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IMPLEMENTING THE MARS SCIENCE LABORATORY TERMINAL DESCENT SENSOR FIELD TEST CAMPAIGN

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The Mars Science Laboratory (MSL) will deliver a 900 kg rover to the surface of Mars in August 2012. MSL will utilize a new pulse-Doppler landing radar, the Terminal Descent Sensor (TDS). The TDS employs six narrow-beam antennas to provide unprecedented slant range and velocity performance at Mars to enable soft touchdown of the MSL rover using a unique sky crane Entry, Descent, and Landing (EDL) technique. Prior to use on MSL, the TDS was put through a rigorous verification and validation (V&V) process. A key element of this V&V was operating the TDS over a series of field tests, using flight-like profiles expected during the descent and landing of MSL over Mars-like terrain on Earth. Limits of TDS performance were characterized with additional testing meant to stress operational modes outside of the expected EDL flight profiles. The flight envelope over which the TDS must operate on Mars encompasses such a large range of altitudes and velocities that a variety of venues were necessary to cover the test space. These venues included an F/A-18 high performance aircraft, a Eurocopter AS350 AStar helicopter and 100-meter tall Echo Towers at the China Lake Naval Air Warfare Center. Testing was carried out over a five year period from July 2006 to June 2011. TDS performance was shown, in general, to be excellent over all venues. This paper describes the planning, design, and implementation of the field test campaign plus results and lessons learned.

INTRODUCTION

The Mars Science Laboratory (MSL)[‡‡‡] Terminal Descent Sensor (TDS) is a new sensor developed at the Jet Propulsion Laboratory (JPL) in Pasadena, CA.[1] It is a pulse-Doppler, Ka-band (35.75 GHz) radar. It provides both velocimetry and range measurements at 20 Hz. It is composed of six independent slotted-waveguide antennas that are oriented in various azimuths and elevations. The TDS is mounted on a pro-

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boscis on the MSL Descent Stage (DS) that provides clear line of site for each antenna when the Curiosity rover is stowed under the DS. When the DS attitude is level, one TDS antenna is aligned with nadir, 3 antennas have 20° elevation relative to nadir and are separated by 120° in azimuth and two antennas have a 50° elevation relative to nadir. The latter two are separated in azimuth by 60° and look out in front of the DS, away from the rover. This ensures clear line of sight for at least two antennas during the sky crane maneuver when the Curiosity rover is lowered to the Martian surface from the DS. The TDS includes both RF and digital electronics and communication with the spacecraft is via a MIL-STD-1553B bus.

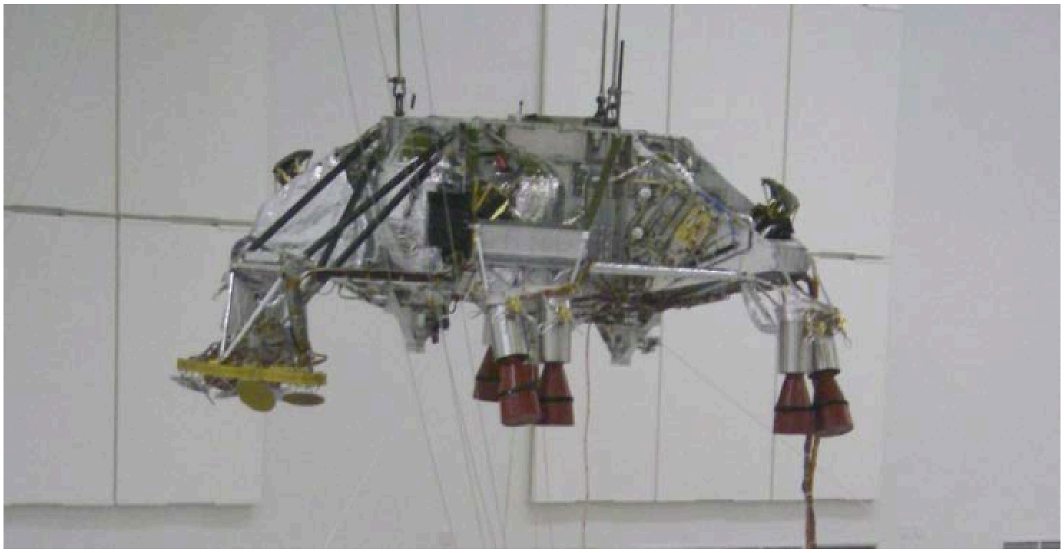

Figure 1. MSL Descent Stage and Terminal Descent Sensor

The MSL DS with the TDS mounted via the proboscis (left side of image) is shown in Figure 1 at JPL. The TDS electronics are mounted on top of a flat honeycomb "surfboard" structure with the six antennas mounted on the underside of the structure.

The MSL TDS Field Test campaign was one component of a larger TDS verification and validation (V&V) effort. This V&V effort also included testing TDS hardware in a lab environment using Electrical Ground Support Equipment (EGSE) as well as using both software-only and hardware-in-the-loop simulations. Each component has strengths and weaknesses that complement each other, allowing a more thorough V&V effort. The lab and simulation components are outside the scope of this paper and will not be discussed further. The primary goal of the field test campaign was to collect time-stamped TDS and ground-truth data using representative and stressing flight EDL profiles over "Mars-like" terrain. Both breadboard (BB) and Engineering Model (EM) TDS radars were tested. This data was used for post-test TDS performance assessment and model validation. A two-pronged approach was used to devise the field test campaign; a Test-As-You-Fly (TAYF) and "Worry Bead" approach.

In the TAYF approach, the flight envelope of the TDS operations was defined for a range of landing sites, entry conditions and entry performance via a number of parameters, including altitude, surface relative velocity, surface off-vertical TDS antenna angles, angular rate, surface topography and backscatter. Flight envelope boundaries for candidate landing sites were determined via Monte Carlo EDL simulations performed at the NASA Langley Research Center and test venues identified to cover the resulting envelope during the EDL timeline. [2] This timeline includes the parachute descent, powered descent and sky crane portions of EDL. [3] During parachute descent, the spacecraft decelerates from over 450 m/s at parachute deployment down to ~100 m/s at backshell separation. During this time, the heatshield is jettisoned and the TDS begins acquisition of the Martian surface in preparation to trigger backshell separation and powered descent. Powered descent is triggered when the spacecraft determines its altitude is 1.5 to 2 km above ground level (AGL) and has a velocity ~100 m/s as measured by the TDS. During powered descent, the

DS will fire 8 Mars Lander Engines (MLEs) to slow down to ~0.75 m/sec vertical velocity and ~0 m/sec horizontal velocity at an altitude of ~20 m AGL at which time the sky crane maneuver begins. Sky crane is a new technique that replaces the air bag approach used for Pathfinder and the Mars Exploration Rovers. During sky crane, the Curiosity rover is lowered on a bridle from the slowly descending DS. Once the rover is on the surface, less thrust is required of the MLEs and this reduced thrust is sensed by the control algorithms. At this point, the bridle is cut and the DS flies away from the rover, leaving Curiosity safely deployed on the surface of Mars.

The TAYF areas of the EDL timeline tested included 1) premature powered descent start, 2) powered descent start trigger, 3) powered descent flight envelope, 4) sky crane flight envelope and 5) integrated sensor validation. For 1) and 2) the tests focused on verifying that the TDS would meet its requirements for triggering powered descent at the proper altitude during parachute descent, 3) and 4) were focused on probing TDS performance within the corresponding envelopes and 5) was concerned with validating the TDS as an integrated sensor in the field.

