Welcome

MSL Loads Reconstruction During Descent and Landing

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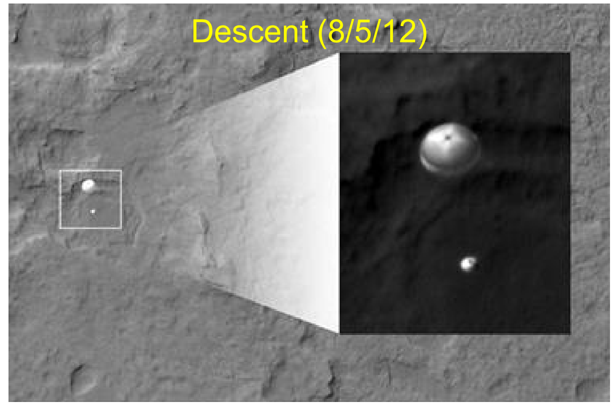
Mars Science Laboratory
The Current Mars Mission

- Mars Science Laboratory (MSL) successfully landed on August 5, 2012
  - *JPL's latest robotic mission to the red planet*
  - *Its rover, Curiosity, is studying Mars habitability*
  - *Curiosity carries the biggest, most advanced instruments ever sent to the Martian surface*
  - *One Mars year surface operational lifetime (687 days)*
  - *Innovative controlled propulsive landing: Skycrane Touchdown Maneuver*
- Acknowledgement: A special thanks to all MSL EDL reconstruction team members (Tom Rivellini, Steve Sell, Alejandro San Martin, Frederick Serricchio, etc.) who have supported and contributed to this work.

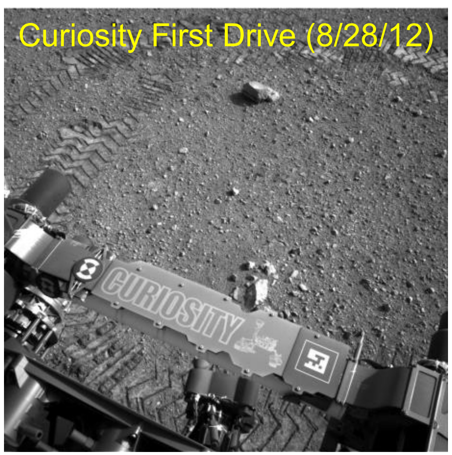
Mars Science Laboratory

JPL's Latest Successful Story

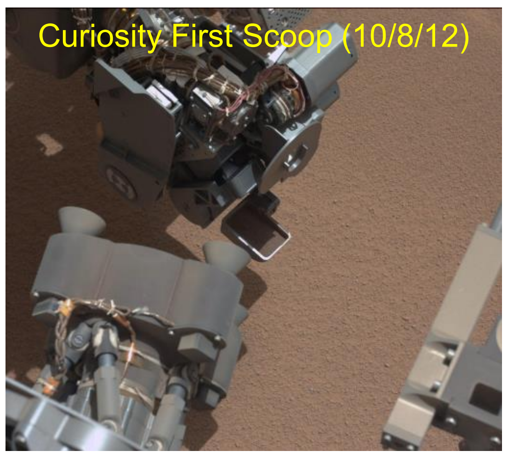

Launch (11/26/11)


Descent (8/5/12)

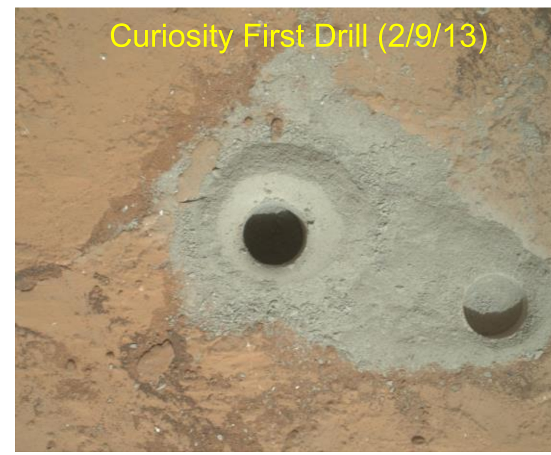

Curiosity First Image (8/5/12)



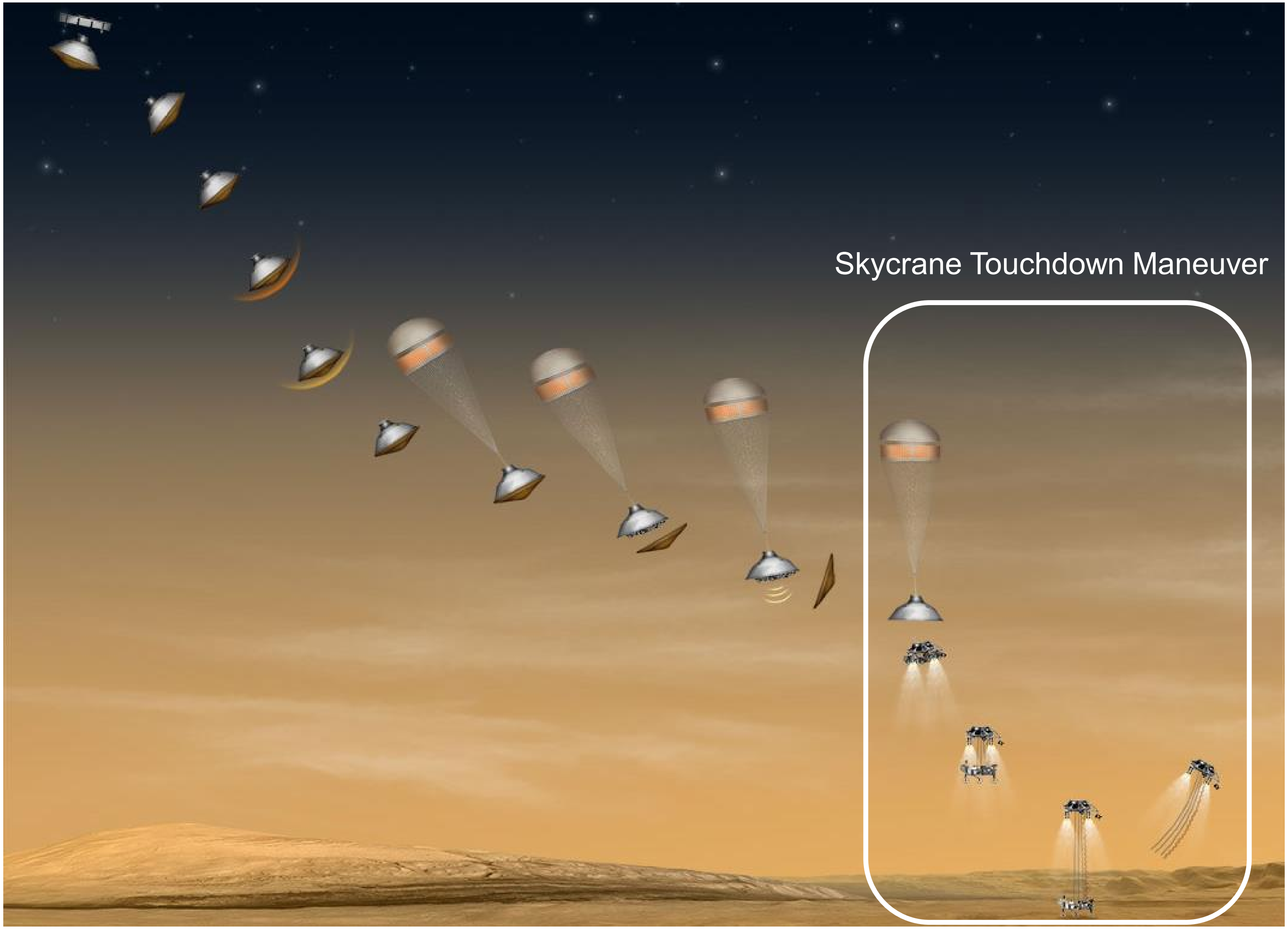
Curiosity First Drive (8/28/12)


