MASS PROPERTY MEASUREMENTS OF THE MARS SCIENCE LABORATORY ROVER[1]

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## ABSTRACT

The NASA/JPL Mars Science Laboratory (MSL) spacecraft mass properties were measured on a spin balance table prior to launch. This paper discusses the requirements and issues encountered with the setup, qualification, and testing using the spin balance table, and the idiosyncrasies encountered with the test system. The final mass measurements were made in the Payload Hazardous Servicing Facility (PHSF) at Kennedy Space Center on the fully assembled and fueled spacecraft. This set of environmental tests required that the control system for the spin balance machine be at a remote location, which posed additional challenges to the operation of the machine.

## KEY WORDS

Center of Gravity, Mass, Moment of Inertia, Product of Inertia, Rover, Spacecraft

## INTRODUCTION

Before the Mars Science Laboratory (MSL) was launched to Mars, the Jet Propulsion Laboratory (JPL) Environmental Test Laboratory (ETL) personnel and vendors tested its mass properties.[2] The fundamental purpose of mass measurement testing is to measure the launch and in-flight mass properties to verify the design of hardware. Mass measurement testing was performed at two levels, the subsystem and the full-up spacecraft or system level. All the mass properties were measured on Space Electronics LLC measurement systems, the KGR 500 and the POI 12000. The subsystem level was usually performed on the smaller KGR 500with a maximum capacity of 500 lb. (226 kg) capacity. Full-up spacecraft or system testing was performed on the large (POI 12000) spin table with a maximum capacity of 12,000 lb (5443 kg). Mission: To search areas of Mars for past or present conditions favorable for life, and conditions capable of preserving a record of life.

### Mars Science Laboratory (Curiosity Rover)

Size: About the size of a small sport utility vehicle -- 10 feet long, 9 feet wide and 7 feet tall (about 3 m long, 2.7 m wide, and 2.2 m tall).

Arm Reach: About 7 feet (2.2 m)

Weight: 900 kg (2,000 lb)

Features: Geology lab, rocker-bogie suspension, rock-vaporizing laser, and many cameras

 This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. 

[2] Camille Marquis of Space Electronics LLC, Berlin, CT, provided documentation and technical support at JPL, Seth Chazanoff, backup operator, Dan Coatta, Nathanial Thompson, and Andrew Rose

