Development of MSL Rover Loads by Integrated ADAMS-GNC Skycrane Simulation

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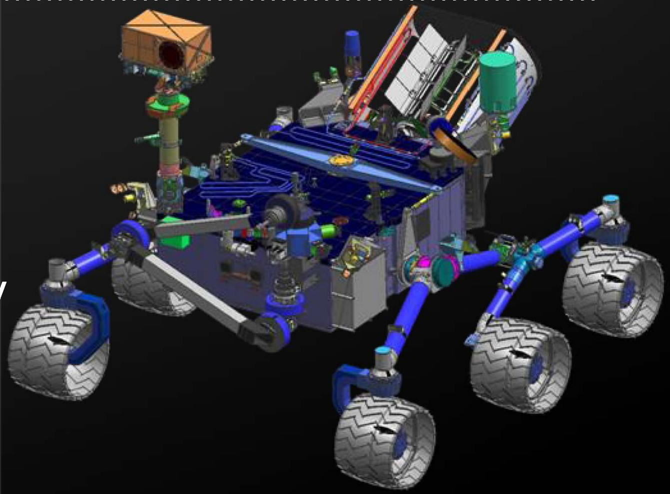
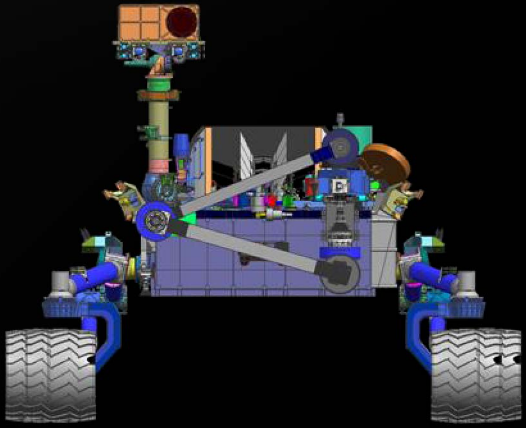
Mars Science Laboratory

- **Mars Science Laboratory (MSL) successfully landed on Aug. 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 (687 days) operational lifetime

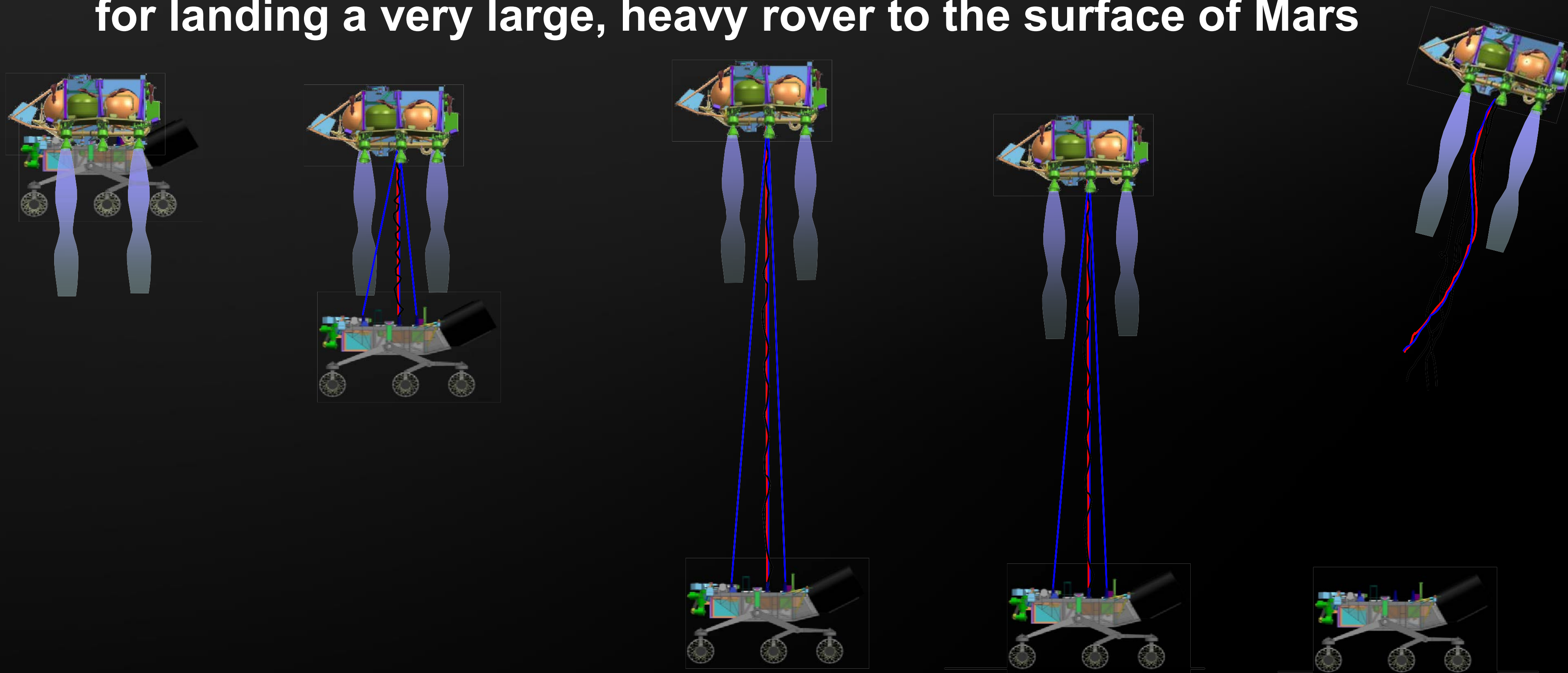




- **Acknowledgement:** Thank the many team members (Tom Rivellini, Steve Sell, Jeff Umland, Chris White, George Antoun, Walter Tsuha, Gurkirpal Singh, Linh Phan, Paul Brugarolas, Alejandro San Martin, etc.) who have supported and contributed to this work.