Curiosity First Scoop (10/8/12)


Curiosity Self-Portrait (11/1/12)

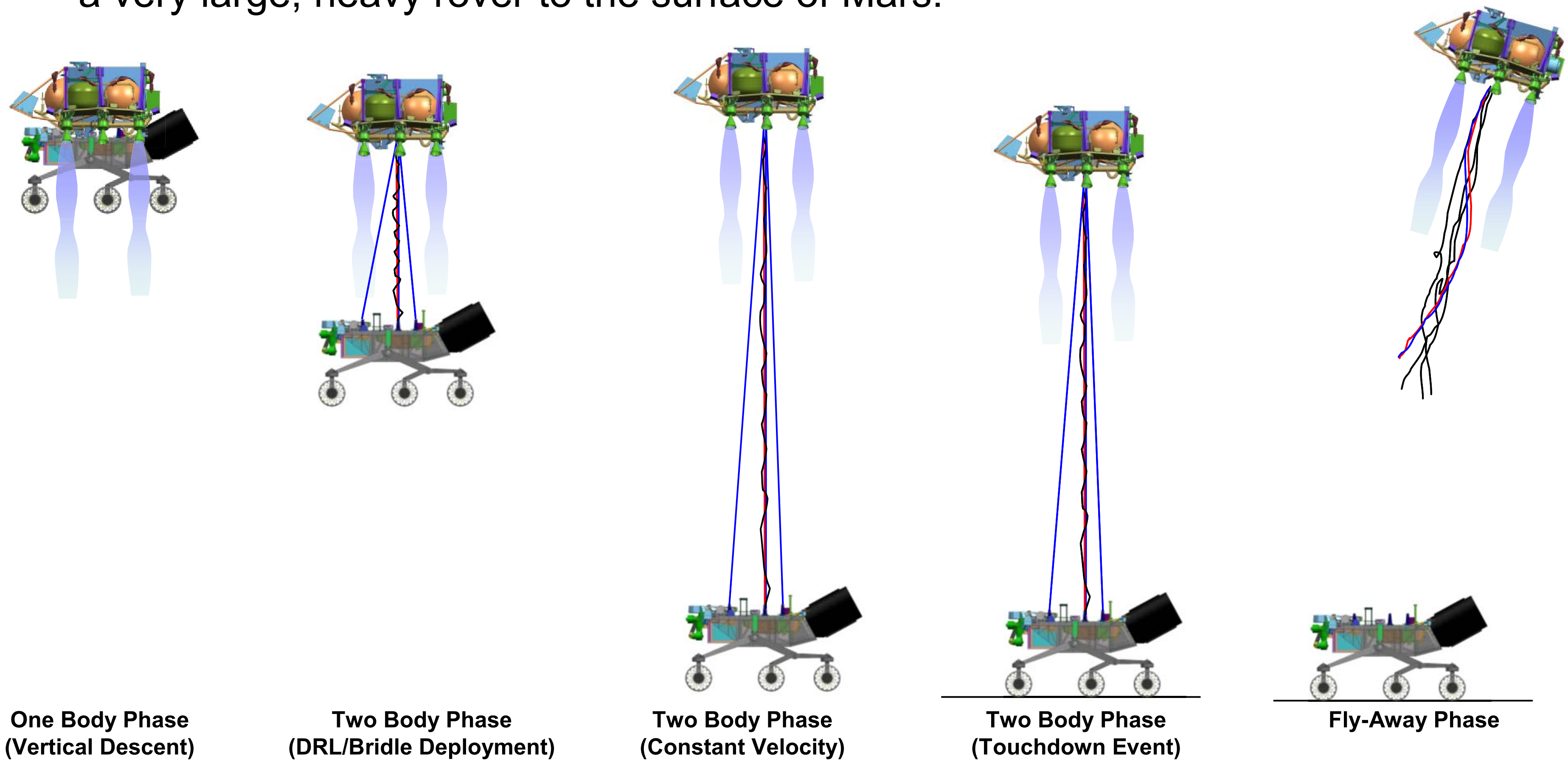

Curiosity First Drill (2/9/13)

