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AEROSPACE
Assuring Space Mission Success

End to End Simulation of the Mars 2020 Rover Mobility Deployment and Touchdown

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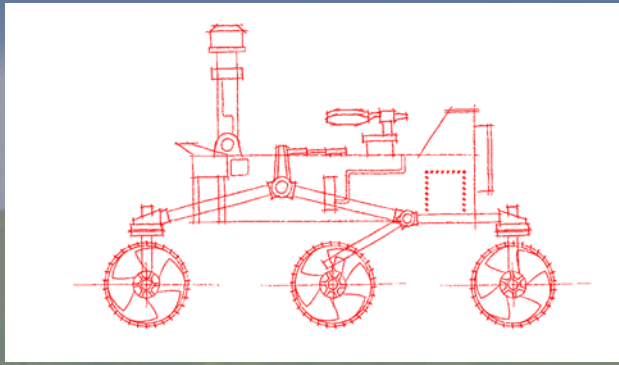

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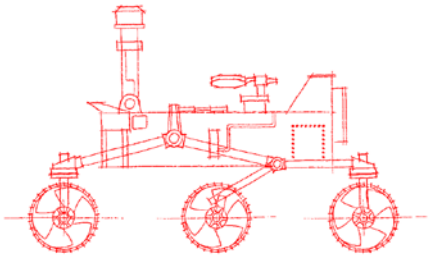
Introduction

NASA/JPL Mars 2020 (M2020) mission will employ the same “skycrane” landing technology as the Mars Science Laboratory (MSL) to land a new and heavier rover to the surface of Mars.

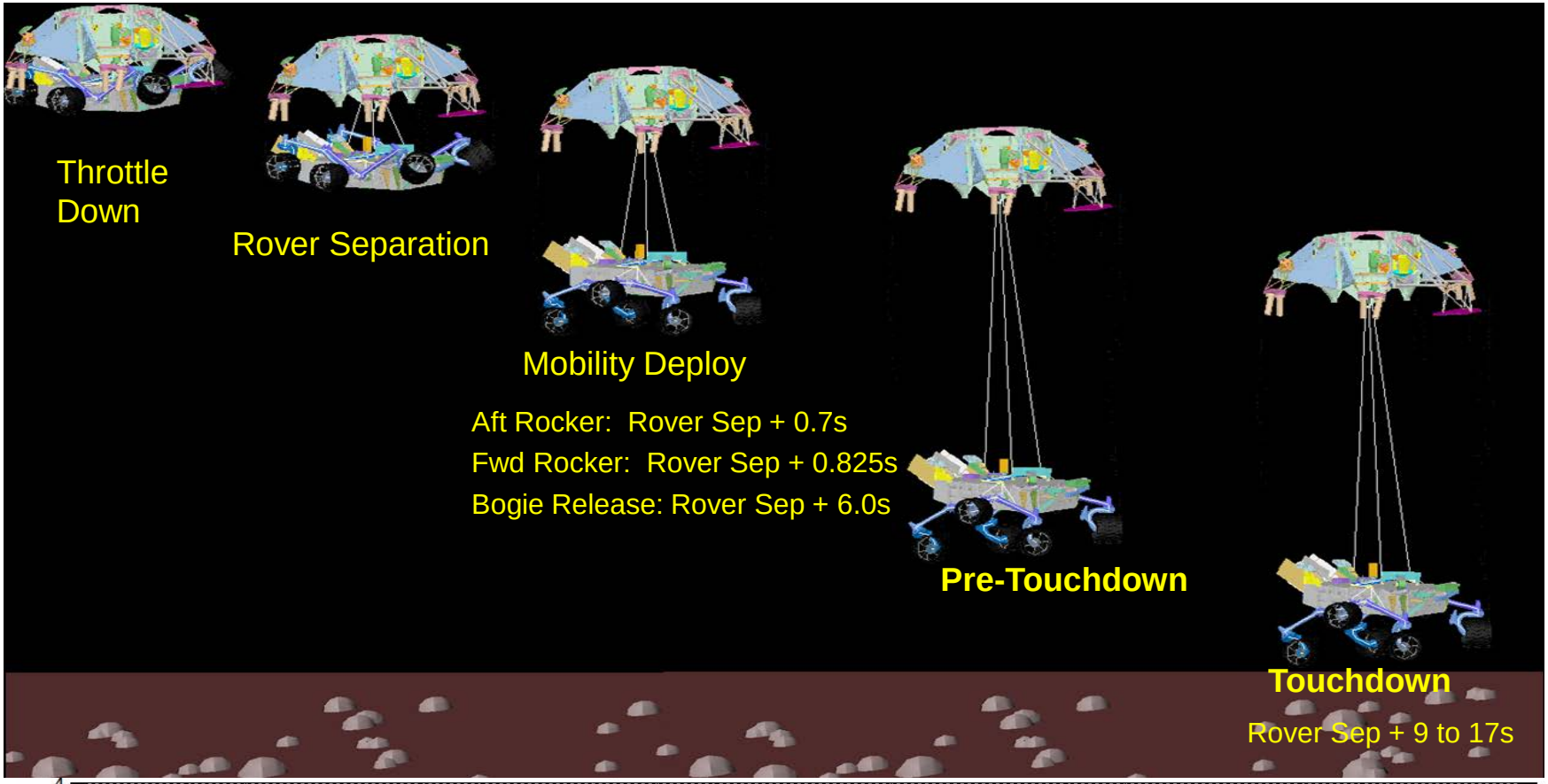
The M2020 rover is being designed to fulfill the next generation scientific exploration of Mars with the new features includes but not limited to:

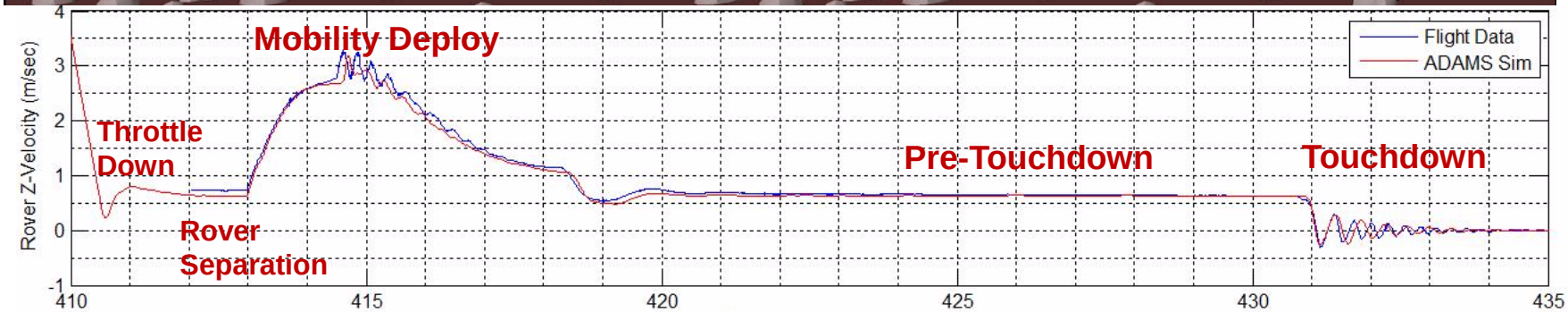
- *Scout helicopter*
- *Enhanced arm*
- *Durable wheels*

This presentation will describe the end to end dynamic simulation of the M2020 Rover Mobility Deployment (MD) and Touchdown (TD) with the integrated flight GNC closed loop control algorithm to predict the MD/TD loads and other critical system performance measures.



