Land with Impunity?

Entry, Descent, and Landing from Mars Smart Lander to Mars 2020

Allen Chen, et al.

Jet Propulsion Laboratory, California Institute of Technology

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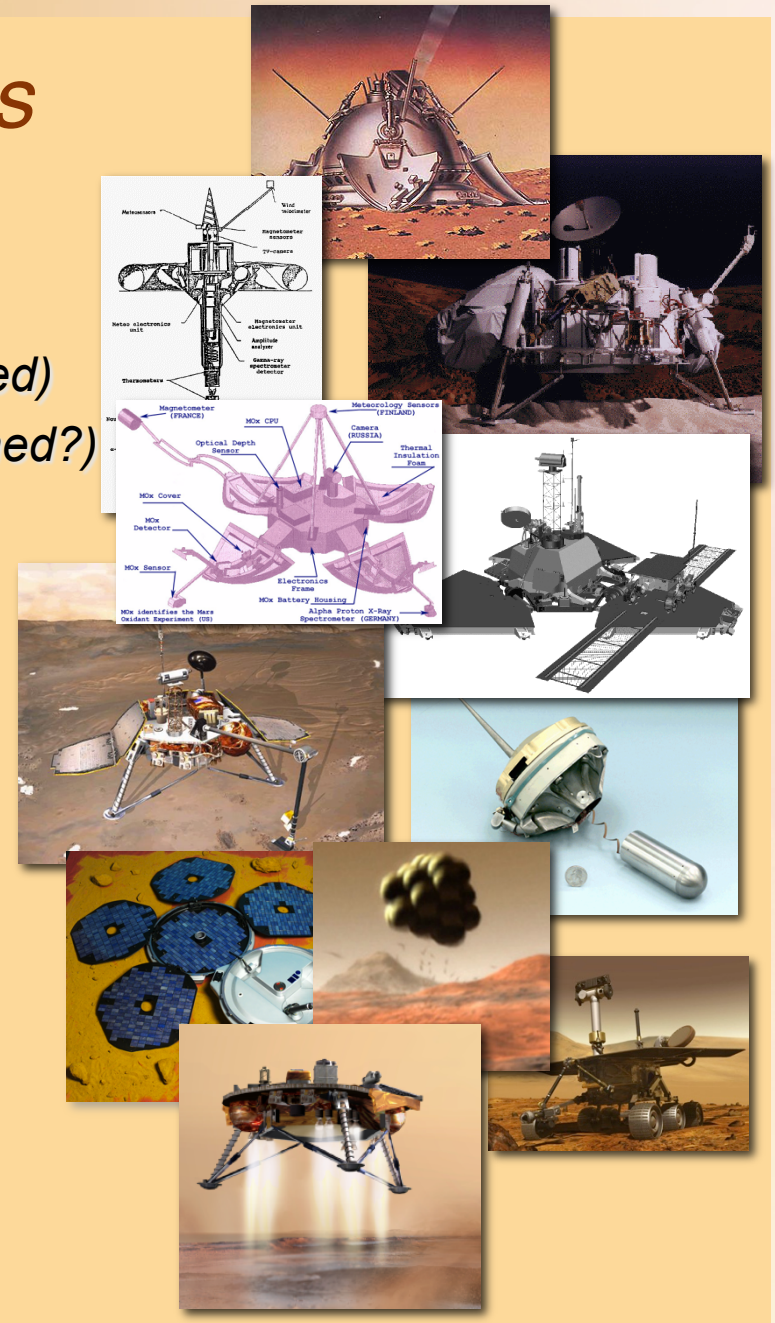
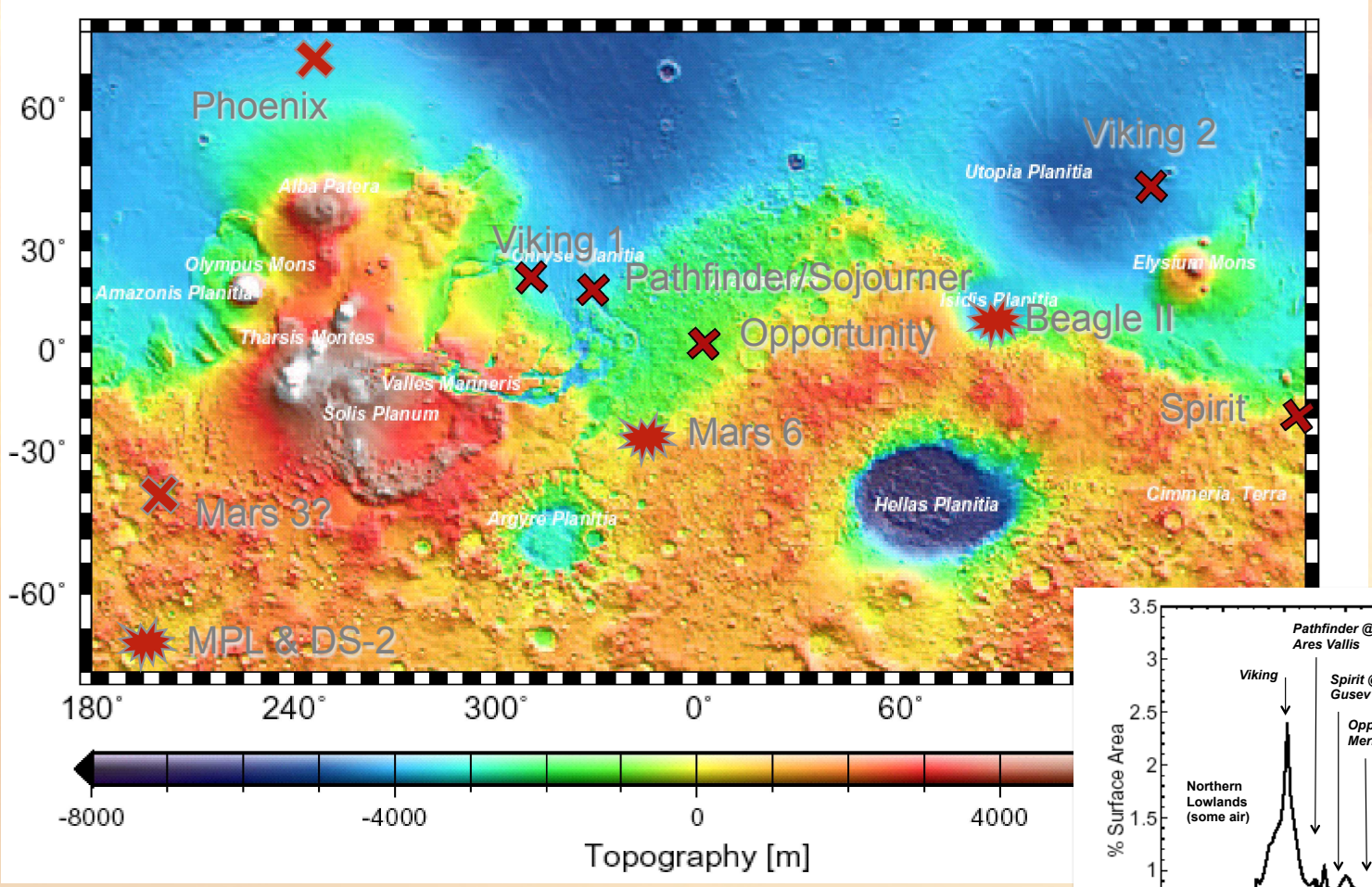
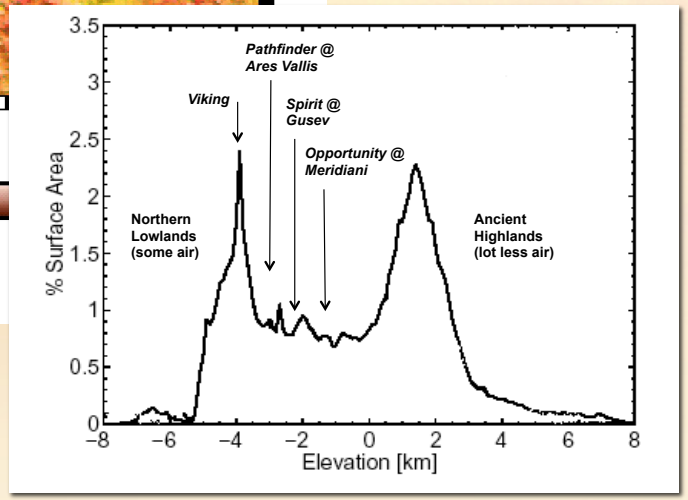
Only ~50% of Mars landers launched have worked

USSR: Mars 2	*1971 (crashed)*
USSR: Mars 3	*1971 (landed, radio died)*
USSR: Mars 6	*1973 (aero data, crashed?)*
USSR: Mars 7	*1974 (missed Mars)*
US: Viking 1	*1975*
US: Viking 2	*1975*
USSR: Mars '96 (2)	*1996 (failed launch)*
US: Mars Pathfinder	*1996*
US: Mars Polar Lander	*1998 (crashed?)*
US: DS-2 Microprobes (2)	*1998 (crashed?)*
Europe: Beagle II	*2003 (crashed)*
US: MER Spirit	*2003*
US: MER Opportunity	*2003*
US: Phoenix	*2007*
US: MSL Curiosity	*2011*