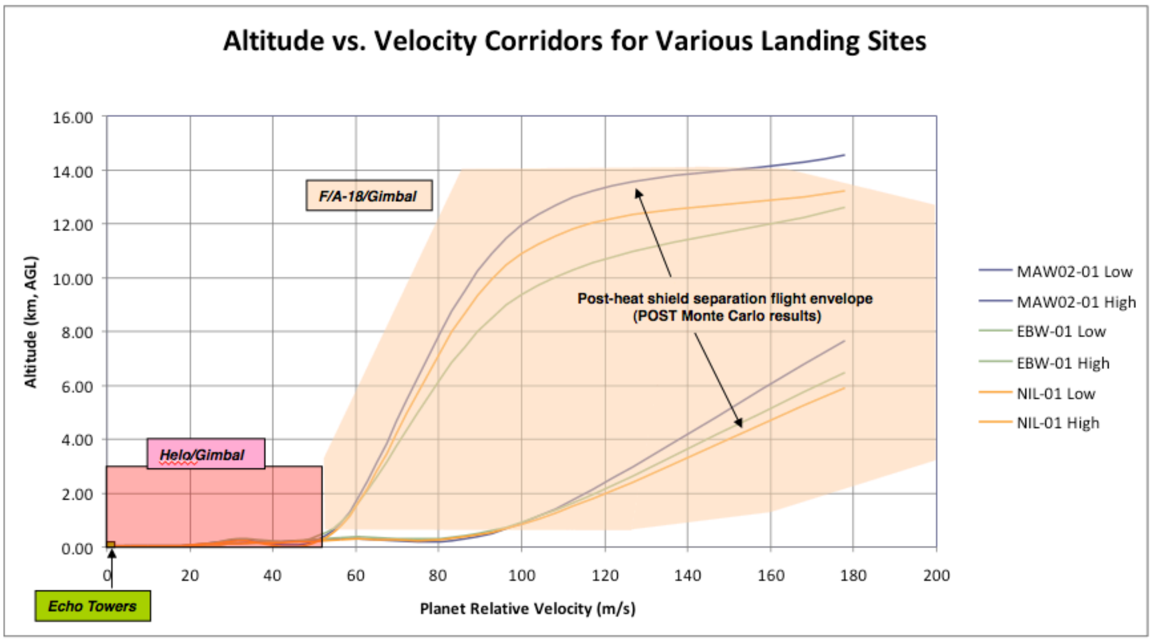

Figure 2. Altitude vs Surface Relative Velocity Envelope.

Flight envelope coverage by the three test venues is shown in Figure 2. In this example, minimum and maximum altitude boundaries above ground level (AGL) were determined for three candidate landing sites on Mars**;** Mawrth Vallis, Eberswalde Crater and Nili Fossae Trough**.** The TDS cannot operate through MSL's heat-shield, so the high altitude boundary is determined by the heat-shield separation time and the elevation of landing site (the lower the landing site elevation, the higher the altitude above ground level the TDS will be operating). Note that these landing sites encompass the EDL capability of MSL for all sites including Gale Crater, the site ultimately chosen. Boundaries for the remaining parameters were also defined and envelope coverage by venue determined. Although a fairly thorough coverage was achieved, it was not always possible to meet all flight conditions simultaneously. In particular, it was difficult to achieve the maximum desired vertical velocity for the lower portion of the flight envelope using the Echo Towers and helicopter. The lab-based EGSE and TDS simulations helped address this limitation.

For the "Worry Beads", potential TDS-specific and TDS/NAV Filter (Navigation Filter) performance limitations were identified and stress tests devised that, while not necessarily flight-like, created conditions that increased the probability of the limitation occurring. This increased understanding of the real-world behavior of the TDS and NAV Filter, explored the limits of TDS performance, and tested areas of EGSE and/or model limitations by providing real-world TDS performance data for cross-checking.

TDS-specific "Worry Beads" included:

WB1. Is our understanding of how range ambiguities occur correct?

WB2. Is our understanding of how velocity ambiguities occur correct?

WB3. Surface acquisition characterization at high altitude, attitude and attitude rate

WB4. Range and velocity performance characterization at low altitude and horizontal velocity

WB5. What is the impact of antenna sidelobes on the velocity bias over real terrain?

WB6. What is the impact of different, more challenging terrains on performance?

TDS/Nav Filter "Worry Beads" included:

WB7. Verify NAV Filter data editing design and robustness when TDS data is out of spec

WB8. Validate NAV Filter design with real sensor data

Field Test Venues

An extensive trade-study was carried out in 2007 that developed the two-pronged TAYF and "Worry Bead" approach described above and determined the baseline venues required to test them. Four general venue types were examined; three types that could cover the low-altitude, mid-altitude, and high-altitude regions and a fourth that could cover the entire altitude profile. Three test venues were selected, the China Lake Echo Towers, a Eurostar AS350 AStar helicopter provided by a commercial vendor and a NASA/Dryden Flight Research Center (DFRC) F/A-18 located at Edwards Air Force Base (AFB). The first two venues had supported BB TDS field testing in 2006 and provided an early verification of the TDS measurement concept. The final venue was required to complete coverage of the TAFY envelope and worry beads. All three venues were used to complete testing with the EM TDS.

The Echo Towers are a pair of 100-meter tall wooden towers with a cable strung between them. A pulley was centered on the cable between the two towers. Another cable was then strung through the pulley with one end connected to the test system and the other end attached to a ground vehicle, which was used to raise and lower the test system vertically between ~5 m and ~70 m AGL. The test system in this case was a single-antenna version of the TDS that could be set to fixed angles relative to nadir. This was the primary venue for assessing extremely low altitude and velocity performance right before landing. The primary limitations associated with this venue were 1) testing was limited to the terrain beneath the system and 2) the inability to achieve vertical descent speeds approaching those expected during landing (typically achieved ~2 m/sec vs expected speeds of, for example, ~20 m/sec at ~55 m AGL).

Helicopter testing covered the lower altitude and velocity portion of the envelope with both a single and full six-antenna versions of the TDS mounted on a single-axis (pitch) gimballed platform. In addition, deployment of a rover mock-up on a winch system mounted on the helicopter allowed characterization of any TDS interactions with the rover when it is lowered during sky crane. As the only venue with the full six-antenna TDS, this was the primary venue for assessing integrated TDS sensor performance, verifying NAV filter data editing (eliminating spurious data), and validating NAV filter design. It also provided a venue for testing over a richer set of terrain types. The main limitations associated with this venue were that 1) the altitude was constrained to ~3 km above sea-level and 2) the very limited vertical velocities (~5 m/sec descent rates).

The F/A-18 configuration tested the radar under high-altitude, high-velocity conditions with a single-antenna TDS mounted on a single-axis gimbal inside a wing-mounted pod. This was the only venue capable of achieving on-chute TAYF flight conditions. It also allowed the greatest coverage in terms of velocity and altitude. The key limitation for this venue was difficulty in matching descent profile as a function of velocity versus altitude given the steep MSL flight path angles. An aircraft speeds up as it descends in a dive, while MSL slows down during parachute descent and powered descent. The F/A-18 was able to achieve desired flight conditions for limited (~5-10 seconds) periods of time. Fortunately, the TDS has a design feature that allowed testing of the envelope in a piece-wise fashion. The TDS operates at 20 Hz and each individual measurement is independent of prior measurements. For each measurement, the TDS acquires the surface anew. Multiple cuts through the envelope were taken for numerous combinations of flight-like parameters and data analysed independently. In addition, the lab EGSE and TDS simulations provided more extensive testing of these flight conditions. The F/A-18 had the additional challenge of extreme temperature and flight dynamics. There were large ambient temperature variations outside the pod over the flight envelope (from +35°C and greater at ground level to approximately -50°C at maximum altitude) that had the potential to exceed allowable temperatures for system components and/or risk condensation in the pod. The pod that contained the test system was unpressurized and non-hermetically sealed, so mitigations were required. Finally there were concerns that vibration could exceed test system limits. Consequently, an extensive environmental qualification effort was required to certify the pod's Environmental Control System (ECS) prior to field testing the system.

Two additional venues were considered. A parachute drop test system was examined as a possible venue to cover the entire altitude profile. Also, a helicopter with a winch-based system like that used to test the JPL Mars Phoenix landing radar was examined that could raise and lower the TDS on a cable. [4] It would provide higher vertical descent velocities at lower altitudes than could be provided with the other venues. It was determined that the V&V of the TDS could be adequately performed without these latter two venues. However, contingency plans were put in place to allow additional venues to be added if testing revealed holes in the field test, EGSE and simulation program, but this turned out to not be the case.

Table 1. TDS/NAV Filter Worry Bead and TAYF Coverage vs Venue.

