Pancam Mast Assembly on Mars Rover

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Abstract

The Pancam Mast Assembly (PMA) for the 2003 Mars Rover is a deployable structure that provides an elevated platform for several cameras. The PMA consists of several mechanisms that enable it to raise the cameras as well as point the cameras in all directions. This paper describes the function of the various mechanisms as well as a description of the mechanisms and some test parameters.

Designing these mechanisms to operate on the surface of Mars presented several challenges. Typical spacecraft mechanisms must operate in zero-gravity and high vacuum. These mechanisms needed to be designed to operate in Martian gravity and atmosphere.

Testing conditions were a little easier because the mechanisms are not required to operate in a vacuum. All of the materials are vacuum compatible, but the mechanisms were tested in a dry nitrogen atmosphere at various cold temperatures.

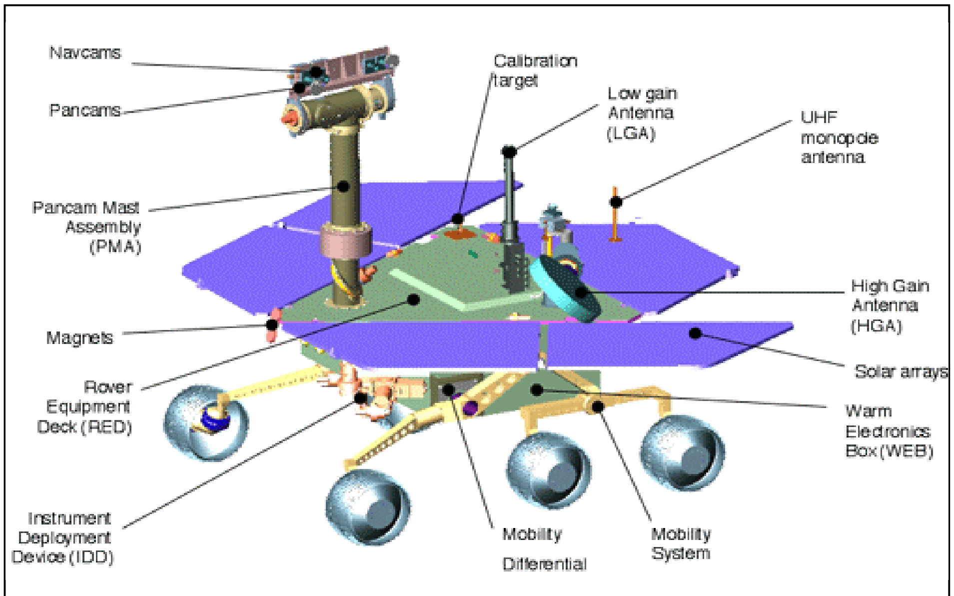

Figure 1. Rover Configuration - Deployed

Introduction

The Pancam Mast Assembly is one of the two main mechanical systems that mount on the top of the Rover Equipment Deck (RED); the other being the High Gain Antenna System (Figure 1). The mast lays flat against the RED from launch to landing and is held in place to the RED with a Launch Restraint Mechanism. After the Rover has landed and the Solar Arrays have deployed, the Launch Restraint is released. The Mast Deployment Drive then elevates the mast from horizontal to vertical to give the cameras better visibility. The Azimuth Drive rotates the upper part of the mast left and right while the Camera Bar Drive raises and lowers the cameras. The Mini Thermal Emissivity Spectrometer, or Mini-TES, is located beneath the RED and looks up through the center of the PMA like a periscope. An

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adjustable mirror at the top of the mast allows the Mini-TES to look up and down independently of the other camera.

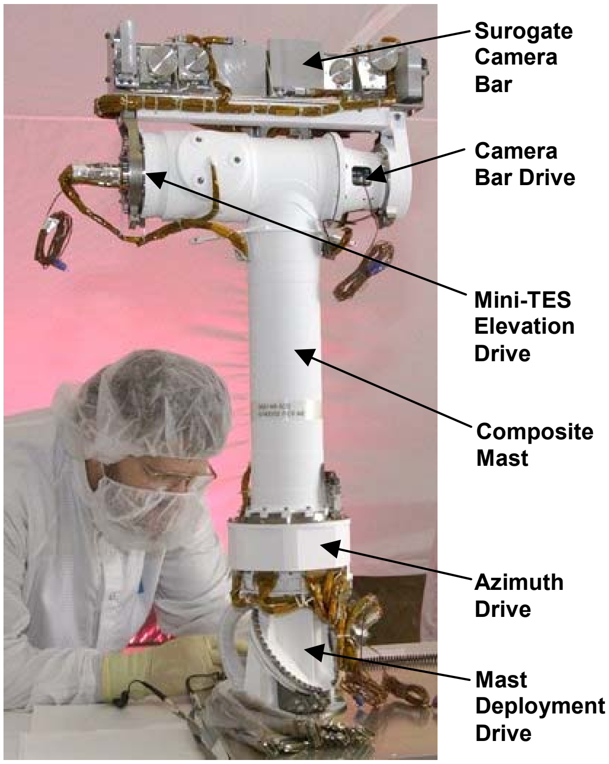


Figure 2. PMA in the Deployed Configuration

PMA Mechanism Overview (Figure 2)

- Launch Restraint holds the mast to the RED and releases on command. Allows for Rover flexibility and thermal expansion.
- Mast Deployment Drive moves mast from the horizontal position to the vertical position. Latches into place when deployed. Contains seals for light and dust.
- Azimuth Drive provides 360 degrees of rotation. Rotates Pancams, Navcams, and Mini-TES mirrors in azimuth.
- Camera-bar Elevation Drive rotates Pancams and Navcams up and down. Hard stop at one end of travel is used to provide pointing reference position.
- Mini-TES Elevation Drive rotates the Mini-TES mirror up and down independently of the camera bar. Also rotates the mirror to point at the internal calibration target. Calibration position closes the aperture to provide dust and stray light protection during calibration. Hard stops provide pointing reference position.

Stowed Configuration

In the stowed configuration, the PMA lays against the equipment deck under the parachute canister as shown in Figure 3. The deck is covered with solar cells except for specific areas reserved for attachments. The Mast Deployment Drive supports the mast at the base but the “head” of the mast needed additional support to withstand the launch and landing loads. The launch restraint mechanism secures the mast-head in two places and when combined with the MDD, results in a three point mount. In addition, the solar panels fold up against the parachute canister to form a pyramid. Three-dimensional CAD modeling was essential for packaging the PMA in the required envelope. Note that the camera bar assembly is tilted toward the center to avoid contact with the solar panel. This volume is also shared with the High Gain Antenna and Low Gain Antenna. Clearance was required to prevent damage to the fragile solar cells mounted on the inside of the deployable panels during launch and landing.

