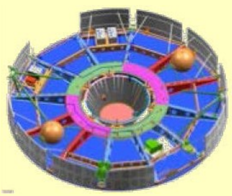
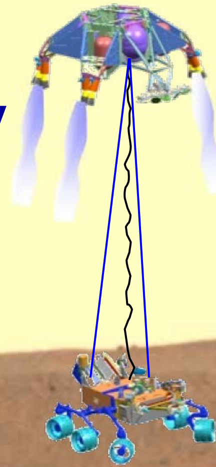
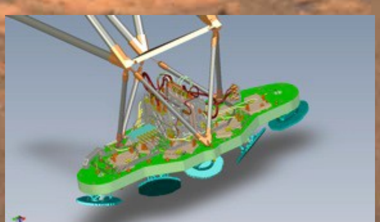
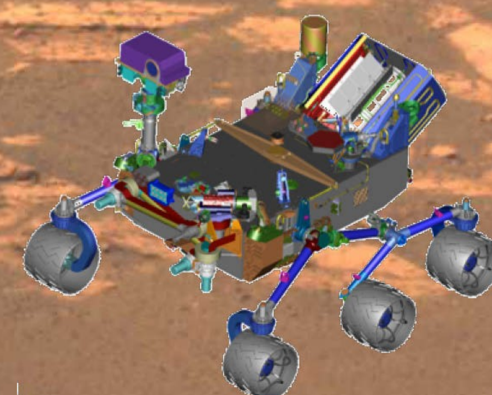




Implementing the Mars Science Laboratory Terminal Descent Sensor Field Test Campaign





Jim Montgomery
monty@jpl.nasa.gov
Jet Propulsion Laboratory
February 8, 2012

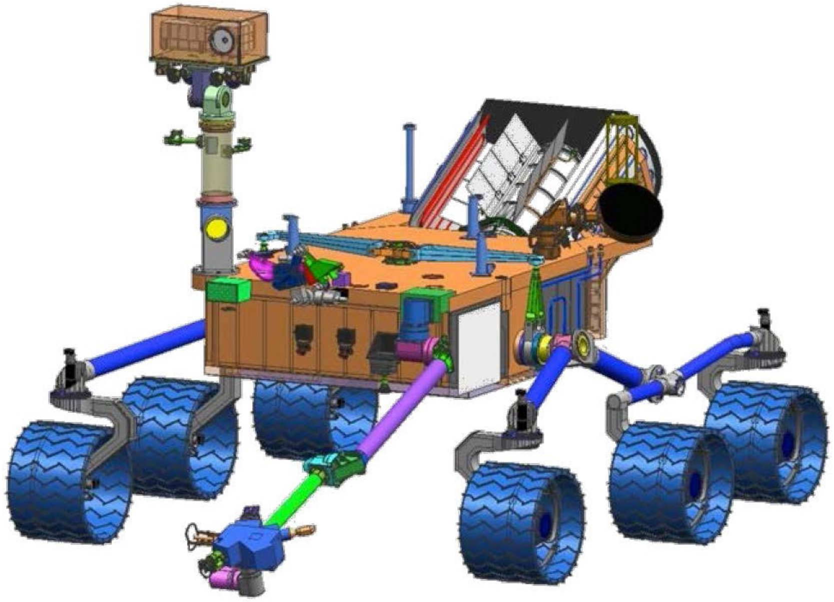
MSL Project Overview

Salient Features

- Large mobile science laboratory (car-sized ~900 kg rover)
- Launched from Cape Canaveral/Kennedy Space Center on Nov 26, 2011
- Lands at Gale Crater on Aug 5, 2012 PDT (Aug 6, 2012 UT)
- One Mars year surface mission
- Land within 10 km of targeted landing site
- Rove up to 20 km

