



Under the Radar: Trials and Tribulations of Landing on Mars

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Phoenix Introduction



- **The Mars Phoenix Mission requires a ground-sensing radar altimeter/ velocimeter to meet touchdown velocity requirements**
- **During Phase C/D, the radar underwent a testing triptych:**
 - Aerial Testing, both captive carry and tethered drop tests
 - 36 sorties, approx. 80 hrs
 - Testing with Electronic Ground Support Equipment (EGSE) on the bench
 - 500+ hrs
 - Detailed Simulation including both RF physics and internal firmware logic
 - 100,000+ simulated landings
- **All three venues were implemented to provide sufficient uniqueness and overlap to:**
 - Verify the radar is meeting its requirements
 - Validate radar performance within the flight system and environment
- **Significant discoveries were attributed to each of the three elements of the testing triptych, leading to greatly improved EDL system robustness**
- **An overview of the testing triptych methodology, discoveries, and responses to them will be subsequently discussed**



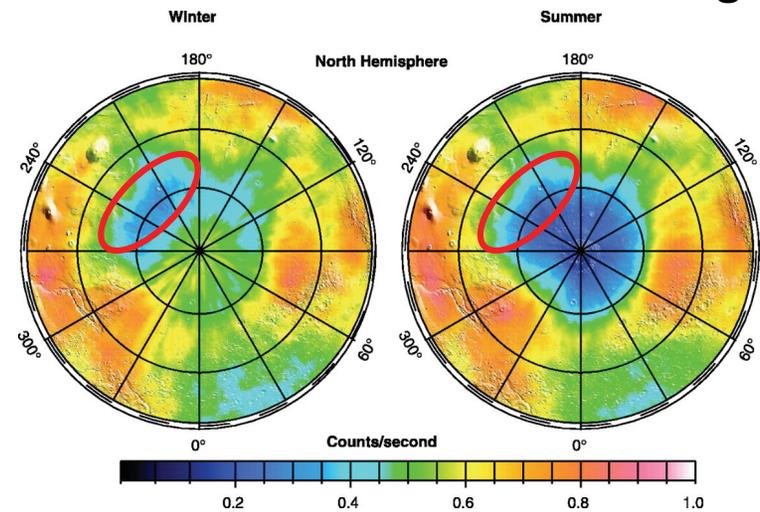
Phoenix Mission Overview



What is Phoenix?

- The first of the PI-Led, NASA Competed Mars Scouts missions launched 8/4/07, Landing 5/25/08
- Utilization of existing designs, hardware and software to enable a very capable mission at Mars Scouts Level costs cap
 - Mars '01 Lander Re-flight (derivative of MPL)
- Partnership between university, NASA center and industrial teams
 - UA (Science leadership, instrument development, surface operations)
 - JPL (Project Management, Mission Design, System Engineering, instrument development, EDL design/validation)
 - Lockheed Martin (Spacecraft design, fabrication, integration and test)

The Lure: A Water Rich Polar Region



Mars Odyssey shows epithermal neutrons: blue = water rich

Four Primary Science Objectives

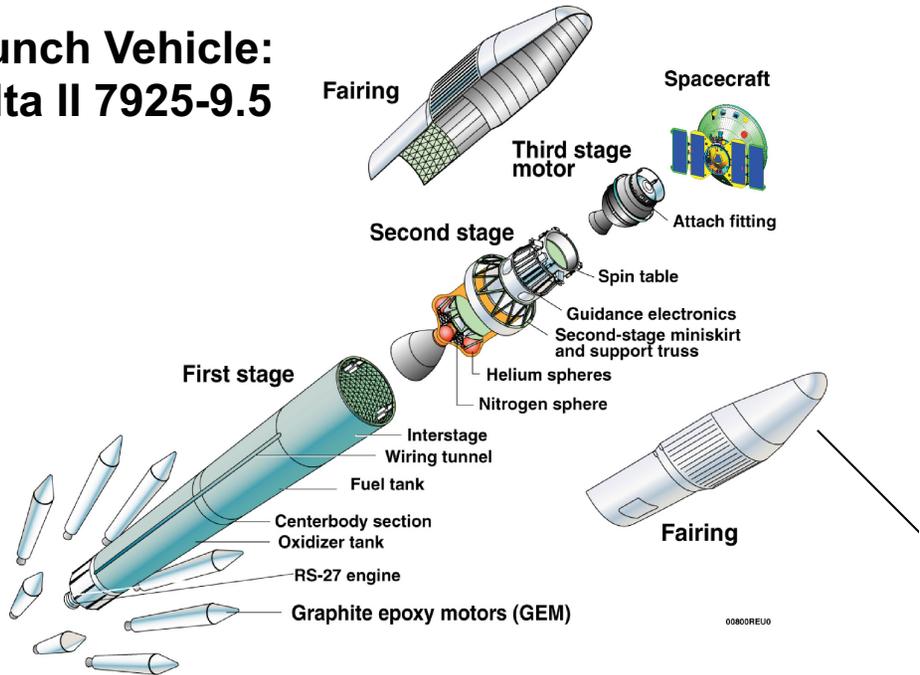
- Polar weather studies
- Characterize Northern latitude geomorphology
- Study regolith mineralogy and chemistry
- Characterize water, ice, and polar climate history