Rover Separation, Mobility Deployment and Touchdown





End-to-End Simulation

- An intensive effort has been made to develop an end-to-end multibody dynamic simulation integrated with the GNC flight codes for the entire skycrane-touchdown phase.

  - Multibody Dynamic Model
  - Mobility Deploy Algorithm
  - Bridle Modeling (Nonlinear Elasticity)
  - Bridle Umbilical Device (BUD) Modeling (Differential Equations)
  - Closed-Loop Control
  - Interface Codes to GNC
  - Rock field Parasolid Generation

M2020/MSL Skycrane-Touchdown Simulation

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 → Mobility Deploy Loads**
  - **Ready for Touchdown → Ready-for-Touchdown States**
  - **Touchdown → Touchdown Loads**
  - **Bridle Cut → Touchdown Trigger Performance**
  - **Fly-away**
- Employed Monte Carlo approach by varying key input parameters.
- Run on multiple CPUs of workstations and perform post-processing for each load cycle.

BUD Modeling Integrated into ADAMS Simulation

- Nonlinear Equation of Motion was implemented in ADAMS.

$$[M]\begin{Bmatrix}\ddot{X}\\ \ddot{\theta}\end{Bmatrix}+[C]\begin{Bmatrix}\dot{X}\\ \dot{\theta}\end{Bmatrix}+[K]\begin{Bmatrix}X\\ \theta\end{Bmatrix}=\{F\}$$

$\begin{Bmatrix}X\\ \theta\end{Bmatrix}$: Translations and rotational degrees of freedom

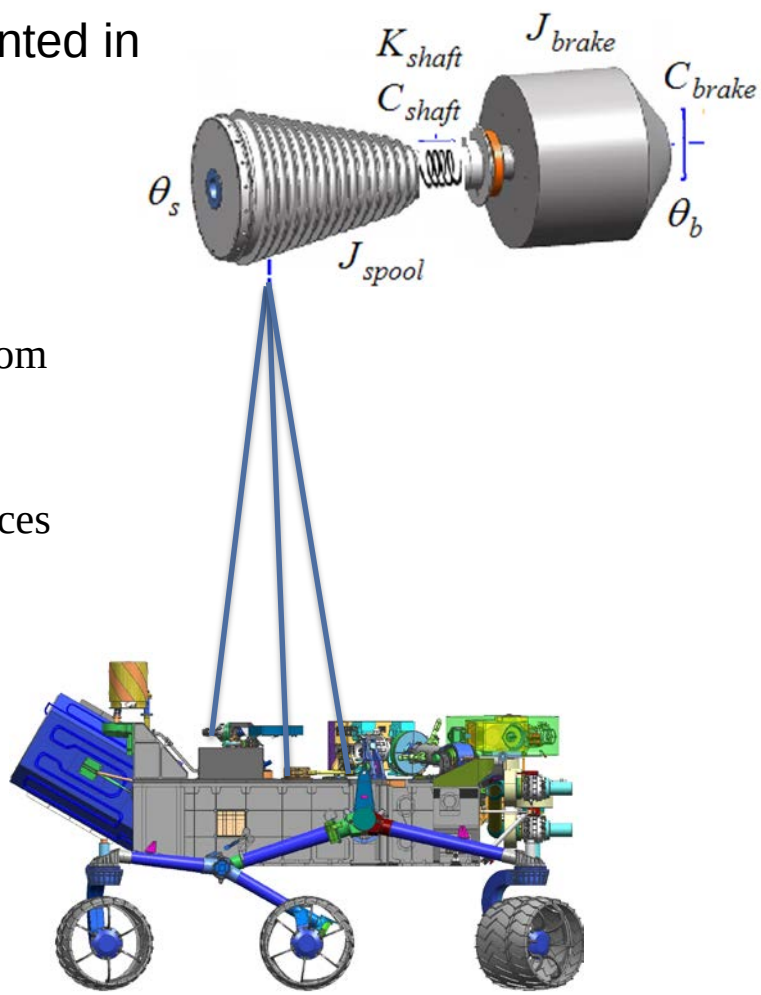
$[M]$: Genralized lumped mass matrix

$[K], [C]$: Gerealized stiffness and damping matrices

$\{F\}$: Load vector

- Each bridle is idealized as a tension-only string with uniform and differential slacks and the stiffness is a function of payout length.

- Bridle damping is applied in both directions (loading and unloading) but not when the bridle goes slack.



Prediction of BUD Loading

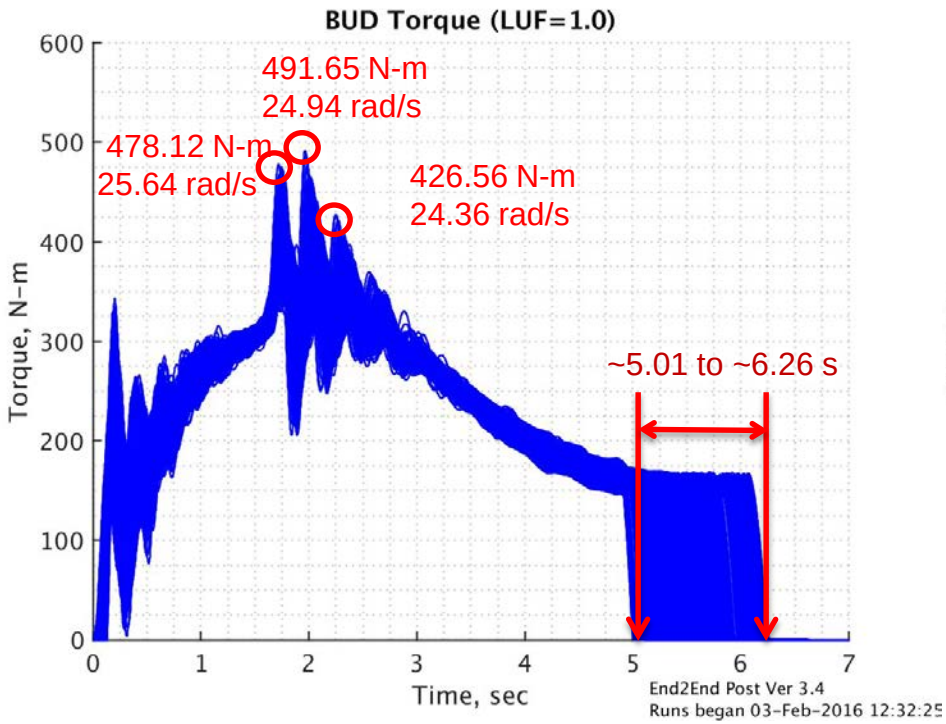
Example of two sets of 500 Monte Carlo runs for M2020 and MSL are compared for the BUD Descent Brake (DB) torque, velocity and acceleration.

