2011 Mars Science Laboratory Trajectory Reconstruction and Performance from Launch Through Landing

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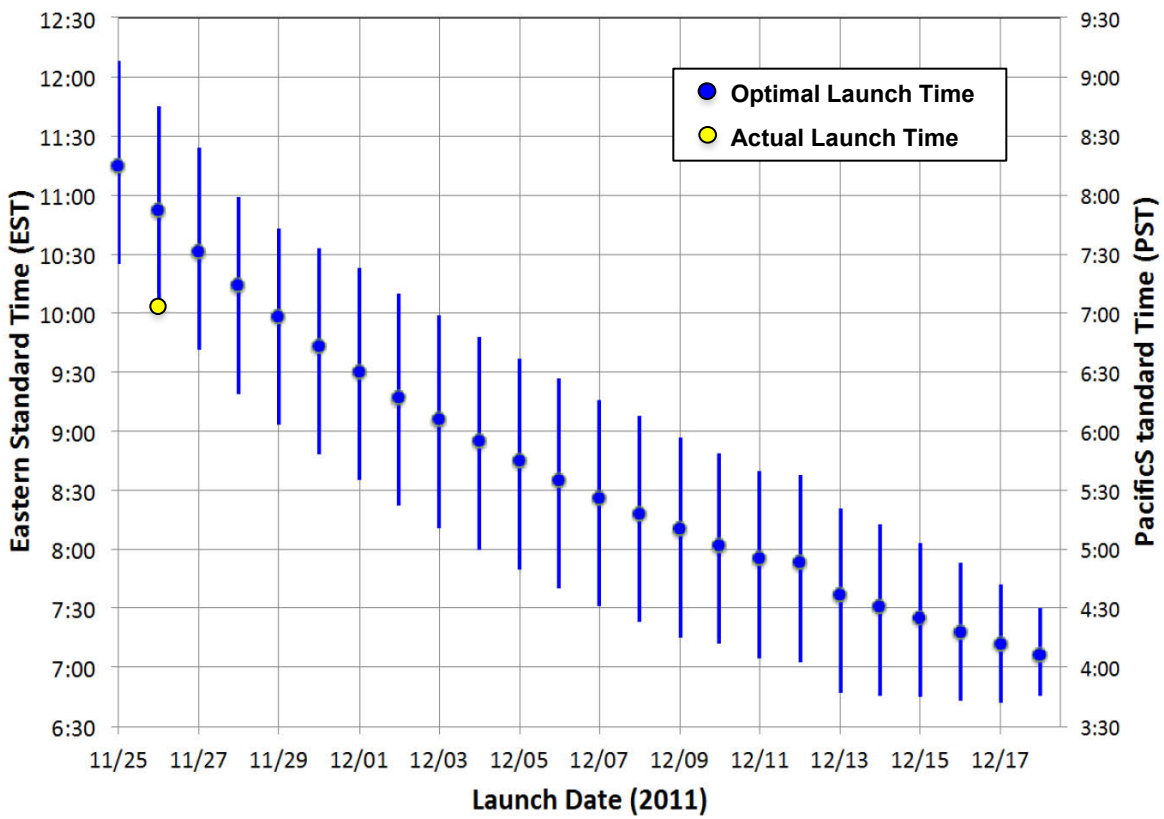
MSL Project Overview

- **Main scientific goal**
  - To assess whether Gale Crater ever had conditions capable of supporting microbial life
- **Mission highlights**
  - 3,883 kg (actual) at launch carrying an 899 kg rover
  - Launched on November 26, 2011 at 7:02 AM PST
  - Landed inside Gale Crater on August 5, 2012 at 10:17 PM SCET PDT only ~2.4 km from its target!
  - First mission with guided entry
  - Latitude accessibility: 25° N to 27° S
  - Altitude capability: -1.0 km elevation
  - Landing ellipse ~ 21 km x 7 km
    - MPF ~ 200 km x 70 km
    - MER-A / MER-B ~ 150 km x 20 km
    - Phoenix ~ 100 km x 20 km
  - Minimum range of 20-km
    - First Mars mission to enable landing/rove to a specific site
    - Total odometry ~ 723 m (through sol 171)

Launch Windows and Launch Times

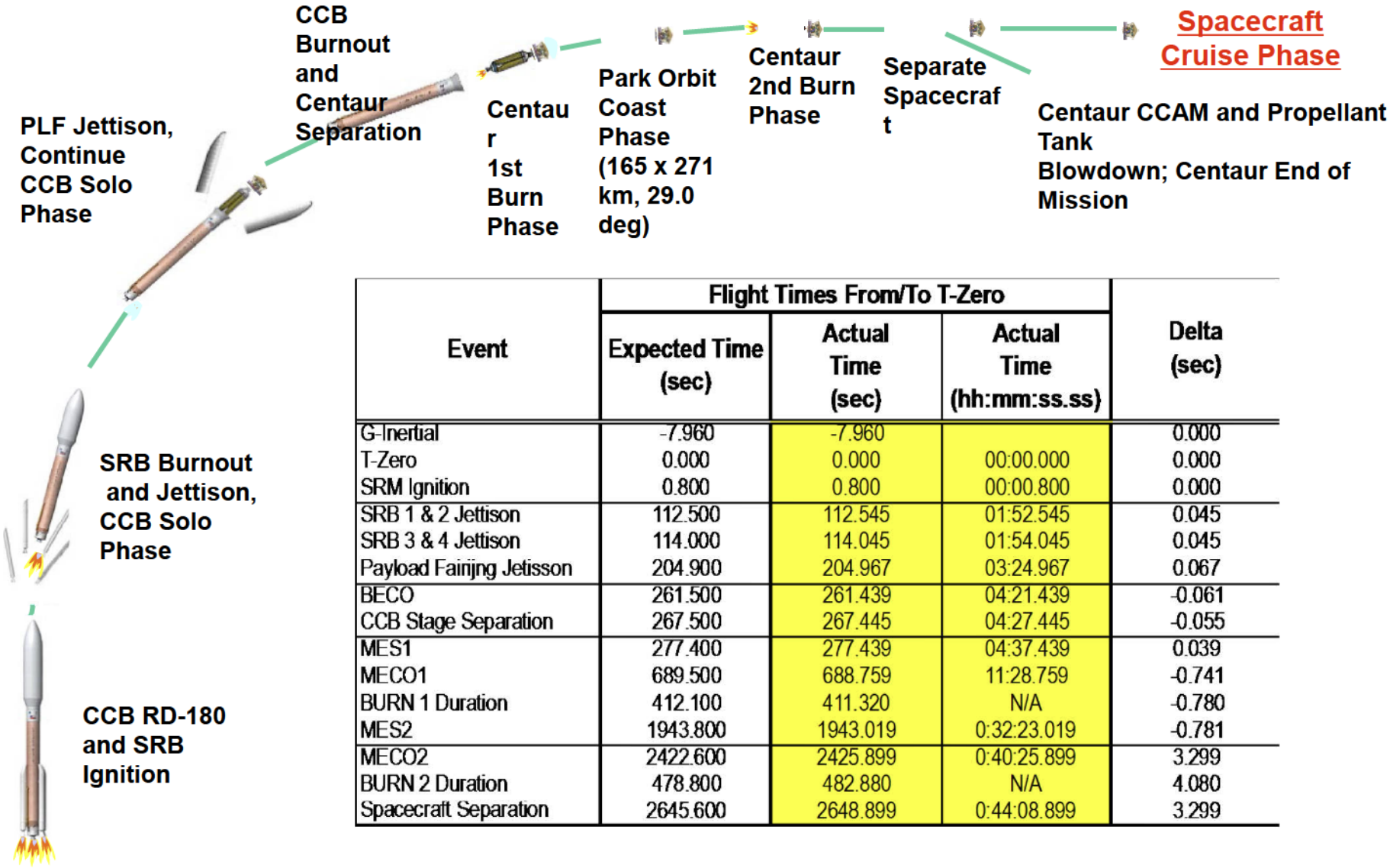
Launch Date (2011)	Launch Window Duration (hh:mm)	Eastern Standard Time		
		Open	Optimal	Close
11/25	1:43	10:25	11:15	12:08
11/26	1:43	10:02	10:52	11:45
11/27	1:43	9:41	10:31	11:24
11/28	1:40	9:19	10:14	10:59
11/29	1:40	9:03	9:58	10:43
11/30	1:45	8:48	9:43	10:33
12/01	1:48	8:35	9:30	10:23
12/02	1:48	8:22	9:17	10:10
12/03	1:48	8:11	9:06	9:59
12/04	1:48	8:00	8:55	9:48
12/05	1:47	7:50	8:45	9:37
12/06	1:47	7:40	8:35	9:27
12/07	1:45	7:31	8:26	9:16
12/08	1:45	7:23	8:18	9:08
12/09	1:42	7:15	8:10	8:57
12/10	1:37	7:12	8:02	8:49
12/11	1:35	7:05	7:55	8:40
12/12	1:35	7:03	7:53	8:38
12/13	1:34	6:47	7:37	8:21
12/14	1:27	6:46	7:31	8:13
12/15	1:18	6:45	7:25	8:03
12/16	1:10	6:43	7:18	7:53
12/17	1:00	6:42	7:12	7:42
12/18	0:44	6:46	7:06	7:30