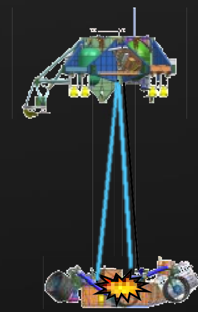
Skycrane Touchdown Maneuver

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



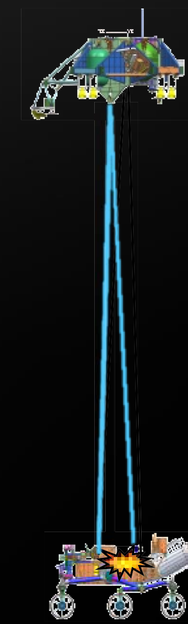
Skycrane Maneuver Timeline

Rover Separation



Mobility Deploy - Rocker Release
Aft: Rover Sep + 0.7 sec
Fwd: Rover Sep + 0.825 sec

Mobility Deploy - Bogie Release
(Rover Sep + 6.0s)



Touchdown/Bridle Cut
(Rover Sep + 9 to 17sec)

ADAMS Simulation of Skycrane Maneuver

- **Objectives**
  - Determine the Rover limit design loads in the mobility elements and joints
  - Determine the Rover limit design loads on the rigid body Rover chassis
- **Loads Analysis Methodology**
  - Develop ADAMS simulations for Rover separation, mobility deploy and touchdown
  - Use ADAMS transient dynamic analysis capability to generate time domain loads
  - Incorporate GNC flight software in ADAMS closed-loop simulations
  - Employ Monte Carlo approach by varying key input parameters
  - Apply a Model Uncertainty Factor (MUF) of 1.2

ADAMS Simulation of Skycrane Maneuver (cont.)

- **Intensive effort to develop an ADAMS simulation with GNC flight software for the skycrane touchdown maneuver till fly-away**
  - 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
- **Run on 8 CPUs of 2 HP workstations with 4 TB institution storage**
  - 17 to 93 minutes per run, average 36 minutes per run

Monte Carlo Loads Analysis Methodology

- **Due to the complex dynamics, Monte Carlo simulation technique employed to take into account the loads uncertainty**
- **500 to 2,000 Monte Carlo runs made to generate Rover mobility deploy and touchdown loads at 99th percentile with a 1.2 MUF**

Absolute min/max Fx at wheel-1 from 2,000 runs

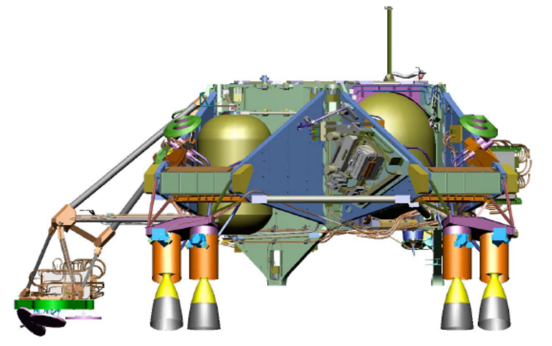
The rest of force/moment components from run ID

Run ID producing absolute max/min Fx at wheel-1

Maximum Run-Consistent Forces and Moments at Wheels with LUF=1.2

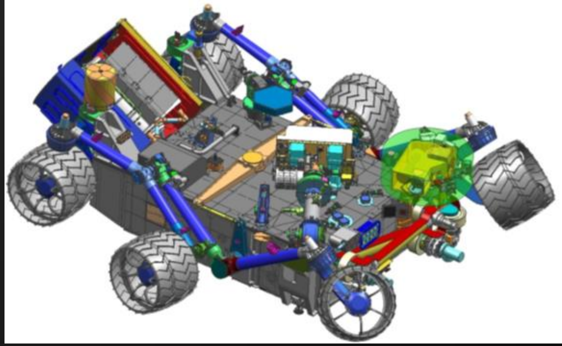
Item	FXa (N)	FYs (N)	FZs (N)	FMs (N)	MXt (N-M)	MYb (N-M)	MZb (N-M)	MMb (N-M)	RUN ID.
W1_FX (N)									
W1_FY (N)									
W1_FZ (N)									
W1_FM (N)									
W1_MX (N-M)									
W1_MY (N-M)									
W1_MZ (N-M)									
W1_MM (N-M)									
W2_FX (N)									
W2_FY (N)									
W2_FZ (N)									
W2_FM (N)									
W2_MX (N-M)	-5.51834E+02	-6.45374E+02	7.19111E+02	7.35529E+02	1.00813E+02	7.50264E+01	5.60698E+01	7.83707E+01	450
W2_MY (N-M)	-3.28861E+02	-7.54991E+02	-6.48367E+02	8.68903E+02	-8.24194E+01	-1.38208E+02	-9.56401E+01	1.48583E+02	446

Descent Stage & GNC Model

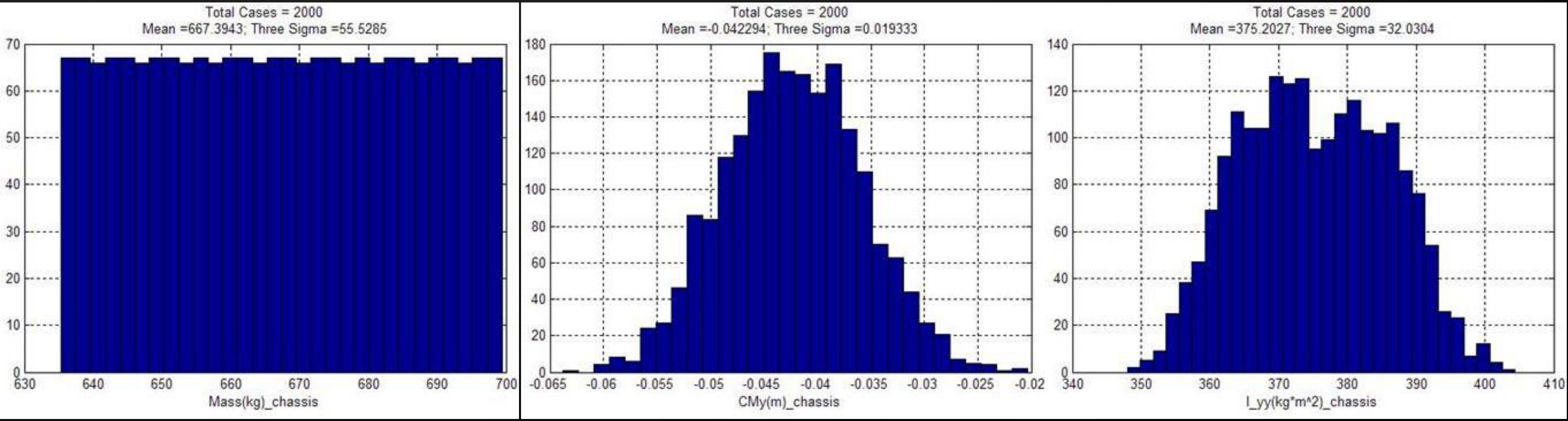


- **Descent Stage**
  - Modeled as rigid body
  - Mass properties dispersed per mass engineer's Monte Carlo analysis
  - MLE forces applied as external 'follower' loads
- **GNC Model**
  - Flight GNC software compiled and linked into ADAMS closed-loop sims
  - MLE thrust dispersed by a uniformly distributed multipliers of [0.95, 1.05]
  - Velocity dispersions done on GNC module side to set touchdown velocity
    - $V_h = 0.00 \pm 0.3$ m/sec (normal distribution)
    - $V_v = 0.75 \pm 0.1$ m/sec (normal distribution)
  - Outputs key time histories and powered descent states to assess GNC touchdown trigger performance