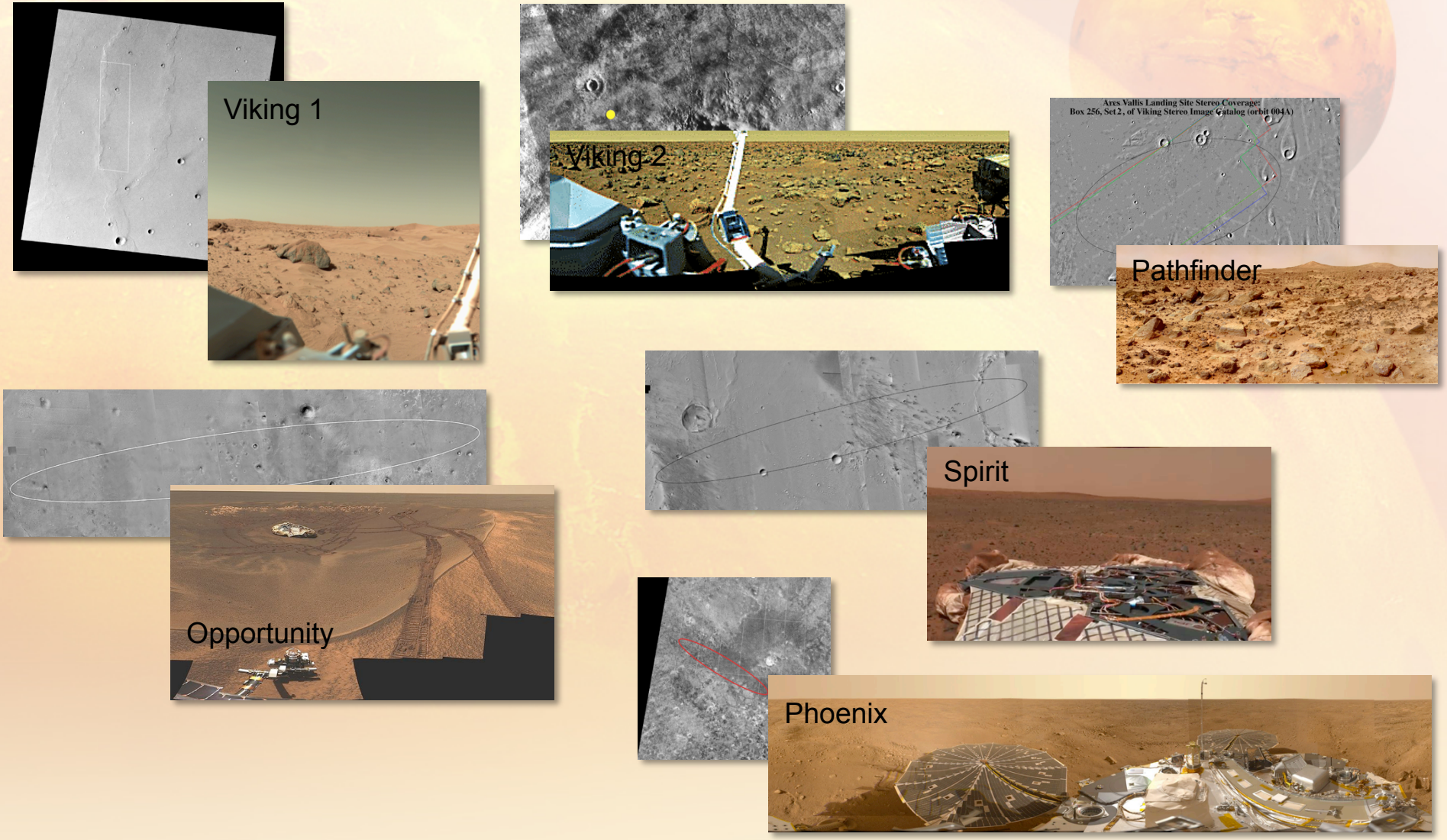


All Our Successful Landings Are On the Skinny Part of the Pear



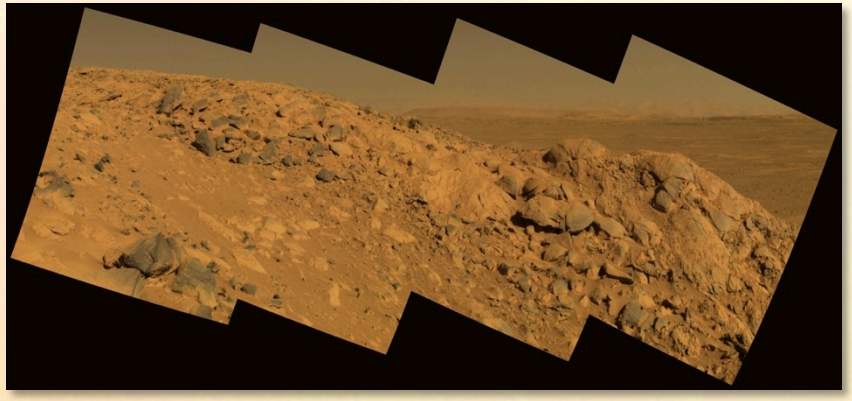


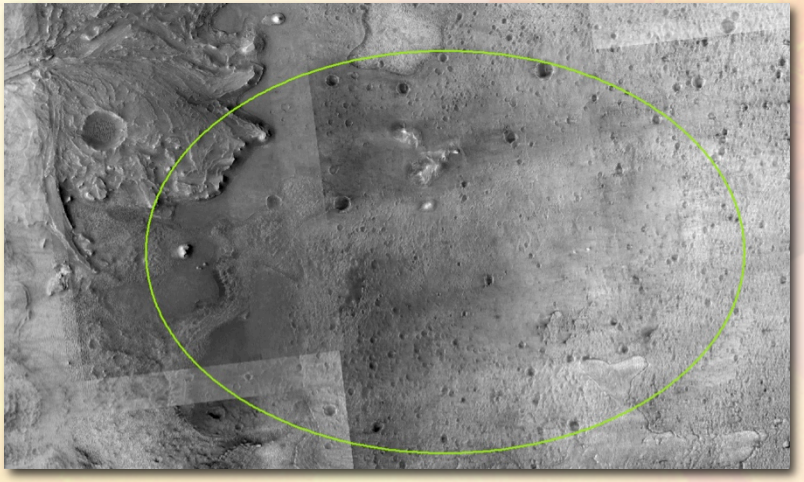
We've Been Landing in Parking Lots

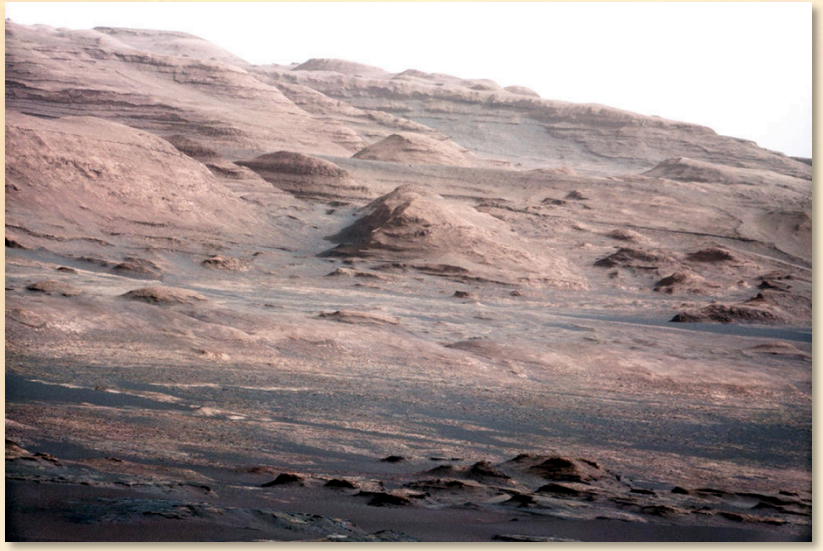


Or, at least places we thought were parking lots…

We Don't Want to Visit Parking Lots





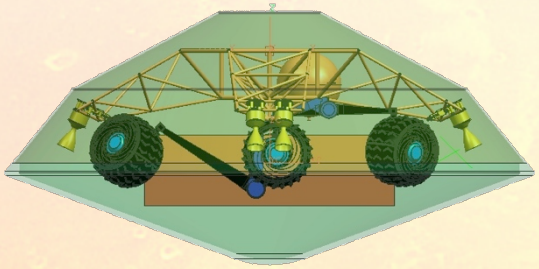


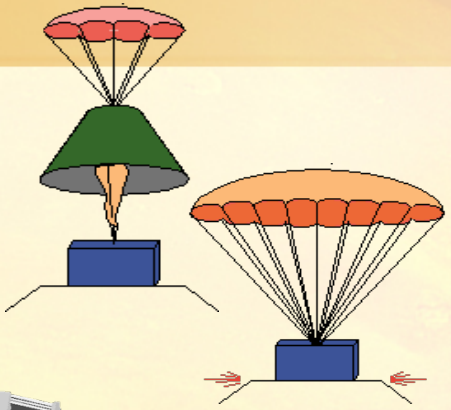
The Best Science Targets Are Landing Hazards

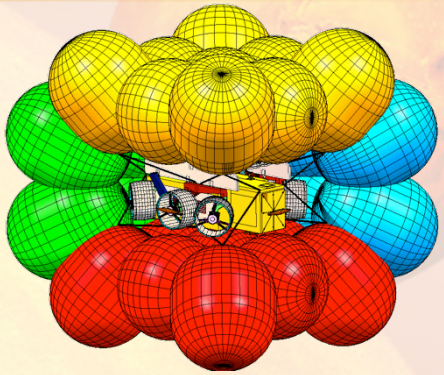
Mars Smart Lander: Land with Impunity

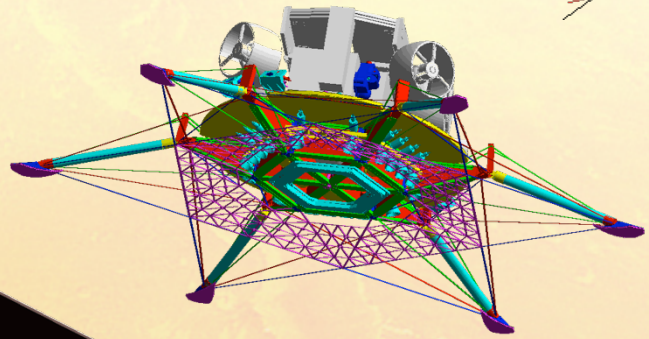
- *Land at sites up +2.5 km MOLA*
- *Land at latitudes from 60°S to 83°N*
- *Land on slopes up to 30° with rocks as tall as 0.5 m*
- *Land on horizontal surfaces with rocks as tall as 1 m*
- *Land within 5 km of a designated target point*

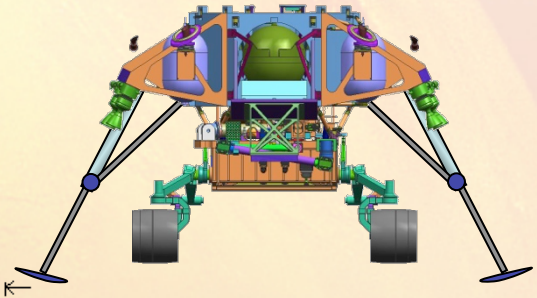
But How?

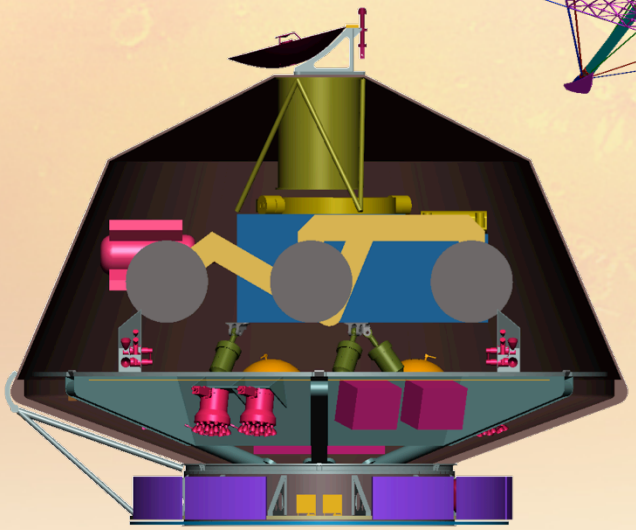


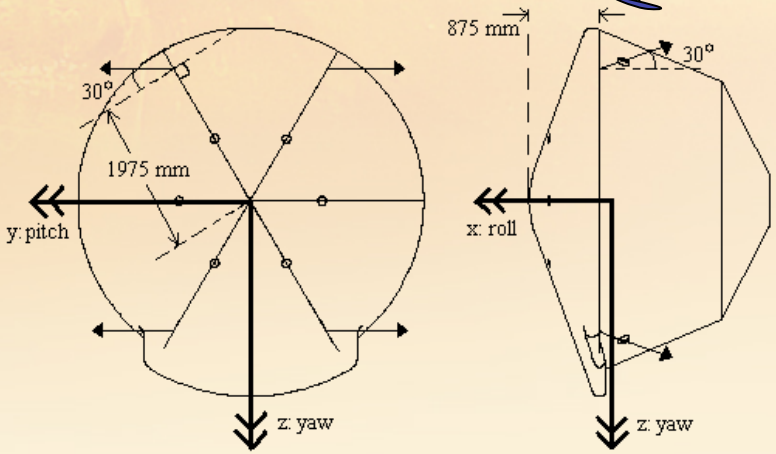












Mars Science Laboratory

Smart Lander Became Science Laboratory

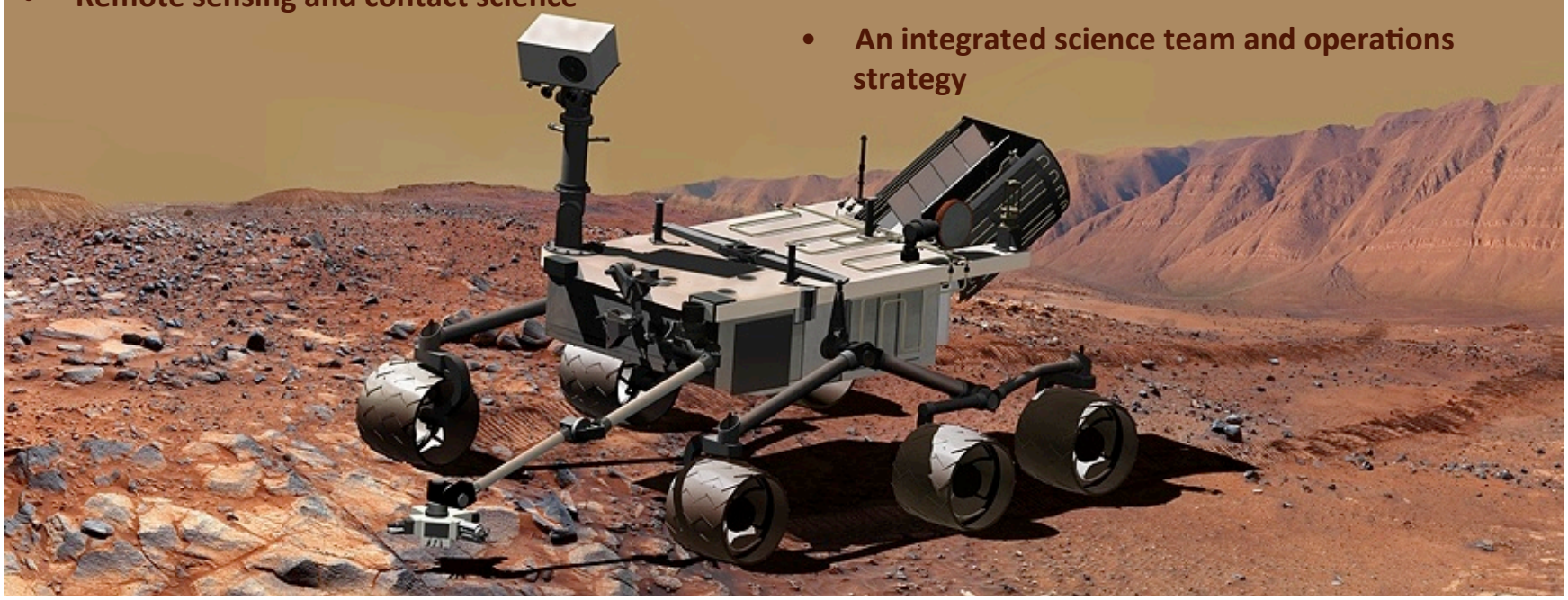
Explore and quantitatively assess a local region on Mars' surface as a potential habitat for life, past or present

A Robotic Field Geologist

- Access to a site mapped from orbit
- Long life, mobility, capability to explore a local region
- Remote sensing and contact science

A Mobile Geochemical Laboratory

- A broad and flexible payload including analytical laboratory instruments
- Ability to acquire and process dozens of rock and soil samples
- An integrated science team and operations strategy



Mass Increased from 600 to 900 kg!

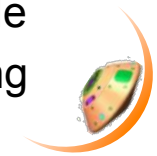
MSL EDL Driving Requirements

Key Driving EDL Requirements:

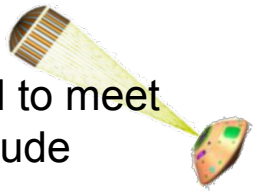
- Deliver 900 kg rover
- 1 km MOLA or greater altitude
- Landing with a maximum error of 10 km from the targeted point
- Robust to environmental variation
  - Derived from discovery responsiveness
  - Slopes up to 25°
  - Rocks up to 0.5 m
  - 30°S to 30°N

Key Design Responses:

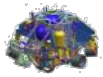
- Guided Entry
  - Lifting entry and entry control to deliver mass to desired altitude
  - Entry guidance to meet landing precision requirement

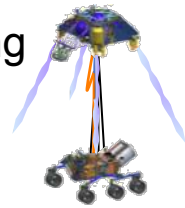


- Parachute
  - Parachute size selected to meet delivered mass and altitude requirements



- Throttled Powered Descent/Sky Crane
  - Delivered mass and interfaces eliminates use of airbag landing system
  - Terrain requirements drive powered descent profile and touchdown system architecture





Resulting Design Features

Key Design Responses:

- Guided Entry
  - Lifting entry and entry control to deliver mass to desired altitude
  - Entry guidance to meet landing precision requirement
- Parachute
  - Parachute size selected to meet delivered mass and altitude requirements
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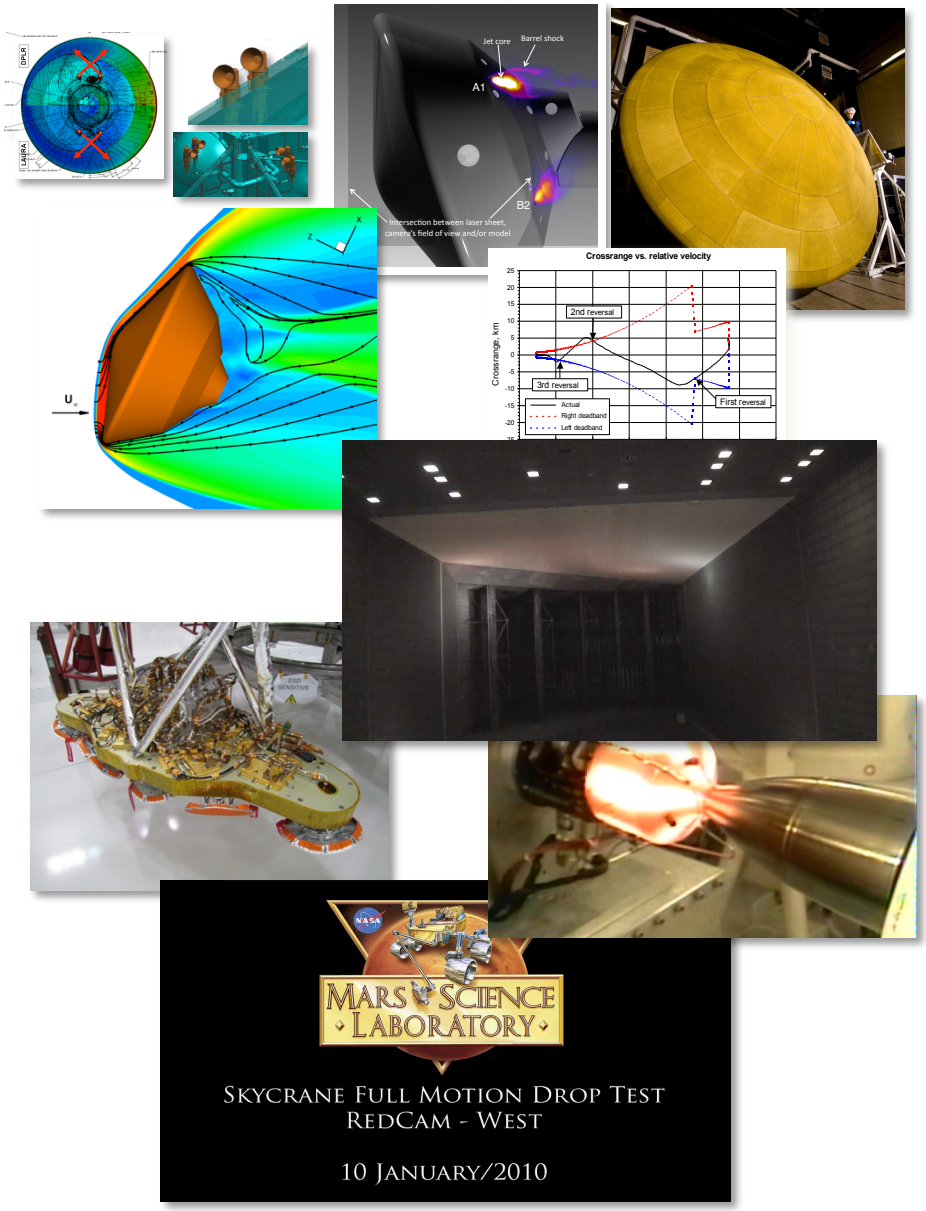