- **Mars2020 1,050kg Rover, 1.75x Wheel Mass, Increased DB Drag Coeff.**
  - *Total rover mass is increased to 1,050 kg (M2020).*
  - *Total tire surface mass is increased to 6.09 kg (M2020).*
  - *DB Drag [min, nominal, max] = [11.67 13.17 14.67] Nms/rad*

- **MSL 914kg Rover, 1.0x Wheel Mass, Original MSL DB Drag Coeff.**
  - *Total rover mass is 914 kg.*
  - *Total tire surface mass is 3.48 kg.*
  - *DB Drag [min, nominal, max] = [9.65 11.0 12.35] Nms/rad*

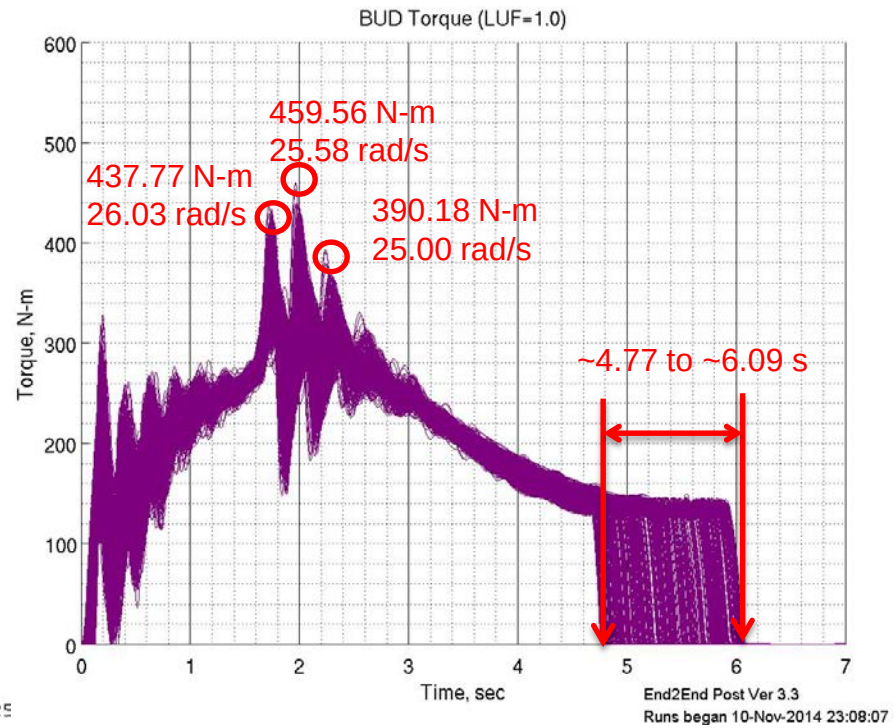
Descent Brake Torque

Mars2020 1050kg Rover, 1.75x Wheel



DB drag coeff. [minimum, nominal, maximum]
= [11.67 13.17 14.67] Nms/rad, uniformly dispersed

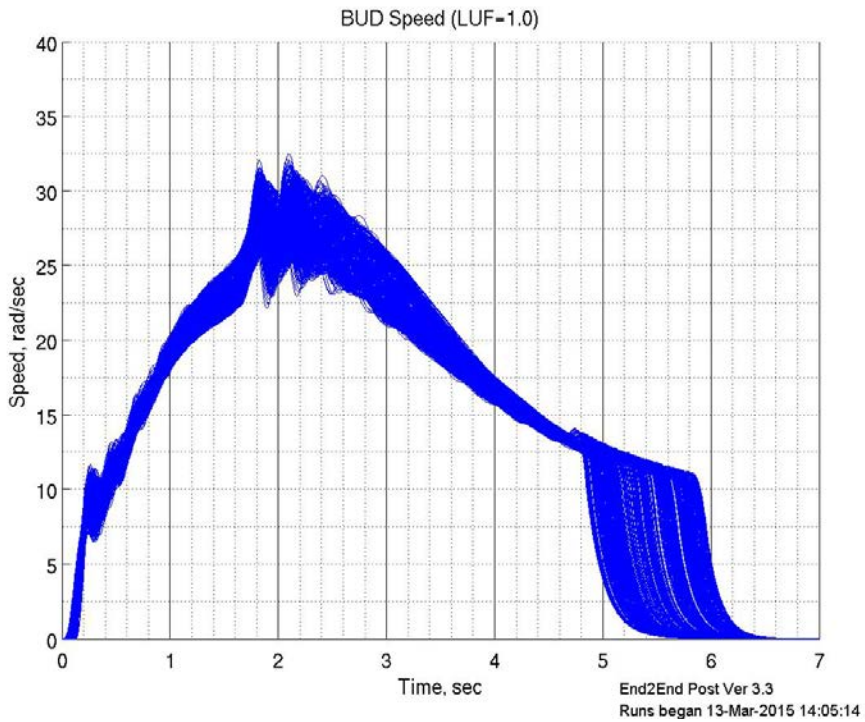
MSL 914kg Rover, 1.0x Wheel



DB drag coeff. [minimum, nominal, maximum]
= [9.65 11.0 12.35] Nms/rad, uniformly dispersed

