Mass Property Measurements of the Mars Science Laboratory Rover

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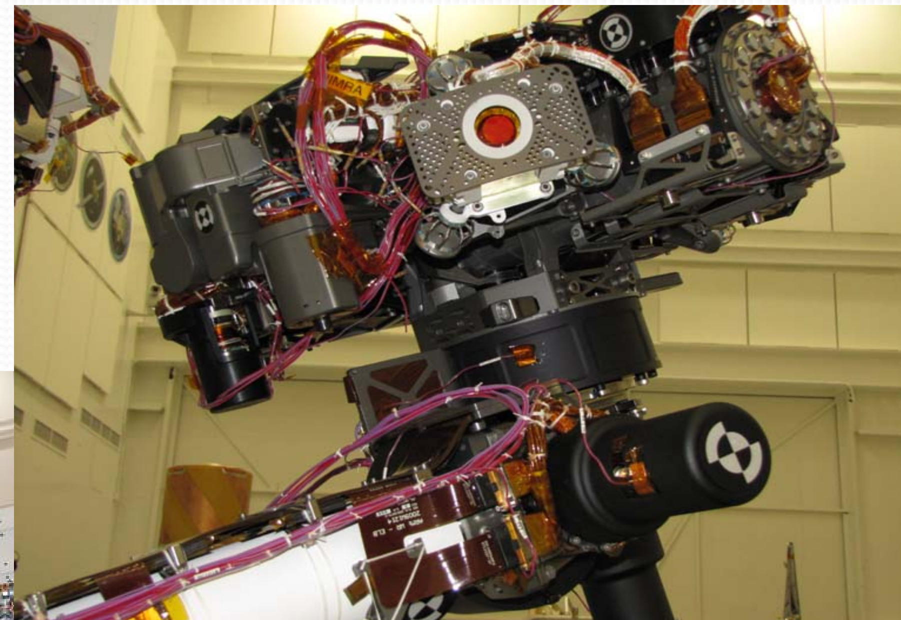
MARS SCIENCE LABORATORY (CURIOSITY ROVER)



ROVER SCIENCE INSTRUMENTS

Cameras

Mast Camera (Mastcam)
Mars Hand Lens Imager (MAHLI)
Mars Descent Imager (MARDI)

Spectrometers

Alpha Particle X-Ray Spectrometer (APXS)
Chemistry & Camera (ChemCam)
Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence Instrument (CheMin) - .
Sample Analysis at Mars (SAM) Instrument Suite

Radiation Detectors

Radiation Assessment Detector (RAD)
Dynamic Albedo of Neutrons (DAN)

Environmental Sensors

Rover Environmental Monitoring Station (REMS)

Atmospheric Sensors

Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI)

Goals and Objectives

Biological

- Determine the nature and inventory of organic carbon compounds.
- Investigate the chemical building blocks of life (carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur).
- Identify features that may represent the effects of biological processes bio signatures.

Geological and Geochemical

- Investigate the chemical, isotopic, and mineralogical composition of the Martian surface and near-surface geological materials.
- Interpret the processes that have formed and modified rocks and soils.