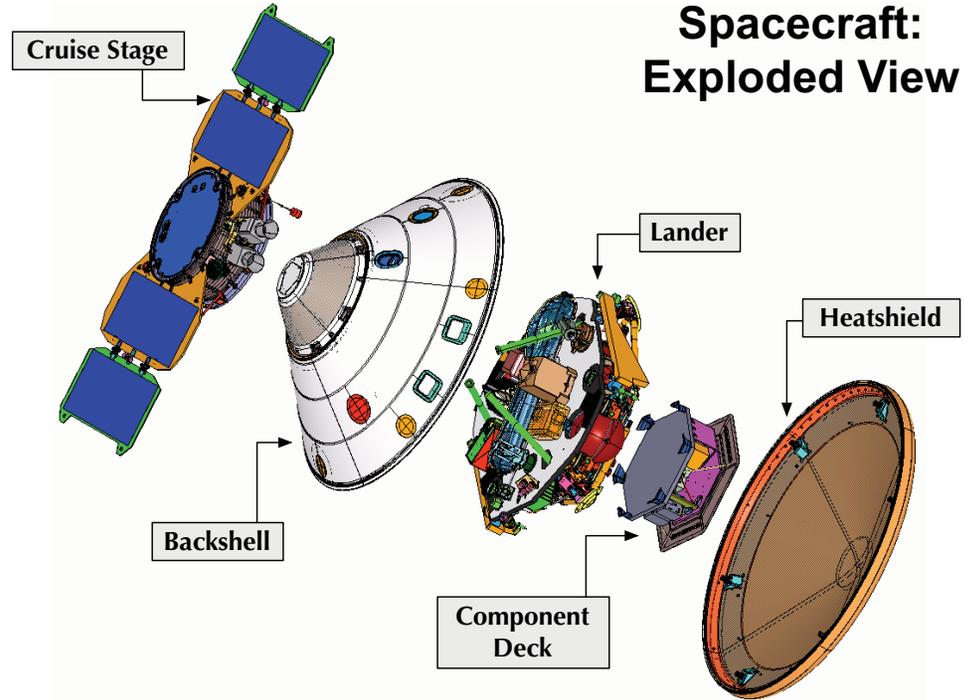
Phoenix Flight System



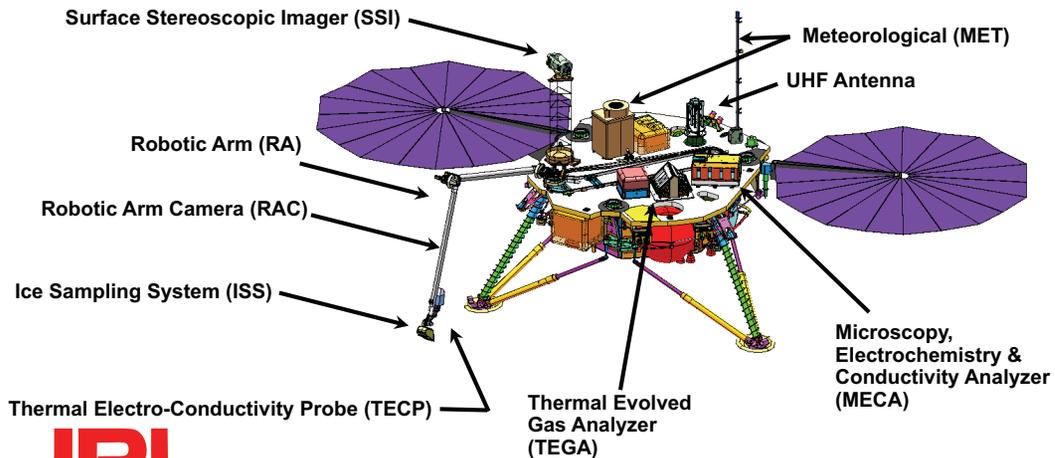
Launch Vehicle: Delta II 7925-9.5



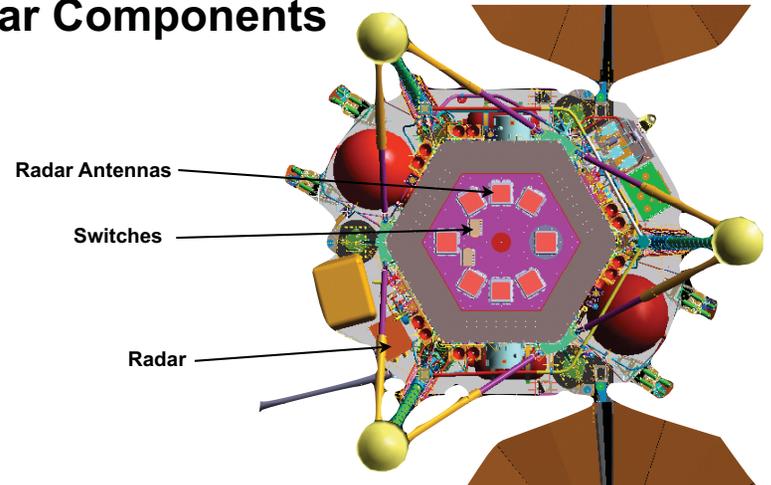
Spacecraft: Exploded View



Lander: Fully Deployed

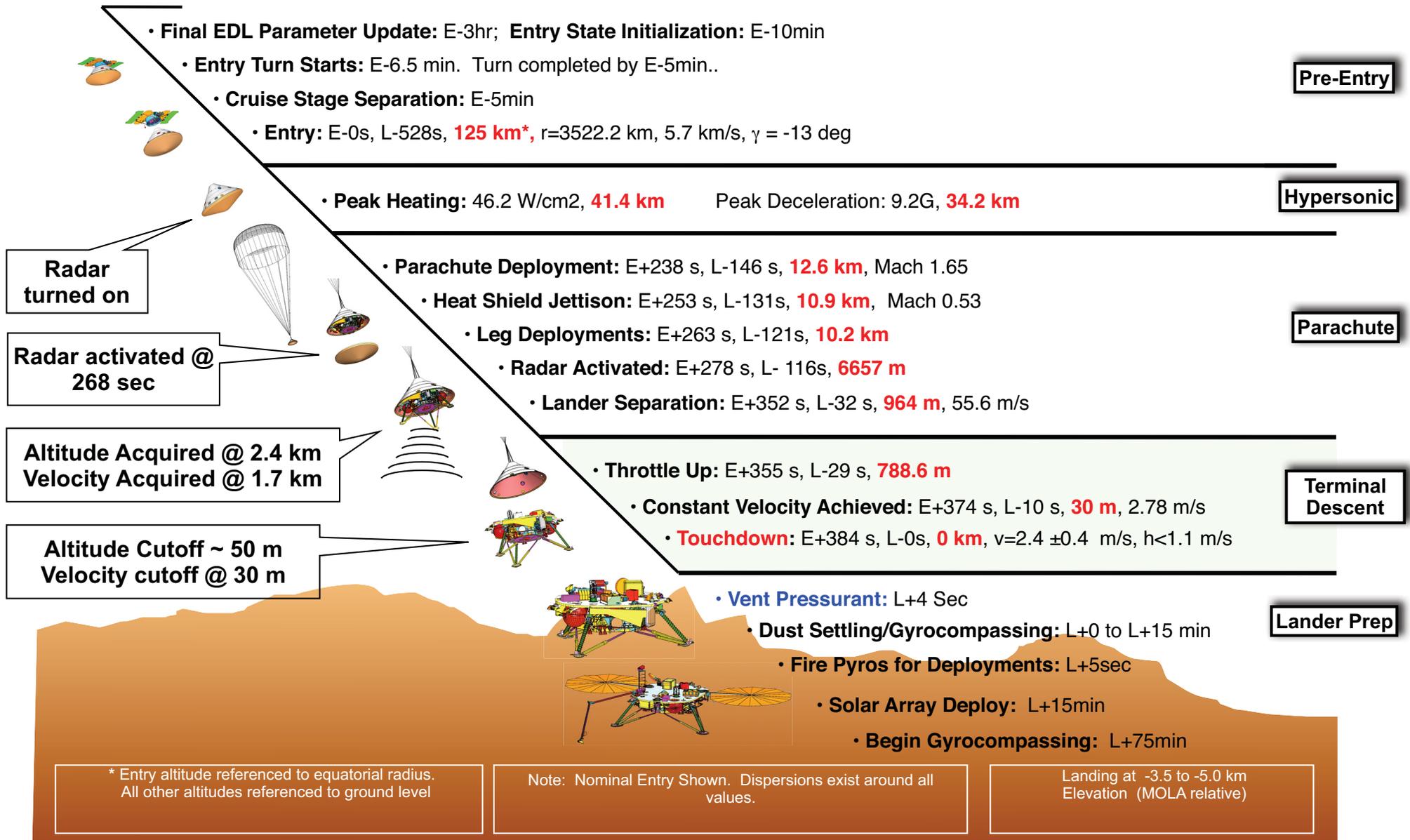


Radar Components





EDL Timeline Overview



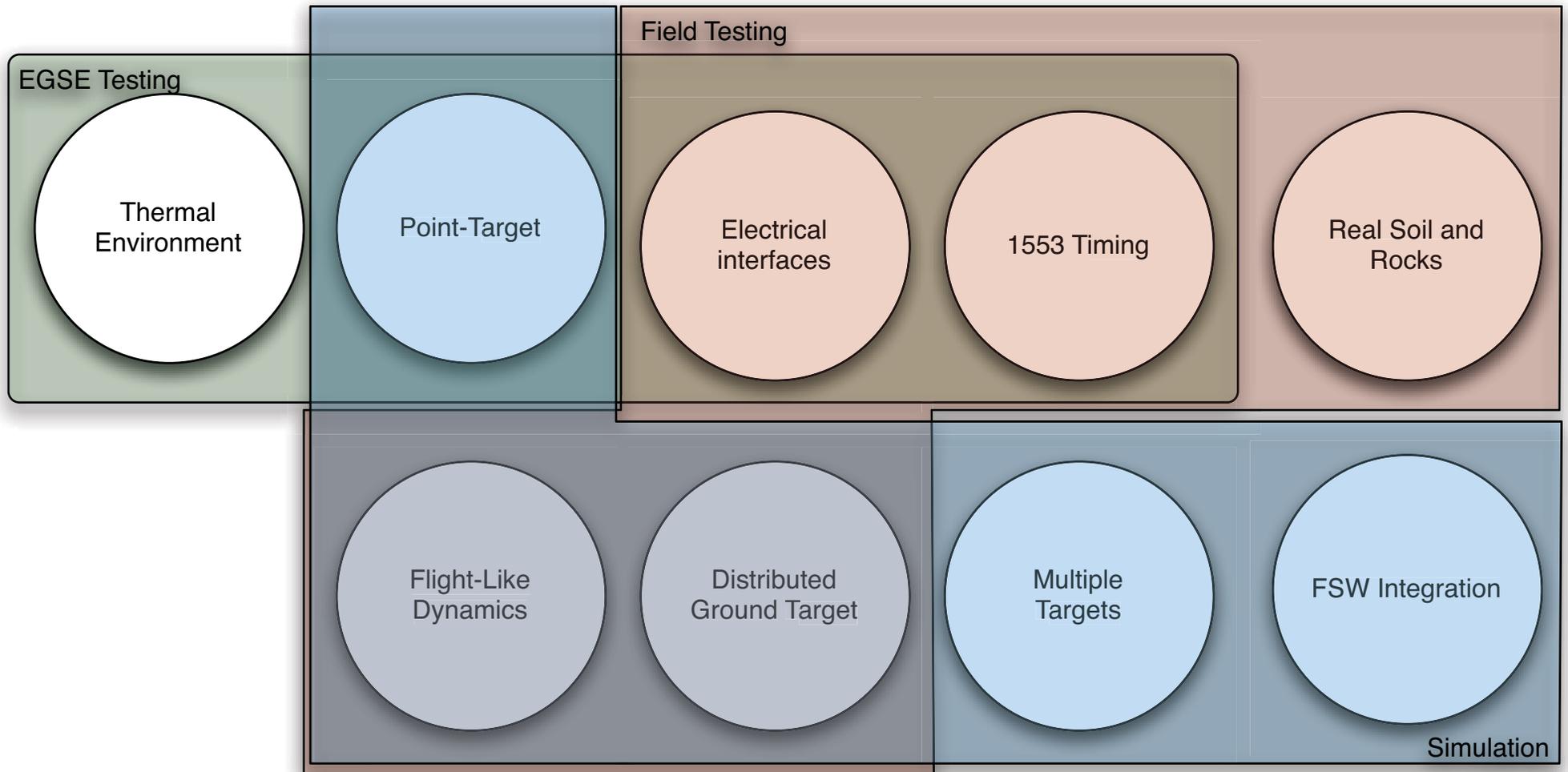


Radars Testing Philosophy (Overview)