Entry, Descent and Landing

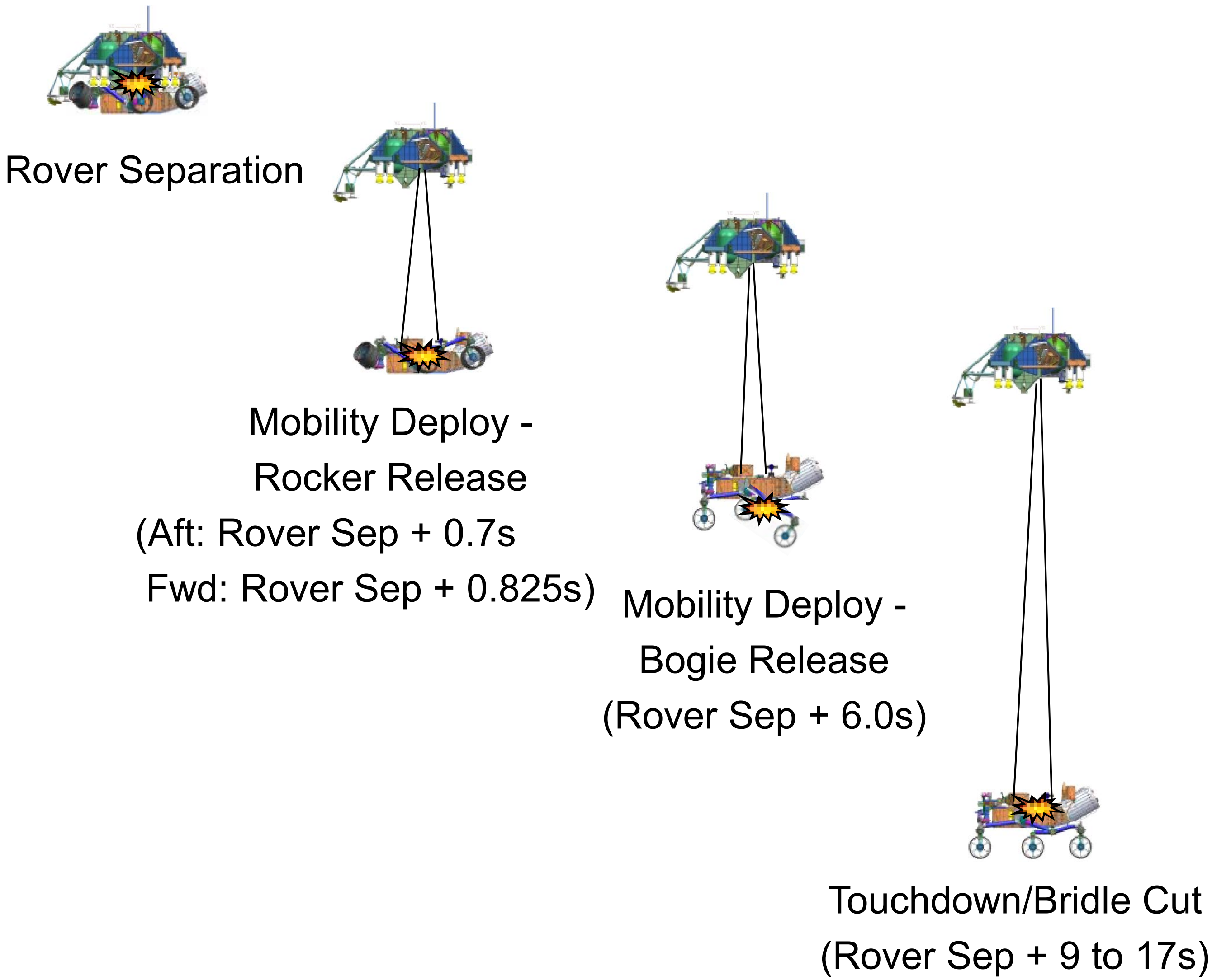


Skycrane Touchdown Maneuver

- MSL developed a very innovative "skycrane" landing technology for landing a very large, heavy rover to the surface of Mars.



Skycrane Maneuver Timeline

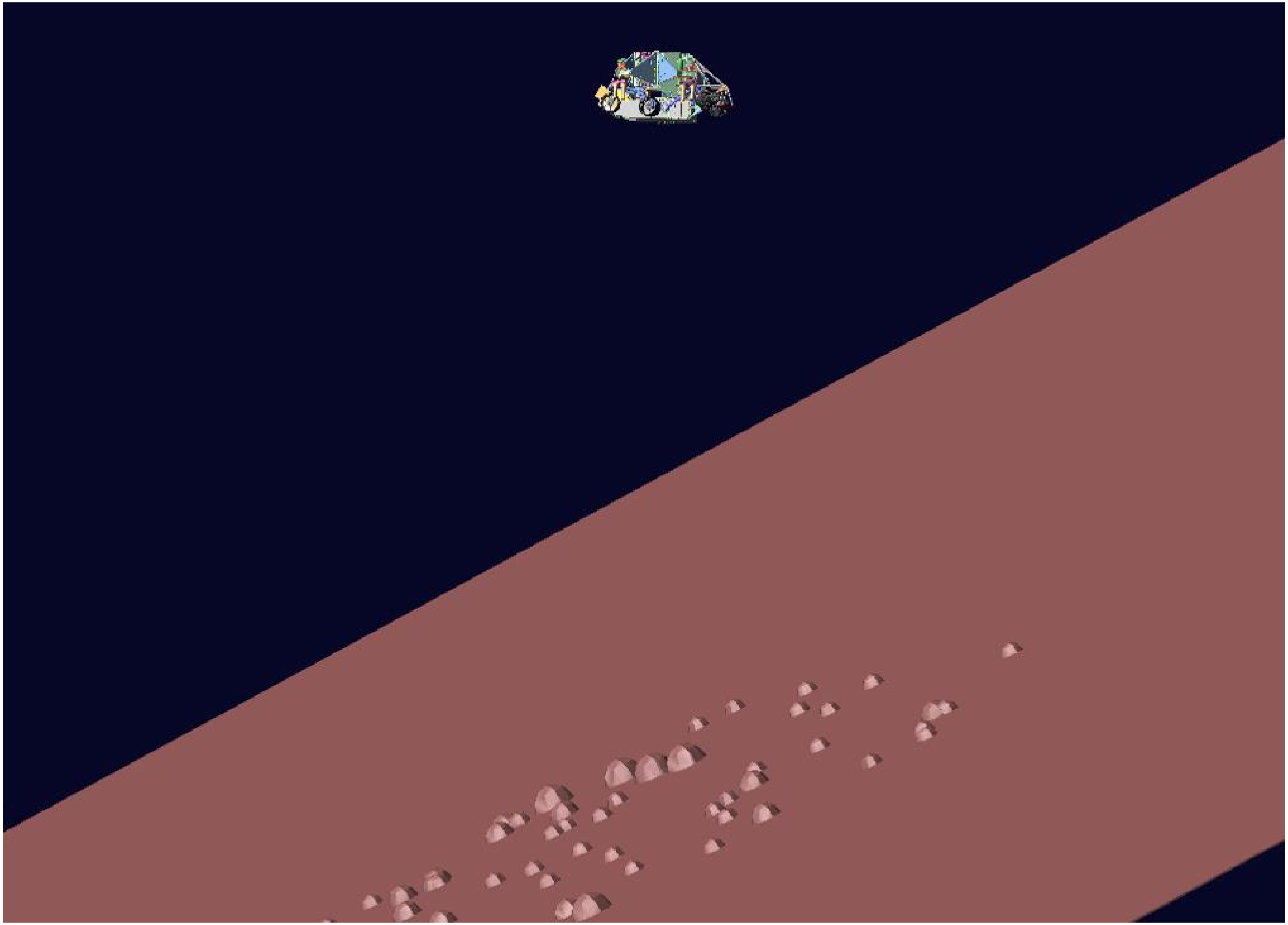


Simulation of Skycrane Touchdown Maneuver

- Multiple year effort to develop an ADAMS multibody dynamic simulation integrated with the GNC flight software for the MSL skycrane touchdown maneuver
  - *Powered Descent ← 55m above ground, (V_h , V_v)= (0, 20) m/sec*
  - *Throttle Down*
  - *Rover Separation → PDV States at Rover Sep, Clearance Check*
  - *Mobility Deploy → Verification Mobility Deploy Loads*
  - *Ready for Touchdown → Ready-for-Touchdown States*
  - *Touchdown → Verification Touchdown Loads*
  - *Bridle Cut → Touchdown Trigger Performance*
  - *Fly-away*
- Employed Monte Carlo approach by varying key input parameters
- Run on 8 CPUs of 2 HP workstations with 4 TB institution storage
  - *17 to 93 minutes per run, average 36 minutes per run*

