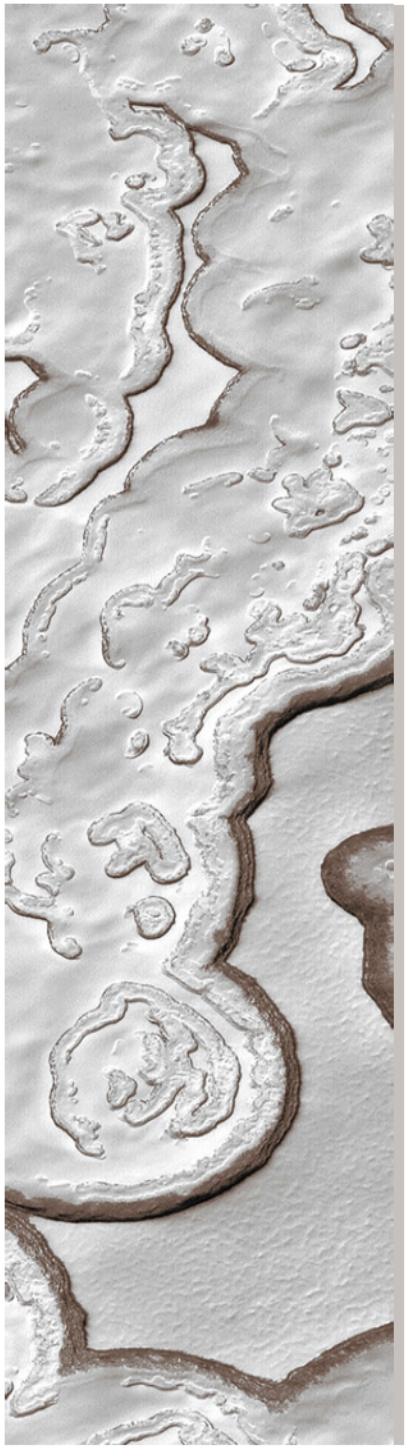


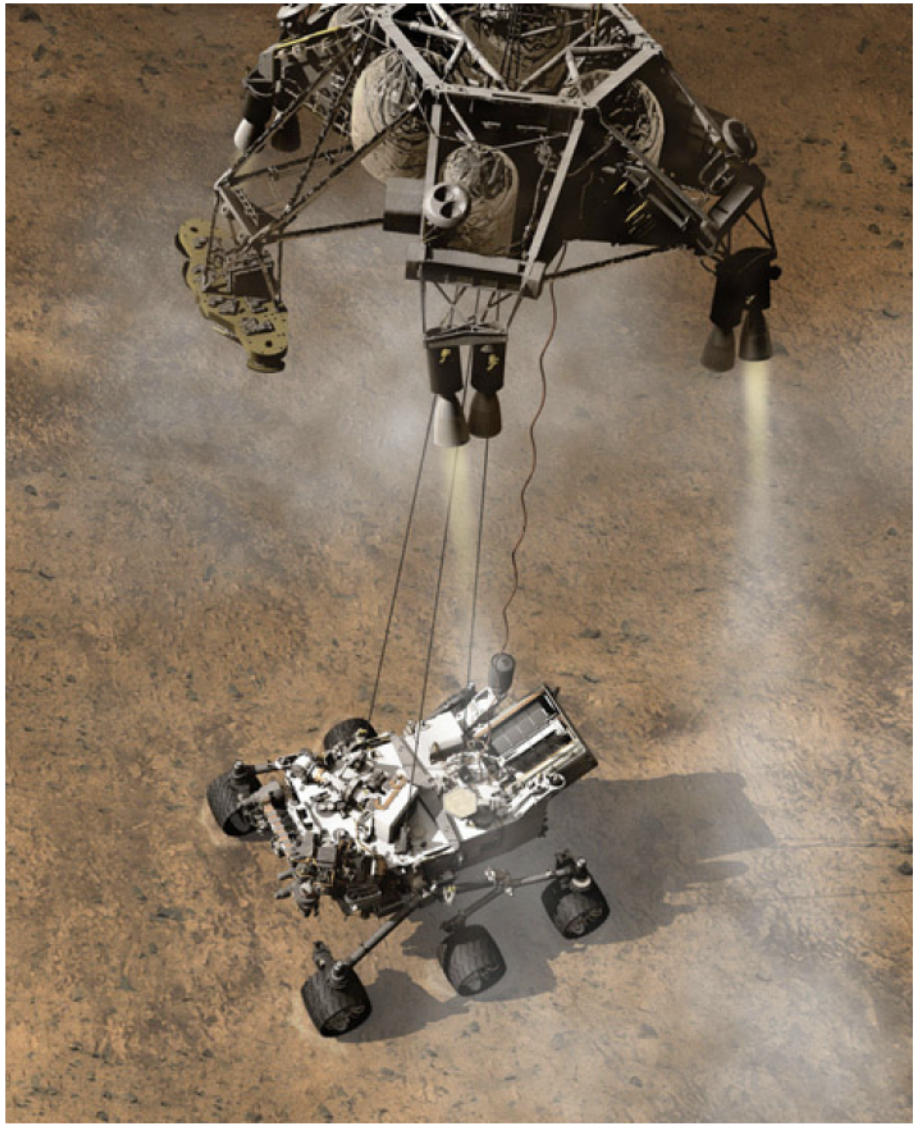
Radar Terminal Descent Sensor (TDS)

section 334 Forum Talk
2012.08.03

Brian Pollard
Radar Science and Engineering Section
Jet Propulsion Laboratory
California Institute of Technology

© 2012 California Institute of Technology. Government sponsorship acknowledged.

MSL Radar Terminal Descent Sensor



- Ka-band radar provides range and velocity measurements through all phases of (post-heatshield separation) Entry, Descent, and Landing (EDL)
- Designed and built at JPL by division 33 / 35 with key subcontracts for assemblies
- Program Duration: 2005-2012
  - *Start early 2005*
  - *Radar PDR July 2006*
  - *Radar CDR May 2007*
  - *FM Radar I&T Start. Dec 2008*
  - *Restarted I&T Oct 2009*
  - *TRM Rework Jan-Mar 2010*
  - *Restarted I&T April 2010*
  - *Delivery to ATLO Sep 2010*
  - *Launch Nov 2011*
  - *EDL Aug 2012*

cast of characters, 2005-present

Programmatic Team: Kent Kellogg, Steve Lee, Søren Madsen, Joe Okonek, Jim Rasmussen, Jeanette Sanderson, Ana Trujillo

System Team: Eric Belz, Alexandra Chau, Sam Chan, Curtis Chen, Steve Durden, Sam Gordon, Mike Johnson, Yunling Lou, Jan Martin, Ana Bertran Ortiz, Mimi Paller, Brian Pollard, Paul Rosen, Scott Shaffer, Barzia Tehrani

I&T Team: Lisa Austin, Bruce Carrico, Elaine Chapin, Duane Clark, Wendy Edelstein, David Escoto, Maurio Grando, Gary Hamilton, Brandon Heavey, Sean Howard, Joe Kwan, Ron Muellershoen, Kyung Pak, Gautamkumar Patel, Josh Ravich, Rich Rebele, Dmitry Strekalov, Kean Tham, Charlie Wu

Antenna Team: Jackie Chen, Jeff Harrell, John Huang, Behrouz Khayatian

Digital Team: Andy Berkun, DJ Byrne, Yong Chong, Anhua Chu, Ann Devereaux, Tim Gregoire, Richard Goodpasture, Dan Gutrich, Tom Jedrey, Igor Kuperman, Caroline Racho, Jeff Srinivasan, Wayne Tung

Ground Support Equipment: Alex Bachman, Jim Granger, Shouhua Huang, Jim Lux, Mike Mckee, Randy Ram, Amy Smith, George Wells, Phil Yates

Harness Team: Glenn Anderson, John Cardone, Ron Deppen, Valerie Pallai, Cao Tran

Mechanical Team: Carolyn Brennan, Gerry Gaughen, Frank Kelly, Kurt Lohman, Alex Nicolson, Keith Novak, Michael Pauken, Charles Wang, Jeff Waldeman

Power Team: Clint Kwa, Tony Severino, Erika Woo

RF Team: Fernando Aguirre, Ahmed Akgiray, Dino Andricos, Eric Archer, Roger Chao, Mike Ciminera, Charles Cruzan, Anthony DeKorte, Harry Figueroa, Jeff Hilland, Jim Hoffman, Vladimir Krimsky, Mike Kobayashi, Remi Labelle, Juan Lezameta, Sam Li, Alina Moussessian, Richard Ohanian, David Pukala, Eric Schwartzbaum, Jim Shell, Kyle Smith, Mary Soria, Scott Stide, Mike Tope, Gerry Walsh, Les White, Ly Yam, Sam Zingales

Notable Contractors: ASI, Custom Microwave, EMS-Atlanta, Miteq, Wenzel

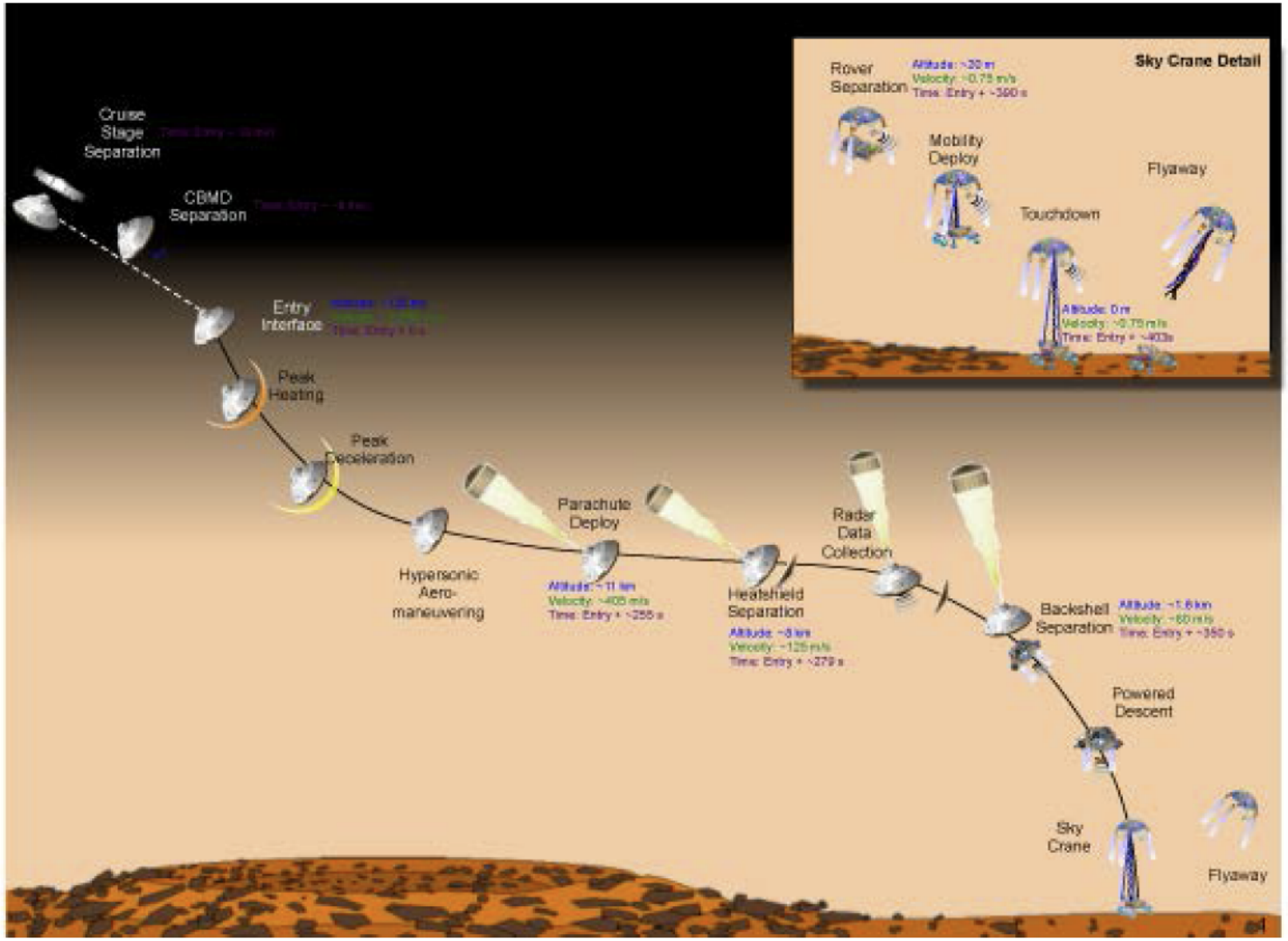
115 names, 33 current 334'ers

List of Topics

- How did we get here? …a short review of the sky crane system and decision process
- How did we get here, part 2? …a short review of the events leading up to the design of the TDS
- What does it do? …the design and performance of the TDS.
- What went wrong, and what went right? …lessons learned from the development.
- Where might we go from here? …a few closing notes on the future.