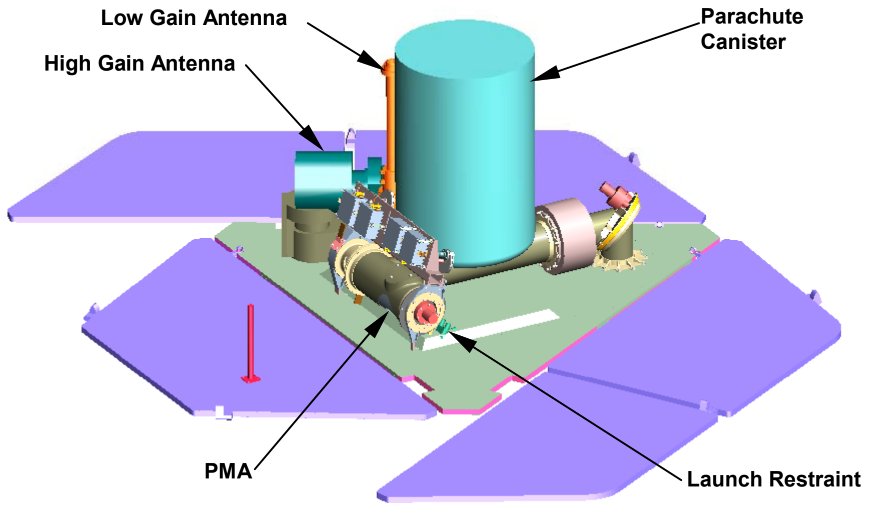


Figure 3 -PMA Stowed

Launch Restraint Mechanism

The first mechanism to operate is the Launch Restraint System. The PMA must be held down to the Rover deck during launch, flight and landing. After the Rover lands and the solar panels are opened, the launch restraint must release to allow the PMA to deploy. In addition, the mechanism that raises and lower the cameras must also be constrained to prevent damage. The customer directed that redundant, pyrotechnically actuated pin-pullers would be used to engage (or disengage) the launch restraints.

The biggest challenge for launch restraint mechanism was to provide a launch lock that would not over constrain the system or be too complicated. There is significant differential movement due to the difference in thermal expansion between the mast and the Rover deck. Also, the Rover deck is somewhat flexible. The restraint system must allow movement along the axis of the mast yet provide restrain in the other two axes. Another constraint is that the top of the rover is a honeycomb panel assembly covered almost entirely with solar cells. Only a few small areas were allocated to support the PMA in the stowed position.

Basic Requirements:
• Hold PMA to deck • Constrain PMA rotation to protect MDD gear train • Constrain Camera Bar rotation to protect Camera Bar Drive gear train • Use maximum of 3 pin-pullers (only 2 implemented) • Accommodate thermal distortion of deck • Allow PMA conical deployment

<u>Mast Restraint</u>

The primary launch restraint function is to secure the mast-head to the Rover deck. This is accomplished by attaching a bracket at the top of the mast that features two "ears" protruding to the side (Figure 4). These ears contain self-aligning journals in the form of spherical bearings. Each spherical bearings fits into a precision clevis or yoke, which are then pinned into place using the above mentioned pin-pullers.

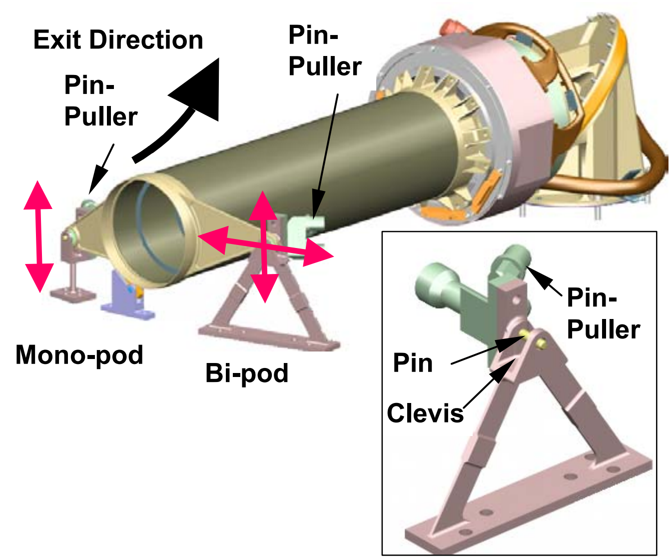


Figure 4. PMA Launch Restraint (Mast-head structure removed for clarity)

The launch restraint system is designed so that the stowed PMA is not over constrained. This is accomplished by making one of the clevis supports in the form of a bi-pod to take lateral and vertical loads. The other clevis support is a simple mono-pod that only takes vertical loads. In this way, the mast-head is prevented from rotating but allowed to expand as needed. The pin-pullers are located at the top of the clevis supports. When deployment is required, a signal is given to actuate the pin-pullers. The securing pins are thereby pulled out of the spherical bearings and the mast is free to deploy.

<u>Mast Launch Restraint summary</u>:

- The bi-pod mount constrains in vertical and horizontal only
- The mono-pod constrains in vertical axis only
- Together they constrain rotation about the mast axis
- Spherical bearing used for self aligning journal
- Dissimilar metals used for sliding surfaces

<u>Camera Bar Restraint</u>

The second function of the launch restraint is to constrain the camera bar. The camera bar assembly is discussed in more detail later in the paper. For this section, however, it is important to note that the camera bar imparts a significant load to the drive motor during launch and landing. The packaging is very tight as shown in Figure 5. Any appreciable movement of the camera bar while the solar panels are folded up would damage the solar cells.

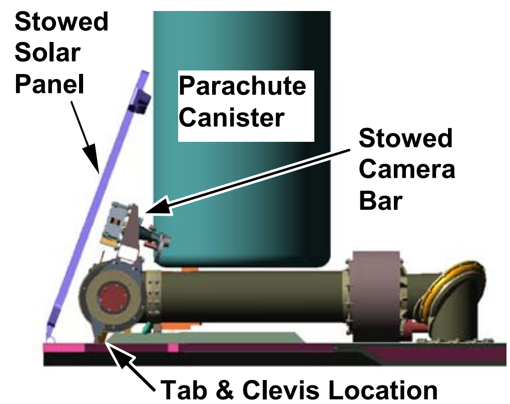


Figure 5. Stowed Configuration

The customer requested that the quantity of pin-pullers be minimized to help reduce complexity and mass so one of the design goals was to avoid the use of any pin-pullers with the camera bar restraint. The design goal, therefore, was to combine the function of securing the mast to the deck with the function of securing the camera bar drive.