Sky Crane System Architecture

Two-Body Architecture
Decouples descent stage control from touchdown event and allows persistent touchdown signature

Prop and GNC Away from Surface
Closed loop during the touchdown event

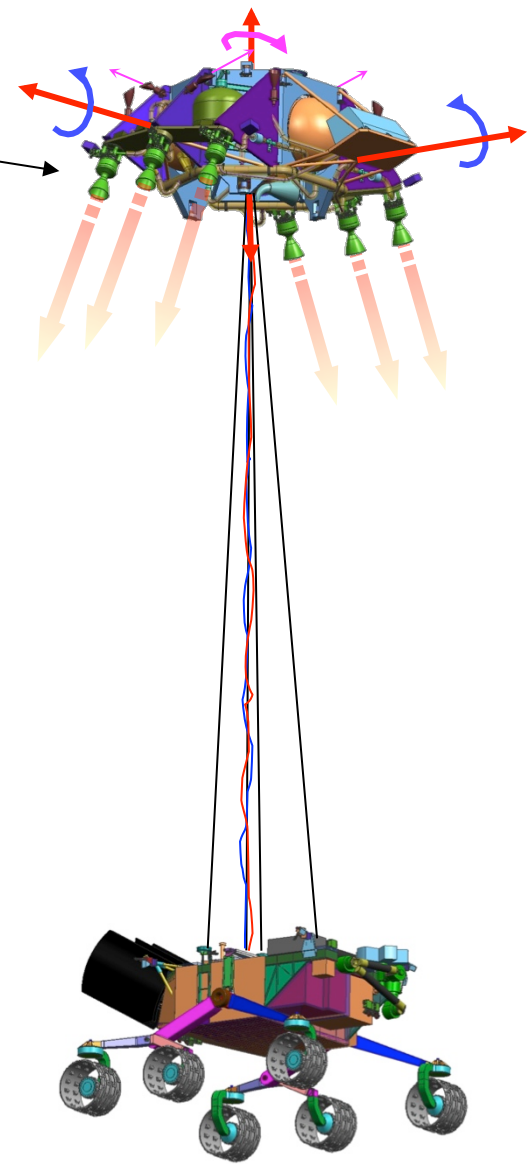
High Bandwidth Vertical Velocity Control
results in low and near constant D/S velocity

Higher Stability
Persistence of tethering during touchdown improves landing stability on rough terrain

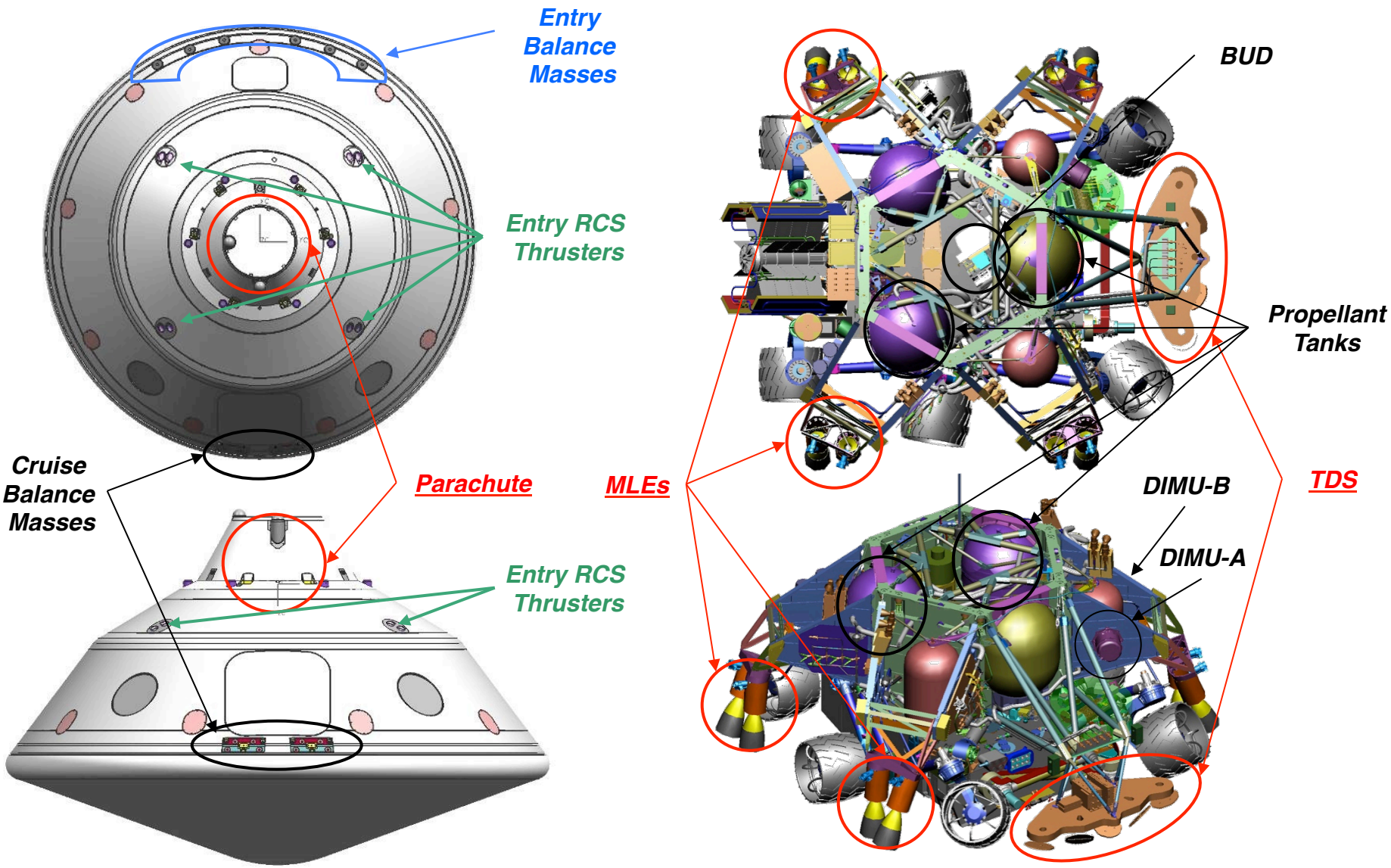
Lower Loads
Low velocities allows rover landing loads to be similar to the rovers driving loads

System Design
High stability and low landing loads mean:
- Separate TD system not required
- Egress system not required

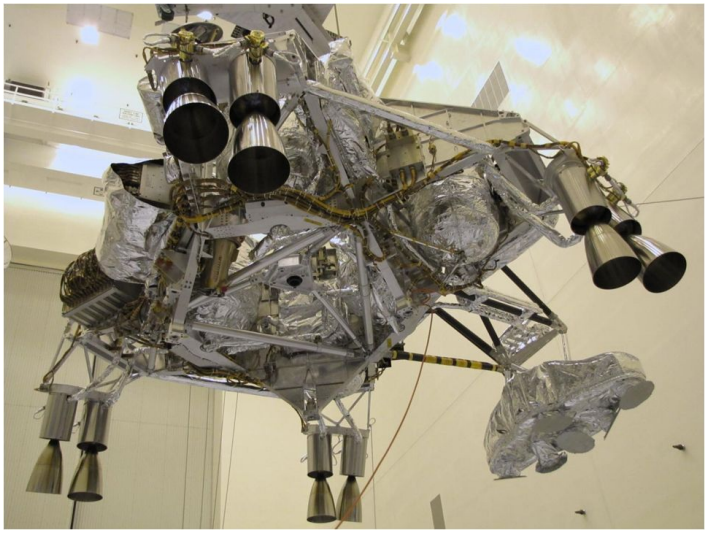
Rover Becomes the Touchdown System
Rover provides ground clearance, static stability, and terrain adaptation

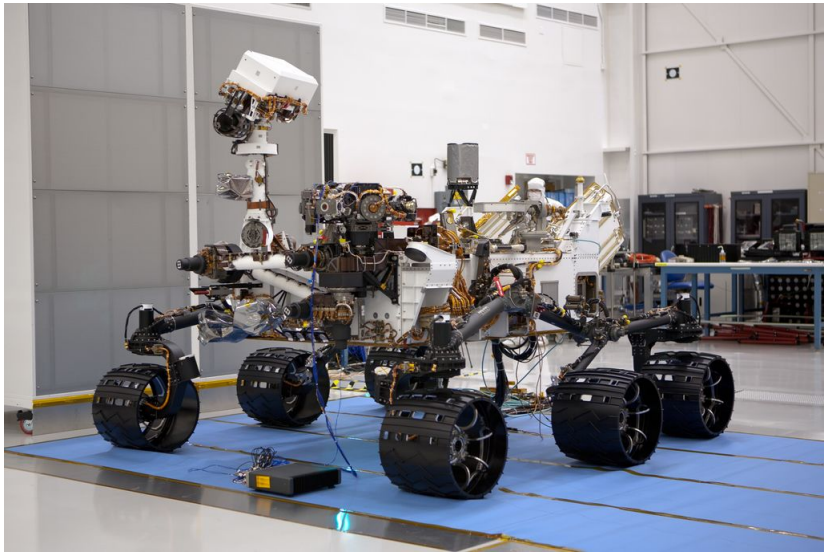


Key EDL Hardware

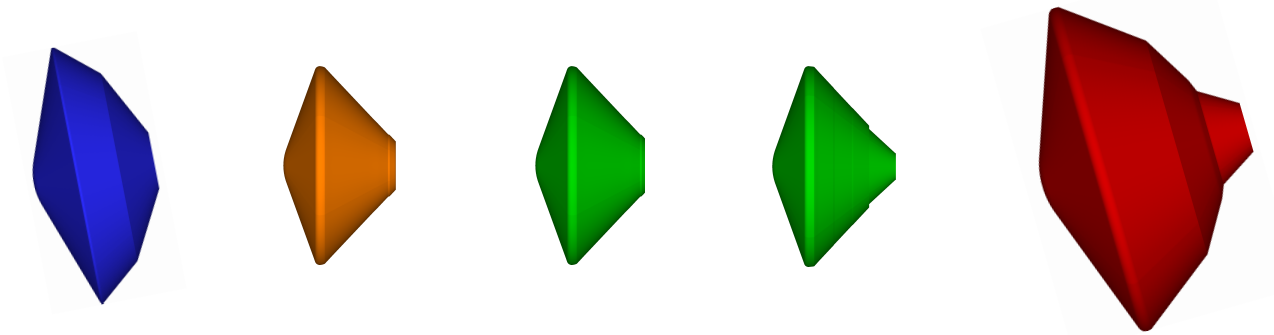


MSL Hardware





Comparison to Past Missions

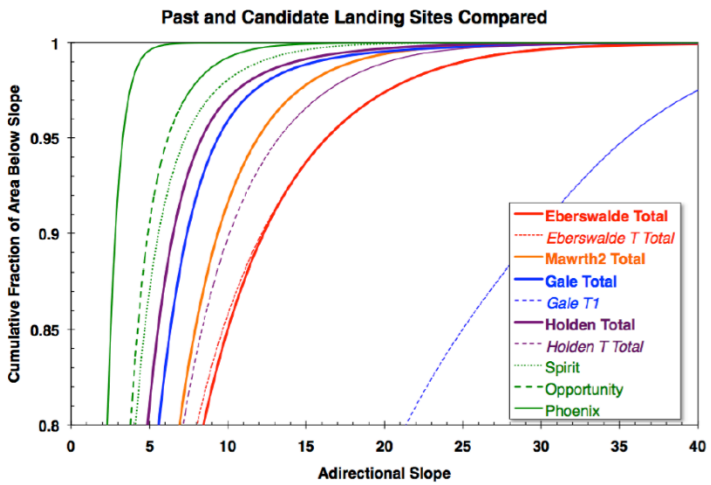


	Viking 1/2	Pathfinder	MER A/B	Phoenix	MSL
Aeroshell Diameter, m	3.50	2.65	2.65	2.65	4.5
Entry Mass, kg	930	585	840	602	3152
Landed Mass, kg	603	360	539/173	364	1561/900
Landing Altitude, km MOLA	-3.5	-1.5	-1.3	-3.5	-4.4 (capability: -0.5)
Landing Accuracy, km	300 x 300	200 x 100	150 x 20	100 x 20	25 x 20 (21 x 7)
Lift/Drag Ratio	0.18	0	0	0	0.24
Entry Guidance/Control	Lift Up RCS Control	None Spinning	None Spinning	None Non-Spinning	Guided RCS Control
Parachute Diameter, m	16.15	12.7	14.1	11.8	21.5
Touchdown System	Legs	Airbags	Airbags	Legs	Sky Crane/ Wheels