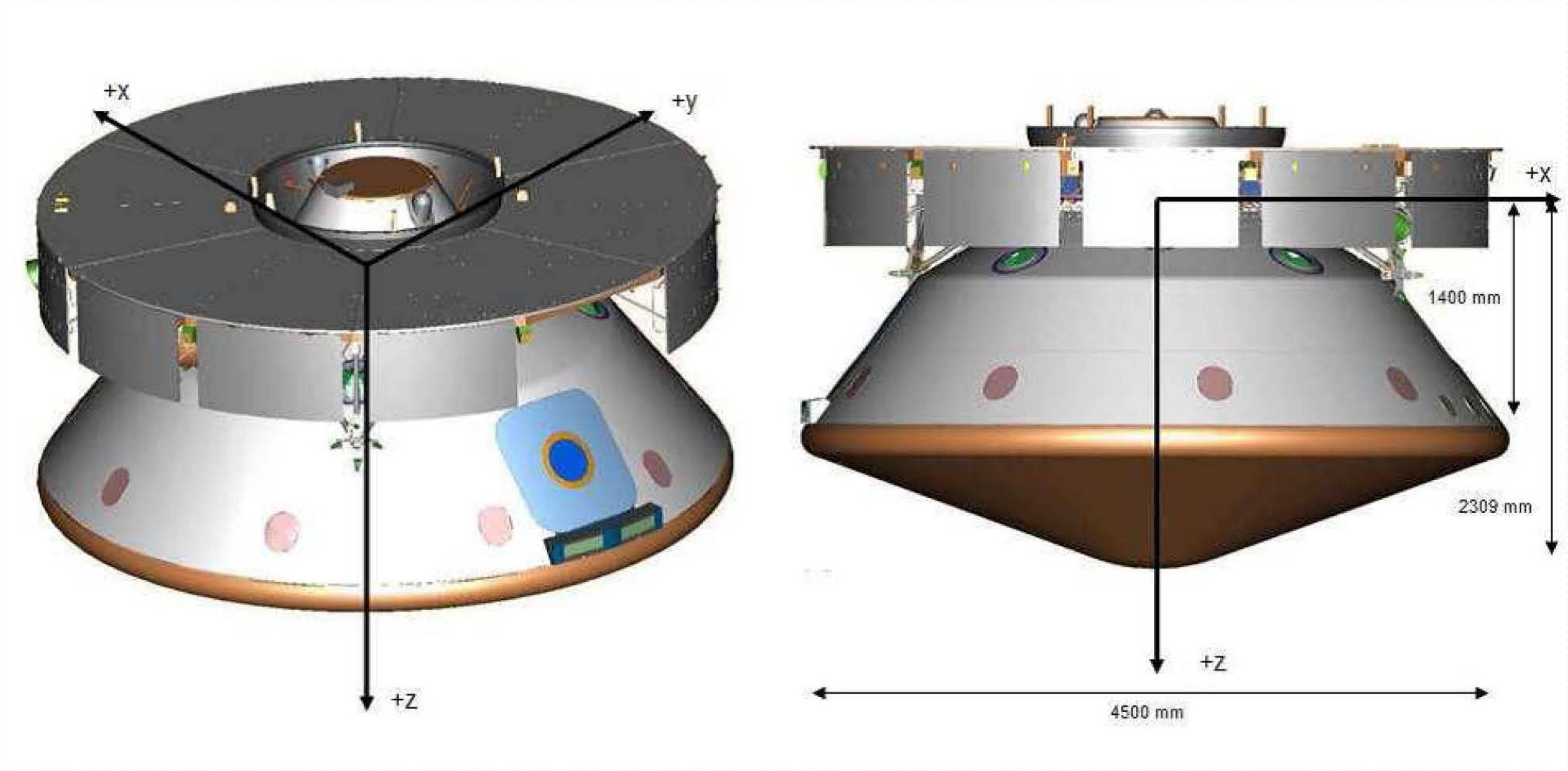
Planetary Process

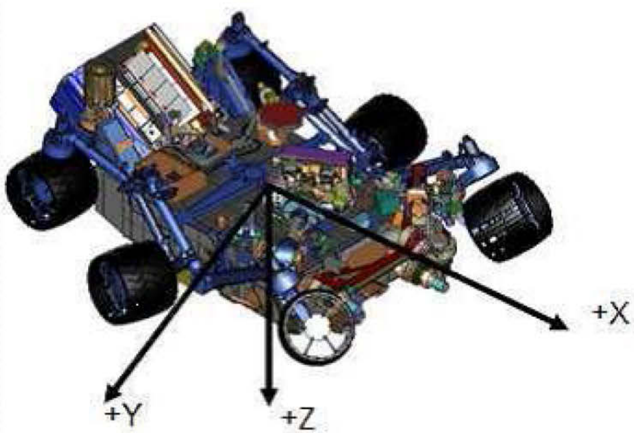
- Assess long-timescale (i.e., 4-billion-year) Martian atmospheric evolution processes
- Determine present state, distribution, and cycling of water and carbon dioxide

Surface Radiation

- Characterize the broad spectrum of surface radiation, including galactic radiation, cosmic radiation, solar proton events and secondary neutrons.
- As part of its exploration, it also measured the radiation exposure in the interior of the spacecraft as it traveled to Mars, and it is continuing radiation measurements as it explores the surface of Mars. This data would be important for a future manned mission.

