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Mars Science Laboratory (MSL) Rover Centrifuge Test

Long Y Chen

Jet Propulsion Laboratory
June 7–9, 2011

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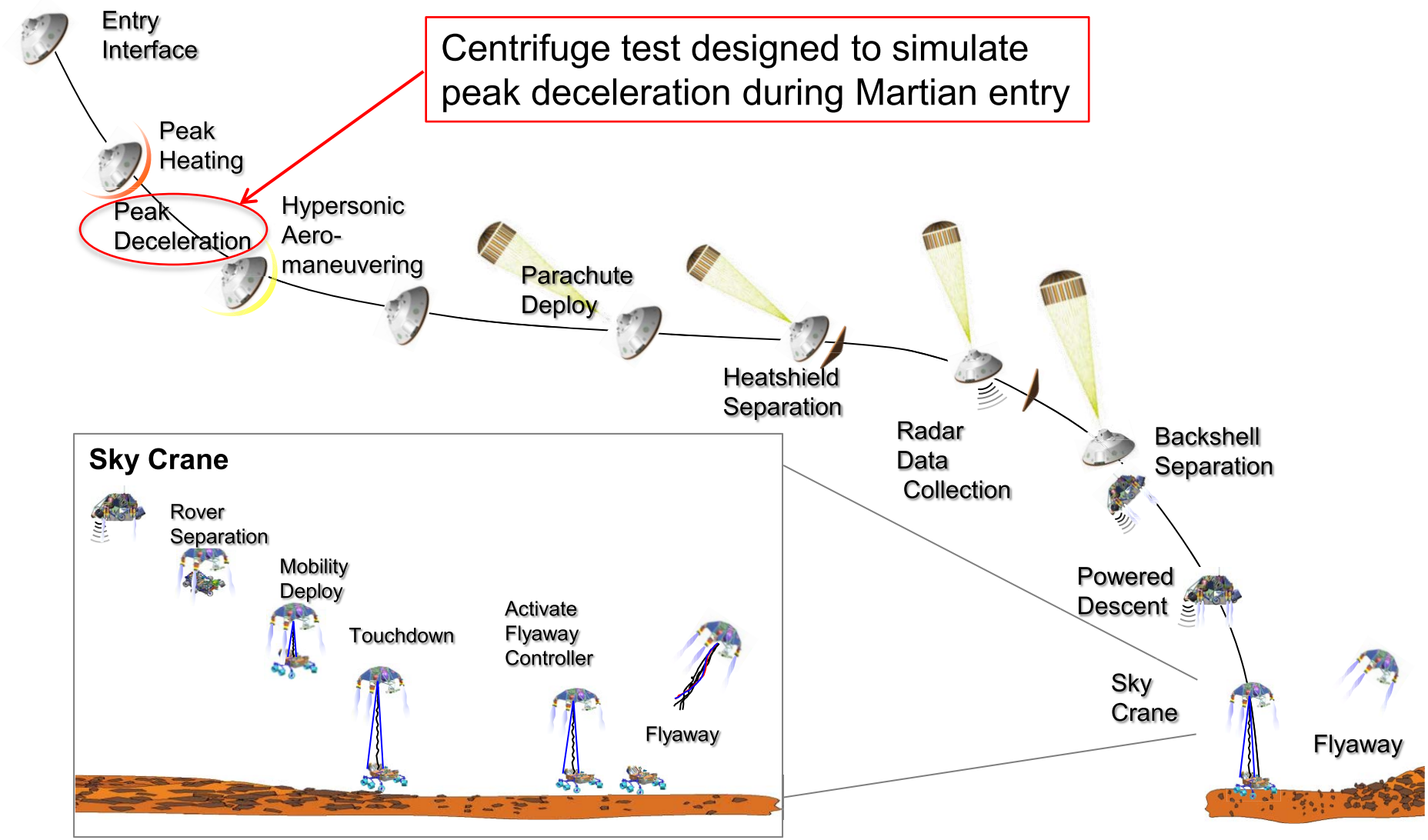
MSL Entry Descent and Landing Events



Centrifuge test designed to simulate peak deceleration during Martian entry

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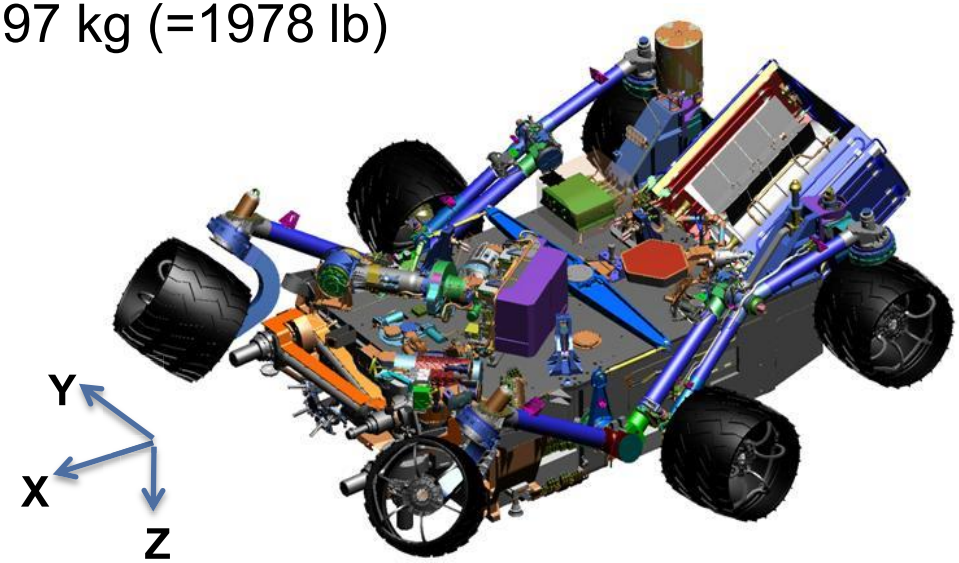
Centrifuge Test Objective and Rationale

- To demonstrate the structural integrity of MSL rover chassis and mobility structure for the loading environment produced during entry into the Martian atmosphere
  - *Aero brake generates 15 g's deceleration in rover z direction*
  - *Angle of entry vehicle produces additional 0.65 g in rover x direction*
  - *Test factor = 1.2 over peak limit load (within -10/+0 % tolerance)*
- Due to the complexity of rover configuration, it is difficult and not practical to conduct load test on all major components and interfaces
- DTM rover mass: 897 kg (=1978 lb)



