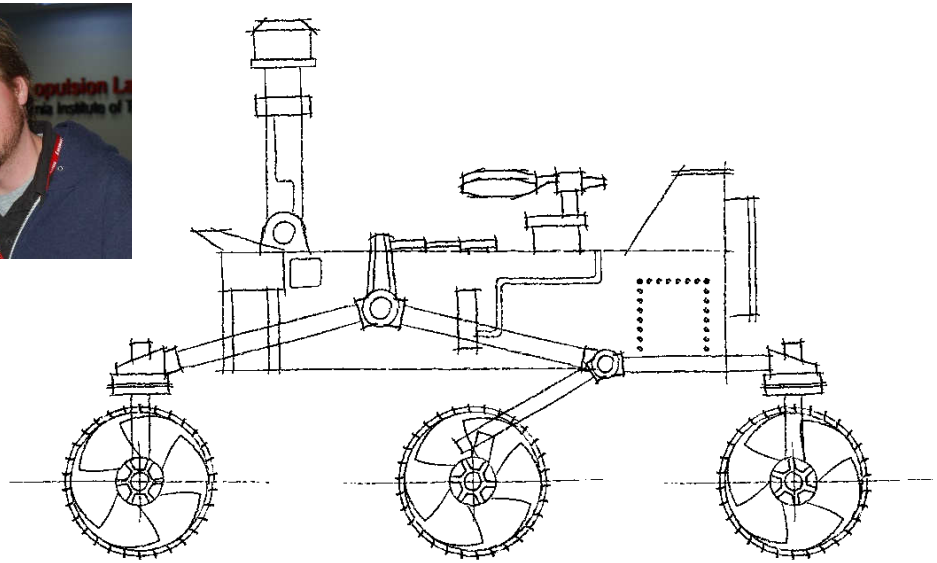
46th International Conference on Environmental Systems

Jet Propulsion Laboratory
California Institute of Technology

Thermal Response of the Mars Science Laboratory Spacecraft during Entry, Descent and Landing



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Hilton Vienna, Vienna, Austria

July 10-14, 2016

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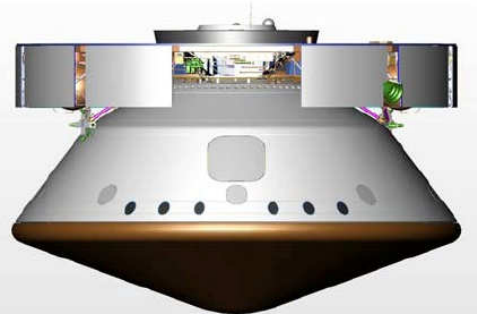
Mission Overview

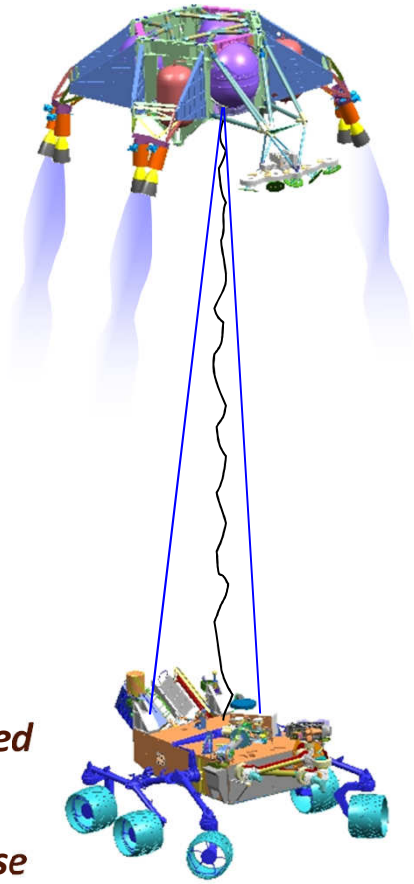


CRUISE/APPROACH

- ***8½-month cruise***
- ***Arrived August 6, 2012***

ENTRY, DESCENT, LANDING

- ***Guided entry and powered "sky crane" descent***
- ***20 ×25-km landing ellipse***
- ***Access to landing sites ±30° latitude, <0 km elevation***
- ***920-kg rover***