Science

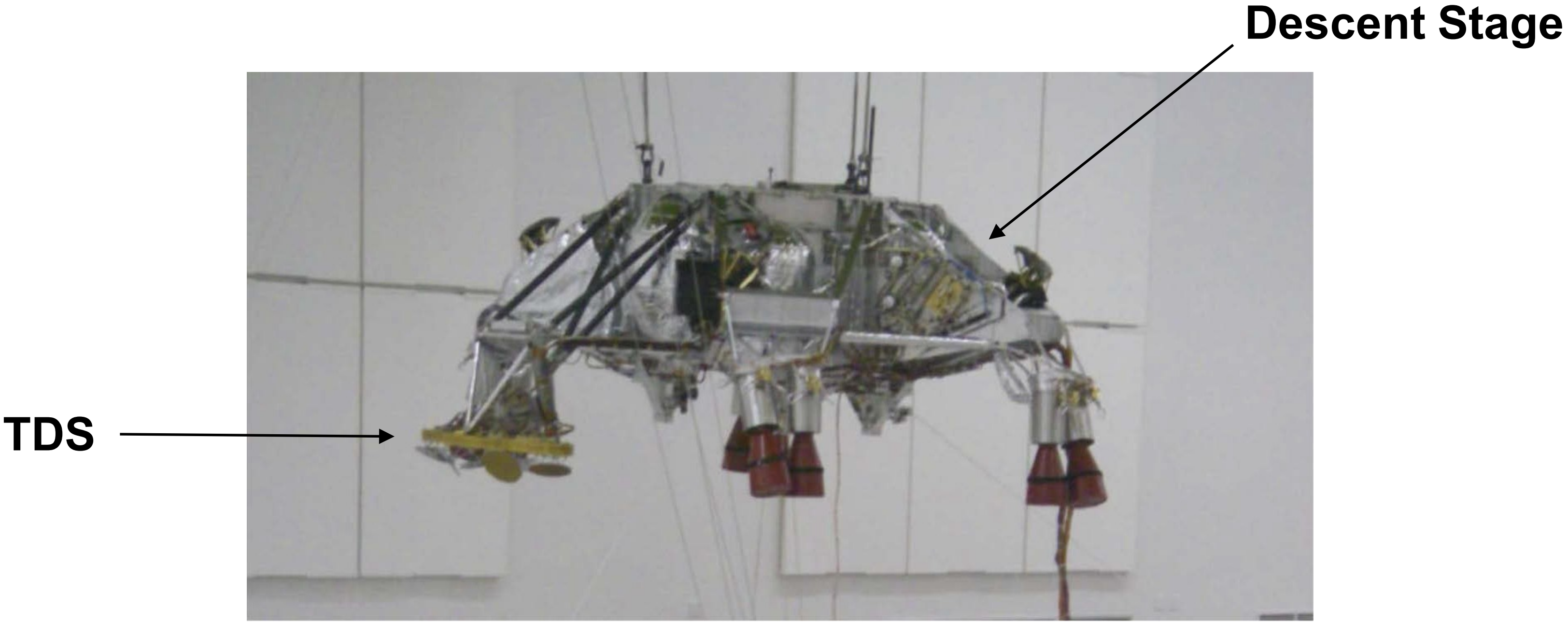
- MSL will be the first mission to "follow-the-carbon" (Prior missions have "followed-the-water")
  - Search for ancient habitats
  - Identify and classify carbon-based/organic minerals
- Instrument suite includes
  - Microscopic imaging
  - Stereo surface imaging
  - Multiple spectrometers
  - Gas chromatograph
  - X-ray diffraction



MSL Descent Stage and TDS

Terminal Descent Sensor (TDS) – radar

- New sensor developed at JPL
- Features
  - Pulsed-Doppler radar
  - Ka-band (35.75 GHz) center frequency
  - Provides velocimetry and altimetry
  - 6 independent slotted waveguide antennas
  - 45 deg near-field keep-out zone (to 6 m)
  - Fresh acquisition on each 50 ms dwell (not dependent on continuous “lock”)

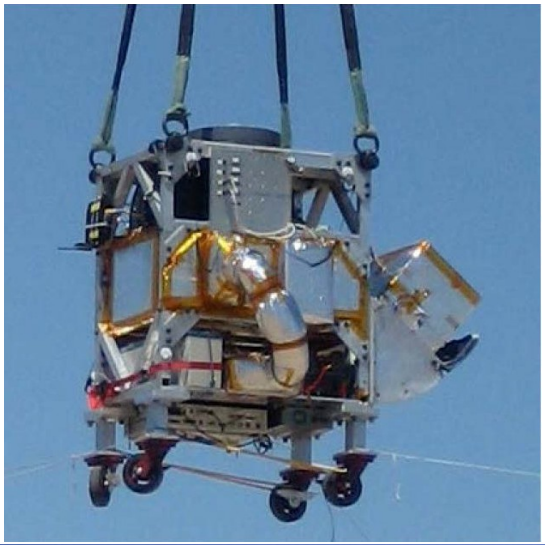


Field Test Campaign V&V Plan Strategy

- Two pronged approach to devising field test campaign
  - Test-As-You-Fly (TAYF)
    - > Define flight envelope of TDS operations during the parachute descent, powered descent and sky crane portions of the MSL Entry, Descent and Landing time-line
    - > Do this for range of landing sites, entry conditions, entry performance
  - TDS/NAV Filter "Worry Beads"
    - > Identify potential TDS and Navigation Filter performance limitations
    - > Devise stress tests, while not necessarily flight-like, create conditions to increase probability of a given limitation occurring
    - Identify flight venues to cover TAYF envelope and worry beads