Actual launch time (EST)



Launch vehicle rollout delayed one day to allow time to replace a flight termination system battery.

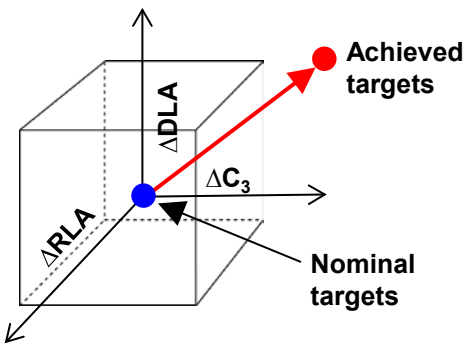
Launch Vehicle Events



Event	Flight Times From/To T-Zero			Delta (sec)
	Expected Time (sec)	Actual Time (sec)	Actual Time (hh:mm:ss.ss)	
G-Inertial	-7.960	-7.960		0.000
T-Zero	0.000	0.000	00:00.000	0.000
SRM Ignition	0.800	0.800	00:00.800	0.000
SRB 1 & 2 Jettison	112.500	112.545	01:52.545	0.045
SRB 3 & 4 Jettison	114.000	114.045	01:54.045	0.045
Payload Fairijng Jetisson	204.900	204.967	03:24.967	0.067
BECO	261.500	261.439	04:21.439	-0.061
CCB Stage Separation	267.500	267.445	04:27.445	-0.055
MES1	277.400	277.439	04:37.439	0.039
MECO1	689.500	688.759	11:28.759	-0.741
BURN 1 Duration	412.100	411.320	N/A	-0.780
MES2	1943.800	1943.019	0:32:23.019	-0.781
MECO2	2422.600	2425.899	0:40:25.899	3.299
BURN 2 Duration	478.800	482.880	N/A	4.080
Spacecraft Separation	2645.600	2648.899	0:44:08.899	3.299

Injection Accuracy Methods

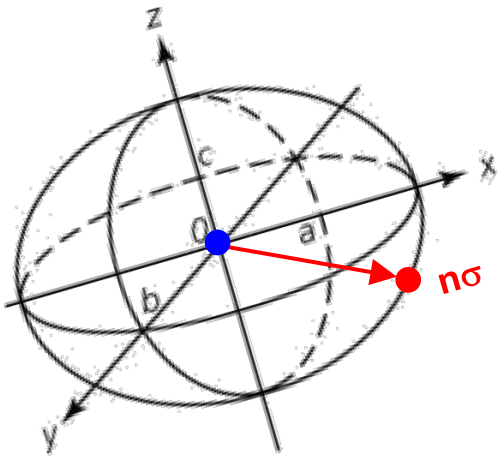
C3, DLA, RLA Error



Pros
- Simple to understand and implement

Cons
- Does not account for effects of injections on cruise propellant
- Does not account for effects of injection errors on Mars impact probability (planetary protection)
- Not dependent on ICMs

Injection Error Ellipsoid



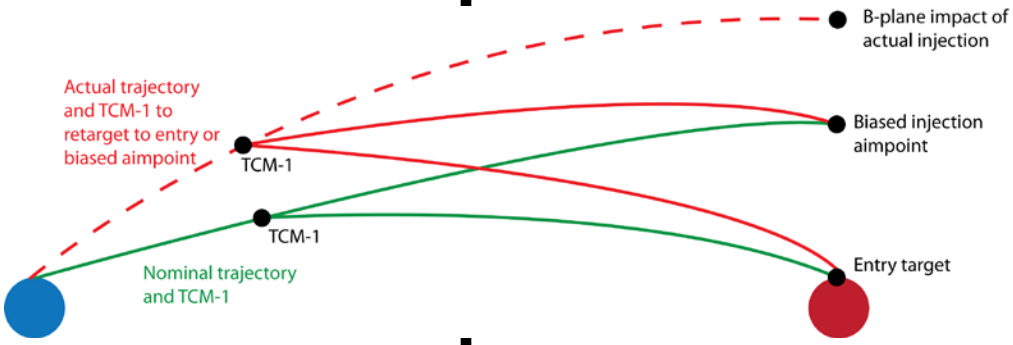
Pros
- Simple to implement
- Accounts for effects of injection errors on cruise propellant usage
- Accounts for effects of injection errors on Mars impact probability (planetary protection)
- Dependent on ICMs

Cons
- Less intuitive than other methods

Post-Launch ΔV to Target Mars Entry Aimpoint

Pros
- Simple to understand
- Accounts for effects of injection errors on cruise propellant usage
- Dependent on ICMs

Cons
- Complicated to implement
- Does not account for effects of injection errors on Mars impact probability (planetary protection)
- Not dependent on ICMs



Post-Launch ΔV to Target to Biased Injection Aimpoint

Pros
- Simple to understand
- Accounts for effects of injections on cruise propellant
- Accounts for effects of injection errors on Mars impact probability (planetary protection)
- Not dependent on ICMs

Cons
- Complicated to implement

Injection and Separation Accuracy Assessment

Injection Accuracy

Parameter	Achieved	Target	Error	OD Uncertainty (1σ)	Expected Dispersion (1σ)	Error σ Level
TIP Epoch	11/26/2011 15:51:09.02					
C_3 (km^2/s^2)	10.7193	10.7209	-0.0016	3.48E-07	±0.0105	-0.15σ
DLA* (deg)	1.6678	1.6698	-0.0020	1.75E-05	±0.0246	-0.08σ
RLA* (deg)	126.6165	126.6105	0.0060	1.13E-05	±0.0222	0.27σ

*EME2000 coordinate system.

