# Qualifying Spirit and Opportunity to Martian landing loads with centrifuge testing

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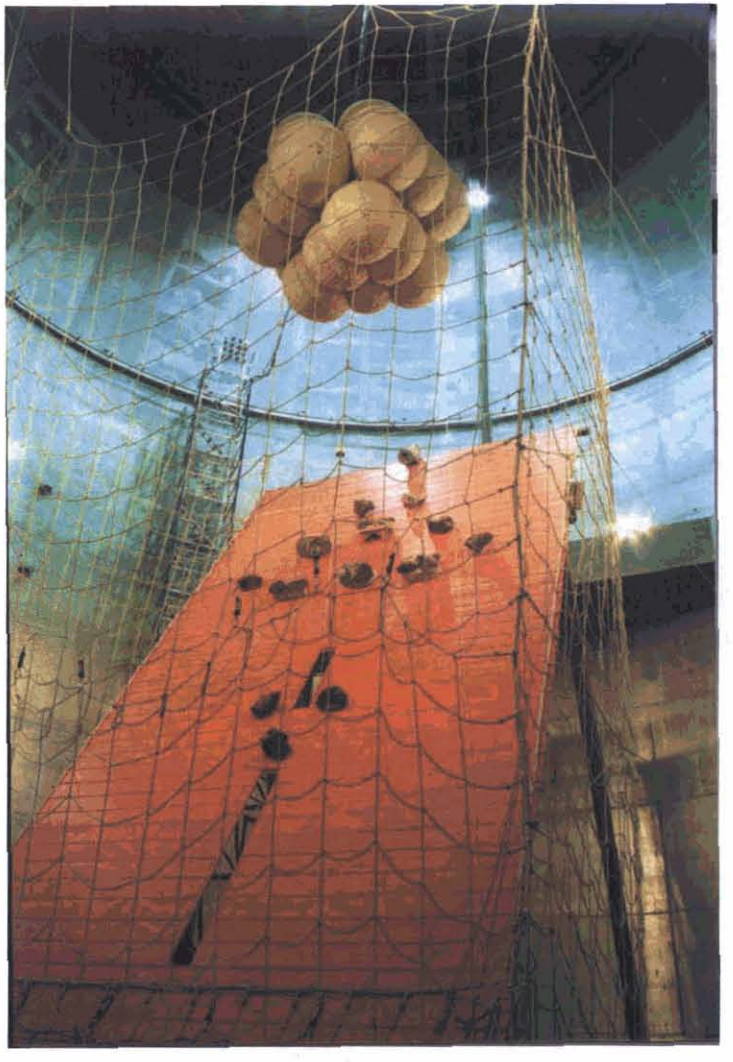
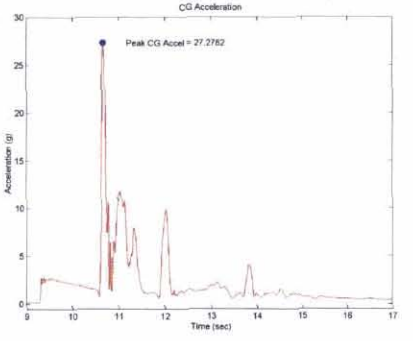
# Airbag Drop Testing