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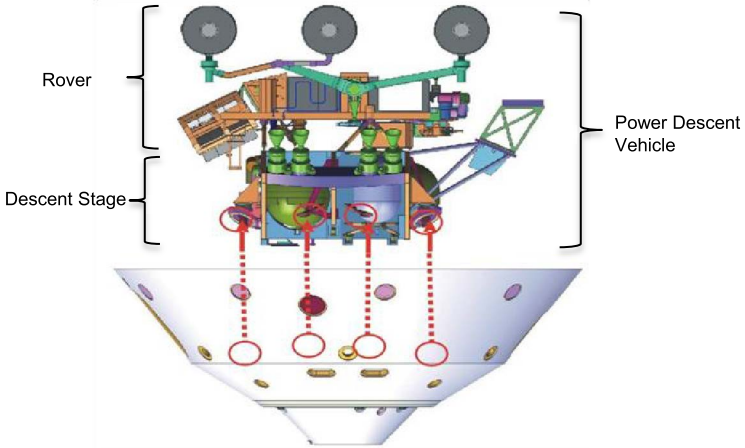
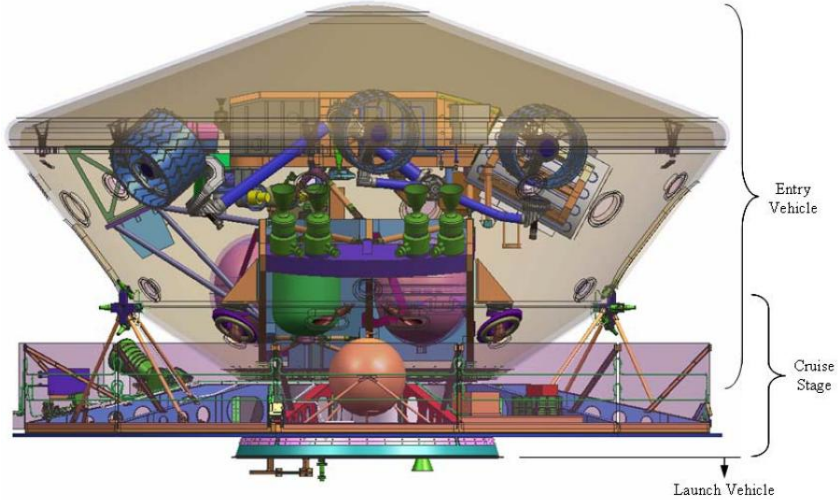
MSL Spacecraft Flight System Assembly

- MSL spacecraft flight system Assemblies
  - *Cruise Stage*
  - *Entry Vehicle*
    - Aeroshell
    - Powered Descent Vehicle
      - *Descent Stage*
      - *Rover*





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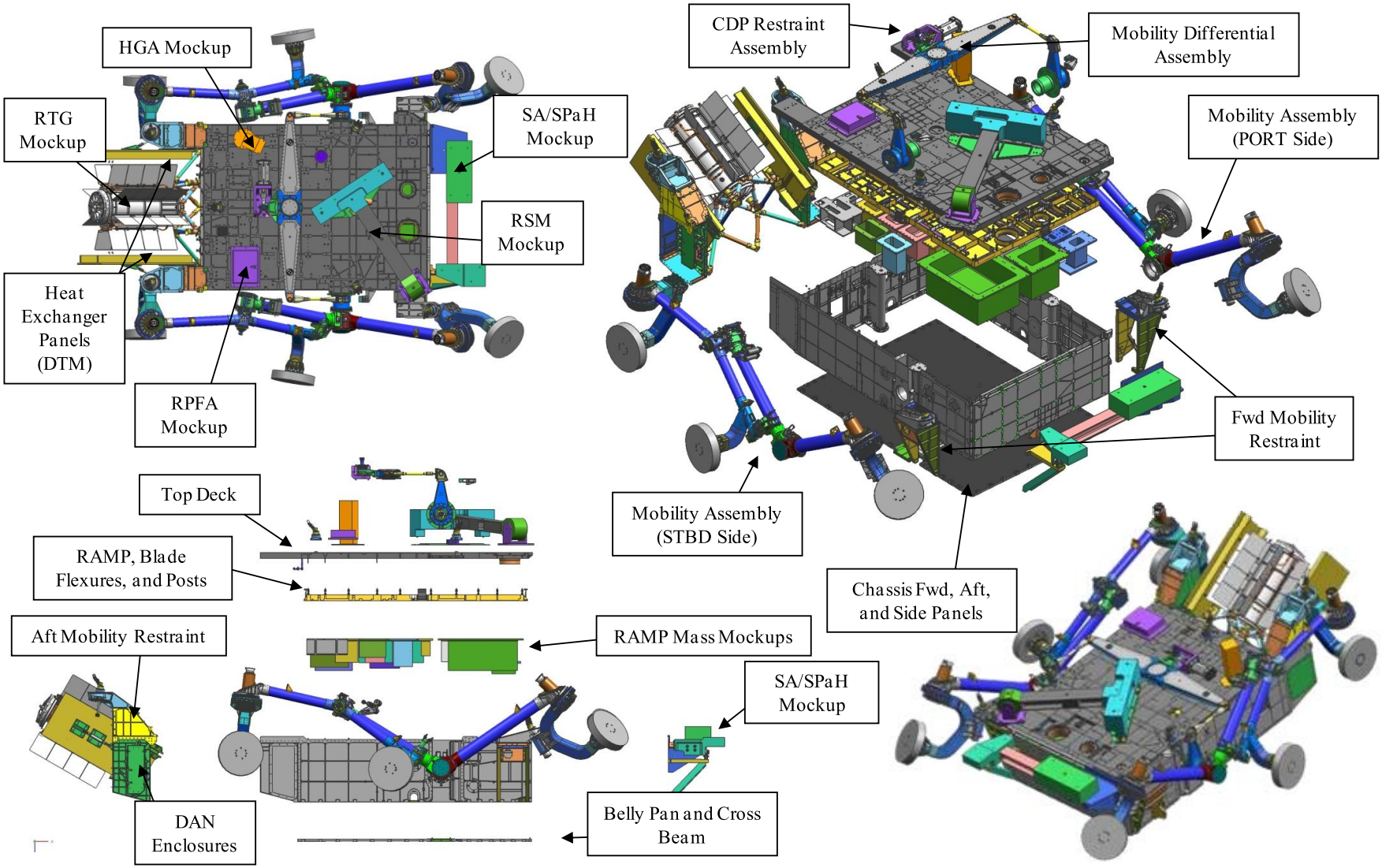
DTM Rover Structural Configuration



