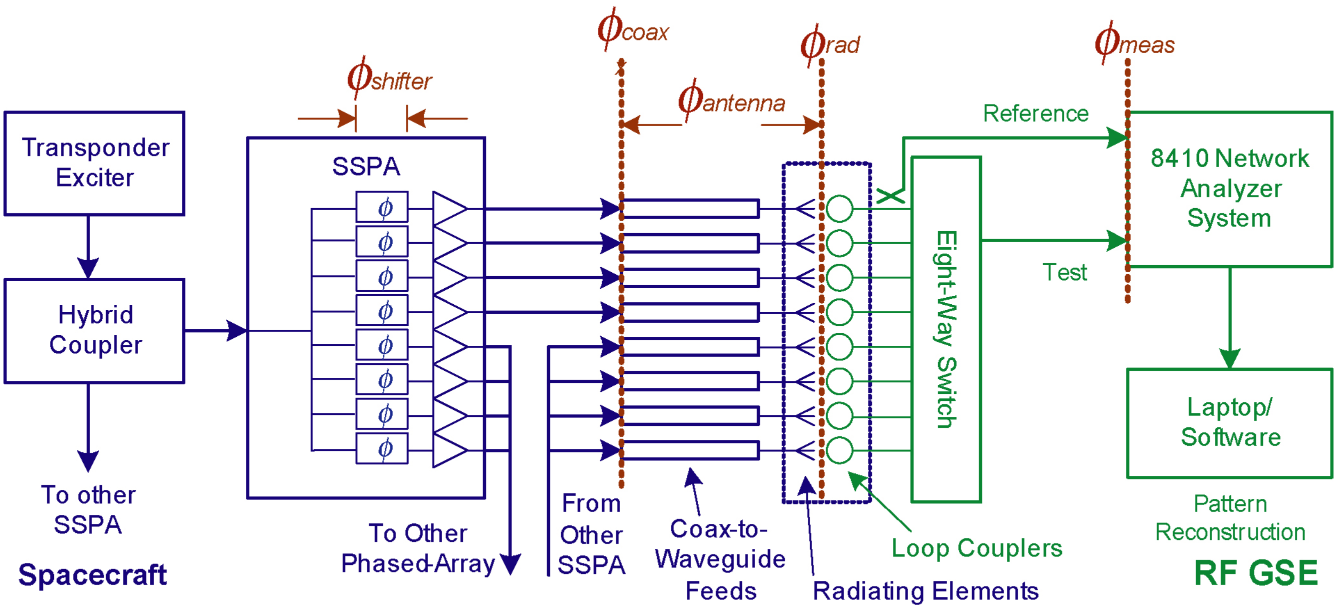
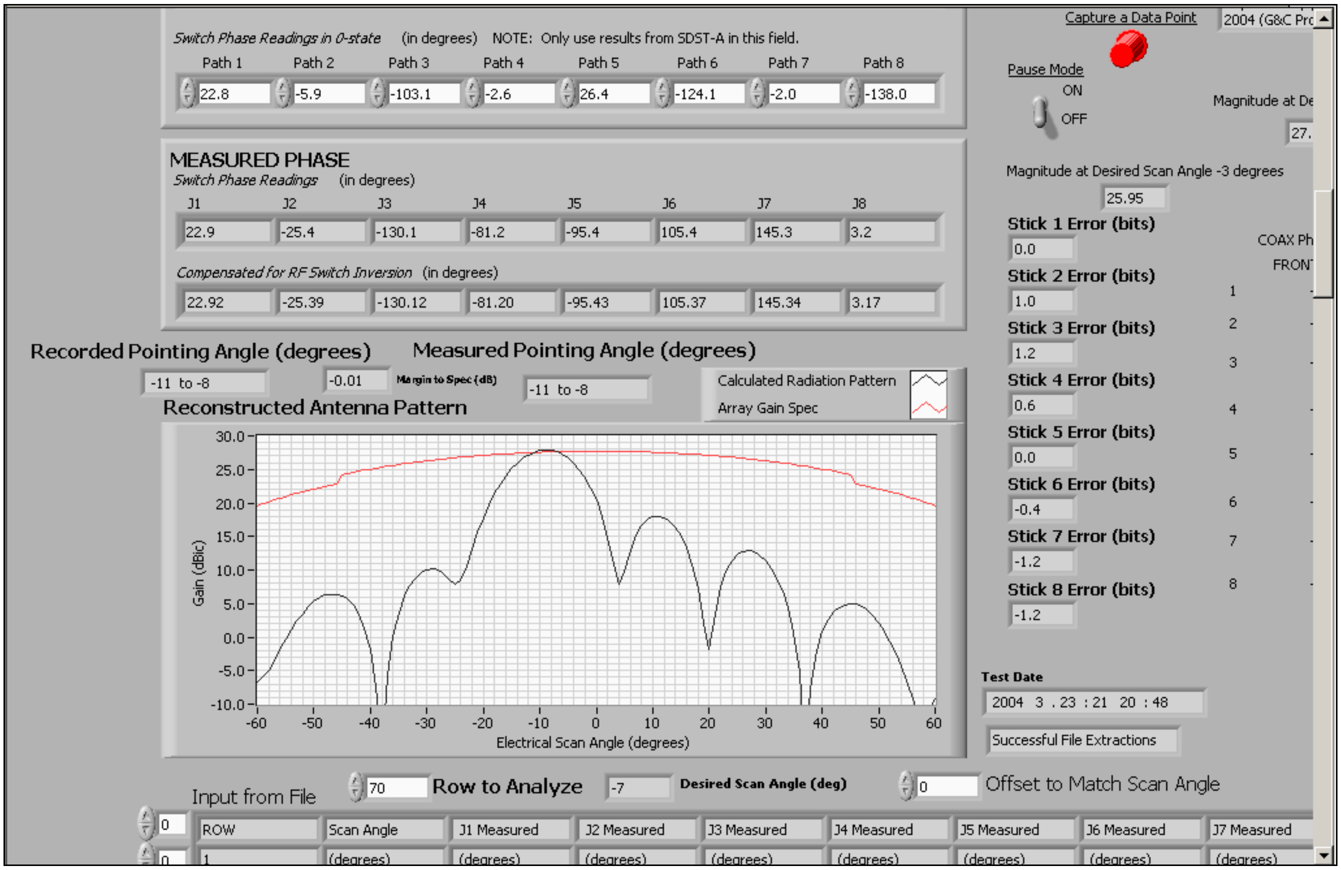