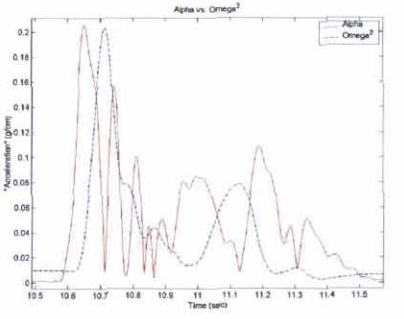




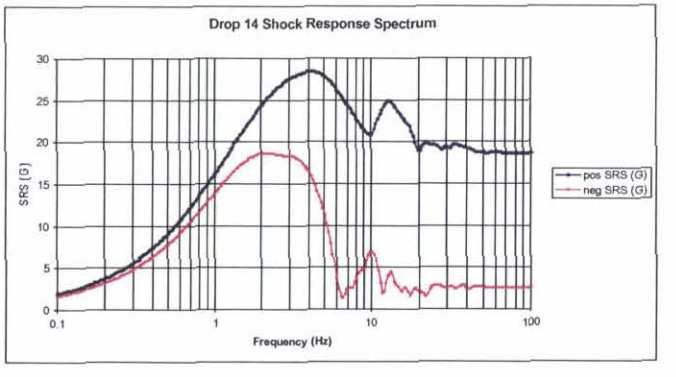
A drop test lander was instrumented with accelerometers to measure the kinematic response of the test article during impact.




Representative accelerations at the center of mass




Representative angular accelerations and angular velocities




SRS of representative landing excitation

# DTM Rover/Basepetal Centrifuge Test



- ***Test Requirement***
  - Verify the test article for Mars landing load environment of 30 g's with a 1.1 test factor (33 g's)

- ***Test Objectives***
  - Demonstrate the structural and functional integrity of the DTM Rover/ Basepetal when subjected to the landing event
  - Qualification level is defined as 1.1 x landing load

- ***Criteria for a Successful Test***
  - No evidence of general or detrimental yielding at limit load
  - No excessive deflection at limit load

- ***Balance of Risk***
  - Rover WEB interface loads to the Basepetal and the REM strut axial load are viewed as barometers for the overall loading of the Rover.

# DTM Rover/Basepetal Centrifuge Test



- ***Hardware Being Tested***
  - **DTM Rover**
    - DTM REM w/ Mass Mock-up (MM) Slices/Instruments, DTM Flex Cable
    - DTM Battery Struts w/ MM Battery and MM Thermal Switch/Radiator (+Y Rover)
    - DTM WEB w/ MM of IDD, MM of Frt/Rear Hazcams, EM Thermal Switch, DTM Radiator, DTM Cutter Bracket/Cutter, DTM Separation Joints and Push-off Springs, DTM Cable Tunnels
    - DTM RED w/ MM of Pancam, MM of HGA
    - DTM Mobility (wheels, tie-downs, bogey system, differential hardware)
    - EM LGA, EM UHF
  - **EM Base Petal**
    - Rover Lift Mechanism
    - Cutters 1 & 2
  - **Centrifuge Configuration Items**
    - DTM Solar Array, Monoballs in Base Petal Hinge Fittings, Rock Protection Hardware (Belly Pan/Sep Nut Covers), Cable Management System