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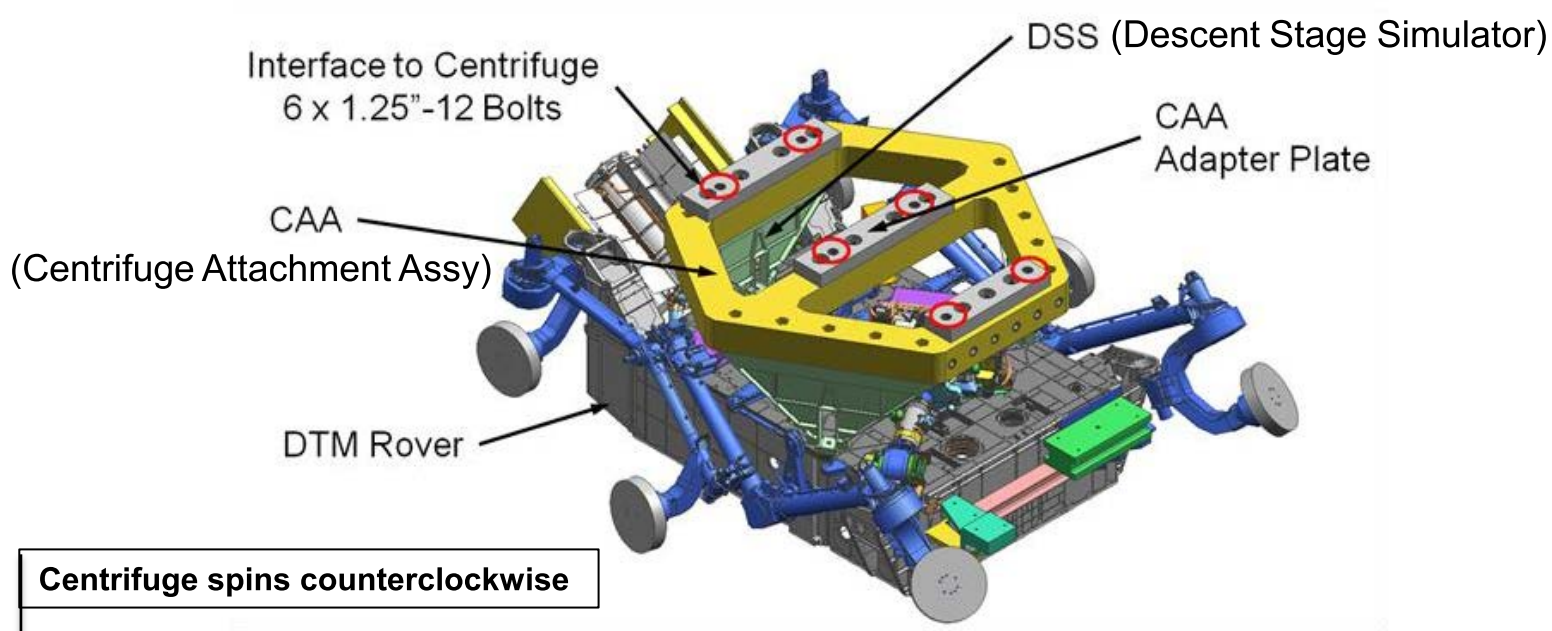
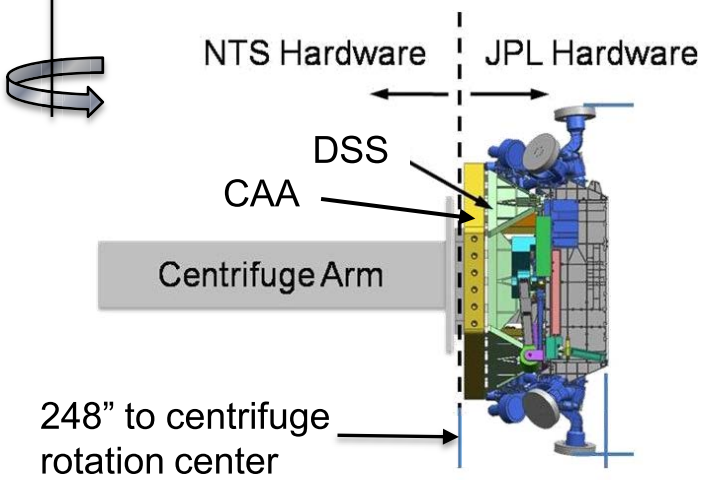
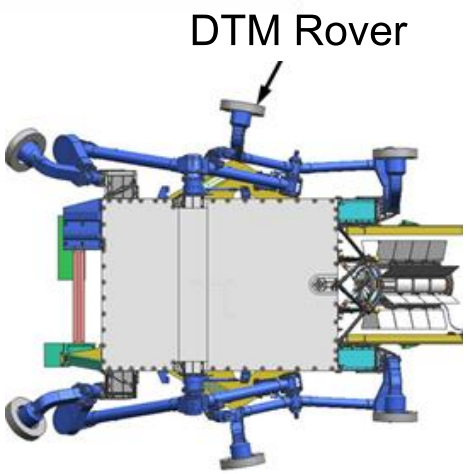
Test Configuration – Rover with DSS and CAA



Centrifuge spins counterclockwise





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Test Approach

- The centrifuge test is targeted at qualifying components and interfaces of the rover structure that, 1) do not meet the no test factors of safety, and 2) experience their critical design flight limit load (FLL) during entry
  - *Major Components:*
    - Top Deck, RAMP, Side and Aft Panels, Bottom Panel, DAN enclosure, RTG adapter, and the mobility support structure
  - *Major interfaces:*
    - Descent Stage to Rover Chassis, RSM head to chassis interface, RTG adapter to chassis, and the mobility restraint interfaces at the separation plane
- To achieve the required qualification level loading
  - *Use a centrifuge to apply a static acceleration to the test article*
  - *Force transducer, accelerometer, and strain gage data were recorded during test*
    - This data would not be required for qualification of the hardware
    - This data would be utilized to check the linearity and to guard against accidental overloading of the test article

