Mechanical Description of the Mars Climate Sounder Instrument

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Abstract—This paper introduces the Mars Climate Sounder (MCS) Instrument of the Mars Reconnaissance Orbiter (MRO) spacecraft. The instrument scans the Martian atmosphere almost continuously to systematically acquire weather and climate observations over time. Its primary components are an optical bench that houses dual telescopes with a total of nine channels for visible and infrared sensing, and a two axis gimbal that provides pointing capabilities. Both rotating joints consist of an integrated actuator with a hybrid planetary/harmonic transmission and a twist cap section that enables the electrical wiring to pass through the rotating joint. Micro stepping is used to reduce spacecraft disturbance torques to acceptable levels while driving the stepper motors. To ensure survivability over its four year life span, suitable mechanical components, lubrication, and an active temperature control system were incorporated. Some life test results and lessons learned are provided to serve as design guidelines for actuator parts and flex cables. [1] [2]

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1. INTRODUCTION

This paper focuses on the mechanical aspects of the MCS instrument. Other authors will describe its sensing principles, the data acquisition methods and the science this instrument enables, in upcoming publications [1, 2]. Current information about the MRO mission, this instrument in particular, mission status, previews of science data and scientific results, etc, can be found in JPL's webpages [3], as well as in articles by the Planetary Society [4, 5].

The MCS instrument is one of six scientific instruments on the MRO spacecraft. It is suspended from the Mars facing instrument deck of the spacecraft, enabling unobstructed views of Mars and the black space above Mars.

Scientific data acquisitions began in November 2006. The duration of mapping operations is scheduled for four years. A nearly identical instrument, to perform similar investigations at the Moon, is now being readied for launch onboard the Lunar Orbiter Spacecraft in late 2008.

2. MCS SCIENCE GATHERING

The instrument uses nine sensor arrays for visible and infrared sensing over a total wavelength range from 0.3 to 45.4μm. It looks primarily at the horizon of Mars to observe the atmosphere in vertical slices. It detects vertical variations of temperature, dust, and water vapor concentrations in the Martian atmosphere. In essence, the instrument is an atmospheric profiler that collects data of the Martian weather and climate.

The acquired data is re-formatted and composed into profiles of temperature, pressure, dust, water and carbon dioxide content of the Martian atmosphere, up to a height of 80 kilometers. Over the course of the mission (one to multiple Martian years), insight is gained into how the Martian atmosphere circulates and how it changes over time.

3. INSTRUMENT DESCRIPTION

The MCS instrument is shown in Fig. 1. This picture was taken before the thermal blankets were attached. The instrument consists of the optical bench, two joint drives, a yoke-like support structure, two different calibration targets and the control electronics that is distributed at several locations in the yoke and at the optical bench.

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[1] 1-4244-1488-1/08/$25.00©2008 IEEE.
[2] IEEEAC paper #1670, Version 5, Updated December 14, 2007