Field Test Venues

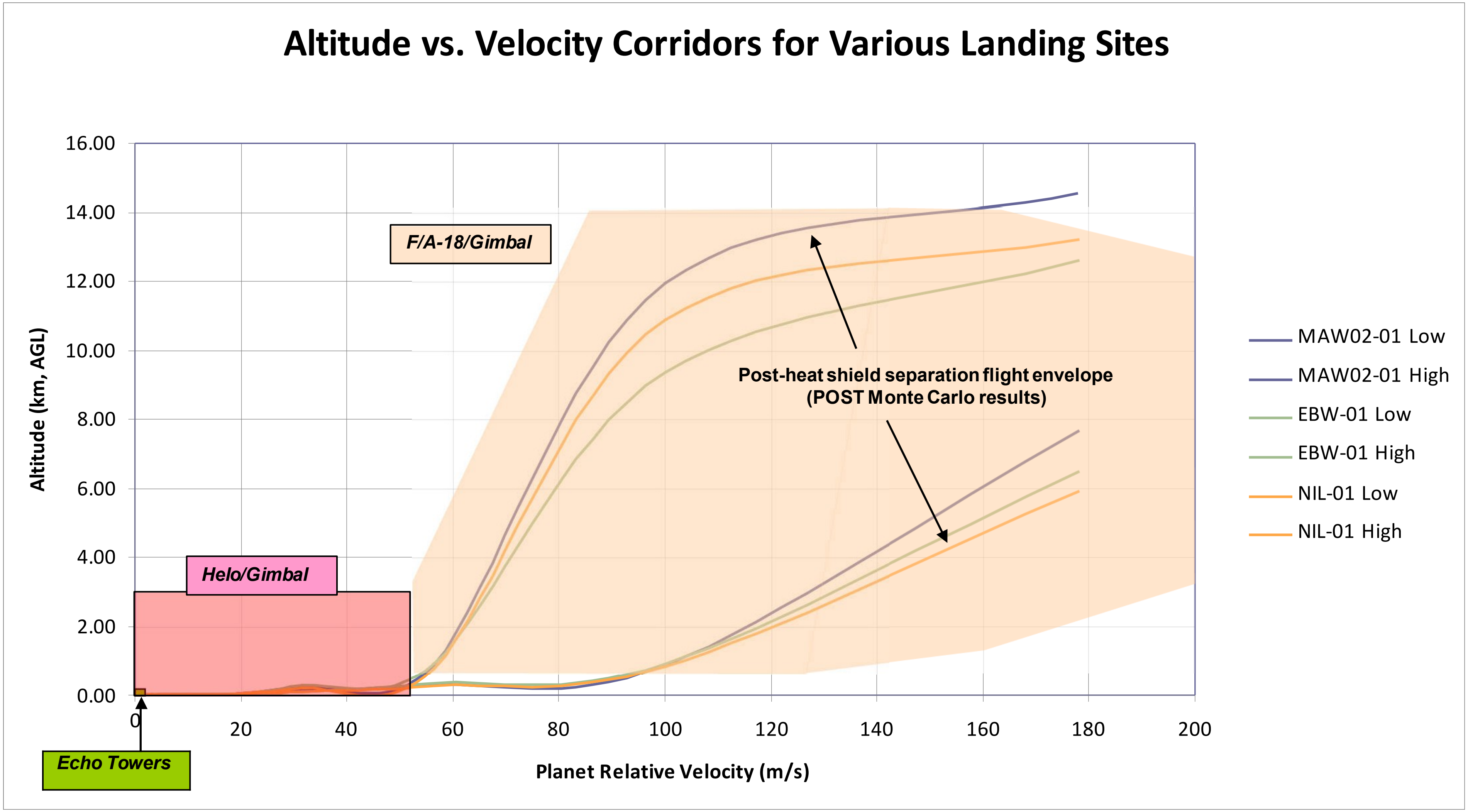
China Lake Echo Towers



NASA Dryden Flight Research Center F/A-18

Eurocopter AS350 AStar Helicopter

Descent Flight Envelope and Field Test Venue Coverage
Altitude vs Velocity



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

China Lake Overview

- China Lake Echo Towers
  - Test article is suspended from a cable/pulley system attached to wire spanning two 100 meter wooden towers
  - Ground vehicle attached to the cable used to raise & lower test article
- Primary Objective of this venue
  - Assess extremely low altitude and velocity performance during sky crane
- Challenges/limitations associated with this venue:
  - Testing limited to the terrain that exists beneath the article
  - Inability to achieve maximum desired vertical descent velocities
    - > Can achieve ~2 m/s vs expected speeds of, e.g., ~20 m/sec at 55 m above ground