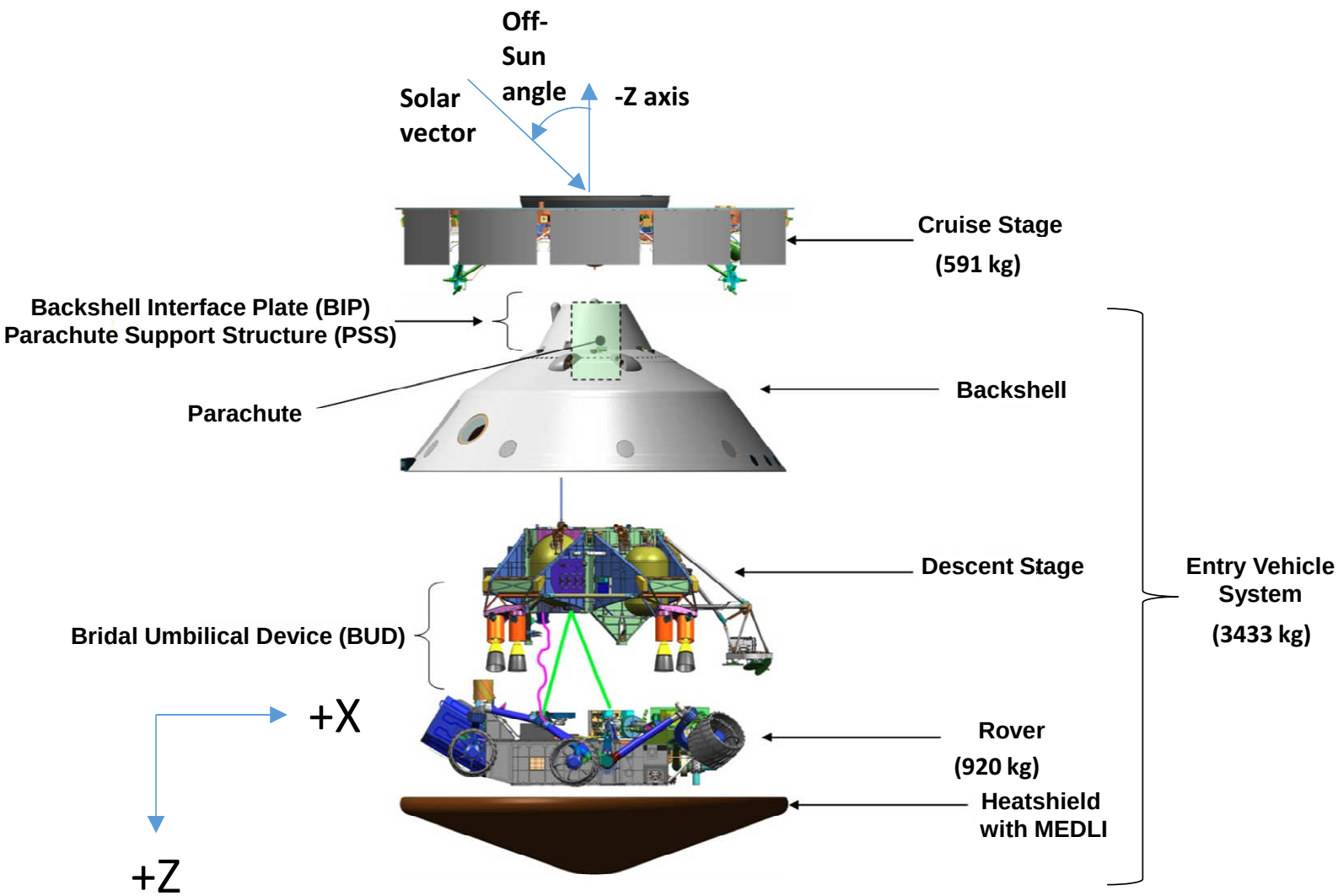


- ***Launched Nov. 26, 2011***
- ***Atlas V (541)***

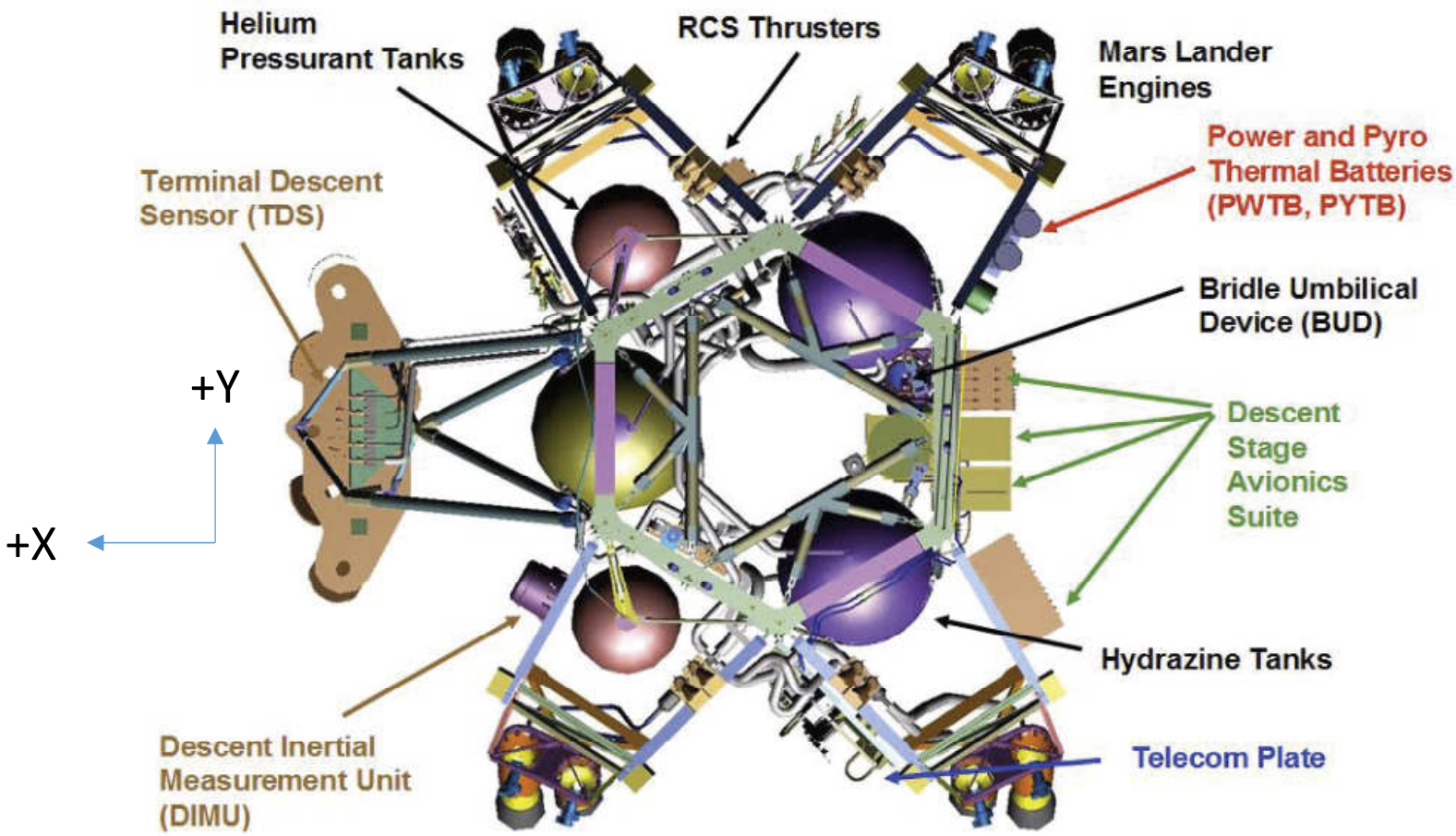
SURFACE MISSION

- ***Prime mission was one Mars year (669 Sols) – today is Sol 1397***
- ***Latitude-independent and long-lived power source***
- ***Ability to drive out of landing ellipse***
- ***72 kg of science payload***

MSL Spacecraft Configuration

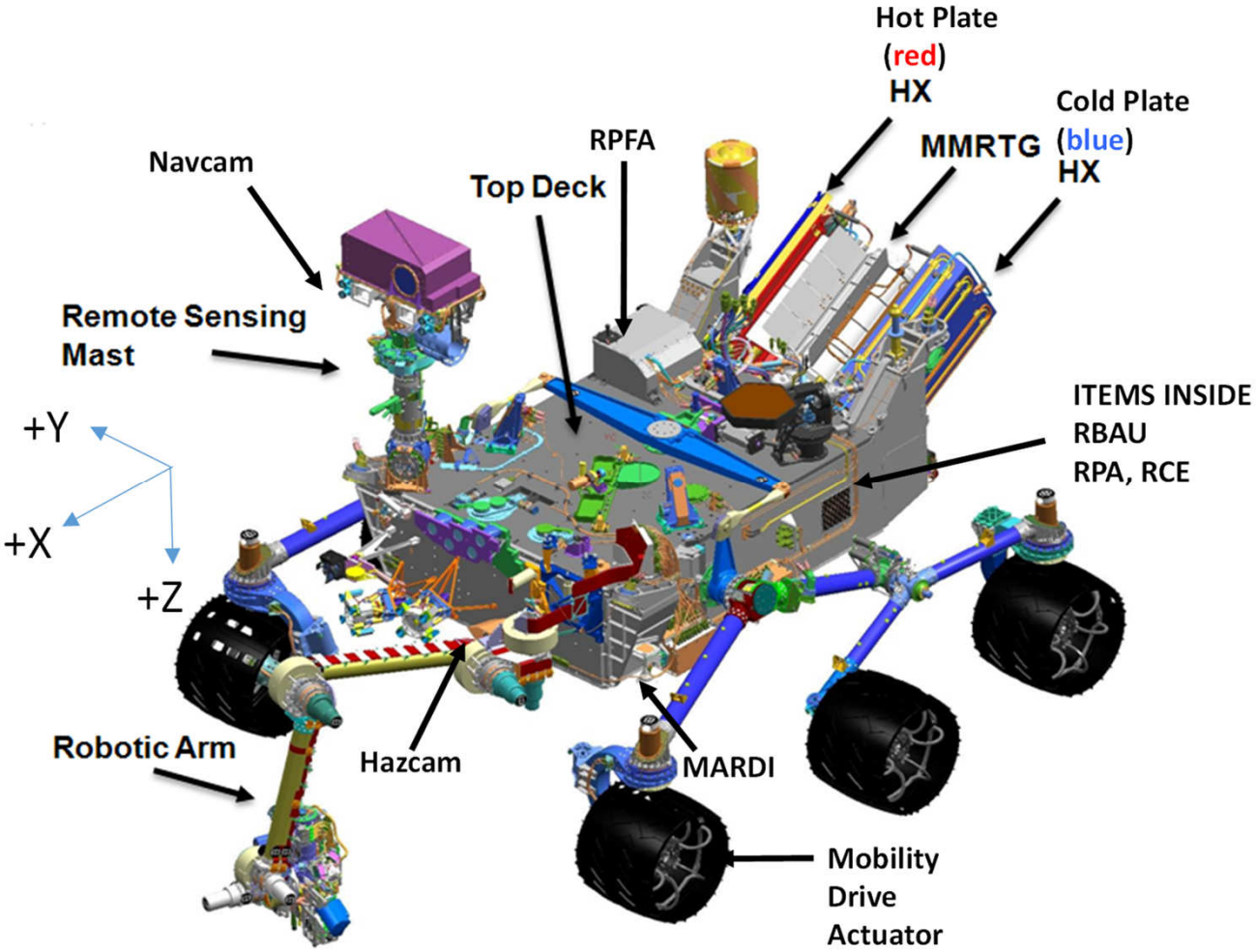


Descent Stage Configuration



- Under Cruise HRS control prior to CHRS vent– Descent Avionics, Descent Telecom

Deployed Rover Configuration



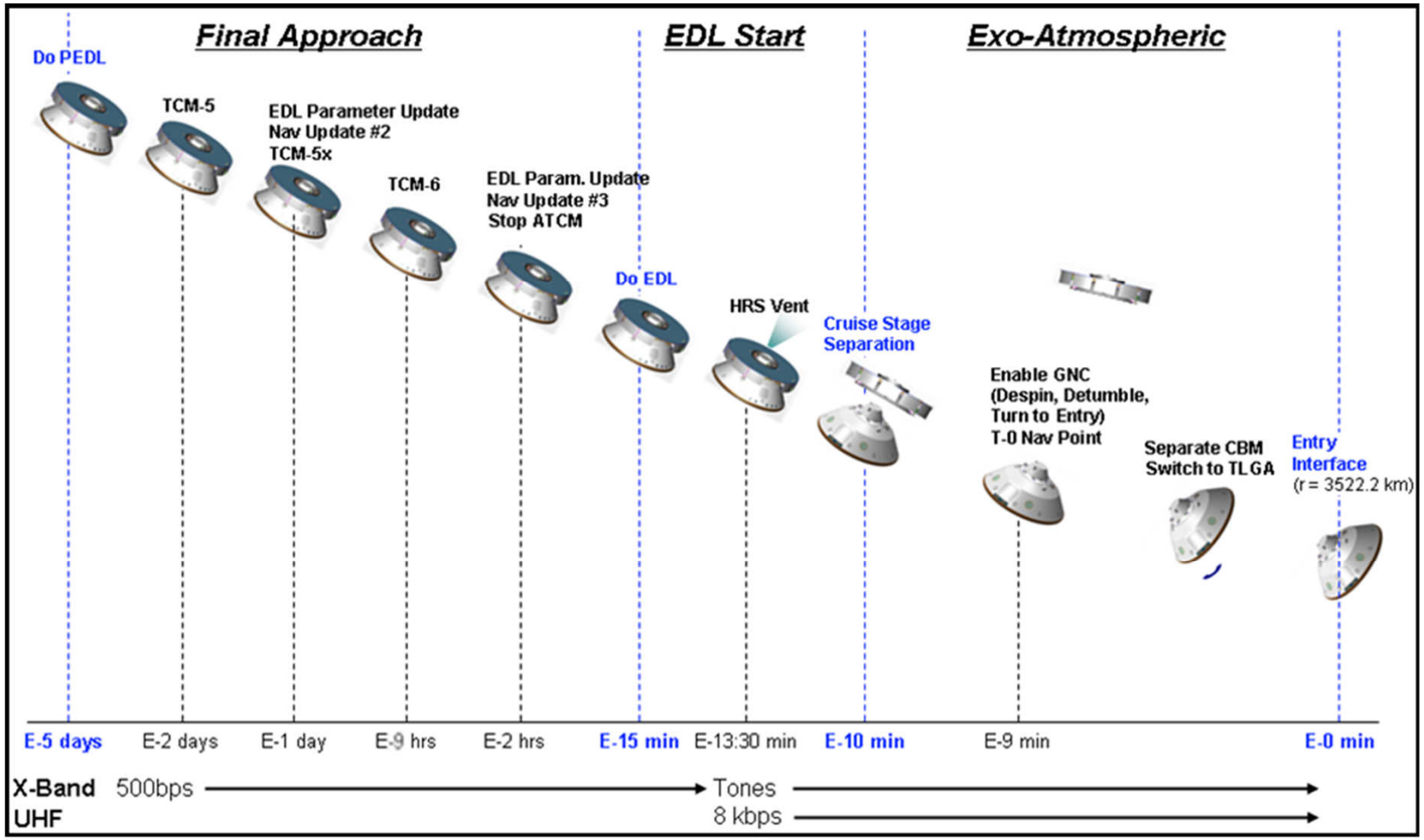
- MMRTG temp influences RHRS Hot Plate temps