Spacecraft Coordinate System

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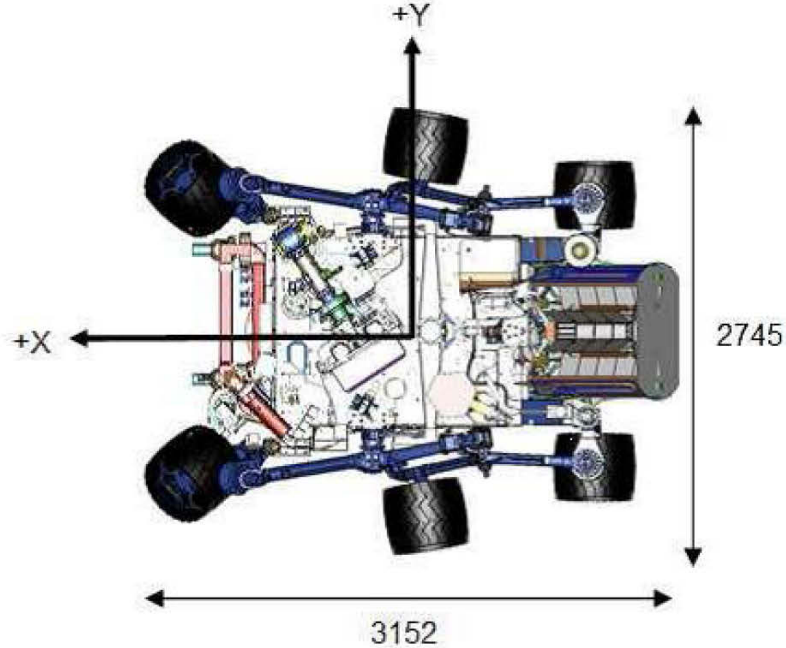
+Y
+Z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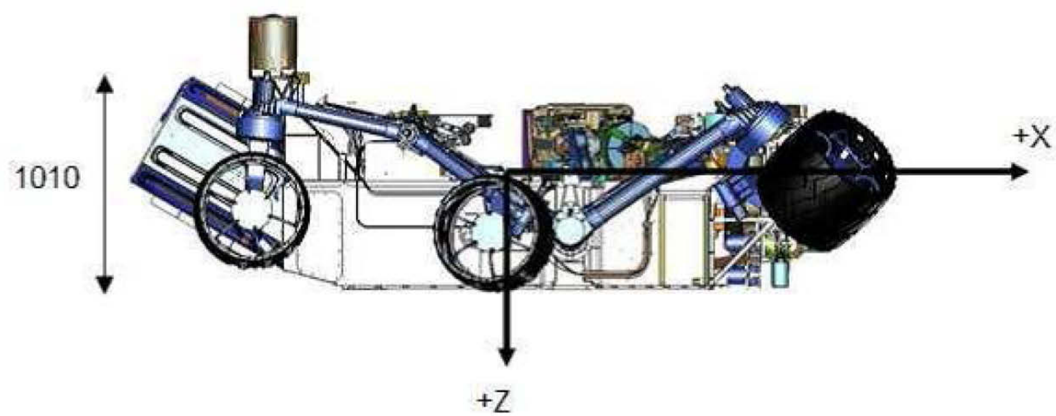
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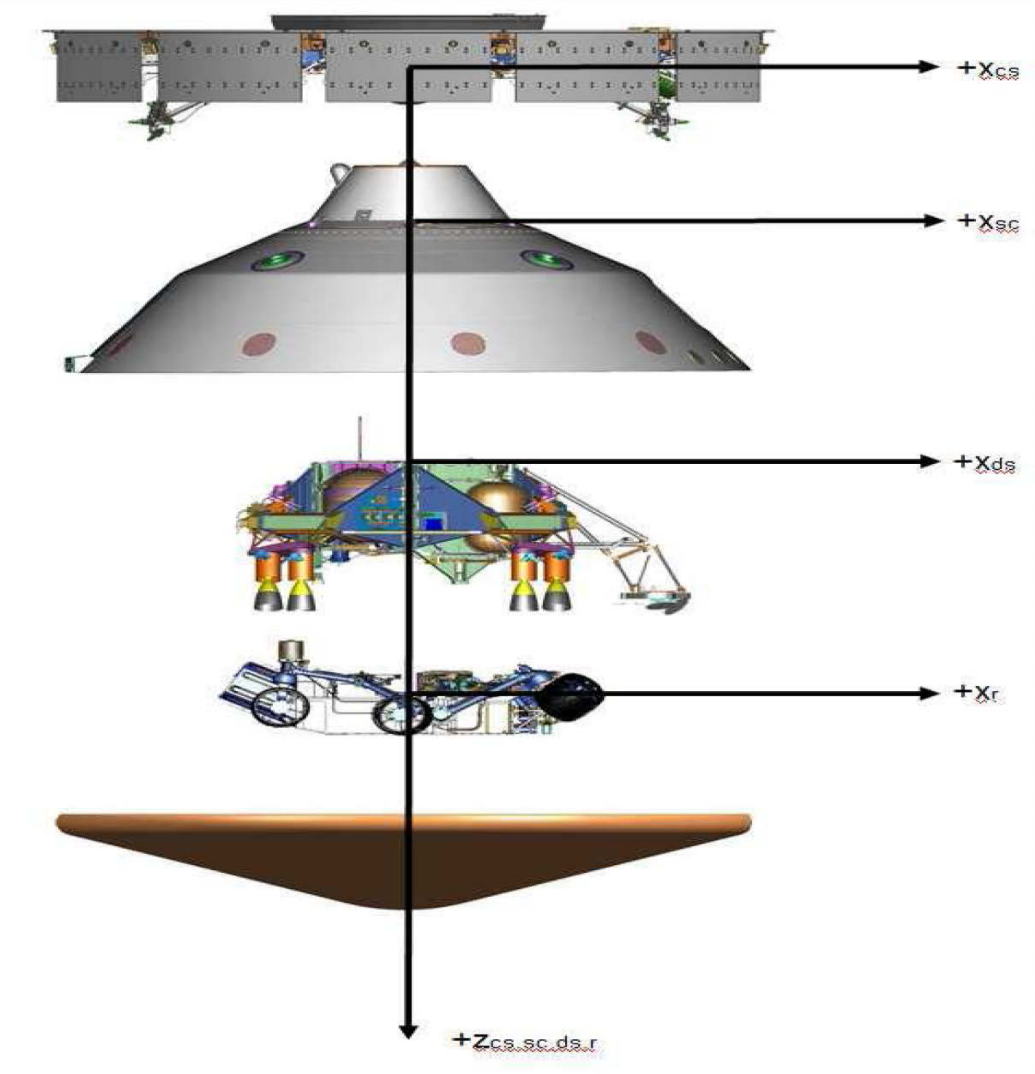


Comparison of Coordinate systems

Mass Properties Equipment

The mass properties measurement systems that were required to measure MSL consisted of two types of equipment.

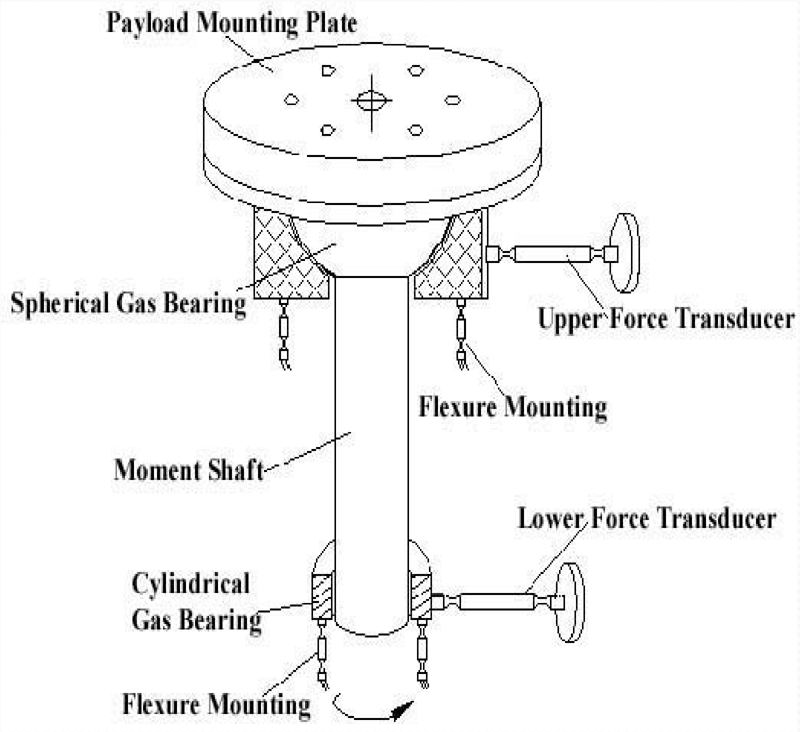
The smaller one (CG and MOI) is the KGR500 for masses up to 227 kg (500 lb.).