Helicopter Overview

- Helicopter with Gimbal
  - Helicopter-mounted test system on a 1-axis (pitch) gimbal
    - > Helicopter max horizontal velocity ~50 m/s, max vertical descent velocity ~5 m/s
    - > Gimbal max angular rate ~90° /sec
  - Both one and six antenna configurations of TDS tested
  - Rover Deploy System (RDS) that raised and lowered full-size rover mock-up using winch
- Primary objectives of this venue:
  - Only venue with full six-antenna configuration, primary venue for…
    - > assessing integrated sensor performance and with dynamics greater than Echo Tower
    - > verifying Navigation Filter data editing performance and validating Nav Filter design
  - Testing over a richer set of terrain types
  - Characterization of possible TDS/Rover interactions during sky crane using RDS
- Challenges/limitations associated with this venue:
  - Altitude-constrained to ~3 km above sea-level
  - Limited vertical descent velocity

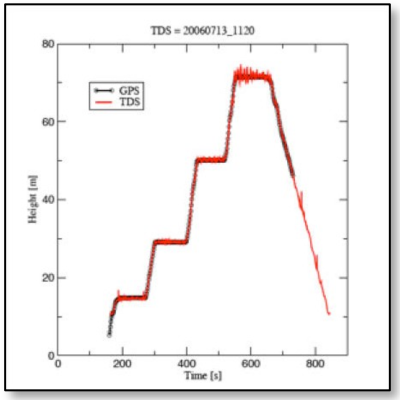
F/A-18 Overview

- High-speed, high altitude fixed wing aircraft
  - High-speed aircraft wing-mounted QTEP pod containing single TDS antenna with a 1-axis gimbal to introduce attitude rates
- Primary objective of this venue:
  - Assess extremely high altitude and velocity performance
  - Only venue which can achieve acquisition (i.e. on-chute) TAYF flight conditions
- Challenges/limitations associated with this venue:
  - Matching descent profile as a function of velocity versus altitude
    - Aircraft speeds up as it descends in a dive, parachute slows down
    - Can achieve desired flight conditions for limited periods of time
    - Mitigated by use of EGSE and simulations
  - Temperature control/humidity
    - Large temperature variation over flight envelope (+30C to -50C) – potential to exceed TDS EM capability and/or risk condensation
    - Mitigated by use of LN2-based Environmental Control System

Field Test Plan Summary

Test Objective	Test Type	Original Date as of May 2007 Plan	Actual Execution Date	Antenna	TDS Elec. l	MU	Data Acq.	Power Supply	Notes
BB antenna test series	Echo Tower (FT1)	Already Completed	Jul 2006	1COTS	BB	LN200	CDSU-1	Battery	1COTS antenna configuration mounted on adjustable pitch fixture
	Helicopter (FT2)	Already Completed	Nov-Dec 2006	1COTS	BB	LN200	CDSU-1	Battery+ Helicoper	1COTS antenna configuration mounted on single-axis (pitch) gimbal on helicopter
EM antenna test series	Echo Tower (fT3)	Jul2007	Descoped	1EMProto	BB	LN200	CDSU-1	Battery	1EM 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 (FTSm)	as of May 2007	Aug 2008	EM1A'		LN200	CDSU-2	Battery	1EM antenna configuration,mounted on adjustable pitch fixture
	Echo Tower (FTS)	Nov 2007	Descoped	EM1C		EM MIMU	CDSU-2	Battery	6 EM antenna configuratbn, no adjustable lpitch fixture, rover deploy system
	Helicopter (FT6a)	Jan 2008	Descoped	EM1C		EM MIMU	CDSU-2	Battery+ Hellcoper	6 EM antenna configuration,hardmounted to helo, no gimbal
	Helicopter (FT6b)	Mar2008	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+ Hellcoper	6 EM antenna configuratbn, mounted on lgimbal, TDSD/TOSR off TOSS
	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	1EM antenna configuration, mounted on !gimbal on helo
	Aircraft (FT8.1)	May 2008	April-June 2011	modified EM1C		EM MIMU	CDSUr	Aircraft power	1EM 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 lgimbal.
	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

FT1: July 2006



Altitude vs time comparing TDS measurements against GPS ground truth

Assembled system lifted above the ground. COTS antenna is mounted underneath on a fixture that allowed changes in antenna angle relative to the surface.