0.23σ (0.30% Probability Error) which easily **satisfied** the 3.36σ accuracy requirement (99.0% probability error)

Spacecraft Separation Accuracy

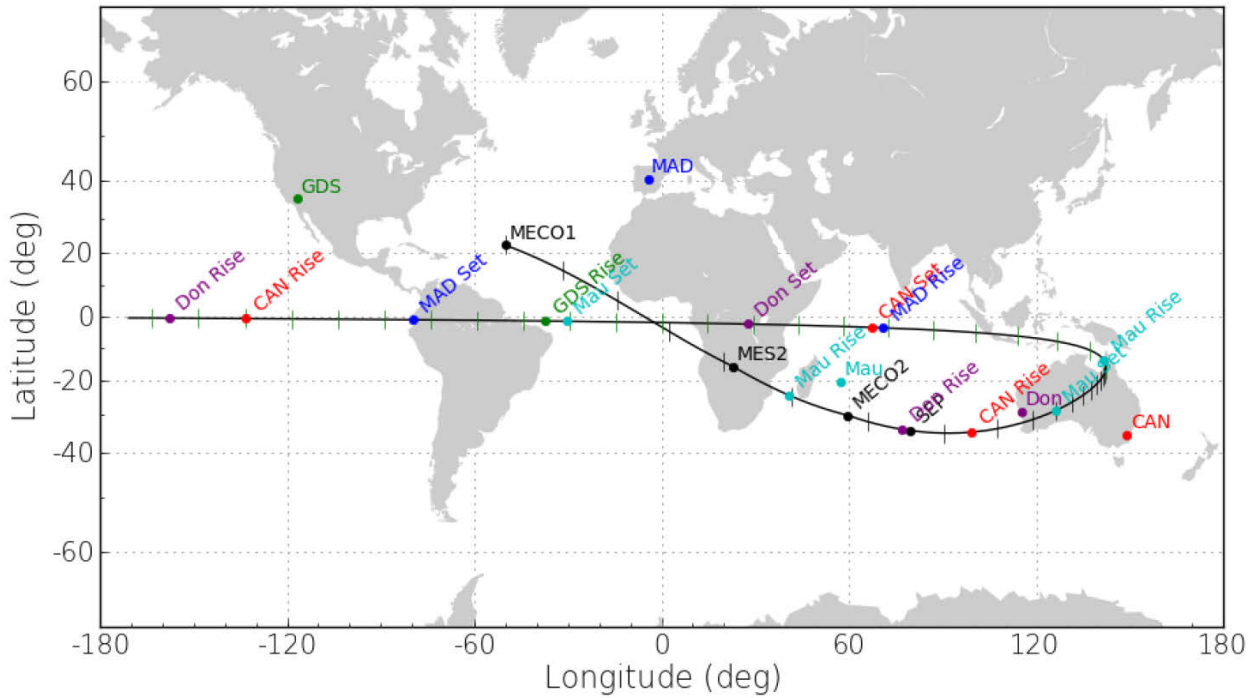
Parameter	Estimated	Desired	Error	Estimate Uncertainty	Required Accuracy
Spacecraft Separation Epoch	26-Nov-2011 15:46:09.02				
-Z Axis Right Ascension[1] (deg)	243.564	243.500	0.064	–	–
-Z Axis Declination[1] (deg)	12.216	12.000	0.216	–	–
Total Attitude Error (deg)	–	–	0.225	±0.5	±8.0
Spin Rate[2] (deg/s)	15.021	15.000	0.021	±0.015	±3.0

[1]EME2000 coordinate system. [2]Positive about +Z axis.

Spacecraft separation as seen from Centaur Upper Stage

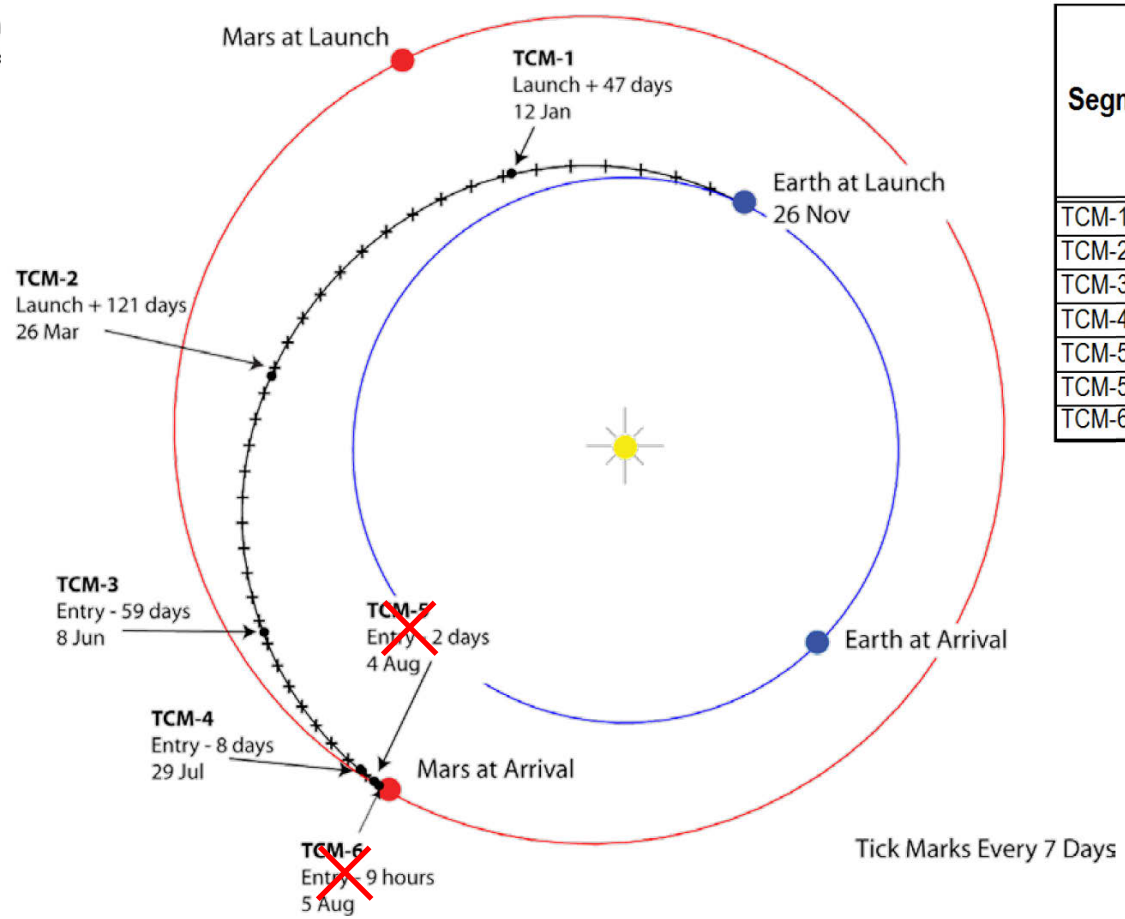
Refer to paper for injection errors mapped to the Mars B-Plane and for full set of MSL launch targets.