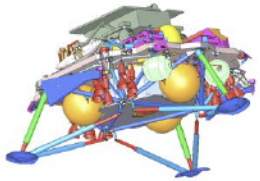
What is the landing sequence, and how is it different?

For an overview of the MSL landing process, look here:
http://mars.jpl.nasa.gov/msl/participate/



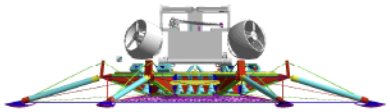
How did the 'sky-crane' concept come into being?

Chart from Tom Rivellini, 'Sky Crane' workshop, May 2004



Mars 98 & MSR

- The failure of the M98 lander mission during MSR's phase A, led to a change in risk posture on landing robustness.
- Several review boards and tiger teams were assembled to redirect MSR's landing/EDL architecture.
- Robust rover egress for MSR was never addressed.

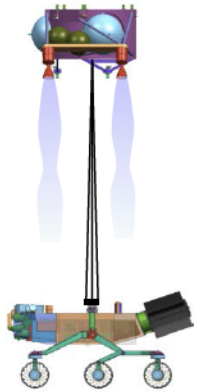


Mars Smart Lander

- Extensive evaluation of many different EDL and Landing architectures suitable for MSR were studied.
- Pallet style landing system with a large rover was selected based on expectation of a 2005 launch.
- Pallet greatly improved egress and landing safety.

Mars Expl. Rover

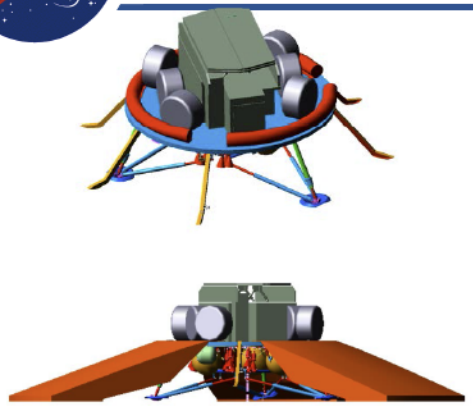
- MSL mission was delayed to 2007 and then 2009, resulting in more time to develop technologies.
- MER made a large investment in developing multi-body control dynamics.
- MER discovered the hidden challenges and costs of egressing a rover.

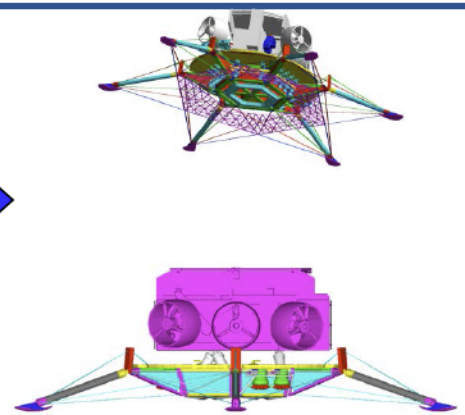


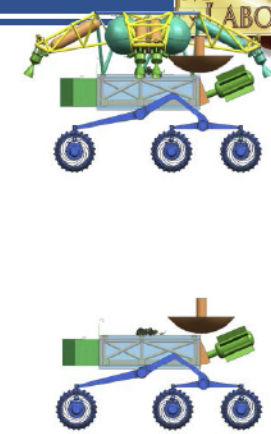
Mars Science Lab.

- EDL architecture given one last "fresh" look, focused on:
  - Cost Reduction
  - Performance Increase
  - EDL Feed Forward
- Desire to incorporate best lessons and technologies from MER; multi-body control, DRL…
- Further advancement of sensor technologies & HDA
- Sky Crane invented

Concept Evolution







Launch through heatshield	Launch through heatshield	Launch through backshell
H/S utility pass-through or gantry	H/S utility pass-through or gantry	BS utility pass-through
Poor landing performance (high CG)	Excellent landing performance (low CG)	Excellent landing performance (low Vel.&CG)
Legs	No Legs	No Legs
Outriggers	Outriggers + rock-net	No outriggers → Damped mobility
TD sensor and software required	TD sensor and software required	NO TD sensor or software required; flyaway
Large scale tank protection	Localized tank protection	No tank protection
Highly coupled loads and interfaces	Moderately coupled loads and interfaces	Highly DE- coupled loads and interfaces
Dedicated Lift mechanism	Dedicated Lift mechanism	No lift mechanism → deployment actuator
Dedicated egress ramps	No dedicated egress ramps → membrane	No Egress
Large drive off height	Low drive off height	No drive off height
Constrained propulsion system packaging	Constrained propulsion system packaging	Ample propulsion system packing volume
Rocket plume ground interaction	Rocket plume ground interaction	NO Rocket plume ground interaction
		Descent Rate Limiter

Chart from May, 2004, sky crane WS

List of Topics

- How did we get here? …a short review of the sky crane system and decision process
- How did we get here, part 2? …a short review of the events leading up to the design of the TDS
- What does it do? …the design and performance of the TDS.
- What went wrong, and what went right? …lessons learned from the development.
- Where might we go from here? …a few closing notes on the future.

Genesis of the radar design part 1: background

- Lunar Surveyor radar (1966) established a three-radar solution to landing on an extraterrestrial body: pulsed system for high altitude (9.3 GHz), an FM-CW ranging radar (12.9 GHz) for low altitude / rendezvous, and an FM-CW for velocity – all built by Ryan Aeronautical

- Apollo LEM (Lunar Excursion Module) used a similar approach, again with Ryan. "The Radars [were] one of the hardest pieces of the lunar module to qualify"

- Viking adopted a similar approach – a standard, broad beam L-band radar altimeter (with a heatshield window), and a Ku-band FM-CW radar velocity sensor

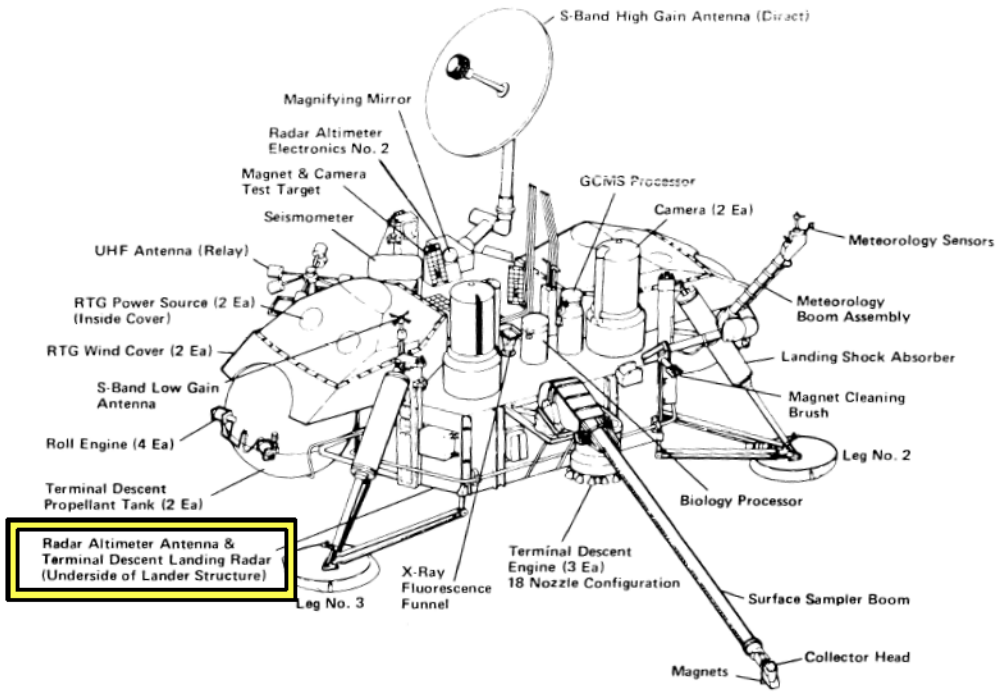
- Only with Pathfinder did NASA move away from this approach. Pathfinder, with its airbags and low cost cap, chose an off-the-shelf, cruise missile altimeter with a limited range of operation (~2400m). MER also flew this altimeter (along with a camera for horizontal velocity estimation / nulling)

- Mars Polar Lander drew on Pathfinder heritage and attempted to develop a C-band velocimeter based on the Pathfinder altimeter and other radars in the Honeywell line. Phoenix also adopted this approach

Radar on Viking

Viking flew two entry, descent, and landing radars:

- Nadir-pointed, wide beam altimeter
  - Accuracy as high as 1 m over a range of 41 m to 137 km
  - Specs:
    - 1.0 GHz +/- 1.0 MHz center frequency
    - High power (175W) & long pulse (6 ms)
- Four-beam, off-nadir pointed velocimeter
  - 3.5° beamwidth per beam,
  - each splayed 21.3° from roll axis,
  - accuracy ~ 1 m/s
  - Ku-band with four independent radars

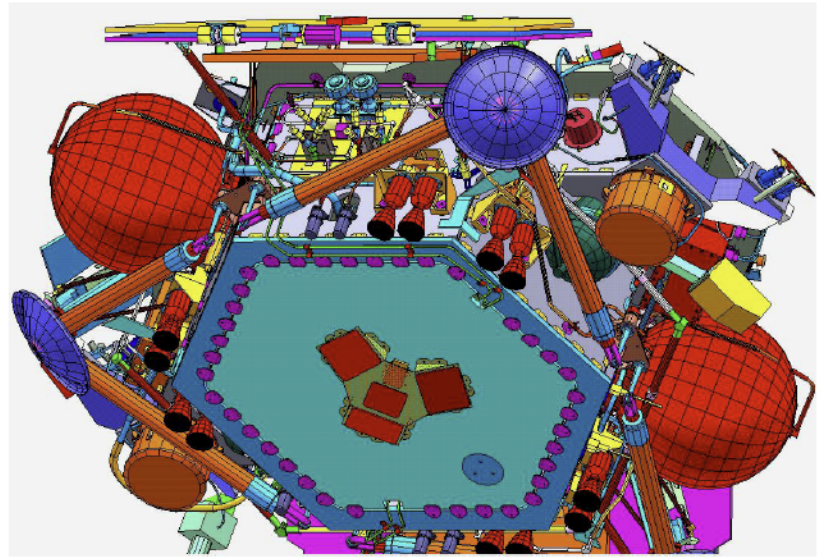


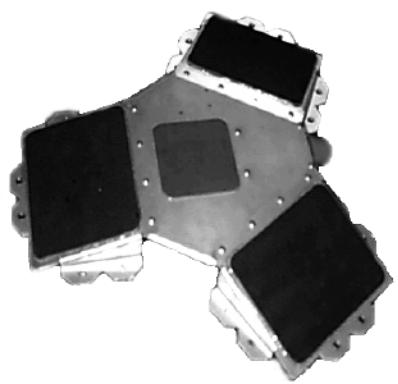
Viking Top Problems List ca. 1973

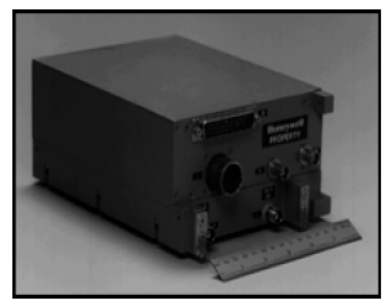
Top Ten Problems		
Item	Added to List	Deleted from List
GCMS progress and schedule	4 May 1970 a	July 1971
Lander gear design	4 May 1970 a	-
Site-alteration program schedule	4 May 1970 a	-
Solder joints, failure mode under sterilization	4 May 1970 a	Dec. 1971
Post-Mars-orbit-insertion orbit determination convergence	4 May 1970 a	May 1971
Lander weight growth	4 May 1970 a	-
Orbiter weight growth	4 May 1970 a	-
Site alteration	4 May 1970 a	Aug. 1971
Wet tantalum capacitor failure under sterilization temperatures	Jan. 1971	Feb. 1971
Completion of data requirement list/data requirements description	Jan. 1971	Feb. 1971
Lander gear design	Feb. 1971	Aug. 1971
Lander weight contingency	Mar. 1971	Oct. 1971
Orbiter weight contingency	Mar. 1971	Aug. 1971
Lander materials	Aug. 1971	Oct. 1972
Lander processes	Aug. 1971	1 June 1972
Lander parts program	27 Aug. 1971	1 June 1972
GCMS configuration and schedule	Oct. 1971	2 Feb. 1972
Balloon-launched decelerator test	2 Feb. 1972	July 1972
Radar-altimeter design-development schedule	Feb. 1972	24 July 1973