- **Over-arching concept: “Test Like You Fly” wherever possible**
- **Provide **unique** and **overlapping** test coverage through multiple test venues:**
 - Radar Field Tests
 - Helicopter Captive Carry
 - Helicopter Tethered Drop Tests (a.k.a. “Radar on a Rope”)
 - Radar Bench Tests using Electronic Ground Support Equipment (EGSE)
 - Fixed-Length Delay Line and Coarse Doppler EGSE
 - Variable Fiber Optic Delay Line (FODL) and “Fine Grain” Doppler EGSE
 - EDL Simulation
 - Includes high-fidelity radar model
- **Different venues discovered different phenomena**
 - Each venue is critical to span space of potential problems
 - EDL simulation has most flight-like system behavior
 - Flight-like dynamics with flight software, timing, and interfaces
 - EGSE provides a repeatable, well-controlled hardware test environment
 - Thermal, timing, and electrical interfaces
 - Field testing provides environmental (terrain) interactions with instrument
 - Varying relief and material reflectivity
 - Ability to put bright ground targets in field of view



Radar Test Venue Overlap





Radar EGSE Overview

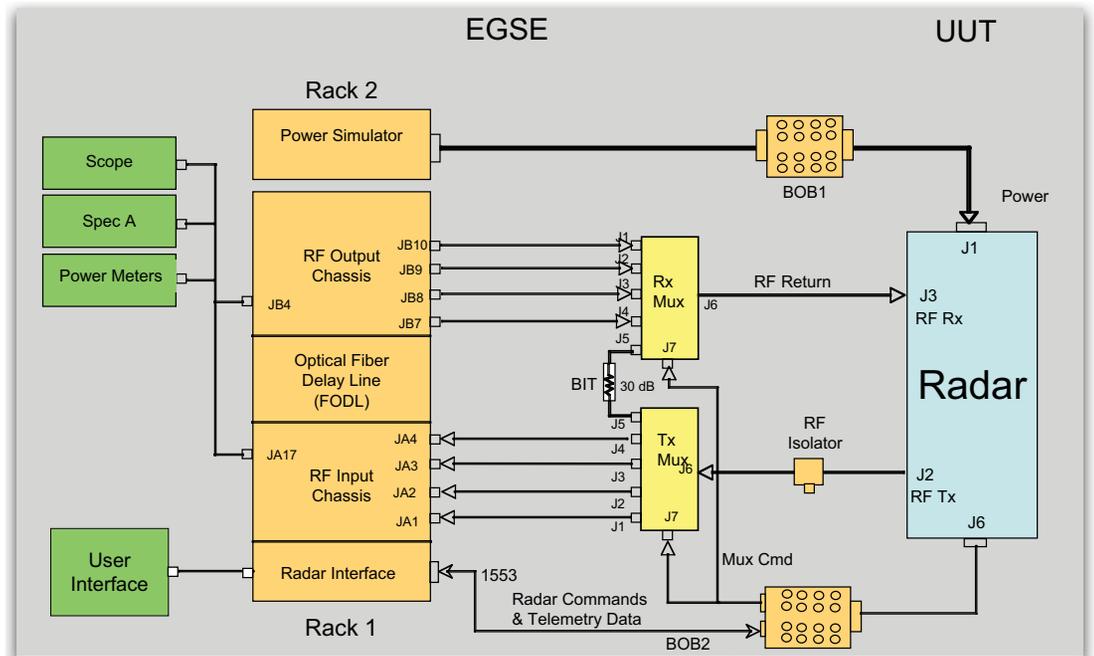


Capabilities

- Dynamic performance assessment in a laboratory environment
- Altitude from 31 m to 12.6 km in 0.2 m steps
- Doppler from ± 10 KHz in 1 Hz steps
- Return loss from 57 dB to 177 dB in 0.25 dB steps
- 250 MHz signal bandwidth
- 60 dB instantaneous dynamic range
- Configuration update rate > 200 Hz

Test Types (abbreviated list)

- Transmit Characteristics
- Make-Track & Break-Track Sensitivity
- Ambiguous Altitude Sweep
- Altitude Range and Accuracy
- Doppler Range and Accuracy
- Doppler Gate Positioning
- Anti-Aliasing Filter Verification
- Radiating BIT Test
- Command Timing
- Radar Voltage Margin
- Leakage Interference





Radar EGSE Testing Discoveries



Delayed Make-Track

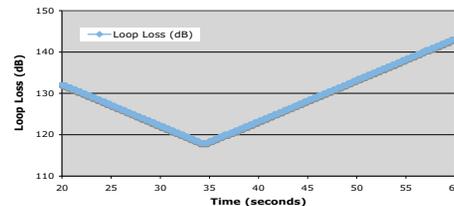
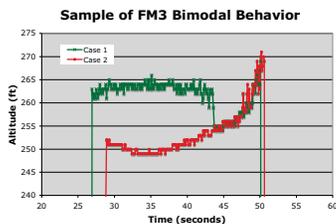
- **Delayed acquisition was observed in 2 of 4 tests that were run using a 250 ft delay and nominal loop attenuation**
- **Concerns:**
 - Several radar fault protection modes lead to power cycling the radar
 - If a power cycle occurs late in terminal descent and the radar takes several seconds to re-acquire, there may be insufficient data for the navigation solution to re-converge
 - Temperature Initialization Firmware Bug

- **Resolution:**
 - Modified firmware logic to fix the discovered bug
 - Adjusted calibration curves in radar firmware to reduce sensitivity to temperature changes

Bimodal Behavior

- **Concerns:**
 - At low returned echo strength, the radar can enter a tracking state where altitude errors can be as high as 5%
 - Not intermittent: error correlated to signal level

- **Resolution:**
 - Phenomenon observed in field tests targeted to reproduce EGSE test conditions
 - Conditions under which phenomenon was observed are not considered to be flight-like given trajectory and expected surface return on Mars
 - Accept as is, with no change required





Radar Simulation Overview



- **Objective is to faithfully represent significant hardware, software, and environmental effects that influence the accuracy of the radar**
- **Implementation**
 - Written in C for a generic unix platform
 - Runs both stand alone or integrated with EDL simulations
 - Including Monte Carlo implementation
 - Run-time is approximately 2 hours for 60 seconds of simulation time (600 radar samples)
- **Features include**
 - Detailed radar firmware algorithms for search and track modes as provided by the manufacturer
 - Some hardware effects such as ADC saturation and detector non-linearity
 - Time-correlated errors such as speckle (fading) and filter time constants
 - Range-ambiguous returns that could cause false locks
 - Arbitrary topography (DEM) and backscatter distribution
 - Arbitrary trajectory and attitude on descent
 - Rock fields and point target scatterers
 - Utilizes predicted or measured two-dimensional antenna patterns