DSN/USN Initial Acquisition



Event	DNS/USN Initial Acquisition Times				
	Expected Time from S/C Transmitter ON (sec)	Expected Time (UTC, hh:mm:ss)	Actual Time from S/C Transmitter ON (sec)	Actual Time (UTC, hh:mm:ss)	Delta (sec)
Dongara Rise	-0:06:27	15:45:39	N/A	N/A	N/A
Canberra (DSS-34) Rise	-0:01:17	15:50:49	N/A	N/A	N/A
Spacecraft Transmitter ON	-	15:52:06	-	15:52:09	~3
Dongara Carrier Lock	N/A	N/A	0:00:16	15:52:25	N/A
Canberra (DSS-45) Carrier Lock	TXR_ON+10 sec	15:52:19	0:00:18	15:52:27	~7
Canberra (DSS-34) Carrier Lock	TXR_ON+10 sec	15:52:19	0:00:19	15:52:28	~8
Canberra (DSS-45) Telemetry Lock	CarrierLock+20sec	15:52:47	0:00:43	15:52:52	~5
Canberra (DSS-34) Telemetry Lock	CarrierLock+20sec	15:52:48	0:00:51	15:53:00	~12

Trajectory Correction Maneuver Performance

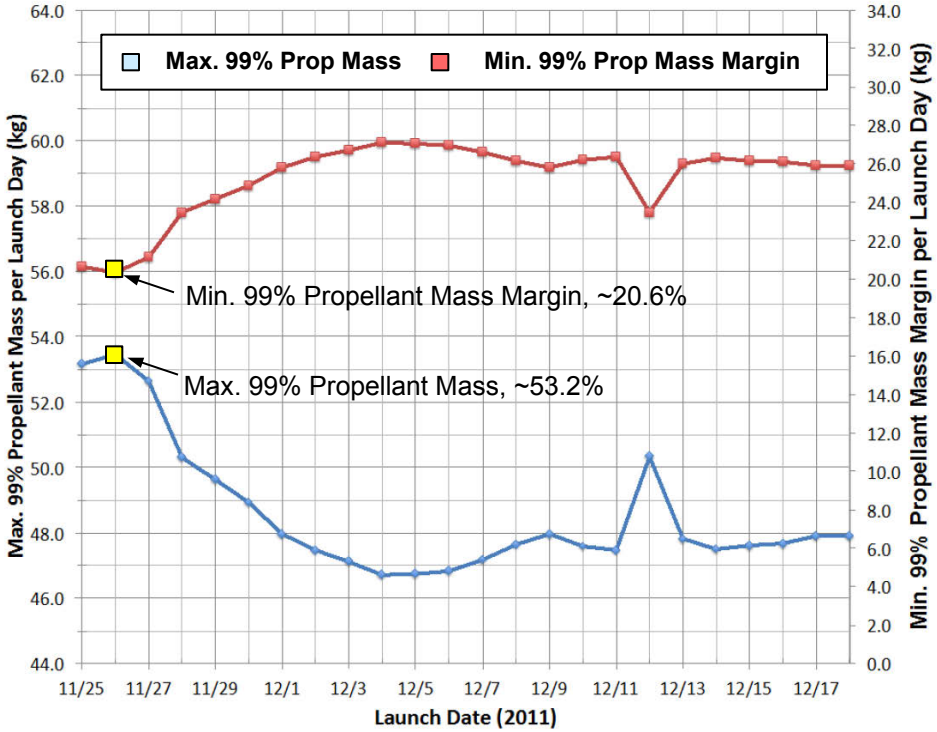


Segment	Actual Date (UTC)	Planned ΔV (m/s)	Estimated ΔV (m/s)	Estimated TCM Propellant Usage (kg)	Magnitude Error (%)
TCM-1	1/11/12	5.5071	5.6350	18.032	2.323
TCM-2	3/26/12	0.7116	0.7119	2.227	0.038
TCM-3	6/26/12	0.0414	0.0418	0.138	1.029
TCM-4	7/29/12	0.0111	0.0104	0.026	-5.702
TCM-5	Canceled	-	-	-	-
TCM-5X	N/A	-	-	-	-
TCM-6	Canceled	-	-	-	-
	TOTAL	6.2712	**6.3991**	**20.423**	

Due to small maneuver execution errors and excellent navigation solutions, TCM-5 and TCM-6 were canceled.