- Results
  - TDS generally behaved well
  - Provided validation of TDS high-level design and measurement concept
  - Met velocity error and bias and slant range error requirements
  - Tested over 11-70 m above ground level, with vertical velocities from 0-5 m/s and antenna angles from 0-25°
  - TDS internal system parameters need optimization

- Lessons Learned
  - Quick-look data validity tool for use in field is critical to uncovering issues with data while still in the field to determine if re-running of tests is necessary
  - Detailed check-lists and procedures with personnel roles and responsibilities need to be in place prior to field test execution

FT2: Nov-Dec 2006

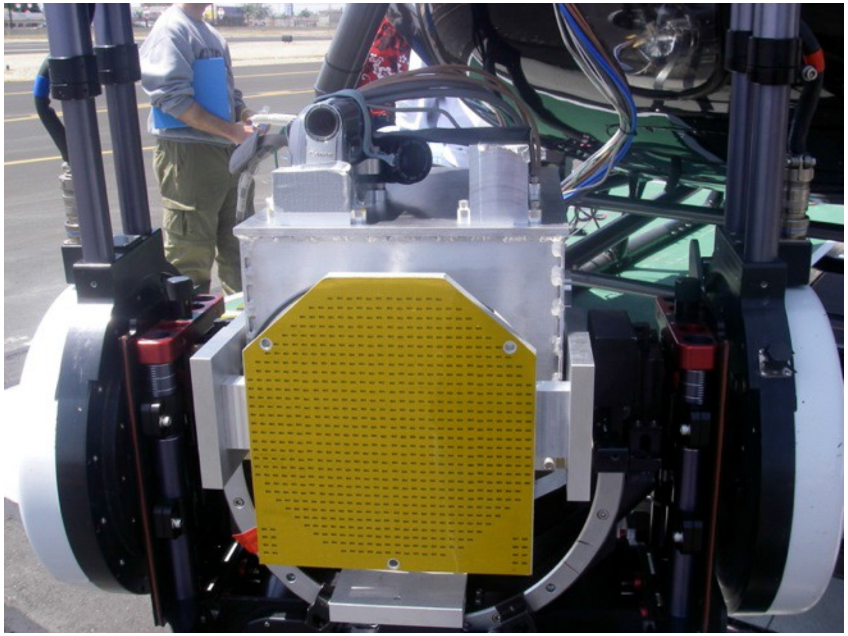
Close-up of the COTS antenna and housing containing the IMU mounted on the gimbal

Helicopter in flight, breadboard TDS electronics and additional test support electronics reside in the helicopter cockpit

- Results
  - First test on helicopter
  - 13 flights executed over 4 days
  - Exposed TDS to larger magnitude slant ranges, total velocity, off-vertical antenna angles and non-zero horizontal velocity
  - Expanded test envelope allowed a number of issues with the TDS to be uncovered and fixed
  - Two-week campaign planned for desert was cancelled due to issues discovered

- Lessons Learned
  - Precede field test proper with shakeout activities that can be performed with reduced logistical overhead prior to the main field test deployment
  - 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

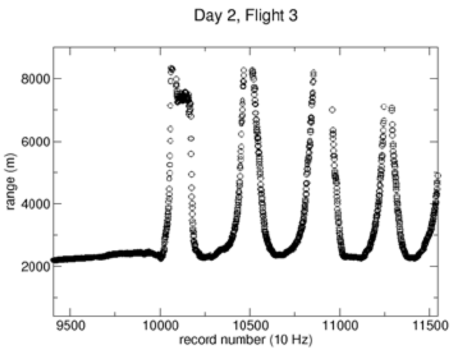
FT4: April 2007



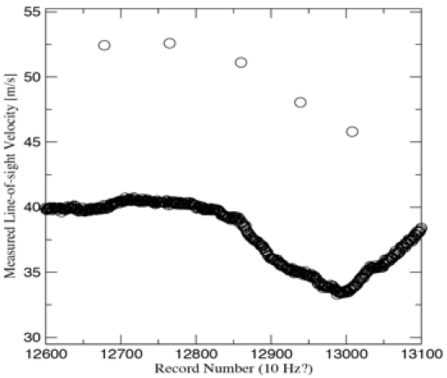
Close-up of the EM prototype antenna and housing containing the IMU mounted on the gimbal

Helicopter in flight, breadboard TDS electronics and additional test support electronics reside in the helicopter cockpit

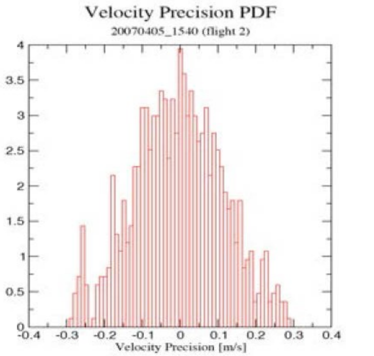
FT4: April 2007



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.