Fully assembled MSL in JPL Spacecraft Assembly Facility clean room

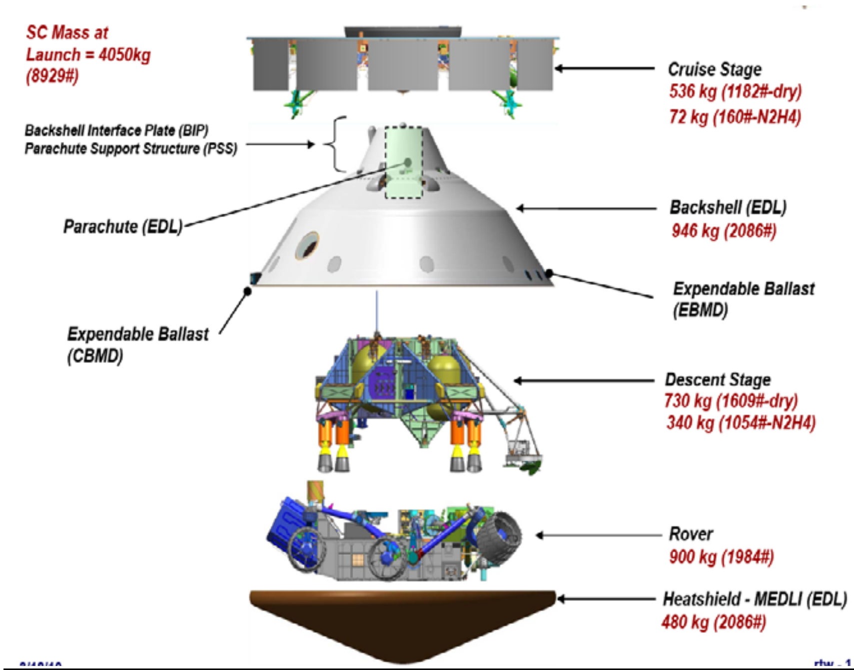
**Rover Science Instruments**

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

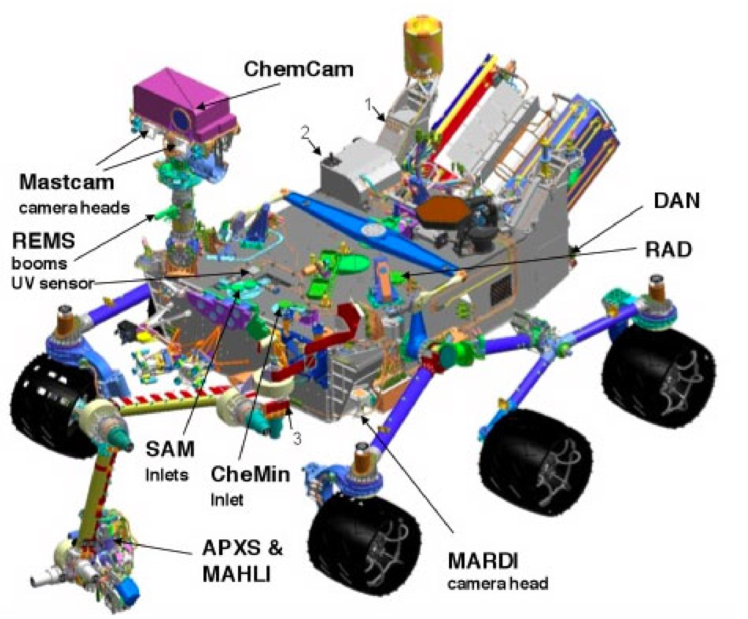
Spectrometers
- Alpha Particle X-Ray Spectrometer (APXS)
- Chemistry & Camera (ChemCam)
- Chemistry & Mineralogy X-Ray Diffraction/X-Ray Fluorescence Instrument (CheMin)
- Sample Analysis at Mars (SAM) Instrument Suite

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

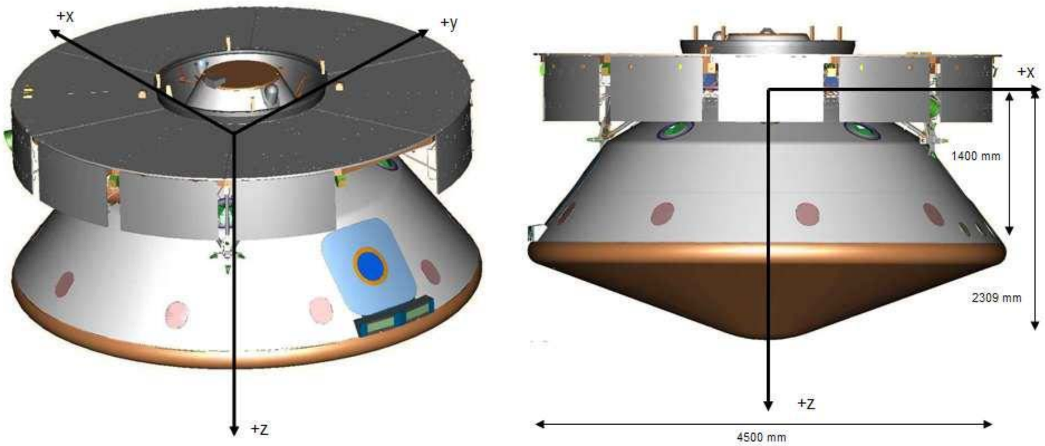
Environmental Sensors
- Rover Environmental Monitoring Station (REMS)
- Atmospheric Sensors
- Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI)