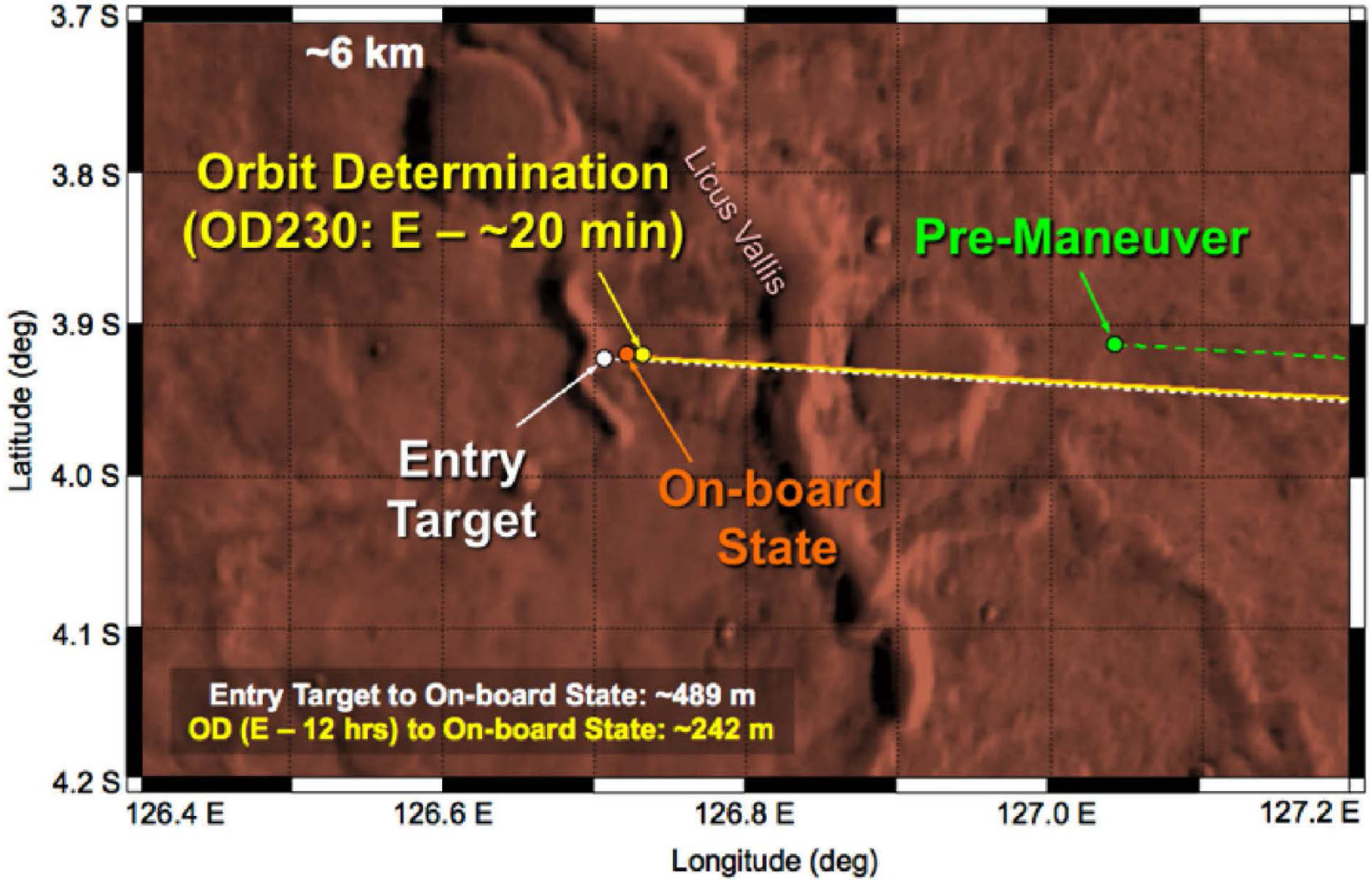
Refer to paper for pre-launch TCM dates and pointing errors.

Cruise Propellant Mass Utilization



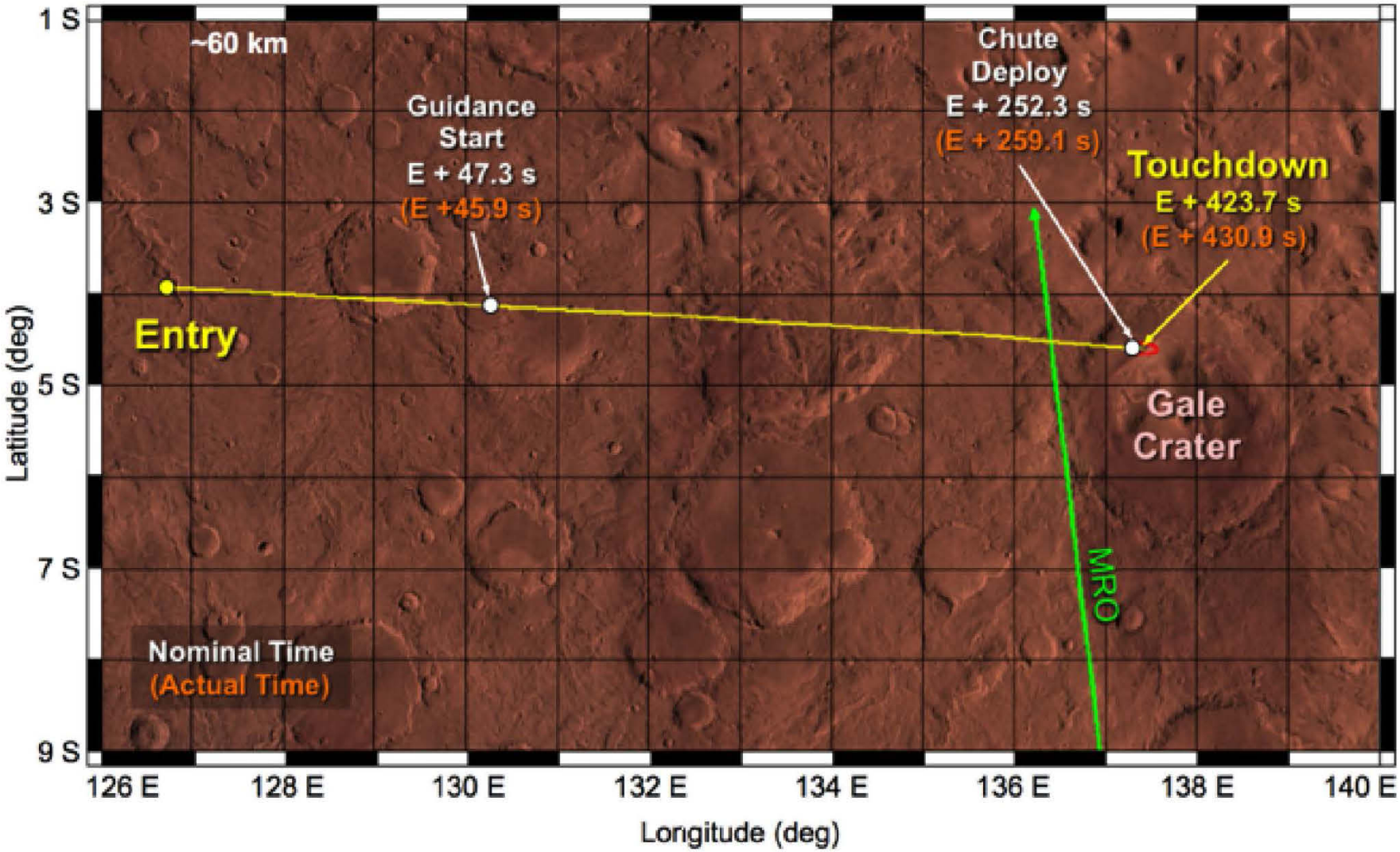
Date	Event	Total Spacecraft Wet Mass (kg)	Propellant Mass Used (kg)	Propellant Mass Available (kg)	Propellant Mass Available (%)
11/26/11	**T-Zero**	3840.5	-	73.8	100.0%
11/26/11	Separation	3838.7	1.78	72.0	97.6%
11/28/11 - 01/06/12	Spindown, ACS Turn #1,#2, and Lat Cal	3837.1	1.63	70.4	95.4%
01/11/12	**TCM-1**	3819.0	18.03	52.3	70.9%
01/25/12 - 03/07/12	ACS Cals, ACS Turns #3-6, DIMU Cal #1	3815.7	3.33	49.0	66.4%
03/26/12	**TCM-2**	3813.5	2.23	46.8	63.4%
03/26/12 - 06/18/12	ACS Turns #7-17, DIMU Cal #2	3811.6	1.90	44.9	60.8%
06/26/12	**TCM-3**	3811.4	0.14	44.7	60.6%
06/26/12 - 07/18/12	ACS Turns #18-21	3811.2	0.19	44.6	60.4%
07/29/12	**TCM-4**	3811.2	0.03	44.5	60.3%
07/29/12	ACS Turn #22	3811.2	0.07	44.5	60.3%
		TOTAL CRUISE PROPELLANT USED	29.33		