Rover Model



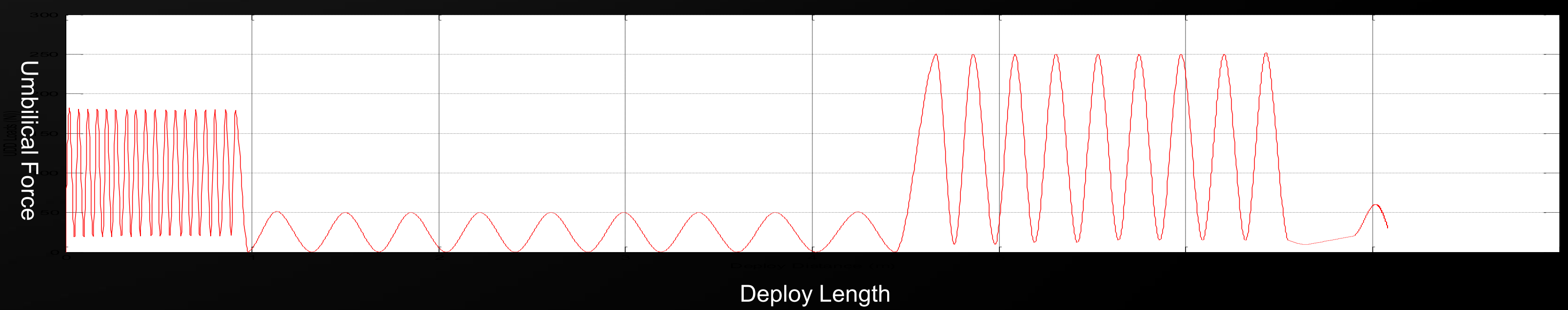
- **Chassis modeled as rigid body**
  - Mass properties dispersed by Monte Carlo analysis



- **Mobility system modeled with flexible beams and hardstops**
  - Joints incorporate nonlinearity due to dead zones and hardstop stiffness
  - Realistic parasolid wheel (tire) model with 6x6 stiffness matrix at hub

Bridle Umbilical Device (BUD) Model

- **Bridles modeled as tension only elements whose length varies per solution of BUD state equations**
  - Stiffness per bridle → Uniformly dispersed by a factor of [0.45, 1.92]
  - Damping per bridle = 100 N/(m/sec), needed by numerical solution
  - BUD brake coefficient → Uniformly dispersed
  - Uniform slack of all three bridles: [0.02, 0.04]m, uniform dispersion
  - Differential slack of each bridle: [-0.02, 0.02]m, uniform dispersion
- **Umbilical force modeled by a bounding "sawtooth" test data**

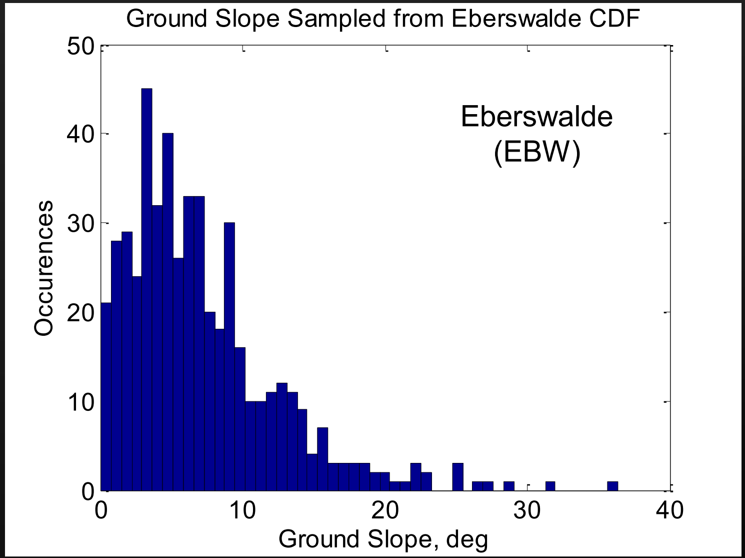


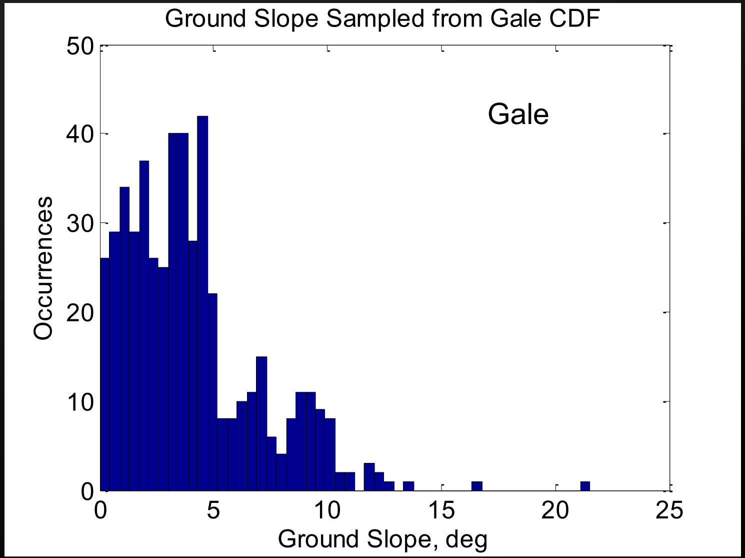
Dispersions of Mobility Deploy Parameters

- **Uniform dispersions of stiffness, damping, friction/drag parameters**
  - Bogie pivot: spring stiffness, Coulomb friction, viscous damping
  - Rocker deploy pivot: Coulomb friction, viscous damping
  - Center differential pivot: spring stiffness, Coulomb friction
  - Main differential pivot: Coulomb friction
- **Mobility deployments captured, using dispersed release times**
  - Nominal aft rocker arm release: Rover sep + T1 sec
  - Nominal fwd rocker arm release: Aft rocker arm release + T2 sec
  - Nominal bogie arm release: Rover Sep + T3 sec
  - Nominal mobility deploy times (T1, T2, T3) dispersed by pyro firing delays
    - Simultaneous release timings uniformly dispersed by (-0,+5) msec
    - Release timing of 0.125 msec apart dispersed uniformly by (-5,+5) msec