# DTM Rover/Basepetal Centrifuge Test



- ***Test Article CBE Mass (± 10%)***

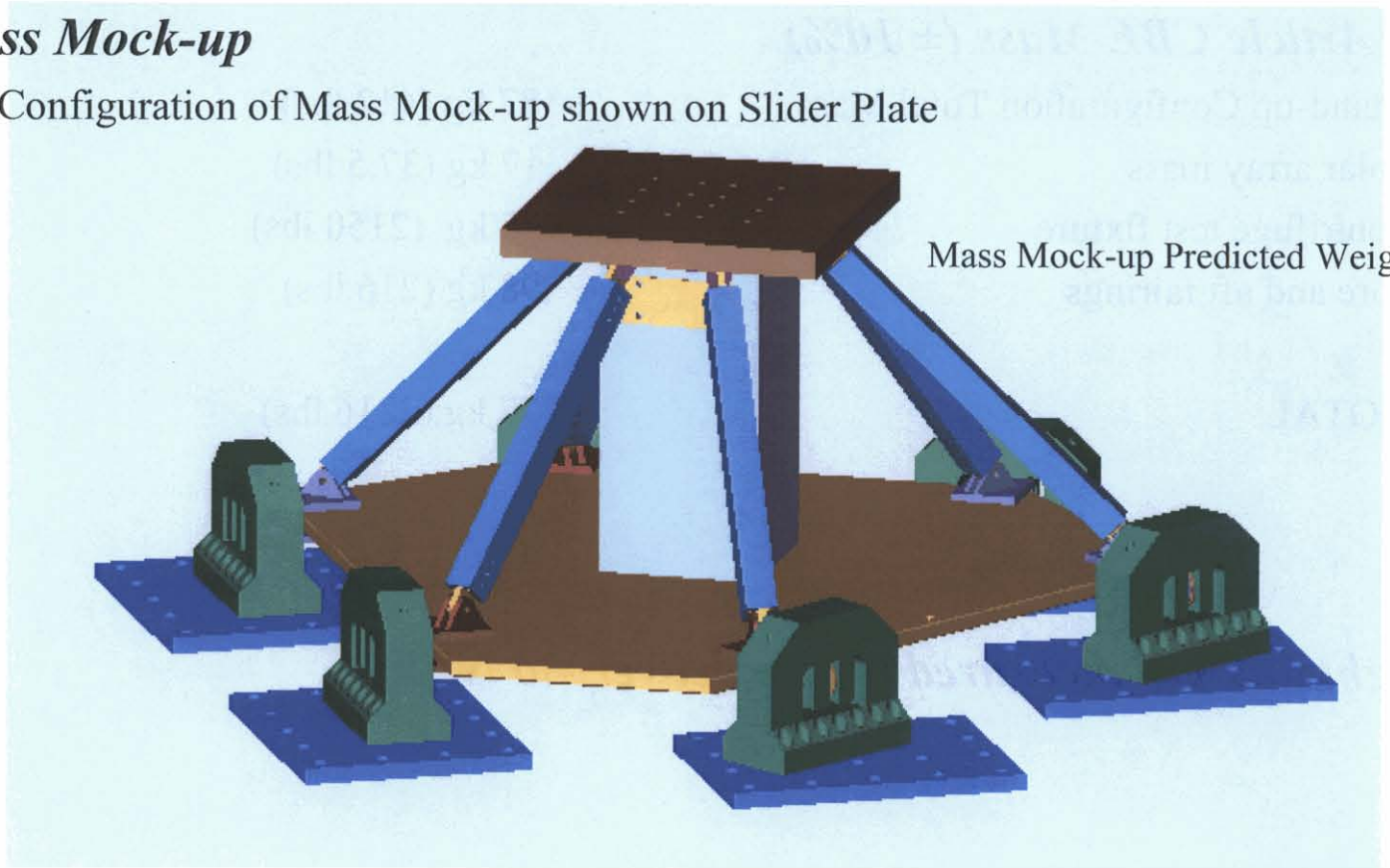
| | |
|---|---|
| – Stand-up Configuration Total Mass | ~187 kg (412 lbs) |
| – solar array mass | 17 kg (37.5 lbs) |
| – centrifuge test fixture | 975 kg (2150 lbs) |
| – fore and aft fairings | 98 kg (216 lbs) |
| – TOTAL | 1277 kg (2816 lbs) |

- ***Weight and CG measured before delivery to NTS***

# DTM Rover/Basepetal Centrifuge Test



- ***Mass Mock-up***
  - Configuration of Mass Mock-up shown on Slider Plate



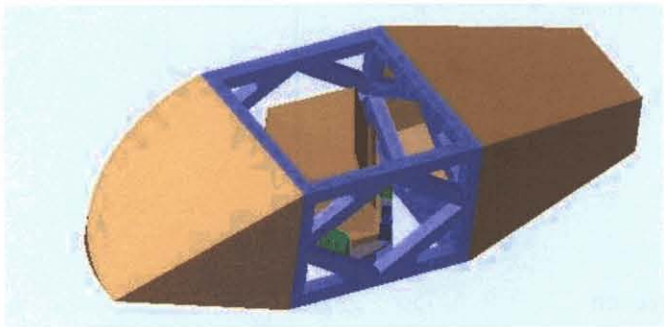
Mass Mock-up Predicted Weight =~ 549 lbs