The camera bar features two small protrusions or "tabs"; one on each end as shown in Figure 6. These tabs rotate with the camera bar. The mast-head also features two tabs, but these are fixed to the mast-head. In the stowed position, the rotating tabs on the camera bar contact the fixed tabs on the mast-head. A floating clevis captures each tab pair, thereby preventing the camera bar from rotating with respect to the camera head. Each clevis is mounted on a compliant support so that the tab pairs can move with respect to the Rover deck but are still captured with respect to each other. As the mast deploys, the tab pairs are no longer captured allowing movement of the Camera Bar Drive. Note that after the mast starts to deploy, the camera bar no longer needs to be secured. This design uses the action of lifting the mast off of the Rover desk to release the camera bar.

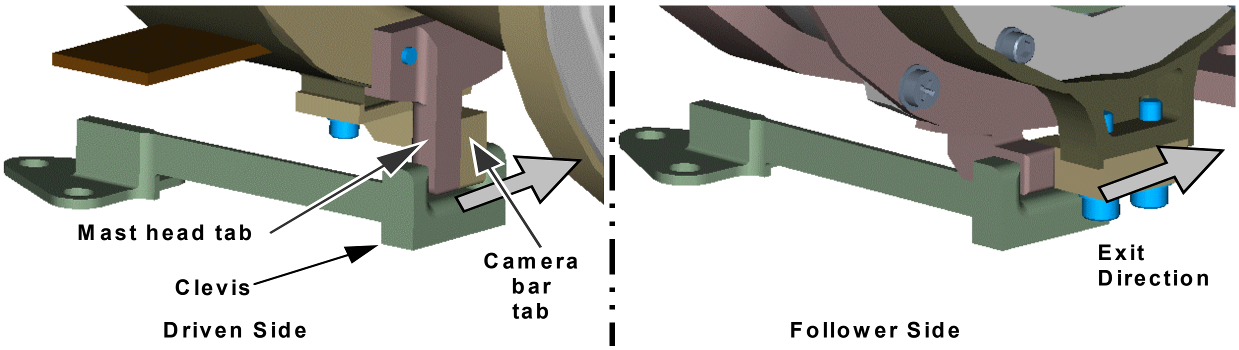


Figure 6. Camera Bar Restraint Components

The clevis surfaces have a slight spherical profile to allow relative rotation and have a slight amount of clearance to avoid binding. As the mast deploys, the tabs pull out of the clevises, which are attached to the deck. The tabs are then free to separate and the camera bar drive then controls the rotation of the camera bar. The materials are carefully chosen and the surfaces are coated to limit the possibility of galling and binding. Mockups of this system were built early in the design to verify the performance. Vibration testing of the final hardware resulted in scuffing of the coated surfaces but no failure of the coatings or galling of the surfaces.

<u>Camera Bar Restraint summary</u>:

- Constrains Camera Bar only in rotation relative to mast-head
- Only engaged in stowed configuration
- Flexible support eliminates over-constrained condition
- Imparts slight friction during deployment

Mast Deployment Drive (MDD)

The second mechanism to operate is the Mast Deployment Drive (MDD). This mechanism drives the mast from horizontal to vertical. The mast is stowed against the Rover Equipment Deck in the horizontal position from launch to landing. On command, the MDD moves the mast into the vertical position where it is latched in place. The MDD also handles the large bundle of wires that are required to operate the cameras and other mechanisms.

Requirement Summary:	Interfaces:
• Drive mast from horizontal to vertical • Provide optical path when deployed • High stiffness • Control & support electrical cabling • “Reasonable” deployment time • Keep dust out	• Base bolts to RED • 5 Electrical cables & connectors to RED • Top bolts to Azimuth Drive • 4 Electrical cables & to Az Drive • 1 Electrical cable to motors

Early in the program, a need was established for a stiffer deployment mechanism for the PMA. The first part of the design effort was to step back and look at how large, thin-walled, tubular structures can be bent. Elastic structures such as a garden hose are inherently flexible but need a secondary structure for stiffness. A bellows structure is very stiff in torsion but flexible in all other directions so it would also need a secondary support structure. The desire was to keep the design simple and to combine the structural function with the optical requirements.

The solution was found on top of a water heater. The flue pipe that carries away the hot gasses is made up of several angled couplings that enable the pipe to be bent as needed while maintaining structural integrity and internal clearance. This was the approach taken for the new deployment drive.

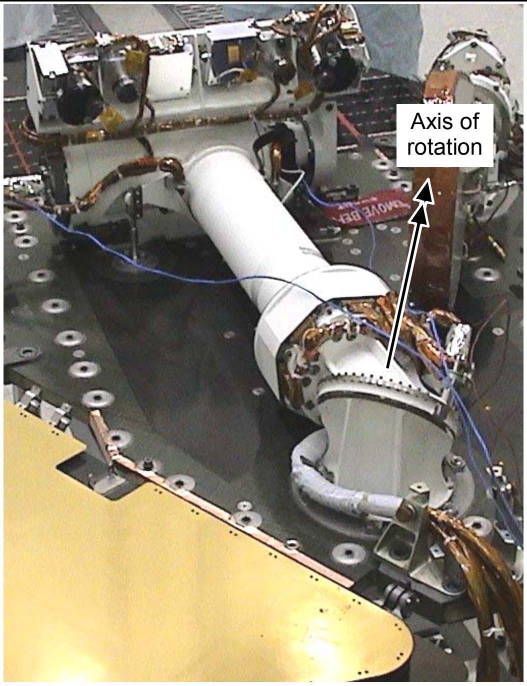


Figure 7. Conical deployment path

Unlike the flue pipe, however, the MDD uses only a single angled coupling in the form of a bearing mounted at an angle. The mast travels from horizontal to vertical in a conical path (Figure 7). The inclined bearing design is a simple and effective way to rotate the mast and keep the Martian dust out while maintaining structural integrity. Although the two main housings are fairly complicated, the overall design is quite simple and robust. There are very few parts and the mechanism is easy to assemble and test.

The single large diameter, small cross section bearing is an X-type that is internally preloaded. The large diameter of the bearing results in good strength and stiffness while the internal preload eliminates the need for a second bearing. This type of bearing does have limited life, but in this application the required operational cycles were well within the life of the bearing.

This conical deployment path also proved to have an advantage in allowing the mast-head to easily exit the launch restraint. The mast-head leaves the deck at about a 40-degree angle so that the vertical vector is about the same as the horizontal vector. The angle of the inclined bearing was made as large as possible to maximize the vertical vector.