Radar Velocimetry on MPL

- For Mars Polar Lander, pencil-beam approach adopted on Viking was abandoned
  - Cost and accommodation issues of larger antenna required to reduce beamwidth
  - Instead, upgraded Mars Pathfinder altimeter to have three off-nadir beams and a Doppler processor
    - Each beam has a large beamwidth producing an "angle of arrival" problem…

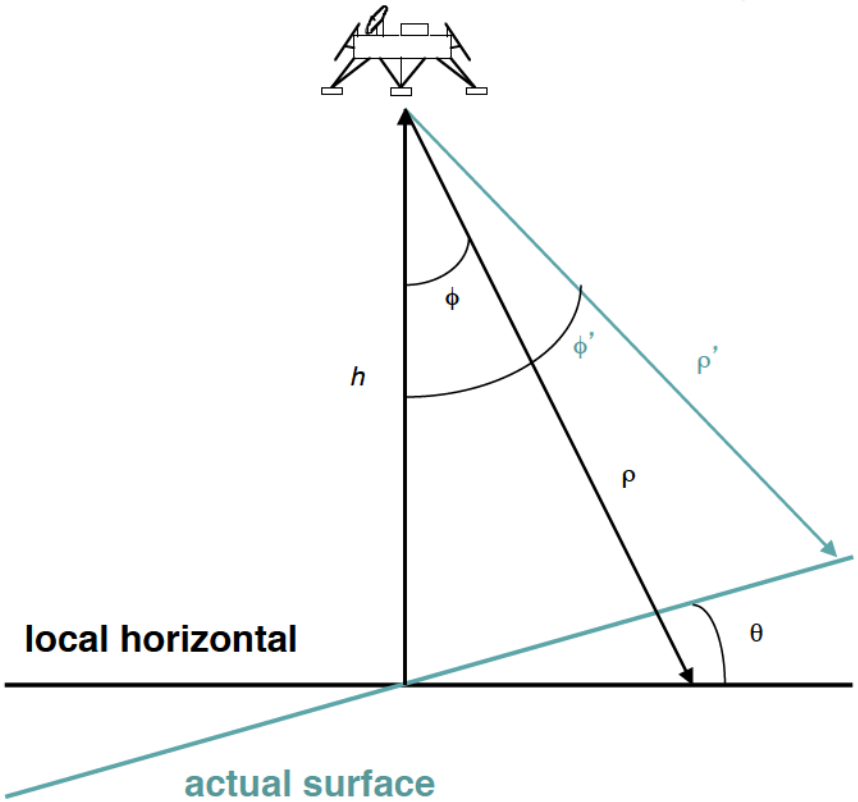






Problems with MPL Approach

- The MPL radar used the altitude (h), the off-nadir antenna boresight, and trigonometry to determine angle of arrival
- A local slope produces a mis-estimate of the angle of arrival which produces an error in estimate of the velocity component
- Biases are dependent on the vertical velocity, and can be higher than 1 m/s for 30° slopes
- To meet a ~0.75 m/s velocimeter requirement, knowledge of the angle of arrival to below ~5° is required

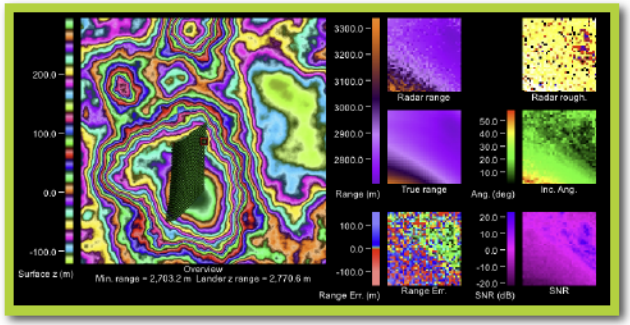


ρ, ϕ = computed slant range and look angle

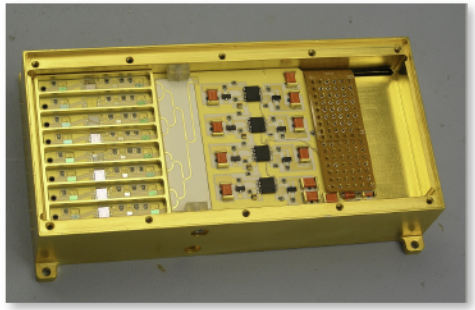
ρ', ϕ' = measured slant range and look angle

Genesis of the radar design part 2: technology

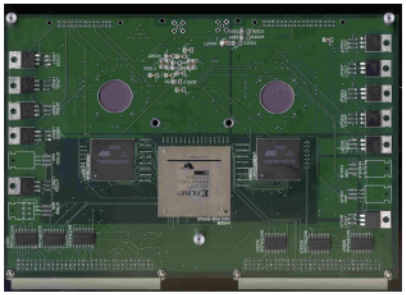
- In the aftermath of the MPL failure, there was significant interest in hazard detection and avoidance for future missions (i.e. part of the Mars Smart Lander)
- 2000-2001, a mm-wave phased-array was adopted as the 'baseline' hazard detection sensor for future missions
  - Built a 800 MHz BW, 5 frequency W-band prototype system and demonstrated initial ranging & hazard detection algorithms
  - Began development of a Ka-band phased array in 2002 working with the MSL project and the MFTP
- Program ended ~MSL MCR in late 2003. Legacy of the tech program ended up in the MSL TDS →



Echo / timing simulation tool, tracker design, range & velocity algorithms (B. Pollard & J. Huddleston)



Ka-band T/R 8-pack on LTCC (C. Andricos et al.)



Xilinx-based 50 GOPs real time processor & adaptive timing unit (A. Berkun)

MSL Range/Velocity Only Solution

- After the MSL MCR (late 2003) the hazard detection component of the mission was deemed un-affordable, and the project was searching for a ranging / velocity system much like that flown on Viking
  - MPL / Phoenix system had the known angle of arrival problem and significant other issues
  - Helicopter navigation systems (Ku-band, based on the Ryan LEM / Viking design) existed, but did not allow for ranging
- Based on the MFTP work, JPL proposed a Ka-band pulsed-Doppler radar with the following characteristics:
  - Line-of-sight range and velocity estimated simultaneously along the line-of-sight of up to 6-8 beams
  - Narrow pencil beams overcome any concerns about angle-of-arrival and allow for body-relative navigation
  - Heritage from Mars Program investment in hazard avoidance sensors: Ka-band; high bandwidth; high speed digitization and onboard processing; range/velocity algorithm
- What was new for the range/velocity system was the abandonment of the 'tracker' and adoption of a 'memory-less' design
  - overcomes significant limitations in validation at the expense of a small amount of performance

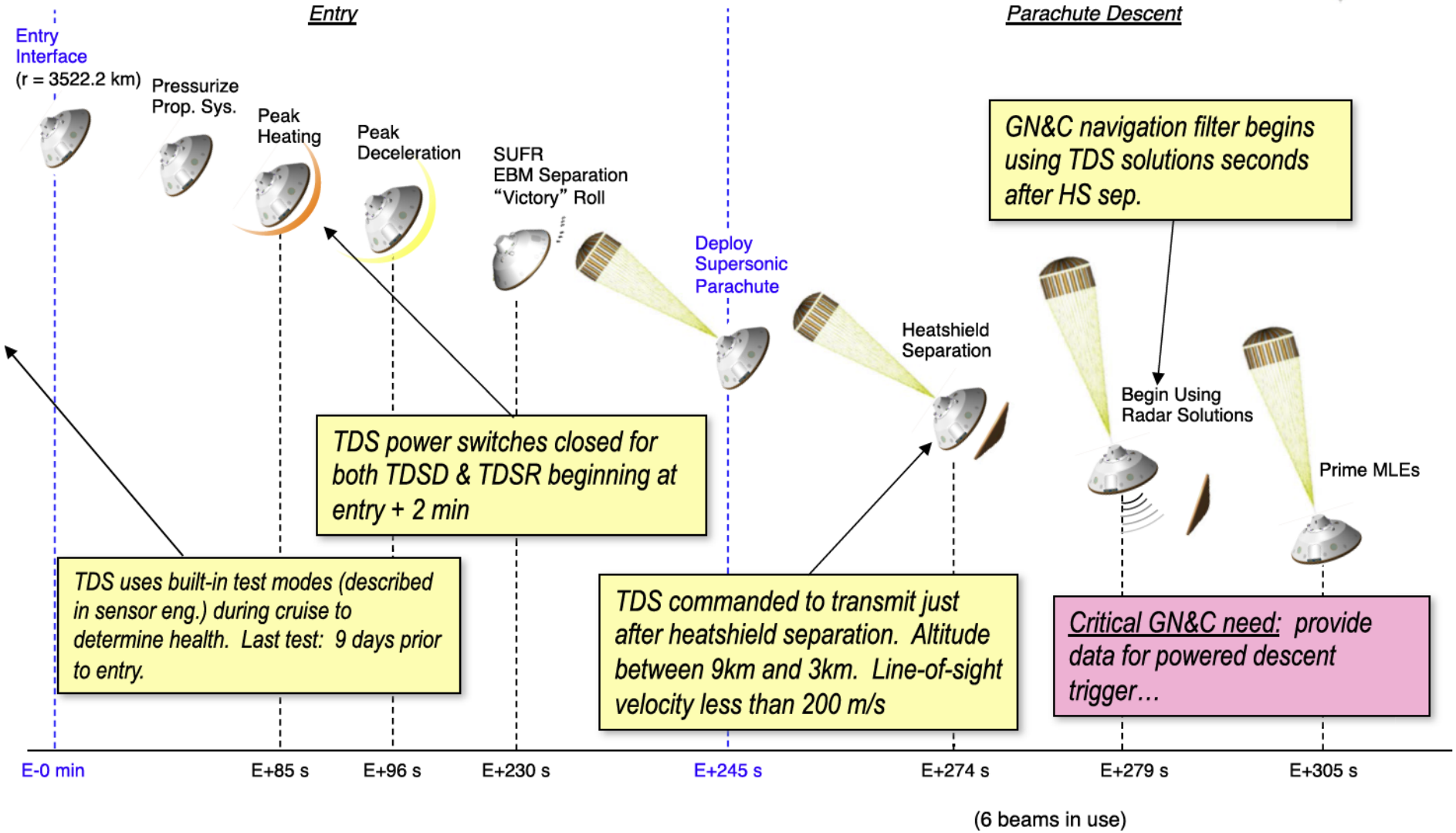
List of Topics

- How did we get here? …a short review of the sky crane system and decision process
- How did we get here, part 2? …a short review of the events leading up to the design of the TDS
- What does it do? …the design and performance of the TDS.
- What went wrong, and what went right? …lessons learned from the development.
- Where might we go from here? …a few closing notes on the future.