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Criteria for Successful Hardware Qualification

- The test article must successfully support all applied qualification level loads without global failure (collapse) or single component failure
  - *Failure shall be defined as a lack of capacity to carry additional load*
- Test article must not demonstrate any of the following during the test
  - *Detrimental yielding which impair the function*
  - *Excessive non-linear deflection*
  - *Excessive or detrimental slippage at friction critical bolted interfaces.*
  - *Loss of functionality of associated mechanisms*
- These qualification success criteria will be verified by:
  - *Evaluation of the linearity of applied load versus measured test data.*
  - *Post-test visual inspection of mechanisms and hardware*
  - *Post-test functional checkout of mechanisms and hardware*
  - *Comparison of pre- and post-test alignments*
  - *Investigation of measured forces, accelerations, and strains*

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Test Article Instrumentation

- Accelerometers – Monitoring accelerations throughout rover
  - *Eleven 3-axis accelerometers installed across structure*
    - 33 channels of acceleration data logged
  - *Four accelerometers (12 channels) selected to be monitored in real time from control room*
- Strain Gages – Checking linearity and hardware protection
  - *Sixteen Gages installed across structure*
    - Twenty channels of strain data logged
  - *Twelve strain gages (12 channels) selected to be monitored in real time from control room*
- Force Transducers – Monitoring total force applied to test article
  - *Fifteen 3-axis force transducers installed on rover support GSE*
    - Five installed on each bipod with net X, Y, Z components reported for each bipod
    - Nine total channels
  - *All force data selected for real-time monitoring from control room*
- Video Documentation
  - *Two HD Cameras, mounted forward and aft*

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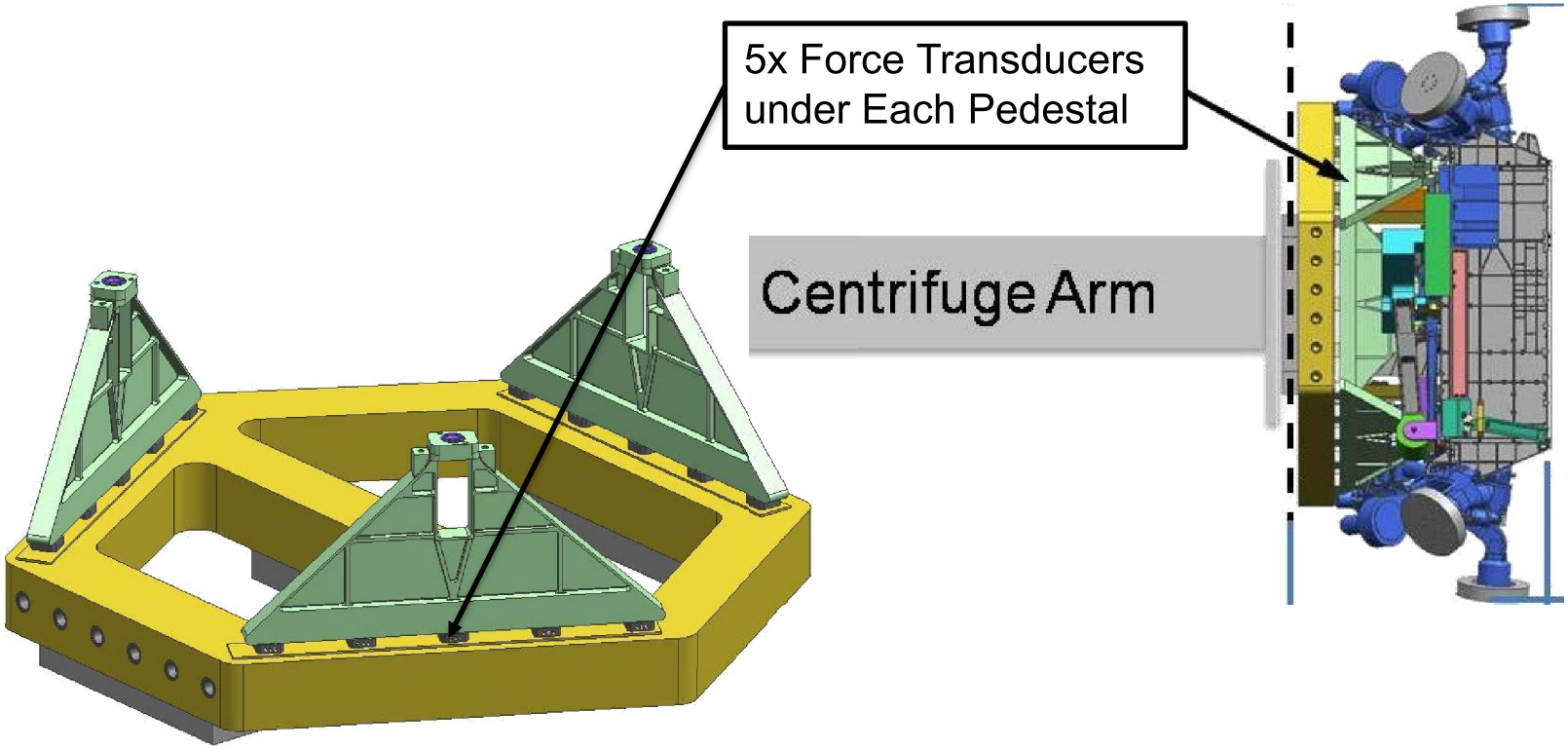
Test Article Instrumentation: Force Transducers