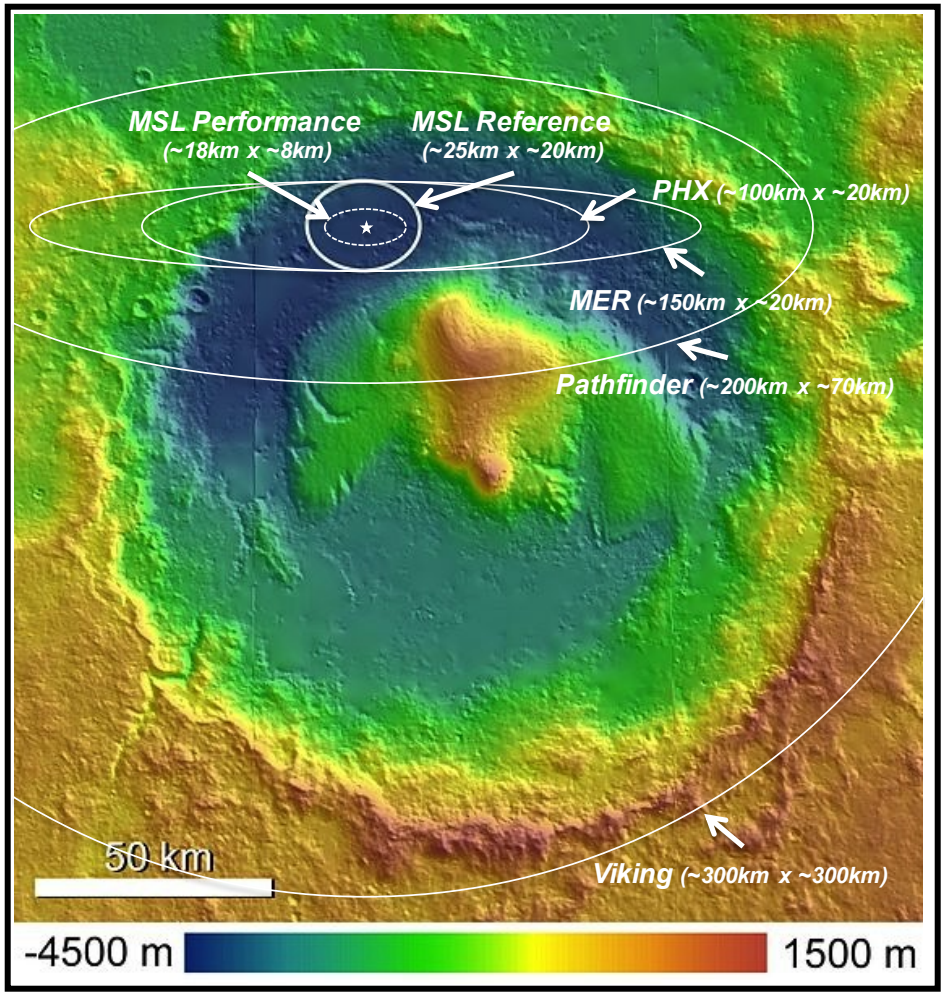
EDL System: MSL vs. Heritage

Improved Terrain Tolerance

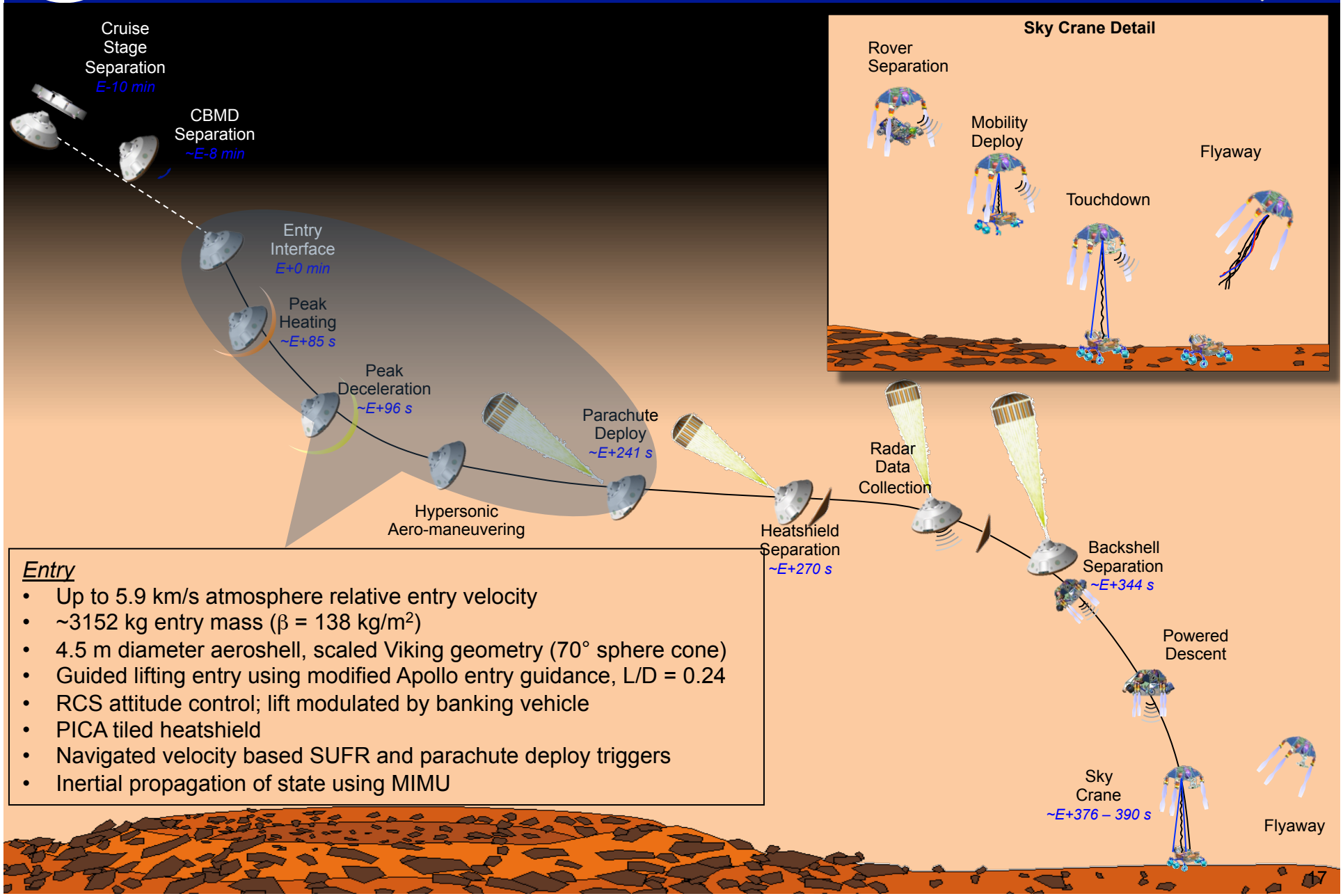
	Viking	MPF	MER	PHX	MSL
Ellipse Size	300km x 300km	200km x 70km	150km x 20km	100km x 20km	25km x 20km
(% of Viking)	100%	15.60%	3.33%	2.22%	0.56%
Slope Tolerance (deg @ 1km)	??	2 - 5	2 - 5	??	10 - 20
Slope Tolerance (deg @ 10m)	10	15 - 30	15	10 - 16	30 - 35
Rock Tolerance (height, cm)	20 - 30	50	50	40	55 - 60



Increased Delivered Mass and Site Elevation, Reduced Ellipse Size



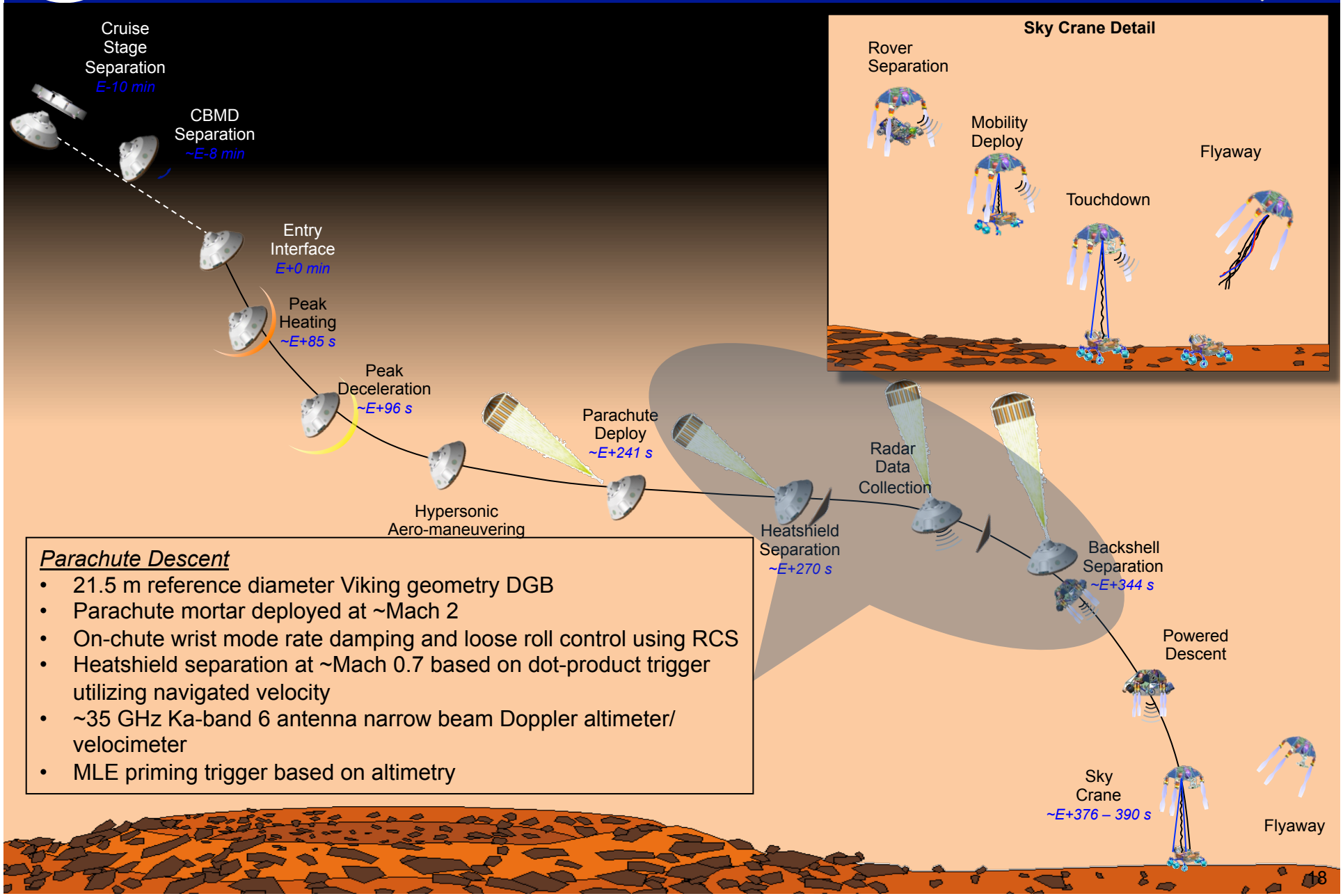
MSL Entry Descent and Landing



Entry

- Up to 5.9 km/s atmosphere relative entry velocity
- ~3152 kg entry mass (β = 138 kg/m^2)
- 4.5 m diameter aeroshell, scaled Viking geometry (70° sphere cone)
- Guided lifting entry using modified Apollo entry guidance, L/D = 0.24
- RCS attitude control; lift modulated by banking vehicle
- PICA tiled heatshield
- Navigated velocity based SUFR and parachute deploy triggers
- Inertial propagation of state using MIMU

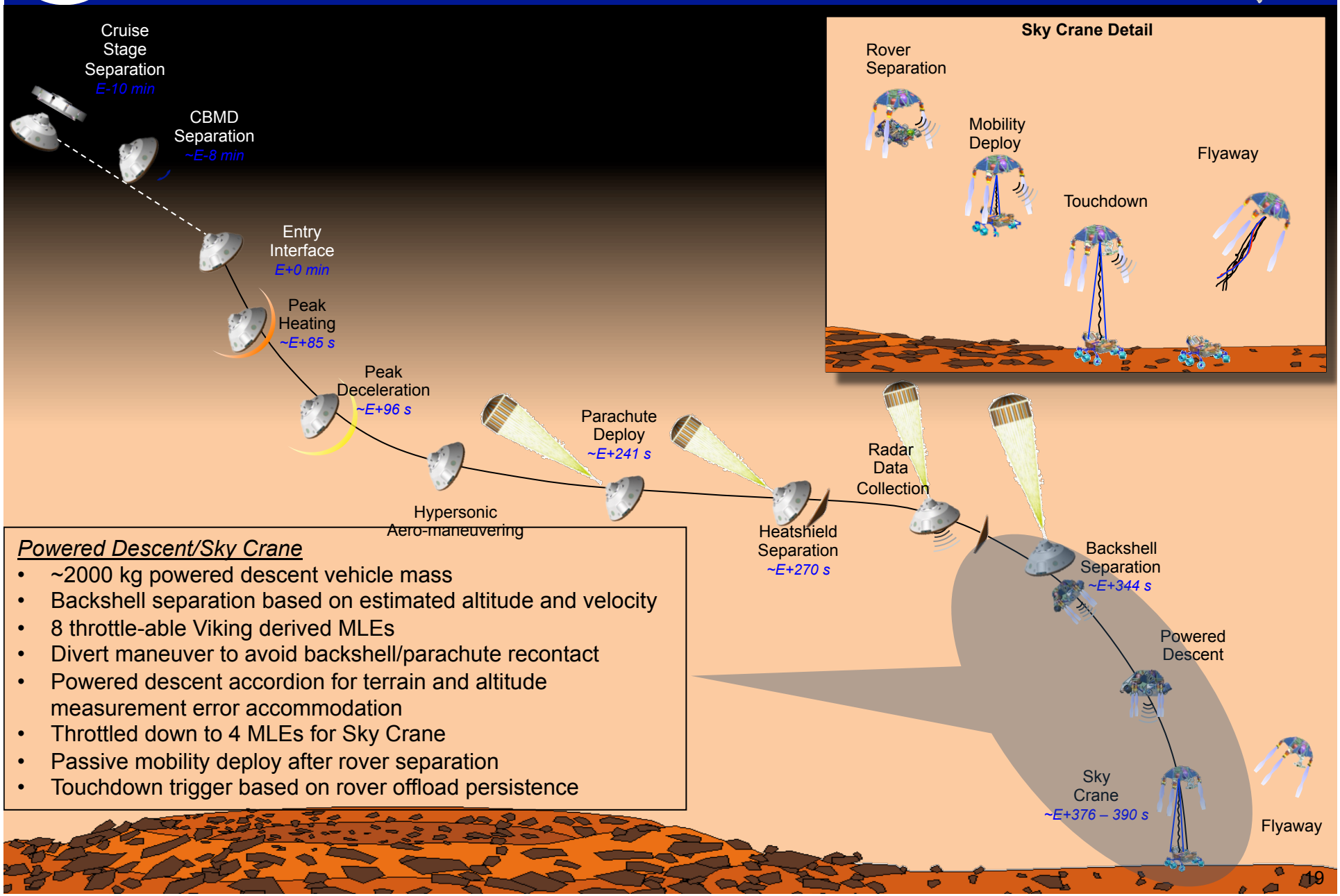
MSL Entry Descent and Landing



Parachute Descent

- 21.5 m reference diameter Viking geometry DGB
- Parachute mortar deployed at ~Mach 2
- On-chute wrist mode rate damping and loose roll control using RCS
- Heatshield separation at ~Mach 0.7 based on dot-product trigger utilizing navigated velocity
- ~35 GHz Ka-band 6 antenna narrow beam Doppler altimeter/ velocimeter
- MLE priming trigger based on altimetry