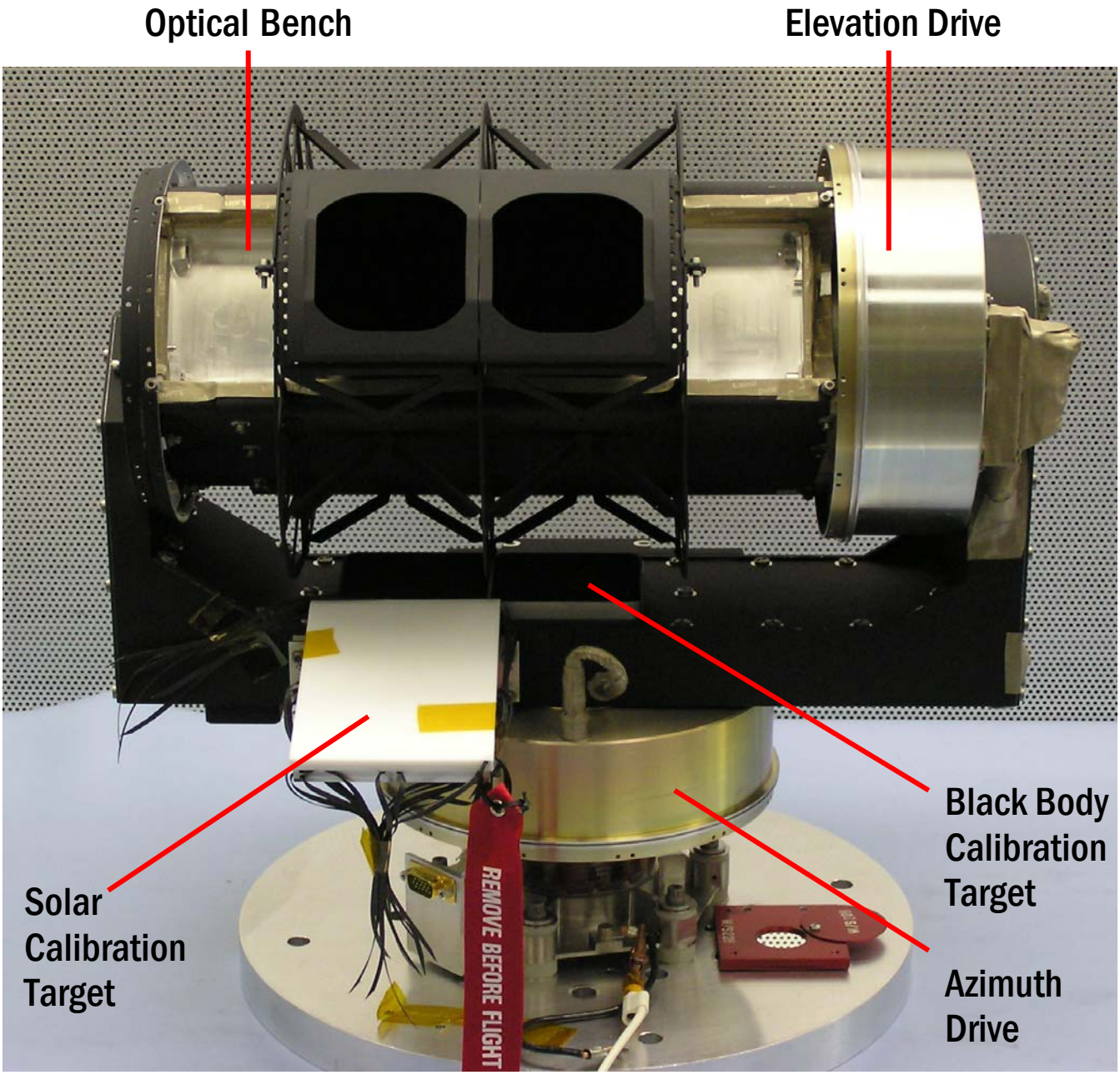


Fig. 1: The Mars Climate Sounder Instrument

The instrument is 390mm tall; it fits into a rotational space of 420mm in diameter and weighs 9.8kg. All outside surfaces are covered by 15-layer carbon-filled Kapton thermal blankets. Otherwise, no surface coatings were applied to metallic surfaces, except to surfaces along the optical path. They are cover by Martin Black® coatings.

The optical bench can be rotated through 270 degrees by the elevation drive on the right. It enables limb, nadir and black space viewing, as well as pointing one of the telescopes to the grainy-surfaced solar reflector, or both telescopes to black calibration surfaces embedded in the horizontal support structure.

Three thermal blanket support rings can be seen at the optical bench. The thermal blanket around them forms a cylinder that also prevents sunlight from illuminating the recessed black calibration target surfaces at any time. It minimizes temperature fluctuations of the black surfaces that otherwise would influence the thermal calibration.