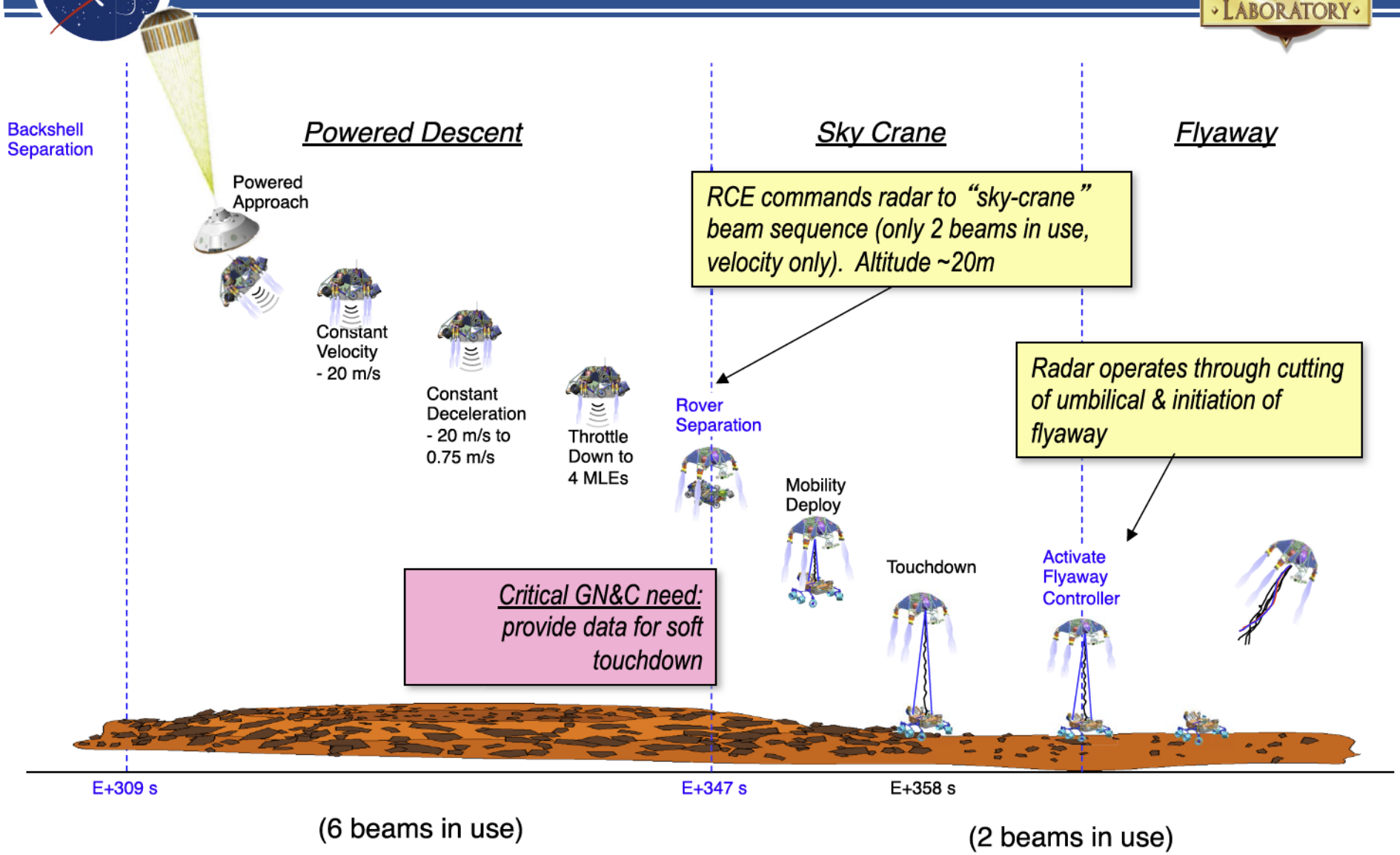
MSL Landing Radar Requirements

Parameter	Requirement
Beamwidth	< 5°
Per Beam Velocity Error (3σ)	0.75% V_{total} + 0.2 m/s
Velocity Scale Factor (3σ)	0.25% V_{total}
Velocity Bias (3σ)	0.03 m/s
Velocity Measurement Quantization	< 0.01 m/s
Slant Range Measurement Accuracy (3σ)	2.0% range
Slant Range Measurement Bias (3σ)	0.5 m
Single Beam Update Rate	50 +/- 0.1 ms
Measurement Latency	< 0.5 s
Maximum Off Nadir Attitude*	***60 deg***
Maximum Altitude of Operation*	***3500 m***
Minimum Altitude of Operation	***[5] m***
Minimum Unambiguous Slant Range	15000 m
Minimum Unambiguous Line-of-sight Velocity	200 m/s
Validity Flags (range & velocity)	95% of data valid
Uncertainty Measurement in Range (1σ)	TBD
Uncertainty Measurement in Velocity (1σ)	TBD
Maximum Attitude Rate	50°/sec
Maximum Acceleration	30 m/s^2

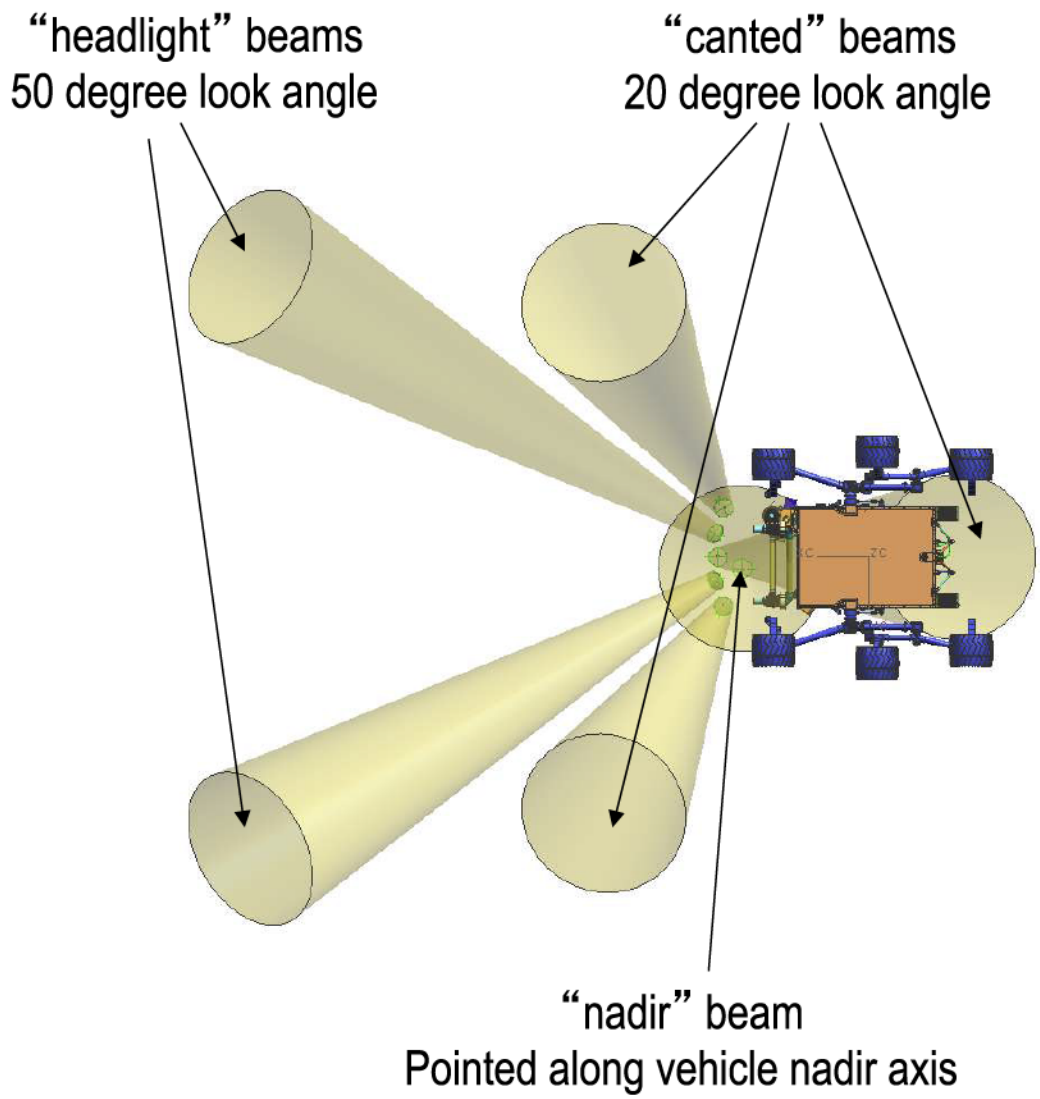
Event Timeline (entry & parachute)



Event Timeline (powered descent)



Radar Usage / Beam Patterns



- *All beams used on parachute & during most of powered descent*
- *Nadir beam measures distance to landing site during constant deceleration*
- *Headlight beams measure velocity after rover separation*

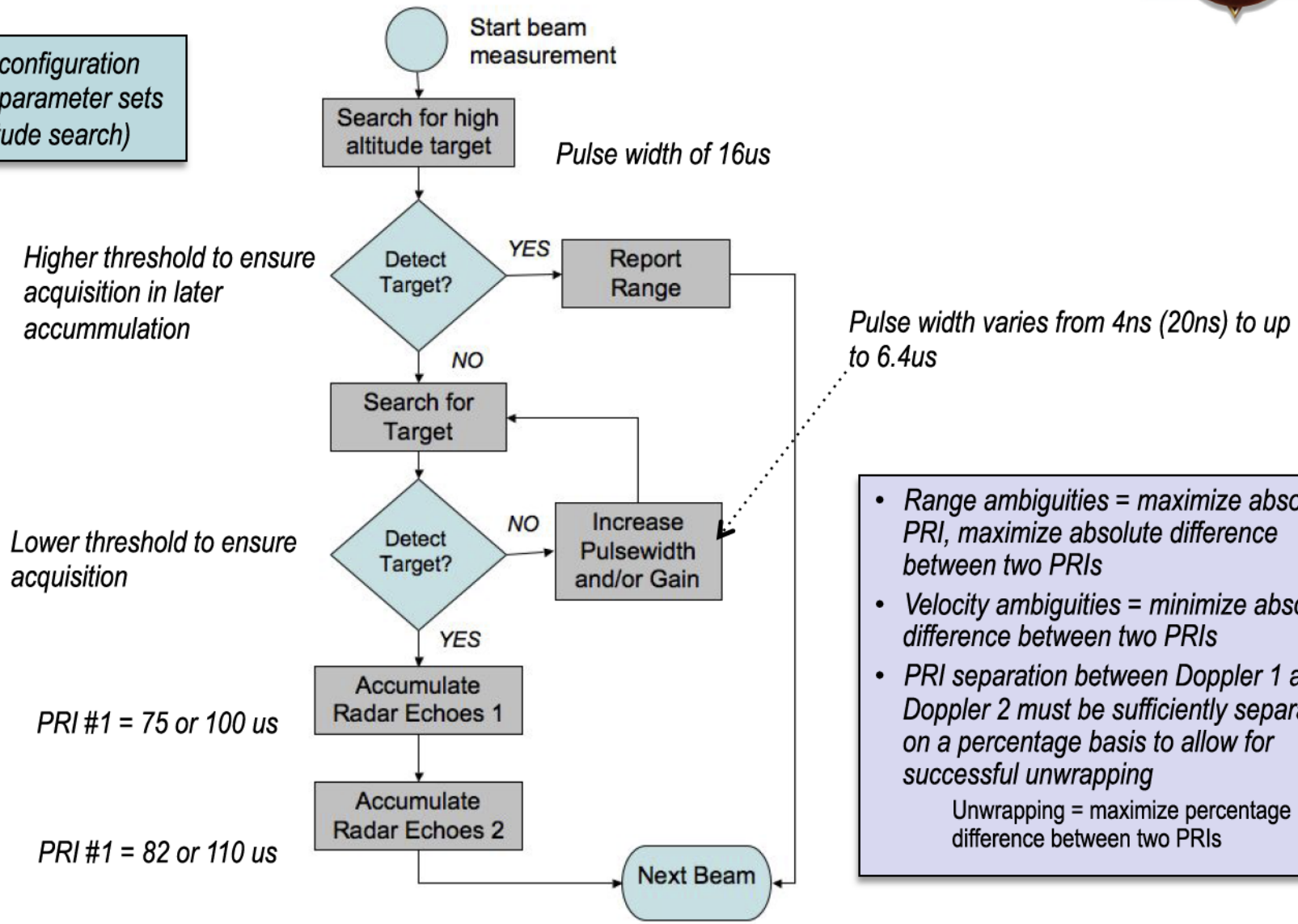
TDS Design Considerations

- **Avoid Memory**: independent beam to beam and repeat beam performance.
  - Avoids "loss of lock" issues
  - Avoids any issue where the heatshield or anomaly puts the radar in a false state
  - Simplifies validation and verification
- **Ambiguities Cannot Be Avoided:** Ka-band radar cannot accommodate simultaneous, unambiguous range and Doppler given MSL profile.
- **Parent Requirements Vary with Altitude:** key requirements are expressed as a percentage
  - Range error of 2% r_{slant}
  - Velocity error of 0.75% x V_{total} + 0.2 m/s of velocity