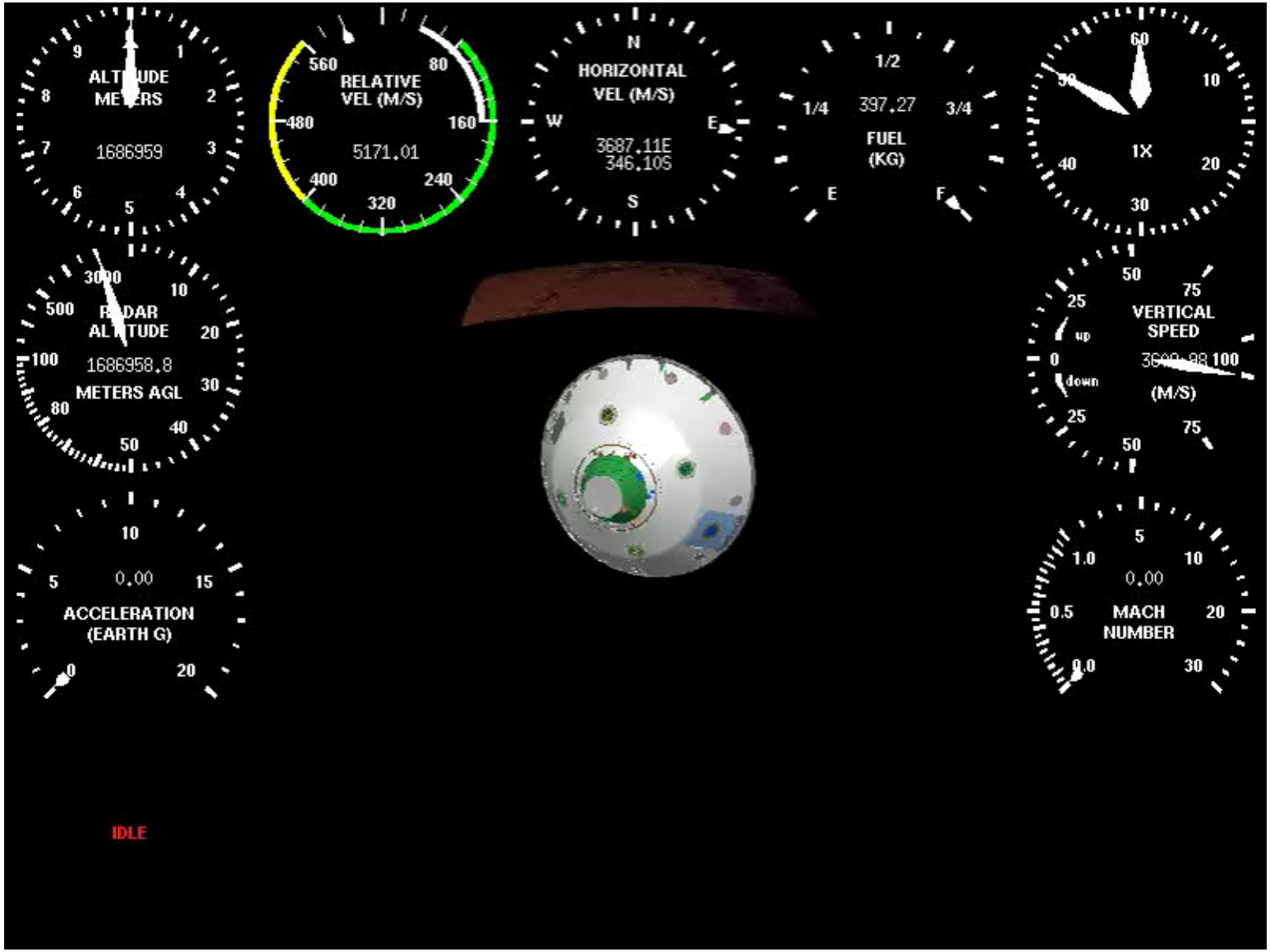
MSL Entry Descent and Landing



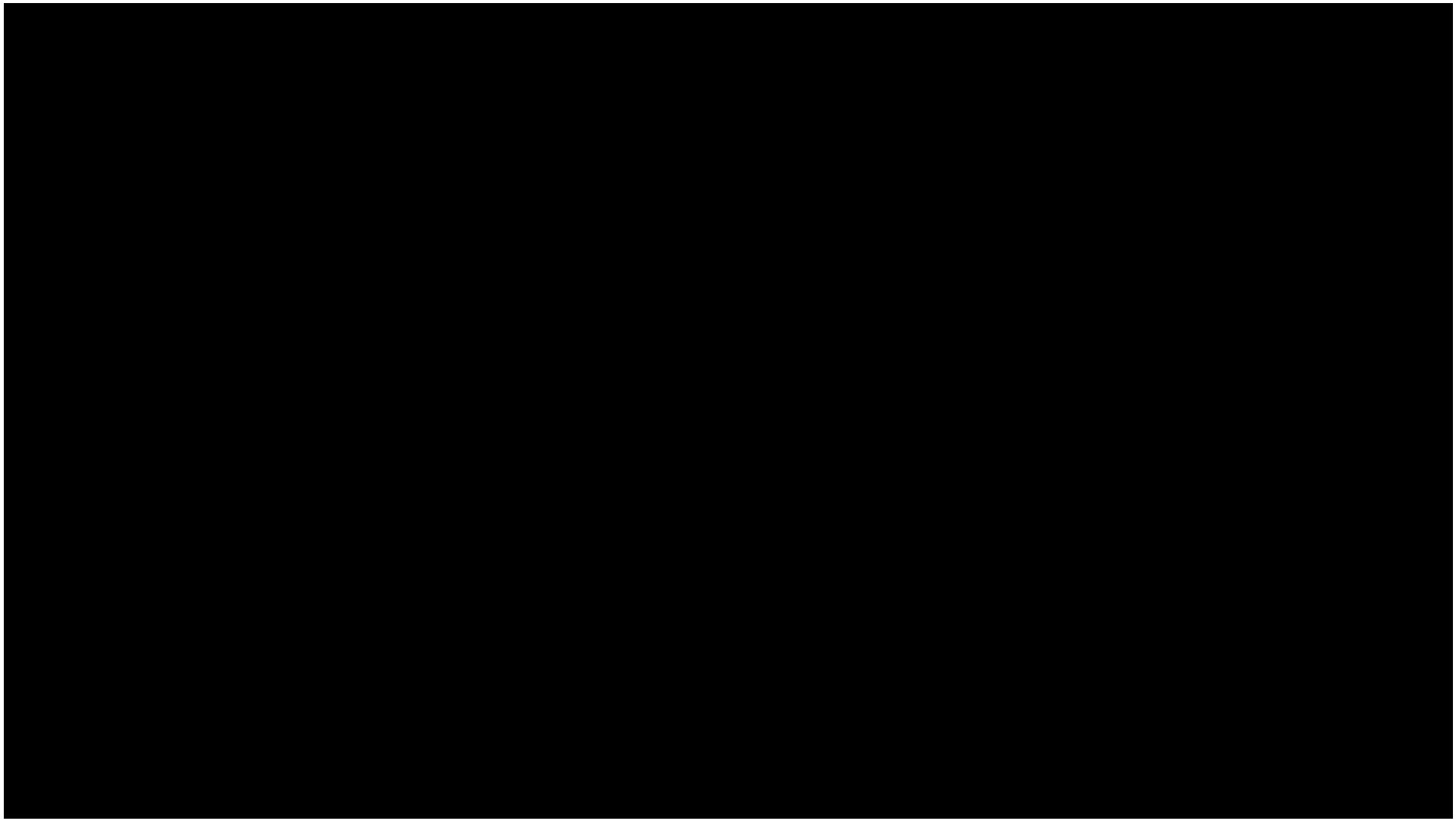
Powered Descent/Sky Crane

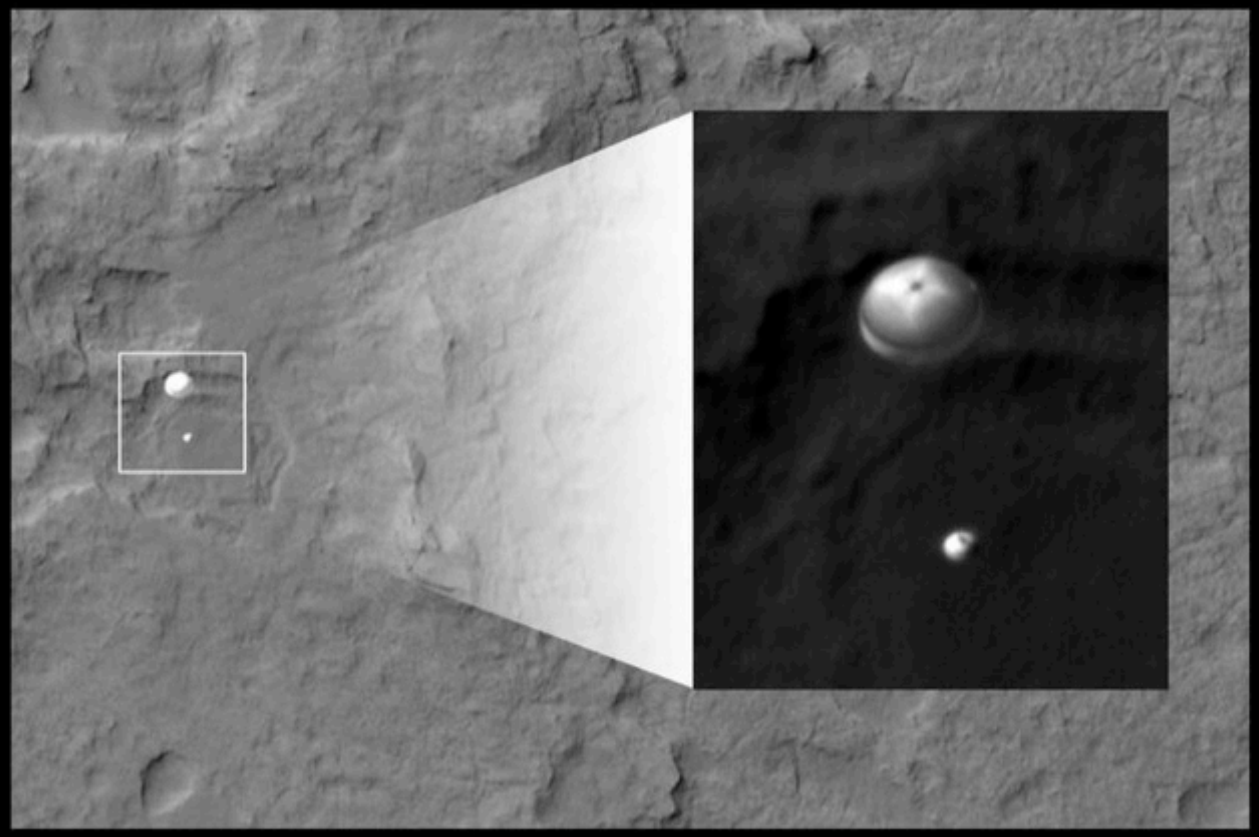
- ~2000 kg powered descent vehicle mass
- Backshell separation based on estimated altitude and velocity
- 8 throttle-able Viking derived MLEs
- Divert maneuver to avoid backshell/parachute recontact
- Powered descent accordion for terrain and altitude measurement error accommodation
- Throttled down to 4 MLEs for Sky Crane
- Passive mobility deploy after rover separation
- Touchdown trigger based on rover offload persistence

Animation


ALTITUDE METERS
1686959
RELATIVE VEL (M/S)
5171.01
HORIZONTAL VEL (M/S)
3687.11E
346.10S
FUEL (KG)
397.27
1X
RADAR ALTITUDE
1686958.8
METERS AGL
VERTICAL SPEED
(M/S)
ACCELERATION (EARTH G)
0.00
MACH NUMBER
0.00
IDLE