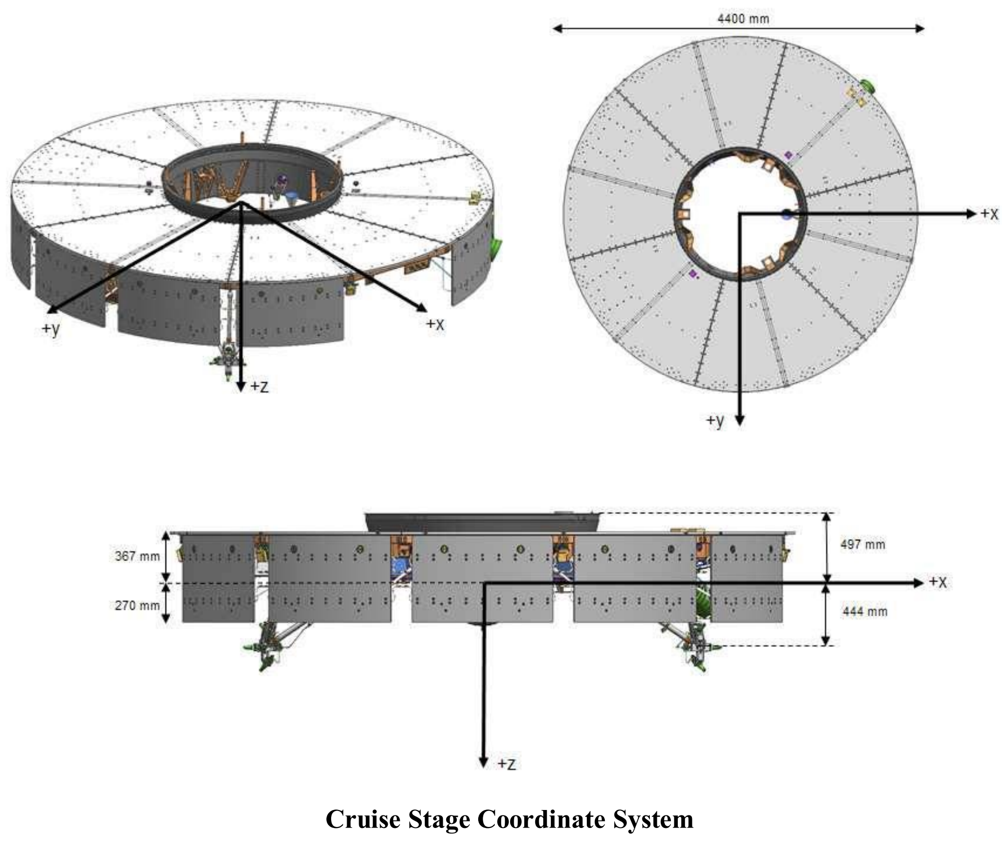

**Major Spacecraft Systems**



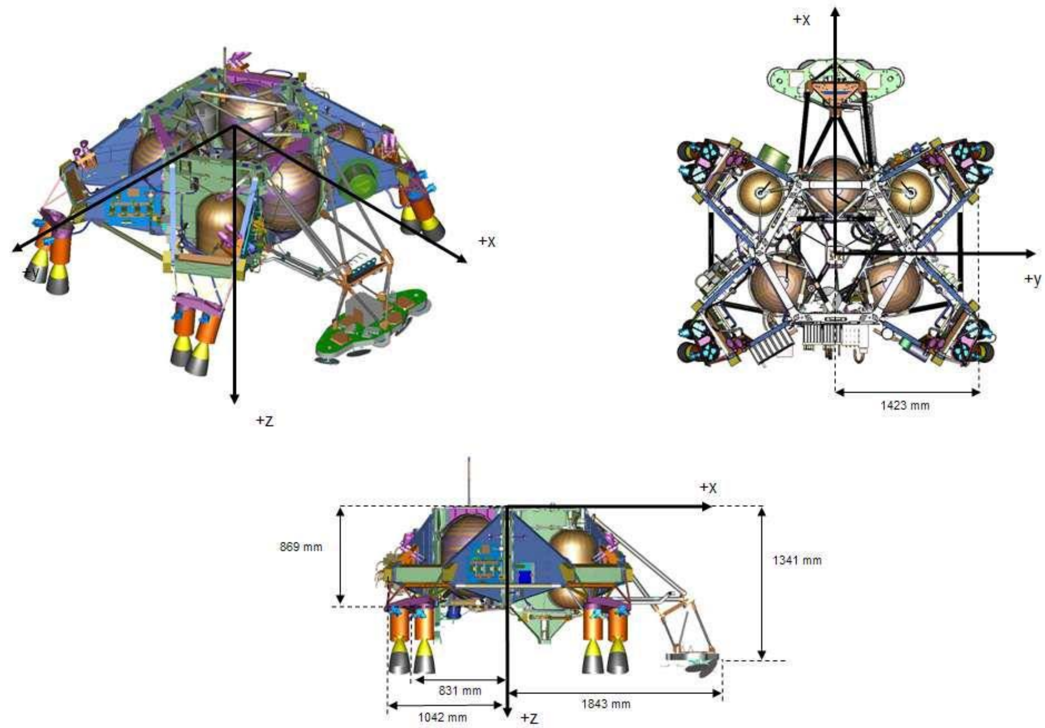

**Locations of the MSL science instruments on the deployed rover**



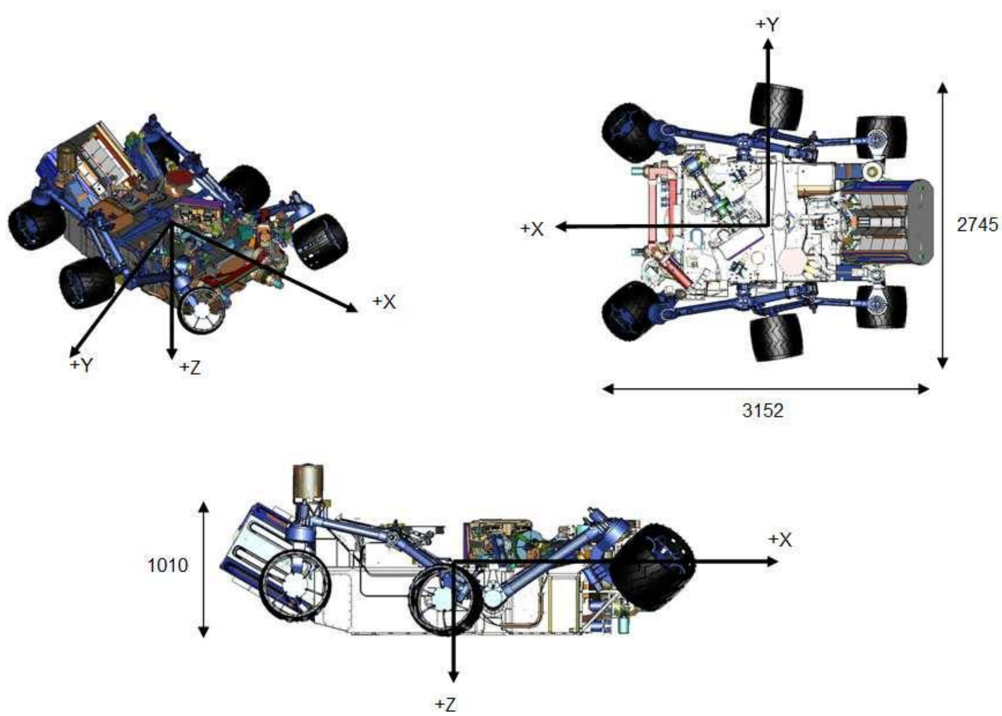

Spacecraft Coordinate System




**Cruise Stage Coordinate System**




**Descent Stage Coordinate System**




**Rover Coordinate System**

## MASS PROPERTIES REQUIREMENTS FOR THE SPACECRAFT

Requirement — The mass measurement of the Fueled Spacecraft at launch shall be to within 0.5%.

Compliance Explanation — The final mass measurement of the fueled spacecraft was performed on 10/24/2011. After accounting for puts and takes, the mass of the fueled spacecraft was found to be 3838.7 kg ± 16.7 kg. The mass uncertainty for the fueled spacecraft was therefore 0.4%, and the margin against the requirement was 0.1% of the fueled spacecraft mass.

### Spacecraft Moment of Inertia Knowledge

Requirement — The principal moments of inertia (MOI) (Ixx, Iyy, and Izz) of the dry spacecraft shall be known to within 5%, with 99.87% confidence per axis.

Compliance Explanation — The only MOI that was directly measured was Izz. The as-measured value of Izz on the spin table typically had an uncertainty of about 0.2%, giving a margin of 4.8% of the Izz value for the dry spacecraft.
The other MOIs were calculated analytically. To estimate the uncertainty of Ixx and Iyy, we compared the measured Izz values with their analytical estimates.

Table 1 below shows the difference between predicted and measured Izz values for various mass properties tests. Each of these tests was the first time the hardware was measured, so the predicted Izz was based solely on an analytical estimate. Over five tests, the maximum Izz analytical error was 4.1%, and the average analytical error was 1.9%.