	Worry Bead/TAYF \ Venue	FT5m Echo Towers 1 antenna, 3 fixed angles	FT6d Helicopter, 6 antenna, gimbaled	FT8.1 F/A-18 1 antenna, gimbaled	Covered?
Worry Bead	WB1: Range ambiguities	Can't achieve slant range >= 12.2 km	Can't achieve slant range >= 12.2 km	PRIMARY	
Worry Bead	WB2: Velocity ambiguities	Can't achieve maximum velocities	Can't achieve maximum velocities	PRIMARY	
Worry Bead	WB3: Acquisition	Can't achieve velocity, altitude or attitude rate	Can't fly >= 3000m AGL	PRIMARY	
Worry Bead	WB4: Low Altitude Performance	PRIMARY	Poor Velocity Control	Can't fly at low velocities	
Worry Bead	WB5: Sidelobe Impact	Can't achieve horizontal velocities	PRIMARY	Limited Antenna Attitude Control	
Worry Bead	WB6: Terrain Impact	Requires Terrain Modification	PRIMARY	Assumes we can fly over a variety of terrain types	
Worry Bead	WB7: Verify NAV Filter Data Editing Design/Robustness	Can't generate bad data to verify data editing	6-antenna real world, low altitude in and out of lock	One antenna informs model, high altitude in and out of lock	Requires union of two venues
Worry Bead	WB8:Validate NAV Filter Design with Real Sensor Data	Flight like data set for skycrane performance	Flight like data set for powered descent performance	Flight like data set for parachute descent performance	Requires union of three venues
TAYF	Parachute Descent Flight Envelope (Premature Powered Descent Start)	Can't operate >= 70m AGL	Can't descend >= 5m/sec	One antenna informs model, high altitude in and out of lock	
TAYF	Parachute Descent Flight Envelope (Powered Descent Start Trigger)	Can't operate >= 70m AGL	Can't descend >= 5m/sec	One antenna informs model, high altitude in and out of lock	
TAYF	Powered Descent Flight Envelope		Can only match limited descent trajectories		
TAYF	Sky Crane Flight Envelope	PRIMARY			
TAYF	Integrated Sensor Validation	Limited dynamics	PRIMARY	Only 1 antenna	

Legend
Covered Unconditionally
Assumptions, Caveats, Conditions
Not Covered

No single venue could provide complete coverage, but each complemented the others to allow unconditional coverage except for the Powered Descent Flight Envelope, as shown in Table 1. This is due to the limited vertical descent velocity in this part of the flight envelope as discussed above. Again, the EGSE and TDS simulation cover this inadequacy. With test objectives and venues identified, detailed field test campaign planning began.

FIELD TEST CAMPAIGN SUMMARY

The TDS field test campaign was extensive both in number and diversity of tests with planning and execution carried out over a 5-plus year period (first test occurring in July 2006 and the last in June 2011). A summary of all testing is given in Table 2.

Table 2. Field Test Campaign Summary.

Test Objective	Test Type	Original Date as of May 2007 Plan	Actual Execution Date	Antenna	TDS Elec.	IMU	Data Acq.	Power Supply	Notes
BB antenna test series	Echo Tower (FT1)	Already Completed	Jul 2006	1 COTS	BB	LN200	CDSU-1	Battery	1 COTS antenna configuration mounted on adjustable pitch fixture
	Helicopter (FT2)	Already Completed	Nov-Dec 2006	1 COTS	BB	LN200	CDSU-1	Battery + Helicoper	1 COTS antenna configuration mounted on single-axis (pitch) gimbal on helicopter
EM antenna test series	Echo Tower (fT3)	Jul 2007	Descoped	1 EMProto	BB	LN200	CDSU-1	Battery	1 EM prototype antenna configuration mounted on adjustable pitch fixture
	Helicopter (FT4)	Already Completed	Apr 2007	1 EMProto	BB	LN200	CDSU-1	Battery + Helicoper	mounted on single-axis (ptich) gimbal on helicopter
EM TDS test series	Echo Tower (FT5m)	as of May 2007	Aug 2008	EM1A'		LN200	CDSU-2	Battery	1 EM antenna configuration,mounted on adjustable pitch fixture
	Echo Tower (FT5)	Nov 2007	Descoped	EM1C		EM MIMU	CDSU-2	Battery	6 EM antenna configuration, no adjustable pitch fixture, rover deploy system
	Helicopter (FT6a)	Jan 2008	Descoped	EM1C		EM MIMU	CDSU-2	Battery + Helicoper	6 EM antenna configuration, hardmounted to helo, no gimbal
	Helicopter (FT6b)	Mar 2008	Descoped	EM1C		EM MIMU	CDSU-2	Battery + Helicoper	Controlled Descent System (CDS) in helo, no gimbal
	Helicopter (FT6c)	as of May 2007	Descoped	modified EM1C		EM MIMU	CDSU-2	Battery + Helicoper	6 EM antenna configuration, mounted on gimbal, TDSD/TDSR off TDSS
	Helicopter (FT6d)	as of May 2007	May-June 2010	EM1C		EM MIMU	CDSU-2	Battery + Helicoper	6 EM antenna configuration, mounted on gimbal on helo, rover deploy system
	Helicopter (F7)	Feb 2008	Descoped	modified EM1A		EM MIMU	CDSU-2	Battery + Helicoper	1 EM antenna configuration, mounted on gimbal on helo
	Aircraft (FT8.1)	May 2008	April-June 2011	modified EM1C		EM MIMU	CDSUr	Aircraft power	1 EM antenna configuration, mounted on gimbal in wing-mounted pod
	Aircraft (FT8.2)	Scheduled as of May 2007	Descoped	modified EM1C		EM MIMU	CDSUr	Aircraft power	Same venue as #8.1, second round of testing on this venue
	Fixed Wing Aircraft (FT9)	as of May 2007	Descoped	EM1C		EM MIMU	CDSUr	Aircraft power	in aft cargo bay or wing mounted pod, no gimbal.
	Drop Test (FT10)	as of May 2007	Descoped	EM1C		EM MIMU	CDSUr	Battery	6 EM Antenna configuration, no gimbal
Contingency Test	TBD (FT11)	as of May 2007	Descoped	TBD		EM MIMU	TBD	Battery	Contingency to allow regression testing or new tests

To give a sense of how the campaign evolved over time, all options originally planned as of May 2007 are included. Tests shaded green were executed, while tests shaded red were never fully baselined and were descoped. In addition, subsequent replans added tests that were not present as of May 2007 (FT5m and FT6d). These replans allowed all technical objectives to be met with a reduced set of test venues.

The field test campaign overlapped with the development of the design and fabrication of the flight TDS hardware. Preliminary field tests were performed using a BB TDS with later tests using more mature EMs. The initial BB TDS tests used a Commercial Off the Shelf (COTS) antenna, where later BB TDS tests were performed using a prototype EM antenna. The three configurations allowed for parallel field testing and radar development work. The Flight Model (FM) TDS used to land on Mars was never tested in the field, but was tested extensively in the lab using the EGSE to show that the FM performance was comparable to the EM units that were tested in the field. Table 2 shows columns for the various test objectives, test venues, planned and executed test dates. The TDS test configuration is shown in the antenna and TDS electronics columns. The Inertial Measurement Unit (IMU) used for a given test was either a Northrup Grumman LN200 or a Honeywell Miniature IMU (MIMU). The MIMU greatly outperforms the LN200 and was necessary in later field tests where highly accurate ground truth was required to verify TDS performance against requirements. The LN200 was less expensive and its performance was sufficient for early field tests and had less rigorous handling constraints. The Command and Data Storage Unit (CDSU) was a critical subsystem responsible for commanding the test system, providing real-time telemetry back to system operators and time-stamping and collecting both TDS and ground truth data. It was a cPCI based computer system with supporting interface cards, running the Linux OS and had substantial custom application software. Power for the entire system was supplied either by battery and/or the test platform itself.