The Night Curiosity Landed

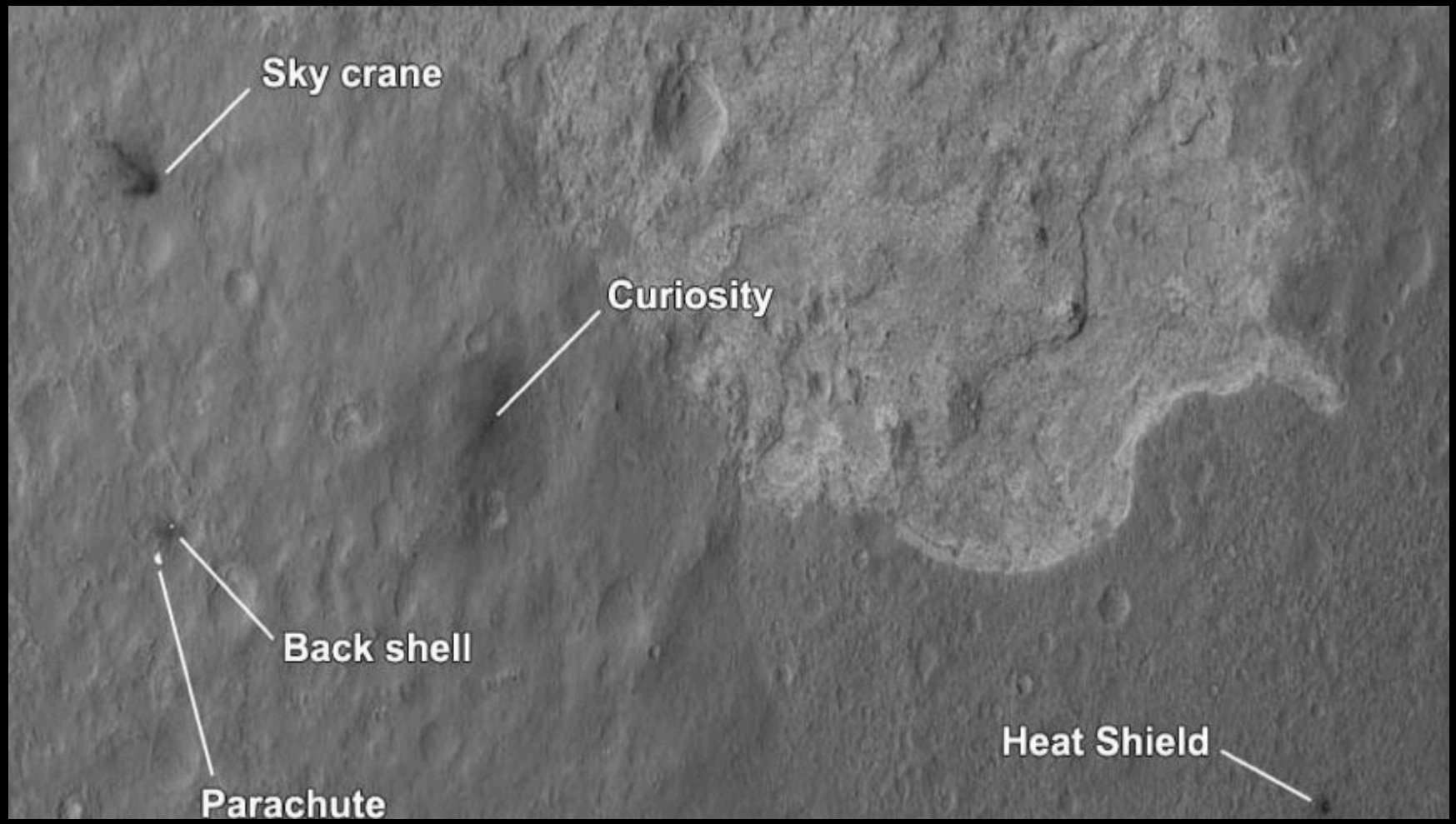




Parachute Deployed
MRO HiRISE camera

Heatshield Jettisoned
MSL MARDI camera

Kicking up dust just prior to landing

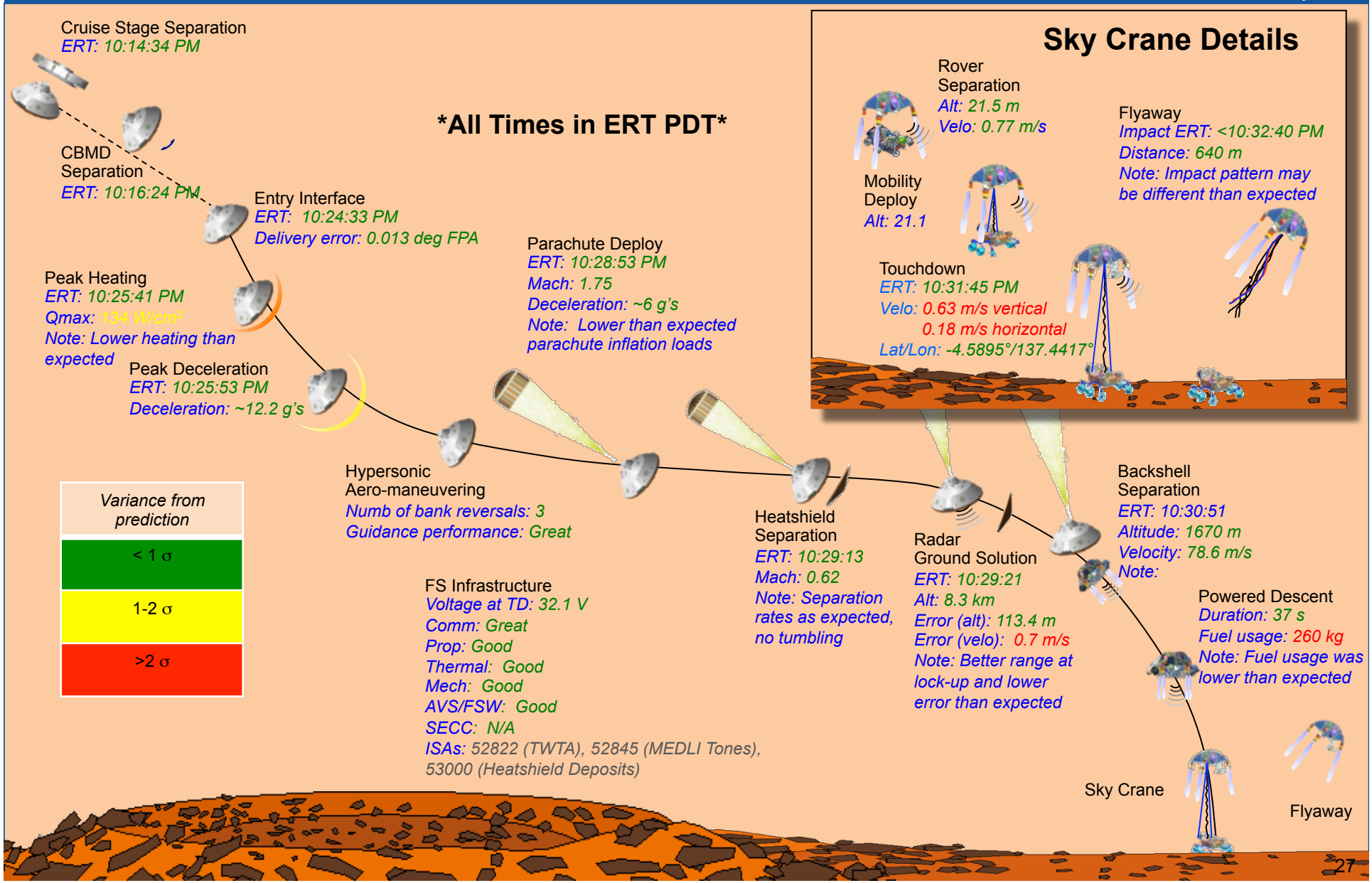


CSI: Mars

How Did We Do?

Jet Propulsion Laboratory
California Institute of Technology

Mars 2020 Project



What Did We Learn?

- Incorrect altitude and velocity estimates during Sky Crane culminated in touchdown conditions outside of predictions

- Root Causes
  - Local gravity differed from onboard gravity estimate
    - Resulted in lower than expected vertical velocity and contamination of horizontal velocity
  - Sandy radar
    - Increased horizontal velocity error

- When you stray away from first principles, you might get burned

Jet Propulsion Laboratory
California Institute of Technology

Mars 2020 Project

Mars 2020

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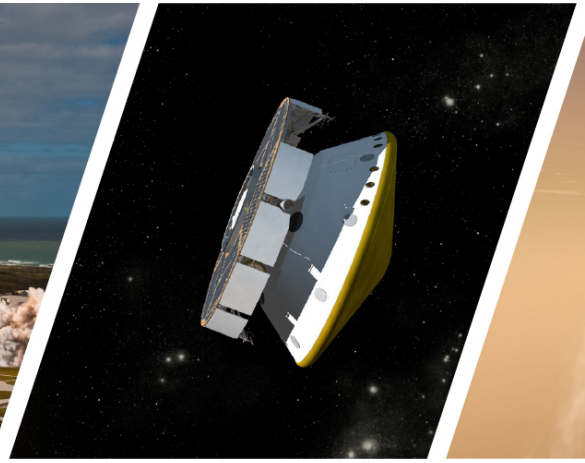
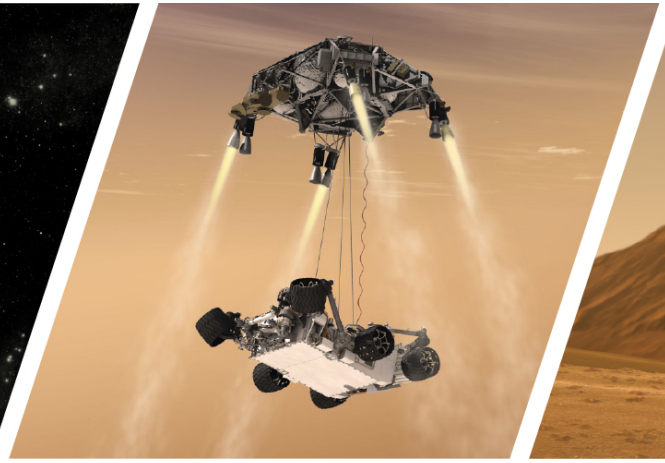
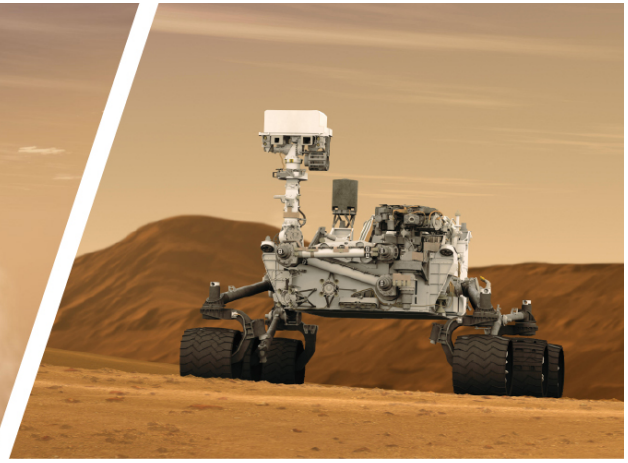
Mars 2020 Mission Overview







LAUNCH

- Atlas V 541 Class Rocket
- Period: Jul-Aug 2020

CRUISE/APPROACH

- ~7 month cruise
- Arrive Feb 2021

ENTRY, DESCENT & LANDING

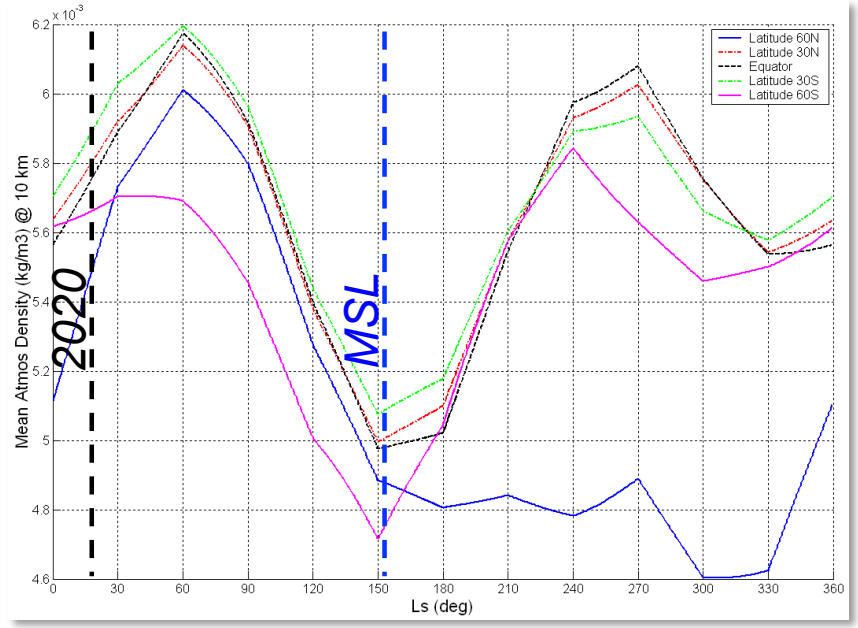
- MSL EDL System: guided entry, powered descent, and sky crane
- Augmented by ***range trigger***: 16 x 14 km landing ellipse
- Augmented by ***TRN***: enables safe landing at a greater number of scientifically valuable sites
- Access to landing sites ±30° latitude, ≤ - 0.5 km elevation

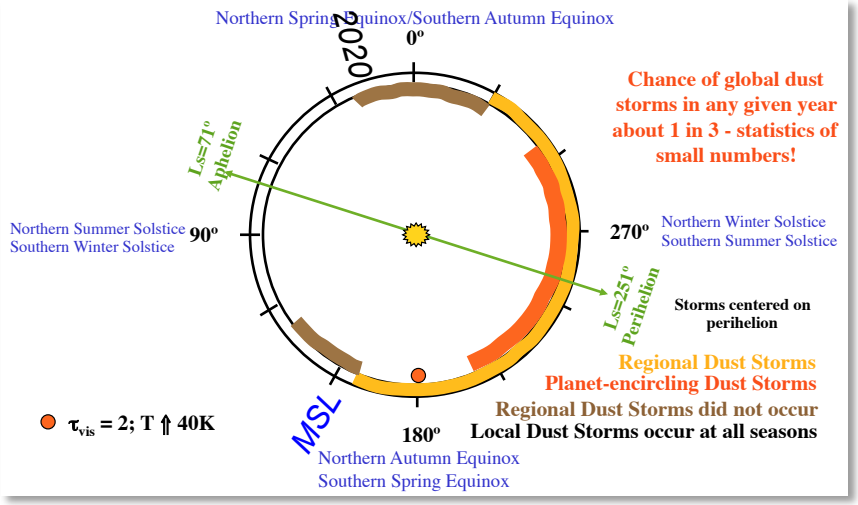
SURFACE MISSION

- Prime mission of 1.5 Mars years
- 20 km traverse distance capability
- Seeking signs of past life
- Returnable cache of samples
- Prepare for human exploration of Mars

EDL in the 2020 Opportunity

- **Pressure cycle very favorable for 2020**
  - Mars orbit eccentricity transfers CO_2 from polar caps to atmosphere
  - Atmosphere significantly more dense than for MSL landing
  - Low risk of dust events
- **More density = capability to land safely at higher elevations**
- **2020 atmosphere provides *significant "no cost" improvements* to landing elevation for same landed mass**
  - Higher altitude capability
  - More propellant margin



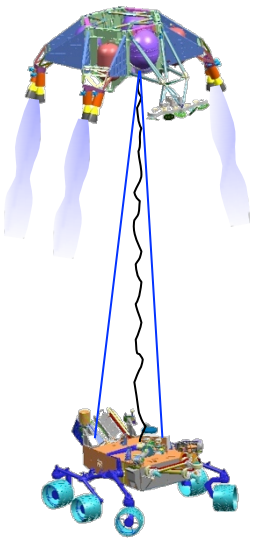


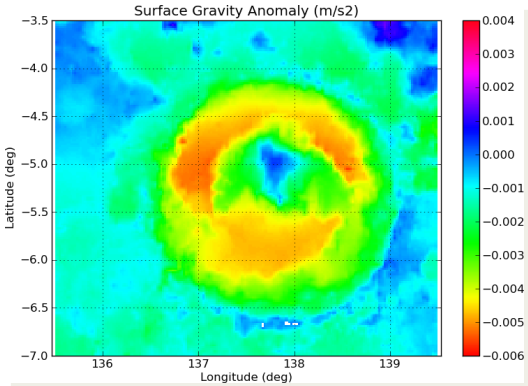
Fixing MSL: Touchdown Velocity

- **Incorrect altitude and velocity estimates during Sky Crane culminated in touchdown conditions outside of predictions**
  - Inaccurate estimation of velocity could result in damage to the rover

- **Root causes**
  - Local gravity differed from onboard gravity estimate
    - Resulted in lower than expected vertical velocity and contamination of horizontal velocity
  - "Sandy radar" – fast-moving dust picked up by radar
    - Misinterpreted as velocity contribution
    - Increased horizontal velocity error, polluted vertical velocity estimation