Atmospheric Entry Delivery and Knowledge Accuracy

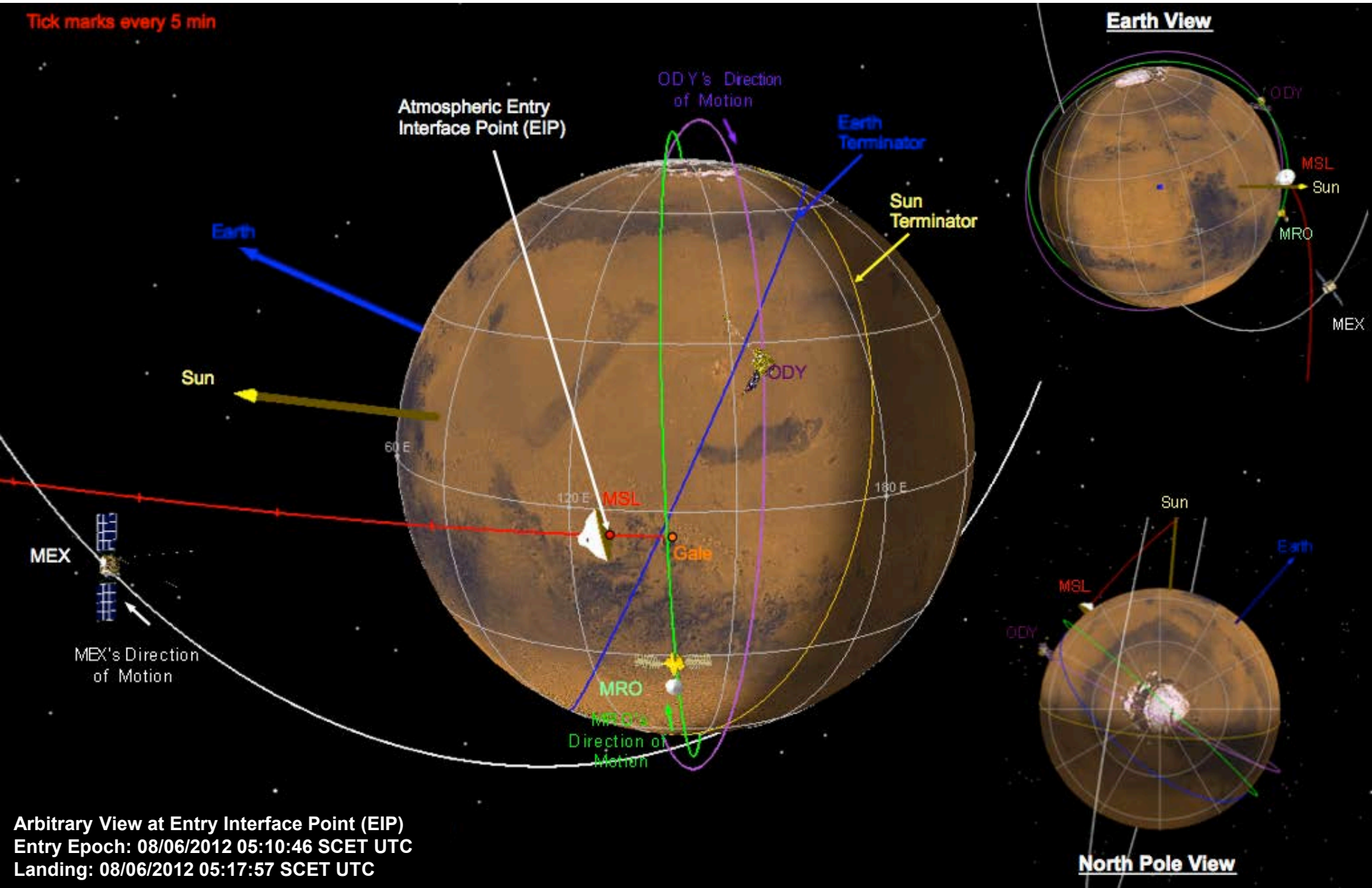


Refer to paper for B-plan locations for TCM-4 target, EPU-1, and OD230

Arrival Geometry Close-Up

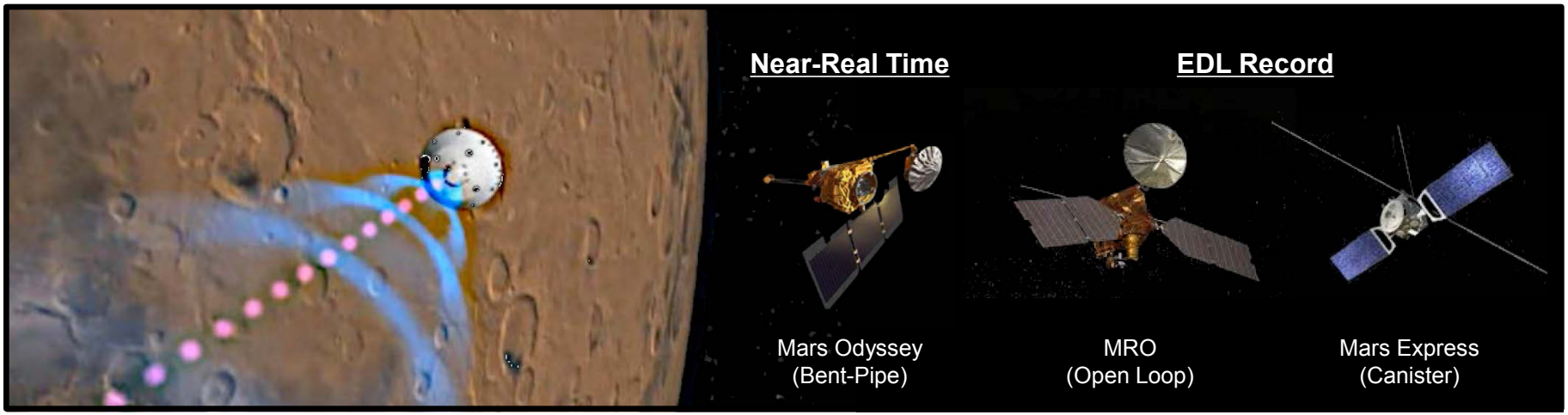


Arrival Geometry at Entry Interface Point (EIP)



Arbitrary View at Entry Interface Point (EIP)
Entry Epoch: 08/06/2012 05:10:46 SCET UTC
Landing: 08/06/2012 05:17:57 SCET UTC