MDD Components

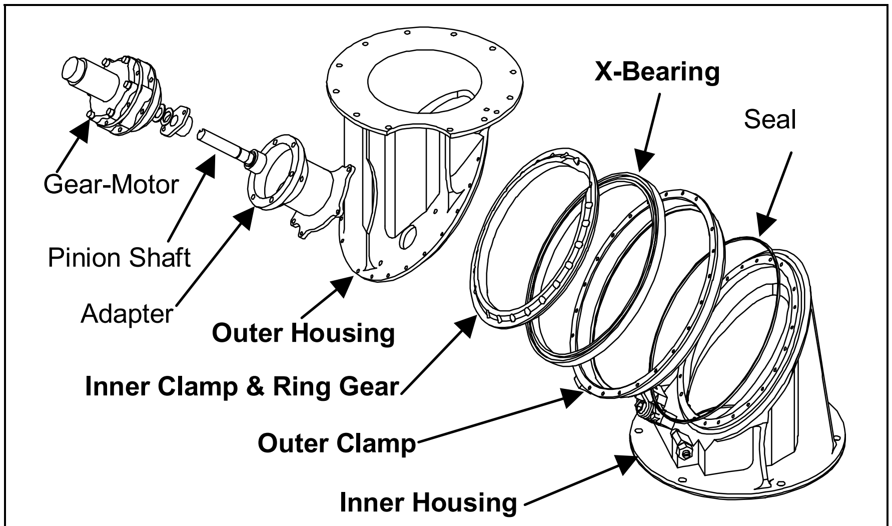


Figure 8: Exploded view of the Mast Deployment Drive

Figure 8 show the five main structural components in the Mast Deployment Drive. The Inner Housing is bolted to the Rover Equipment Deck and remains fixed. The inner ring of the bearing is clamped to the Inner Housing with the Inner Clamp. The outer ring of the bearing is clamped to the outer housing with the outer clamp. The Outer Housing and Clamp are thus free to rotate on the bearing. The inside of the fixed inner clamp features a large diameter internal tooth ring gear. The gear-motor is attached to the Outer Housing by means of an adapter. The Pinion Shaft coming off the Gear-motor engages the ring gear to drive the outer housing. Note that the gear-motor rotates with the outer housing. This was done so that the gear-motors for the MDD and the Azimuth Drive (see next section) could share the same wire path. The Outer Clamp features a protrusion that engages a hard stop at full deployment.

Design Trade

One of the first design trades to be made with this mechanism was whether or not to have a separate latch to hold the mast in place in the deployed position. The detent in the motor through the gear train was enough to hold the mast in place under most conditions. The benefit of not having a latch is that the mast can be remotely deployed and retracted as often as needed. The benefit of having a latch is that the gear-motor is not in the load path so the gear teeth and bearings do not need to be as strong. The disadvantage of having a latch is that once the latch falls into place, it must be manually unlatched in order to stow the mast. The mass for the stronger bearings and gears was about the same as for the latch components. It was finally decided that the ability to remotely stow the mast was not as important as the guarantee that the mast would not creep out of alignment so the latch was added to the mechanism.

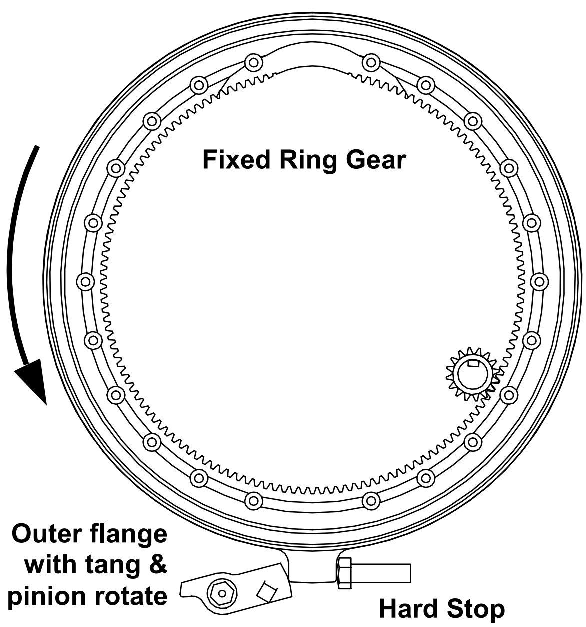


Figure 9. Latch Detail

The hard stop was made adjustable in order to adjust the final deployed position of the mast. Materials were chosen so as not to have similar metals in contact with each other. The outer flange and tang are made of hardened Titanium. The latch and hard stop are made of hardened Nitronic 60. Published data shows that Titanium against Nitronic has very good resistance to galling.

MDD Test Description

The fundamental requirement for the Mast Deployment Drive is to move the mast from the horizontal position to vertical on Mars. A safety factor of two was imposed upon this requirement to assure adequate margin over uncertainties. In addition, it was desired to be able to deploy the mast on Earth for testing without counter-balances or other support structure. And if deployment on Earth was to be feasible, a factor of 20% was determined to be needed.

Designing a variable mass to simulate these different conditions on the Pancam Mast Assembly for testing was considered for a while but found to be very difficult to implement. Because the MDD primarily reacts torque, and torque is simply force times distance, it was decided to keep the force the same and change the distance.

The design of the variable load test fixture is shown in Figure 10. The main structure consists of a thin-walled Aluminum tube with flanges at each end. The threaded rod that runs the full length of the fixture is supported at each end by Vespel bushings. The sliding mass has a threaded feature in the middle to engage the rod and a slot on the outside to prevent it from rotating. Rotation of the rod causes the weight to translate, thus changing the torque on the MDD. The load test fixture was calibrated using a torque wrench to verify the torque at the various weight positions.