- **Mitigations**
  - Gravity related fixes
    - Developing high fidelity Mars gravity maps
    - Added site-specific gravity parameter
  - Sandy radar fixes
    - Tightened attitude initialization requirement
    - Tightening filtering of suspect TDS measurements
    - Augmenting TDS model for additional sandy radar effects and studying nav filter tuning strategies

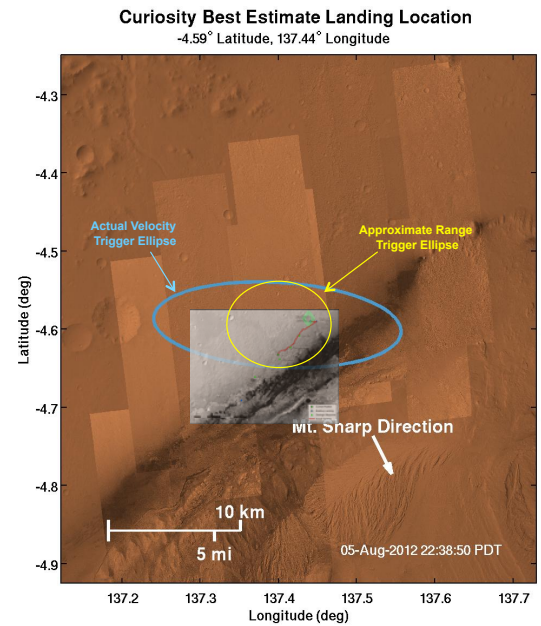


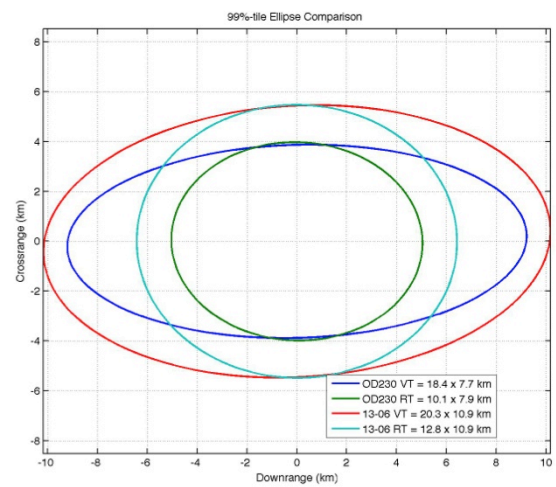


Range Trigger

Baselined

- **Range trigger deploys the parachute based on navigated range instead of navigated velocity**
  - No new hardware is required
  - Simple parachute trigger logic change in EDL FSW
- **Using range trigger can significantly shrink the landing ellipse**
  - Conservatively shrinks,
    - From 20 km x 11 km
    - To 12 km x 11 km
  - ~40% reduction in ellipse area
  - ~8 km reduction in ellipse length
- **Key benefits:**
  - Makes previously inaccessible landing sites accessible
  - Could save ~1 Earth year of driving
  - Makes the TRN job easier
- **Magnitude of the improvement depends on landing site wind uncertainty and site elevation**
- **Range trigger is not a new idea – it's actually a very old idea that we couldn't adopt on MSL because we were chasing altitude performance**

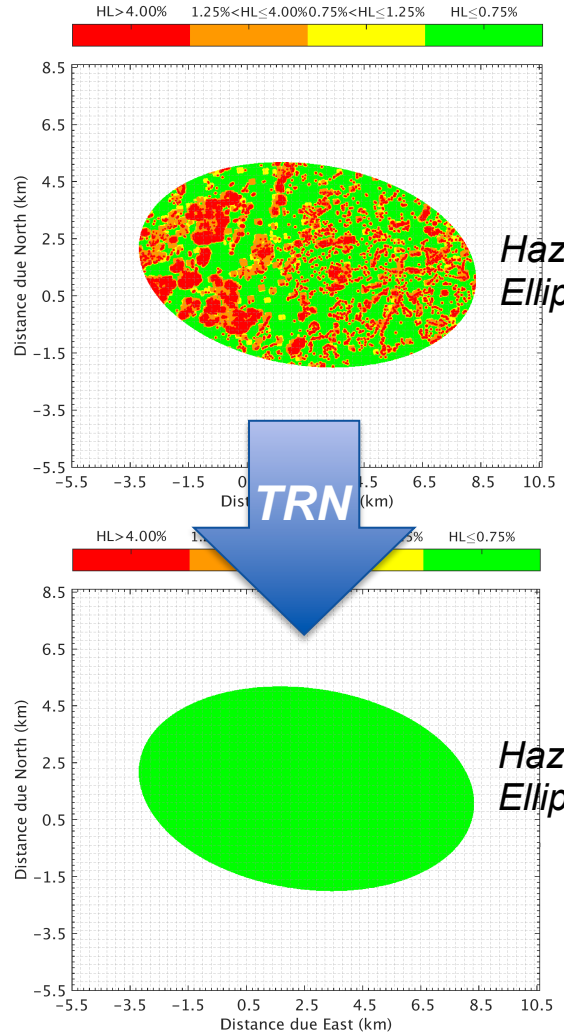




Terrain Relative Navigation

Baselined

- TRN (Terrain Relative Navigation) provides the capability to avoid large scale landing hazards during EDL
- Enables safe access to scientifically compelling landing sites and reduces post-landing surface drive distances
- TRN hardware also provides key surface processing capability to support surface mobility and autonomy
- Adding TRN judged by EDL review board as acceptably low risk to the heritage EDL system
- Baselined in January 2016