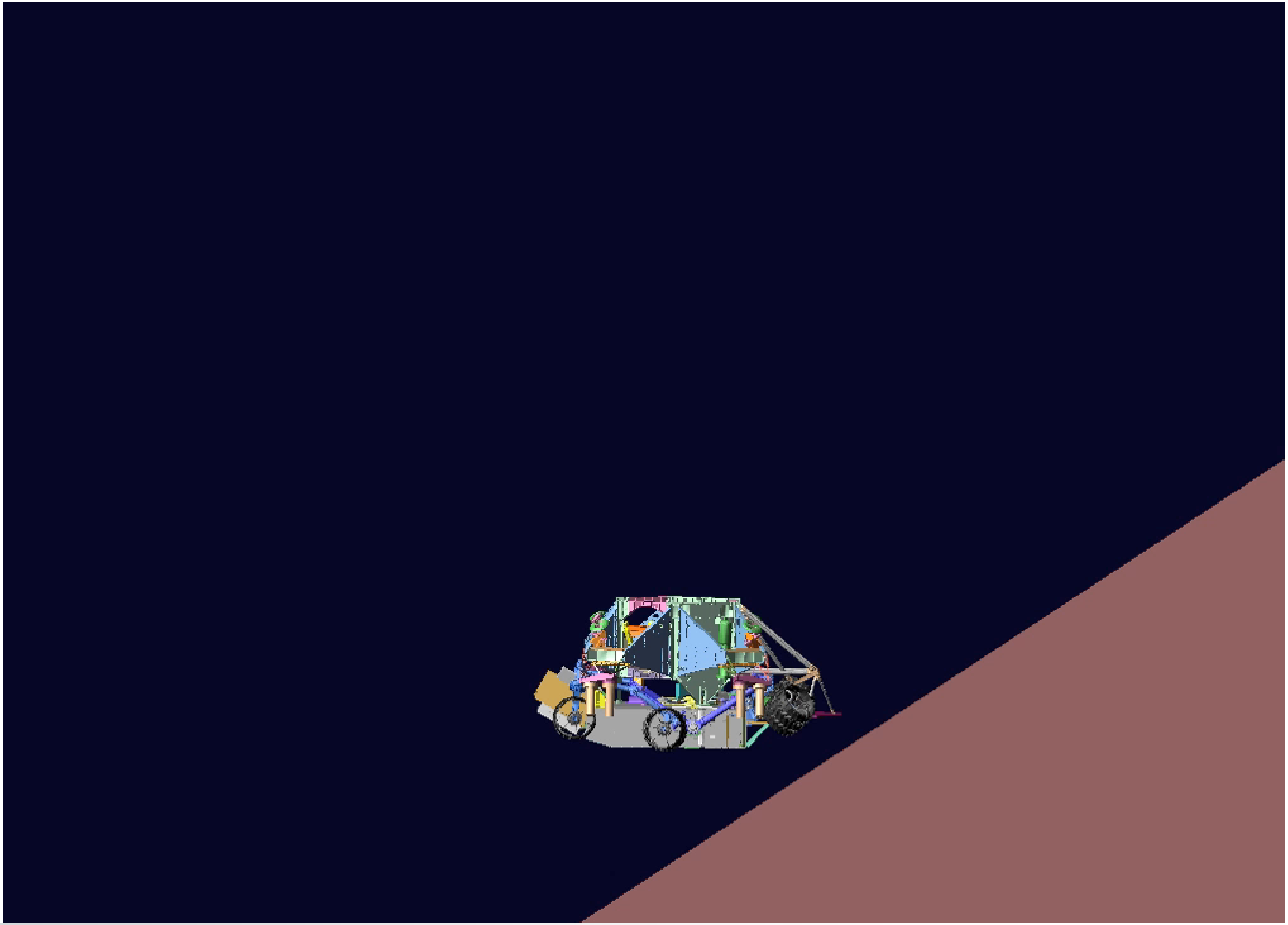
Animation of Skycrane Touchdown Simulation

Overall View



Animation of Skycrane Touchdown Simulation

Zoom-in View



Reconstruction of Rover C.G. Loads

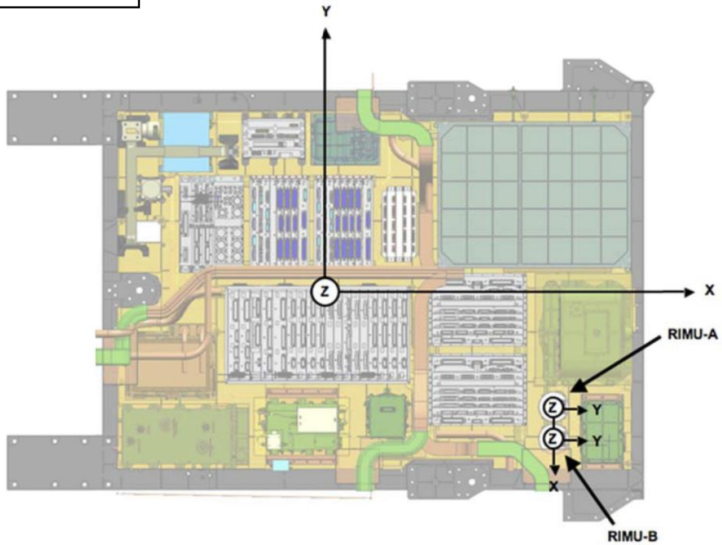
- Based on “MSL Surface Pointing, Positioning, Phasing, and Coordinate Systems (PPPCS) Document, Volume 9, Rev. B, JPL D-34651, MSL-476-1306,” the flight data were measured in the RIMU-B coordinate system, not in the Rover coordinate system.
  - *Transformation between RIMU-B and Rover (RM) coordinate systems*

$X_{RIMU\text{-}B}$ = positively directed along $-Y_{RM}$ direction

$Y_{RIMU\text{-}B}$ = positively directed along $+X_{RM}$ direction

$Z_{RIMU\text{-}B}$ = positively directed along $+Z_{RM}$ direction

- So one of the reconstruction process is to perform the coordinate transformation on the RIMU-B acceleration and velocity data in order to output them in the Rover coordinate system.



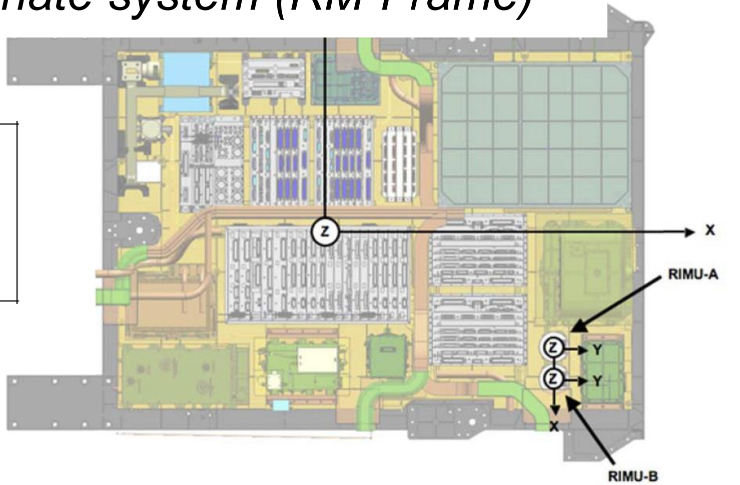
Reconstruction of Rover C.G. Loads (cont.)

- Based on "MSL Surface Pointing, Positioning, Phasing, and Coordinate Systems (PPPCS) Document, Volume 9, Rev. B, JPL D-34651, MSL-476-1306," the sensing point of RIMU-B is not at the Rover C.G. and not at its geometric center either.
  - *RIMU sensing point w.r.t. its geometric center in the RIMU coordinate system*

$$^{RIMU}T^{CON} = \begin{bmatrix} 0.215 \\ 0.220 \\ 0.950 \end{bmatrix} in. = \begin{bmatrix} 5.461 \\ 5.588 \\ 24.130 \end{bmatrix} mm, \text{ in the RIMU frame}$$

  - *RIMU geometric center in the Rover coordinate system (RM-Frame)*

RIMU-B	RM-Frame	$^{RM}T^{RIMU\text{-}B}$	X [550.89] mm Y [-427.04] mm Z [86.00] mm in rover mechanical frame



Reconstruction of Rover C.G. Loads (cont.)