Each field test required extensive subsystem and system design, implementation, integration and testing prior to test execution in the field. Significant mechanical, electrical, computing, sensing, and software subsystems were required across all venues and in some cases additional specialized subsystems were required. For example, the F/A-18 Field Test required an Environmental Control System (ECS) to provide a safe thermal and low-humidity environment for sensitive hardware descending rapidly from high altitudes. The major hardware and software architecture remained common through each test, but each new venue had requirements that necessitated further development. In addition to the field campaigns, there were numerous precursor tests, both on the ground and in the air to shakeout systems. Beyond this significant effort was invested in planning, reviews, test site location and evaluation, vendor selection, logistics, etc.

FIELD TEST 1 (FT1): ECHO TOWERS

The first test of the BB TDS took place at China Lake over 3 days in Jul 2006. It used a single COTS antenna as a stand-in for a TDS antenna as one was not yet available for testing. The BB TDS was a single-channel radar developed for the verification of the TDS measurement concept. It was flight-like in many ways, but also had some key differences, such as having a single antenna channel instead of six. The main objective was to provide early validation of the TDS high-level design and measurement concept in the field for the first time. A secondary test objective included examining a worry bead, WB4. The radar generally behaved well. It met velocity error and bias and slant range error performance requirements. No problems were exposed due to varying vertical velocities (0-5 m/s), altitudes (11-70 m AGL) or surface off-vertical TDS antenna angles (0-25°, vertical = 0°). The main problem uncovered with the BB TDS was that internal system parameters were not yet optimized. This caused a loss of ~5% of data due to an FPGA issue. This was corrected for subsequent data collections. Also, the TDS did not meet the minimum required operational range (6 m AGL at the time, since increased to 10 m) for MSL during landing on the surface. Parameters related to minimum range were still not tuned appropriately before FT1 ended. They have since been tuned to provide the minimum range required by MSL.

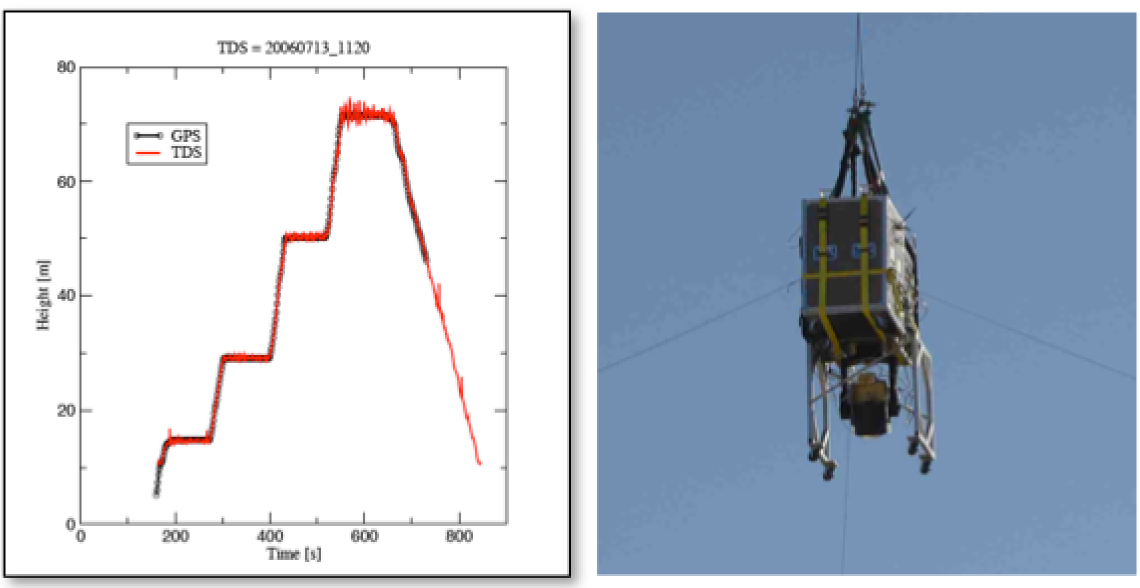

Figure 3. FT1, Echo Towers, Jul 2006.

The right image in Figure 3 shows the assembled system lifted above the ground. The COTS antenna is mounted underneath on a fixture that allowed changes in antenna angle relative to the surface. The plot on the left is altitude versus time comparing TDS measurements versus GPS ground truth. On the way up, the system was raised to various altitudes and allowed to hover while taking measurements. On the way down, the system was lowered in a continuous fashion to the ground.

Two key lessons were learned. First, a quick look data validity tool for use in the field is critical. TDS, GPS and IMU data were time-stamped and collected in the field, but only cursory examination was performed. Upon return from the field test and upon closer look at all data, it was discovered that a software bug occasionally occurred that caused data to be corrupted for a given run. Had a quick look analysis tool been in place, tests could have been re-run as necessary. Second, detailed checklists and procedures with clear roles and responsibilities for all team members were not in place prior to field test execution. The consequence was that team members were unclear on what they should be doing at a particular time and testing was not as efficient as it could have been.

Prior to the execution of FT1, an informal review of test readiness was held at JPL with a small group. Based upon lessons learned, a more formal Test Readiness Review process was instituted for future tests with a larger group of stakeholders to review goals, plans, procedures, tools, test article (hardware/software), residual risks and overall readiness.

FT2: HELICOPTER

FT2 was the first test of the BB TDS on a helicopter and it took place over four days in Nov-Dec 2006. Flights were carried out over terrain local to JPL. This field test used the same single COTS antenna used in FT1 although this time it was mounted on a gimbal that provided the ability to point and slew the antenna in a single axis (pitch) over a range of 0-90° (0° = straight down, 90° = forward along longitudinal axis of helicopter) and rates up to 90°/s. The helicopter was capable of top horizontal speeds of ~100 knots (~50 m/s) and vertical descent speeds of ~5 m/sec and maximum altitude ~3 km AGL. As in FT1, the main objective was to provide early validation of the TDS high-level design and measurement concept. FT2 exposed the TDS to larger magnitude slant ranges, total velocity, off-vertical antenna angles and for the first time, significant horizontal velocities, attitude rates and a variety of terrain types. Secondary test objectives included examining two worry beads, WB5 and WB6.

A two-week test campaign was planned with shakeout flights local to JPL coupled with desert testing further from JPL and over a variety of terrain types. However, shakeout testing with greater TDS slant ranges (> 100m to 1000's of meters) uncovered a number of issues with the BB TDS electronics that created enough residual risk that warranted cancellation of the desert testing. For example, a radar return receive window was shorter duration than expected and limited the slant range of TDS data that could be acquired. Testing proceeded locally to allow further data to be gathered and TDS debugging to continue. Thirteen total flights were executed with various altitudes, TDS off-vertical angles and attitude rates while collecting time-stamped TDS, IMU and GPS measurements.

Analysis of the TDS data (standalone, not against ground truth) revealed six problems that were later fixed. In addition to finding these issues, the team gained valuable experience in the helicopter testing of the entire system and allowed refinement of processes, procedures logistics, system components, etc. The main lesson learned was the value of preceding the field test proper with local shakeout testing that is less expensive and quicker than the main field test deployment. Also, and this is especially true when undertaking an activity that is substantially new in some dimension (system configuration, venue, etc), be prepared for significant issues to occur that may precipitate a major change in plans. In the field test world, one should plan on either repeat field test attempts or sufficient time in between shakeout activities and the actual field test deployment to allow for adjustment to problems.

Figure 4. FT2, Helicopter, Nov-Dec 2006.

The left image in Figure 4 is a close-up of the COTS antenna and housing containing the IMU mounted on the gimbal. The breadboard TDS electronics and additional test support electronics reside in the helicopter cockpit. The right image shows the helicopter in flight.

FT4: HELICOPTER

FT4 was largely a repeat of FT2 (with some incremental advancements), took place over five days in April 2007 and was conducted local to JPL. These advancements included updated BB TDS electronics and a TDS EM prototype antenna used in place of the COTS antenna. The support electronics and software remained largely unchanged and the same helicopter and gimbal system were used. The plan was to 1) shakeout the integrated system prior to testing, 2) verify that the issues discovered in FT2 were fixed and 3) complete the test objectives previously set in FT2. Nineteen flights over various sites local to JPL were completed with test profiles similar to FT2.