EDL Video

Curiosity's Seven Minutes of Terror

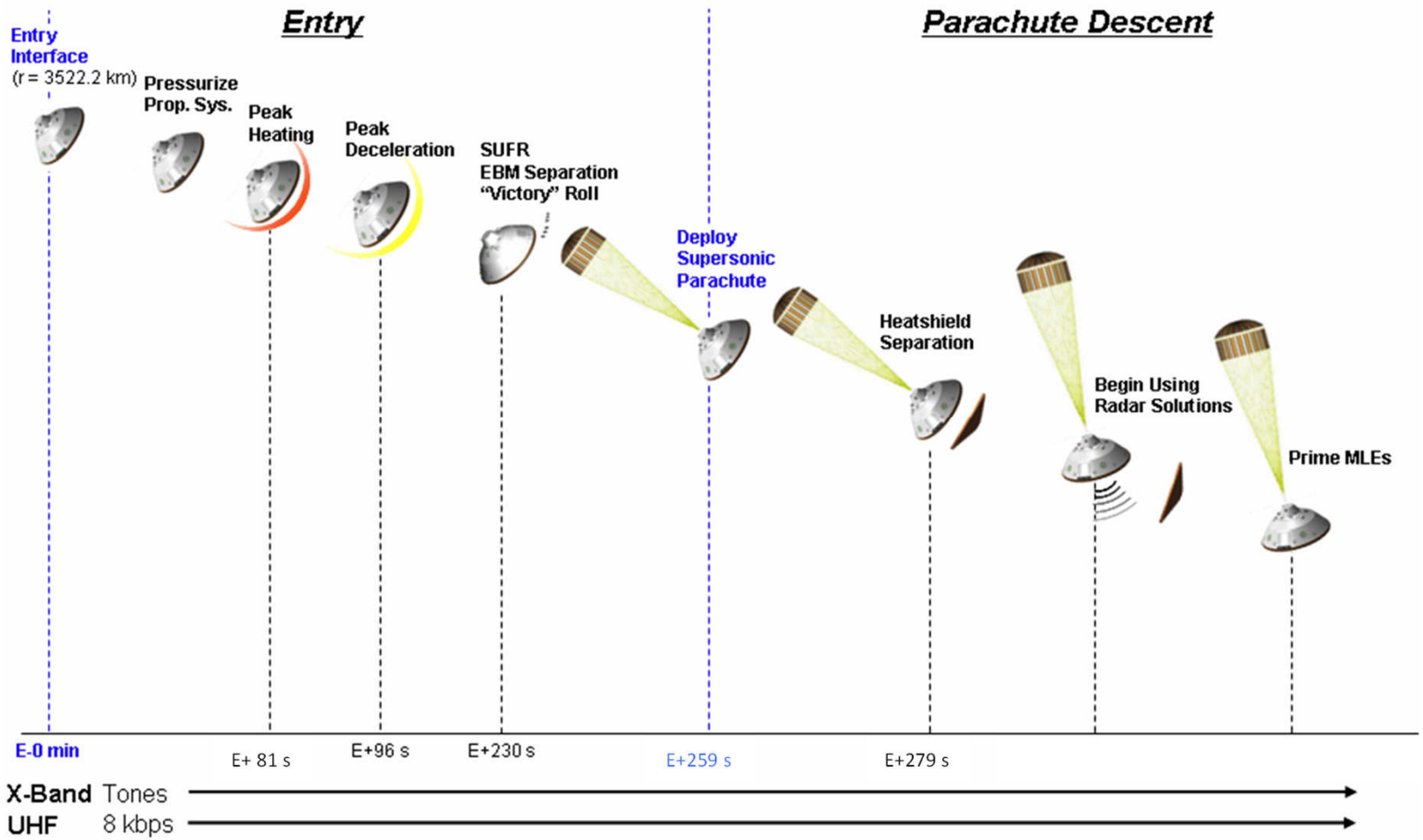
- In 5 min and 7 sec video

EDL Initialization & Exo-Atmospheric Segments



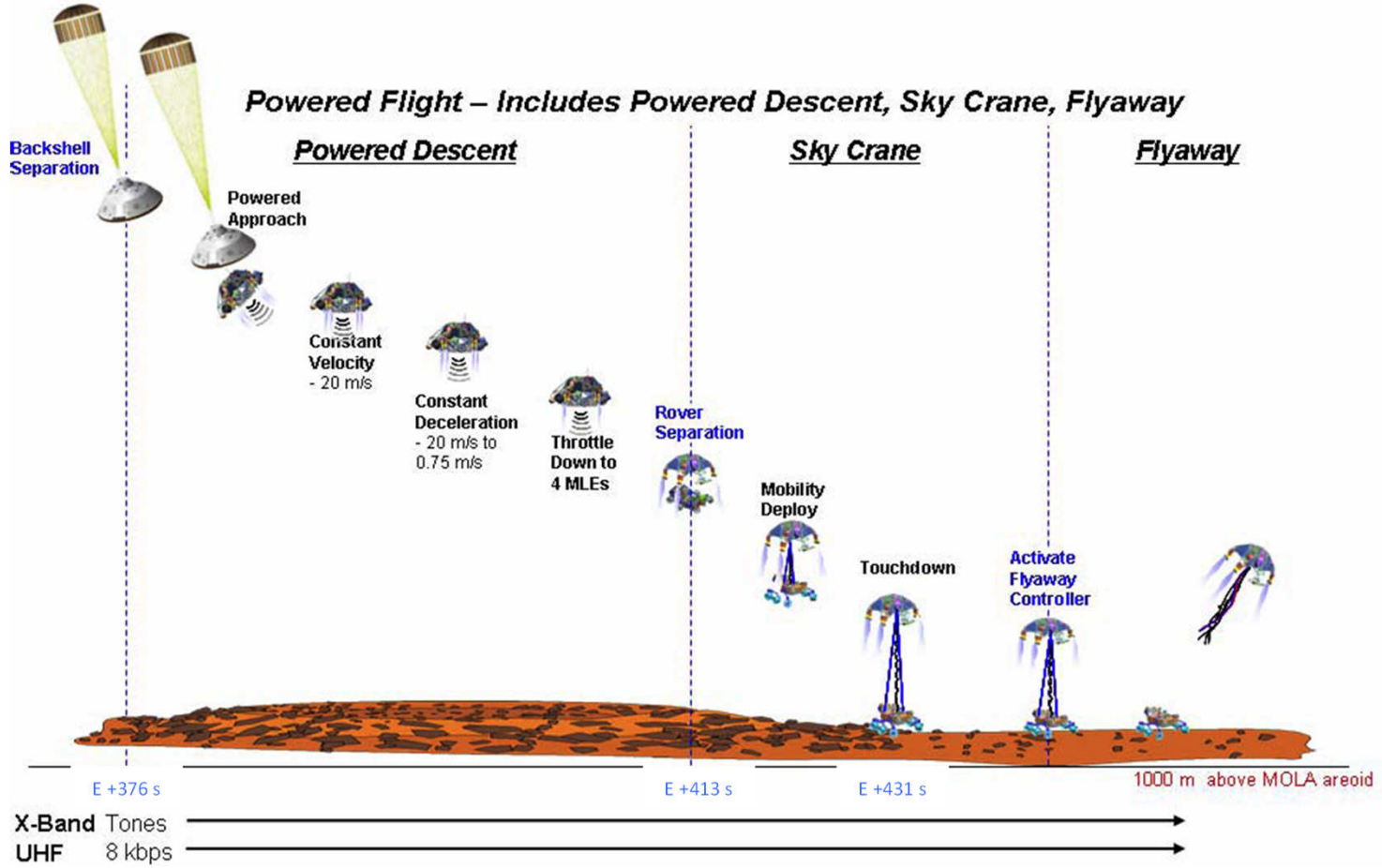
- Key thermal events
  - HRS vent, Cruise Stage Separation, Turn-to-Entry