- Based on the information described in the previous slide, the reconstruction requires computing the acceleration and velocity at the Rover C.G. from the measured acceleration and velocity at the RIMU-B sensing point using the following equations.

$$\vec{V}_{rover\_chass\_cg} = \vec{V}_{rimu\_sen} - (\vec{\omega} \times \vec{r})$$

$$\vec{a}_{rover\_chass\_cg} = \vec{a}_{rimu\_sen} - \vec{\omega} \times (\vec{\omega} \times \vec{r}) - \frac{d\vec{\omega}}{dt} \times \vec{r}$$

$$\vec{r} = \text{vector from rover chassis cg to rimu sening center}$$

$$\vec{\omega} = \text{angular ve locity of rover}$$

- Due to the noise in the measured RIMU-B data, the reconstructed Rover C.G. acceleration/velocity time history data are low-pass filtered with the cut-off frequency of 25 Hz.
  - *Remove high frequency noise*
  - *Retain as much raw data as possible*
- The reconstructed loads during the descent and landing phases are compared to the pre-flight predictions in the following charts.

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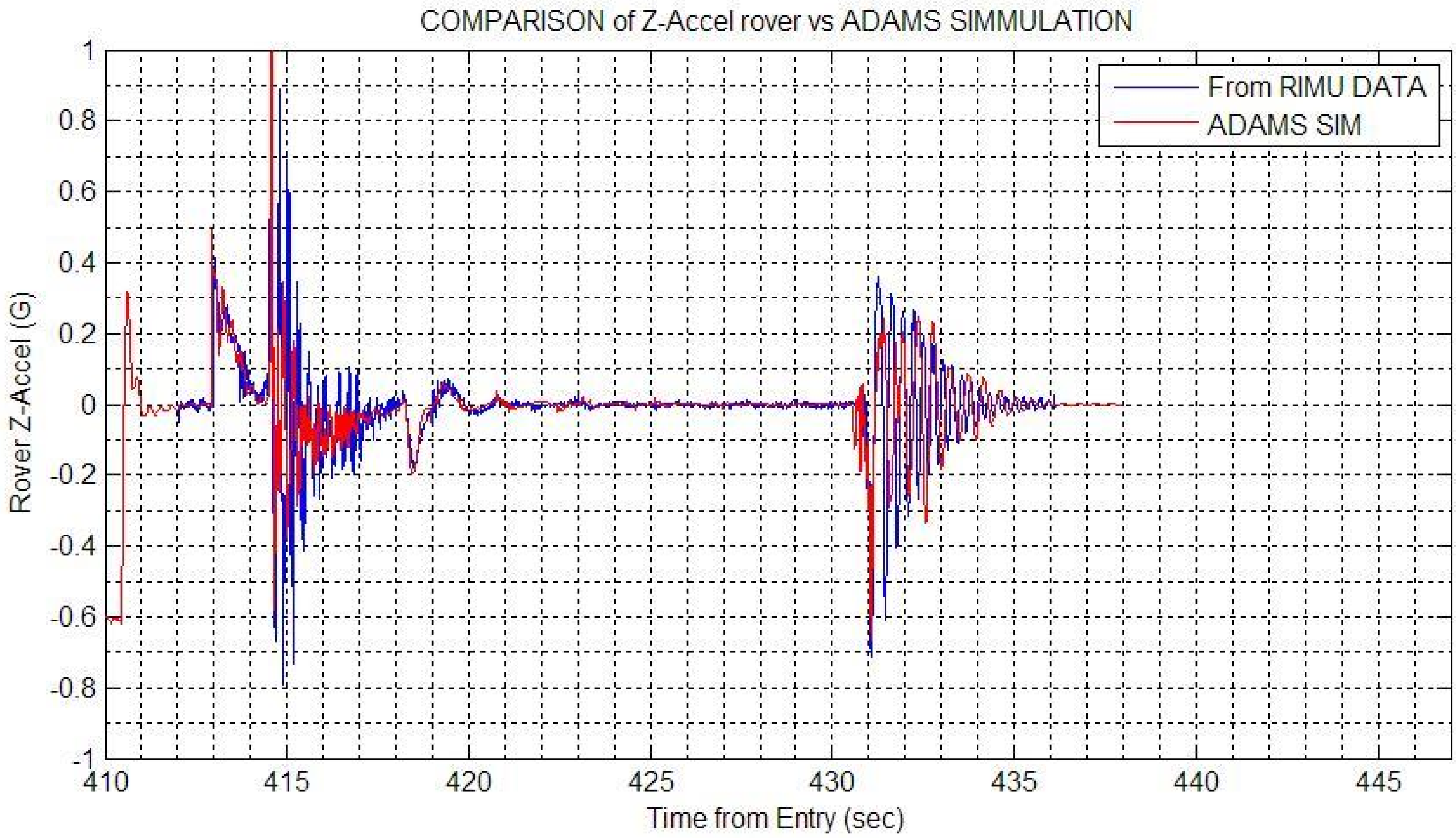
Reconstruction vs. Prediction

Rover C.G. Acceleration



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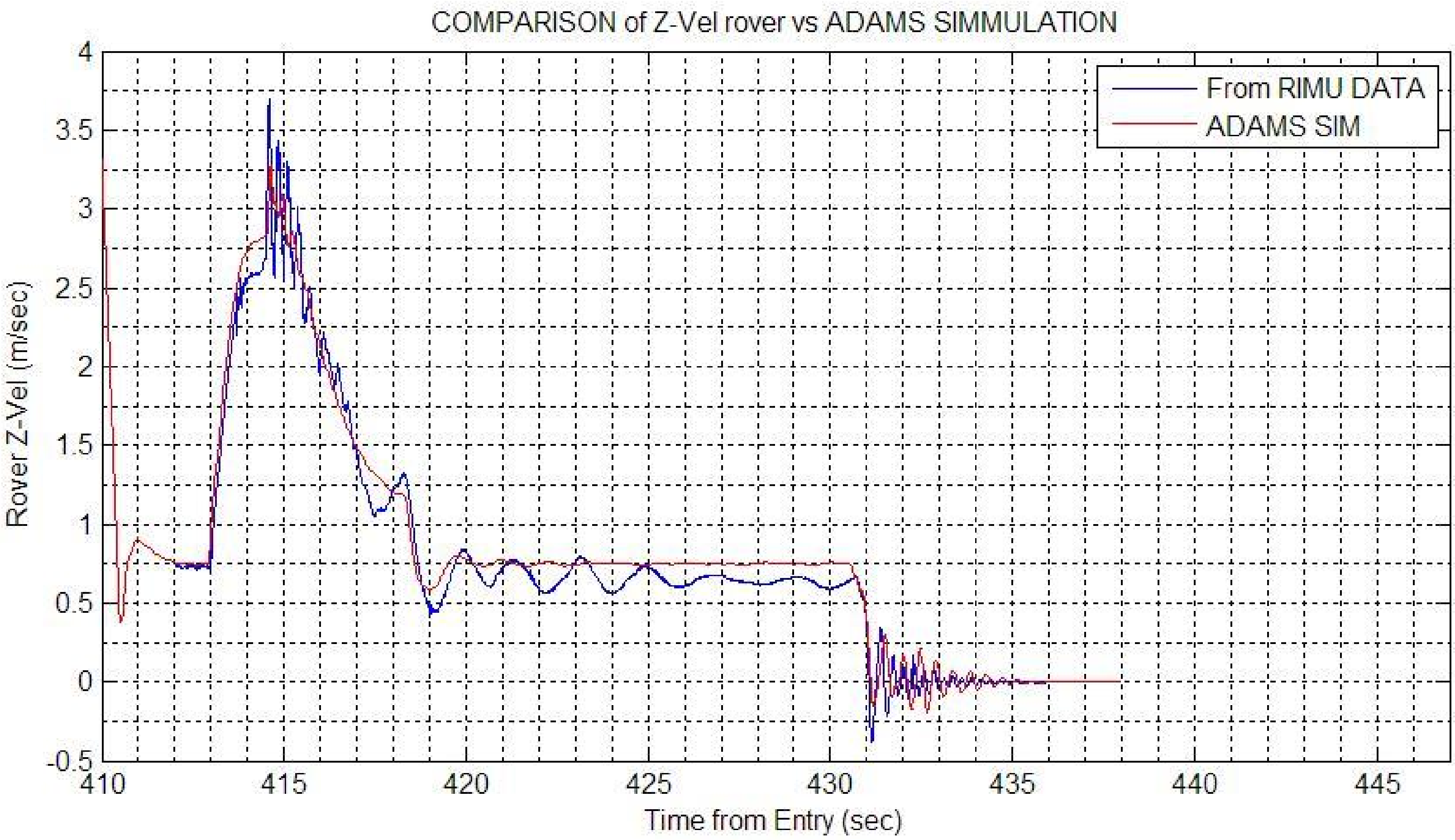
Reconstruction vs. Prediction