Because Ixx and Iyy were calculated using the same analytical model as Izz, we concluded that the analytical error for Ixx and Iyy was less than or equal to 4.1%, and the margin against this requirement was 0.9% of the Ixx and Iyy values for the dry spacecraft.

**Table 1. Difference between predicted and measured Izz values**

| Test | Izz (kg-m$^2$) | | Percent Difference |
|---|---|---|---|
| | Predicted | Measured | |
| Rover (RV1) | 768.9 | 772.2 | 0.4 |
| Descent Stage (DS1) | 713.3 | 723.6 | 1.4 |
| Backshell (BS1) | 1039.9 | 1039.6 | 0.0 |
| Heatshield (AS1) | 1318.1 | 1365.0 | 3.4 |
| Cruise Stage (CS1) | 1115.1 | 1163.1 | 4.1 |
| **Max Difference (%)** | | **4.1** | |

## INTRODUCTION TO THE MASS PROPERTIES EQUIPMENT

The mass properties measurement systems that were required to measure MSL consisted of two types of equipment. One was the KGR500 for masses up to 227 kg (500 lb). The other was the POI12000 or the “spin table” for masses as great as 5443 kg (12000 lb)

The model KGR500 is a general purpose mass properties instrument capable of testing parts whose combined weight, including the test fixture, does not exceed 500 lb. The KGR instrument determines the MOI of the test object and locates its center of gravity CG. A computer interfaces with the system to control machine operation, performs calculation, and print the test results.

The POI 12000 spin balance table is a piece of dynamic testing equipment that measures CG, MOI, and (product of inertia (POI). The payload revolves about the centerline of the machine at different preset speeds depending on the type of measurement and the mode.

Both mass measurement systems use nitrogen purged spherical gas bearing which supports the payload and rotates without any drag or friction.

## KGR 500 CG/MOI

KGR 500 installed at JPL

*KGR 500 MASS PROPRETIES PRERFORMANCE SPECIFICATIONS*

| | |
|---|---|
| Maximum weight of Test Part and Fixture | 227kg (500 lb) |
| Maximum CG Offset | 50.8 cm (2 in.) |
| Maximum Moment during loading | 750 lb-in. |