Entry & Parachute Descent Segments



- Key thermal events
  - Entry aeroheating, "Victory" Roll, Heatshield Separation

Powered Descent, Sky Crane & Flyaway Segments



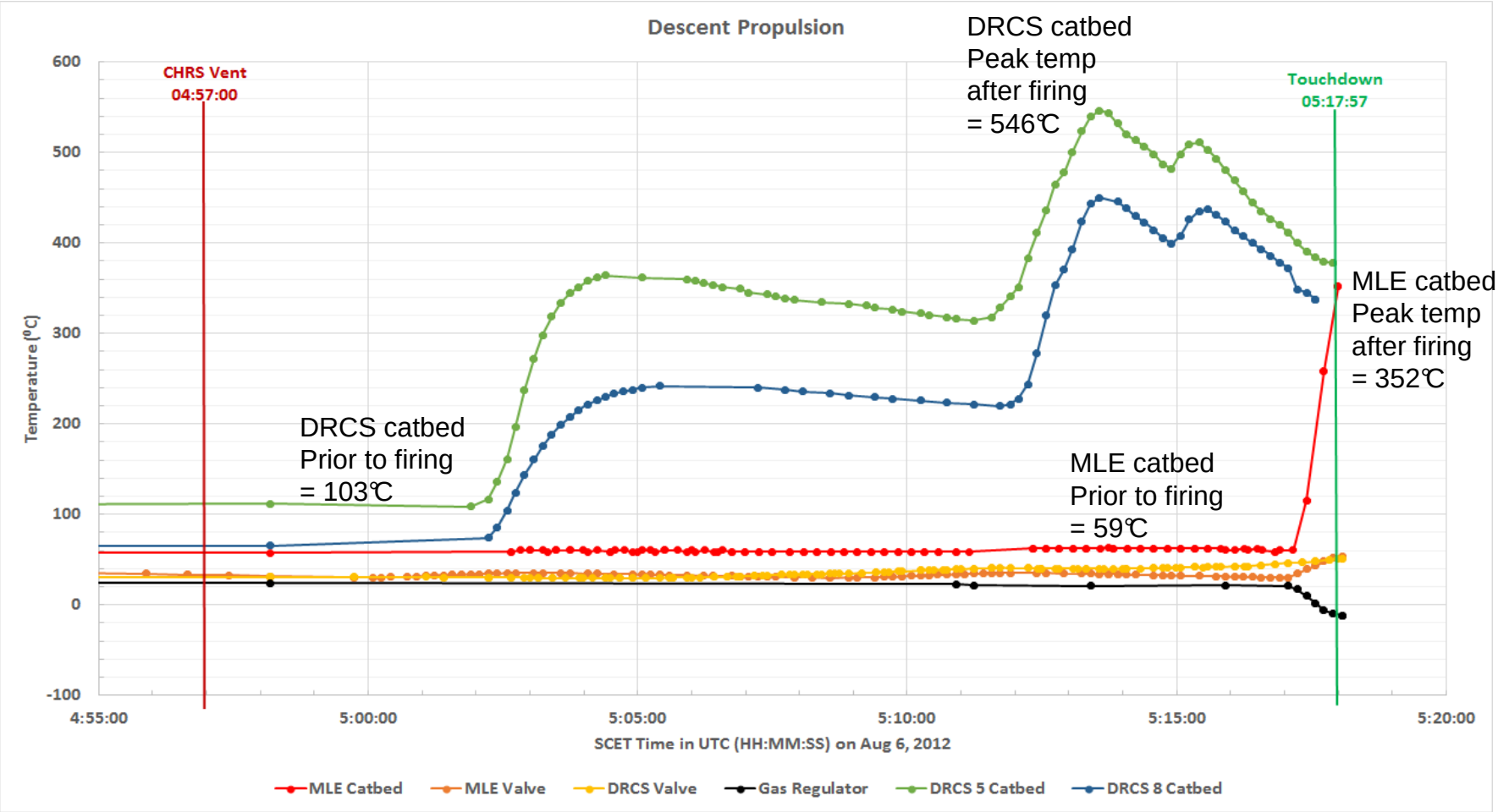
- Key thermal events
  - Backshell Separation, MLE firing, Rover Separation, Touchdown, Flyaway

Thermally Significant EDL Events

No	Event Name	Time Relative to Entry	Altitude AGL (m)	Mars Relative Velocity (m/sec)	SCET Date (UTC)	SCET DOY (UTC)	SCET Time in UTC (HH:MM:SS)
1	Turn ON MLE Catbed heaters	E - 31 hr			8/4/2012	217	22:00:00
2	Turn ON RCS Catbed heaters	E - 3 hr			8/6/2012	219	2:15:00
3	Turn OFF MARDI warmup heater	E - 41 min			"	"	4:29:29
4	Activate EDL sequence	E - 30 min			"	"	4:40:46
5	HRS Vent (end CHRS control)	E - 13.5 min			"	"	4:57:00
6	Cruise Stage Sep (TDS power ON)	E - 10 min			"	"	5:00:46
7	ENTRY INTERFACE POINT	E - 0 sec	124,994	5,845.4	"	"	5:10:46
8	Peak Heating	E + 81 sec			"	"	5:12:07
9	Parachute Deploy	E + 259 sec	12,147	406.4	"	"	5:15:05
10	Heatshield Separation (start forced conv. on DS & Rover)	E + 279 sec	9,997	146.0	"	"	5:15:25
11	Backshell Separation (start of Powered Descent)	E + 376 sec	1,671	78.9	"	"	5:17:02
12	Rover Separation (down on bridle)	E + 413 sec	22	0.7	"	"	5:17:39
13	TOUCHDOWN	E + 431 sec	9	0.6	"	"	5:17:57

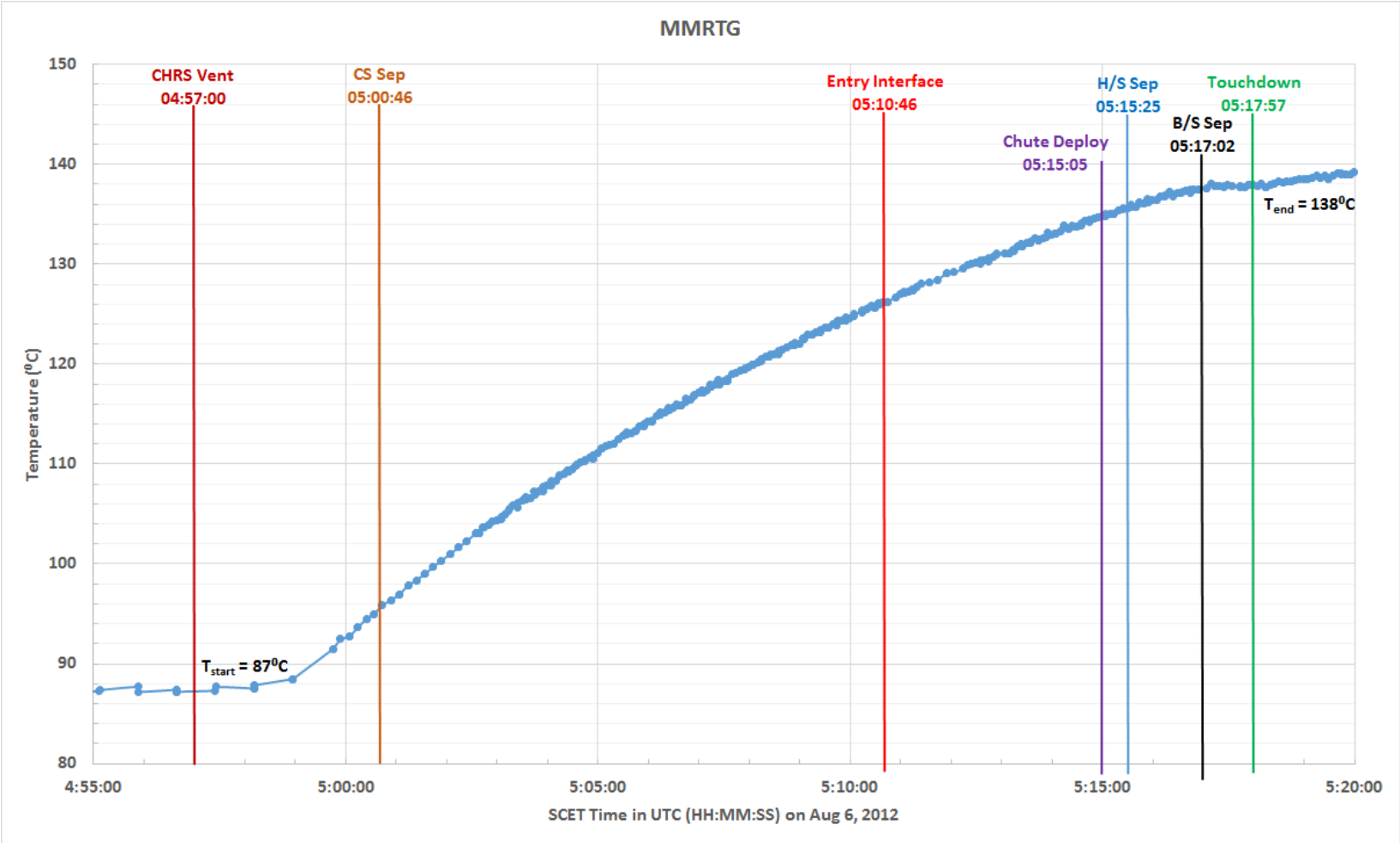
Touchdown occurs on Sol 0 at 15:03 Local Mean Solar Time on Mars