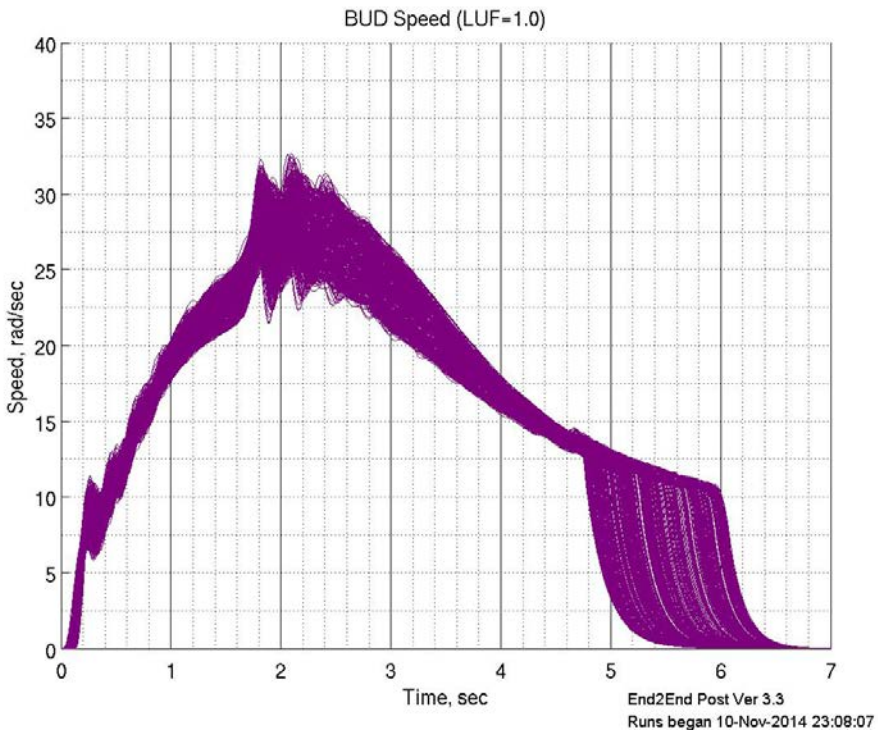
Descent Brake Speed

Mars2020 1050kg Rover, 1.75x Wheel



DB drag coeff. [minimum, nominal, maximum]
= [11.67 13.17 14.67] Nms/rad, uniformly dispersed

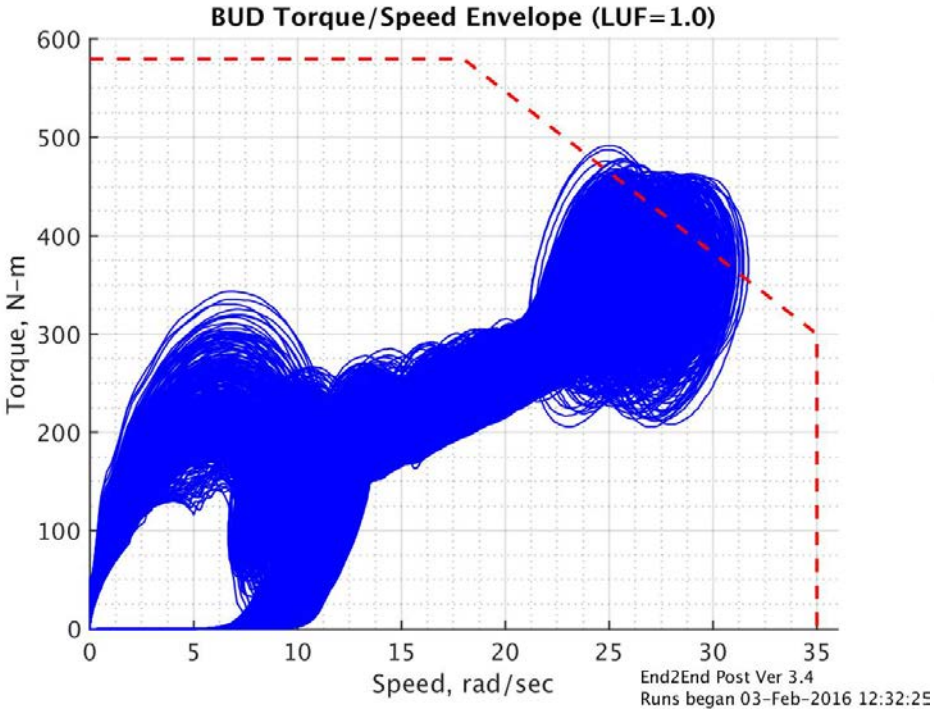
MSL 914kg Rover, 1.0x Wheel



DB drag coeff. [minimum, nominal, maximum]
= [9.65 11.0 12.35] Nms/rad, uniformly dispersed

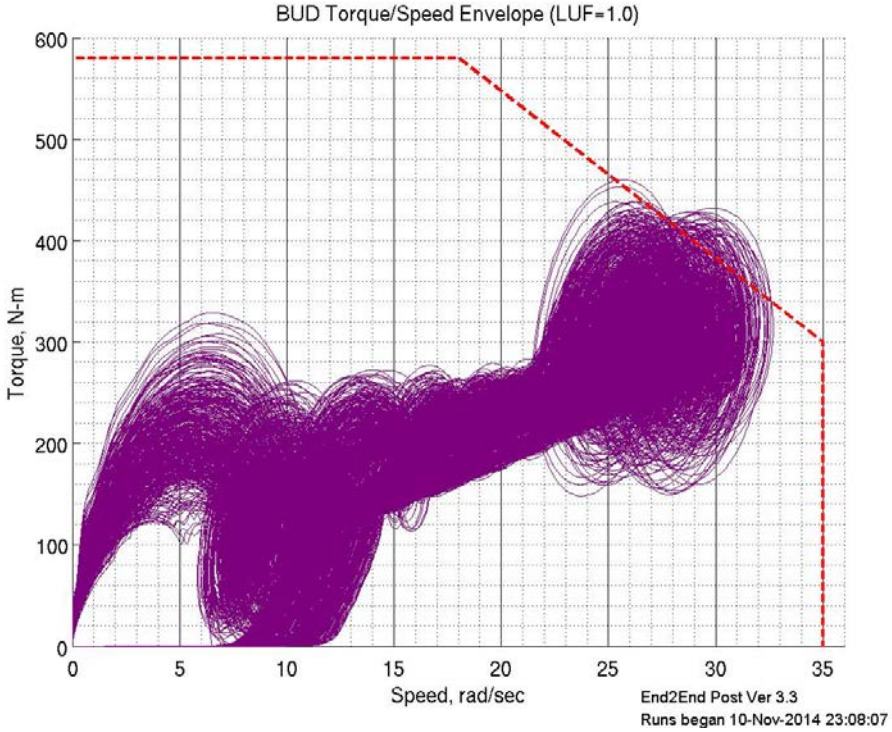
Descent Brake Torque vs. Speed

Mars2020 1050kg Rover, 1.75x Wheel



DB drag coeff. [minimum, nominal, maximum]
= [11.67 13.17 14.67] Nms/rad, uniformly dispersed

MSL 914kg Rover, 1.0x Wheel



DB drag coeff. [minimum, nominal, maximum]
= [9.65 11.0 12.35] Nms/rad, uniformly dispersed

Integration of ADAMS-GNC Simulation

Incorporation of the flight GNC controller in ADAMS enables the highest fidelity simulation of the M2020 Skycrane-TD landing system.