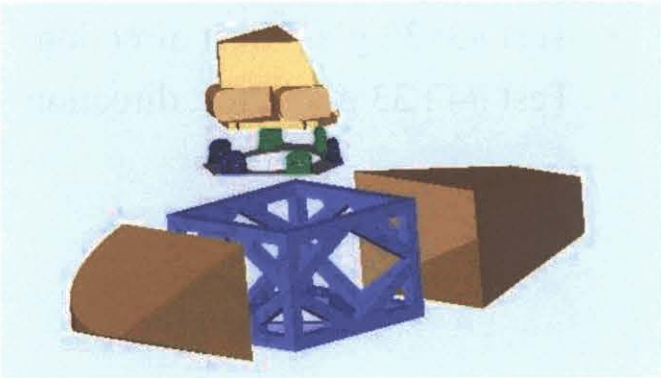
  - Associated Hardware (Yoke, Base Block, Pins, Bolts) = ~32 lbs * 6 locations = 192 lbs.

# DTM Rover/Basepetal Centrifuge Test

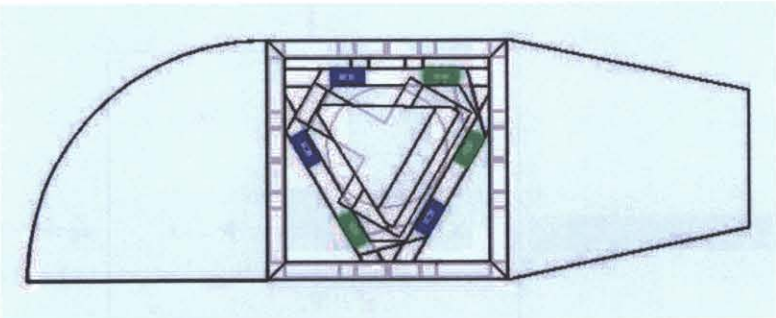


- ***Test Fixture***
  - 80" x 80" x 60" welded Aluminum 6061 T6 box
  - 4 - 1.25" diameter bolt interface to centrifuge arm
  - 80" length Fairings are constructed of Aluminum honeycomb panels