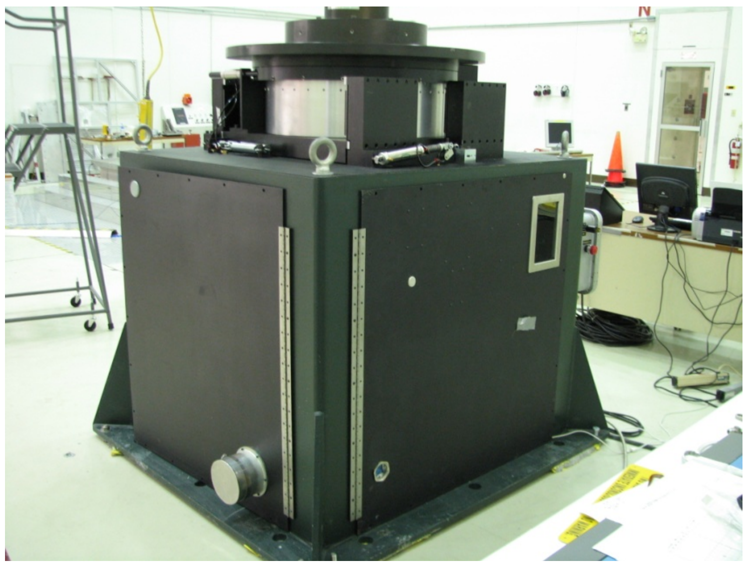
**Center of Gravity**

| | |
|---|---|
| Maximum offset Moment due to test part CG | (9500 lb-in.) |
| Moment Sensitivity (smallest detectable change) | (0.25 lb-in.) |
| Moment Linearity 0.5% | |
| Rotary Table Centering Error | 0.0127 (0.0005 in.) |
| CG Error example on a 400 lb part offset | 0.1 in.: |
| Moment Sensitivity / Part weight | (0.25 lb-in / 400 = 0.000625 in.) |
| Offset Linearity 0.1 in * 0.5% | 0.0127 (0.0005 in.) |
| | |
| Total Error | 0.00412242 cm (0.001625 in.) |

**Moment of Inertia**

| | |
|---|---|
| Basic Accuracy | ± 0.25% of value |
| Tare MOI (typical) | 315 $lb\text{-}in^2$ |
| MOI Error for | 30,000 $lb\text{-}in.^2$ part: |
| Typical Basic accuracy | (0.25-75.0 $lb\text{-}in.^2$ |
| Tare MOI error (KGR500) | 788 $lb\text{-}in^2$ |
| Total | 75.788 $lb\text{-}in.^2$ |

## POI 12000 CG/MOI/POI



POI 12000 Installed in JPL

*POI 12000 Mass Properties Performance 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 in. (0.0250 mm |

Maximum Static Unbalance—The maximum static unbalance (CG offset multiplied by weight) which can be measured (when product of inertia unbalance is negligible) is defined by the equation:

Maximum moment ______________________ *(lb-in.)* = $(563 \times 10^6)/(RPM^2 \times (HCG + 46)) + 35207$

Where $H_{CG}$ = CG height in inches

Maximum static unbalance (16000 lb-in)*constant (35207)= $(563 \times 10^6)$

______________

Transducer separation = 46 in(1168.4 mm)

Constant=35207

Table 2. This results in the following limits

| RPM | 30-in. CG Height (lb-in) | 762 mm CG Height kg-mm | 60-in. CG Height (lb-in.) | 1524 mm CG Height (kg-mm) |
|---|---|---|---|---|
| 0 (static) | 16000 | 18,4340 | 16000 | 18,4340 |
| 30 | 5437 | 62641 | 4313 | 46,691 |
| 50 | 2501 | 28815 | 1876 | 21,614 |
| 100 | 708 | 8157 | 514 | 5922 |
| 200 | 183 | 2108 | 131 | 1509 |

Maximum Static Unbalance—The maximum static unbalance CG offset multiplied by weight, which can be measured statically is 16000 lb-in. (184340 kg-mm)

Maximum Moment of Inertia—The largest moment of inertia that can be measured with the specified accuracy is 25,000,000 lb-in$^2$. Larger moments of inertia may be measured with some loss of accuracy.

*LIMITATIONS ON TEST PART*

Weight—The machine can support, measure, and balance within the minimum allowable residual unbalance (UMAR) of the machine, payloads (part + fixture) weighing 12000 pounds (5440 kg) or less.

Part Height—The machine has no obstruction or limitations to the total height of the payload. There is a CG height limit (see below).

CG Height—The instrument can measure a 8000 lb. (3600 kg) payload with a CG height of 100 in. (2540 mm) above the mounting plate at a spin rate of 50 rpm, provided the unbalance also meets the specified limits. If the limits specified by the following formula are exceeded, then accuracy may be reduced:

$$W * HCG^2 * RPM^2 \leq 7.0 * 10^{10} \text{ lb-in.}^2/\text{min}^2$$

$$(W * HCG^2 * RPM^2 \leq 20.5*10^6 \text{ kg-m}^2/\text{min}^2)$$

Where: W = mass of test object in kilograms,
$H_{CG}$ = distance from top of interface plate to test object center of gravity in meters.
RPM = spin speed in revolutions per minute.