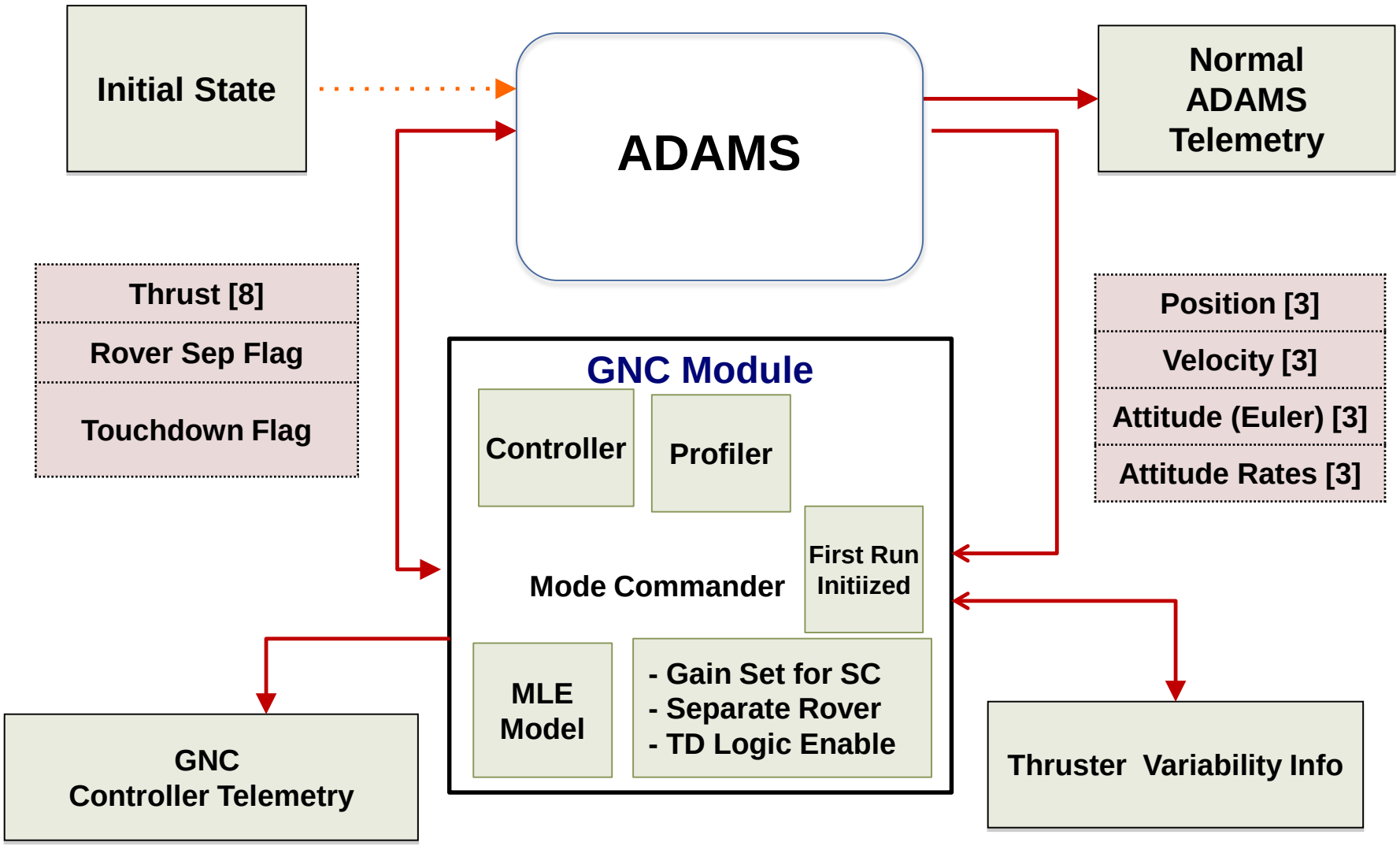
- GNC flight software is linked into ADAMS.
  - High fidelity rover separation dynamics
  - GNC contributions to BUD loads and dynamics for initial catch, mobility deploy and final snatch
  - Flight GNC controller subjected to BUD deploy disturbances
  - Exercise touchdown trigger with terrain interactions
- MLE forces applied as external loads
- Thrust variations implemented on ADAMS model
- Velocity dispersions done on GNC module side to set TD velocity
- Outputs key time histories and powered descent states to assess GNC touchdown trigger performance

How GNC Incorporated into ADAMS

- The GNC module is self contained.
  - Flight GNC Codes
    - Profiler
    - Attitude and Position Controller
    - Touchdown Trigger Logic
  - Internal/Simplified Mode Commander
  - MLE Model
    - First rev. will model each MLE as a “n-RTI” delay
    - Final rev. will include full CAST MLE model

- The output of the GNC function is 8 force values and 2 flags.
  - Forces are applied at 8 MLE locations.
  - Two flags indicate to ADAMS when to separate the rover and when TD has occurred.