- Force Transducers: Descent stage Bipod Simulators
  - *Monitored Real-Time*



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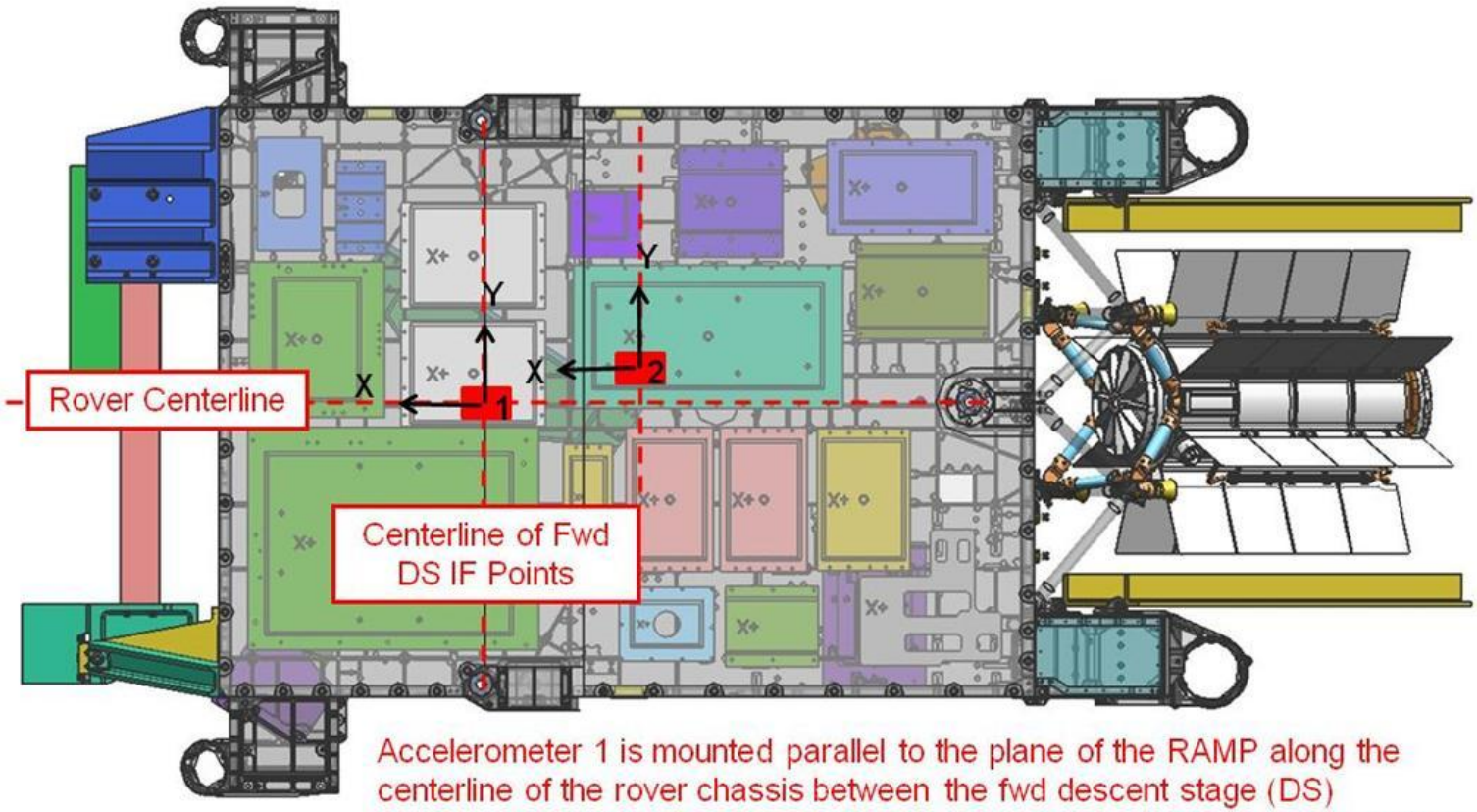
Test Article Instrumentation: Accelerometers

- Accelerometers 1,2: Monitored in Real-Time



Accelerometer 1 is mounted parallel to the plane of the RAMP along the centerline of the rover chassis between the fwd descent stage (DS) interface (IF) points. Accelerometer 2 is mounted parallel to the plane of the RAMP, as close to the rover X, Y C.G. location as possible (see above). Both accelerometers are oriented such that their X measurement directions aligned with the rover coordinate system X axis.

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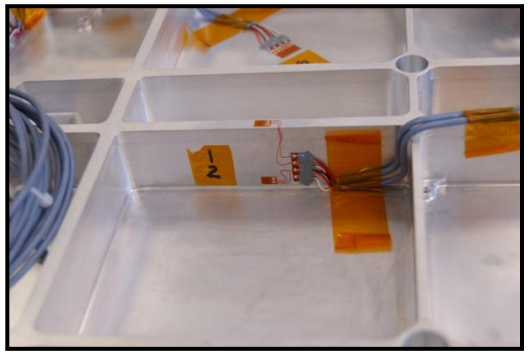
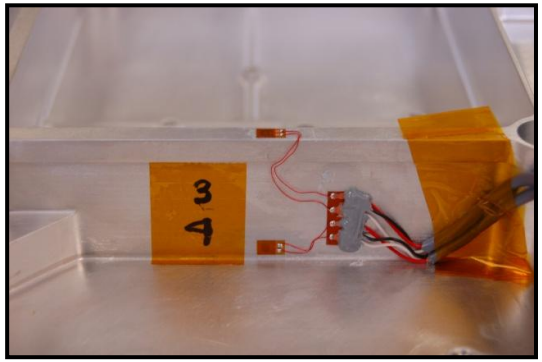
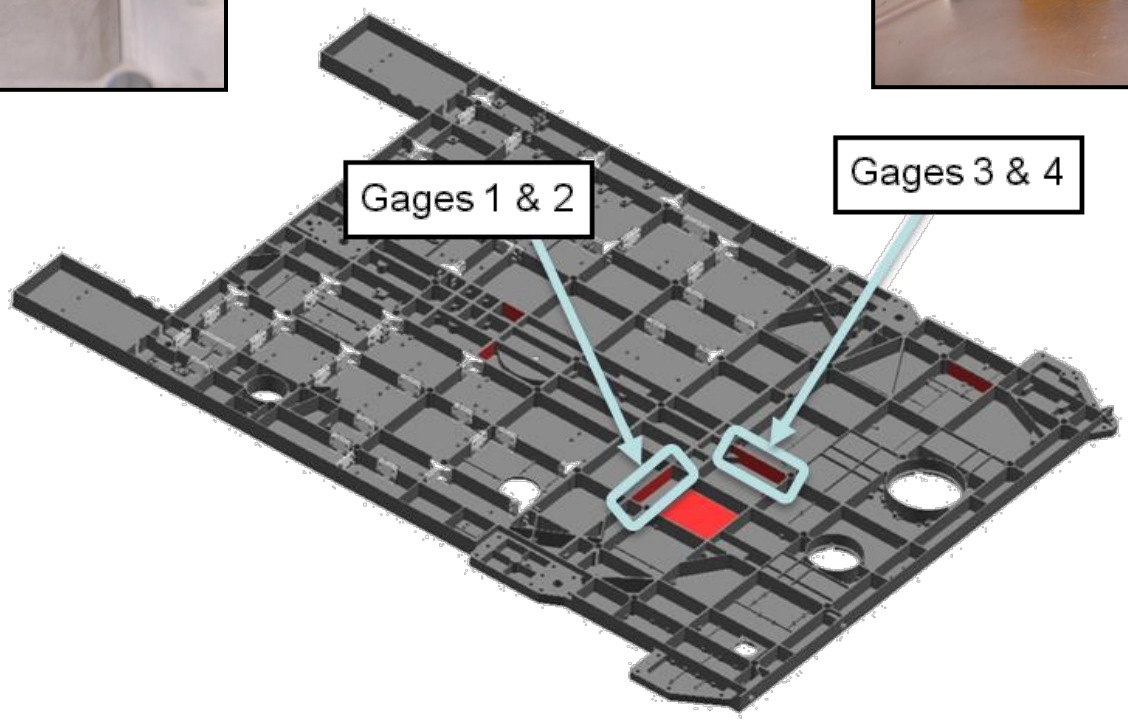
Test Article Instrumentation: Strain Gages