Descent Stage Propulsion



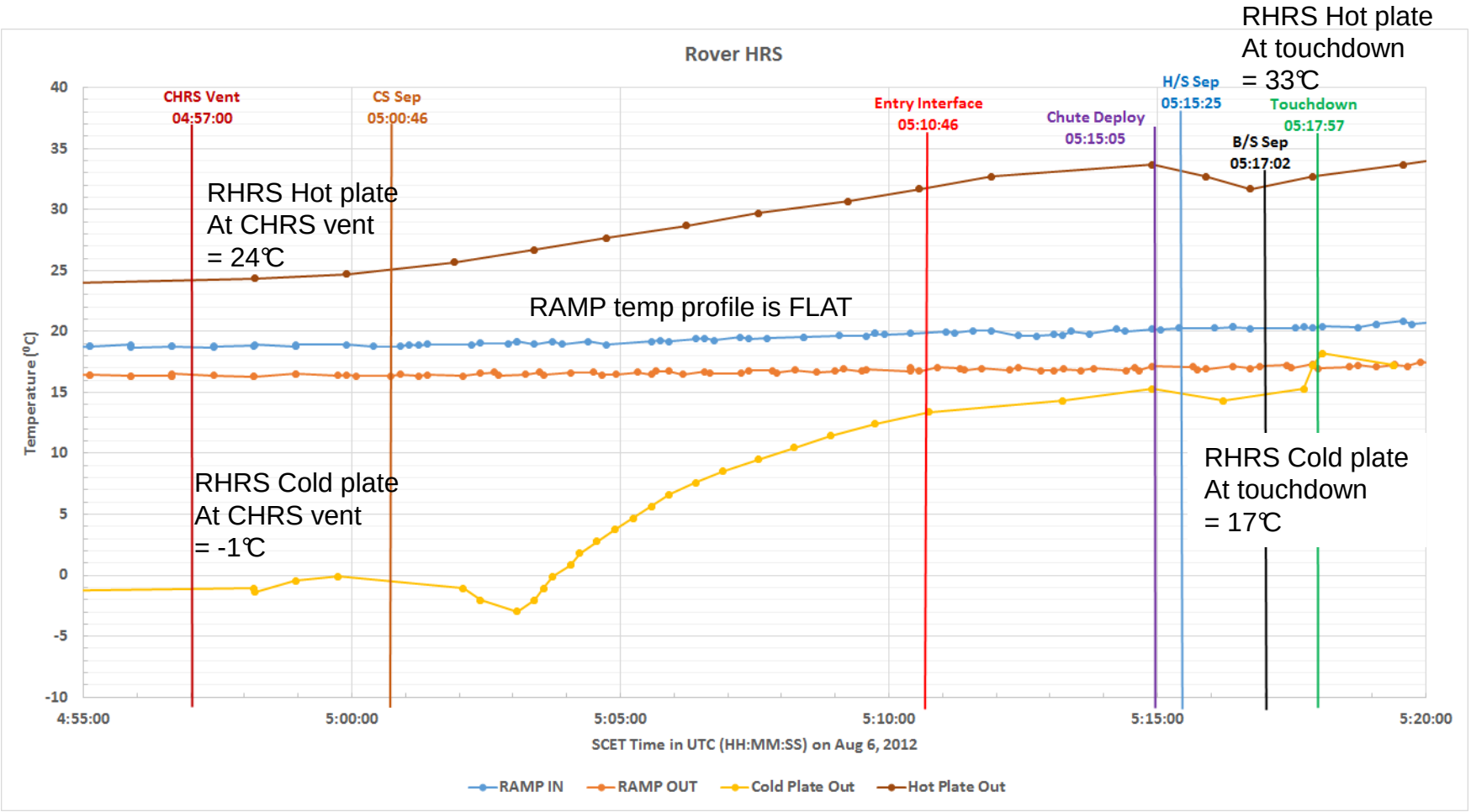
- Catalyst beds react to thruster & engine firings
  - Valves show small temperature rises

MMRTG



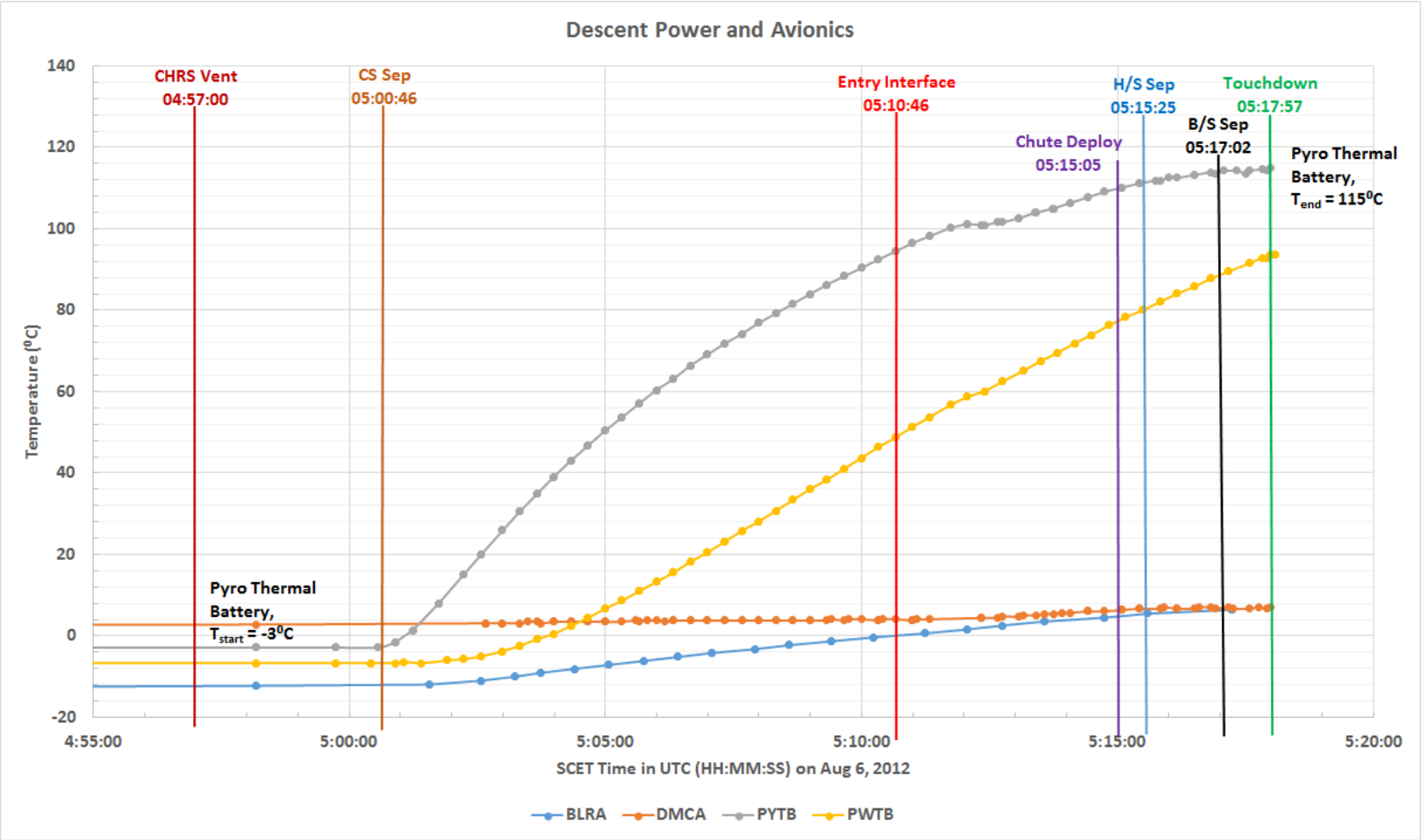
- MMRTG reacts to venting of CHRS Freon
- 2000W heat source warms up by 51℃ in 21 minutes