Dispersions of Slope and Rock

- **Terrain slope dispersed based on two candidate landing sites**

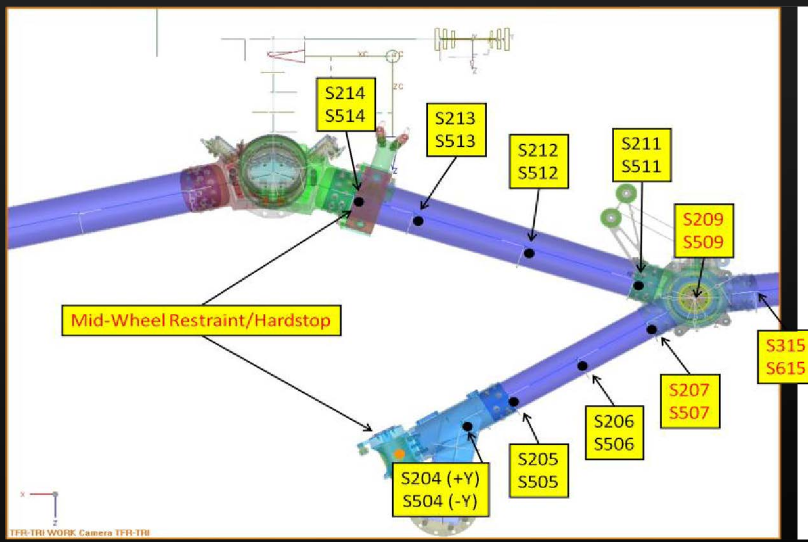


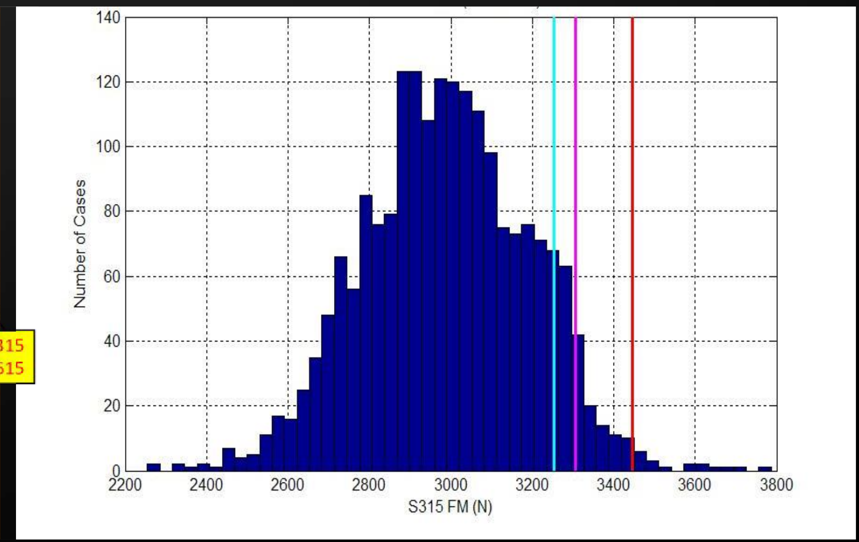


- **Rock field also dispersed based on two candidate landing sites**
  - 20mx20m random rock field with a bounding rock population of 20%
  - Hemisphere rocks of discrete sizes, e.g. 30cm, 40cm, or 55cm radius

Representative Results – Mobility Deploy Loads

- Based on 99th percentile mobility deploy loads with a MUF of 1.2, small/negative margins were observed initially at critical locations

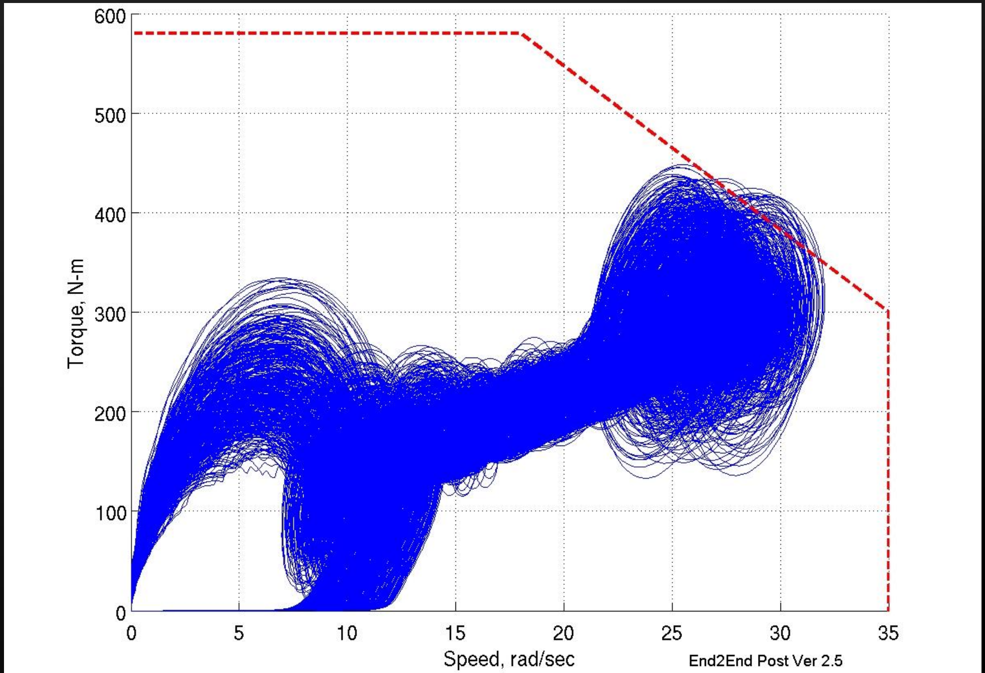




- Based on many Monte Carlo studies (with vs. without soft deploy, new vs. old MD timing, etc.), it was shown that the MD loads problem could be resolved by new MD timing without soft deploy

Representative Results – BUD Loads

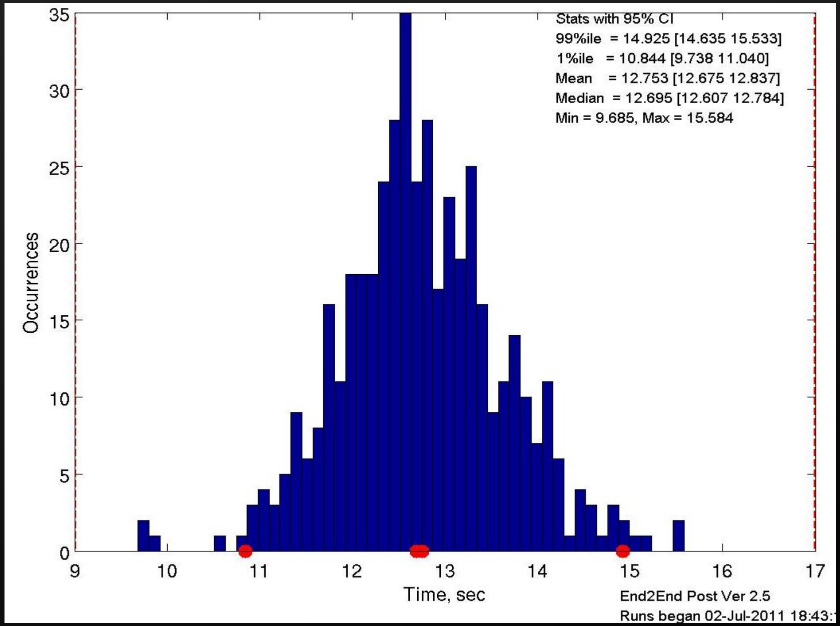
- **Descent brake torque vs. angular velocity with a MUF of 1.0 from a typical set of 500 Monte Carlo runs with new MD timing**

