Methods for Testing the Mars Science Laboratory's Landing Radar

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***Abstract*— The Mars Science Laboratory's rover named Curiosity successfully landed on Mars on August 6, 2012. One component of the Mars Science Laboratory (MSL) Entry, Descent, and Landing (EDL) system was the Terminal Descent Sensor (TDS) landing radar. In this paper we describe laboratory testing of this radar performed before launch.**

I. Introduction

The Mars Science Laboratory (MSL) Terminal Descent Sensor (TDS) was a pulse-Doppler, Ka-band (35 GHz) radar used to produce radial velocity measurements with decimeter-per-second accuracy and range measurements with up to 20 cm accuracy during the entry, descent, and landing (EDL) of the spacecraft on Mars. Figures 1 and 2 are photographs of the topside of the radar where the electronics are mounted and the bottom side of the radar where the six antennas are mounted. Since the radar itself has been described previously [1], only those aspects of the radar central to its testing will be reviewed here.

The radar was expected to operate at ranges between 10 m and 10 km. This posed two challenges for the test equipment. Firstly, it implies almost 100 dB of variation in the power of the return the radar sees. This large variation was compounded by uncertainty in the Ka-band scattering coefficient of Mars. Secondly, the small minimum range provided very little time after the end of the transmit event for the test equipment to generate a return to feed into the radar.

Over the 50 ms period when data were accumulated to make an individual range and radial velocity estimate, the radar could adaptively select uncoded pulses as short as 4 ns or as long as 16 μs. Only one of the six beams was active at a time, and the sequence used to cycle through the beams was commandable. One of the antennas was pointed at nadir, and three of the antennas were oriented to allow a three dimensional reconstruction of the spacecraft position. An additional two antennas were canted forward of the vehicle so that they would not be blocked when the rover was lowered during the Sky Crane maneuver.

The radar's operational environment was unusual. The radar's full, operational, transmitting lifetime was approximately 2 minutes during the EDL in the cold, thin Martian atmosphere. In addition, it has to work properly. Had the radar failed, it would have resulted in the loss of the $2 billion MSL mission.

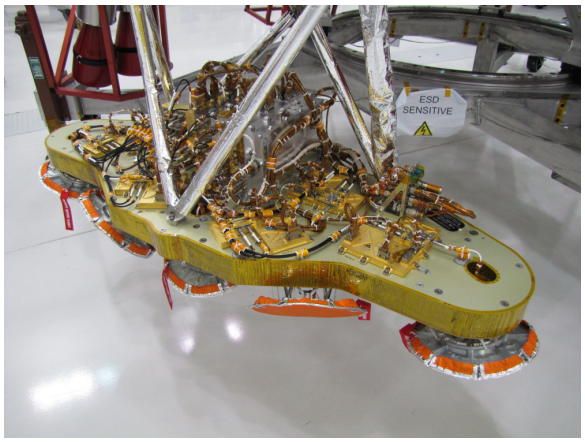

Fig. 1. Photograph of the flight model TDS. Orange "shower-caps" cover the slot antennas.

From the time that the heat shield was released allowing the radar's antennas a clear view of Mars to the successful landing of the rover on the Martian surface, the radar received only four commands from the spacecraft: two to change modes and two to change beam sequences. The radar, and in particular the Radar Processor Field Programmable Gate Array (FPGA), was responsible to command and control all the parts of the radar to make the measurements properly including the on-board processing converting the digitized range samples into radial velocity and range estimates. These internal command, control, and processing functions had to be verified extensively.

II. Ground Support Equipment

A large amount of Ground Support Equipment (GSE) was utilized to test the radar stand alone and after it was integrated to the spacecraft. In this section we will list most of it and highlight each piece's capabilities.

A. Mechanical Ground Support Equipment (MGSE)

- The moving target assembly included a servo motor and a collection of pulleys which allowed a small corner reflector to be moved at a variety of known, low (≈3 cm/s) velocities. The corner reflector could be mounted on a skateboard and pulled horizontally or mounted to move vertically. After running the radar for a short amount of time, the servo motor was stopped, and the distance from

Fig. 2. Photograph of the flight model TDS while mounted on the descent stage during a fit check with the Curiosity rover. Orange "shower-caps" cover the radar's six slot antennas. The radar's silver thermal blanket is installed.