Three shakeout flights on the first day showed a largely functional system although there were some dropouts evident in the data logged. Robust TDS range and velocity estimation was demonstrated out to 3.5 km, which was better than the 2 km shown in FT2 but still well below requirements and TDS design capabilities. Over the remaining days of testing, TDS parameter tuning and data gathering continued. By field test end, all objectives had been met.

The TDS was shown to acquire targets and produce self-consistent results out of more than 95% of possible good data. Functionally, the TDS worked through internal states as expected, including the "memory-less" operation mentioned above. Velocity and range measurement errors were within requirements. In general, the TDS was shown to function and perform very well over a wide range of flight conditions and terrains. There were still some residual issues with the TDS that remained, including a maximum ceiling in the range of about 8300 m that was localized to TDS FPGA timing issues and was later fixed. Also, velocity unwrapping problems caused about 5% of velocity measurements to be impacted. This was determined to be due to TDS parameter table settings, also fixable, and not due to hardware.

Velocity unwrapping resolves the 2pi ambiguities in observed Doppler phase in order to estimate the true line-of-sight velocity. Beyond the issues with the parameter table settings, unwrapping errors occurred because the unwrapping algorithm was not designed to account for non-flight conditions that the TDS was exposed to during a subset of testing. Specifically, the combination of (1) very high attitude rates, (2) near-zero flight path angle, and (3) nearly vertical antenna boresight vector, all of which caused phase differences between the two Doppler-estimation dwells. During a nominal EDL profile, no more than a handful, if any, measurements are expected to have unwrapping errors. If errors do occur, the NAV Filter will edit out the measurements and not make use of them.

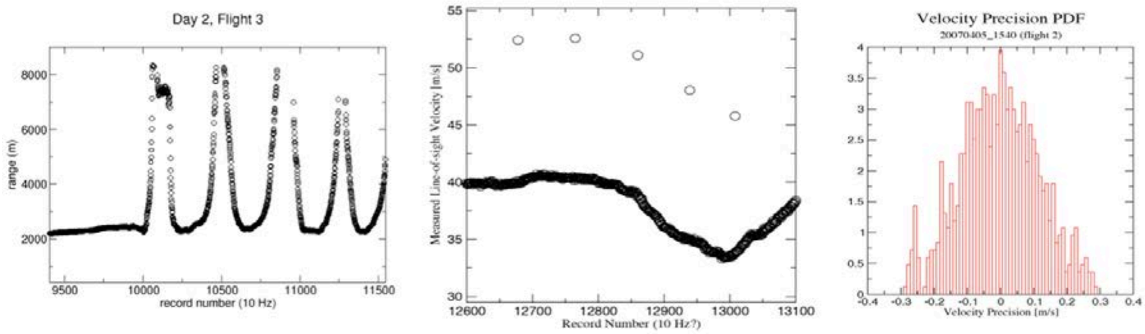

Figure 5. TDS Results, FT4 Helicopter, Nov-Dec 2006.

Figure 5 shows plots of representative results from FT4. The leftmost plot is slant range as a function of time. The helicopter was hovering at about 2 km AGL and the gimbal was slewed from pointing at nadir up to the horizon and back down again numerous times. Slant range returns are robust up to a range of ~8300 m as described above. The middle plot is line-of-sight velocity versus time as measured by the TDS and is largely correct except for the outliers due to the unwrapping problem. The right plot is a Probability Density Function (PDF) of velocity precision and is estimated to be ~0.27 m/s, 3 sigma, well within the requirement of 0.75%*Vtotal + 0.2 m/s, or ~0.46 m/s, in this case.

Figure 6. FT4, Helicopter, Apr 2007.

The left image in Figure 6 is a close-up of the EM prototype antenna and housing containing the IMU mounted on the gimbal. The BB TDS electronics and additional test support electronics reside in the helicopter cockpit. The right image shows the helicopter in flight.

Numerous issues occurred during the testing beyond those above, with major ones including hardware and weather issues. Loose connectors to batteries and the IMU caused significant data loss on some of the flights and internal memory on a GPS unit filled up and stopped logging on one flight. This data loss made reconstruction of ground truth trajectories to compare against TDS data difficult, sometimes impossible, and was a serious problem. High winds on one of the test days impacted IMU-based gyrocompassing used to estimate initial system attitude, as a relative quiescent environment is needed. This degraded ground truth reconstructions. Lessons were learned and in some cases re-learned during this field test. A major one was making sure all hardware interfaces and connectors are designed for the environment that they will be subjected to and are secured properly. Also, making sure quick-look tools are in place that will validate data integrity in the field correctly is critical. These issues caused a loss of valuable test data. In addition, making sure sufficient schedule margin exists to allow mitigation of uncovered problems and allow for weather delays is important.

This ended the testing that preceded the EM TDS field test series and in general was extremely productive, informative and demonstrated the value of testing hardware in the field. The TDS design and implementation versus requirements was shown to be generally sound and robust in operation once parameters were tuned properly. Open issues still remained but many were uncovered and mitigated. In addition, valuable experience was gained by the team in many facets of field testing, including planning, preparation and execution.

FT5M: ECHO TOWER

FT5m was the first test of EM TDS digital and RF electronics and took place over 3 days at China Lake in Aug 2008. However, it was not a flight-like TDS in that it only had a single antenna as opposed to six. A mechanical fixture for the TDS antenna allowed it to be set into the three off-vertical orientations seen by the TDS antennas during the sky crane phase of landing (0, 20 and 50°).

There were major system changes between FT1 and FT5m. The entire test system was greatly reduced in size and carried on a single custom-built test cart as opposed to the 2 large chassis used in prior tests. The CDSU-1 was upgraded to support additional sensors, interfaces and functionality and was dubbed the CDSU-2. A major change was that whereas the BB TDS was powered, commanded and TDS data logged by independent system elements in earlier tests, in this incarnation the CDSU-2 and support systems were modified to "be the MSL spacecraft" in terms of power, command and data interfaces for the TDS. In addition to the IMU and GPS used in prior tests, a short-range laser rangefinder co-boresighted with the TDS antenna boresight provided an additional ground truth measurement that could be compared directly with the TDS. Also, an independent GPS/INS system provided a complete navigation solution for quick-look comparison to TDS data. A more accurate solution was obtained after the field test completed by post-processing the LN200 and GPS data. Temperature sensors were added to allow real-time monitoring of critical components to ensure they stayed within allowable temperatures during testing. As temperatures at China Lake can easily exceed 40°C in the summer, the test cart was loosely enclosed and a dry ice based cooling system implemented to help keep the system within allowable temperature ranges. Finally, a ground station laptop running a GUI and connected to the CDSU-2 via a wireless link provided a conduit for commanding the system and receiving reduced bandwidth telemetry during testing. Full bandwith TDS and other sensor data were time-stamped and logged onboard the CDSU-2 for later post-test data analysis.

The primary objective was to test WB4. There were a number of secondary objectives, including partial testing of WB7 and WB8. Later field tests would be required to fully test WB7 and WB8. In addition, TDS "saturation" tests were accomplished by encasing the TDS Transmit/Receive Module (TRM) in an enclosure that could be filled with dry ice and cooled to -40°C. At a given transmit gain setting, as the TRM is cooled, its amplifier gain increases to the point of saturation and could impact TDS performance.

FT5m was extremely successful and all objectives were met. Range and velocity measurement noise was as good or better than required with a minimum operational range of ~9.5 m (still not optimized for flight requirements). TDS measurement validity codes and diagnostic data mostly worked as expected.

There were few issues once in the field; both the system and the team performed very well. Test execution was crisp, the system operated robustly, test procedures were in place to be followed, team members knew their roles and responsibilities and validated analysis tools existed to quick-look the data soon after test completion to allow data integrity to be determined and whether a test in the matrix of planned tests could be checked off or needed to be repeated. These lessons had all been learned from prior field tests.