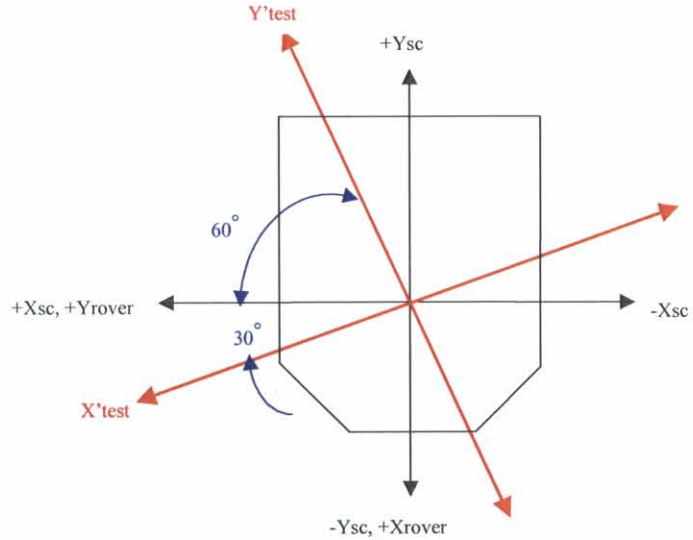
Top View

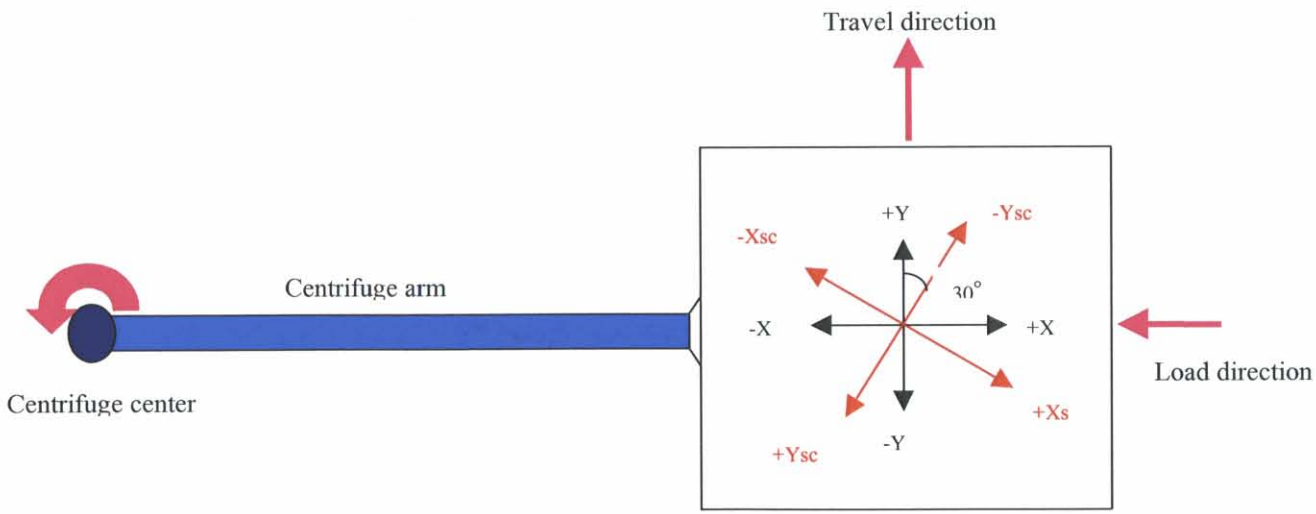


# DTM Rover/Basepetal Centrifuge Test



- ***Test Article Orientation***
  - *Test Cases*
    - Test #1: 33 g's Xtest direction
    - Test #2 : 33 g's Ytest direction
    - Test #3: 33 g's -Xtest direction
    - Test #4 : 33 g's -Ytest direction



# DTM Rover/Basepetal Centrifuge Test



- ***Pre-test Analysis***
  - Pre-test analysis was performed to verify that the intended loading would not exceed 85% of the capability of various critical components.
  - The Rover/Basepetal Interface, Basepetal hinges, REM struts, solar array hinges and Wheels to Basepetal Interface predicted test results are compared with the FLL and design capabilities.
  - Through these analyses, it has been determined that the off axes lateral loading of the test article induces axial load in the most critical components.
    - In order to increase test simplicity and decrease cost and schedule, the Z axes tests were eliminated.
    - The DTM article will have experienced a 20 g vertical sine pulse on the shaker before centrifuge testing.