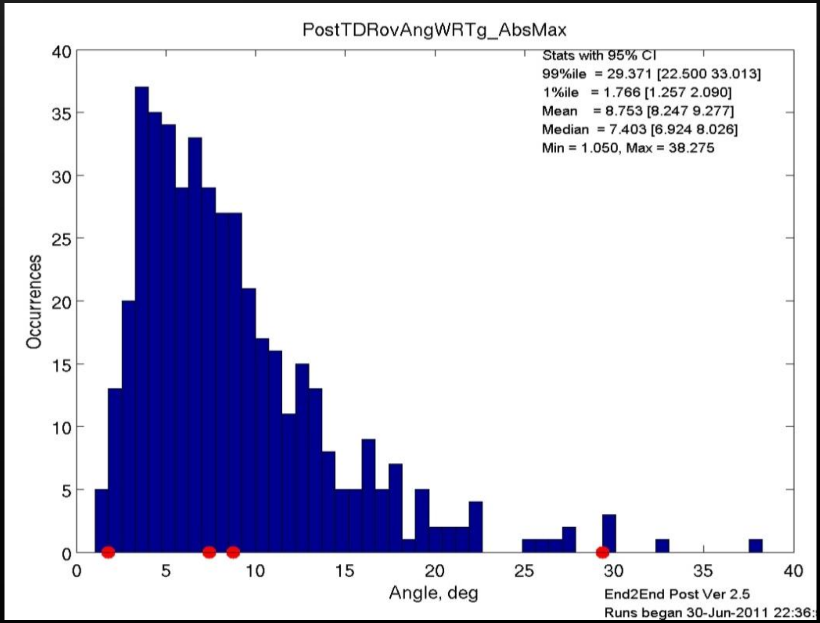


- **Descent brake loads with new MD timing slightly outside capability envelop (red dashed line)**

Representative Results – TD Time & Stability

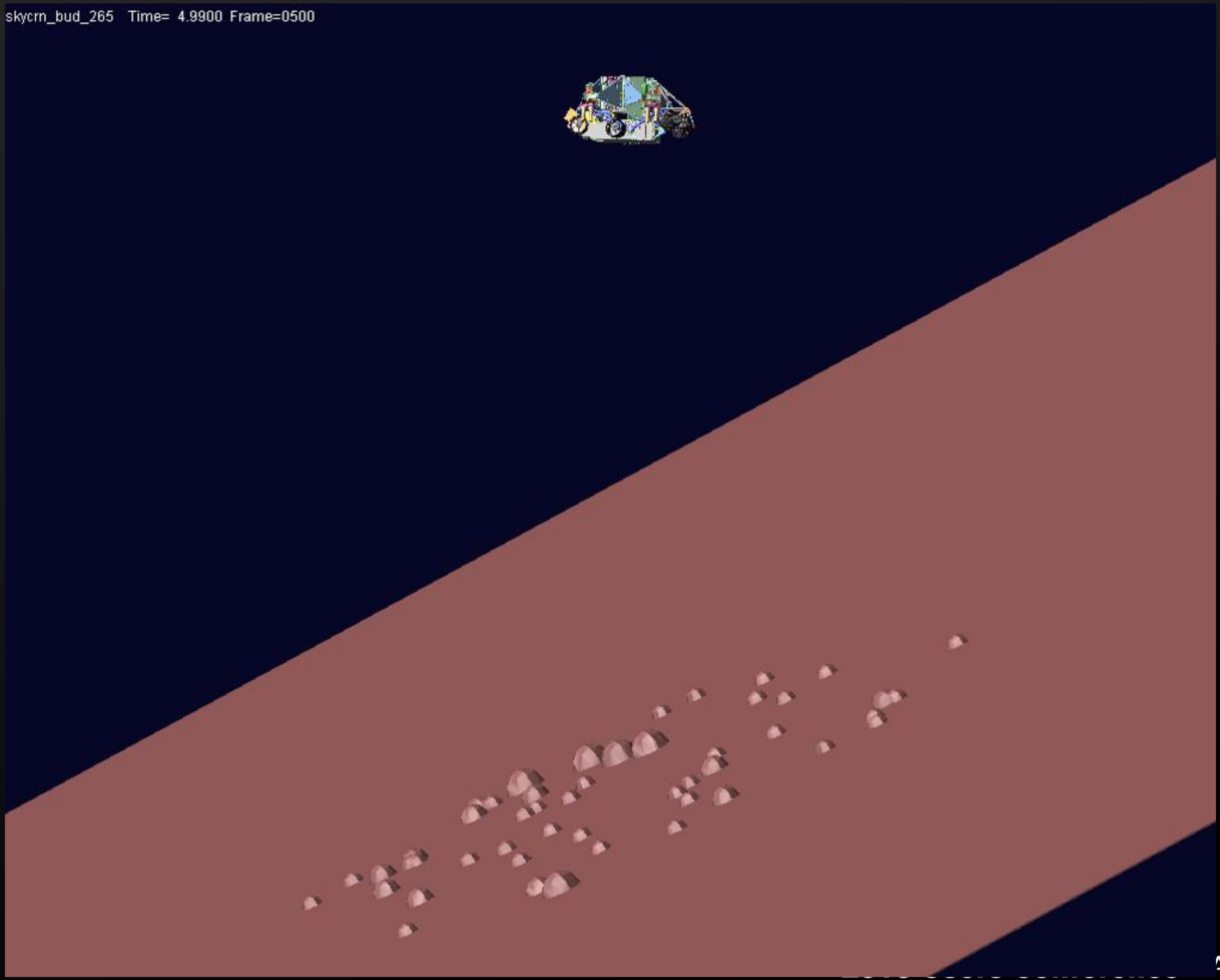
- [1%, 99%] 1st contact time = [11, 15] sec, which is within the design touchdown window of [9, 17] sec after Rover separation