The larger one (CG, MOI, POI) is the POI 12000 or the “spin table” for masses up to 5443 kg (12000 lb.)

Both mass measurement systems use nitrogen/clean dry air to purge a spherical gas bearing which supports the payload and rotates without any drag or friction.

Spherical Gas Bearing

The payload is mounted on both machines on a spherical gas bearing which is suspended from the machine base. A tube extends from this bearing to a flexibly mounted lower air bearing. Two independent force cells measure the reaction forces on both the upper and lower bearings due to an unbalance in the object being measured.



images courtesy of Space Electronics

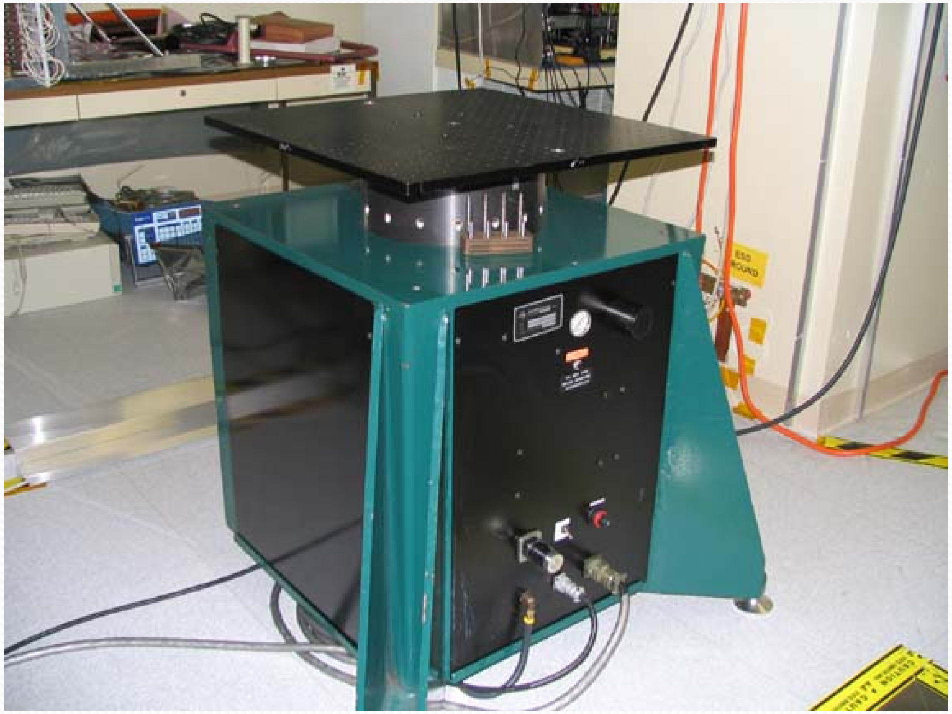
Spherical Gas Bearing

System Gas Reservoir

Model KGR500

This is a general purpose mass properties Instrument capable of testing parts whose combined weight, including the test fixture, does not exceed 500 pounds.

The KGR instrument determines the moment of inertia (MOI) of the test object and locates its center of gravity (CG). A computer interfaces with the system controls machine operation, performs calculations, and prints the test results.



KGR 500 MASS PROPRETIES PRERFORMANCE SPECIFICATIONS

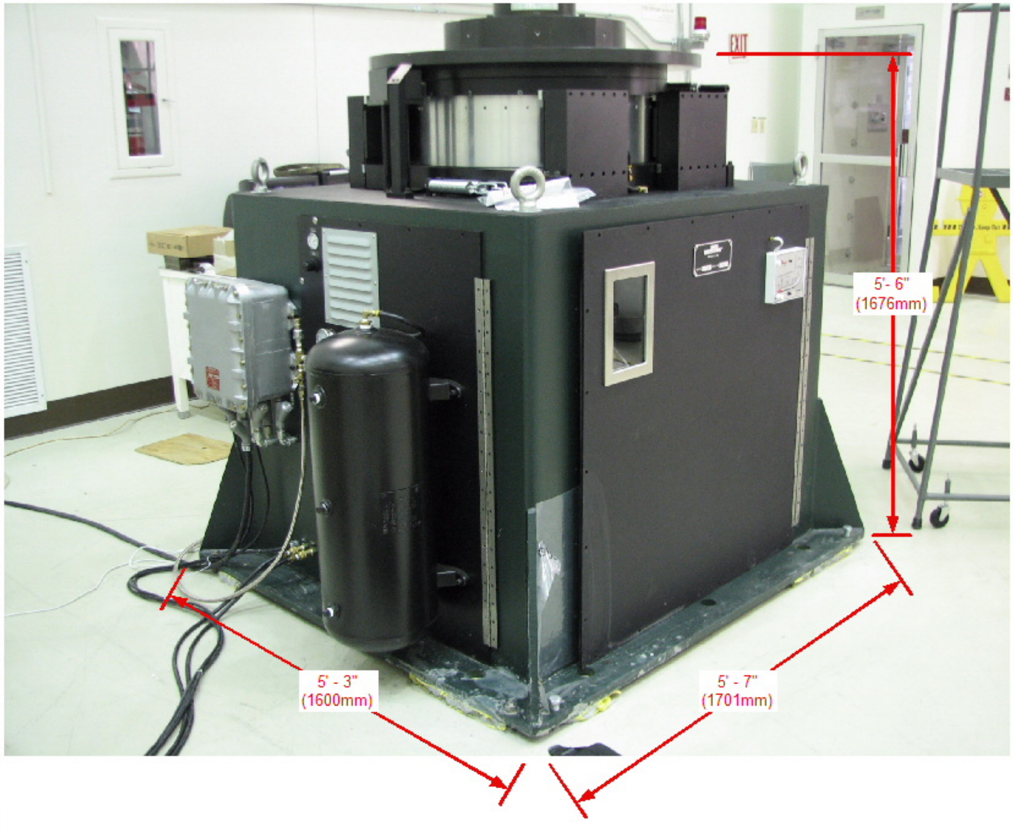
Maximum weight of Test Part and Fixture 226.7 kg (500 lbs)
Maximum CG Offset………………………… 2 inches
Maximum Moment during loading……………… 750 lb-in