➢ **the "Parameter Set"**:
  - varying parameters (pulsewidth / bandwidth, pulse repetition frequency, etc.) as a function of altitude
  - parameters determined on a beam-by-beam, dwell-by-dwell basis
  - pulse repetition interval & pulse pair separation vary to allow resolution of ambiguities

Parameter Set Flow Diagram

Final flight configuration file has 12 parameter sets (+ high altitude search)



- *Range ambiguities = maximize absolute PRI, maximize absolute difference between two PRIs*
- *Velocity ambiguities = minimize absolute difference between two PRIs*
- *PRI separation between Doppler 1 and Doppler 2 must be sufficiently separable on a percentage basis to allow for successful unwrapping*

  Unwrapping = maximize percentage difference between two PRIs

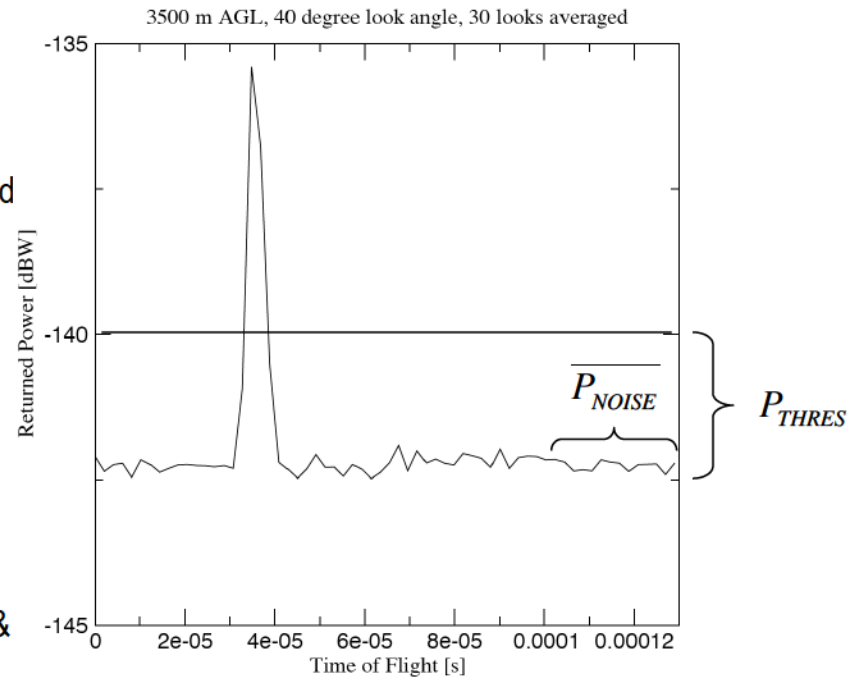
Product & Algorithm Definition

Radar Processor algorithm:

Estimate Noise Power: *N* points at end of averaged range line
Detection: any points above threshold
Centroid: integer (ACQ) or fractional (DOP) bin of points above threshold
Width: difference of min & max points above threshold
Power: value in centroid bin
Pulse Pair Product: complex value from two adjacent (or nearly adjacent) pulses

Radar Controller algorithm:

Range: average of DOP centroids
Velocity: average pulse pair products, then extract phase via arctan()
Validity & Uncertainty: from power, noise, width, & difference of ranges & velocities from ACQ, DOP1 & DOP2



Measurement Validity

Radar also computes whether or not it thinks a measurement is valid through some simple checks

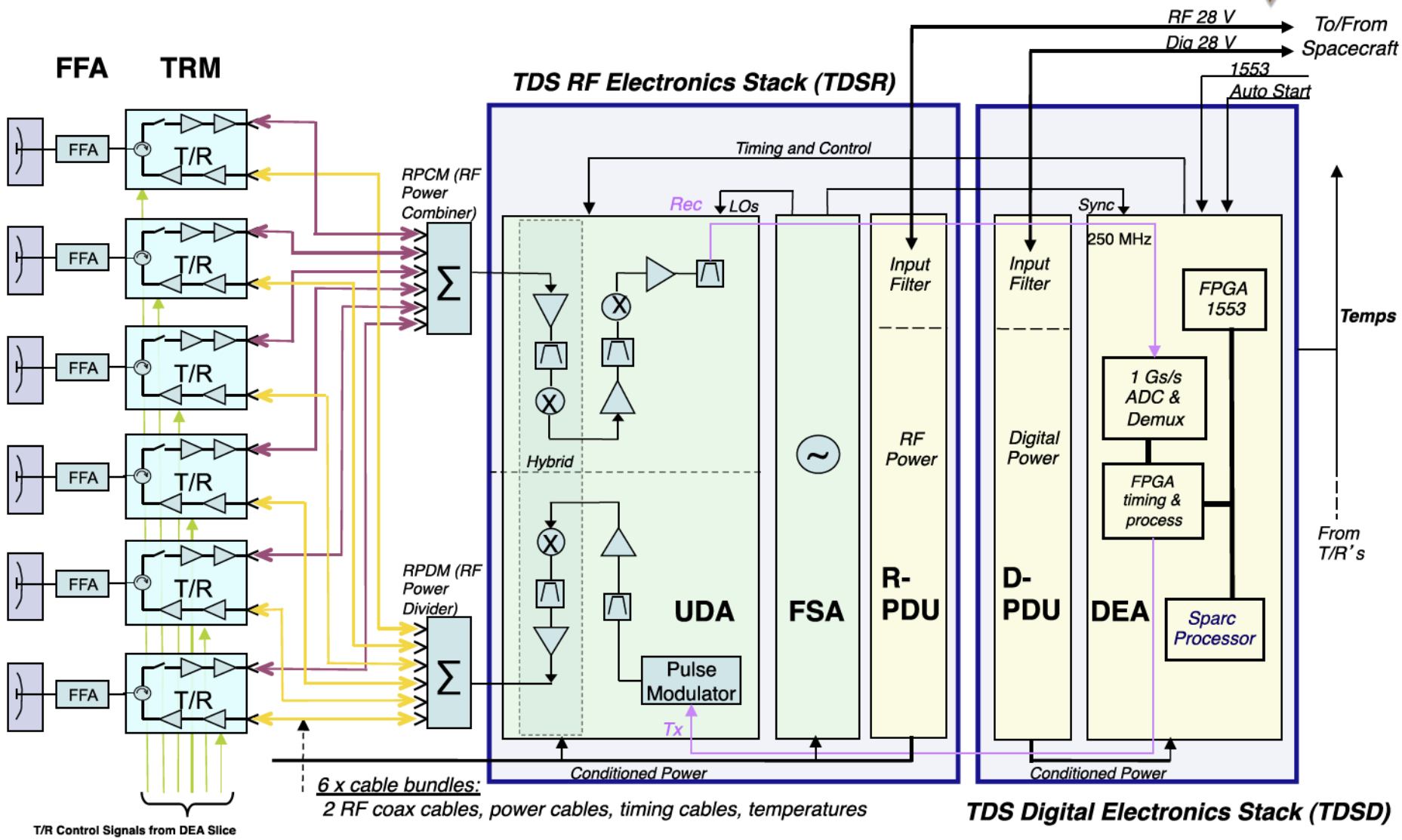
- **Some are mode based**
  - is the radar in a self-check mode?
  - Are other parameters outside their operating range (i.e. beam > 6)
- **Others are derived from limits on the measurement technique:**
  - Is the computed width too wide to be physical or reliable?
  - Are the different centroids (ranges) between the dwells too large to be physical?
  - Are the different dwell velocities too large to be physical or reliable?
  - Is the SNR computed lower than the threshold should allow?
- **A final set was added to deal with discovered problems**
  - Zero measured noise
  - “double bounce” bit

The navigation filter on the spacecraft rejects invalid data

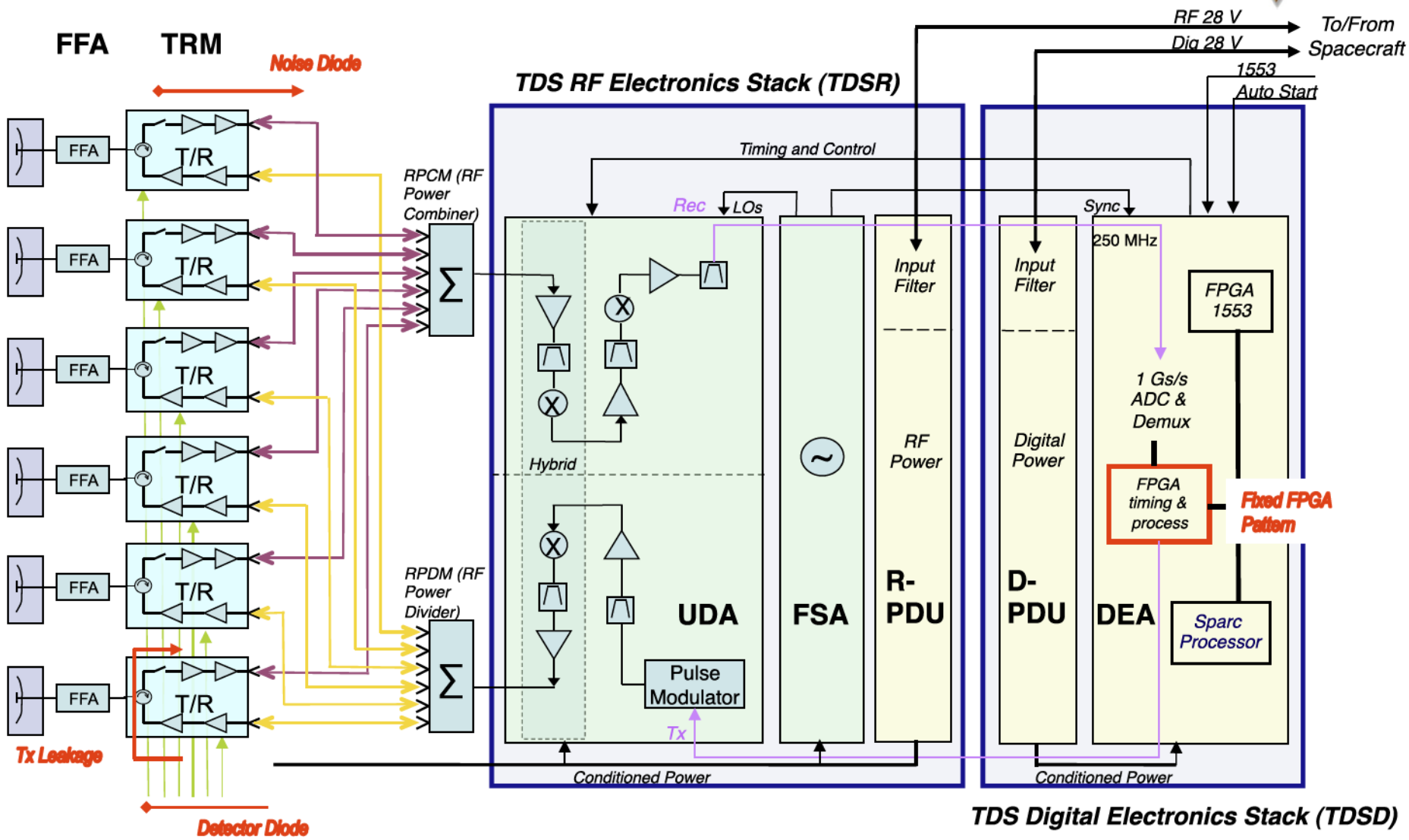
Notional Performance Requirement Flow

Level 4 (from GN&C)	Level 5 (to assemblies)	
• Acquire with 95% probability • 3500 m slant range • 60° incidence angle • 2% slant range	• Transmit power • Range of pulse widths • Antenna gain • Noise figure & Rx gain	*Link Budget (2W Tx power, 22 cm antennas, ~9 dB NF)*
• Velocity precision • Unambiguous velocity • Unambiguous range	• Range of pulse intervals • Range of pulse widths • Thresholds for detection • Temporal baseline	*Parameter Set Values (i.e. 4-16000ns pulse widths)*
• Range bias • Velocity bias	• Antenna sidelobes • RF spurs • RF phase drift	*Other Performance Req'ts (-24 dB antenna PSL, sub-25 mV ripple on atten. voltages, 0.4 dB passband flatness*)*
• Operate 5 m to 3500 m	• ADC ENOB & saturation • Range of attenuation • RF gain & saturation • RF switching time • RF pulse rise/fall time	*Dynamic Range (~106 dB signal variability)*