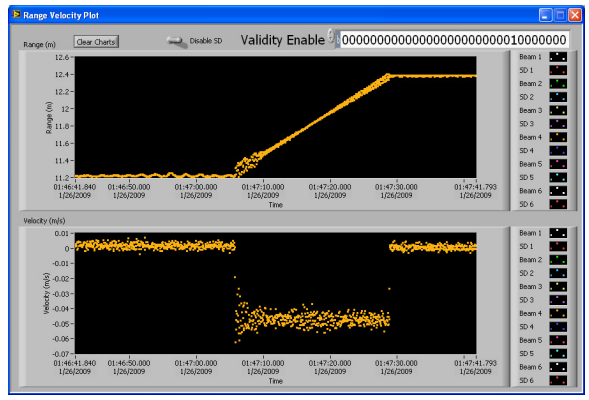

Fig. 3. A screen capture from the operator's work station showing the range and velocity reported by the radar during a moving target test when the servo motor was commanded to 5 cm/s.

the radar to the target was measured with a tape measure to verify the radar's range measurements. Figure 3 shows the ranges and velocities reported by the radar during a test using the moving target assembly.

- The cart mounted reflector consisted of a small corner reflector mounted on a hand-pushed cart and surrounded by 1.5 m^2 of absorber to hide the cart and the operator pushing the cart. This was used for functional check out such as checking the antenna beam mapping and the Doppler sign after the radar was electrically integrated to the spacecraft.
- The RF absorbing covers were a set of Faraday cages lined with absorber. Each antenna had its own RF absorbing cover which fit over only it. These were used to reduce stray signals leaking into the antennas and to allow personnel to work near the radar while it was transmitting.
- Shower caps were covers made of orange thermal-blanketing material fit over each antenna to keep dust out of the antenna slots.
- An antenna hat was made by taking a copy of one of the RF absorbing covers, installing a spare TDS antenna on the inside of the cover, and connecting that antenna to a waveguide-to-coax adapter mounted in a hole cut in the cover. The antenna hat was useful for functional testing but was of limited use for performance testing due to the reflections and interactions between the antenna under test and the antenna which was part of the hat.
- The rotation fixture was a Commercial Off the Shelf (COTS) item with custom adapters to hold the TDS. The TDS has no flat sides to allow it to be placed on the ground or on a bench.
- Sets of cross bars and legs were made which attached to the TDS and allowed it to be placed on a flat surface when the rotation fixture was unavailable.
- A special fixture was made to hold the TDS to the shaker table for dynamics and vibration testing.
- A special fixture was made to hold the TDS inside the chamber used for thermal-vacuum testing.
- A shipping container was customized to safely transport the radar between test locations.

B. *Electrical Ground Support Equipment (EGSE)*

- The TDS RF Target Simulator generated point targets which were used to stimulate the radar during testing. The point targets could be delayed, adjusted in amplitude, and Doppler shifted. Sequences of pulses with different characteristics could be played back allowing simulation of a full EDL. The TDS RF Target Simulator was a mixture of custom and COTS equipment.
- The Test Controller emulated the spacecraft's power and Command and Data Handling (C&DH) interface to the radar. All commands sent to and all packets sent from the radar were logged. The primary C&DH interface between the radar and the spacecraft was 1553B. In addition, this unit was the main command interface for the TDS RF Target Simulator and logged information regarding every pulse generated by the TDS RF Target Simulator. Figure 4 shows an example of part of the display seen by the operator during a simulated descent. The Test Controller also provided common clock signals that were distributed throughout the test equipment.
- The Fiber Optic Delay Line (FODL) had a fixed 8 km range delay. The FODL did not apply any Doppler shift to the pulses transmitted by the radar.
- The Coax Delay Line (CDL) was a collection of coax cables, a circulator, and two isolators which could be configured to reroute the radar's transmitted pulse to provide a variety of short, fixed range targets with no Doppler shift. The CDL provided a simple, portable way to test the radar end-to-end.
- The Transmit Monitoring and Switch Assembly (TMSA) contained a detector for measuring pulse power and a series of switches to route signals to and from various test equipment.
- COTS test equipment (spectrum analyzers, oscilloscopes, etc.) were used, particularly for analysis of the transmitted pulse characteristics.