Rover C.G. Velocity



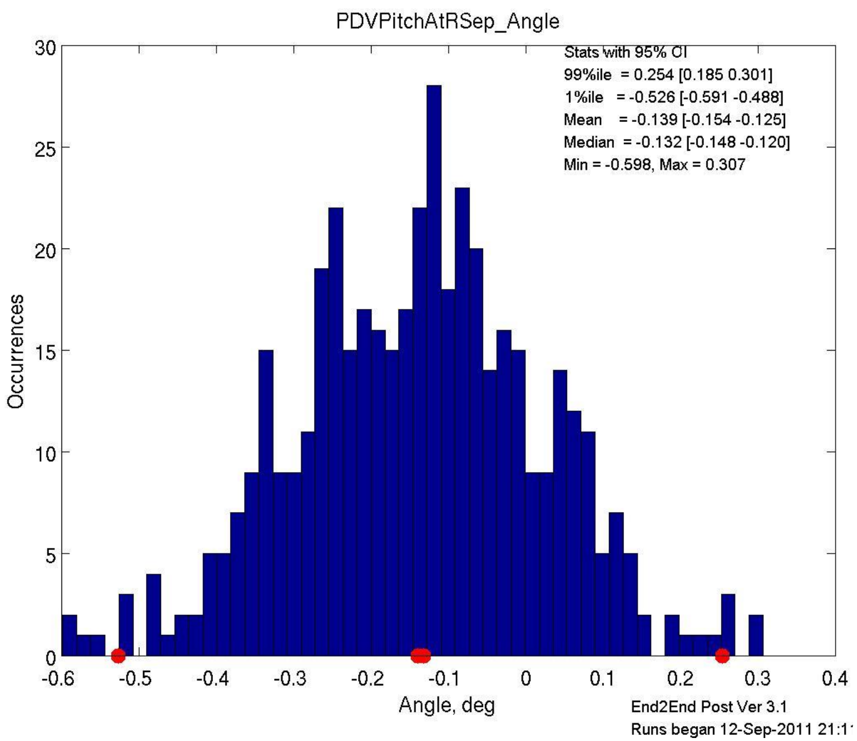
Reconstruction vs. Prediction

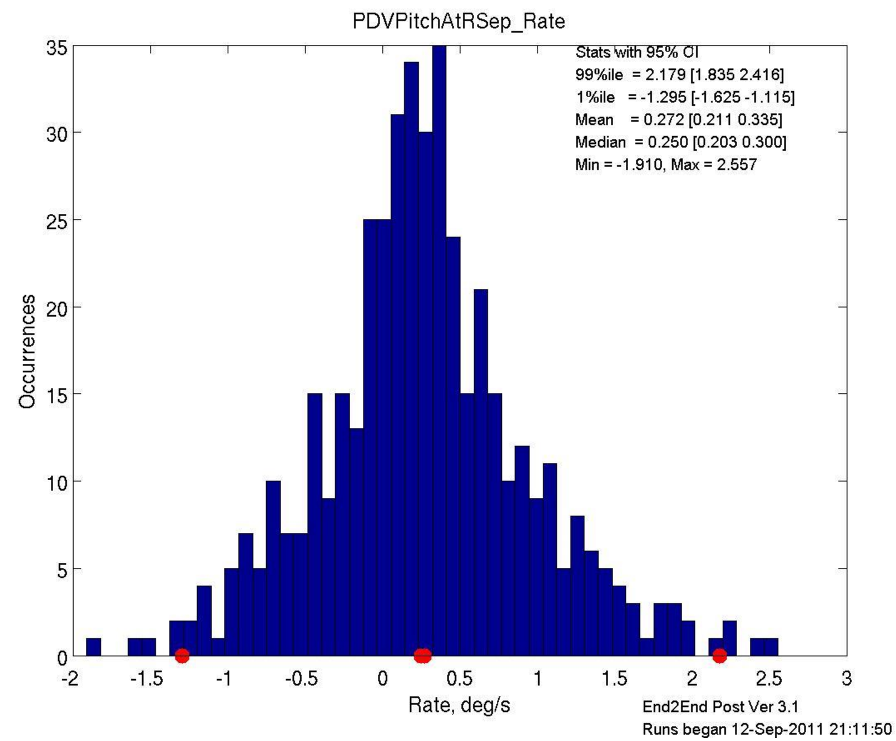
States at Rover Separation

- Pitch Angle = 0.0521 deg vs. 0.526 deg (1%-tile)
- Pitch Rate = 0.175 deg/sec vs. 2.179 deg/sec (99%-tile)