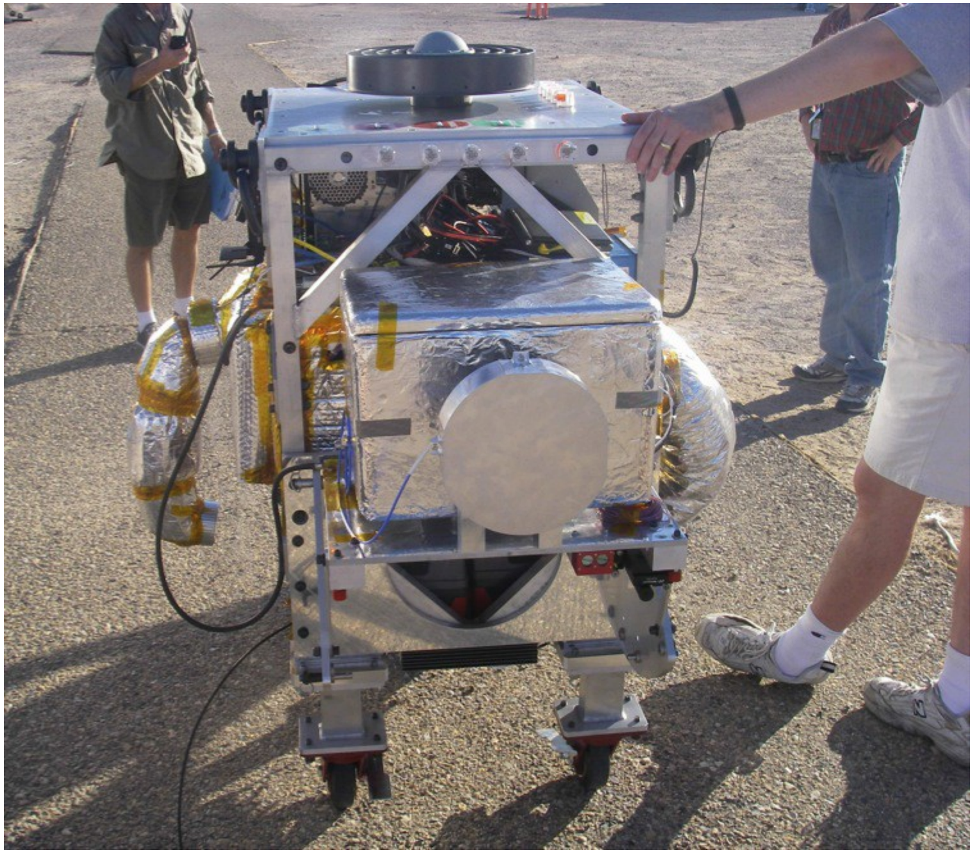
Line-of-sight velocity versus time as measured by the TDS and is largely correct except for the outliers due to a velocity unwrapping problem, which was later corrected. Velocity unwrapping resolves the 2pi ambiguities in observed Doppler phase in order to estimate the true line-of-sight velocity.



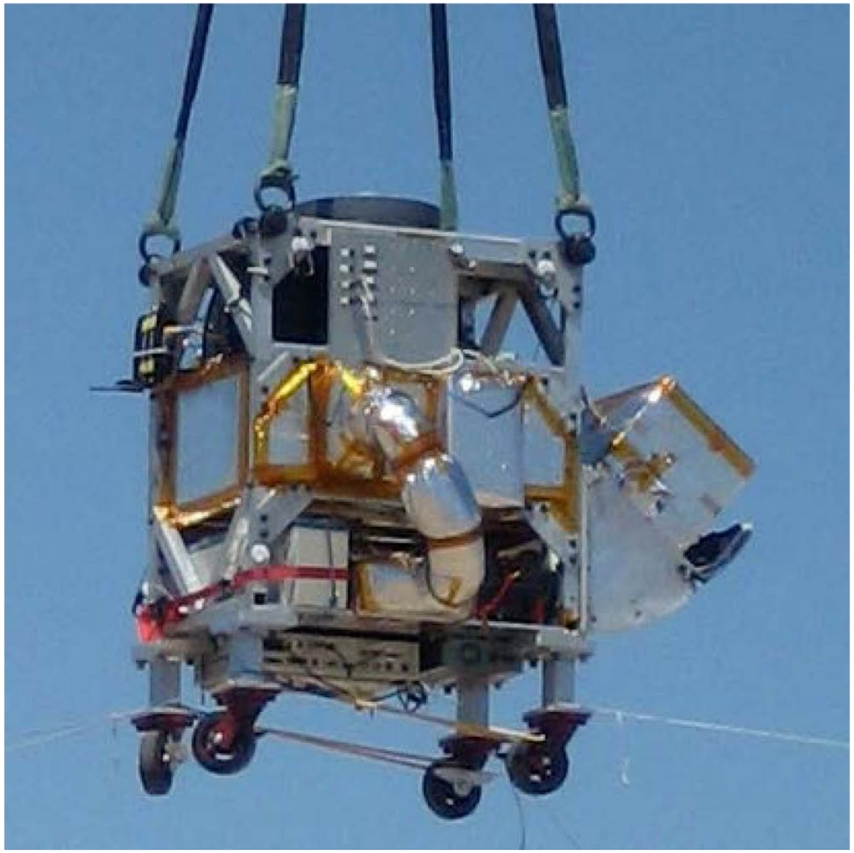
Probability Density Function of velocity precision and is estimated to be ~0.27 m/s, 3 sigma, well within requirements.