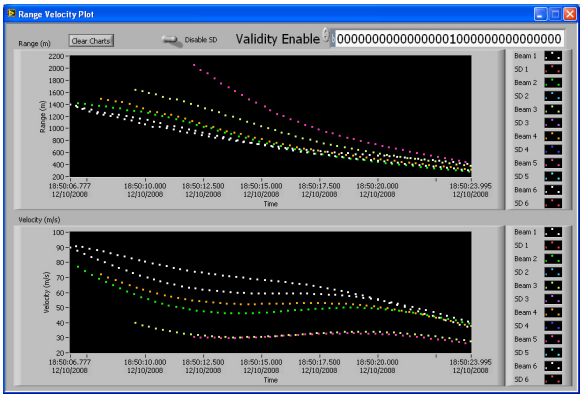

Fig. 4. A screen capture from the operator's work station showing the range and velocity reported by the radar during part of a simulated descent. The different colors represent the different beams.

- The Data Quality Analyzer captured the digitized radar return range samples for all the radar pulses. The pulses were then transferred to another computer where they were automatically processed using both a floating point and a pseudo-fixed point version of the code in the on-board processor. The three results were then compared and an automated report generated if discrepancies were found.
- The radar had survival heaters to keep it warm enough during the cruise to Mars, and platinum resistance thermometers (PRTs) to monitor the radar's temperature. GSE was built to provide power to the heaters, log the heater power draw, and log the PRT temperatures during thermal-vacuum testing.

III. Radar Ground Test Accommodations

Modifications were made to the radar design to support ground testing.

A 23 dB coupler was added between the Transmit/Receive module and the antenna for each beam. The vast majority of the radar testing was performed with the RF absorbing covers installed on the antennas and the test equipment connected via the antenna coupler. The antennas' patterns had been measured individually and again when mounted in their flight configuration before integration with the radar electronics. The antennas have been described previously [2].

The special test mode, called Identical Pulse Train, was added to the modes supported by the radar. The radar's normal operating modes cycle through a variety of different pulse widths, pulse repetition intervals, and attenuator settings over the 50 ms when an observation is made. In the Identical Pulse Train mode the radar was held with a fixed pulse width, pulse repetition interval, and attenuator setting until commanded to leave the mode. This test mode was needed to make RF measurements of the transmit pulse characteristics. No range or velocity estimates were produced in this mode. The radar always had to be pulsed and was not capable of transmitting continuous wave.

A test port was added to the radar's Digital Electronics Assembly which allowed its Radar Processor FPGA to output radar settings, to announce 1 μs in advance that a pulse would be transmitted, and to output digitized range samples. The radar state information and the announcement that a pulse would be transmitted were sent to the TDS RF Target Simulator. The TDS RF Target Simulator used these to generate a return for the radar after logging the data. The digitized range samples were captured by the Data Quality Analyzer.

A test port provided a copy of the radar's Frequency Synthesizer Assembly's base 125 MHz clock signal. This was monitored and logged to make sure that the radar's clock was not drifting. Also this 125 MHz clock signal was provided to the TDS RF Target Simulator to synchronize the target generation with the radar.

IV. Simulating a Descent

The RF Target Simulator was used to verify the radar's performance during simulated descent profiles. A variety of descent profiles were generated testing the radar's performance and degradation of performance in a variety of conditions. Below we outline how this testing was done.

- **Design Spacecraft Descent Profile** The first step was to construct a descent profile with the spacecraft position, orientation, velocity, and acceleration as a function of time in addition to the mounting of the radar antennas relative to the spacecraft coordinate system. Sometimes the profiles were physical and based on EDL simulations. Other times the profiles were pathological to examine particular aspects of the radar's performance.
- **Select Terrain Topography and Scattering Coefficient Curve** A Digital Elevation Model (DEM) and scattering coefficient as a function of incidence curve were selected. Over the range of profiles, we tested both very bright and very dim back-scatter profiles to investigate the impact of low signal to noise ratio (SNR) and of saturation.
- **Calculate Radar Descent Profile** The next step was to calculate the position of the center of the beam on the surface from the spacecraft position, spacecraft orientation, and the terrain topography. Then the range and the Doppler frequency were calculated. Finally the software calculated the back-scattered signal amplitude using the orientation of DEM facets contributing to the return to calculate incidence angle for look up into the back-scatter curve and finding the size of area illuminated on the ground from the beam pattern and range bin size. These calculations were done for all beams, for all possible radar parameters, for the whole profile typically with a 50 μs time step.
- **Upload Radar Descent Profile to the RF Target Simulator** Because the computation to calculate the radar descent profiles was significant, the profile calculation was done on a separate computer system and uploaded to the RF Target Simulator.
- **Start Radar** Via the 1553B interface using the same commands that the spacecraft uses to communicate with

the radar, the EGSE brought the radar up, verified the configuration parameters loaded in the radar, specified a beam sequence, specified a radar mode, and had the radar start collecting data.