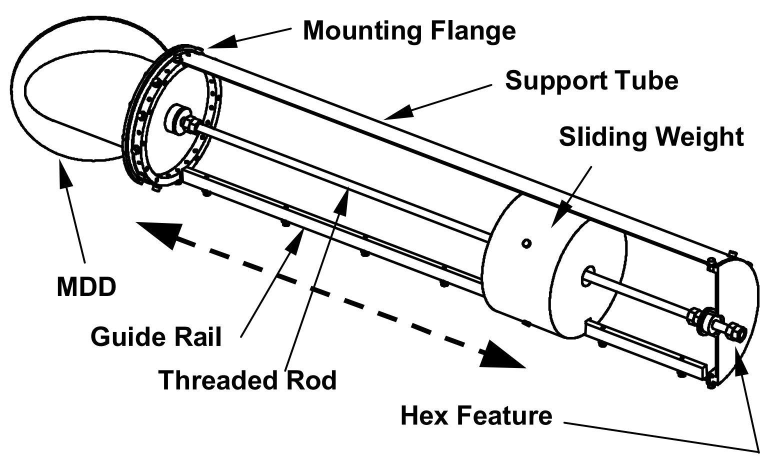


Figure 10. MDD Load Test Fixture

For the thermal functional test, the MDD was first bolted to a surrogate Rover deck. The load test fixture was then bolted to the MDD. The MDD was then deployed and stowed several times to obtain ambient deployment data. The assembly was then placed inside a large thermal chamber. A socket wrench was inserted through a small opening opposite the drive nut to rotate the shaft as needed. The weight and torque change due to the rod rotation is shown in the following table:

Gravity Condition	Weight of Mast (Deployed section)	Torque on MDD 0.46 M (18.1 in.)	Turns
1 X Mars	33 N (7.4 lb)	15 N-m (134 in-lb)	0
2 X Mars	66 N (14.8 lb)	30 N-m (268 in-lb)	163
1 X Earth	87 N (19.6 lb)	40 N-m (355 in-lb)	271
1.2 X Earth	104 N (23.5 lb)	48 N-m (426 in-lb)	357

Mast Deployment Summary

- Cable is well managed, not subject to extreme bending
- Big central hole for light path
- Meets Envelope and Interface Requirements
- Time to Deploy at -70 C is 2.5 Minutes
- Hard Stops can be adjusted to .012 mm.
- Position against stop repeatable to 0.0025 mm
- Tested under 1 X Mars, 2 X Mars, 1 X Earth, 1.2 X Earth
- Tested at warm, ambient and cold conditions
- Works well with launch restraint mechanisms

Azimuth Drive

The third mechanism is the Azimuth Drive, which rotates the upper part of the PMA. This drive allows the Rover to look left and right. The optical path for the Mini-TES instrument must pass down the middle of the drive. The principle requirements are as follows:

Property	Requirement
Angular range	+/- 180 degree
Angular accuracy	+/- 1 mrad.
Angular speed	0.5 revolutions per minute
Optical clearance	100 mm bore
Electrical interface	Upper flange: 4 x 37 pin connectors Lower flange: 4 x 37 pin connectors
Cable management	+/- 180 degree
Mechanical Interface	Upper flange to Mast Lower flange to MDD

The Azimuth drive was originally designed by American Technology Consortium (ATC) for the APEX program. ATC was then acquired by Starsys Research Corp. who redesigned the drive to reduce the outer diameter and add a fourth cable path.

The Azimuth drive is mounted to the top of the MDD to form the Lower Drive Assembly (Figure 11). By mounting these two drives at the base of the PMA, a significant portion of the mass is located near the RED. This has the effect of lowering the overall mass center of the assembly.

These two drives also take advantage of commonality in the areas of rotating shaft seals, large diameter bearings, lubrication, motor shielding and motor electrical connections. Internal and external surface coatings are also the same.

Note that the two motors are located in the same proximity. For both the MDD and the Azimuth drive, there was a choice to mount the motor on the fixed part of the mechanism or the moving part. By mounting the motor on the moving part of the MDD and the fixed part of the Azimuth Drive, the two motors could be mounted adjacent to each other. This, in turn, facilitated the routing for the motor electrical cables.

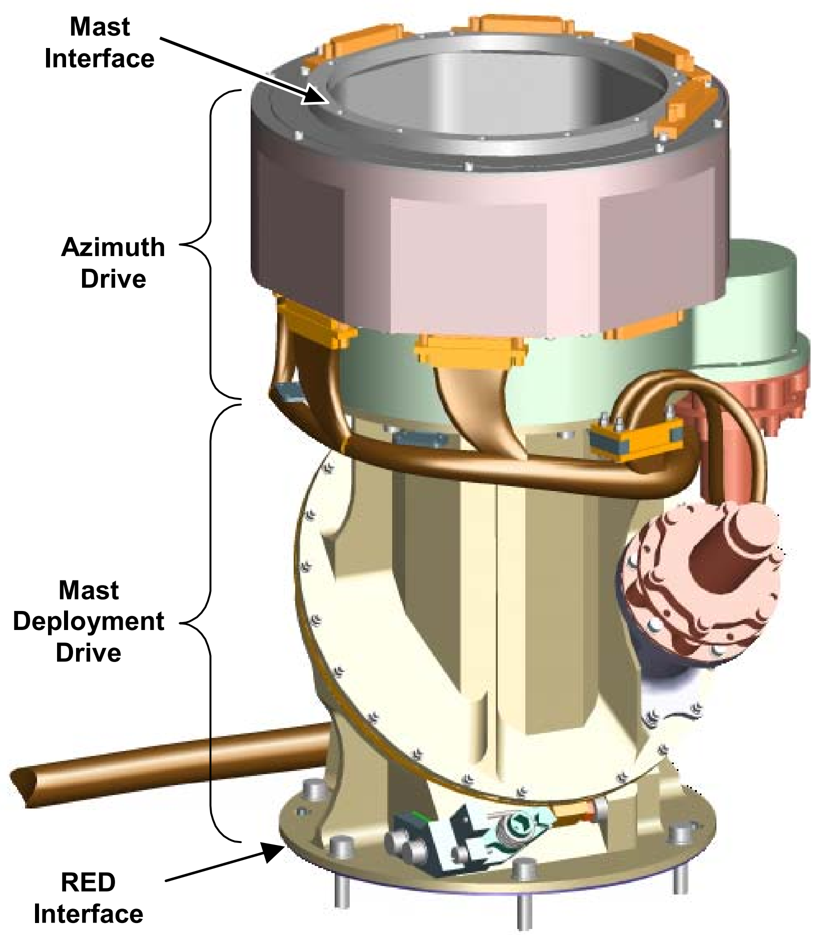


Figure 11. Lower Drive Assembly

Camera Bar Drive

The fourth mechanism is the Camera Bar Drive (Figures 12 & 13). A pair of panoramic wide-angle cameras and a pair of navigational small angle cameras are mounted on a common bar at the top of the mast. The camera bar drive rotates the camera bar allowing the cameras to look up and down.

Basic Requirements:
Provide support of the Pancam and Navcam cameras
Move the cameras about the elevation axis at 2 degrees/sec with a pointing error of 0.1 degrees
Carry power and signals across the rotating joint
Accommodate relative thermal distortions between mast and camera bar
Allow separate integration and alignment of cameras as a sub assembly

The four cameras are mounted to a rigid angle bracket that maintains precise alignment between each camera. The assembly of cameras and angle bracket was integrated and qualified separately from the mechanism and the two were integrated during final integration of the rover. The camera bar mechanism consists of a rigid titanium box section tube that is supported at each end.