Rover Heat Rejection System



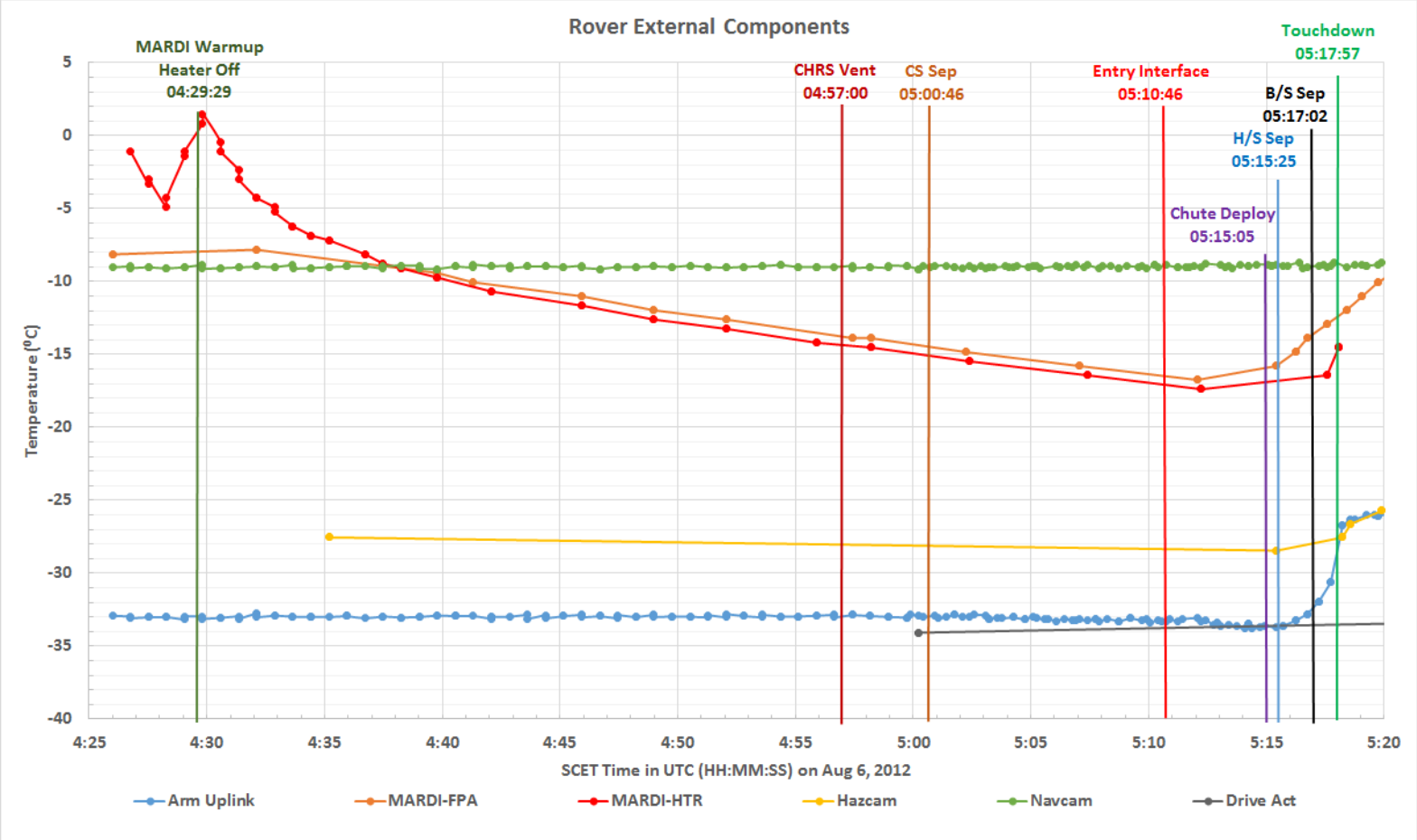
- Rover HRS plates react to warming MMRTG
- RAMP-mounted boxes are <u>very</u> stable in temperature

Descent Power & Avionics



- Pyro & Power Thermal batteries warm up after initialization

Rover External Components



- MARDI camera cools down after warmup heater turn-off
  - Warms back up during operation
- Robotic Arm tube warms up after exposure to warmer Mars atmosphere

Affect of EDL on Hardware Temperatures

- Aeroheating pulse (external heatshield surface rises to 1400℃) did not cause dramatic temperature changes on Descent Stage and Rover H/W
  - Heatshield and backshell were very effective at shielding hardware from short (< 4 min) entry heating environment

- Most Dramatic temp rises on S/C Hardware were due to planned/sequenced events
  - Catbed heaters reacted to thruster and main engine firings
    - MLE catbeds (59℃ to 352℃)
    - DRCS Catbeds (103℃ to 546℃)
  - MMRTG – warmed after CHRS vent (87℃ to 138℃)
  - Pyro thermal batteries warmed after activation – (-3℃ to 115℃)
  - MARDI cooled down after warmup heater turnoff (1℃ to -17℃)

- Robotic Arm Ti tube was convectively warmed after heatshield separation (-33℃ to -30℃)
  - Predicted surface-level atmosphere temp at Gale Crater (4.5S latitude) for landing date (Sol 0: Ls=150, Southern Spring) and time (1503 LMST) was -27℃

- Most Rover hardware had small temperature changes
  - External cameras, mobility actuators, internal RAMP boxes

Conclusions

- It may be terrifying, but it's over quickly
  - Most hardware items have thermal time constants much longer than 7 minutes
  - Utilized thermal mass to ride out transient warmups
- Rover & DS are well-shielded from aeroheating pulse by highly effective aeroshell
- Rover electronics controlled by Rover HRS
- Convective cooling effects were small (surface-level atm at -27℃)
- MSL EDL was highly successful
  - Rover has been operating for more than 2 Mars years
  - Today is Sol 1397
- Looking forward to another successful M2020 EDL on Feb. 29, 2021

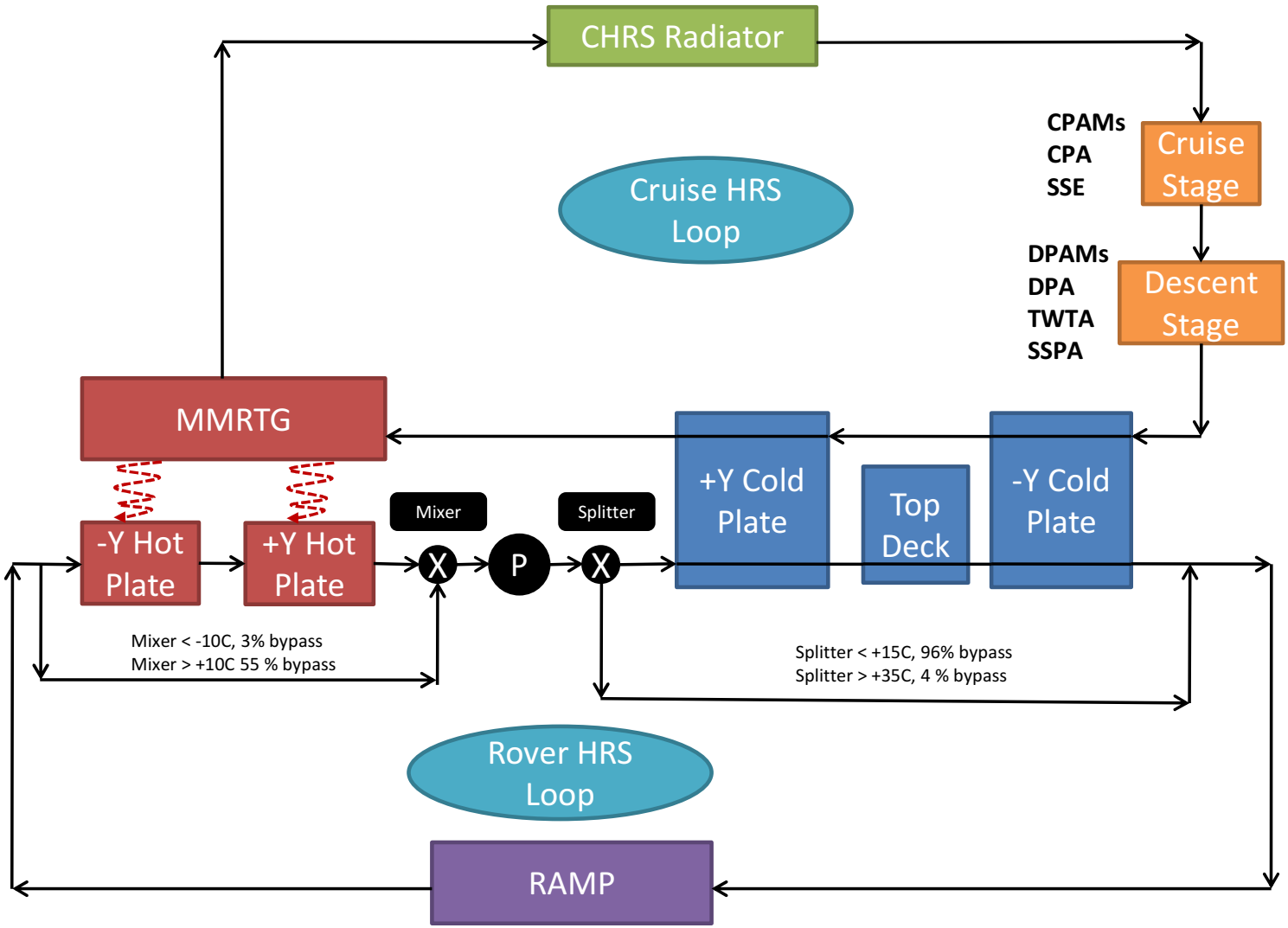
Acknowledgements

- ***The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.***

- ***The authors wish to acknowledge the many engineers and scientists who worked collaboratively on the Mars Science Laboratory Project and brought it to a successful landing and a continuing surface mission.***