# DTM Rover/Basepetal Centrifuge Test



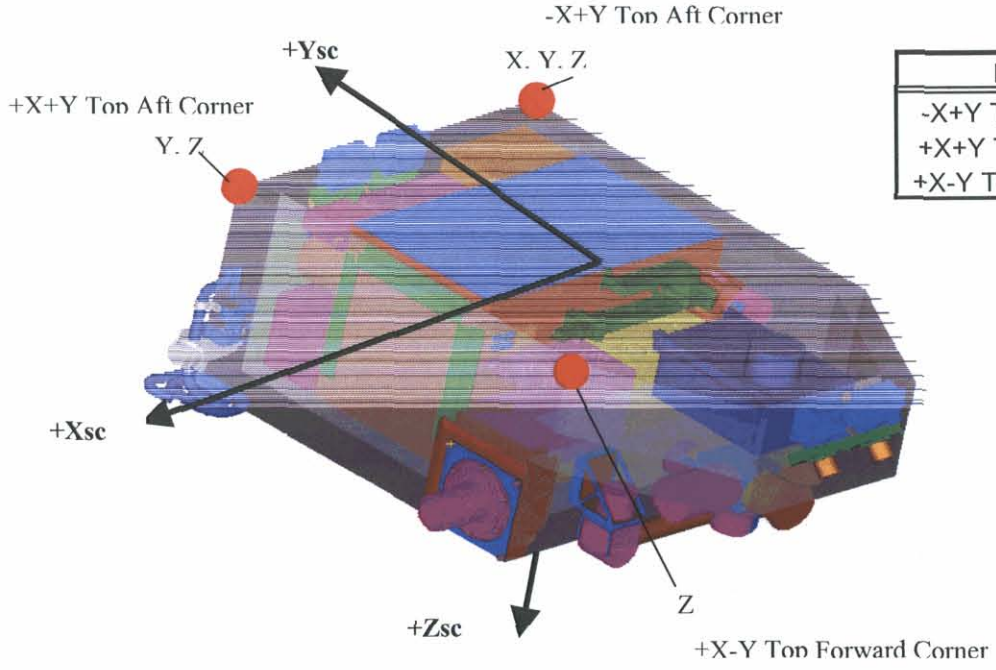
- *Instrumentation*
  - Hardware protection only!!!
  - Data will be monitored in real-time to ensure linearity with increasing g level.

| ID | Location | DOF | Coord System | Type of Instrumentation |
|---|---|---|---|---|
| 1 | Y1 strut | | | strain gage - axial only |
| 2 | Y2 strut | | | strain gage - axial only |
| 3 | Z2 strut | | | strain gage - axial only |
| 4 | Web Forward +Y, 1 | | | strain gage - rosette |
| 5 | Web Forward +Y, 2 | | | strain gage - rosette |
| 6 | Web Forward +Y, 3 | | | strain gage - rosette |
| 7 | Web Forward -Y, 1 | | | strain gage - rosette |
| 8 | Web Forward -Y, 2 | | | strain gage - rosette |
| 9 | Web Forward -Y, 3 | | | strain gage - rosette |
| 10 | Web Aft -Y, 1 | | | strain gage - rosette |
| 11 | Web Aft -Y, 2 | | | strain gage - rosette |
| 12 | Web Aft -Y, 3 | | | strain gage - rosette |
| 13 | Basepetal - Mars Side 1A | | | strain gage - uni-axial |
| 14 | Basepetal - Mars Side 2A | | | strain gage - uni-axial |
| 15 | Basepetal - Mars Side 3A | | | strain gage - uni-axial |
| 16 | Basepetal - Mars Side 4A | | | strain gage - uni-axial |
| 17 | Basepetal - Rover Side 2B | | | strain gage - uni-axial |
| 18 | Basepetal - Rover Side 4B | | | strain gage - uni-axial |
| 19 | Web -X+Y Top Aft Corner | X | SC | LVDT |
| 20 | Web -X+Y Top Aft Corner | Y | SC | LVDT |
| 21 | Web -X+Y Top Aft Corner | Z | SC | LVDT |
| 22 | Web +X+Y Top Aft Corner | Y | SC | LVDT |
| 23 | Web +X+Y Top Aft Corner | Z | SC | LVDT |
| 24 | Web +X-Y Top Forward Corner | Z | SC | LVDT |
| 25 | RED deck center aft | X | SC | Accelerometer |
| 26 | RED deck center aft | Y | SC | Accelerometer |
| 27 | RED deck center aft | Z | SC | Accelerometer |
| 28 | -YDIFHS | | | Thermocouple |
| 29 | REMSTWEB | | | Thermocouple |

# DTM Rover/Basepetal Centrifuge Test



- ***Instrumentation***
  - LVDT locations and predictions




| Location | 33g, -30 deg Xsc (in) | 33g, -30 deg Ysc (in) | 33g, -30 deg Zsc (in) | 33g, +60 deg Xsc (in) | 33g, +60 deg Ysc (in) | 33g, +60 deg Zsc (in) |
|---|---|---|---|---|---|---|
| -X+Y Top Aft Corner | 0.07 | -0.03 | -0.02 | 0.04 | 0.06 | 0.00 |
| +X+Y Top Aft Corner | - | -0.03 | 0.03 | - | 0.06 | 0.03 |
| +X-Y Top Fwd Corner | - | - | 0.06 | - | - | -0.03 |