Center of Gravity
Maximum offset Moment due to test part CG 500 lb-in
Moment Sensitivity (smallest detectable change) 0.25 lb-in
Moment Linearity 0.5%
Rotary Table Centering Error 0.0005 in
CG Error example on a 400 lb. part offset 0.1 in.:
Moment Sensitivity / Part weight 0.25 lb-in / 400 = .000625 in
Offset Linearity 0.1 in * 0.5% = .0005 in
Rotary Table Centering Error .0005 in
Total Error .001625 in

Moment of Inertia
Basic Accuracy +/- 0.25% of value
Tare MOI (typical) 315 lb-in^2
MOI Error for 30,000 LB-IN^2 part:
Typical Basic accuracy (0.25%) 75.0 lb-in^2
Tare MOI error (KGR500) 788 lb-in^2
Total 75.788 lb-in^2

Model POI 12000

The spin balance table is dynamic testing equipment that measures CG (center of gravity), MOI (moment of inertia), and POI (Product of inertia). The payload revolves about the centerline of the machine at different preset speeds depending on the type of measurement and the mode.



POI 12000 MASS PROPERTIES PRERFORMANCE SPECIFICATIONS

The instrument shall be capable of withstanding a downward force of 19,000 lb (8,636 kg), and an overturning moment of 40,000 lb-in (460,850 kg-mm) during loading of the payload.

Maximum Measurable Moment due to part offset CG…………16000 lb-in (184 kg-m)

Moment Resolution (smallest increment of moment display)…..0.27 lb-in (3.6 kg-mm)

Moment Accuracy…………………………………..0.1% of reading + 5 lb-in (57.6 kg-mm)

Maximum CG displacement (if not limited by moment)…………………12 in (305 mm)

Mechanical Centering Error (interface plate pilot)…………………..0.001" (0.0250 mm)

Testing Logistics

The spin table was re-located in four different times.

- First Time: It was installed to JPL/ETL, Bldg. 144-100 a cleanroom hi-bay on 08/08/2007.
  (To perform acceptance tests, train operators and write standard operating procedure)

- Second Time: It was moved to JPL/SAF Bldg. 179 Hi-bay #1 cleanroom hi-bay on 04/22/2010
  (To perform the flight mass measurements on the sub assemblies)

- Third Time: It was moved to KSC/PHSF a cleanroom hi-bay on 04/11/2011.
  (To perform the final flight mass measurements on the spacecraft)

- Forth Time: Moved back to JPL

The CG/MOI machine was only used at JPL/SAF

POI 12000 INSTALLATION AT JPL/ETL (Environmental Testing Laboratory)

The machine was installed at JPL for the acceptance testing and training in Bldg. 144 HI bay