Red: Reconstructed Rover C.G. states at Time from Entry = 421.9 sec

Blue: Based on Sep-2011 ADAMS Monte Carlo simulation runs





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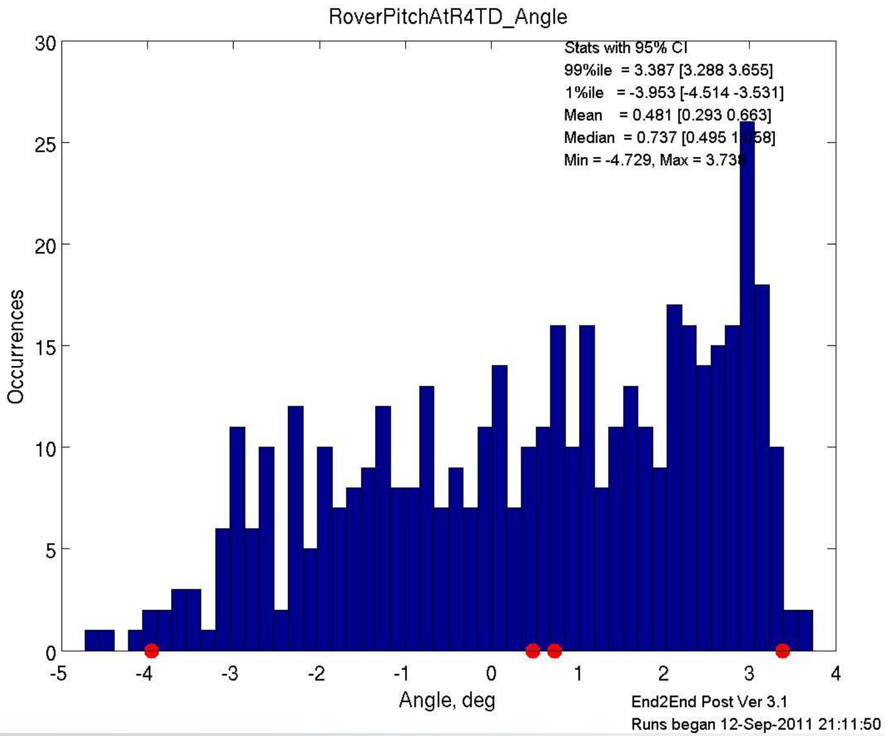
Reconstruction vs. Prediction

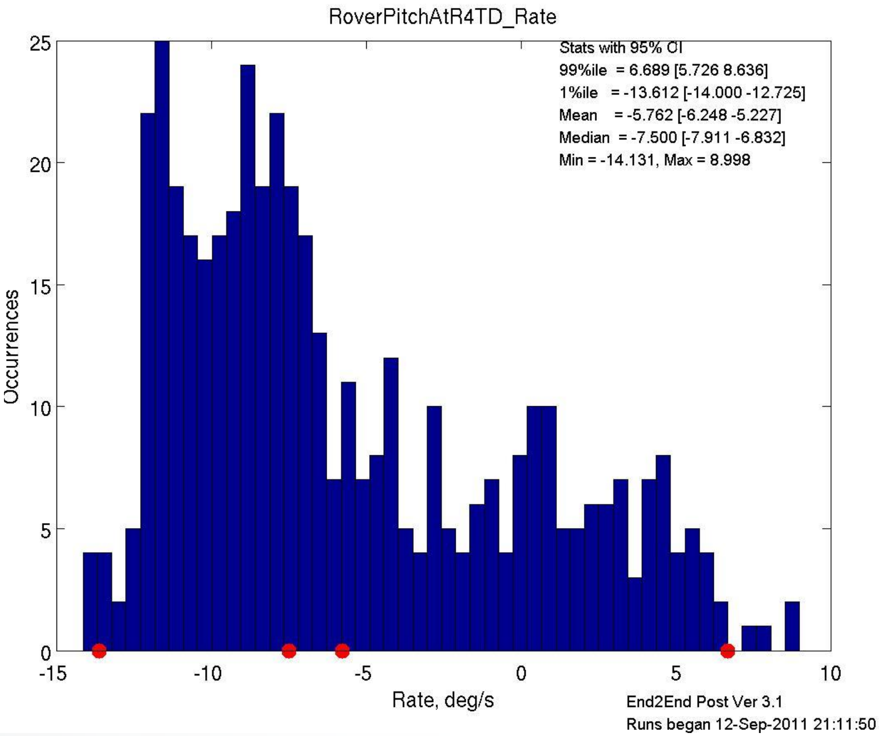
States at Ready-for-Touchdown

- Pitch Angle = 0.515 deg vs. 3.953 deg (1%-tile)
- Pitch Rate = 7.344 deg/sec vs. 13.612 deg/sec (1%-tile)

Red: Reconstructed Rover C.G. states at Time from Entry = 421.9 sec

Blue: Based on Sep-2011 ADAMS Monte Carlo simulation runs





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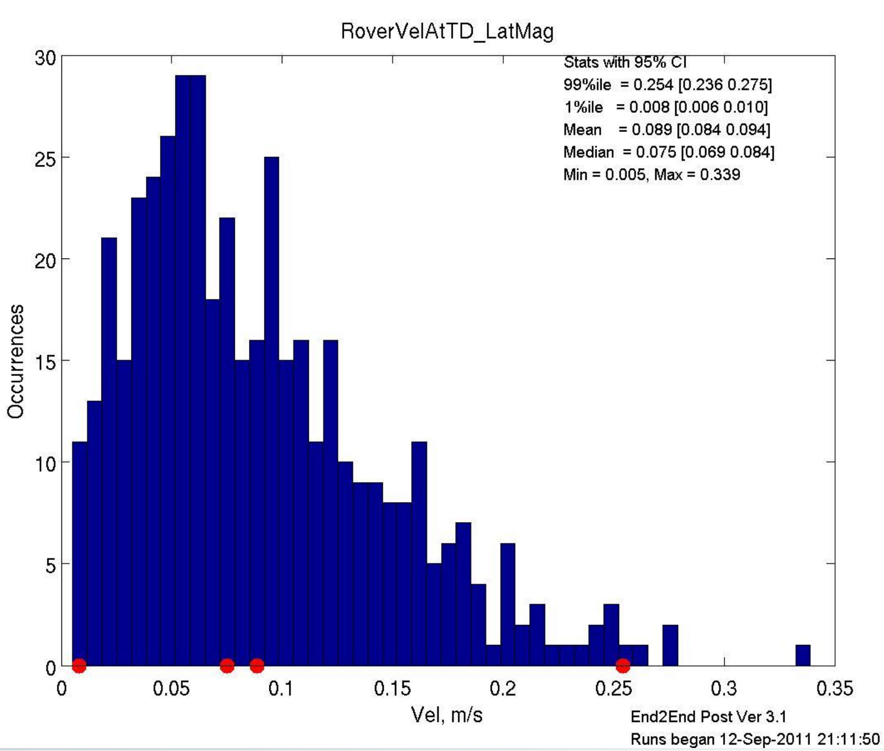
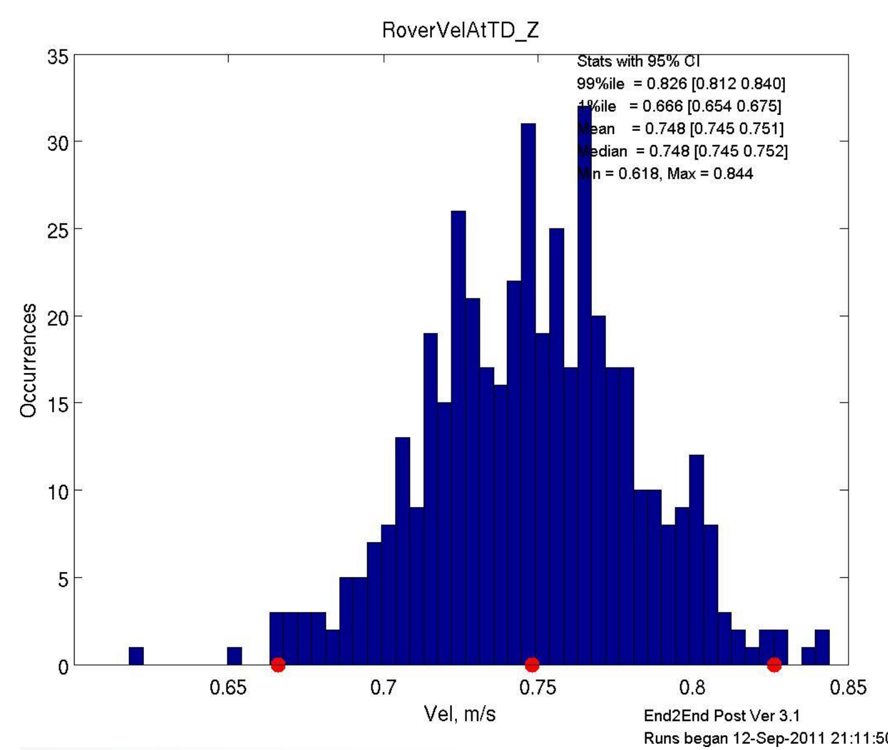
Reconstruction vs. Prediction
States at First Ground Contact