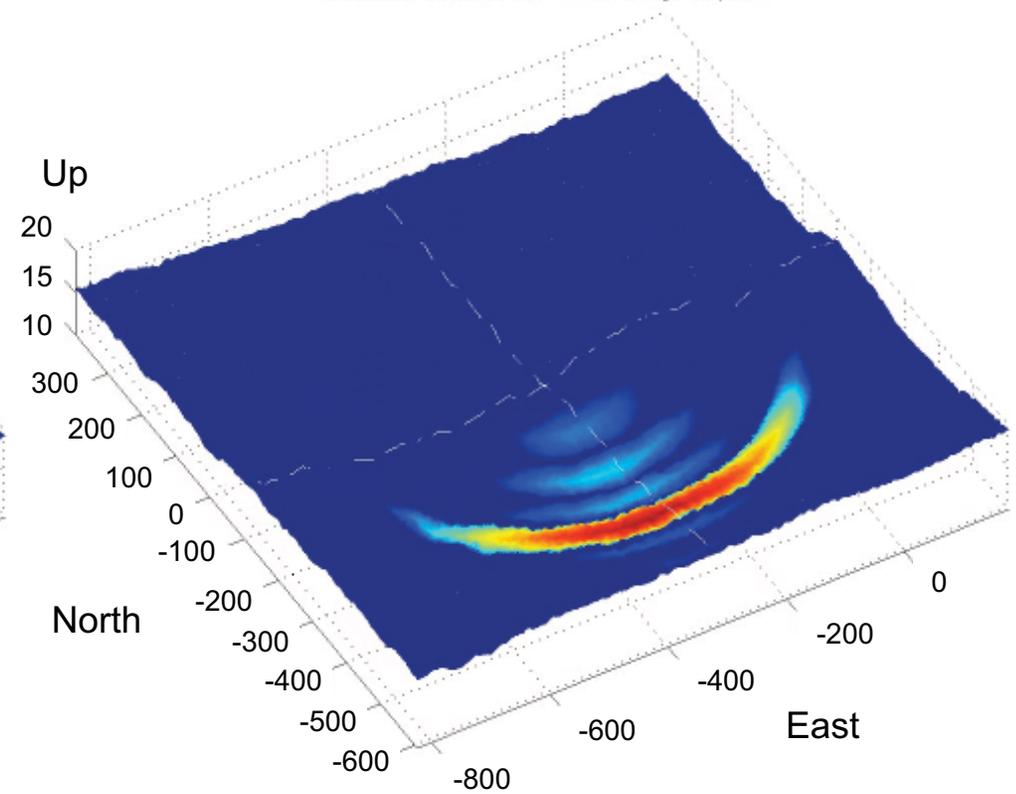
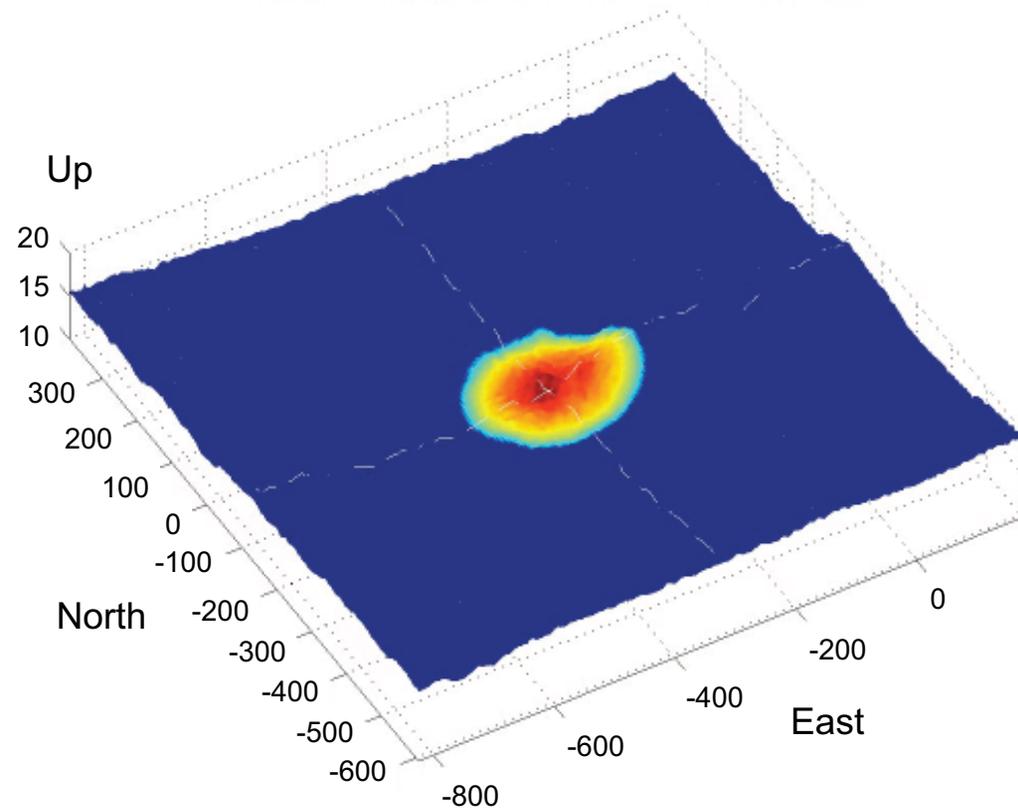


Radar Simulation Images



Altitude (nadir) Beam: $h = 457$ m Range Step #4

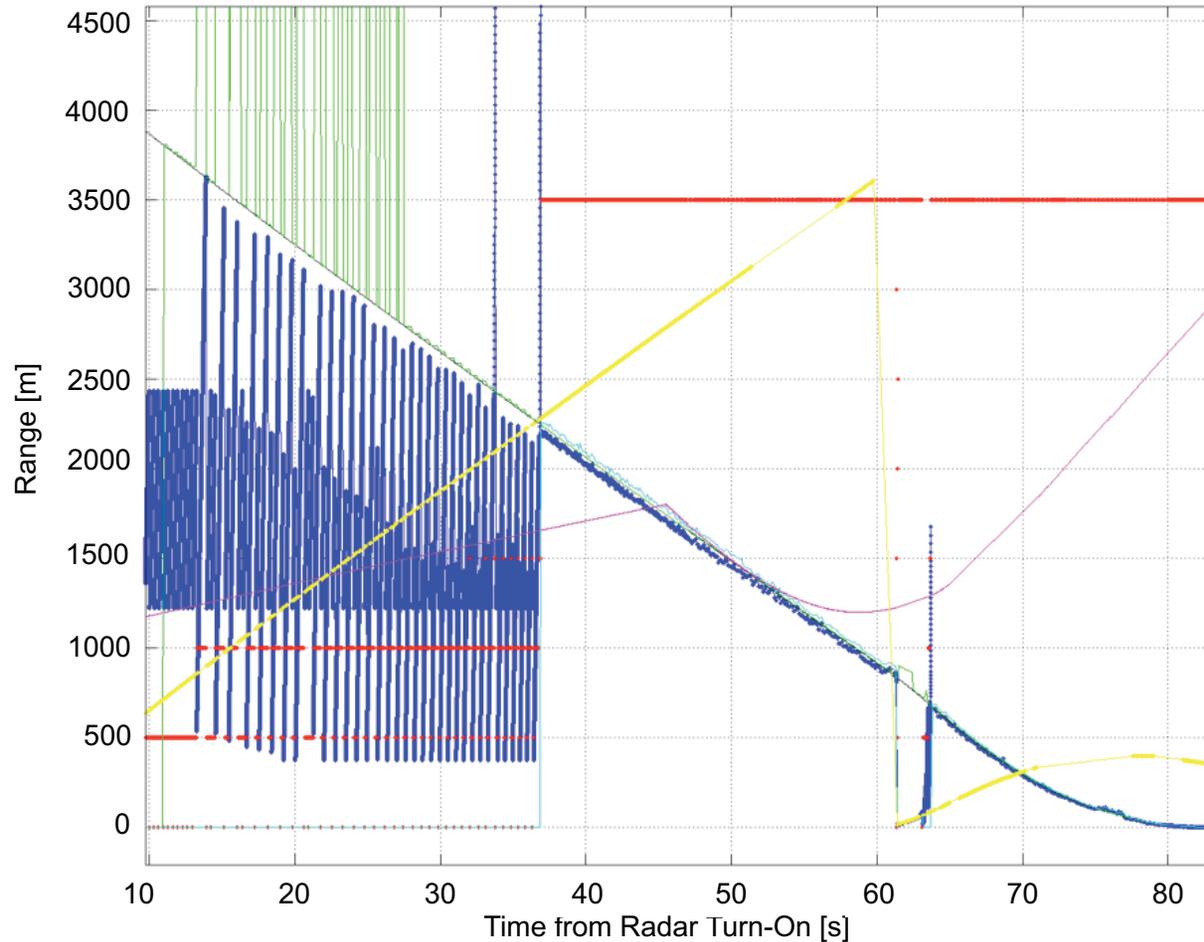
Velocity (canted) Beam: $h = 457$ m Range Step #4



All axes in meters



Radar Simulation Altimetry Example



Blue = radar adjusted internal altitude
Red = radar sim internal mode x500
Black = nadir altitude
Green = min range to examined part of surface
Cyan = reported altitude (different time sampling than s/c)
Magenta = heat shield range
Yellow = backshell range



• Discovery:

- At particular lander/heat shield ranges, the heat shield can confuse the search logic in the radar firmware
- Radar locks on an ambiguity, which causes the unit to report shorter-than-true ranges
 - Typically occurs at ~6.5 km true altitude; radar reports ~1.5 km altitude
 - Lander separation logic immediately commands backshell separation, resulting in failure
- Phenomenon occurred in 20-50% of simulations

• Resolution:

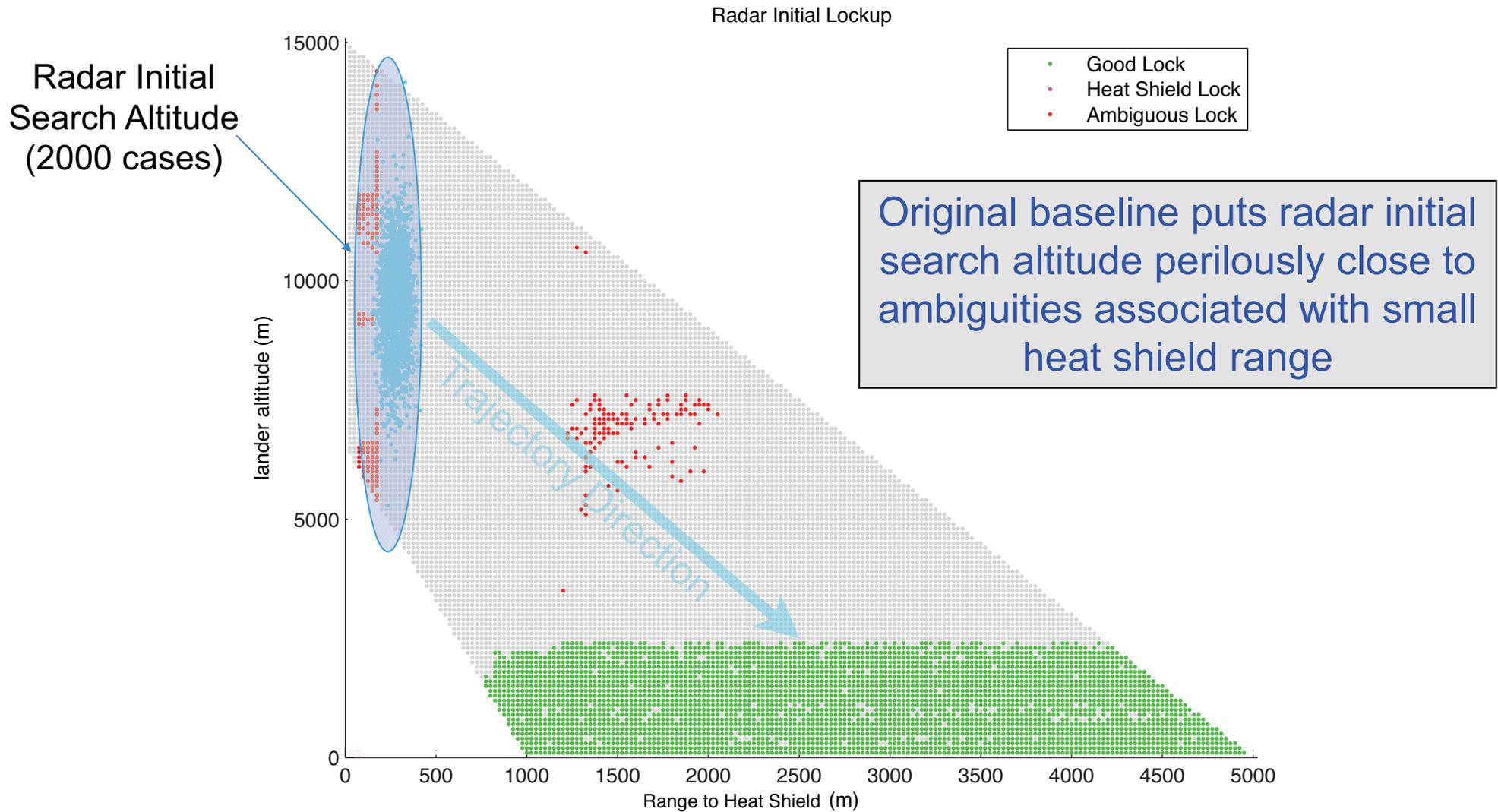
- Delay radar initial search and double the Pulse Repetition Interval
 - Ambiguity Maps (following three slides) developed to visualize vulnerability and solution
- Preclude lock on initial targets < 300 m
- Improve heat shield lockup logic