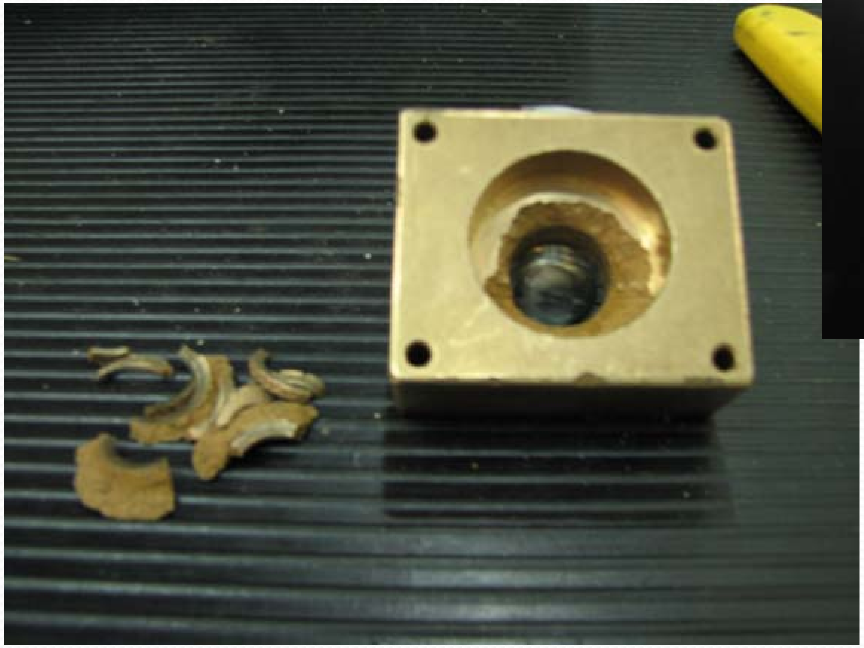
POI 12000 Spin Table

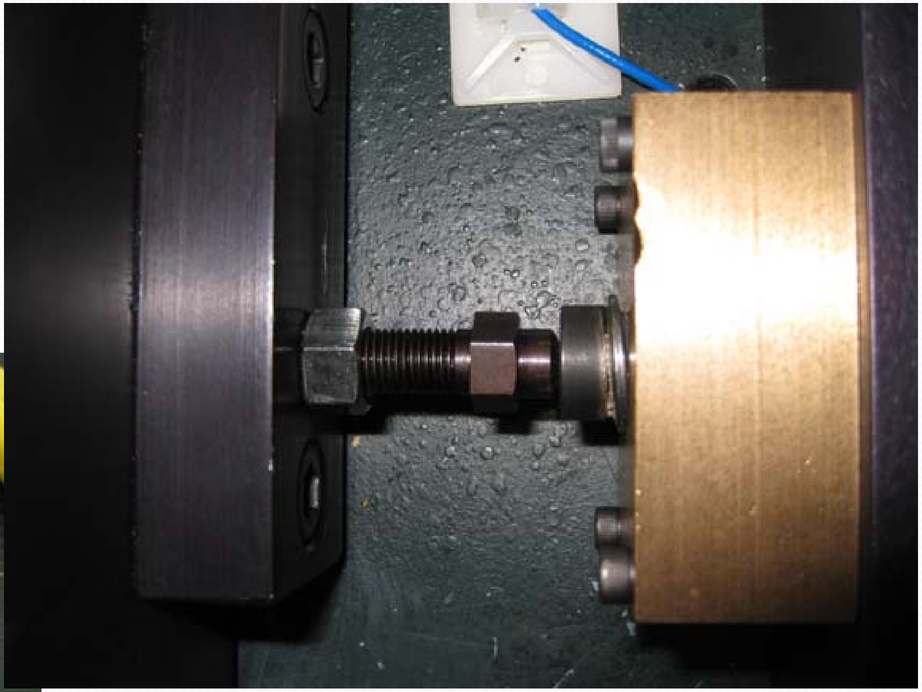
Misc. parts

Calibration Beam

POI 12000 INSTALLATION AT JPL/ETL (Environmental Testing Laboratory)

During the setup discovered damaged brass threaded bushing

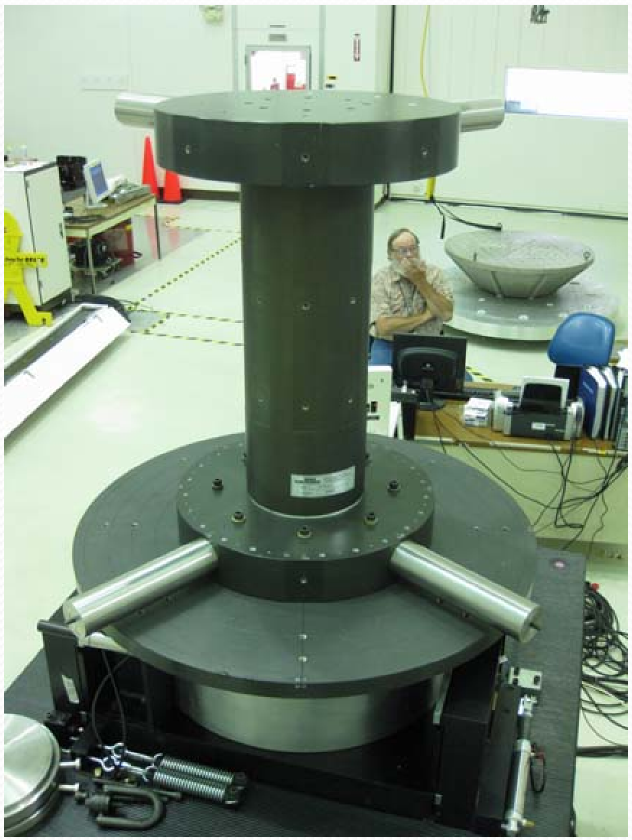




After investigating, found that machine was shipped from Connecticut to JPL on a rail car.

POI 12000 AT JPL/ETL (Environmental Testing Laboratory)

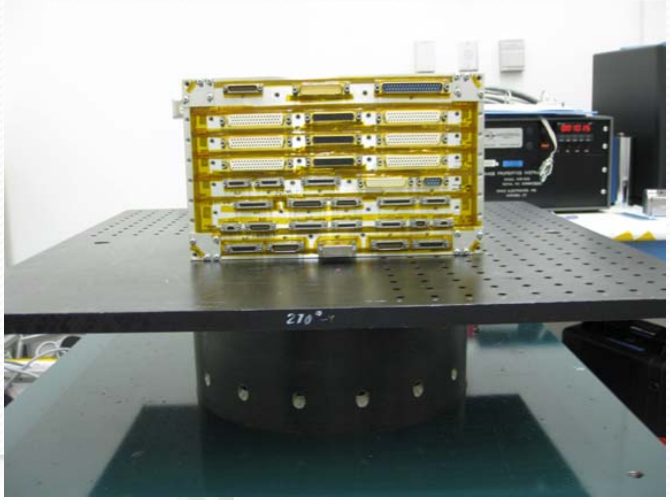
Calibration and Acceptance Tests



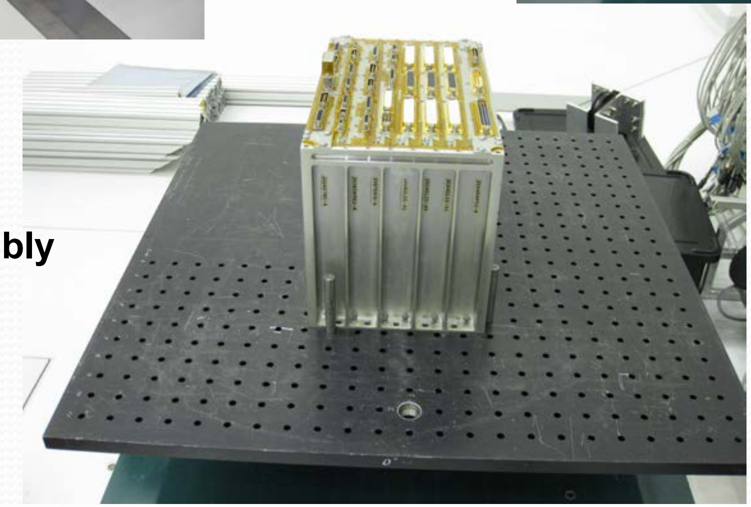
Calibration Rotor

Calibration Beam

KGR 500 AT JPL/SAF
(Spacecraft Assembly Facilities)