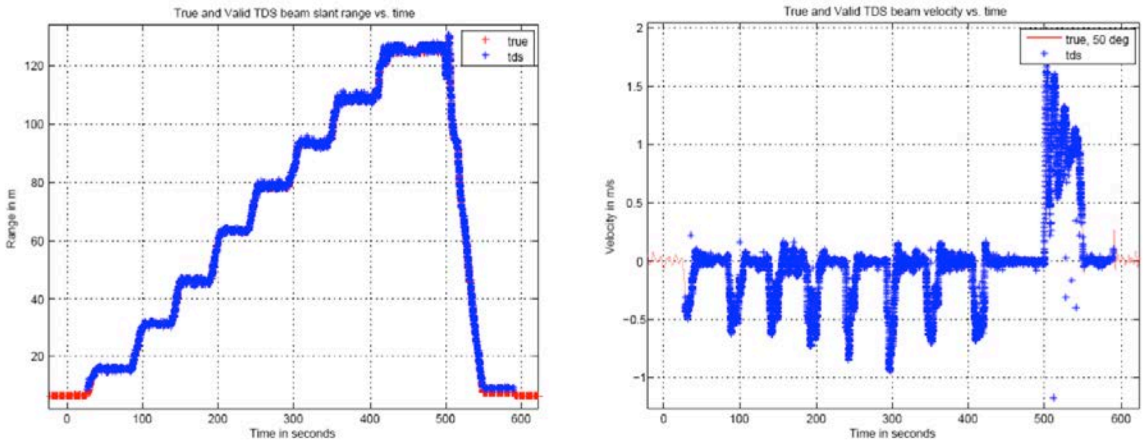

Figure 7. TDS Results, FT5m Echo Towers, Aug 2008.

Figure 7 shows plots of representative results from FT5m. TDS slant range measurements as a function of time versus ground truth is on the left and TDS line-of-sight velocity measurements versus ground truth on the right. For this test, the TDS antenna angle was set to 50° off-vertical and the test cart was raised in 10 m altitude increments with 1 minute pauses in between. After pausing at the maximum altitude, it was lowered in a continuous fashion at rates above 1 m/s.

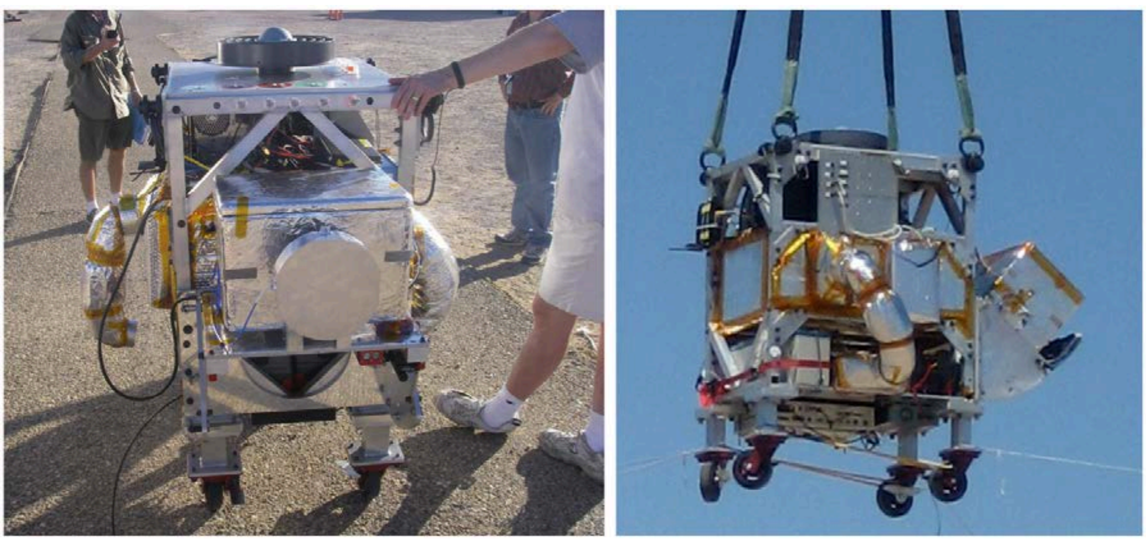

Figure 8. FT5m Echo Towers, Aug 2008.

Figure 8 shows the FT5m system both on the ground and in the air during testing. The left image gives a sense of scale for the test system. The TDS antenna is canted at 50° during the test on the right.

There were new lessons to be learned prior to deployment to the field and they were quite significant. JPL Critical Items (JCIs) that required special handling constraints were now being field tested (the EM TDS and MIMU) and this had ramifications that were grossly underestimated in terms of process, products, reviews, various JPL institutional group involvement, etc. This consumed much more personnel, schedule and cost resources than had been planned. Mechanical fixtures required stress analyses and to be proof loaded, electrical and power interfaces required failure analyses and safe-to-mates performed prior to integration to JCI, and software that interfaced to the TDS had to go through an acceptance test procedure. JPL quality assurance and safety were involved in prior tests, but had a much more involved role now and required additional processes to be followed and documented. Paperwork, procedures and other data products were required, multiple reviews were held, etc. This was probably one of the greatest lessons learned during the entire campaign—to make sure that institutional processes and procedures are understood prior to planning an activity so it can be scoped properly in terms of personnel, cost, and schedule.

After the completion of FT5m, preparation for the helicopter and F/A-18 tests began. However, the MSL launch, which was originally scheduled for 2009, was slipped to 2011. The TDS Field Test effort was put in hibernation as the MSL project focused on higher priority areas. The team was disbanded at the end of calendar year 2008 and went to work in other areas of JPL. A few personnel were retained to replan for when the Field Test effort would be restarted in October 2009. This would have detrimental impacts in the future.

During late 2008 and through Sep 2009, a substantial replanning effort was carried out with the reduced workforce. Once concluded, FT5 at China Lake had been descoped and the full six antenna EM TDS plus Rover Deploy System (RDS) testing planned for FT5 was merged with FT6d. It was felt the residual risk was low as the single antenna EM TDS had already been tested at China Lake and conversations with the helicopter vendor and pilot made an RDS on the helicopter appear feasible. It was taken on risk that a China Lake test might be needed in the future if the RDS could not be successfully deployed on the helicopter. The Field Test team was reconstituted Oct 2009 and preparations for FT6d and FT8.1 were restarted.

FT6D: HELICOPTER

For FT6d, testing took place May-Jun 2010. The same helicopter and gimbal was used, but beyond that there were substantial changes across all subsystems. For the first (and only time) the full 6 antenna EM TDS was used. It was also the first time the MIMU was used. Numerous mechanical fixtures were required to mount the test system on the helicopter as well as Ground Support Equipment (GSE) to assist integration and test in the lab and in the field. Plus, a full-size rover mockup and Rover Deploy System (RDS) had to be designed and approved by JPL and the Federal Aviation Administration for integration and flight on the helicopter, including a pyro-based cutaway system that would allow the pilot to jettison the RDS if issues occurred during testing. An extensive set of computing, sensors and support electronics was mechanically and electrically integrated into a complete system along with substantial custom application software and dubbed the Field Test Support System (FTSS). The FTSS included everything other than the TDS; the CDSU-2, MIMU, GPS, short range and long range laser range finders, narrow and wide field-of-view fire-wire cameras and a GPS/INS system that provided a complete navigation solution. Power was provided by a combination of battery and helicopter power with a hot-swap capability. It also included a laptop running the Linux OS and a GUI as the primary interface to the FTSS. The software for this field test required additional code to interface to all the sensors as well as supporting the new functionality to allow commanding the TDS and viewing all necessary telemetry in real-time from the TDS and other sensors. For this field test, more intricate operation of the TDS required that a JPL Flight Engineer operate the FTSS during flight.

Individual subsystems required substantial design, implementation integration and test. In Aug 2008 and prior to Field Test hibernation, a structural/mechanical shakeout of the gimbal fixture that would hold the TDS and other equipment was flown on the helicopter local to JPL. These flights demonstrated that the helicopter and gimbal would be able to operate at the maximum flight speeds, gimbal angles and rates desired and that the fixture would not fail (stress analyses had been performed prior to flight but the actual flights reinforced this conclusion). In Feb 2010, the winch used in the RDS was tested at JPL on a drop tower using dummy weight to verify it could lift the mass required. Problems were uncovered during this testing and design modifications implemented and retested. Following these tests, in Mar 2010 the RDS was integrated onto the helicopter and tested at an airport in Hawthorne, CA, giving confidence it would function as desired in the field. Finally, subsystems were integrated and tested together. Prior to deployment to the field, a system shakeout test was performed on the JPL Mesa also in Mar 2010. The Mesa is the highest point at JPL and allowed for unobstructed, outdoor testing of long-range targets for the TDS, including static and dynamic motion tests and specialized ground-based performance tests. Data sets were gathered for early checkout of quick-look and detailed analysis tools. Helicopter shakeout flights were performed local to JPL in mid-Apr 2010 that allowed a complete checkout and validation of the system and tools prior to deployment in the field.