Backup

Cruise & Rover HRS Loops

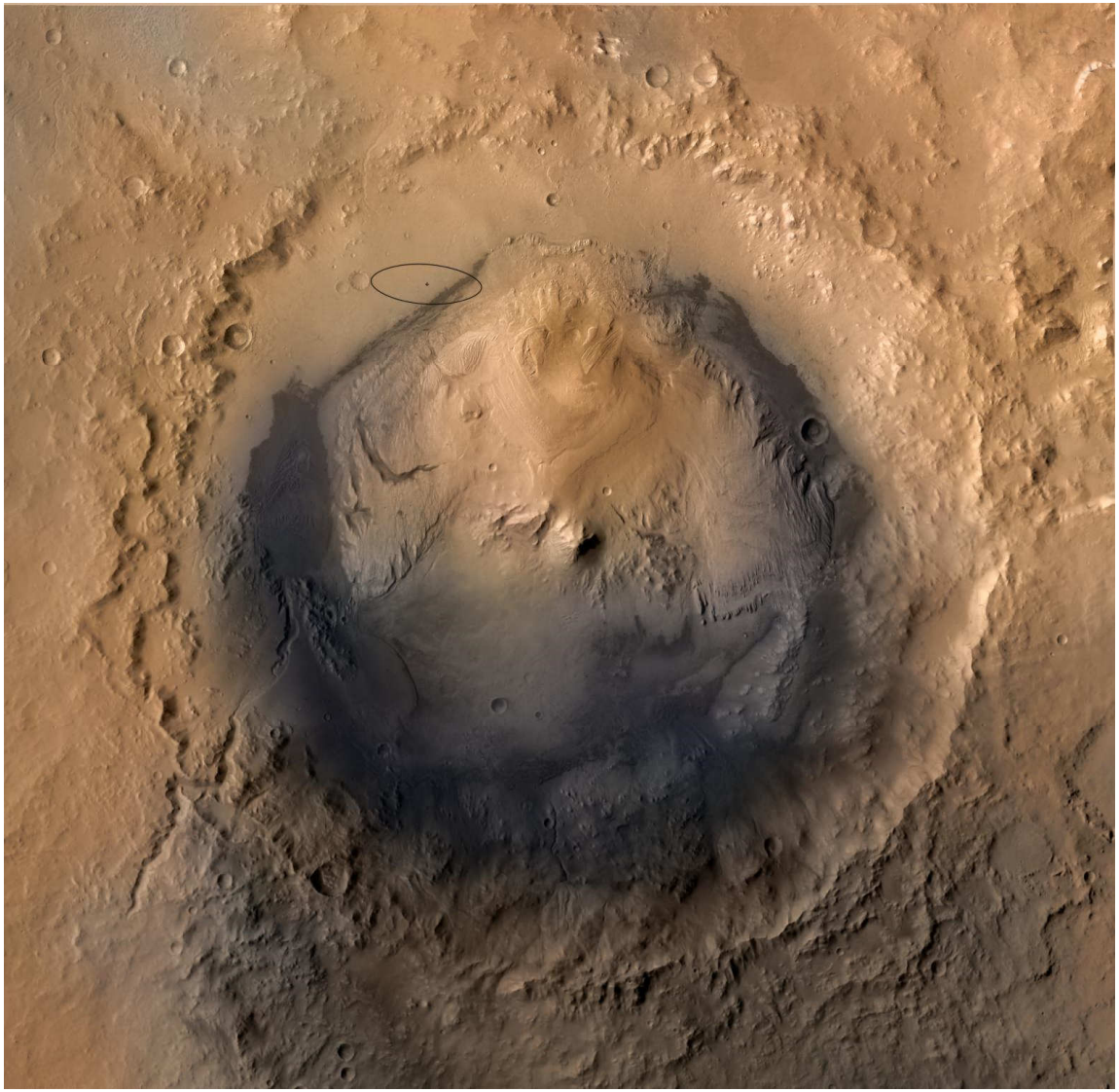


Propulsion Components during EDL

Hardware Components	EDL Flight Telemetry (°C)			Operational AFT (℃)		Non-op (℃) AFT		Thermal Margins (℃)	
	T start	T end	change	min	max	min	max	min AFT	max AFT
PROPULSION									
Descent Stage									
DS High Flow Regulator	23.8	-11.4	-35.2	N/A	N/A	15	50	+9	+26
DS MLE Throttle Valve (liquid flow sections)	29.9	53.0	23.1	25	50	25	50	+5	-3
DS MLE Catalyst Bed	58.8	351.6	292.8	N/A	N/A	25	N/A	+34	
DS RCS Thruster Valves, Firing/Soakback	30.8	50.7	19.9	20	50	20	50	+11	-1
DS RCS Catalyst Beds, Firing/Soakback (min)	71.9	445.0	373.1	93	N/A	N/A	N/A	-21	
DS RCS Catalyst Beds, Firing/Soakback (max)	114.2	552.0	437.8	93	N/A	N/A	N/A	+21	

- DS MLE Throttle Valve & DS RCS Thruster Valve slightly exceeded max op AFT limits by 1 – 3 ℃
  - Still plenty of margin to the qualification limits
- DS RCS catalyst bed needed the planned pre-condition firing to bring all catbeds above min op limit of 93℃