1x PRI, No Radar Initial Search Delay



PRI = Pulse Repetition Interval

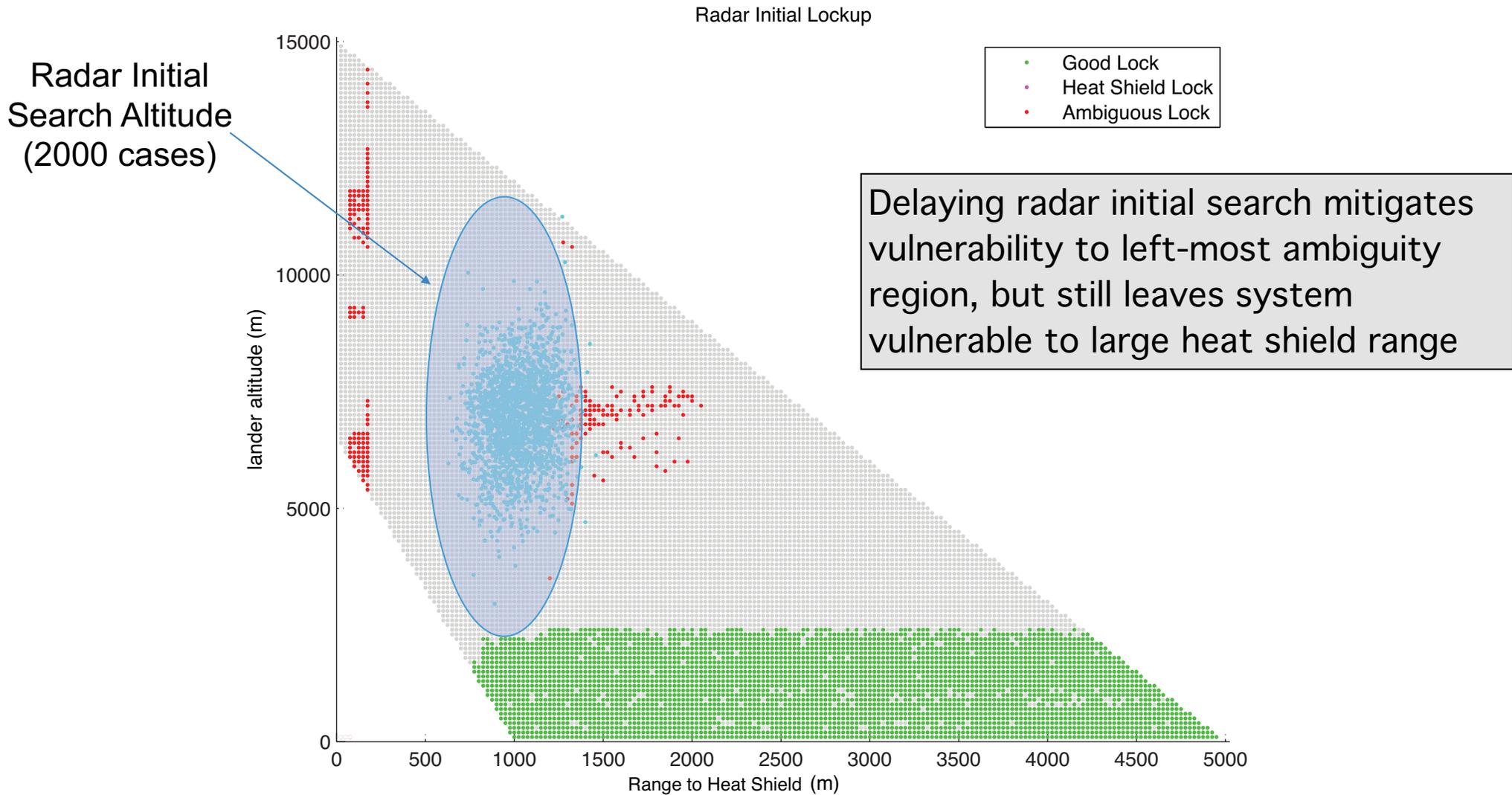




1x PRI, Radar Initial Search Delayed 40 sec



PRI = Pulse Repetition Interval



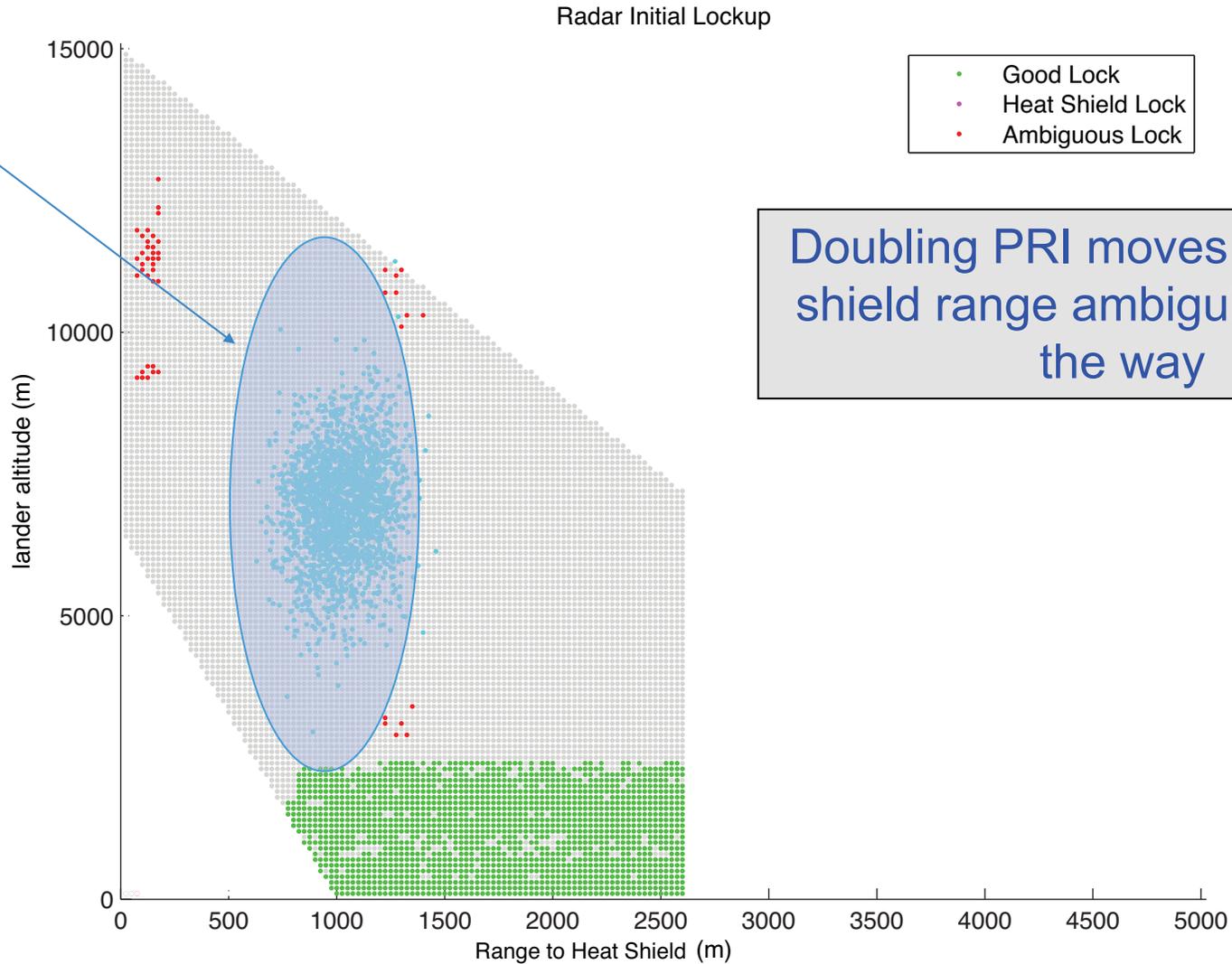


2x PRI, Radar Initial Search Delayed 40 sec



PRI = Pulse Repetition Interval

Radar Initial Search Altitude (2000 cases)



Doubling PRI moves large heat shield range ambiguities out of the way



Sim Discovery: Slant Range Lock Persistence



• Discovery:

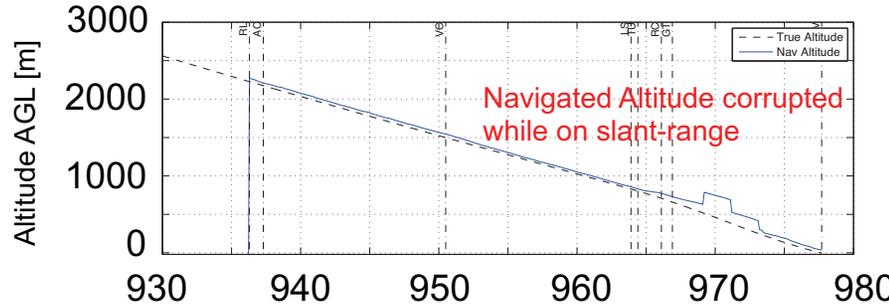
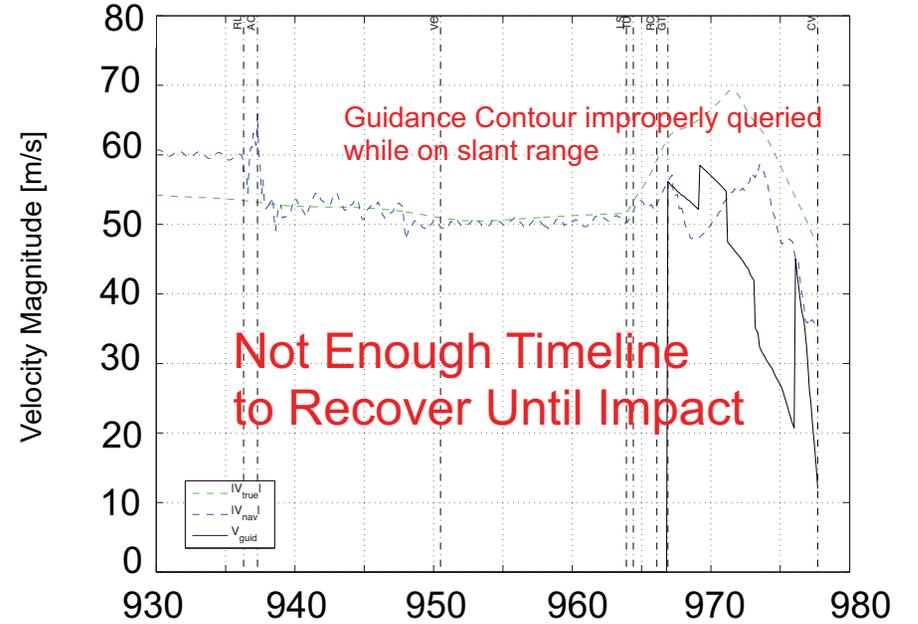
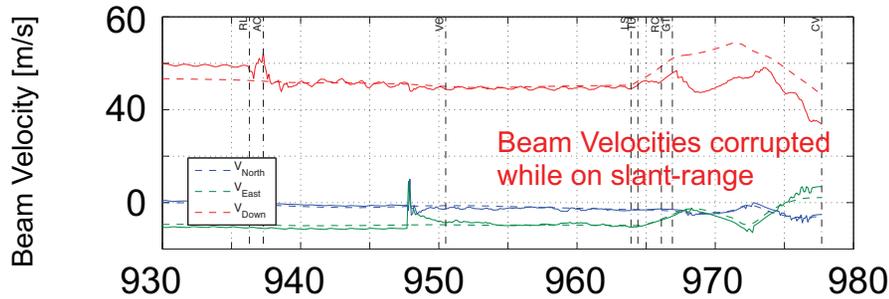
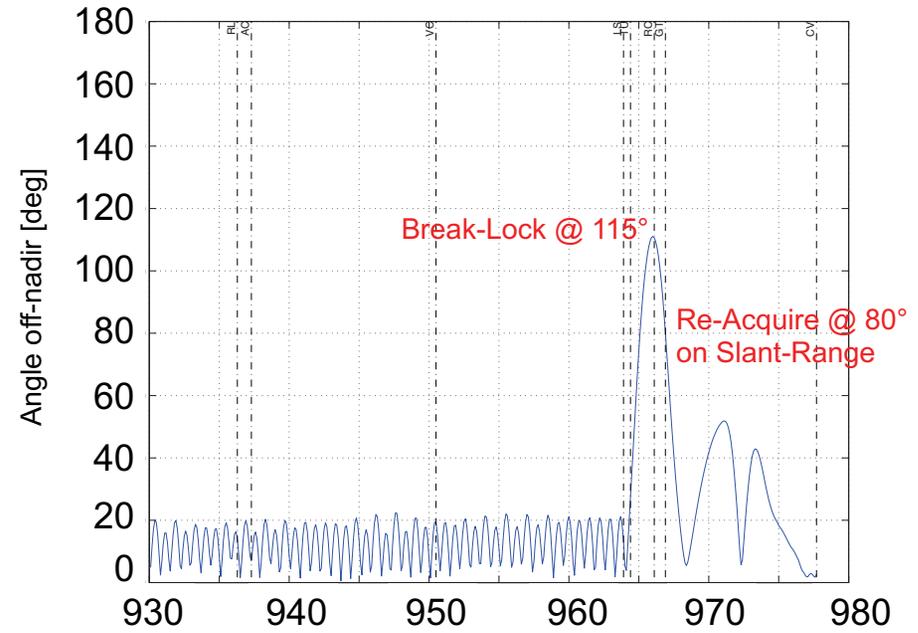
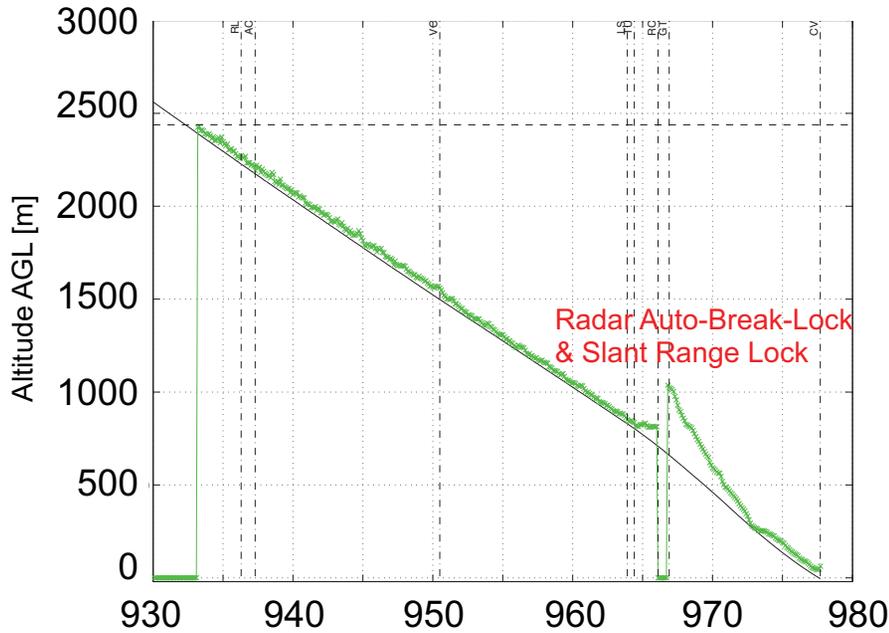
- Large **off-nadir** angles during search for the ground can cause locks on large slant ranges (slant range \gg than true range to ground)
- Even when returning towards nadir point, these locks take 5-10 sec to recover
 - Spacecraft can run out of timeline or control authority to respond to anomaly
- Also evident in test data from field tests