- 99% Rover top deck angle = 29 deg → Touchdown stability OK

Representative Results – Skycrane Animation



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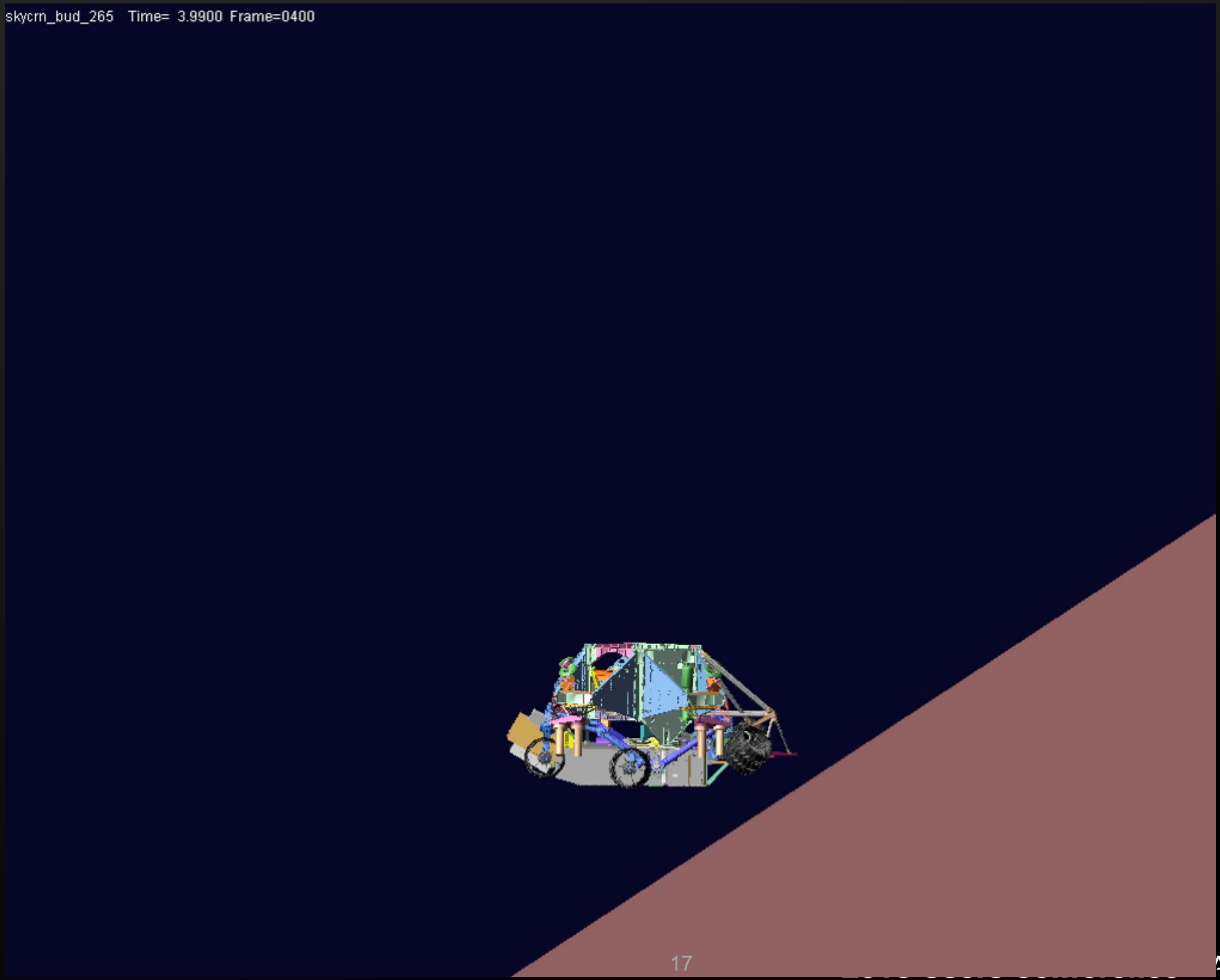
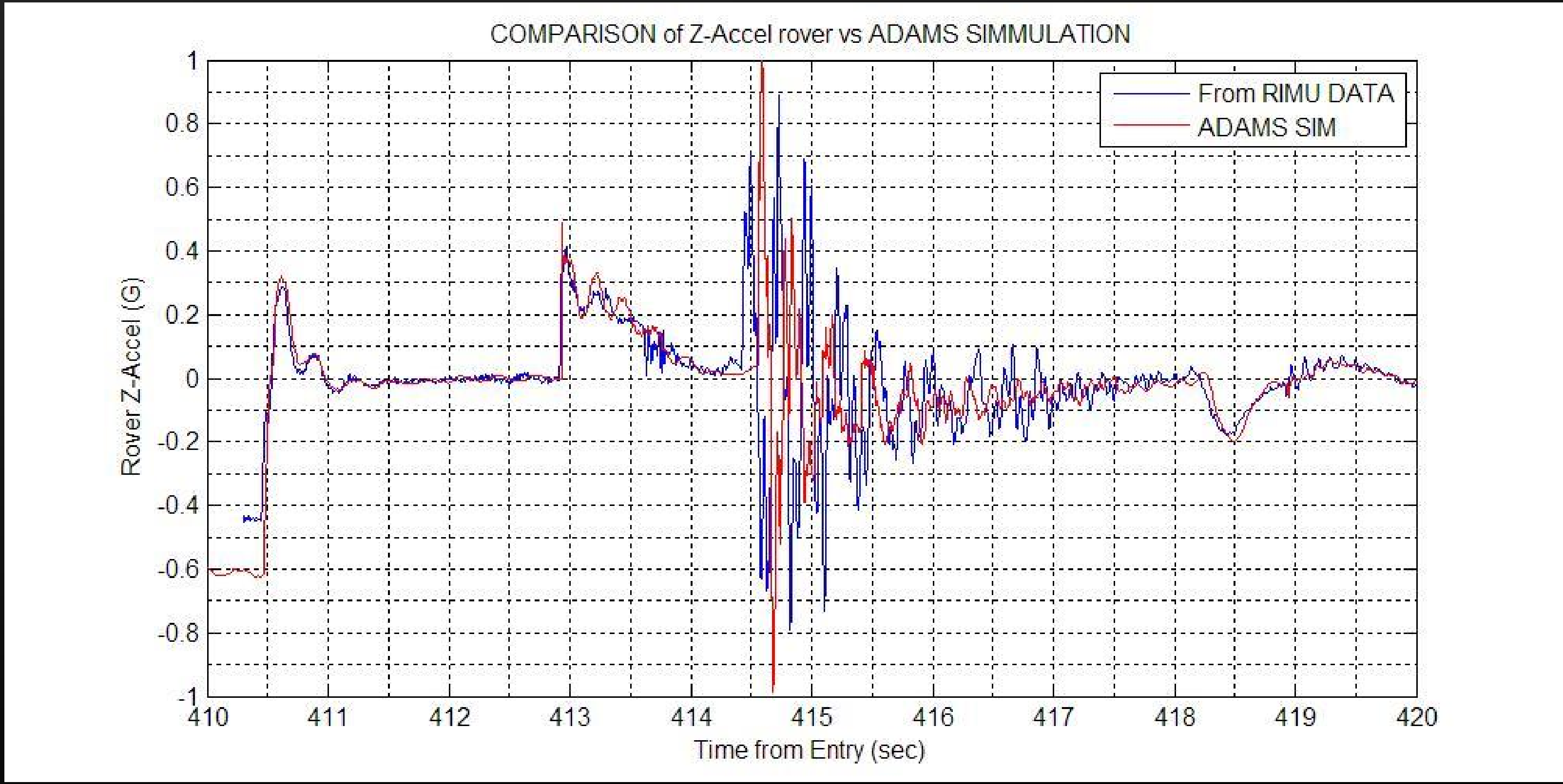