Static Unbalance (measured dynamically)—The following Table 3 defines the static unbalance measuring sensitivity:

Table 3. static unbalance measuring sensitivity

| RPM | $H_{CG}$ = 30 in. | $H_{CG}$ = 762 mm |
|---|---|---|
| 50 | 0.06 lb-in. | 0.069 kg-mm |
| 100 | 0.02 lb-in. | 0.24 kg-mm |
| 200 | 0.01 lb-in. | 0.12 kg-mm |

Total static unbalance measurement error is equal to 5% of the measured static unbalance plus the static unbalance measurement sensitivity at the measurement RPM.

The test operators can meet the minimum allowable residual (MAR) specifications for dynamic and static unbalance f they correct both static and dynamic unbalance during the balancing process. A large residual static unbalance increases the minimum achievable readout for dynamic unbalance. Conversely, a large dynamic unbalance increases the minimum achievable readout for static unbalance when measured dynamically.

Moment of Inertia Measurement Error—The maximum error for MOI measurement shall be less than the sum of 0.15% of test part inertia plus 110 lb-in$^2$ (32190 kg-mm$^2$) plus the total tare inertia. The tare MOI of the instrument itself limits the minimum moment of inertia that can be accurately measured. The recommended minimum is 30,000 lb-in.$^2$ (8.78 kg-m$^2$)
Electrical Description—The spin table has only two electrical components that drive the system: a slow-speed indexing motor and a high-speed spin balancing motor. Both have multiple safety interlocks that stop the machine in case of all anomalies. The machine operates at 208 VAC, 3-phase, and 20-A power. Over-voltage, over-current, and ground fault protection are provided by the building electrical facilities. The interconnect box design also includes a fuse block for over-current protection.

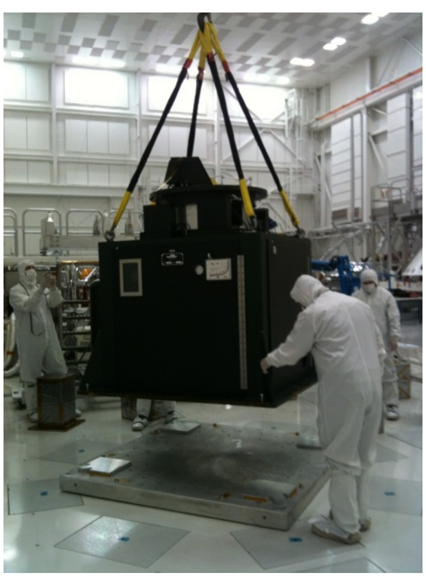
**POI 12000 INSTALLATION AT JPL**

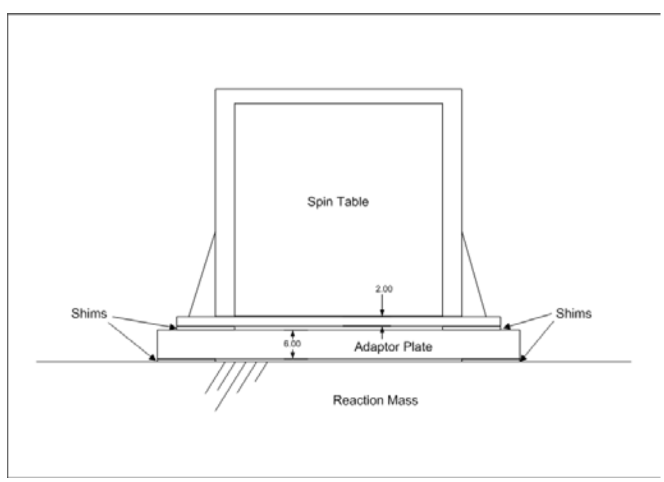
**Delivered to JPL from Space Electronics – 08/08/2007**
Building 144-100, Environmental Testing Laboratory

The table was moved into the Building 144-100 high bay/cleanroom. ETL personnel installed the equipment with help from the Space Electronics service technician. The table was leveled using mortar on all four corners to support the load. During the setup, we identified a bronze bearing that had been damaged. This bearing changes the table from the POI mode to the safe mode. After an investigation, we found out that the spin table had been shipped on a railroad car, which caused a hammering of the bearing. We checked even more carefully during the balance of the installation but did not find any other damage. This impressed the author with the design and the building practices of a very sensitive piece of equipment.

During the familiarization and training phase, we had a facility issue with controlling the temperature in the room. It fluctuated about 7 degrees C during an hour while we were performing some extended acceptance testing. We found the stability of the machine measurements were not within the factory specification. Once the facility issue was resolved we continued to run the acceptance tests,
During this phase the JPL operators were trained by Space Electronic and the JPL SOP (standard operating procedure) for the table was written.