• Resolution:

- Added dual-threshold flight software check
 - Command radar break lock when off-nadir angle $> 45^\circ$ (below expected auto-break)
 - Allow search when off-nadir angle $< 30^\circ$ (below angle where slant-range lockups expected)
- Strategy maximizes amount of data collected while preventing radar from going into search while still far off-nadir

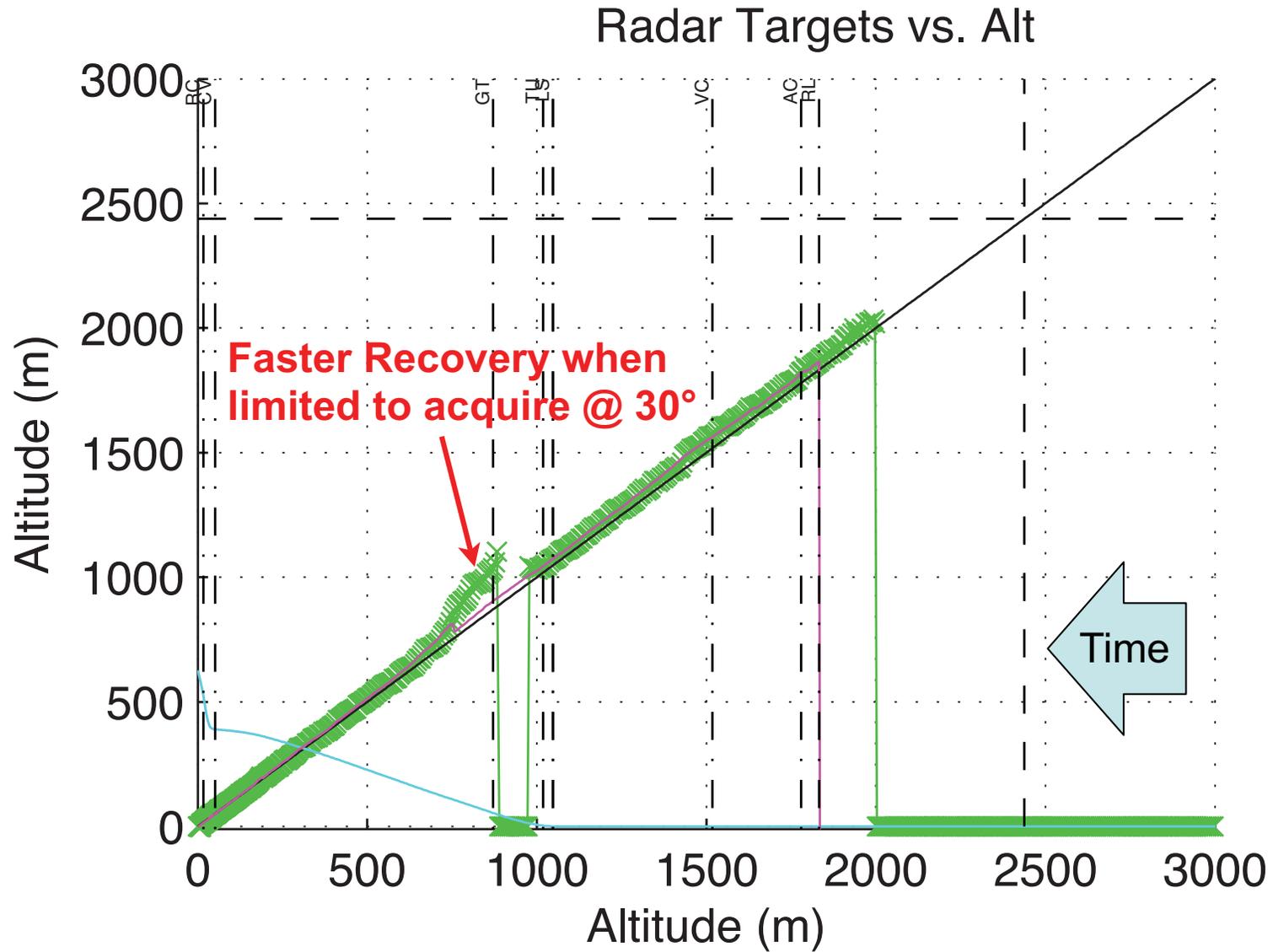


Slant Range Lockup Example (without fix)





Slant-Range example (with fix)