- **Run Profile** For every pulse the EGSE would:
  - **Receive Transmit Trigger Signal** This signal indicates that the radar is going to transmit a pulse. As discussed in Section III this signal comes 1 μs before the transmit pulse.
  - **Read Direct Access Radar Parameter Data** The RF Target Simulator received directly from the radar the direct access radar parameter data including (a) the beam number being used and (b) the radar parameter set. With this, the RF Target Simulator then looked up the transmitted pulse width corresponding to that radar parameter set. The EGSE time tagged the Transmit Trigger Signal and logged the direct access radar parameter data.
  - **Check Time** The index into the radar descent profile is time, so the test equipment needed to check what time it is.
  - **Look Up Return Characteristics in Radar Descent Profile** From the direct access radar parameter data, the RF Target Simulator knew the transmitted pulse width. From the radar descent profile, the RF Target Simulator knew the range to delay the pulse by, the Doppler frequency to apply to the returned pulse, and the amplitude for the radar return.
  - **Send Simulated Return to Radar** Having calculated the characteristics of the return, next the RF Target Simulator generated a return with the appropriate characteristics. Key to this process was receiving the Radar Clock to ensure that the generated pulse has the same phase reference as discussed in Section III.
  - **Log Data** The EGSE received the radar's range and velocity measurement packets and other telemetry via the 1553B. The Test Controller logged this data for *a posteriori* analysis. The radar measurements are not used for decision making during a profile.
- **Shutdown Radar** When the profile ends, the EGSE commands the radar to stop collecting data and to shutdown cleanly.
- **Compare Range and Velocity Estimates from Radar with "Truth"** This step was done on a separate analysis computer due to the computational load of the comparison and the desire to not tie the EGSE up with analysis.

Designing, building, and testing the RF Target Simulator posed both digital and RF challenges. The unit had to generate pulses as short as 4 ns with different range delays, amplitudes, pulse widths, and Doppler shifts as frequently as every 50 μs. The requirements on the accuracy of the Doppler shift correction applied were strenuous given the radar's required radial velocity performance.

V. Transmitter and End-to-End Testing

The testing with the RF Target Simulator described in Section IV involves the EGSE generating a radar return. We decided to generate a return (instead of distorting, delaying, and feeding back the transmitted pulse) due to the short time to do this given the 10 m minimum range. Although the simulated descents were excellent for testing the receivers and the processing, they did not test the transmitter and did not test the end to end phase fidelity of the radar system.

The characteristics of the transmitted pulses such as pulse shape were measured primarily at the sub-assembly level before the RF electronics were integrated to the rest of the radar. The TMSA was used to measure transmit power and to route signals to commercial test equipment as described in Section II.

The end-to-end radar performance was tested using the fiber optic delay line, the coax delay line, and the moving target assembly. An additional benefit of the moving target assembly was its ability to verify the sign of the radial velocity estimates produced by the radar. Doing this with electronics can be difficult since sign flips in the electronics can mask sign flips in the unit under test.

VI. Conclusion

A variety of MGSE and EGSE were used to test the TDS landing radar. The core tests performed were the simulated descents where the electronic ground support equipment feed the radar simulated returns that matched what would be expected during the actual EDL. Thousands of simulated descents were run with a diversity of input assumptions.

All of the testing of the radar in the laboratory involved point targets. The radar's performance with distributed targets was covered during a field test campaign on an engineering units since the flight unit could not leave clean room conditions. The field test campaign has been described elsewhere[3]. The laboratory testing with point targets was used to prove that the engineering model radar was functioning properly before the field test campaign, to prove that the flight model radar was functioning properly, and to boot strap the expected performance between the engineering model and the flight model of the radar.

Acknowledgment

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