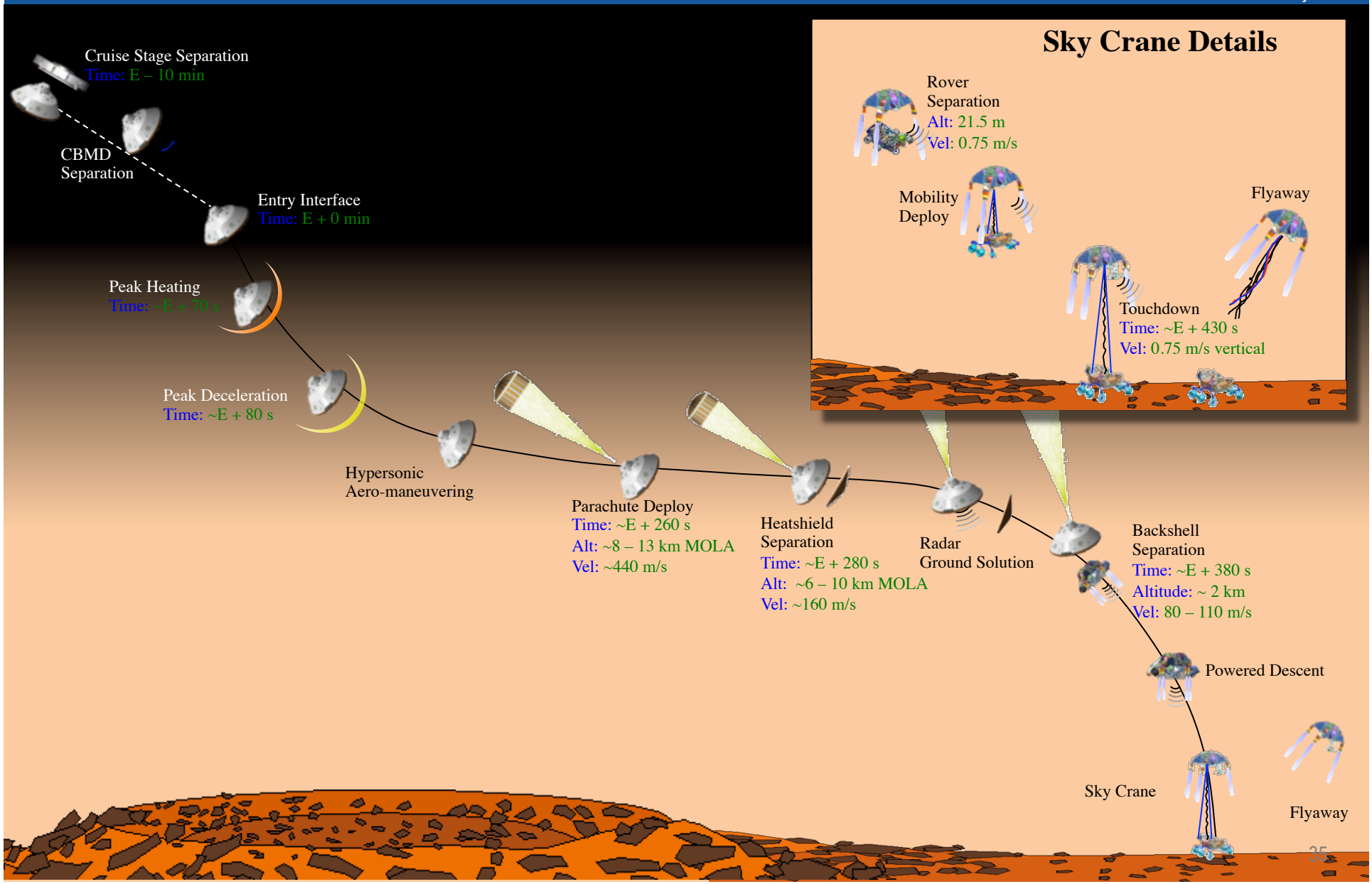


Hazards in Landing Ellipse without TRN

Hazards in Landing Ellipse with TRN

TRN increases the probability of safe landing

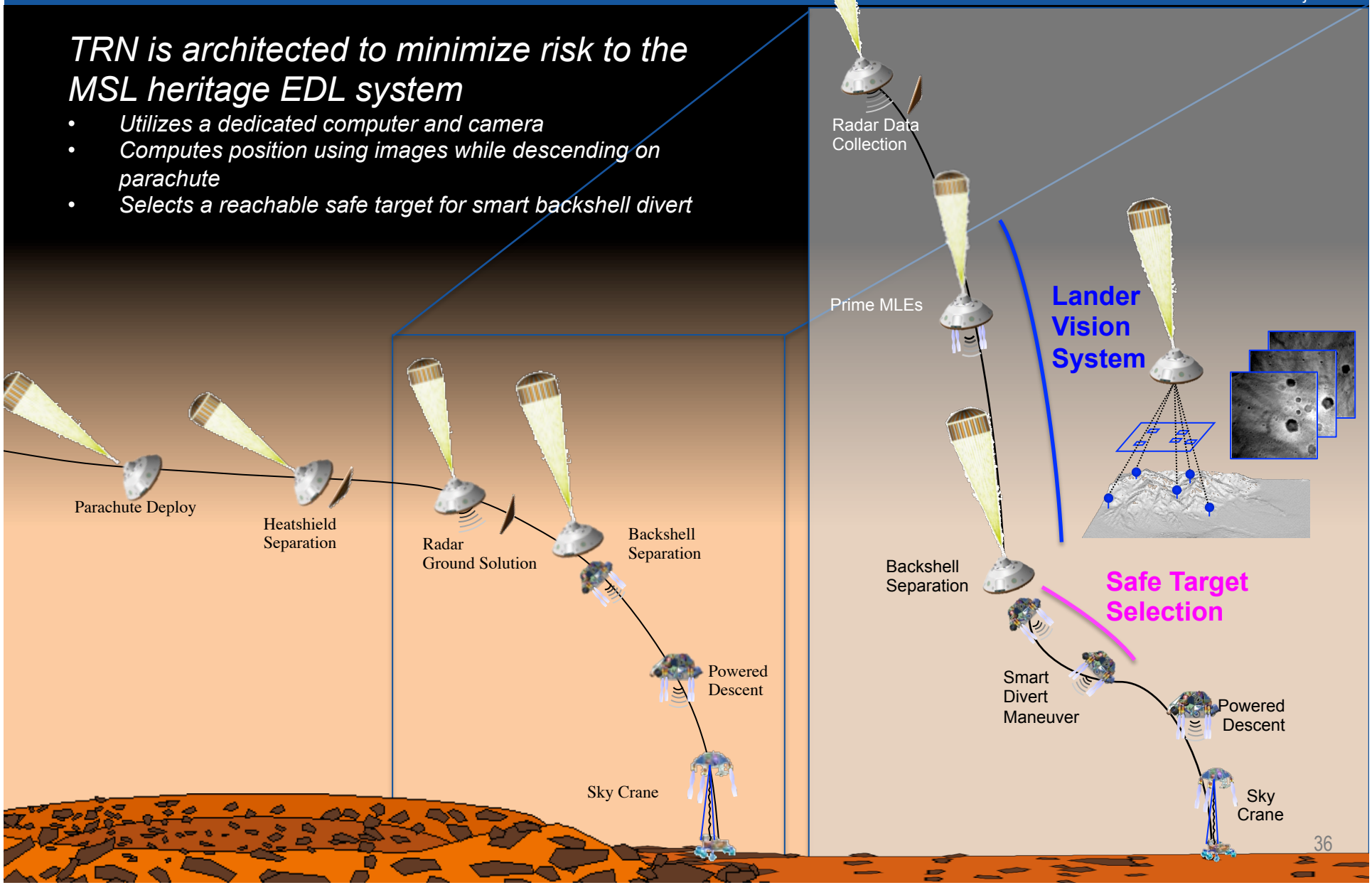
EDL Timeline



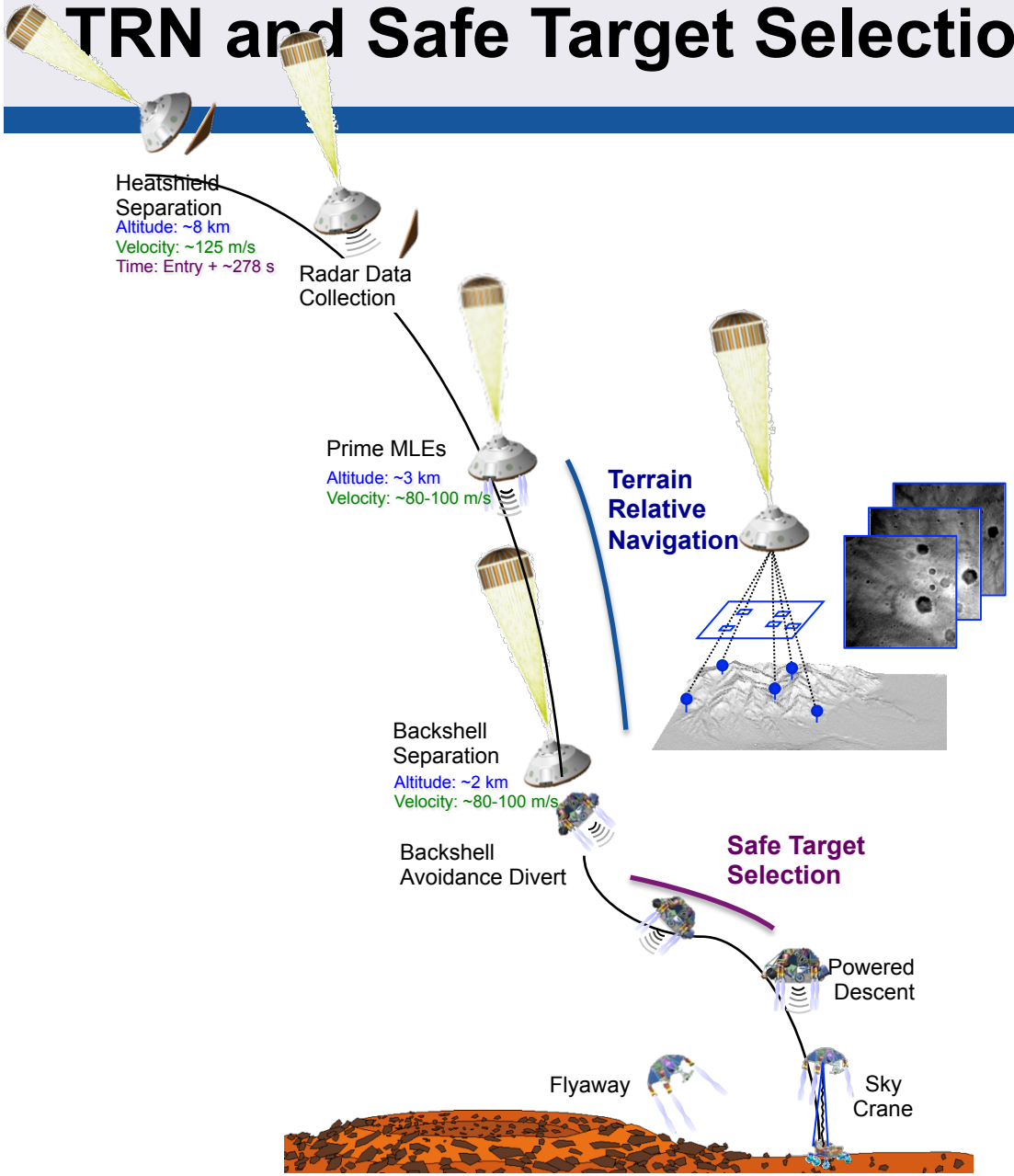
EDL Timeline with TRN

TRN is architected to minimize risk to the MSL heritage EDL system

- *Utilizes a dedicated computer and camera*
- *Computes position using images while descending on parachute*
- *Selects a reachable safe target for smart backshell divert*



TRN and Safe Target Selection



Terrain Relative Navigation

- Takes images during parachute descent and matches them to an onboard map
  - Uses a dedicated computer and camera
  - Yields a position solution
- Performs terrain relative navigation while the spacecraft is priming the descent engines
- Executed by the Lander Vision System (LVS)

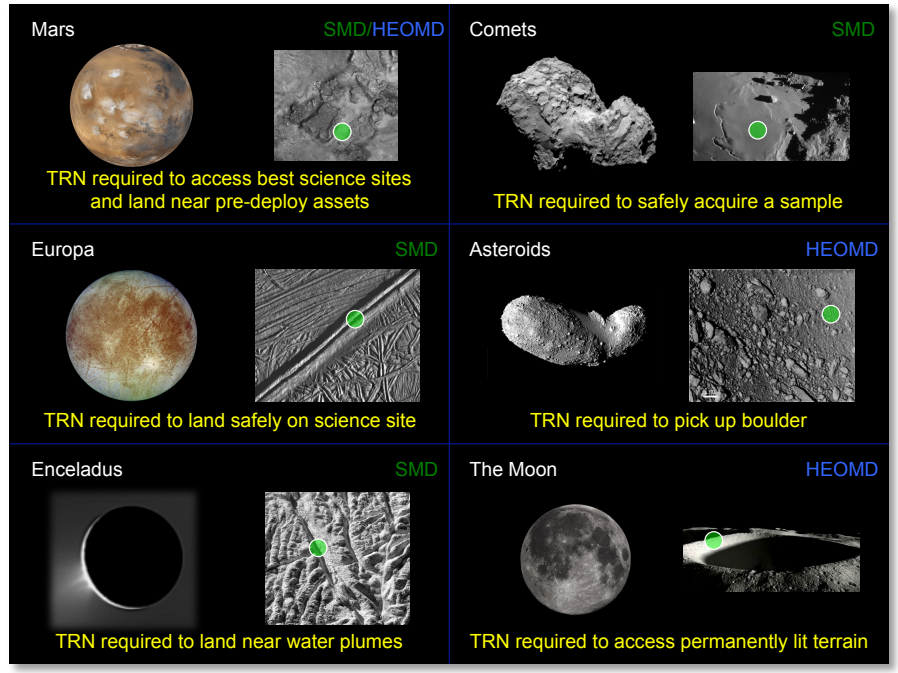
Safe Target Selection

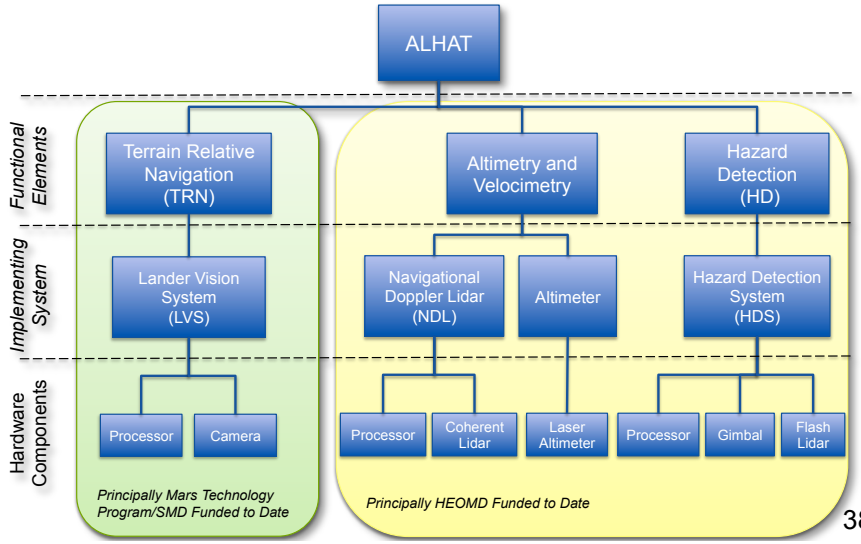
- Uses position solution and list of safe landing locations to select a safe landing target
- Augments original MSL backshell avoidance divert
- Lives within MSL fuel and control constraints
- Not “pinpoint” landing

TRN gives Mars 2020 “eyes” to avoid identified landing hazards

TRN Has Cross-Cutting Value

- TRN is a required piece of all current human and robotic precursor EDL architecture concepts for Mars
- TRN is also a key element of several future robotic SMD mission concepts
- If TRN isn't developed and demonstrated in flight with Mars 2020, future missions will have to develop TRN as the foundational piece of precision/safe landing
- A flight demonstration of the full system on Mars 2020 is directly applicable to future SMD and HEOMD applications





Preliminary Engineering Assessment of Candidate Landing Sites *(in Alphabetical Order)*

Site	w/o TRN	w/ TRN	Comments
Columbia Hills (Gusev)			Can land directly on Columbia Hills with or without TRN
Eberswalde		TBC	Near complete terrain data products available; likely requires TRN; potentially difficult traversability
Holden (MSL target)			Data product coverage is excellent; Southern latitude may be a surface productivity and longevity concern
Jezero		+3.75%	Requires TRN; traverse difficulty may impact surface performance
Mawrth		+1.93%	Near complete terrain data products; requires TRN; etched slopes will impact surface productivity
NE Syrtis		+1.75%	Requires TRN; surface situation good
Nili Fossae			Data product coverage is good; TRN not required; surface situation good. High site elevation.
SW Melas		+1.22%	Safe with TRN; surface looks good as long as ellipse shrinks somewhat

*Color coded normalized to assessed risk of MSL final four landing sites

= in family with MSL risk (<1% terrain failure rate)

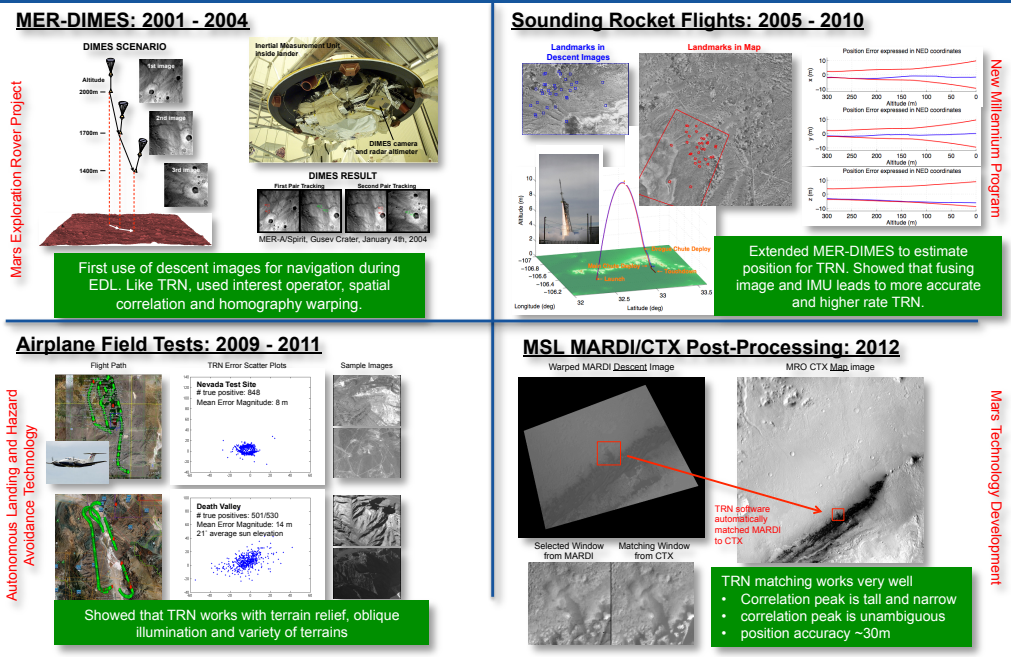
= somewhat out of family with MSL risk

= out of family with MSL risk (>2% terrain failure rate)

Significant increase in probability of safe landing for high priority sites

TRN Development Status

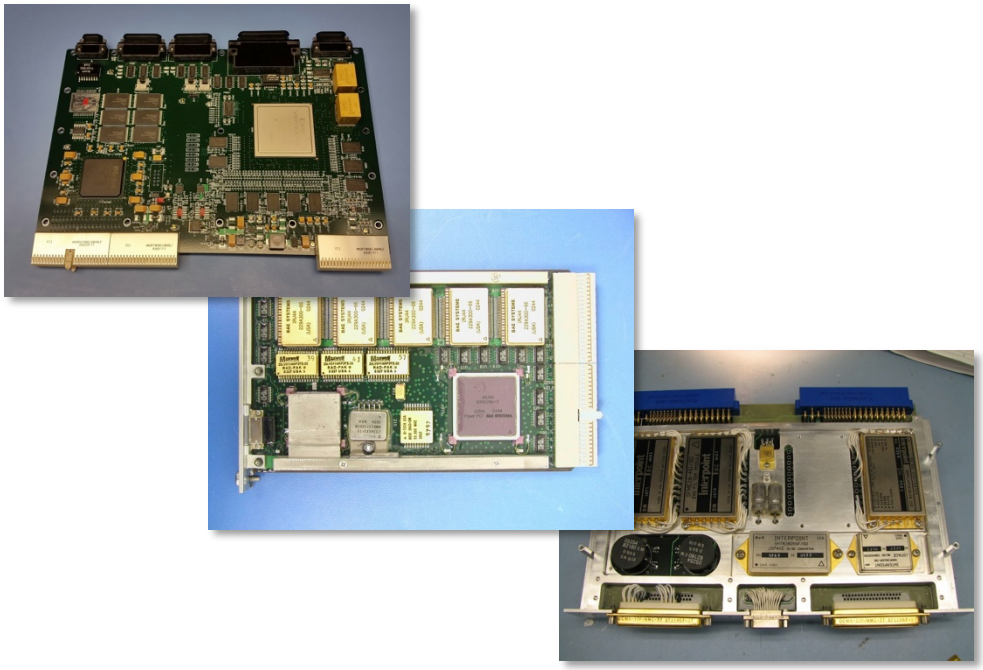
- **TRN as designed for Mars 2020 is the culmination of ~15 years of technology and flight developments**
- **TRN prototype tested over a wide range of Mars analog terrains and operational conditions**
  - Position accuracy and robustness requirements met with margin
  - Informed by the Mars 2020 flight envelope
- **Field test demonstrated maturity of the architecture and algorithms**



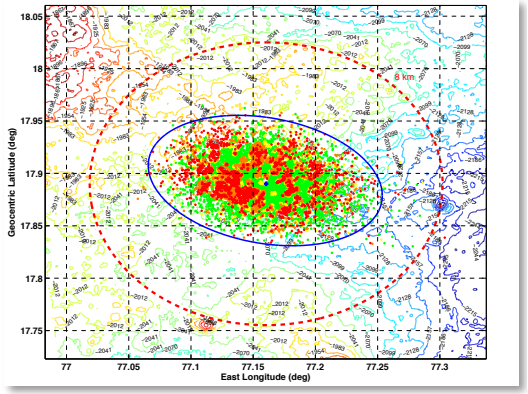
TRN Development Status

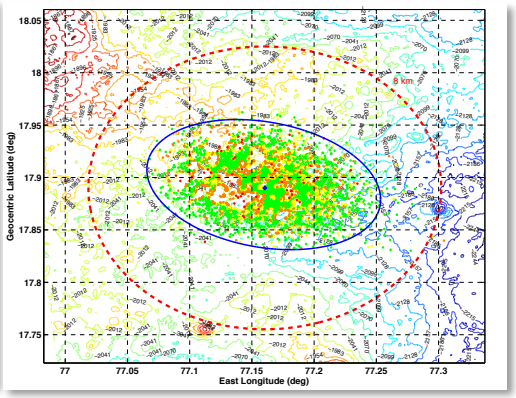
- **Preliminary design is complete**

- **LVS development status**
  - Algorithms and software provide 40 m position estimate
  - Vision Compute Element development at PDR level



- **Safe Target Selection development status**
  - Prototype developed and integrated with heritage FSW
  - Tested in EDL end to end simulation and testbed environments





Summary

- **MSL EDL design and heritage remains largely intact in the Mars 2020 EDL system**
  - Issues from MSL have been addressed
  - Selected augmentations have been accepted without threatening the overall architecture
- **2020 is a very favorable launch opportunity**
- **TRN is a major EDL augmentation that will improve landing site access and surface productivity**

We can't quite land with impunity yet…but we're working on it