EDL Relay Target Phasing Performance



		Time to Target Latitude Crossing (s)																	
		ERTF Response																	
		ERTF 8A			ERTF 9			ERTF 10			ERTF 11			ERTF 12			ERTF 13		
		MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX
ERTF Request	ERTF 8A	0.0	-124.5	34.7	0.0	-124.5	34.7	9.8	-25.1	39.8	9.0	-25.0	41.5	9.0	-25.0	41.5	**9.0**	**-25.0**	**41.5**
	ERTF 9	-	-	-	-5.2	-124.4	34.8	-	-	-	-	-	-	-	-	-	-	-	-
	ERTF 10	-	-	-	-	-	-	19.0	-24.3	41.4	-	-	-	-	-	-	-	-	-
	ERTF 11	-	-	-	-	-	-	-	-	-	18.7	-24.4	43.1	-	-	-	-	-	-
	ERTF 12	-	-	-	-	-	-	-	-	-	-	-	-	18.9	-24.3	43.1	-	-	-
	ERTF 13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.9	-24.3	43.0

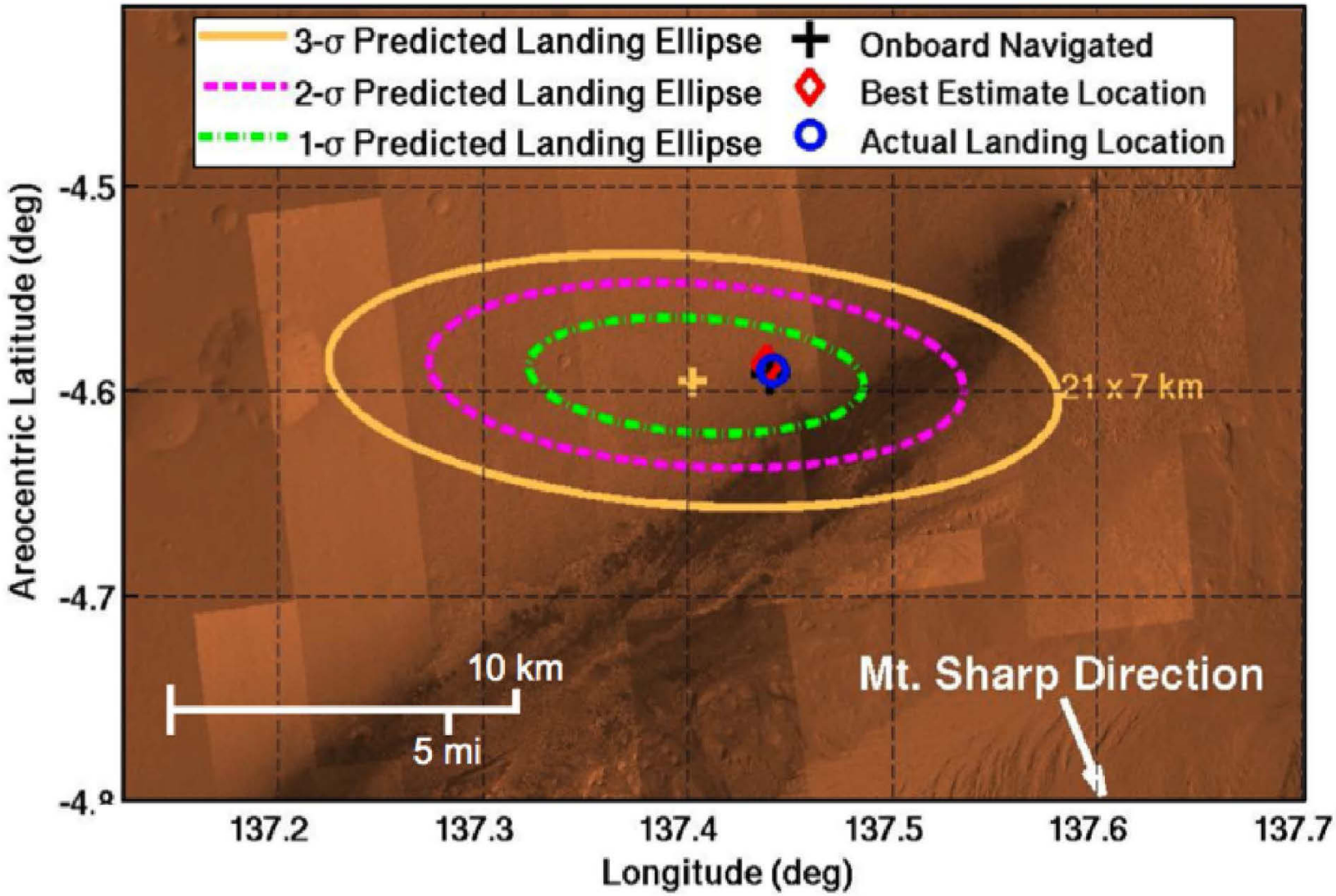
Time to target latitude crossing requirement : ± 30 (MRO), ± 60 s (ODY), ± 60 s (MEX – best effort basis)

EDL Trajectory Performance

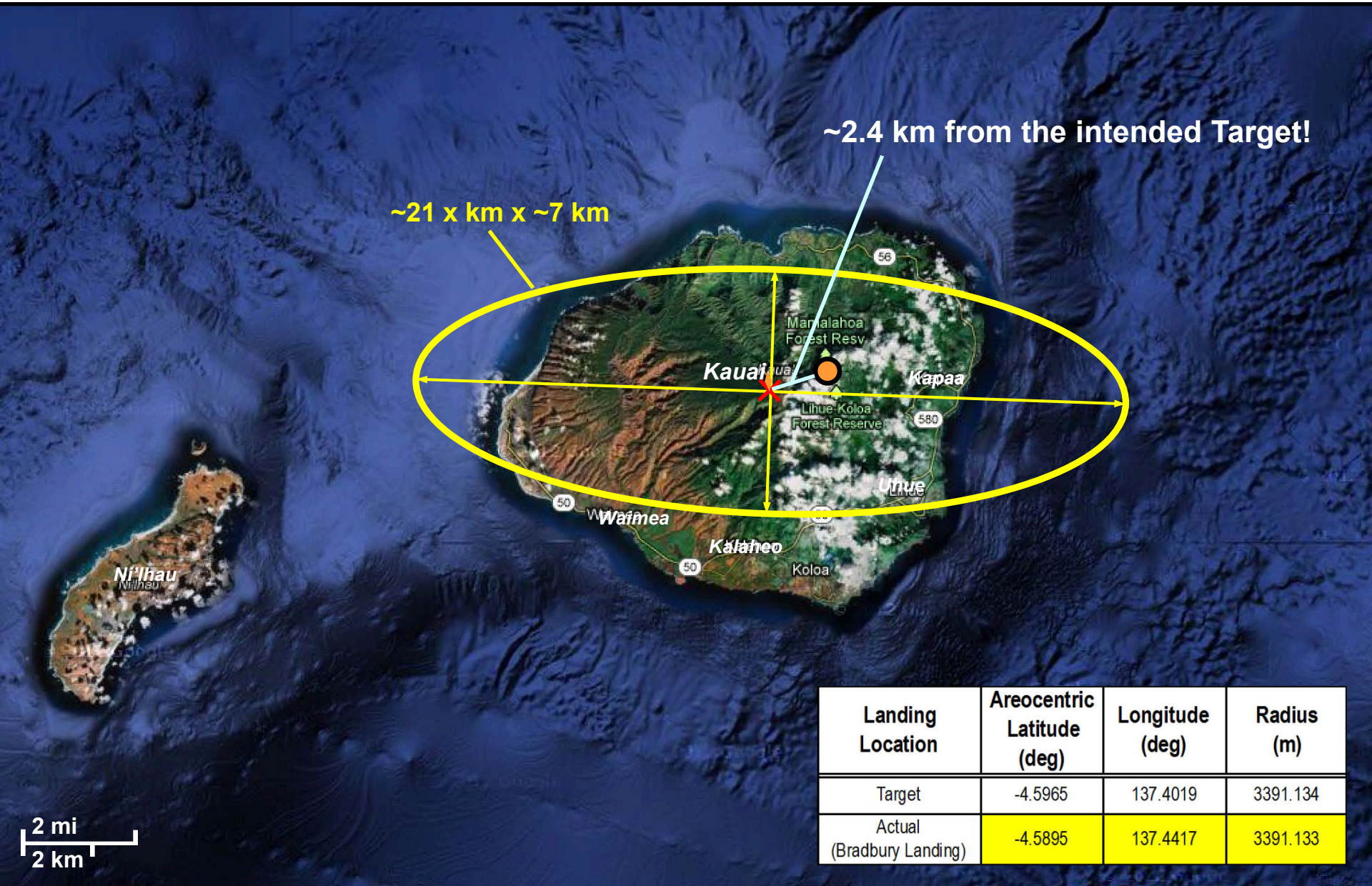
	Time from Entry (s)									