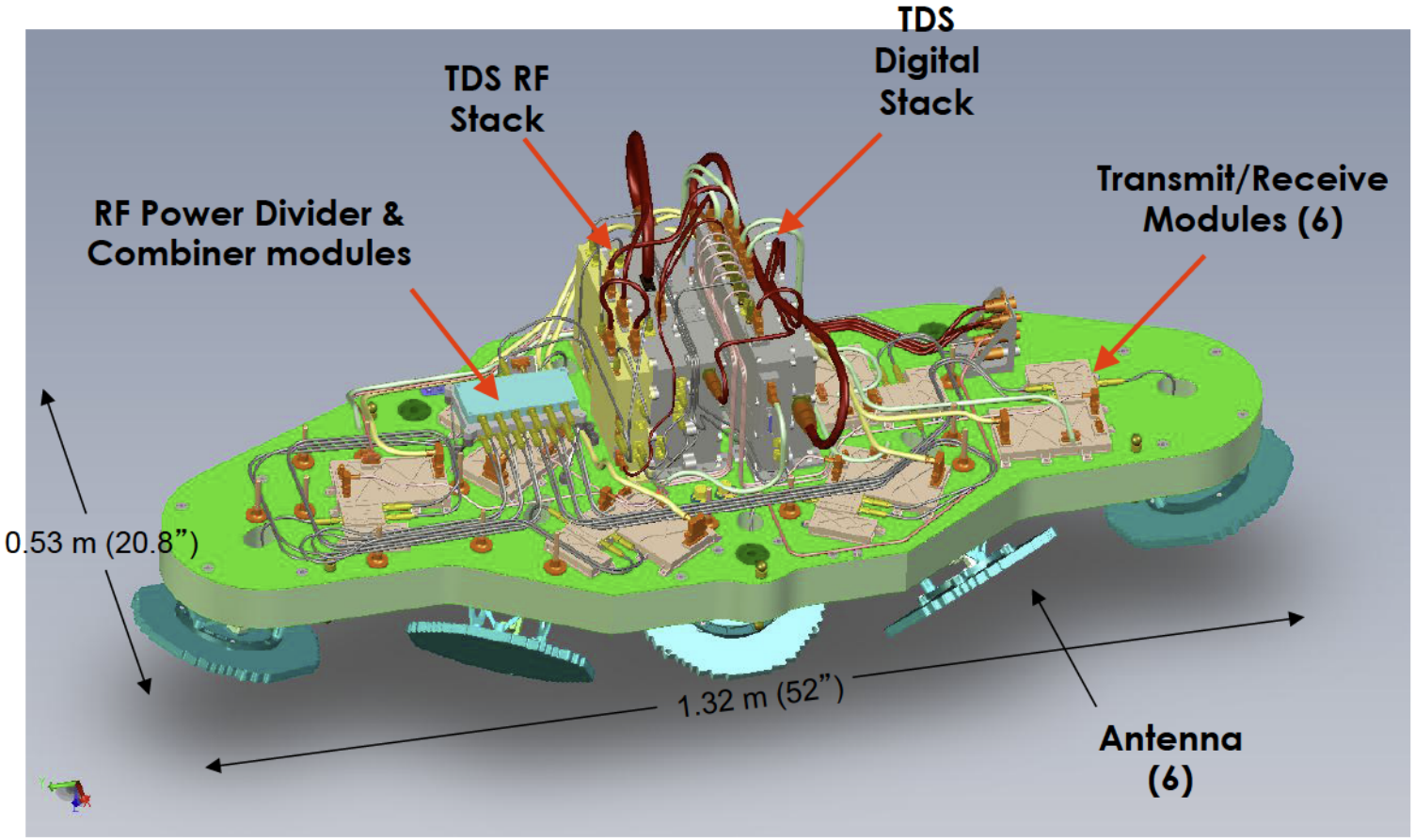
TDS Block Diagram



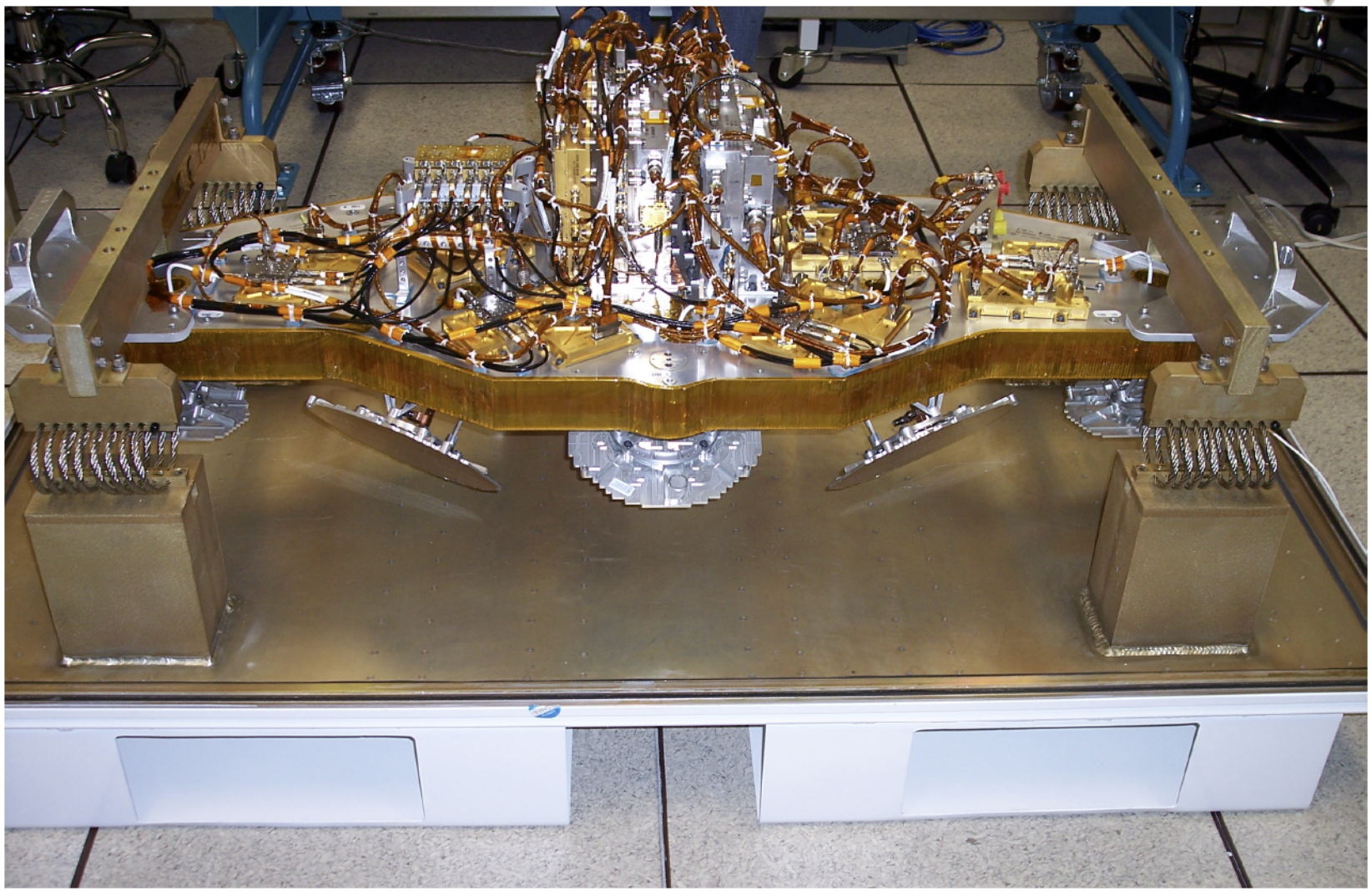
TDS Built In Tests



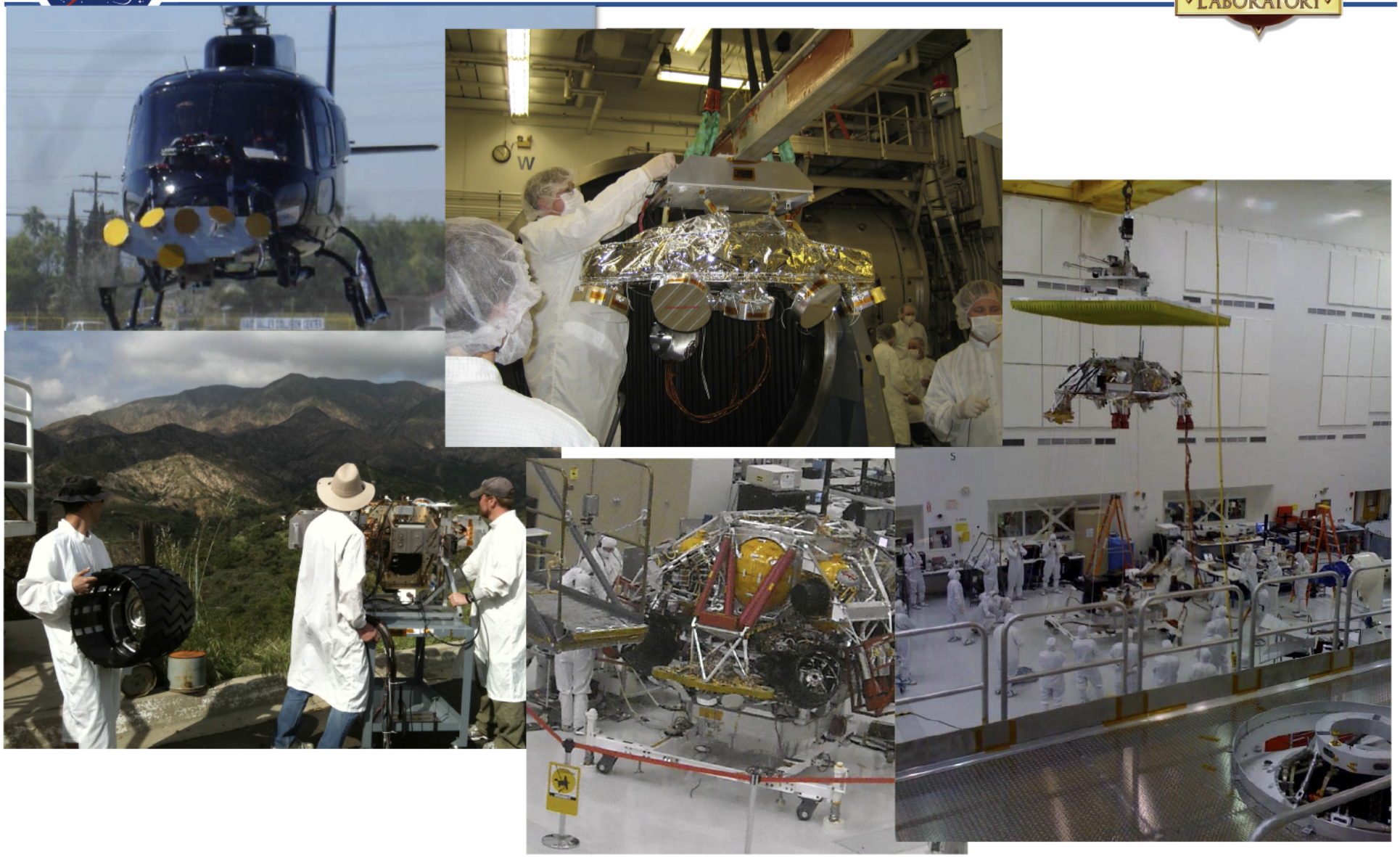
TDS Physical Configuration



FM Unit

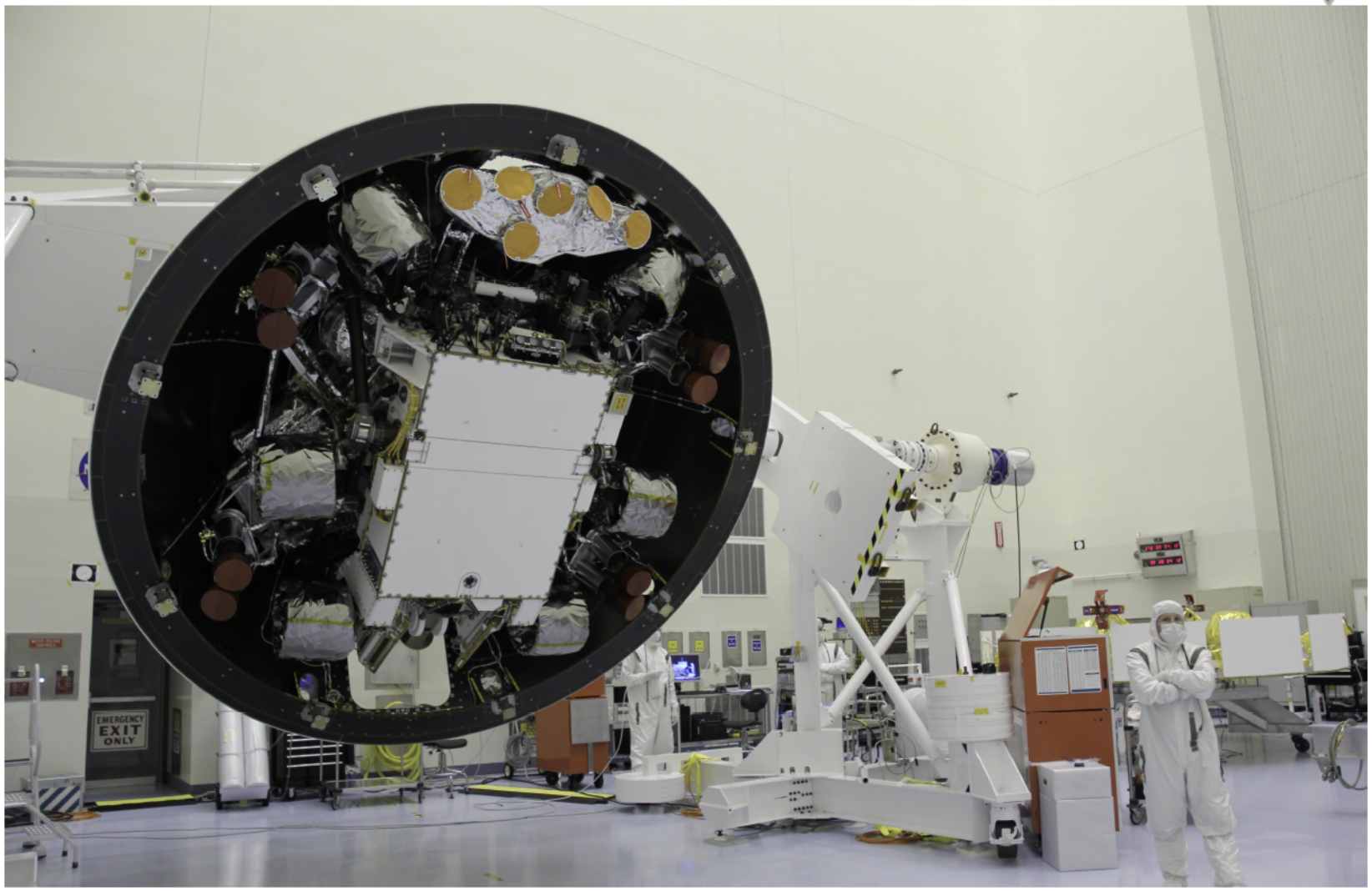


Validation Campaigns



Other fun test configurations

At KSC

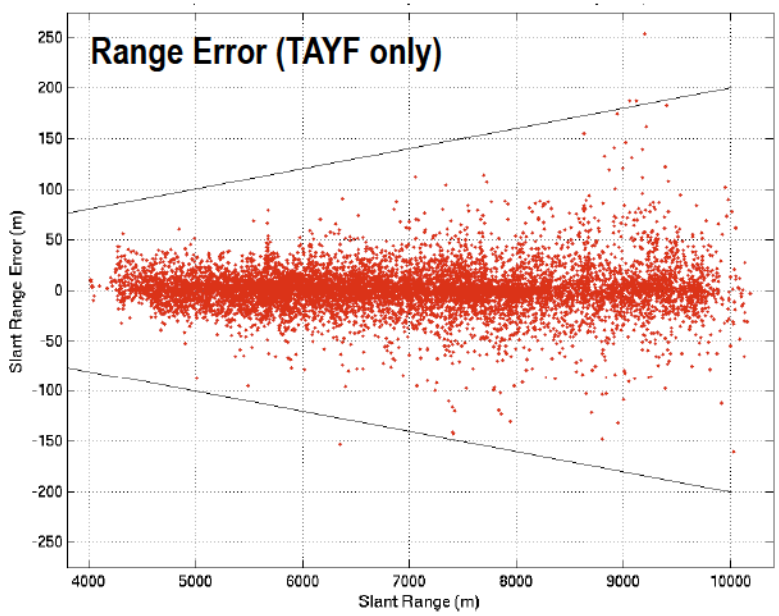


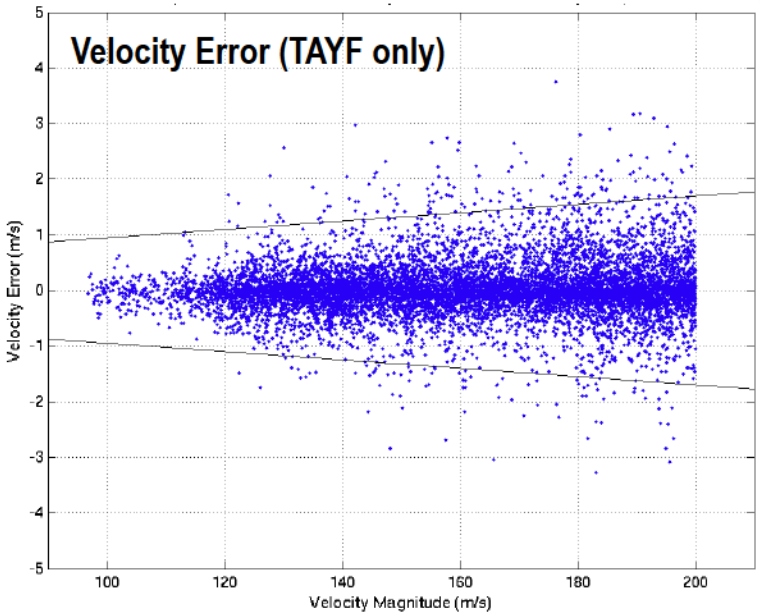
Into the Fairing

List of Topics

- How did we get here? …a short review of the sky crane system and decision process