One end of the tube is supported by a large diameter thin section ball bearing and the other end is mounted to a bracket that is supported by the output shaft of a gear-motor. This gear-motor bracket serves as the housing for spiral wound flex cable assembly that carries power and signal across the rotating joint. The bracket design also incorporates a diaphragm that provides additional compliance within the assembly.

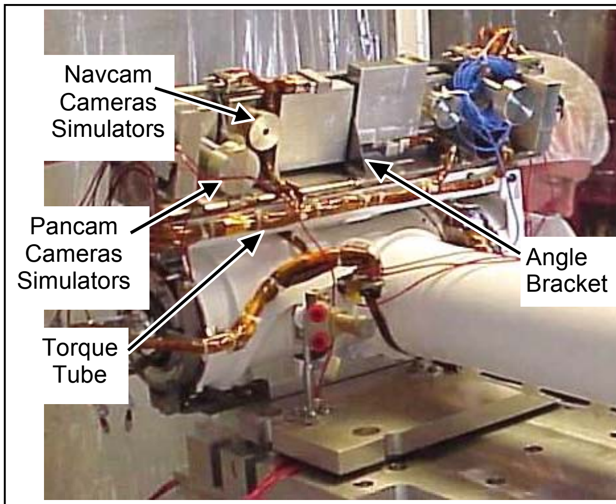


Figure 12. Camera Bar Drive

The motor is a custom DC brush motor with a custom hybrid planetary-harmonic gear-head with 8118:1 gear ratio. A magnetic detent mechanism is integrated between the motor and gear-head to resist back driving that may be caused by the cantilevered mass of the cameras and the jostling that occurs as the rover moves. The magnetic detent consists of a very small multi poled magnetic rotor inside a magnetic stator housing. To initiate significant rotation the magnetic detent must be overcome, but then it provides additional torque as you get over the "hump". This repeats every few degrees as the shaft is rotated. The detent increases the starting torque required of the motor but does not affect the operating torque margin since this torque ripple averages out.

The gear-motor assembly includes a relative position encoder. Before each use, the mechanism must be rotated against the hard stop to zero the encoder. The gear train, structures, and hard stops must be capable of tolerating full motor stall torque many times. The same hard stops that are used for the launch lock are also used for this application.

The thin section bearing that supports one end of the camera bar has very large internal clearance between balls and races. This slop in the bearing is required to accommodate the different thermal expansions of the titanium camera bar and the graphite mast structure. Since the cameras only image when the rover is stationary and the camera bar is not moving, the loose bearing does not lead to blurry images. Concern over damage to the bearing from rattling was alleviated by analysis that showed that motion of less than .010" did not allow enough velocity to cause damage.

Twist of the camera bar assembly due to gravity sag or due to follower bearing drag was a concern. The sag due to gravity was easily calculated and mitigated, but the drag of the bearing was unknown and subject to many variables. Contamination by Mars dust blown into the bearing after deployment or kicked up during landing could significantly increase the drag. Due to the configuration of the mechanism, if the follower bearing were to drag and twist the bar, additional torsion would be imparted to the bearing potentially causing even more drag and a lockup situation could be created.

To exclude debris from the follower bearing, a careful seal design was implemented. Initially labryinth-type convolutions were envisioned to exclude debris and impart the minimum amount of drag to the motor. Following the critical design review this design was modified to focus more on debris exclusion and less on motor drag. The seals are risky because of the –70°C operating temperatures and the large amount of play in the bearing. A plastic seal with enough contact pressure to seal the bearing in one position may provide too much contact force when very cold and in a different relative position of inner to outer races. The solution was to use a thin metal shield with a relatively long cantilever. The stiffness of the metal changes much less with temperature and the long cantilever provided adequate deflection. On the inner side of the bearing a more convoluted labyrinth seal was selected which added no additional drag.

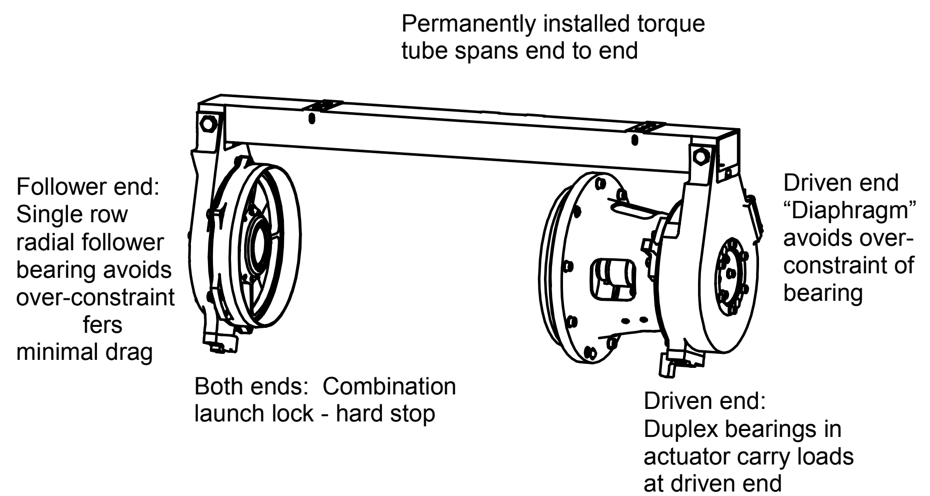


Figure 13. Camera Bar Drive Mechanism

Mini-TES Drive

The fifth mechanism is the Mini-TES Mirror Rotation Drive. The Mini-TES is an Infrared spectrometer that is located below the Rover deck. The PMA serves as a periscope to enable the Mini-TES to look around from a higher vantage point. The Mini-TES mechanism rotates a mirror so that the instrument can look up and down and provides an enclosed calibration target. The Azimuth drive described earlier provides the left/right motion.