GNC / ADAMS Interface Diagram

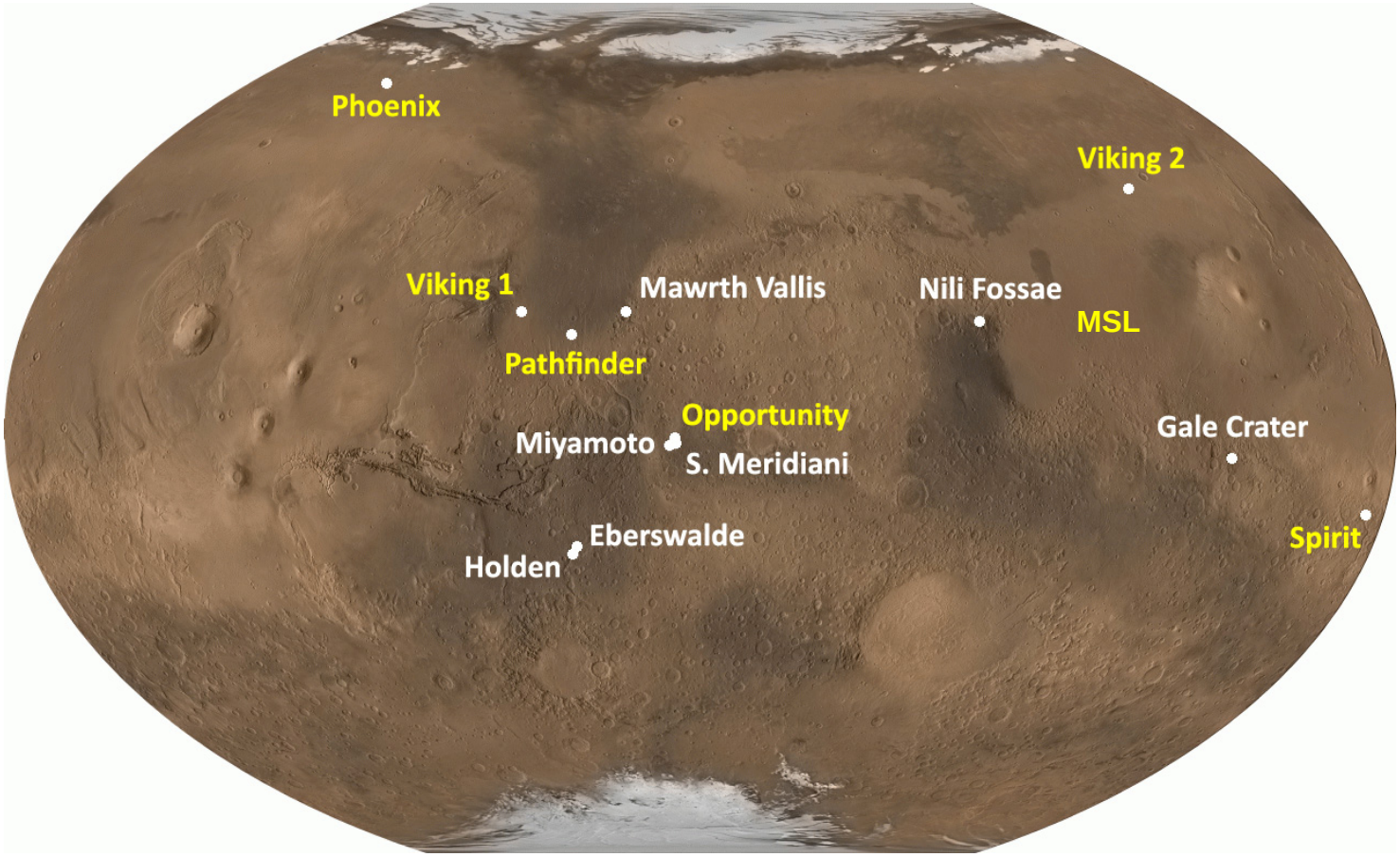


Rock Strike Risk Assessment

To predict the probabilities of a rock contacting to any part (except the wheels) of the M2020 Rover during landing, the following enhancements and updates were made in the ADAMS Skycrane-TD simulation for the Monte Carlo rock strike analysis.

- Mobility components (rocker arm, bogie arm, etc.) that have the potential of rock contact during landing
- Two contact envelope planes of belly pan and RIMFAX antenna
- New M2020 wheels
- Mars helicopter scout NTE and stowed robotic arm NTE
- Dispersing slope angles based on MSL Eberswalde slope CDF (bounding all current M2020 landing sites) plus eliminating all the cases with slope >35°
- Dispersing 20m x 20m rock fields based on bounding CFA = 0.12 with rock diameter = 0.3 – 0.75 m with rock diameter increment = 0.05m

Rock Strike Risk Assessment (cont.)



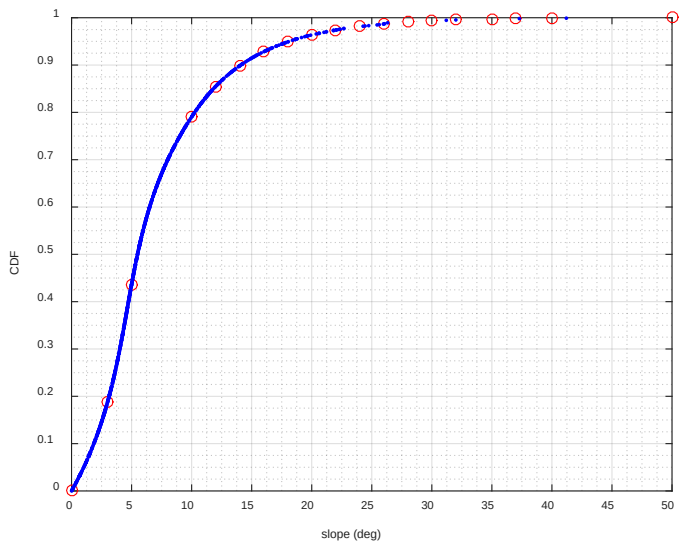
Candidate Landing Site for M2020 – Eberwalde

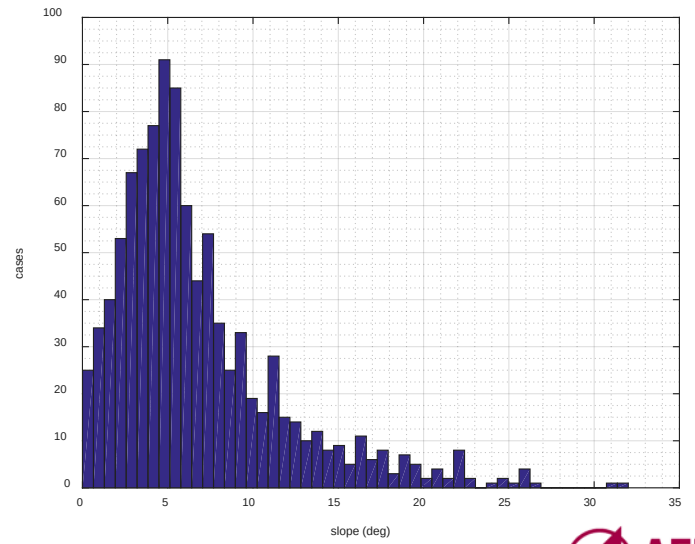
* Picture Credit NASA/JPL

Rock Strike Risk Assessment (cont.)

A total of 1,000 ADAMS Skycrane-TD runs were made in the Monte Carlo rock strike analysis, as described in the following.