- Gages 1-4: Top Deck Longitudinal and Transverse Ribs
  - *Monitored Real-Time*







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Data Acquisition System

MSL Rover Chassis Centrifuge Data Acquisition System

Data Sensors

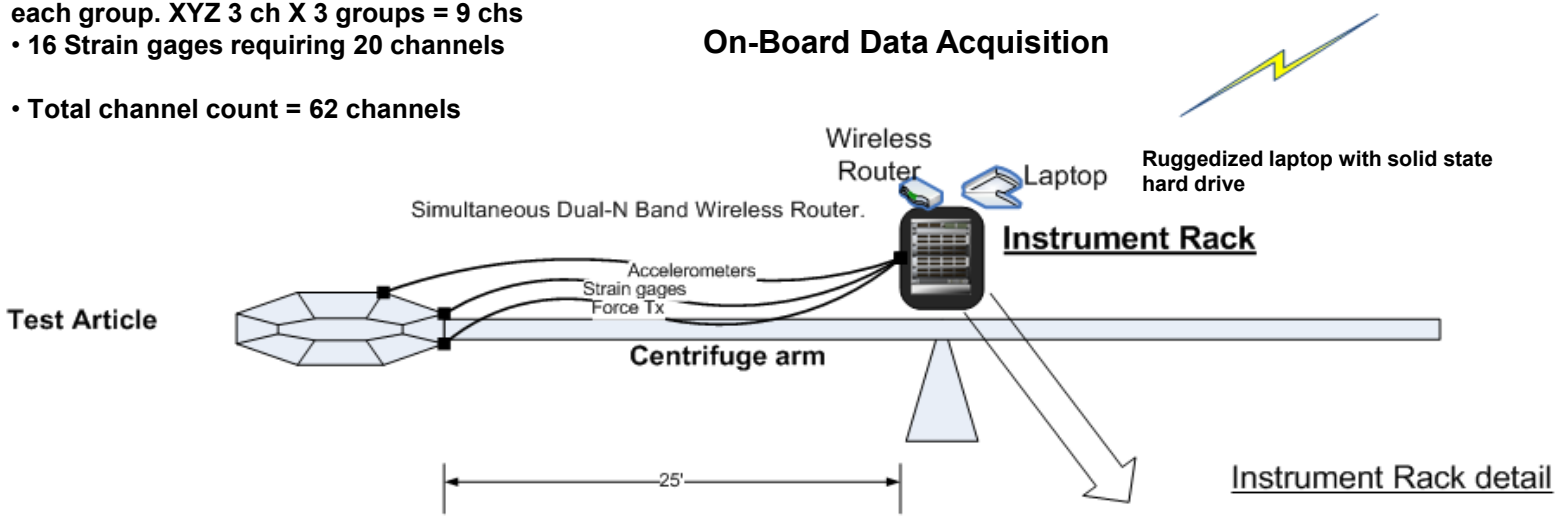
- 11 Accelerometers x 3 ch(xyz) = 33 chs
- 15 Force transducers – 3 Groups of 5 summed resulting in X, Y & Z sums for each group. XYZ 3 ch X 3 groups = 9 chs
- 16 Strain gages requiring 20 channels

- Total channel count = 62 channels

Remote Monitoring

Wireless remote monitoring of on-board DAQ system via "Windows Remote Desktop"

On-Board Data Acquisition



Ruggedized laptop with solid state hard drive

Instrument Rack detail

AC Power Conditioner

Force Tx Sig. Cond.