stage IMU.

Predicted Landing Ellipses and Actual Landing Location



Curiosity's Landing Dispersion Ellipse (Projected on Kauai)

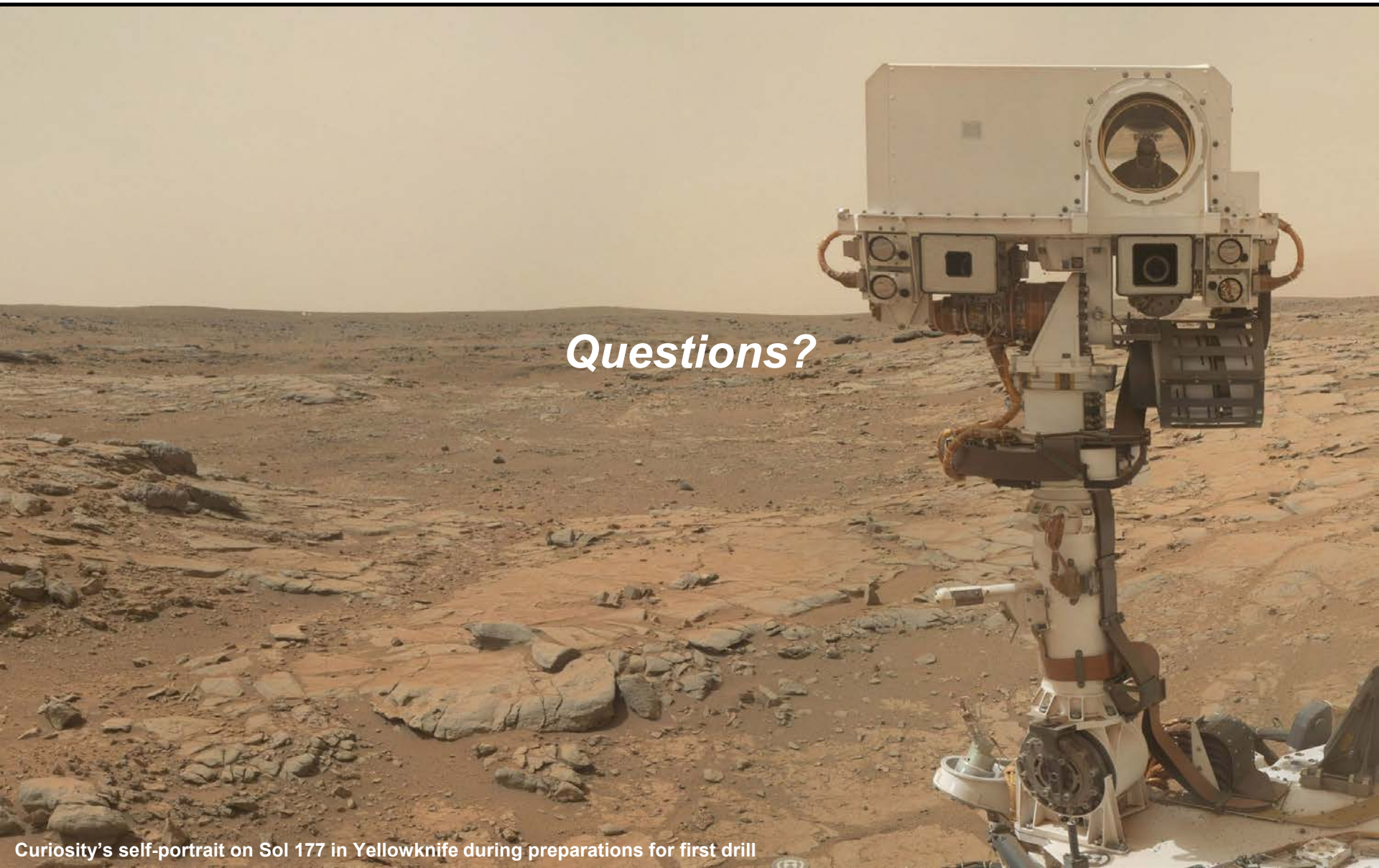


Landing Location	Areocentric Latitude (deg)	Longitude (deg)	Radius (m)
Target	-4.5965	137.4019	3391.134
Actual (Bradbury Landing)	-4.5895	137.4417	3391.133

Conclusions

- **Performance of the MSL spacecraft and all associated assets and resources required was outstanding**
  - Launch vehicle injection errors ~0.23σ
  - DSN carrier lock and telemetry lock within 12 s from predicted times
  - Trajectory correction maneuver errors < 5% coupled with nominal cruise maintenance activity performance resulted in >60% cruise propellant available at cruise stage separation
  - Entry target to on-board state ~ 489 m, actual entry to on-board state ~ 242 m, entry target to actual entry point ~ 699 m
  - MRO/ODY and MEX were < 30 s and < 60 s from the target latitude crossing respectively
  - All EDL event times were within 10 s from the predicted times
  - Actual MSL landing was ~2.4 km (~0.75σ) from target site

- **MSL arguably set a new standard in robotic exploration of the Solar System!**



Questions?

Curiosity's self-portrait on Sol 177 in Yellowknife during preparations for first drill