Flight Hardware Sub Assembly Mass Measurements

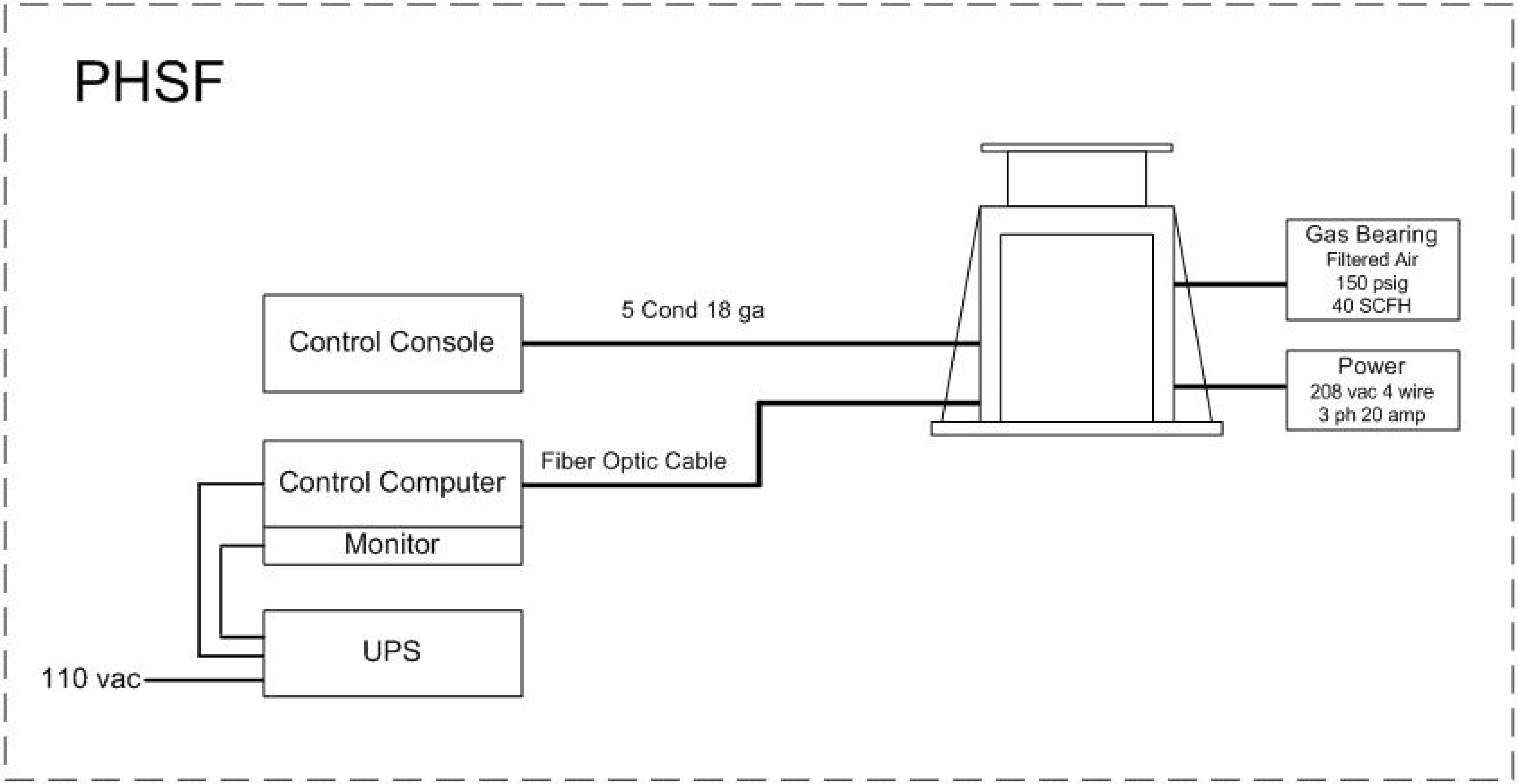


POI 12000 AT JPL/SAF
(Spacecraft Assembly Facilities)