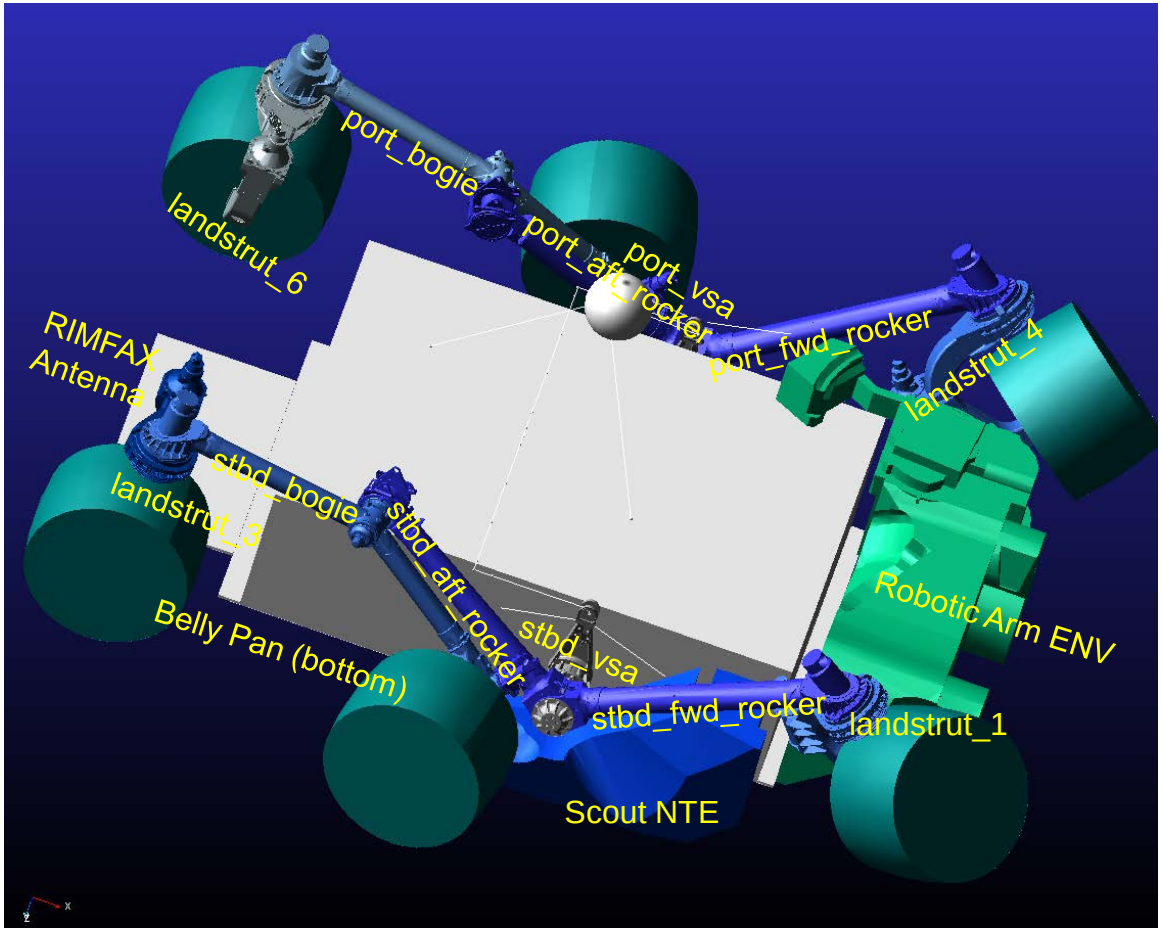
- *Total rover mass = 1,050kg, tire mass = 1.75x MSL tire mass*
- *Total DB Drag [min, max] = [11.67, 14.67] Nms/rad, uniformly dispersed*
- *Flight-correlated surface contact friction parameters*
- *Target touchdown velocity Vv_td = 0.75 m/sec*
- *Rock field CFA = 12% plus rock height dispersion = from 0.3m (no upper limit) with a step size of 0.05m*
- *Slope angle <35°, per MSL EBW CDF that bounds current M2020 landing sites*





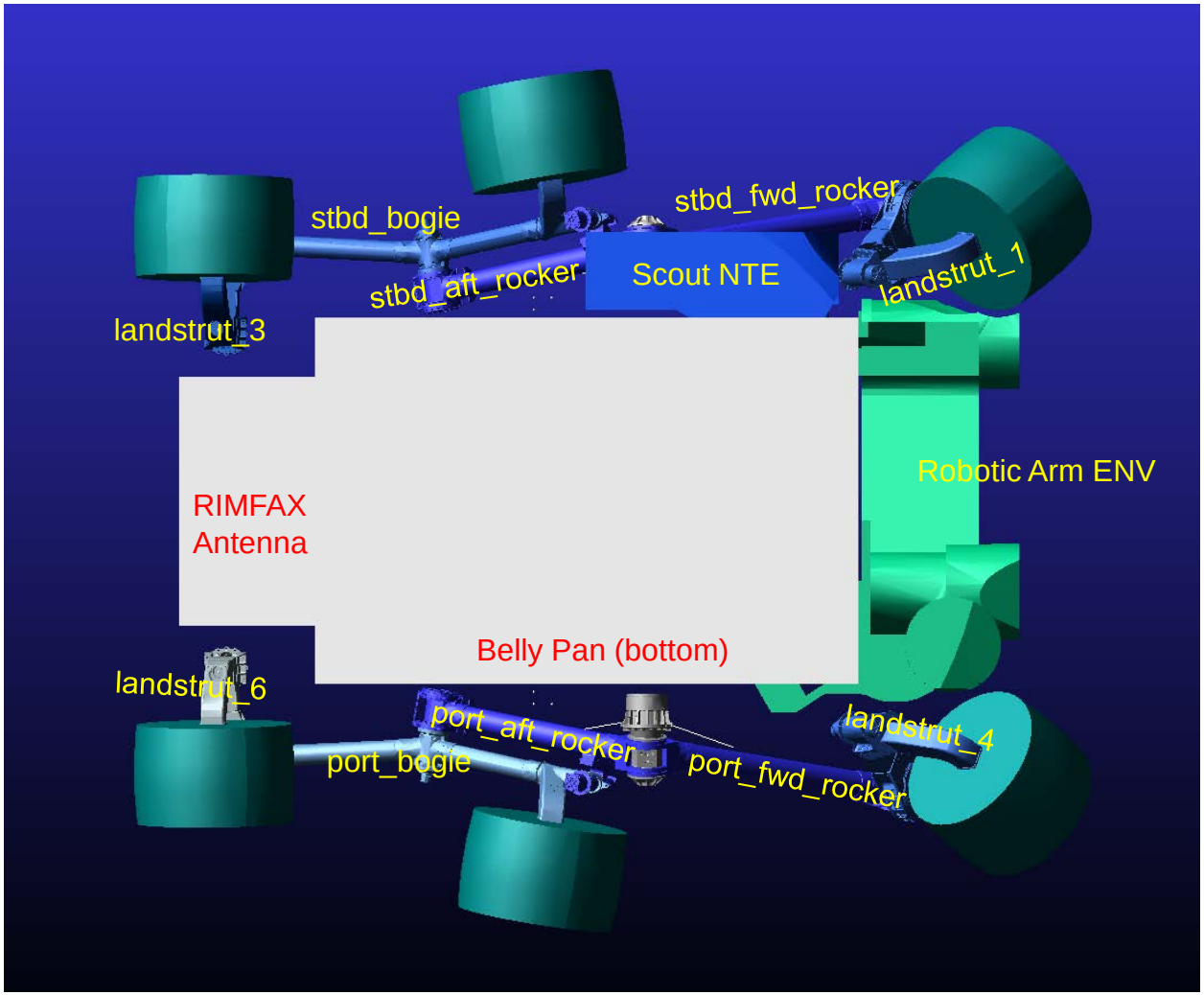
Rock Strike Risk Assessment (cont.)

The following figure illustrates the IDs of the parasolids of belly pan, RIMFAX antenna, Mars helicopter scout NTE, stowed robotic arm NTE, and mobility components that were incorporated in the ADAMS model for the rock strike analysis.