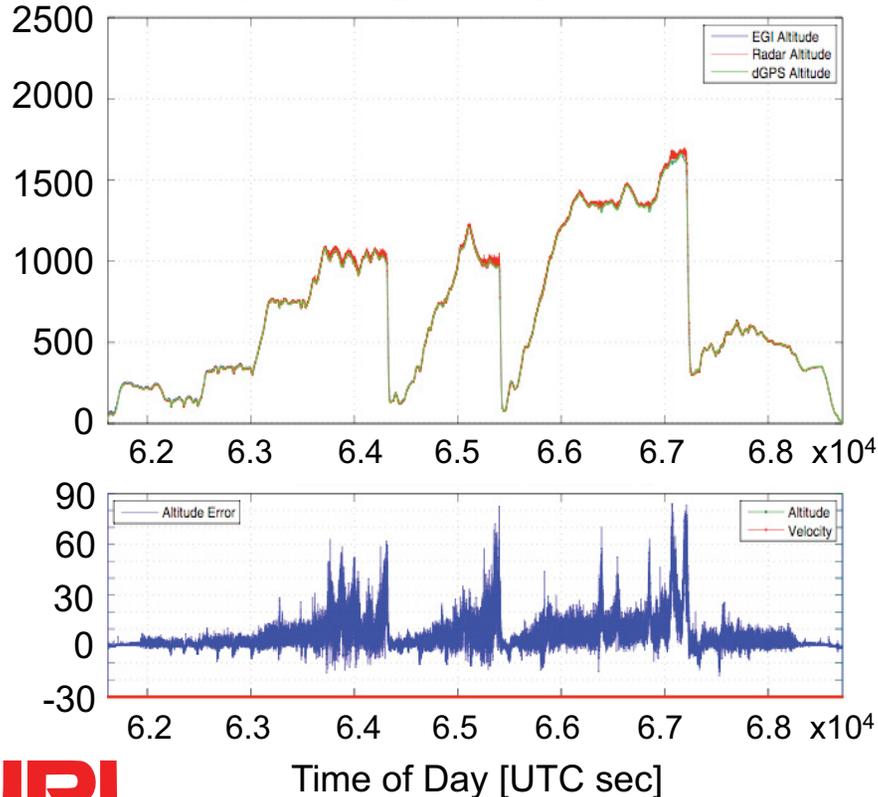


Radar Field Test Overview



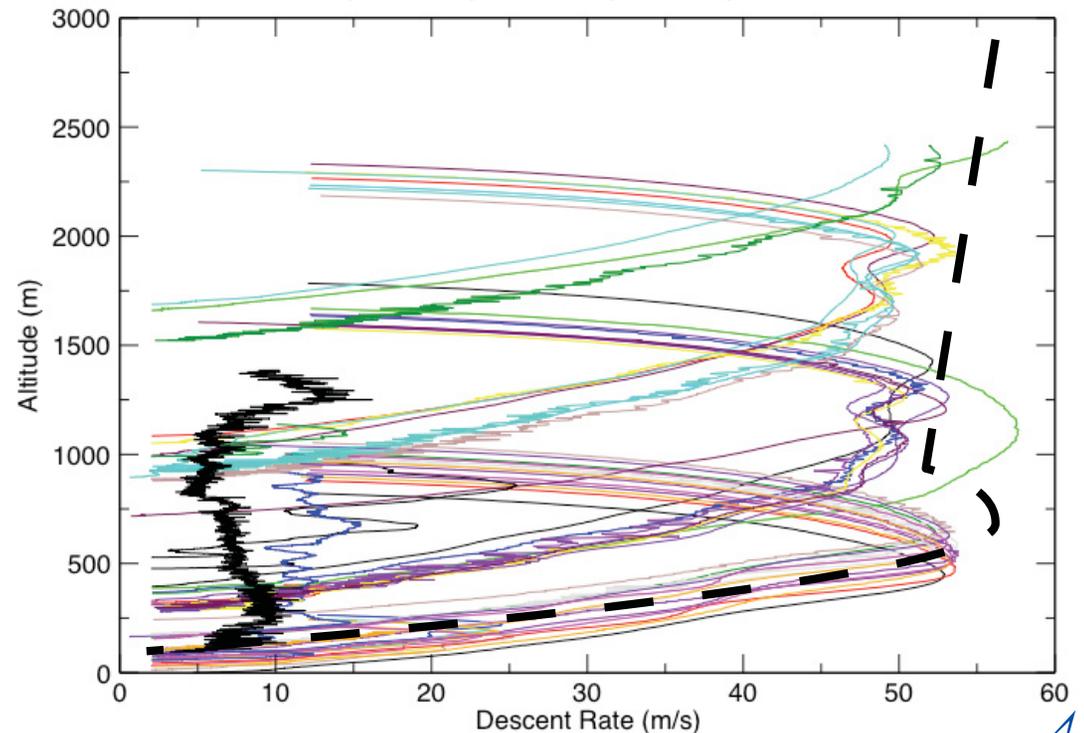
- **Exercise radar over real terrain**
 - Featured and featureless, with different soil packs and consistencies
- **Two types of tests**
 - Captive carry
 - Cannot achieve vertical velocity of true trajectory
 - Tethered drop
 - Covers full flight envelope in segments, with repeatability

Altitude + Error AGL vs. Time



Altitude Velocity Profile

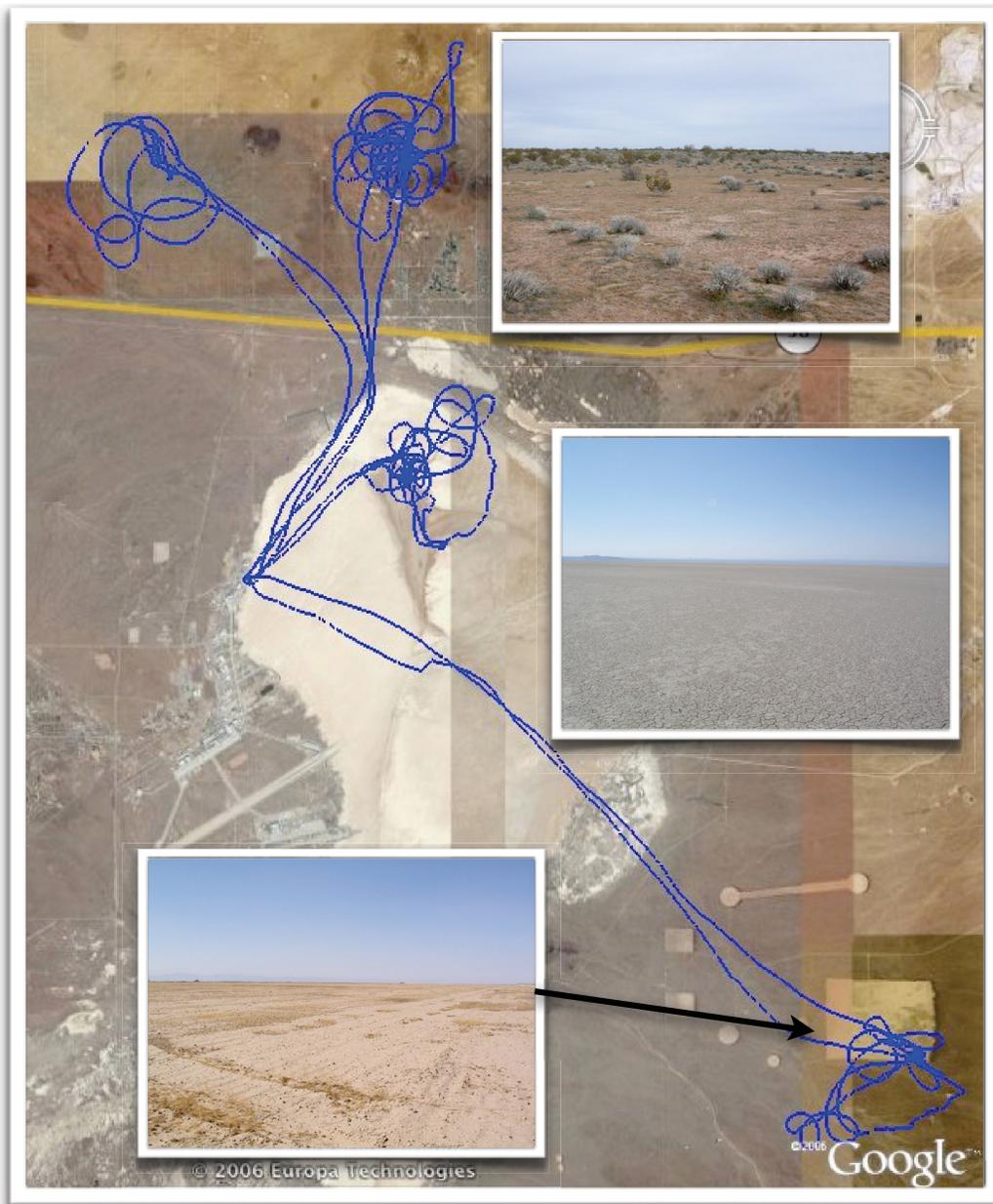
All Drop Test Sequences - Dryden - May/October 2006





Phoenix

Radar Field Test Images

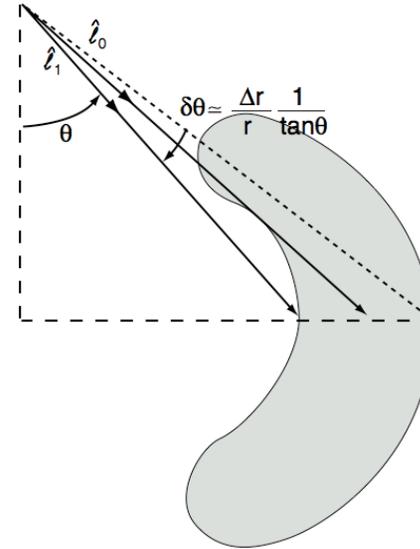


Example of Radar Field Test Discovery

Doppler Spectrum Variability

- Doppler spectra can have more than one peak
 - Inbound (nadir) peak contamination can have higher energy return
- Shift in velocity magnitude on canted beam measurements
 - Suggests a slightly different angle of arrival than originally assumed

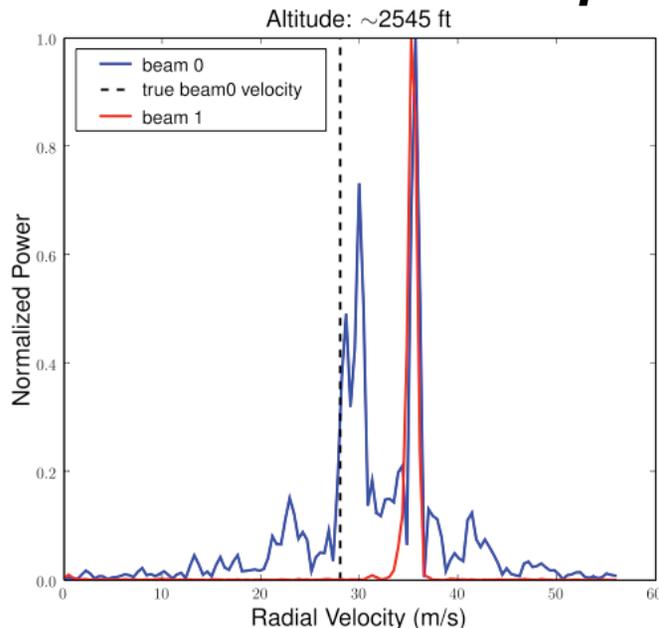
Angle of Arrival Error



Any bias in the elevation angle will result in true velocity biases

Assuming that elevation angle is the main systematic source of error, the bias can be estimated from the drop data

Measured Multi-Peaked Spectrum



Resolution

- Flight software modified to be more robust at selecting velocity from FFT peaks
 - Use knowledge of location of nadir contamination to ignore it
- Use as-measured angle of arrival instead of theoretical value



Mission Status & Conclusion



- Radar successfully passed in-flight checkout
 - Closed-loop radiated functional test
 - Software command/response test
- Waiting for second in-flight checkout closer to EDL
- Multi-test strategy caught many system ramifications previously not observed or understood
- Findings led to critical firmware, hardware and software changes that dramatically increased system robustness
- Recommend multi-pronged testing for all critical sensors