**Moved to SAF (Spacecraft Assembly Facility) - 04/21/2010**
Set up Spin table in Building 179 (High Bay 1)





**Installing the spin table in the high bay/cleanroom using the adapter plate and shims**

**MGSE Functional Failure Modes and Effects Analysis (FFMEA)**
There is a requirement that a failure analysis shall be performed on every ground support equipment that interfaces with flight hardware. The matrix that was developed was so large that this paper only includes the more important failure modes and causes. The final matrix shows the failure effects controls/mitigations, and the action plans if anything did happen. The failure analysis showed that all the possibilities of problems that could happen were identified and that they would not harm the flight hardware during the mass measurements.

Gas / Pneumatic System
Facility $GN_2$ supply is interrupted

- Clogged inline filter
- Mechanical problem with facility equipment
- Facility $GN_2$ supply pressure regulator diaphragm leaks
- Aging of regulator
- External $GN_2$ hose rupturing
- Manufacturing defect

Computer/Communication/ Electronics

- Operator Error
- Incorrect speed entered by operator when in the POI setup screen
- Incorrect ramp rate entered by operator when in the POI setup screen
- Communication error between the control modules and the computer software
- Failure of one of the control modules
- Computer malfunctions
- Computer/hard, drive failure

Workmanship, component random failure

- Loss of facility power
- Facility problem
- Force Prediction (in POI testing) disabled
- Computer/drive motor controller failure

Other

- Hold down bolts for adaptor plates or test article missing or loose
- Flight technician's error

**MASS MEASUREMENTS**

The spacecraft has a multitude of science instruments that required the measurement of CG (center of gravity), MOI (Moment of inertia), and POI (Product of inertia). All of the instruments listed below required that the CG and MOI dictated that they were measured on the KGR 500 because of the small mass weight of the instruments. The MSL

*Spacecraft Instrument Suite*

| **PAYLOAD NAME** | **Mass (kg)** |
|---|---|
| **APXS** Alpha Particle X-Ray Spectrometer | 1.6 |
| **ChemCam** Chemistry and Camera | 10.9 |
| **CheMin** Chemistry and Mineralogy X-ray Diffraction Instrument | 10.1 |
| **DAN** Dynamic Albedo of Neutrons | 4.7 |
| **MAHLI** Mars Hand Lens Imager | 0.6 |
| **MARDI** Mars Descent Imager | 0.6 |
| **Mastcam** Mast Camera | 1.7 |

| | |
|---|---|
| **MMM DEA** | 2.1 |
| **RAD** Radiation Assessment Detector | 1.8 |
| **REMS** Rover Environmental Monitoring Station | 1.2 |
| **SAM** Sample Analysis at Mars | 39.9 |
| **MEDLI MSL EDL** ( Entry Descent and Landing) Instrument | 14.1 |
| Total on rover | 75.2 |
| Overall Total | 89.3 |

During the mass measurements phase at JPL we experienced only a few issues that we had to resolve. One of the problems was that we were trying to measure the cruise stage a very large diameter structure about 4400 mm (14.5 ft). The top surface was flat because of the solar array, but the bottom was open with exposed struts. The goal was to spin it at 30 RPM, but because of the air resistance we could not achieve the needed RPM speed. One proposal was to build a temporary tent around the machine and the part and partially fill it with helium. This proposal was rejected because of the delay in the schedule, cost, and the space in the hi-bay that it would require. The decision was made to have Space Electronics make software changes that would allow the program to increase the power to the motor to compensate for the drag.

Another issue was that the spin table was dynamically proof tested at the maximum moment the spin table was designed to measure. This damaged a force transducer. However, it was a good test result because it showed that the spin table can handle the abuse and be field repairable in just such an occurrence.

**Moved to KSC (Kennedy Space Center) – 04/10/2011**

Set up spin table in PHSF (Payload Hazardous Servicing Facility)

The spin table was installed in the KSC PHSF high bay/cleanroom using the adapter plate and shims which was the same installation methods as those used at JPL in Building 179 (SAF). Two different electrical and pneumatic connection configurations where used, one for the dry phase and another for the wet phase (with the fuel tanks full with hydrazine).

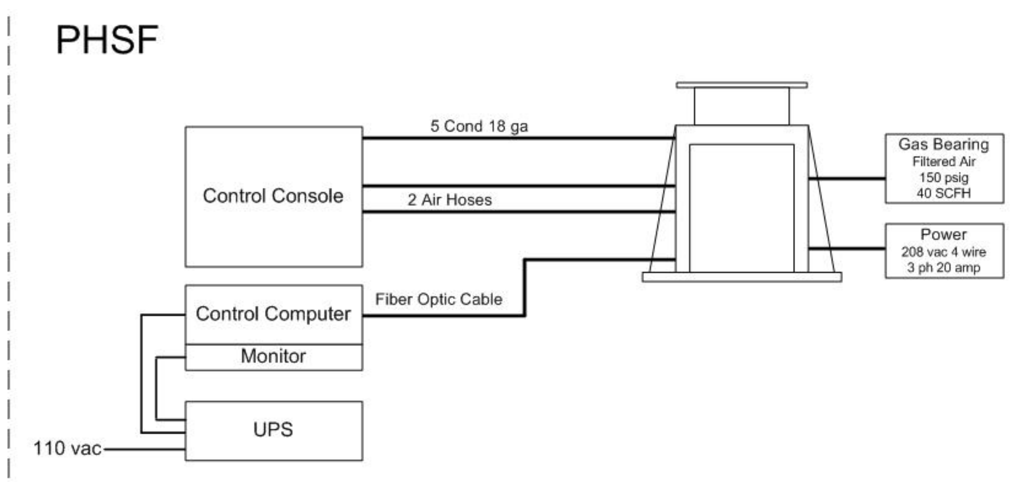
During the initial setup/verification (dry) phase, there were decisions that we had to make. The location of the table was identified, But because there were existing anchors in the floor that were used for mass properties measurement configurations of previous projects we decided to use them as long as the KSC personnel proofed them to our requirements. We had to decide on a table orientation that would work with the facility connections and the video cameras that needed to be used during the wet phase.