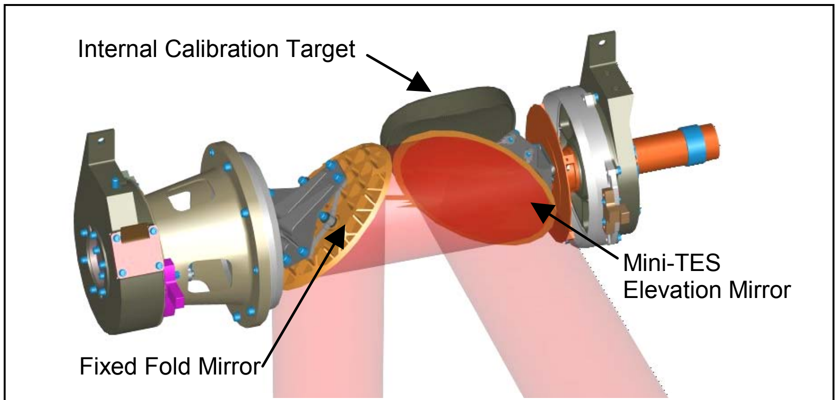
Basic Requirements:
Support the mirror and provide an elevation axis of rotation
Move the mirror at 5.7 degrees/sec with a pointing error of 1 mrad
Provide an enclosed calibration target of known temperature
Incorporate a rotating baffle that will exclude light and limit debris when closed

There are two 45 degree angled mirrors inside the head of the PMA. One mirror is fixed and the Mini-TES rotation drive controls the other. Light enters the PMA through an opening in the top "T" section, reflects off the moveable mirror and travels to the fixed mirror and then travels down the mast to the instrument as shown in Figure 14. A custom DC motor with custom hybrid planetary – harmonic gear-head is located in the top of the PMA and drives the first angled mirror about the horizontal or elevation axis. This elevation axis together with the mast azimuth drive provides the capability to point the Mini-TES field of view.

To limit the complexity and weight of the system the mirror is mounted directly on the gear-motor with no additional support. The mirror is cantilevered off the motor shaft and does not include a launch lock element or brake mechanism. There was concern that the launch vibration environment might cause the cantilevered mirror to rotate even though it is rotationally balanced. Deflection of the cantilevered mass under load effectively unbalances the system. In a rich vibration environment this configuration could rotate. The issue was addressed by implementing dynamic braking in which the motor windings are shorted so that the motor acts as a brake. Dynamic braking is turned off during operation.

The bearings on the output shaft of the gear-motor were sized to support the mirror and support structure weight so that no additional support was required.

System level testing of pointing to meet the 1 mrad (0.057 degree) requirement was carried out at a number of specific pointing angles. The largest pointing error in tests prior to vibration was 0.035 degree, and after vibration of 0.046 degree.



FFigure 14. Mini-TES Elevation Mechanism

Subsequent testing revealed a potential additional line of sight error of 0.03 degree when the mast assembly was subjected to lateral loads, however this error was found to be a single time error in the azimuth bearing immediately after the load was applied. Once the azimuth bearing was run through at least 90 degrees of motion, the alignment returned to its previous state.

In order to calibrate the instrument after arrival at Mars and periodically during the mission, the instrument is required to observe a calibration target of known temperature and emissivity mounted in front of all mirrors. To accomplish this, the elevation mirror was capable of rotating completely around to point at the inside of the back of the mast where the calibration target was mounted in a recessed pocket. This target was constructed to have a high emissivity surface by machining small groves across its surface and then applying high emissivity black paint. The temperature of the calibration target was measured with redundant sensors potted in a blind hole in the back of the target. When the elevation mirror is rotated completely around to view the target, the Mirror Shroud effectively seals the front opening to exclude ambient light. The shroud, shown in Figure 15, is a thin graphite structure mounted so that it rotates with the mirror. It prevents stray light from entering the periscope and allows the instrument to be closed up somewhat when not in use to limit contamination. The contamination concern is significant in the Martian environment. Martian dust is very fine and is easily carried up to the mirror level by the Martian wind. The air bags that surround the rover during landing are separate and do not form a sealed envelope around the rover. During landing, dust that is kicked up by the impact and subsequent 5 minutes of bouncing and rolling across the surface can easily pass between the air bags and affect the rover.

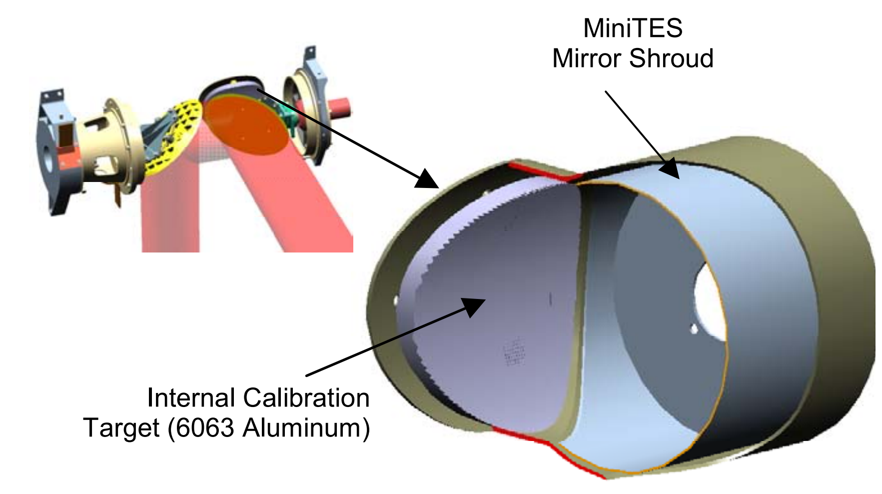


Figure 15. Calibration Target

Tribology

There are four areas of tribology for the PMA mechanisms: bearings, gears, hard-stops, pin-pullers. The mechanisms must all operate under the same conditions and therefore have similar operational requirements. The most significant requirement is the lower operating temperature of -70ºC. In addition, the mechanisms must function throughout ground testing under various temperatures, survive the hard vacuum during the trip to Mars and then function in the dusty Martian atmosphere. The mechanisms are mostly slow moving and the mission life is fairly short.

Several lubricants were considered for use on the PMA mechanisms. Silicone lubricants eventually break down and become abrasive. Silicone contamination on optical components is considered a major risk. Perfluoropolyether (PFPE) lubricants such as Brayco 815Z oil and Braycote 601 grease also polymerize, but generally outperform silicone lubricants. The lower operating temperature limit is -80ºC. Dry film lubricants such as those based on Molybdenum Disulfide (MoS_2) or thin metal films can operate well at temperatures near 0 Kelvin. However, this type of lubricant has a lower load capability than wet lubricants. It is also a less robust lubricant because its life is compromised by humidity. Hybrid bearings such as those with Silicon Nitride balls in metal races can sometimes operate with little or no lubricant if the contact stress is very low. This was not feasible for the PMA mechanisms because the contact stress was too large due to the mass of the payloads and the Martian gravity.