# DTM Rover/Basepetal Centrifuge Test



- ***Instrumentation***
  - Strain gages
    - REM struts Y1, Y2, and Z2 back to back to cancel bending and record axial load
    - Three rosettes on WEB bottom plate at both forward bipods as well as the back WEB panel near the aft bipod
    - Six axial gages on the Basepetal

| Strain Gage Location | Material | E (psi) | ν | Predicted σ (psi) | Ultimate σ (psi) |
|---|---|---|---|---|---|
| Web | Astroquartz (0,90 layup) | 3.90E+06 | 0.25 | 11000 | 24000 |
| Basepetal | composite | 1.50E+07 | 0.3 | 15000 | 40000 (comp)<br>80000 (tension) |

| Strain Gage Location | Material | E (psi) | ν | Predicted σ (psi) | Ultimate σ (psi) | Predicted Axial (lbs) | Ultimate Axial (lbs) |
|---|---|---|---|---|---|---|---|
| REM Strut, Y1 | Astroquartz (45 layup) | 2.20E+06 | 0.5 | 30825 | 50000 | 2392 | 3890 |
| REM Strut, Y2 | Astroquartz (45 layup) | 2.20E+06 | 0.5 | 24150 | 37000 | 1874 | 2867 |
| REM Strut, Z1 | Astroquartz (45 layup) | 2.20E+06 | 0.5 | 18620 | 36700 | 1445 | 2848 |

# DTM Rover/Basepetal Centrifuge Test

- ***Instrumentation***
  - DC Accelerometer
    - A single tri-axial DC accelerometer, which is supplied by NTS, will be installed by JPL on the RED deck.
    - Verify that the test article experienced the intended 33 g loading.
  - Thermocouples
    - Channel 28 is located outside the Rover on the WEB fitting / differential housing near the launch tie down. Channel 29 is located on/near WEB wall fitting which +X REM strut attaches.
    - If the temperature inside the box exceeds 100° F, the test article will be removed.
  - Camera and Lights
    - NTS will provide a camera and lighting inside the JPL centrifuge box as another means of monitoring the DTM hardware. The camera and light will be installed during proof runs to ensure their survivability.

# DTM Rover/Basepetal Centrifuge Test



- ***Pre-test Phase***
  - Proof test of arm with JPL mass mockup inside test fixture box with fairings, LVDTs, camera and lights.
  - Proof testing verified the aerodynamic tuning of the arm as well as centrifuge engine capability. In the event that the engine capability determines the maximum g level (less than 33 g's), then the test article g level will not exceed 90% of the proof tested engine capability g level.
  - Verify handling procedures
  - Verify instrumentation functionality
  - Verify bolt torques of box to centrifuge arm
  - Record test article mass and distance of it's cg to center of centrifuge

# DTM Rover/Basepetal Centrifuge Test



- ***Test Phase***
  - The centrifuge was run at incrementally increasing levels of 25%, 50%, 75%, and 100% of the required G level with instrumentation recorded at each level. The rpm was stabilized for at least 10 seconds before recording data. The centrifuge remained at 100% for no longer than required for the rpm to stabilize (less than or equal to10 seconds). The same procedure was run for each test configuration.

- ***Post-Test Phase***
  - The Rover/Basepetal were successfully tested to 33 g's in all lateral axes on the centrifuge. Therefore, the structural qualification of the DTM for the Mars landing environment was successfully verified.

# DTM Rover/Basepetal Centrifuge Test



- Testing

# DTM Rover/Basepetal Centrifuge Test

Mars Exploration Rover

BOLTING TO THE CENTRIFUGE ARM