Before deployment significant work went into selection of the eventual test sites. In Jul 2008, a Field Test Site Selection Workshop was held at JPL and three basic test sites were defined, flat terrain (dry lake bed), lava fields, and sand dunes. Candidate sites were identified as Bristol Dry Lake Bed, Amboy Crater and Cadiz Sand Dunes, all east of Barstow, CA in the Mohave Desert. When test time came in 2010, a wet winter flooded Bristol, so Rogers Dry Lake Bed at Edwards AFB was used instead. Death Valley, CA was added as an additional test site for further terrain variety and Mars-like morphological landforms, including Eberswalde, Holden and Mawrth-like terrain. Digital Elevation Models (DEMs) were acquired for all of these sites and coupled with ground truth flight trajectories allowed performance verification of the TDS. Detailed flight profile planning was made in concert with stakeholders at JPL and iterated on with the helicopter and gimbal operator to determine what was possible and what was not. And as usual, test procedures were developed, institutional processes and procedures were followed and numerous reviews were held. With shakeout flights successfully completed and final TRR passed, the team deployed to the field.

Primary TAYF objectives were powered descent and sky crane flight envelope testing as well as integrated sensor validation. Primary worry beads tested include WB4 through WB8. In addition new worry beads were identified, specifically "Does performance degrade during rover deployment and sky crane?" and "Validate high-fidelity TDS simulation". From May 10 to 18, 2010 testing at Edwards AFB was carried out, including RDS testing. From there, the team travelled to Cadiz and testing was performed over Amboy Crater and Cadiz Sand Dunes from May 19 to 28. Finally, the team travelled to Death Valley and tested from May 30 to Jun 2. The team returned home on Jun 2 and system de-integration from the helicopter occurred thereafter. FT6d was also extremely successful, with all test objectives met. One hundred twenty-nine (129) individual tests were completed with 37 flights over four sites, with 34 full EDL runs (helo maximum altitude down to 5 m AGL), 47 sky crane tests (300 m to 5 m AGL), 23 TDS "worry bead" tests, 14 TDS high-fidelity simulation validation tests and 11 "special" tests.

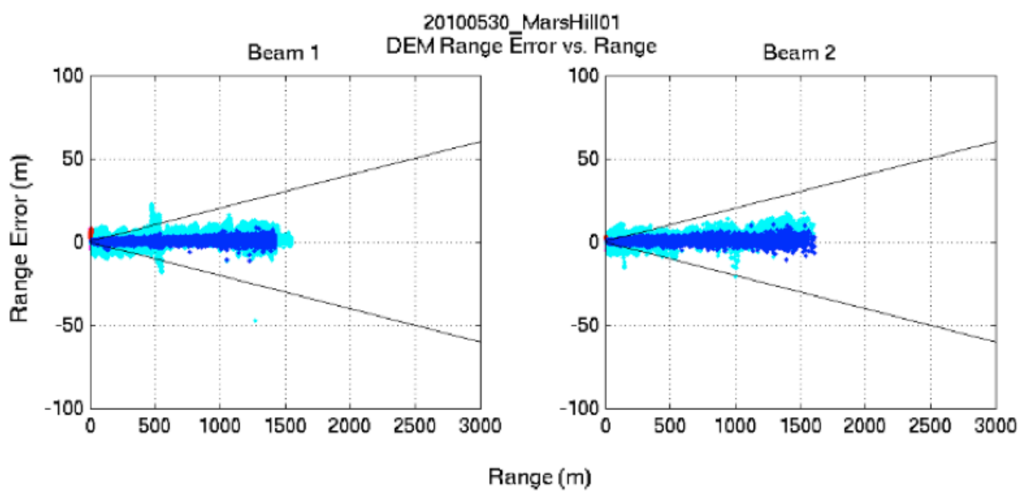

Figure 9. TDS Results, FT6d Helicopter, May-Jun 2010.

Figure 9 shows representative results from FT6d. Both plots are range error as a function of slant range for 2 of the 6 antenna beams. Error requirements (99%) are given by the two solid lines and increase with slant range. Two DEMs were used to compute error, one higher resolution that the other. DEM range error is less when computed using the higher resolution DEM and is indicated by blue, while the lower resolution DEM error is indicated by cyan.

Figure 10. FT6d Helicopter, May-Jun 2010.

Figure 10 shows the FT6d system on the ground (left), in flight over Rogers Dry Lake Bed during RDS testing (middle) and over "Mars Hill" in Death Valley (right).

There were numerous issues that occurred during the run-up and execution of the field test, but no major issues were uncovered with TDS functionality or performance. The main issue in the run-up related to deficient plans made in terms of resources required to complete the task in terms of personnel, cost and schedule. During the field test execution issues related to weather and helicopter problems that required maintenance delayed testing. Also, there were issues related to FTSS robustness that caused inefficiencies in testing and in some cases loss of data.

The major lesson learned related to the replan that was made while most of the team was off on other tasks. Subsystem leads and other team members were minimally involved in contributing to the replan and needed to be more intimately involved in the detailed planning, including cost and schedule development and risk identification. A gross underestimation in terms of resources may have been avoided with greater involvement with those doing the technical work. An independent review process was performed during the replan, but wasn't detailed enough, this also was an opportunity to catch the inadequacies in the cost and schedule plan. Finally, trying to do two field tests in parallel (FT6d and FT8.1) with largely the same teams is challenging and prone to failure. Team members became oversubscribed and tasks slipped. It is better to either serialize activities or have two independent teams working individual field tests. Field test management also became oversubscribed, focusing on the nearer term helicopter field test to the exclusion of the F/A-18 field test.

FT8.1: F/A-18

The F/A-18 field test took place Apr-Jun 2011, was a unique venue with numerous constraints and operated under extreme environmental conditions. This greatly impacted system design, implementation, test, qualification and execution. Like FT6d, there were substantial changes across all subsystems.

The EM TDS was flown on a wing-mounted pod to minimize any interaction with other objects in the radar field of view. The pod was volume constrained making system packaging challenging. The TDS was reconfigured into a single antenna version for placement in the pod. The antenna was mounted on a single-axis (pitch) gimbal that allowed the antenna to be pointed at fixed angles and slewed (up to ~90°/s) from roughly straight down (0°) to 30° above the horizon (120° total range) when the aircraft was level. An outside vendor provided a custom-built radome that the TDS could transmit and receive through.

Another extensive set of computing, sensors and support electronics was mechanically and electrically integrated into a new FTSS, which again required specialized mechanical fixtures, GSE and harnessing. Computing became more distributed, with the CDSU-2 repackaged into a smaller, more ruggedized version called the CDSUr. A COTS computer was required to interface to the gimbal and the laptop computer was replaced with a more compact, rugged tablet PC. A major addition to the FTSS was the Environmental Data Acquisition and Control Subsystem (EDACS). Its primary function was to monitor and maintain a safe environment inside the pod for the electronics. It measured temperature, humidity, pressure and three axis acceleration inside the pod and provided control of a liquid nitrogen and fan subsystem that helped purge the pod of heat and humidity during operation. It also controlled power relays for turning the MIMU and TDS off and on. These four computers; CDSUr, Gimbal PC, EDACS and tablet PC were all networked together via Ethernet. A fifth computer (ISHM) provided by Dryden could sniff F/A-18 bus traffic and provided a subset of aircraft telemetry to the JPL network in real-time. The lasers, cameras and GPS/INS were not useful for this venue and were removed, leaving the MIMU and Dryden provided GPS as the two primary ground truth sensors. Telemetry provided by the Gimbal PC and ISHM were also part of ground truth reconstruction. There were additional F/A-18 subsystems that completed the overall test system. These subsystems were physically located in multiple locations on the F/A-18, including the pod, F/A-18 avionics bays and cockpit. The software effort was significant, including new computers, subsystems and functionality required. For FT6d, a JPL Flight Engineer (FE) operated and monitored the system during flight. A lesson learned was that the operational overhead on the FE was high. For the F/A-18 Field Test, special emphasis was put on the software regarding system automation, situational awareness and hardware safety. This paid dividends during test execution and was well worth the effort. A lesson learned is not to skimp in this area.