- How did we get here, part 2? …a short review of the events leading up to the design of the TDS
- What does it do? …the design and performance of the TDS.
- What went wrong, and what went right? …lessons learned from the development.
- Where might we go from here? …a few closing notes on the future.

What Went Right? Performance & Capability



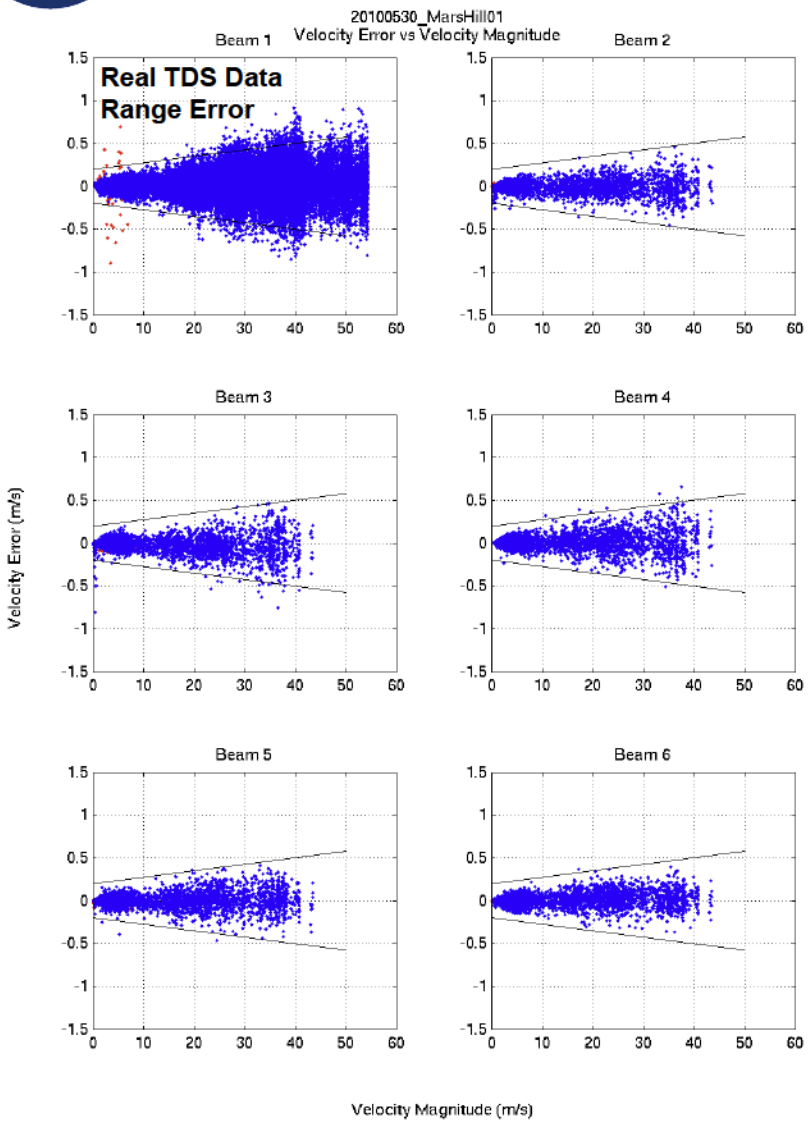


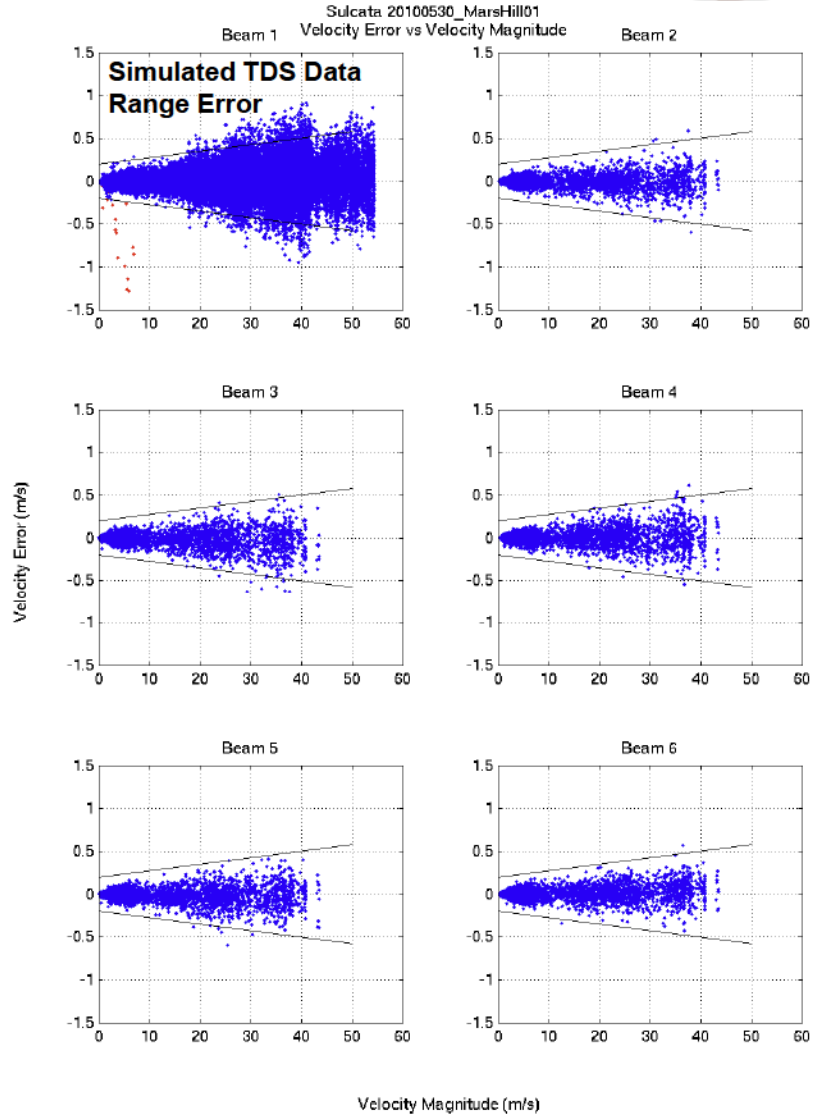
Performance: Range / velocity errors agree to a remarkable extent to the original design concept (probably to a fault)