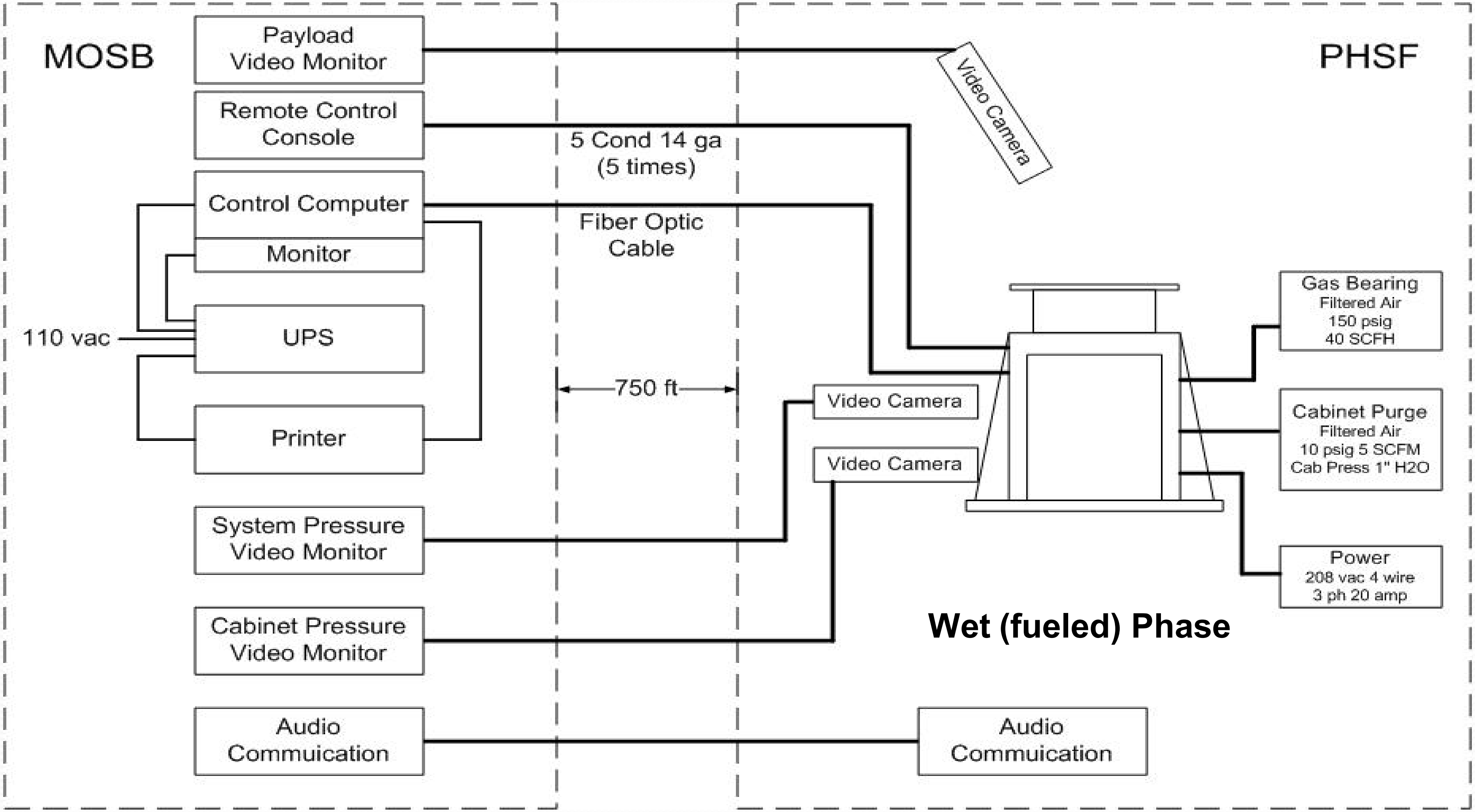
Flight Hardware Main Assembly Mass Measurements

Mass Measurements KSC (Kennedy Space Center)
PHSF (Payload Hazardous Servicing Facility)

Dry Phase
To perform calibration and verification runs after moving)



Mass Measurements KSC (Kennedy Space Center)
PHSF (Payload Hazardous Servicing Facility)
MOSB (Multi-Operation Support Building)



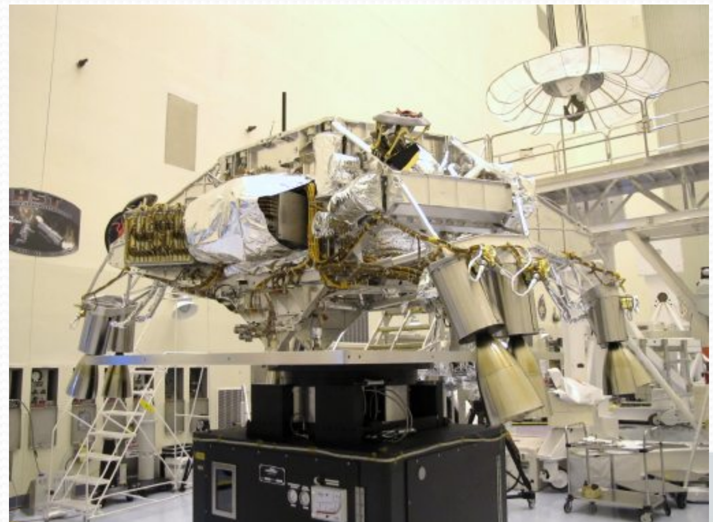
Wet (fueled) Phase

Mass Measurements KSC (Kennedy Space Center)

Arrival of the Curiosity Rover on the C-17

POI 12000 INSTALLATION KSC
(Kennedy Space Center)
PHSF (Payload Hazardous Servicing Facility)

Installing the two 75 kg offset weights



Descent Stage

Cruise Stage

Mass Measurements KSC (Kennedy Space Center)
PHSF (Payload Hazardous Servicing Facility)
MOSB (Multi-Operation Support Building)

Remote Operations
Control Room

POI 12000 INSTALLATION KSC (Kennedy Space Center)
PHSF (Payload Hazardous Servicing Facility)

30 RPM Complete Spacecraft
No Fuel

MSL Mass Properties Crew

Summary

- The mass properties measurements of the MSL spacecraft and rover was an arduous and demanding task. There were numerous people involved over a five year effort. It was a good learning experience for a lot of people.

- I want to thank Camille Marquis the Space Electronics field rep for helping us resolve some perplexing issues. Also Dan Coatta the JPL Dynamists and Nathanial Thompson the JPL mechanical engineer.

- The mass properties measurements of any spacecraft are very important to verify the dynamic properties that it will encounter during the mission. This was a life changing experience for the author because the measurements that we were taking were crucial to ensuring a successful landing on Mars.