Rock Strike Risk Assessment (cont.)

Parasolid IDs – Overall (Bottom View)



Rock Strike Risk Assessment (cont.)

The following table summarizes the statistics of rock strikes from 1,000 ADAMS skycrane-touchdown Monte Carlo runs.

- For each component, rock strike probability is from 0.0 to 0.6%.
- Including all components, rock strike probability is about 1.2%.

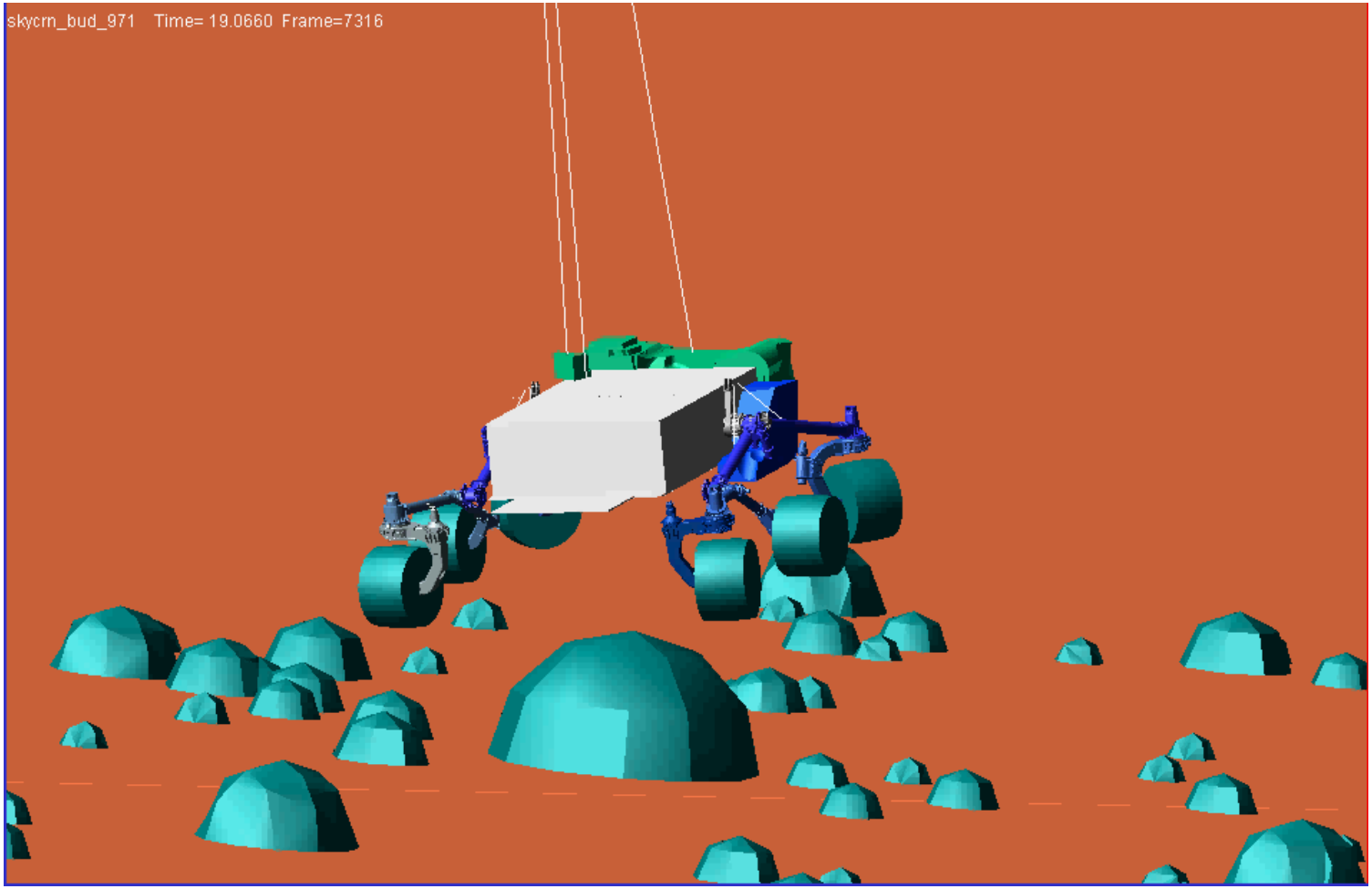
	Contact Run #												Cases	Percentage
Contact Run ID	151	164	196	201	275	344	379	846	921	938	952	971	12	1.2%
Rover Belly Pan	0	0	0	0	0	0	1 (0.6125)	0	0	0	0	1 (0.8375)	2	0.4%
RIMFAX Antenna	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
SCOUT NTE	0	0	0	0	1 (0.7125)	0	0	0	0	0	0	0	1	0.2%
Robotick arm env	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
stbd landstrut_1	0	0	1 (0.4875)	0	0	0	0	0	0	0	0	0	1	0.2%
stbd landstrut_3	1 (0.5125)	0	0	0	0	0	0	0	0	1 (0.3875)	1 (0.3875)	0	3	0.6%
stbd_fwd_rocker	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
stbd_aft_rocker	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
stbd_bogie	0	1 (0.4625)	0	0	0	0	0	0	0	0	0	0	1	0.2%
stbd_vsa	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
port landstrut_4	0	0	0	0	0	0	0	0	1 (0.5875)	0	0	0	1	0.2%
port landstrut_6	0	0	0	1 (0.5625)	0	1 (0.4875)	0	0	0	0	0	0	2	0.4%
port_fwd_rocker	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
port_aft_rocker	0	0	0	0	0	0	1 (0.6125)	0	0	0	0	0	1	0.2%
port_bogie	0	0	0	0	0	0	0	1 (0.5125)	0	0	0	0	1	0.2%
port_vsa	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%
Groud Slope (deg)	6.48	4.53	5.65	3.87	16.61	2.69	1.97	1.58	17.54	4.85	8.81	11.95		

contact= 1 (rock height (m)), 0 = no contact

Rock Strike Risk Assessment (cont.)

Rock strike at belly pan & port aft rocker

Rock Strike Risk Assessment (cont.)



Rock strike at belly pan

Concluding Remarks

- The end to end dynamic simulation of the M2020 rover mobility deployment and touchdown integrated with the GNC closed loop control algorithm has been developed for the M2020 mission.
- The critical parameters based on the MSL flight data, the M2020 scout helicopter, enhanced M2020 robotic arm, and the increased M2020 Rover mass were incorporated into the simulation model.
- The end to end M2020 skycrane-touchdown simulation has been used to predict the BUD loads, MD and TD loads, and other system performance measures.
- The risk of any rover mobility part hit by a rock during landing has been assessed.
- The simulation presented herein has been extensively used as an effective and efficient tool in support of the M2020 mission.

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