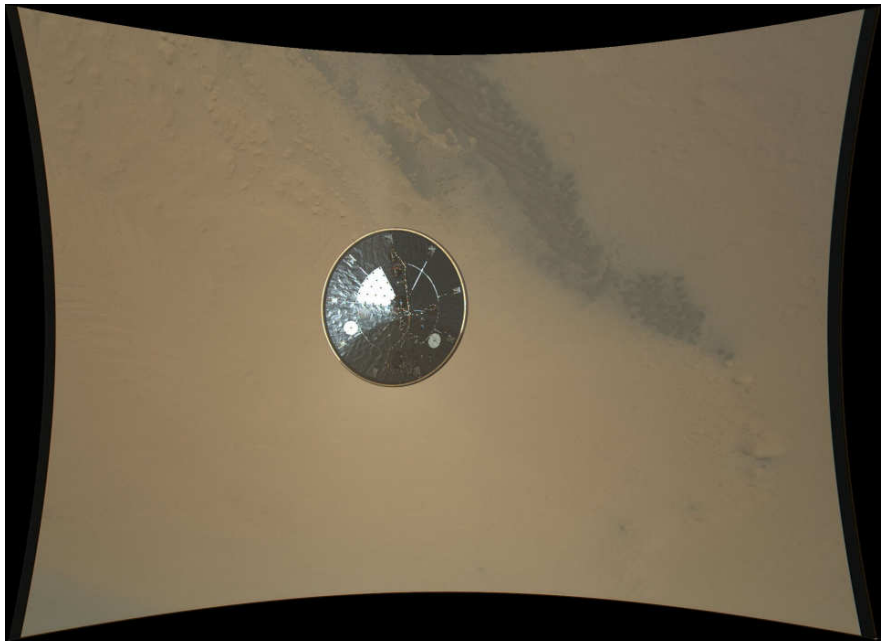
MSL Landing Ellipse in Gale Crater



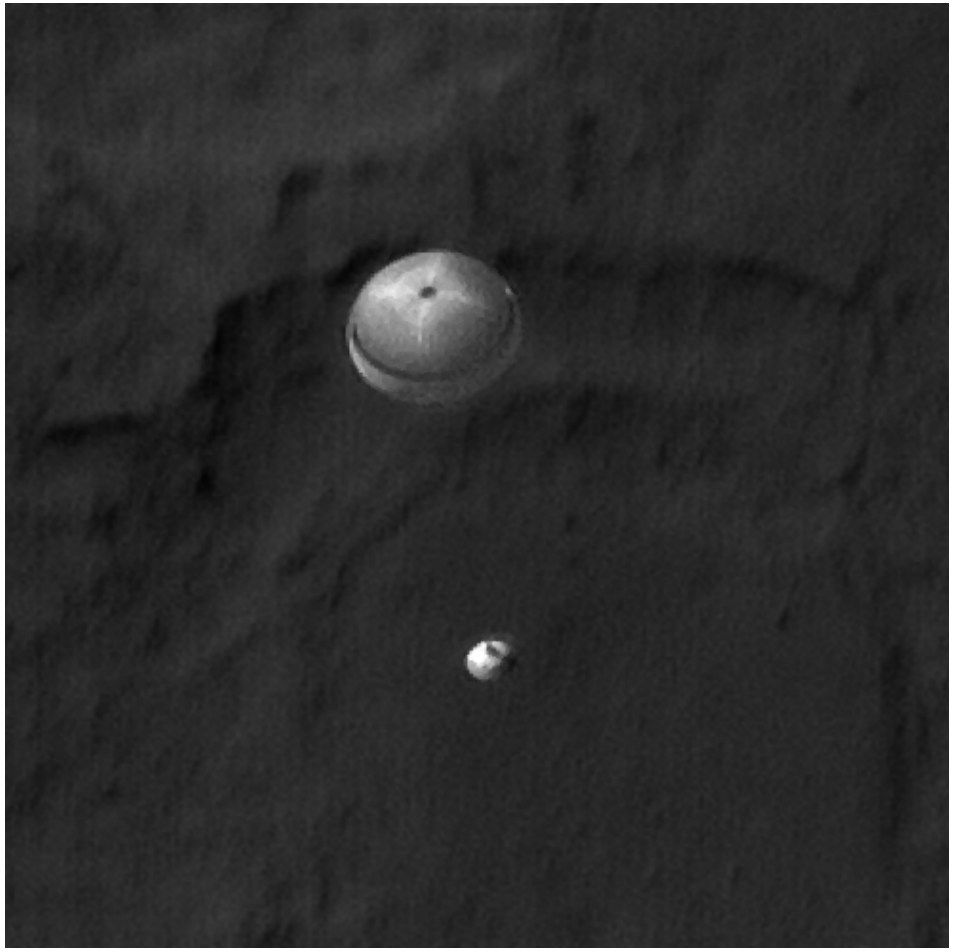
MSL Rover During Surface Operations

Mount Sharp

Heatshield and Parachute

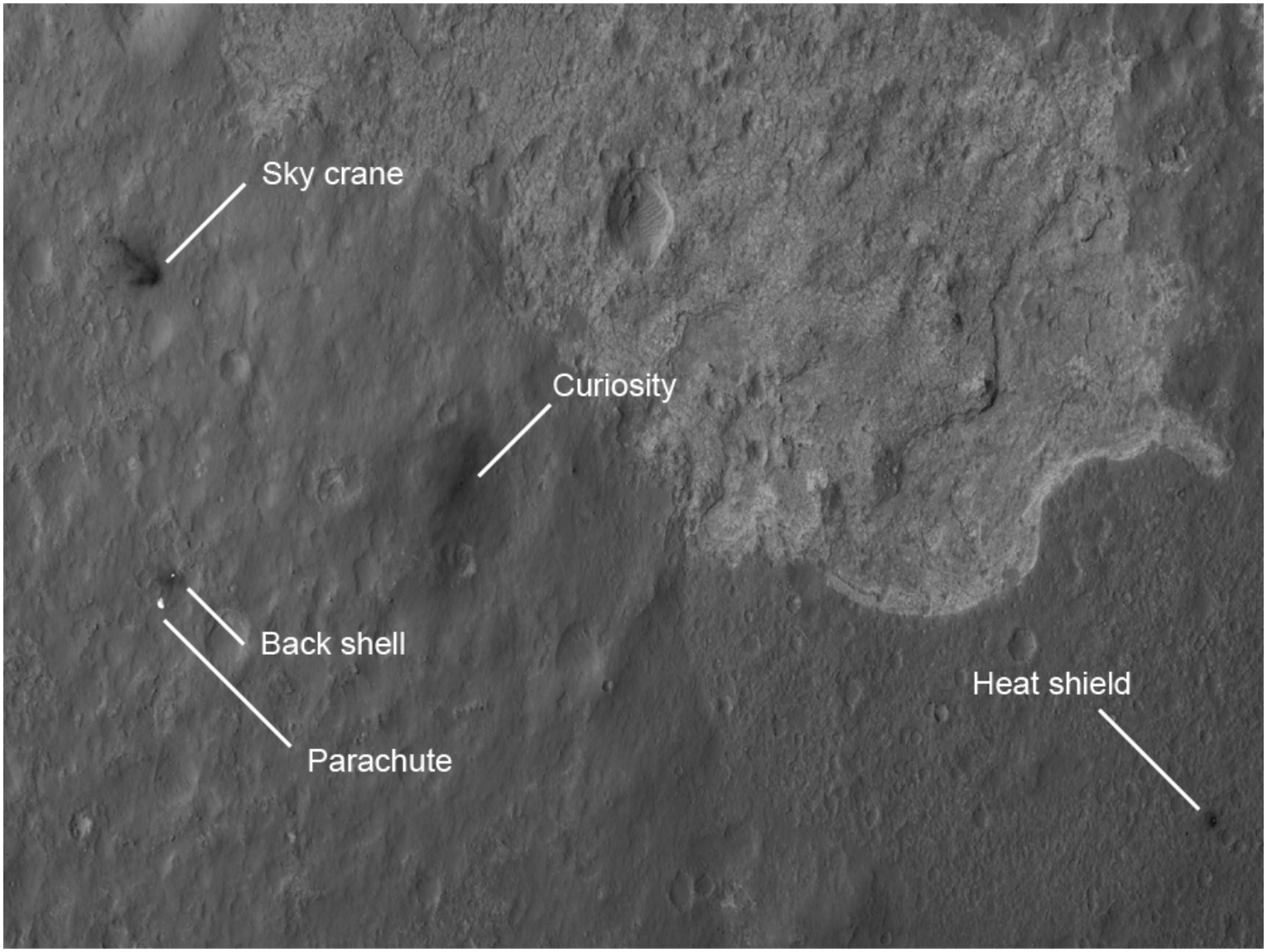
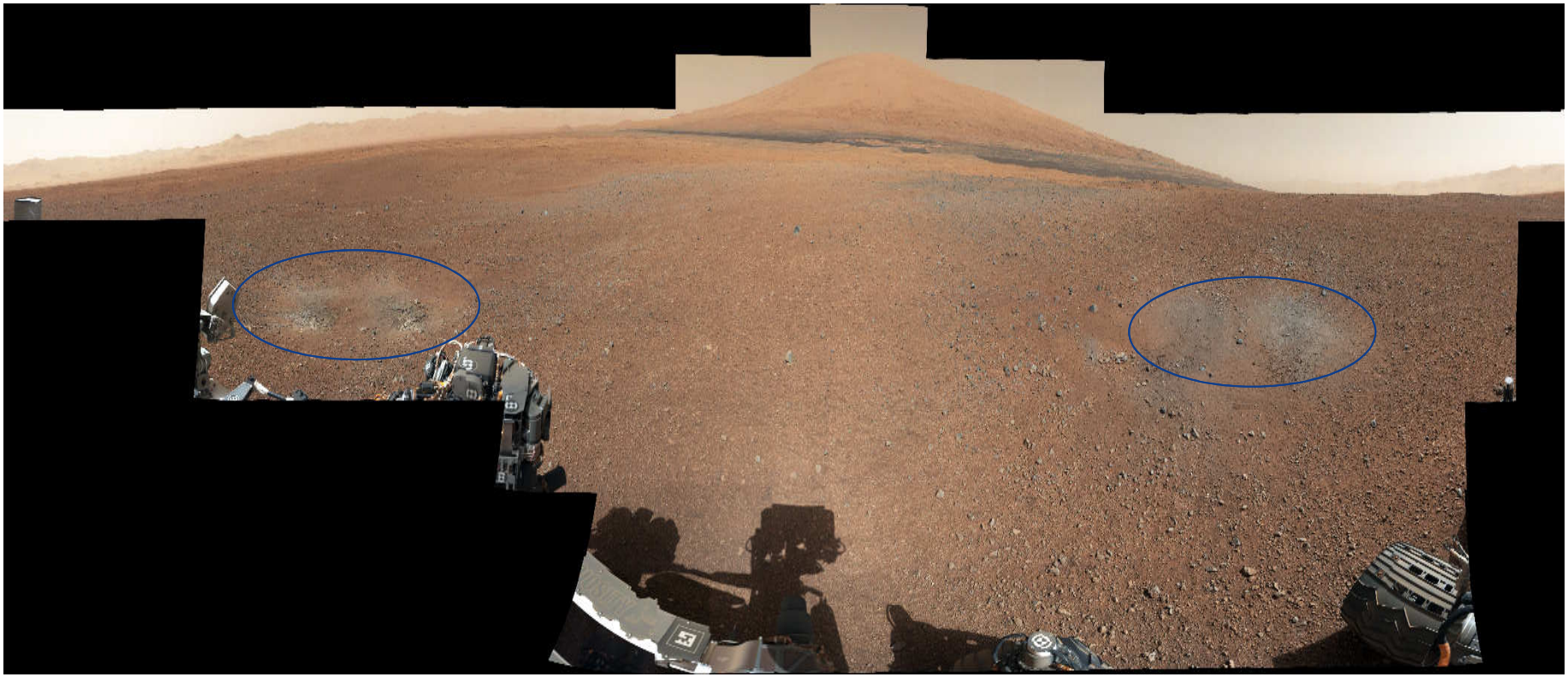


From MSL Rover taken by
Mars Descent Imager



From Mars reconnaissance Orbiter
taken by HiRISE Imager

MSL Hardware on Mars



Landing Site with MLE scarf regions