Capability:

- Improved the state-of-the-art in landing sensors
- First JPL spaceborne Ka-band radar
- Altimeter experience that can be applied to other uses
- Single board Digital Subsystem with 1 GS/s throughput & onboard processing

What Went Right? Curtis' Simulation





- **BLUE**: TDS error relative to GPS+MIMU, inside envelope
- **RED**: TDS error relative to GPS+MIMU, outside envelope

- **BLUE**: Sim error relative to sim truth, inside envelope
- **RED**: Sim error relative to sim truth, outside envelope

What Went Right? Many Had a 'Character Building' Experience

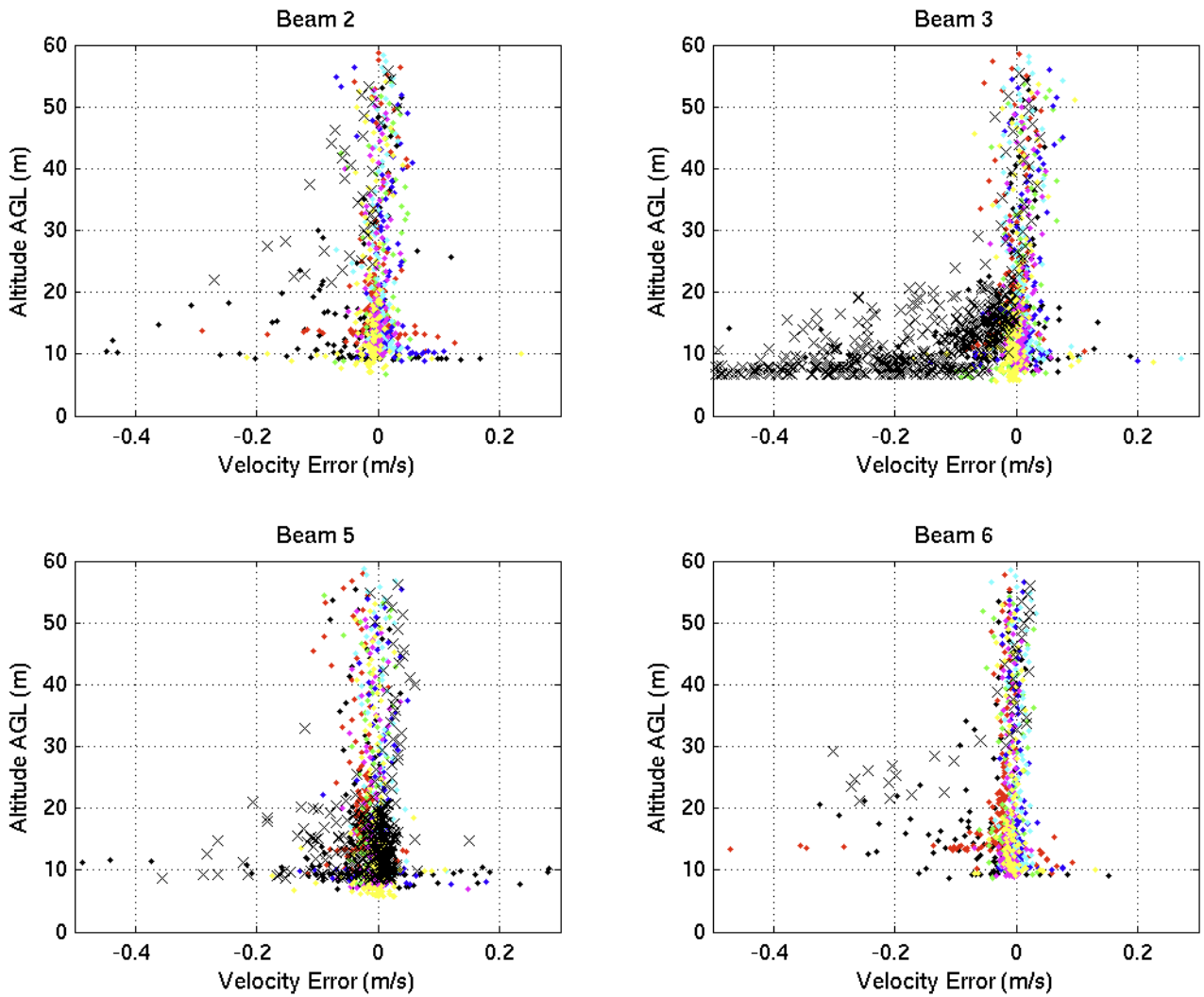
What Went Wrong? One Viewpoint

- The TDS was a difficult development. Some of the notable problems – programmatic and scope…
  - A shortage of system engineering in phase A/B created numerous problems of over specified or incomplete requirements, incomplete test plans, and incomplete interface requirements. Ultimately the system engineering budget approached historical averages, but the profile was inverted and the paperwork created (waivers / PFRs) was significant
  - End-to-end modeling paid for itself many times over, but would have increased in value if funded in phase A/B (rather than in phase C)
  - EGSE – particularly that which is used throughout the lifecycle of the program – should receive similar design scrutiny and verification as flight hardware. (The TDS EGSE had a very visible failure at KSC). The same can be said for test ports
  - An “it must work autonomously” environment is much different than a standard “C+” LEO mission

What Went Wrong? One Viewpoint

- The TDS was a difficult development. Some of the notable problems – more specifically…
  - Capacitor failure within a sealed TR module required opening of all modules and inspection / replacement of all related parts. Proper parts screening/specification and rework accessibility can pay for themselves many times over
  - It is never too early to 'test as you fly'
  - Never underestimate the need for self compatibility. The test constraints that potential front-end vulnerabilities placed on the radar were very costly in time
  - The peculiarities of two STALOs and their interactions caused at least one real problem and plenty of idiosyncrasies

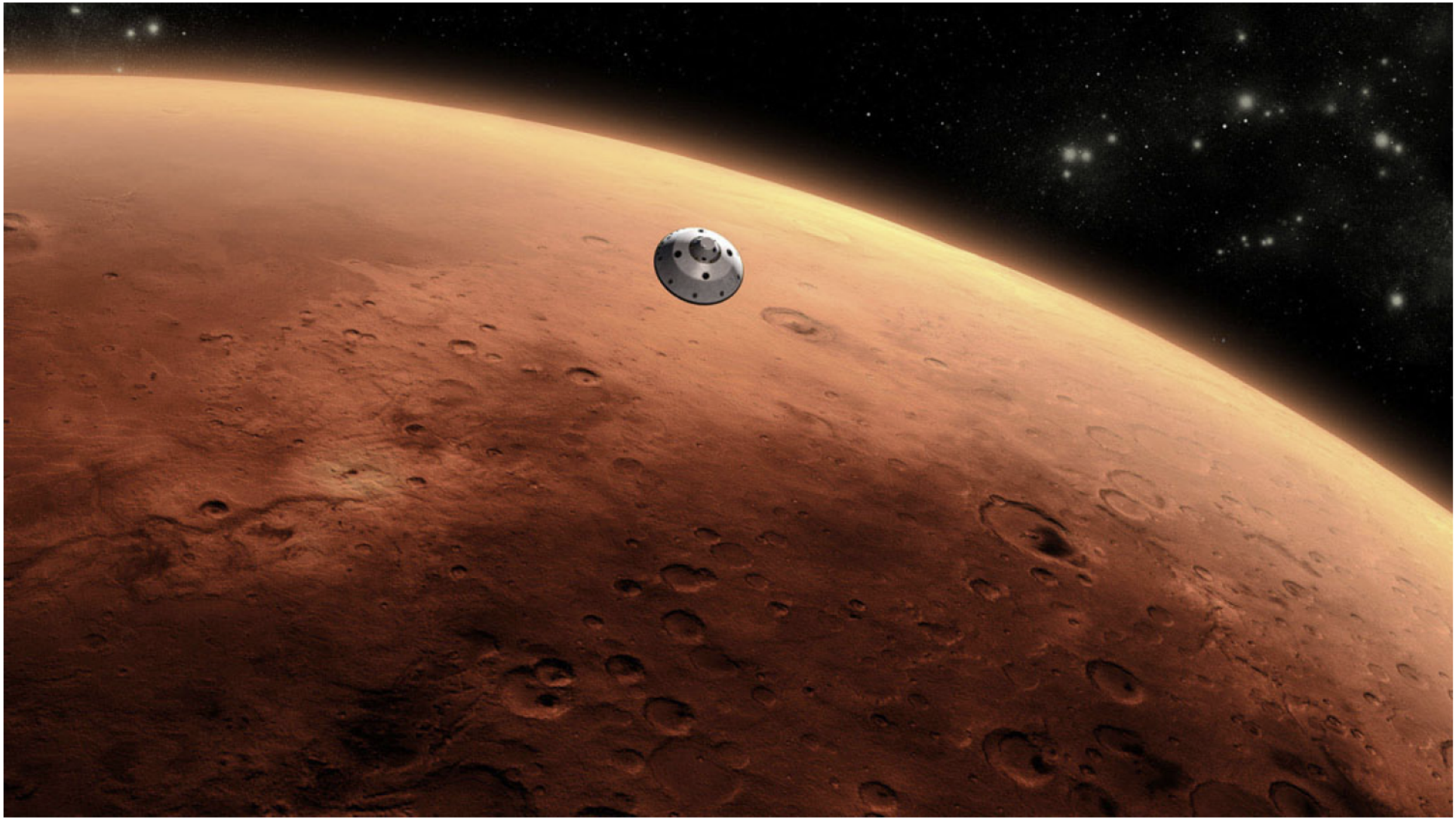
One other fun, little problem…



List of Topics

- How did we get here? …a short review of the sky crane system and decision process
- How did we get here, part 2? …a short review of the events leading up to the design of the TDS
- What does it do? …the design and performance of the TDS.
- What went wrong, and what went right? …lessons learned from the development.
- Where might we go from here? …a few closing notes on the future.

What could happen next?

- For future large scale missions…
  - The MSL TDS design is very capable and meets the need of sky-crane-class of landing vehicles
  - I know of no motivation to improve significantly the ranging / velocity capability for precision landing beyond a few additional points (i.e. higher altitude acquisition through the HS)
  - The implementation is awkward and would benefit from any improvements in *reproducibility*, power reduction, and volume reduction
- The laboratory is still reliant on Honeywell for simple landing radar systems
- Hazard detection / terrain-relative navigation is still be an important NASA desire, but the optical community has a significant head start

“Good luck and Godspeed”, Curiosity