- Lateral Velocity = 0.173 m/sec vs. 0.254 m/sec (99%-tile)
- Vertical Velocity = 0.628 m/sec vs. 0.826 m/sec (99%-tile)

Red: Reconstructed Rover C.G. states at Time from Entry = 430.6 sec

Blue: Based on Sep-2011 ADAMS Monte Carlo simulation runs





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Reconstruction vs. Prediction

Mobility Deploy Loads

- Reconstructed Rover C.G. accelerations vs. August-2011 Rover C.G. accelerations predicted by 442 ADAMS Monte Carlo simulation runs

MSL Rover VLC Mobility Deploy Loads from End to End Monte Carlo Runs - Chassis CG Accelerations (August 18, 2011)

diagonal values = 99 percentile of absolute max values over 442 runs (signs preserved)

off-diagonal values = max abs value within 300 msec window (+/- 150 msec) of diagonal value (signs preserved)

Note: LUF = 1.2 included, output in Rover Body-Fixed Coordinate System

Item	AX (G)	AY (G)	AZ (G)	AM (G)	RX (RAD/S^2)	RY (RAD/S^2)	RZ (RAD/S^2)	RM (RAD/S^2)
AX (G)	0.83	-0.31	0.74	0.86	14.2	24.4	6.3	26.3
AY (G)	0.51	-0.77	1.09	1.11	-31.8	10.8	7.5	31.9
AZ (G)	0.55	-0.22	-1.57	1.59	-21.7	-13.4	3.4	23.1
AM (G)	0.55	-0.22	-1.57	1.59	-21.7	-13.4	3.4	23.1
RX (RAD/S^2)	-0.44	0.58	1.03	1.06	-36.8	16.2	10.9	38.2
RY (RAD/S^2)	0.75	-0.18	-0.57	0.77	-10.4	27.4	4.4	27.5
RZ (RAD/S^2)	-0.37	-0.55	-0.70	0.81	-21.3	-11.4	-11.3	24.1
RM (RAD/S^2)	0.43	-0.53	1.22	1.28	37.2	-12.7	-11.7	37.7

MSL Rover Flight Mobility Deploy Loads from the EDL Loads Reconstruction Using the RIMU-B Data (February 21, 2013)

diagonal values = absolute max values from RIMU acceleration data (signs preserved)

off-diagonal values = max abs value within 300 msec window (+/- 150 msec) of diagonal value (signs preserved)

Note: LUF = 1.0 included, output in Rover Body-Fixed Coordinate System

Item	AX (G)	AY (G)	AZ (G)	AM (G)	RX (RAD/S^2)	RY (RAD/S^2)	RZ (RAD/S^2)	RM (RAD/S^2)
AX (G)	0.56	-0.41	0.71	0.83	-17.33	-16.92	2.82	24.03
AY (G)	0.56	-0.41	0.89	0.99	-17.63	-16.92	-7.14	24.03
AZ (G)	0.42	-0.41	0.89	0.99	25.65	-16.92	-7.14	26.60
AM (G)	0.42	-0.41	0.89	0.99	25.65	-16.92	-7.14	26.60
RX (RAD/S^2)	0.42	0.36	0.89	0.99	25.65	10.15	-7.14	26.60
RY (RAD/S^2)	0.56	-0.41	0.89	0.99	-17.63	-16.92	-7.14	24.03
RZ (RAD/S^2)	0.42	-0.41	0.89	0.99	25.65	-16.92	-7.14	26.60
RM (RAD/S^2)	0.42	0.36	0.89	0.99	25.65	10.15	-7.14	26.60

Reconstruction vs. Prediction
Touchdown Loads

- Reconstructed Rover C.G. accelerations vs. August-2011 Rover C.G. accelerations predicted by 442 ADAMS Monte Carlo simulation runs

MSL Rover VLC Mobility Deploy Loads from End to End Monte Carlo Runs - Chassis CG Accelerations (August 18, 2011)

diagonal values = 99 percentile of absolute max values over 442 runs (signs preserved)

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AY (G)	0.51	-0.77	1.09	1.11	-31.8	10.8	7.5	31.9
AZ (G)	0.55	-0.22	-1.57	1.59	-21.7	-13.4	3.4	23.1
AM (G)	0.55	-0.22	-1.57	1.59	-21.7	-13.4	3.4	23.1
RX (RAD/S^2)	-0.44	0.58	1.03	1.06	-36.8	16.2	10.9	38.2
RY (RAD/S^2)	0.75	-0.18	-0.57	0.77	-10.4	27.4	4.4	27.5
RZ (RAD/S^2)	-0.37	-0.55	-0.70	0.81	-21.3	-11.4	-11.3	24.1
RM (RAD/S^2)	0.43	-0.53	1.22	1.28	37.2	-12.7	-11.7	37.7

MSL Rover Flight Mobility Deploy Loads from the EDL Loads Reconstruction Using the RIMU-B Data (February 21, 2013)

diagonal values = absolute max values from RIMU acceleration data (signs preserved)

off-diagonal values = max abs value within 300 msec window (+/- 150 msec) of diagonal value (signs preserved)

Note: LUF = 1.0 included, output in Rover Body-Fixed Coordinate System

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AM (G)	0.42	-0.41	0.89	0.99	25.65	-16.92	-7.14	26.60
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RZ (RAD/S^2)	0.42	-0.41	0.89	0.99	25.65	-16.92	-7.14	26.60
RM (RAD/S^2)	0.42	0.36	0.89	0.99	25.65	10.15	-7.14	26.60

Conclusions

- JPL Loads and Dynamic Simulation Team has developed several advanced capabilities for predicting the mobility deploy and touchdown loads and for validating/optimizing the system performance in support of the innovative but challenging MSL skycrane landing system.
  - *High-fidelity ADAMS simulation capability for complicated mechanical and structural systems*
  - *Monte Carlo loads analysis capability by dispersing key input parameters*
  - *Integrated simulation capability of linking the flight GNC software directly to ADAMS closed-loop simulation*
- The integrated ADMAS-GNC simulation of the MSL skycrane touchdown system was validated by the MSL loads reconstruction effort presented herein.

Look forward to next successful mission to Mars!

Thank you