- Results
  - Updated breadboard TDS electronics and replaced COTS antenna with EM TDS antenna
  - 19 flights executed over 5 days
  - TDS shown to acquire targets and produce self-consistent results out of more than 95% of possible good data
  - Velocity and range measurement errors within requirements
  - Still some issues related to TDS parameter settings
- Lessons Learned
  - Make sure all hardware interfaces and connectors are designed for the environment that they will be subjected to and are secured properly
  - Make sure that quick-look tools are in place that will validate data integrity in the field (lesson re-learned)
  - Ensure adequate margin in schedule to deal with unexpected issues (weather delays, for example)

FT5m: August 2008

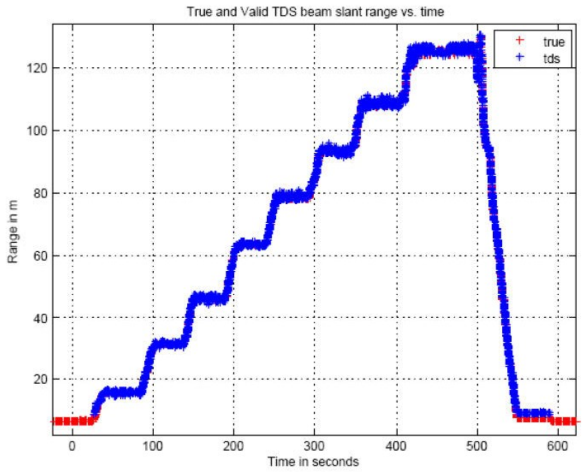


System on the ground

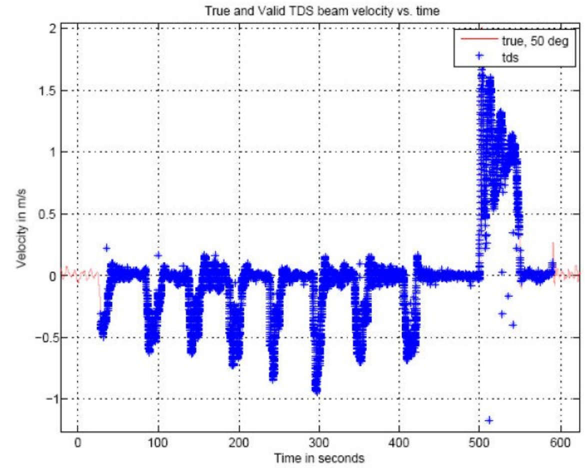


System in the air, TDS antenna canted at 50° off-vertical.

FT5m: August 2008



Altitude vs time comparing TDS measurements against ground truth. TDS antenna angle set to 50° off-vertical and test cart 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.



Line-of-sight velocity vs time comparing TDS measurements against ground truth for test profile on left

- Results
  - First test with 1-antenna EM TDS
  - Tests executed over 3 days
  - TDS performed extremely well and all test objectives met
  - Velocity and range measurement errors within requirements
- Lessons Learned
  - First time testing with JPL Critical Items which required additional safe-handling constraints and greatly increased amount of institutional processes and procedures to be followed
  - Resources required (time, money, people) were underestimated due to not taking into account these additional constraints when plans were made