PFPE lubrication was selected for use on all ball bearings and gears in the PMA mechanisms. Molybdenum Disulfide was added to the PFPE lubricant for sliding components such as the gears and the 4-Point contact bearing discussed in the Mast Deployment Drive section. Dry film lube in the form of Molybdenum Disulfide was used for the launch lock mechanism in which the pin-pullers have sliding pins within spherical bearing bores. No lubrication was used on the hard stops. Material combinations with anti-galling properties were carefully selected for both the pin-puller interface and the hard stops.

Testing

Testing was critical on the program. Even with the tight schedule, an extensive test program was established. The philosophy behind the test program was that since the design phase was short, testing was even more important. Working jointly with JPL, a comprehensive test program was put into place starting with testing of the gear-motor actuator at the subcontractor (Figure 16). The actuators for each mechanism were exposed to qualification levels for vibration and speed toque curves were generated over the operating temperature range. After delivery, the actuators were integrated into their respective mechanisms. Safe to mate testing was performed to ensure the mechanisms were wired correctly. Thermal tests were then performed to characterize the mechanisms as an assembly.

Figure 16. Program test flow

Actuator Testing
- Integrate Actuator
- Safe-to-mate verification
- Actuator Run-in
- Vibration testing
- Drive characterization (speed/torque at temp)

Mechanism Testing
- Integrate Actuator to mechanism (Establish current limits)
- Safe-to-mate verification
- Drive run-in
- Drive characterization at temperature
- Pointing accuracy at temperature

System Testing
- System integration
- Continuity & isolation check
- Optical alignment
- Ambient functional test
- Vibration tests
- Pin-puller test
- Functional test
- Load testing
- Thermal testing
- Ambient functional

Three Pancam Mast Assemblies were built and tested. The first unit was the Engineering Development Unit (EDU) followed by the two flight units. All three were fabricated to the same specifications. One of the units was designated the EDU and additional testing including life cycle testing was performed on it. The EDU could be refurbished to flight standards, if needed.

In order to facilitate the compressed test schedule, four separate test racks were built for the program. This allowed multiple mechanisms to be under test at one time. The test systems were configured to allow the use with any on the PMA mechanisms. These test systems had integrated commercial motor controllers, power supplies and a PC loaded with a specialized LabView program. The LabView program allowed many parameters to be controlled and also record all the mechanism/test parameters. Specialized thermal chambers were built that operated on liquid nitrogen to eliminate scheduling issues with the company's thermal chambers. Electronic controllers were used to maintain the specified temperatures. The mechanisms were loaded using weights and pulleys as shown in Figure 17. This allowed incremental loading of the mechanism to characterize the performance.

Once the mechanism level testing was completed and the PMA was integrated, the assembly was optically aligned and ambient functional tests performed. The PMA was then exposed to system required vibration levels. Testing of the pyro pin-pullers were also performed while on the shaker table. This facilitated instrumentation of the unit with small accelerometers to measure the shock levels.

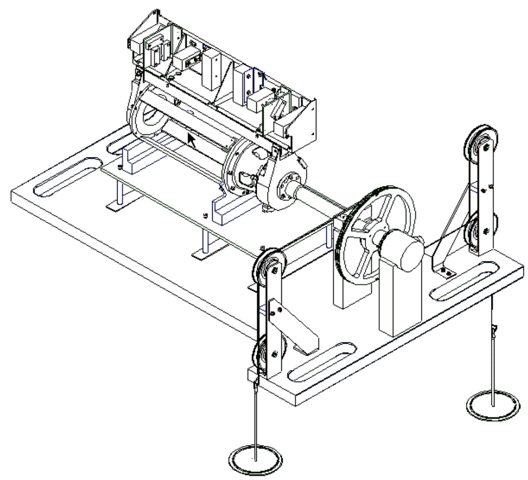


Figure 17. Typical Test setup

In the stowed configuration, the PMA was subjected to 3-axis sine sweeps, random vibration and a quasi-static sine pulse. In addition, All, the units were subjected to a pyro-shock test from the pin-pullers. In the deployed configuration, the PMA was subjected to 2-axis sin sweeps and a quasi-static sine pulse.

Next, the PMA was mounted on a thermal fixture and installed in a thermal vacuum chamber. A 10^{-5} torr vacuum was pulled on the chamber and a 3-hour bake-out at 110°C was performed to remove any moisture in the hardware. The chamber was back-filled with dry nitrogen to a pressure of 10 torr before proceeding with the remainder of the thermal tests. This pressure of nitrogen is thermally equivalent to the CO_2 atmosphere on Mars. The thermal testing profile exposed the hardware to the non-operational temperature limits before deploying the mast at the low operational temperature extreme.

Functional testing was performed at several different temperature plateaus as the temperature was cycled between the operating limits. At the end of the thermal tests, a 50-hour planetary protection bake-out was performed. Motor revolutions were recorded anytime the mechanisms were operated.

One of the challenges in the test program was the reduction of the test data. In most cases, the data was collected at a 10-Hz rate with tests lasting 10 to 20 hours for mechanism level testing, so the amount of data collected was substantial. Many different MATLAB scripts were developed to automate the data reduction. These scripts enabled engineers to quickly and accurately locate critical parameters within the large data files as well as to facilitate statistical analyses.

Lessons Learned

Communication and cooperation is critical between the contractor and the customer. Many unexpected issues were encountered over the duration of the program, which required both sides to understand the issues and impacts to the hardware. Both Ball and JPL have a deep commitment to get the job done right, so issues were resolved relatively quickly in order to keep the program on schedule.

Requirements creep in a program is costly, both in dollars and schedule. Many small changes add up to a large impact.

Define all interfaces early. Undefined requirements always need to be specified at some time and this can lead to changes late in the program.

Proven technologies sometimes aren't! Technology from a prior program cannot be assumed to transfer directly over to another program. The PMA program was initially envisioned as a rebuild of the Athena program hardware with some changes to meet the new requirements. By the end of the program, virtually every drawing was changed.

Testing is sometimes as complicated as the design and assembly. Good definition of the test requirements are important to delivering a qualified product in a timely manner. The PMA test program increased in scope over the length of the program to include unforeseen tasks. The finished assembly performed very well and was characterized to the level that JPL required.

Conclusion

The three qualified Pancam Mast Assemblies were delivered to JPL in September and October 2002. JPL then integrated the PMA on the rover and performed extensive environmental testing before delivery to Cape Canaveral in Florida. The Rovers were integrated on a Delta rocket and launched on June 16th, 2003 and June 30th, 2003. The rovers are scheduled to land on Mars in January 2004.

Recognition

The authors would like to thank all the many technicians, machinists, designers, engineers and managers at Ball for their commitment to developing these state of the art mechanisms. Also all the great folks at Starsys for the gear-motor actuators and Azimuth drive. And especially the entire Rover Team at JPL.

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