**The processes of installing the spin table for hazardous operations are quite involved. Below are the steps that we used to install the table in the PHSF.**

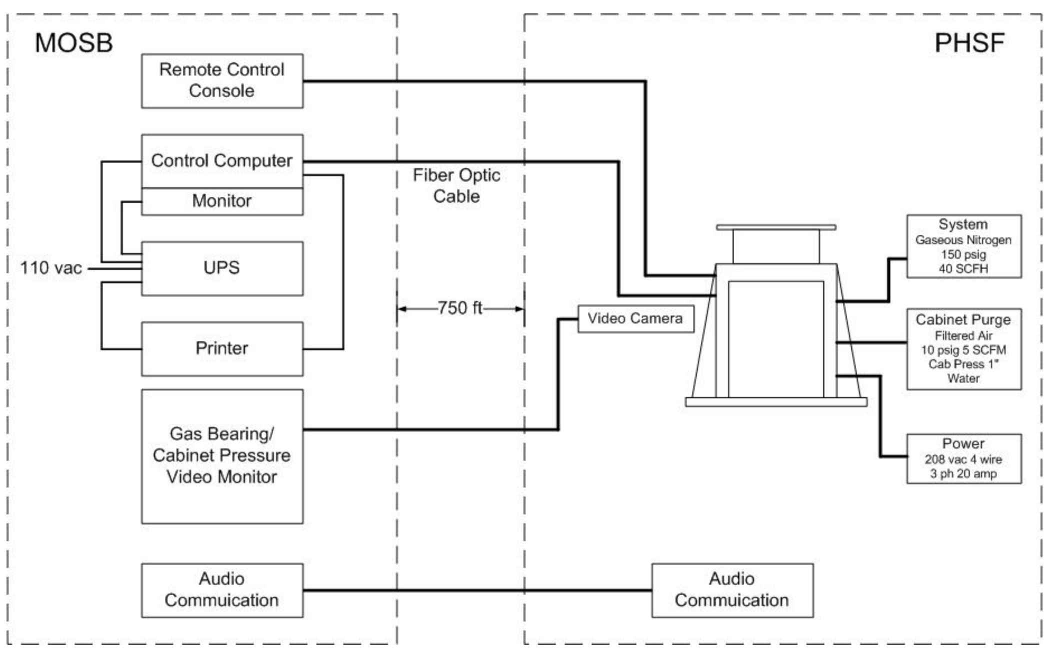
1. Unload table from the truck and stage in airlock.
2. Inventory all the support equipment.
3. Clean/wipe down everything with alcohol.
4. Install adaptor plate using shims to level it.
5. Move spin table into hi-bay/cleanroom and install the spin table to the adaptor plate using shims to level it.
6. Connect electrical cables from table to computer/control box.
7. Connect fiber optics cable from table to computer.
8. Connect the $GN_2$ supply hose from the facility to the regulating panel for the pneumatic system.
9. Connect the $GN_2$ supply hose from the facility to the regulating panel then to the table base cabinet for supplying a positive pressure of inert gas.
10. Power up the system, remove the lock-down brackets, and adjust the gaps used to align the critical parts of the system.
11. Calibrate system.
12. Perform the acceptance tests.

13. Perform the verification tests.
14. Measure the mass properties of the main parts of the spacecraft.

Two different electrical and pneumatic connection configurations where used, one for the dry phase and another for the wet phase (with the fuel tanks full with hydrazine).




**Configuration of system during nonhazardous (dry) operations phase**




**Configuration of System during Hazardous Operations Phase**

**Complete spacecraft including the rover on the POI12000 spin balance table in the KSC PHSF high bay**

**LESSONS LEARNED**

When testing a mass that has a windage concern, always start at a slower speed and gradually increase.

Do not push the limits of the machine when dynamically proof loading.

Verify the temperature of the room that the measurements are being measured in, and monitor regularly at all times. Temperature swings of ± 3 degrees Celsius will affect the measurements.

**SUMMARY AND CONCLUSIONS**

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.

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