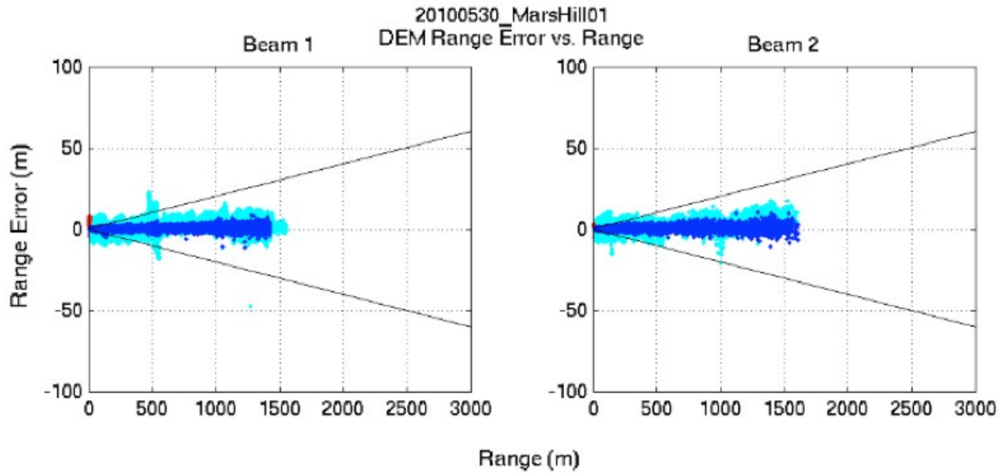
FT6d: May-June 2010

Close-up of the EM TDS and support electronics mounted on the gimbal

Flight over Rogers Dry Lake Bed at Edwards Air Force Base during Rover Deploy System testing

Testing over “Mars Hill” at Death Valley

FT6d: May-June 2010



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.

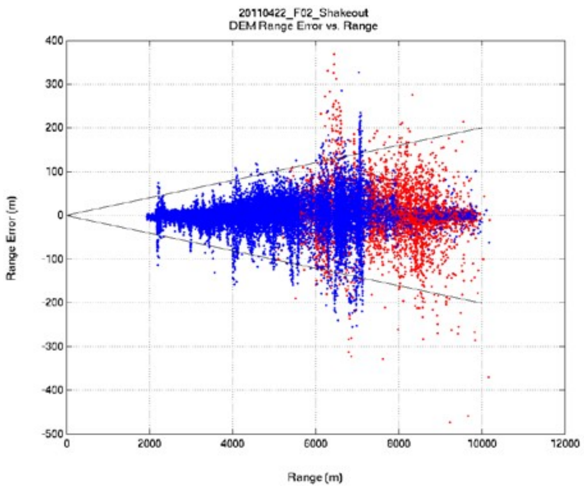
- Results
  - First test with complete 6-antenna EM TDS
  - 37 flights executed over 4 test sites
  - TDS performed extremely well and all test objectives met
  - Velocity and range measurement errors within requirements
  - No concerns uncovered due to RDS testing
- Lessons Learned
  - Major lesson learned related to a replan that occurred in between FT5m and FT6d
    - Replan occurred without inputs of many of personnel doing the low-level work
    - Scope of field test plus cost, schedule and personnel required were all underestimated
    - Make sure to involve all key personnel during planning
  - Don't attempt to do two field tests in parallel unless there are two independent teams

FT8.1: April-June 2011

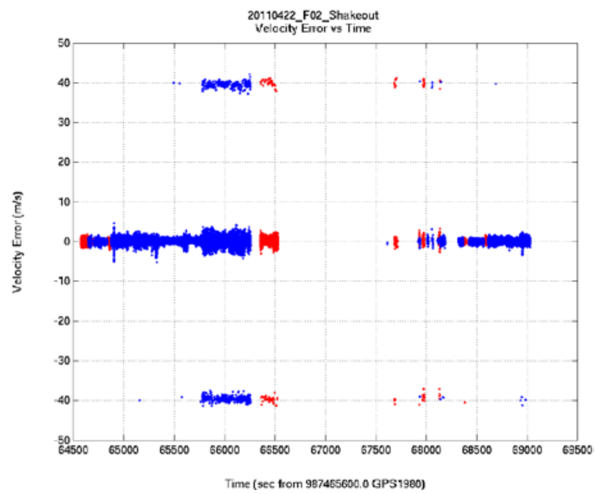
System with radome removed from the pod and MIMU, gimbal and TDS antenna visible

The F/A-18 in-flight over Edwards AFB

FT8.1: April-June 2011



Range error as a function of slant range. Error requirements (99%) are given by the two solid lines and increase with range. Blue indicates measurements marked valid by the TDS, while red indicates measurements marked invalid. Invalid measurements are not used by the NAV filter



Velocity error as a function of time. Outliers above and below the main data set are due to velocity unwrapping errors expected under these operating conditions and are not a concern. Color indicators are the same as the left plot.

- Results
  - First (and only) test on F/A-18
  - 19 flights with ~21 flight hours and TDS "on-condition" ~44 minutes
    - Low ratio of on-condition to total flight time is indicative of how difficult it is for an aircraft to achieve MSL EDL flight profile
  - TDS performed extremely well and all test objectives met
  - Velocity and range measurement errors within requirements

- Lessons Learned
  - Make sure to put sufficient schedule and budget margin in plans, commensurate with the complexities and unknowns associated with the effort

Conclusion

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

FT6d: May 2010 (movie)

FT8.1: June 2011 (movie)