Figure 6. Phased-Array Measurement Technique.



Switch Phase Readings in 0-state (in degrees) NOTE: Only use results from SDST-A in this field.

Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8
22.8	-5.9	-103.1	-2.6	26.4	-124.1	-2.0	-138.0

MEASURED PHASE

Switch Phase Readings (in degrees)

J1	J2	J3	J4	J5	J6	J7	J8
22.9	-25.4	-130.1	-81.2	-95.4	105.4	145.3	3.2

Compensated for RF Switch Inversion (in degrees)

J1	J2	J3	J4	J5	J6	J7	J8
22.92	-25.39	-130.12	-81.20	-95.43	105.37	145.34	3.17

Recorded Pointing Angle (degrees): -11 to -8

-0.01 Margin to Spec (dB)

Measured Pointing Angle (degrees): -11 to -8

Reconstructed Antenna Pattern

2004 (G&C Prc

Magnitude at De: 27.

Magnitude at Desired Scan Angle -3 degrees: 25.95

Stick 1 Error (bits)	0.0
Stick 2 Error (bits)	1.0
Stick 3 Error (bits)	1.2
Stick 4 Error (bits)	0.6
Stick 5 Error (bits)	0.0
Stick 6 Error (bits)	-0.4
Stick 7 Error (bits)	-1.2
Stick 8 Error (bits)	-1.2

COAX Ph
FRON
1
2
3
4
5
6
7
8

Test Date: 2004 3 . 23 : 21 20 : 48

Successful File Extractions

Input from File

70 Row to Analyze

-7 **Desired Scan Angle (deg)**

0 Offset to Match Scan Angle

0	ROW	Scan Angle	J1 Measured	J2 Measured	J3 Measured	J4 Measured	J5 Measured	J6 Measured	J7 Measured
0	1	(degrees)	(degrees)	(degrees)	(degrees)	(degrees)	(degrees)	(degrees)	(degrees)

Figure 7. Reconstructed Pattern and GSE Control Screen.