1st 48 Ch DAQ Unit
2nd 48 Ch DAQ Unit

Force Tx Patch Pnl

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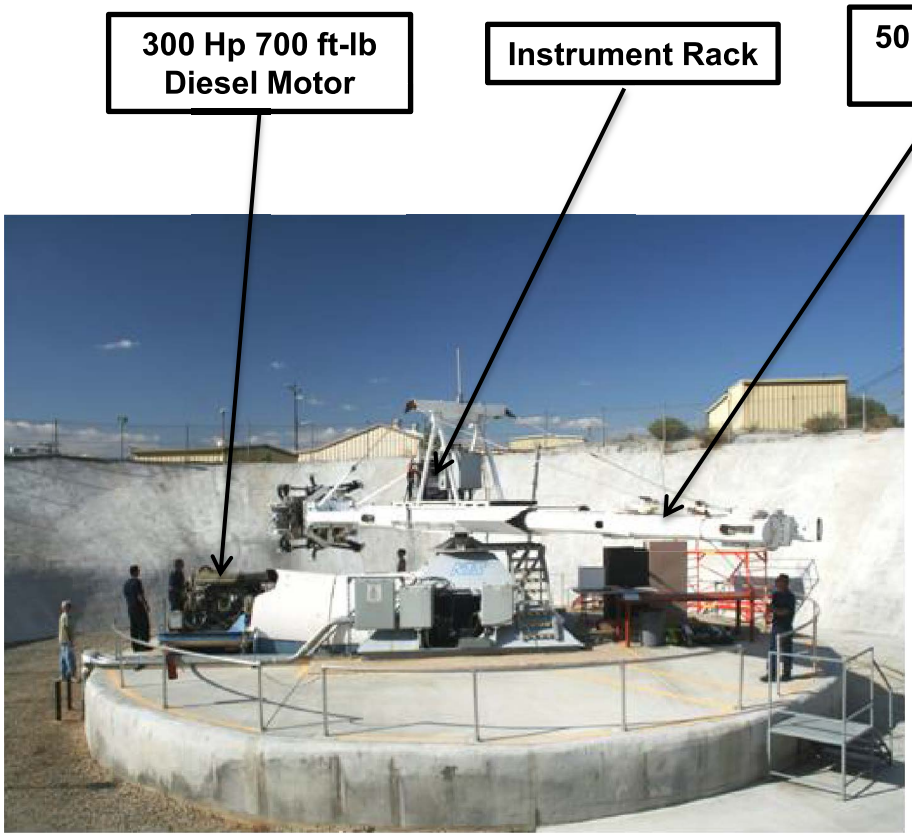
Centrifuge Test Facility

- Test performed at National Technical Systems (NTS), Santa Clarita, CA



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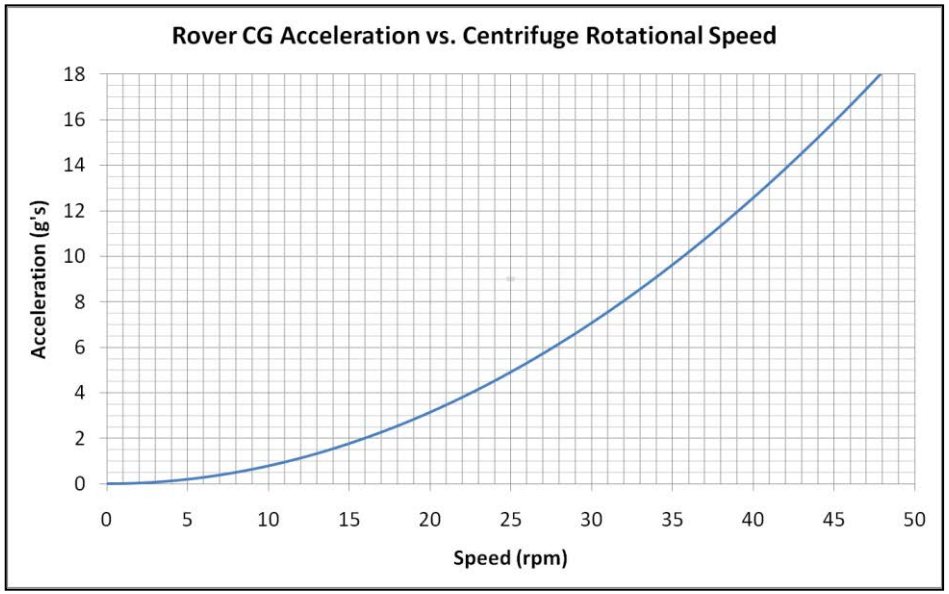
Rover CG Acceleration vs. Centrifuge Velocity

Gz at Rover CG	Gy at Rover CG	Rover CG Tangential Velocity (in/s)	Rover CG Tangential Velocity (MPH)	Centrifuge Angular Velocity (RPM)
1	1	327	18.6	11.3
2	1	462	26.3	16.0
3	1	566	32.2	19.5
4	1	653	37.1	22.6
5	1	731	41.5	25.2
6	1	800	45.5	27.6
7	1	864	49.1	29.9
8	1	924	52.5	31.9
9	1	980	55.7	33.9
10	1	1033	58.7	35.7
11	1	1084	61.6	37.4
12	1	1132	64.3	39.1
13	1	1178	66.9	40.7
14	1	1223	69.5	42.2
15	1	1265	71.9	43.7
16	1	1307	74.3	45.1
17	1	1347	76.5	46.5
18	1	1386	78.8	47.9



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Executed Test Steps and Levels

- Force transducer readings drifted up when the centrifuge was at rest
  - *Unable to definitely explain this behavior but the drifting was gradual*
  - *Zero out readings before calibration test started*
- Checkout and Calibration
  - *Performed at 25% level*
  - *Reduced centrifuge rotation rate to zero after checkout*
  - *After checkout run, zeroed all readings before the formal test started*
- Incremental Level
  - *25% level with ~2 minutes data reviewing*
  - *50% level with ~2 minutes data reviewing*
  - *75% level with ~5 minutes data reviewing*
    - Planned for 2 minutes but RTG strut gage reading exceeded prediction
    - Capability and margin existed and test determined safe to proceed
  - *100% level within (-10%, +0%) tolerance range with ~1 minute holding*
    - Transmission temperature reached 225 ^{o}F due to high power output
    - Just below NTS Temperature shutdown limit 230 ^{o}F