Many aspects of the FT8.1 Field Test had never been done before and so required substantial planning, design, implementation, integration, qualification and test. The pod provided by Dryden had been flown for other experiments, and so it was qualified for a certain flight envelope and mass. Fortunately, our mission requirements fit within these parameters. However, for a subsystem to fly on the F/A-18, stringent DFRC environmental qualification requirements in terms of vibration, temperature and altitude (pressure) had to be met. Numerous system components were COTS and had to go through a qualification process. This included subsystem level vibration, temperature and altitude testing at Dryden and a full pod level system test at JPL that covered temperature and humidity and was carried out in custom built Thermal Humidity Chamber at JPL in Feb 2011. The pod was not hermetically sealed and had no environmental control. So, a campaign to first characterize the environment in the pod over expected flight envelope and profiles and then design a system to mitigate that environment was carried out. The first set of flights in Oct 2008 flew a dummy system with mass and heat loads to simulate the expected payload and outfitted with the precursor of the EDACS. The environment was more benign than expected, but still required an active system to monitor and control the temperature and humidity environment. In addition, the vibration environment was severe enough to require isolation for the CDSUr. The EDACS and LN2 system described above was designed, implemented and tested over two sets of flight campaigns in Mar 2010 and Dec 2010. The radome was tested at JPL to make sure performance requirements were met and any degradation of antenna signal in terms of strength, beam deflection, etc. was understood. The radome was also flown on the final EDACS/LN2 system check flight in Dec 2010 prior to usage during the actual test campaign.

A key difference between this field test and all others was that the JPL test system was much more tightly coupled with the venue and required greater detailed planning and interaction with the venue provider (DFRC). The first meeting was held with DFRC in Dec 2006 to explore feasibility of using their aircraft for FT8.1. Over the next 4.5 years, there were a substantial number of DFRC personnel and resources involved that contributed to making the F/A-18 field test campaign a success. Similar to the helicopter field test, a great deal of planning was undertaken to determine test sites and flight profiles to fly over which parts of the flight envelope that involved both JPL and DFRC personnel. Sites local to Edwards AFB were chosen; Rogers Dry Lake Bed (flat terrain) and also more rugged terrain northwest of Edwards. DEMs were acquired for all of these sites. Numerous meetings were held with DFRC pilots and FE to work out operational concepts. Practice flights were made to determine the most efficient way to put and keep the TDS “on-condition”, essentially meeting required aircraft and TDS flight parameters. An extended set of subsystem and system level tests were carried out at JPL and DFRC prior to the field test execution proper. In addition to the testing above, a Mesa test with the integrated pod system was held in Mar 2011, and integrated pod and F/A-18 tests were held on the ground at DFRC in Apr 2011. Also, a set of toe-dip and system functional shakeout flights were held where both the flight envelope and operation of the test system were slowly expanded to gain confidence in the system to be operated safely and properly. This completed in Apr 2011. Performance flights were carried out in May and Jun 2011.

Primary TAYF objectives were parachute descent and powered descent trigger testing. Primary worry beads tested include WB1 through WB3, with partial testing of WB7, WB8 and “Validate high-fidelity TDS simulation”. Nineteen F/A-18 flights were executed between Apr 20 to Jun 20, 2011 and all test objectives were either met or exceeded. The total number of flight hours was ~21 hours and the TDS was put "on-condition" for ~44 minutes where desired flight parameters for both the aircraft and the TDS were met. This low ratio of on-condition to total flight time is indicative of how difficult it is for an aircraft to achieve the MSL EDL flight profile. There were 124 TAYF dives covering the entire MSL flight envelope, 14 dedicated to TDS high-fidelity simulation validation tests, 11 high-altitude dives where WB1 was probed and 5 additional special tests added to examine interesting results uncovered during the campaign.

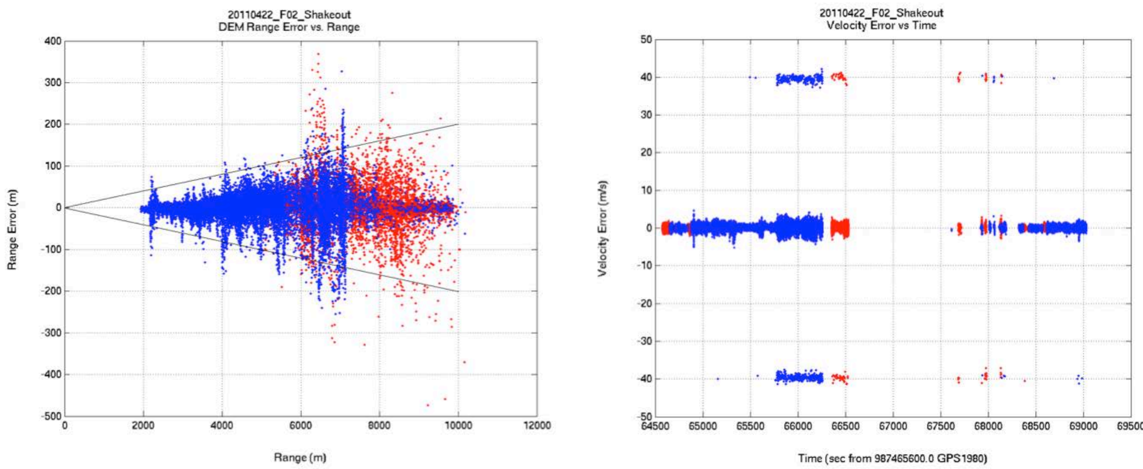

Figure 11. TDS Results, FT8.1 F/A-18, Apr-Jun 2011.

Figure 11 shows representative FT8.1 results. The left plot is range error as a function of slant range and the right is velocity error as a function of time. Error requirements (99%) on the left are given by the two solid lines and increase with range. Outliers above and below the main data set on the right are due to velocity unwrapping errors expected under these operating conditions and are not a concern. Blue indicates measurements marked valid by the TDS, while red indicates measurements marked invalid. Invalid measurements are not used by the NAV filter.

Figure 12. FT8.1 F/A-18, Apr-Jun 2011.

Figure 12 shows the FT8.1 system in the left image with the radome removed from the pod and MIMU, gimbal and TDS antenna visible. The right image shows the F/A-18 in flight over Edwards AFB.

As was the case in FT6d, numerous issues occurred during the run-up and execution of the field test itself, but no major issues were uncovered with TDS functionality or performance. The main issue was that this field test was very complex and had many new aspects. During the field test execution issues related to weather, F/A-18 aircraft problems, and conflicts for usage of Edwards AFB range resources with other users occurred. The major lesson learned was to make sure to put sufficient margin in plans, both for schedule and budget, commensurate with the complexity and unknowns associated with the effort. For all field tests, using COTS electronics in non-lab environments can prove difficult and require re-work (ruggedization), mitigation (temperature control, vibration damping) and/or additional qualification testing. This should not be underestimated in terms of making COTS systems work in these more challenging environments.

CONCLUSION

Overall, the MSL TDS Field Test Campaign was very successful and the TDS was shown to perform extremely well over the required operational envelope. The early BB TDS field tests uncovered a number of issues, but none that invalidated the TDS design or implementation, both were shown to be sound. The EM TDS tests uncovered minor things of interest but nothing of great concern. These tests gave further confidence in the TDS design, implementation and performance. The value of testing hardware in the field was demonstrated, and significantly contributed to the overall TDS V&V effort. Over the 5-plus year TDS field test campaign, numerous lessons were learned that will inform future field test efforts.

ACKNOWLEDGMENTS

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