Comparison of Simulation vs. Flight Data

- **Rover z-acceleration time history during mobility deploy phase**



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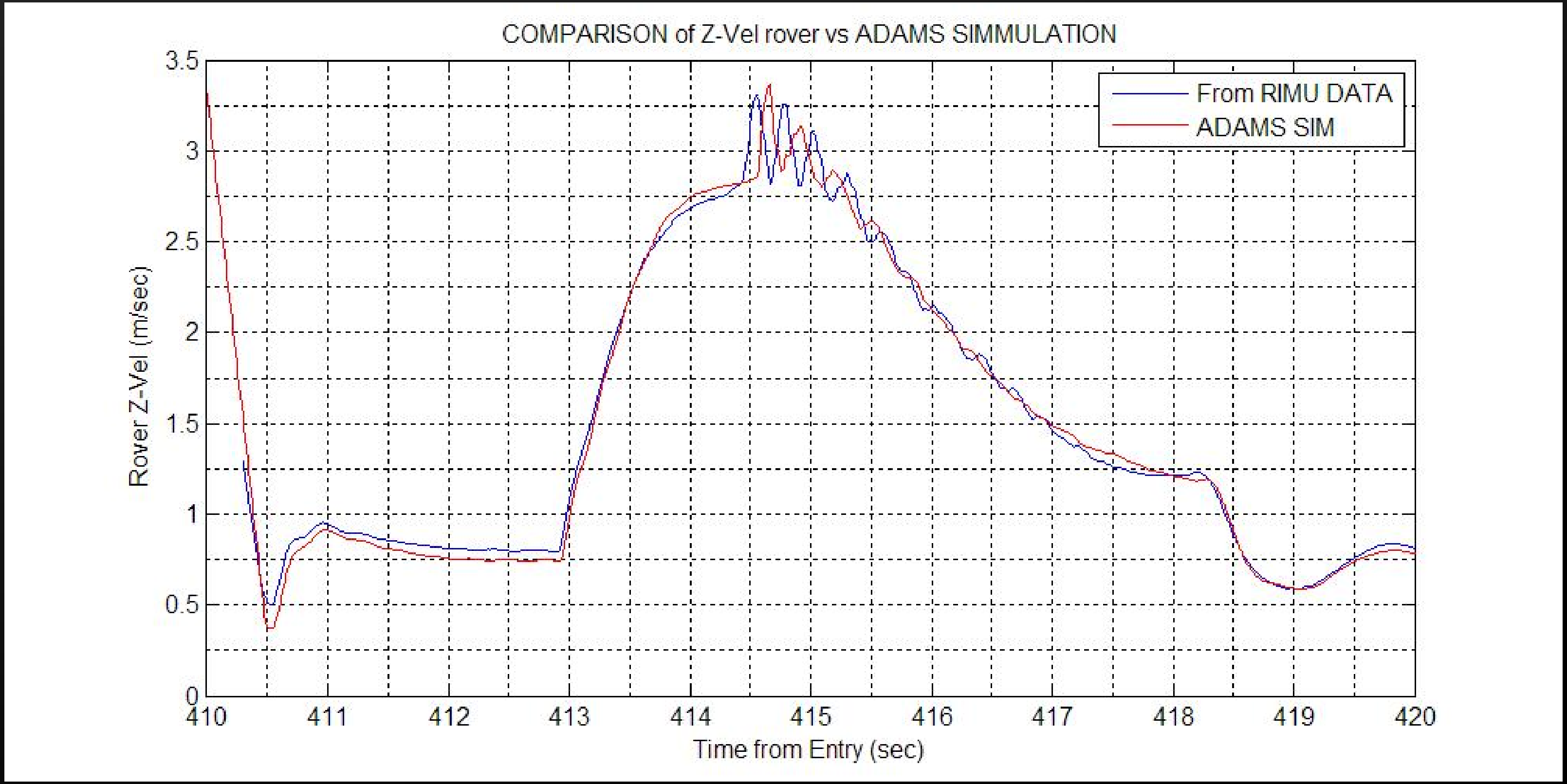
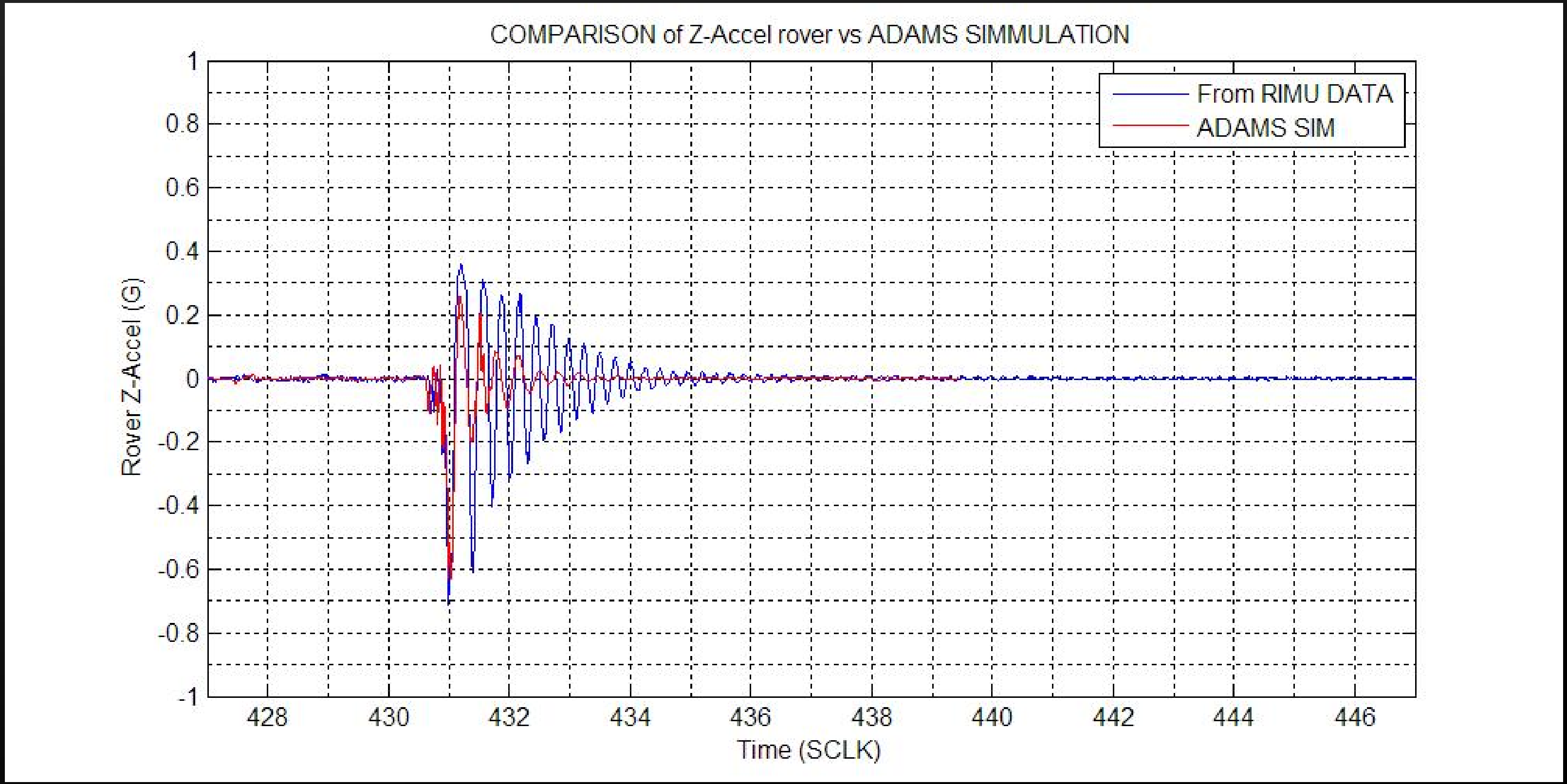