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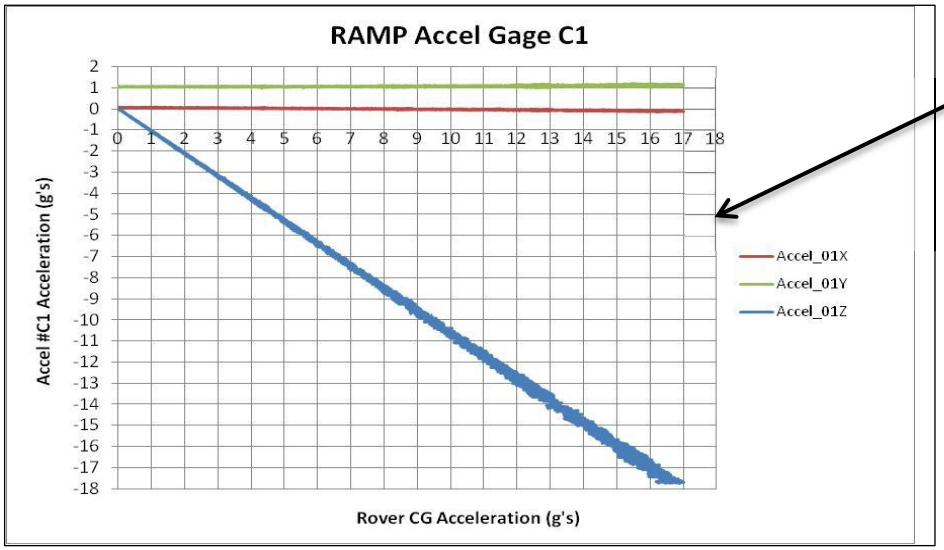
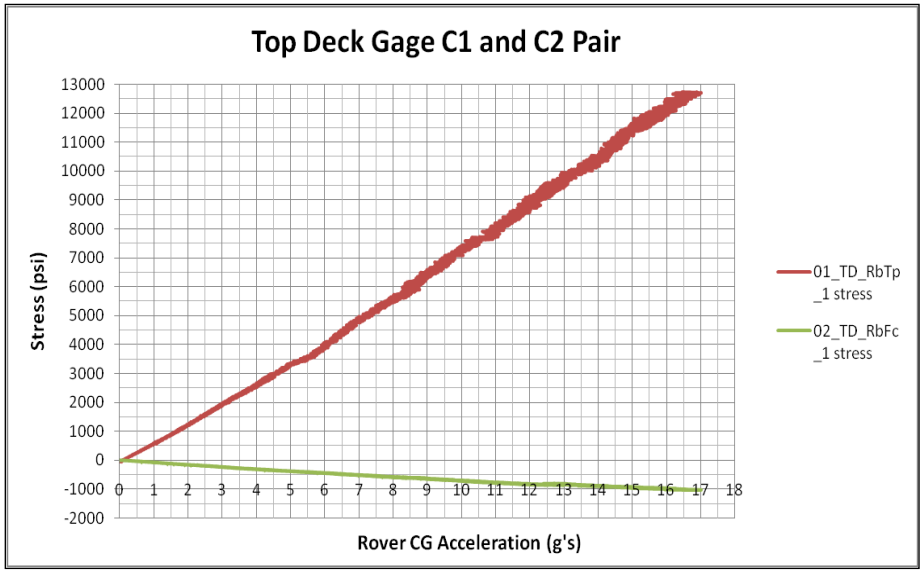
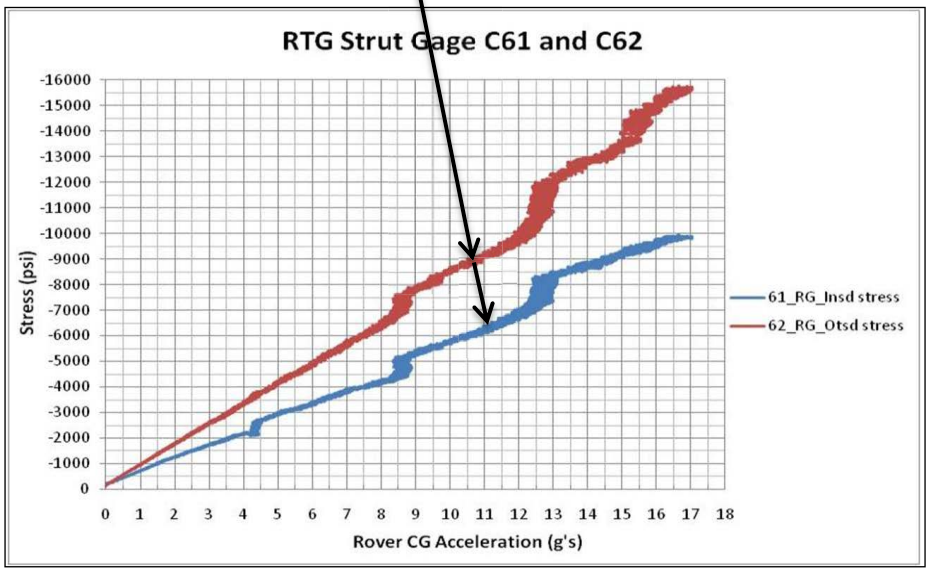
Sample Test Result Measurements



RAMP accelerometers tracked linearly with rover cg acceleration
Peak CG acceleration = 17.3 g's

Strain gages generally demonstrated linearity except the gages mounted on the RTG support strut which were directly exposed to wind





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Post Test Inspection and Conclusion

- Performed the structural and functional inspections after the test and no anomalies and changes were found
  - *Total three levels of tear-down visual inspections conducted on all major and secondary components and interfaces*
    - 1st Level: Rover in the original centrifuge test configuration
    - 2nd Level: Belly pan and most of the external components removed
    - 3rd Level: RAMP (Rover Avionics Mounting Plate) removed to gain unobstructed view to the inside of rover
  - *Visual inspection of all accessible joints, cutouts, and fasteners*
  - *Mobility full-motion deployment and range of motion test*
  - *RTG adapter and sub-adapter fitting position check*
  - *RSM pyro firing test followed by full motion deployment test including actuators*
- The DTM rover was successfully tested to the simulated inertial loading environment during entry into the Martian atmosphere

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Lessons Learned

- Always verify the centrifuge direction of rotation
  - *NTS large centrifuge rotates counter-clockwise, not reversible*
  - *Only until two weeks before the test we corrected our assumption of directionality*
- The rover could have been tested to the exact entry loading environment with a timely communication
  - *Entry: 15 Gz + 0.65 Gx; Centrifuge: 15 Gz + 1 Gy*
  - *Analyst proposed to rotate the rover by ~ 3 degrees in two axes to produce the precise load environment but it was too late to modify hardware*
  - *Off-axis loading is nonetheless secondary and verified by pre-test analysis*
- Know the hardware capability limit with adequate pre-test analysis
  - *RTG strut experienced higher-then-expected stresses*
  - *Causes of higher stress were not clear but the hardware had robust margin*
- Develop a quick data reviewing methodology is very important
  - *Centrifuge unloading is a slow process if problems occur during test*
  - *Transmission temperature rises quickly especially at high speed*
  - *Full level test reached 225 ^{o}F, only 5 degrees below the shut down limit of 230 ^{o}F*
- Plan adequate time for instrumentation checkout prior to testing

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