ϕ variations within the unique paths of the spacecraft, phased array, loop couplers, or eight-way switch would force relative variations within $\phi_{0\text{-}state}$. Therefore, monitoring $\phi_{0\text{-}state}$ provided an indirect confirmation that $\phi_{coax}\big|_{\phi_{shifter}=0}$ had not changed over time.

Since the phased array test measured only phase, an amplitude calibration was also conducted during each test. Using a spectrum analyzer, the relative amplitudes were sampled at the output of the eight-way switch. This also checked for relative variations within the unique paths of the spacecraft, phased array, loop couplers, or eight-way switch.

After completion of the calibrations, the antenna pattern was tested. $\phi_{shifter}$ was set for a corresponding array pointing angle via the beam steer table. The RF GSE sampled all 8 phases from the phased array and processed the reconstructed antenna pattern as shown in Figure 7. The GSE software displayed the antenna pattern and indicated the peak of the pattern for a visual agreement with expected results. This process was repeated for a set of test angles to complete an entire phased-array test.

7. SUMMARY OF RESULTS AND CONCLUSIONS

In actual use during MESSENGER I&T, the RF GSE phased-array testing required little time after calibrations were complete. The tests confirmed the angle of the peak amplitude from the reconstructed antenna pattern and provided test calibration values. After an initial calibration, these test calibration values tracked for any variations in the spacecraft over the I&T period.

Because the test was so fast, each MESSENGER phased array was tested 12 times during the I&T period. The calibrations of $\phi_{0\text{-}state}$ and the amplitude variations of all 8 sticks required less than 30 minutes to complete. The antenna pattern at any particular angle took only a few seconds once $\phi_{shifter}$ was set. This allowed phased-array tests to be conducted both before and after spacecraft vibration tests and transport to different locations. In addition, each array was tested at various temperature conditions inside a TV chamber.

For each of the 12 tests, the measurement of the desired antenna pattern, ϕ_{rad}, was collected at three separate pointing angles. Additional testing included pointing at all possible angles of the array; these were repeated four times. For all of these measurements of ϕ_{rad}, the resultant antenna pattern produced a peak within ±1° of the selected pointing angle. This matched the expected scanning resolution of 1° discussed in Section 2. So all measurements of ϕ_{rad} matched the expected design performance over all the environmental tests.

Furthermore, the calibration data varied only a small amount over all 12 tests. $\phi_{0\text{-}state}$ typically repeated within a range of ±10°, with an occasional peak that spread over ±23°. This latter spread corresponds to about double the quantization of the phase shifters, or ±1 bit. Amplitude typically repeated within a range of ±1 dB. (Once a 10-dB shift was observed, which led to the detection of loose mounting screws associated with a particular loop coupler.) So in addition to the accuracy of the measured antenna patterns, the repeatability of $\phi_{0\text{-}state}$ confirmed that the MESSENGER flight hardware performed as designed after vibration and transport as well as during the temperature extremes of TV.

This methodology of testing the MESSENGER phased-array systems provided a relatively quick test that could be performed multiple times and during the TV environments. By depending upon the RF GSE loop and hat coupler, the standard test configuration of the spacecraft readily supported the phased-array test without the need to free radiate. The multiple repetitions of the test provided enough statistics to look for error trends in the calibration data as well as confirm the reconstructed antenna pattern pointing. This methodology both confirmed the operation of the phased array and met the speed and safety requirements of the I&T environment.

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BIOGRAPHIES

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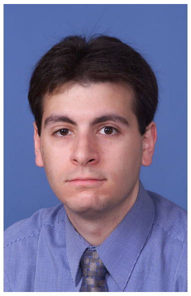

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