Comparison of Simulation vs. Flight Data

- **Rover z-acceleration time history during touchdown phase**



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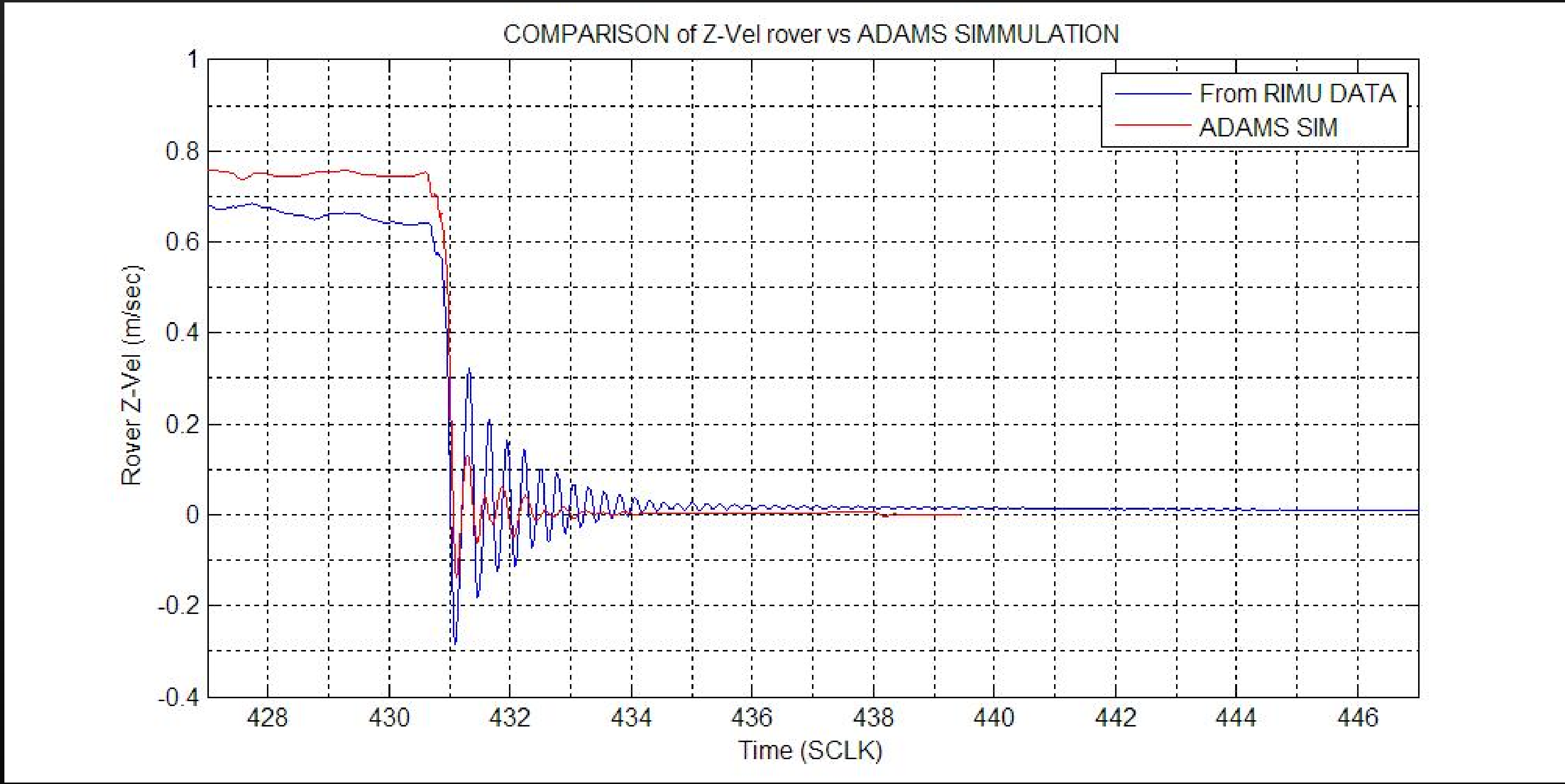

Conclusions

- **JPL Loads and Dynamics Team has developed several advanced capabilities for predicting the mobility deploy & touchdown loads and validating/tuning 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
- **Look forward to next successful mission to Mars!**

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YEARS
OF INNOVATION

A NEW ERA **BEGINS.**