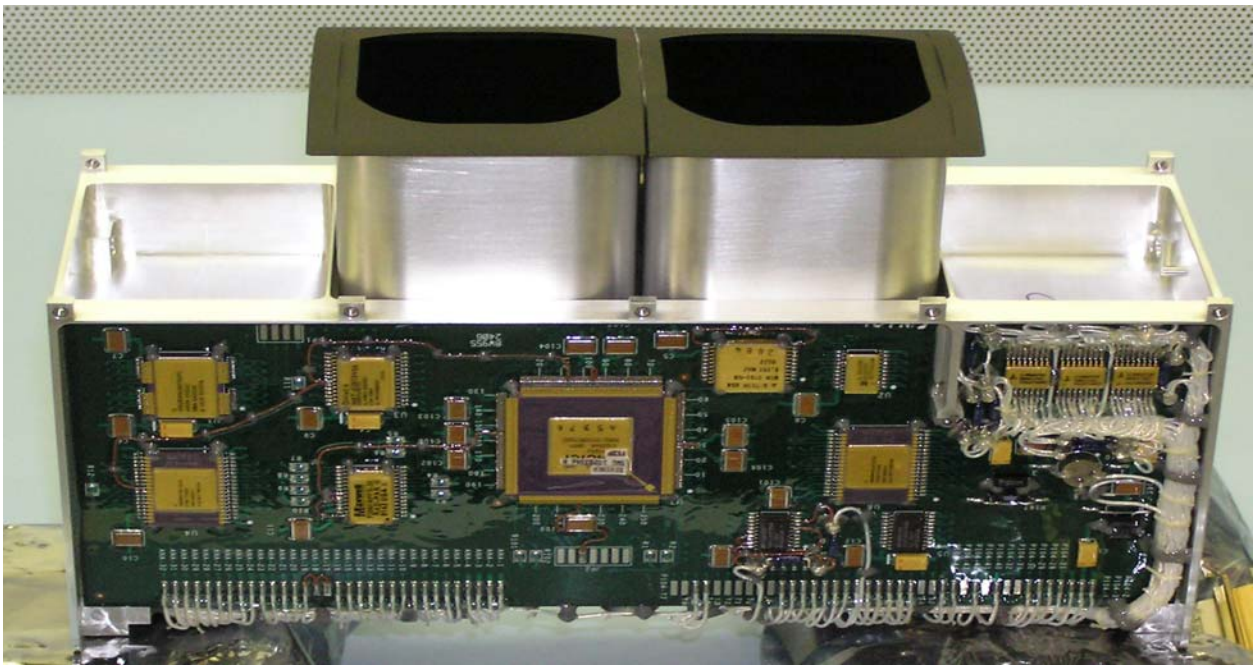


Fig. 2: The Optical Bench

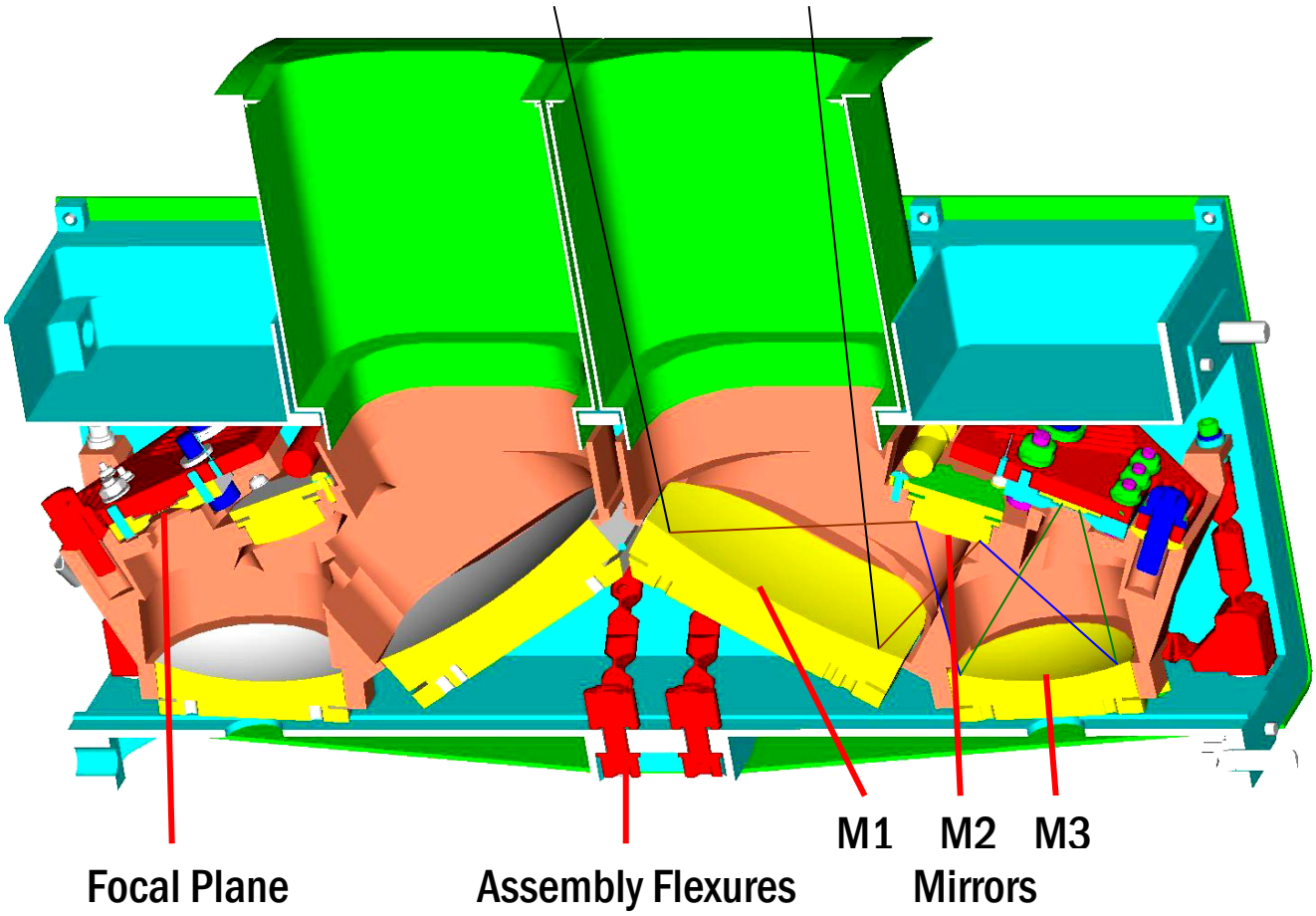


Fig. 3: Cross Section through the Optical Bench Assembly

The structural support for the upper assembly is provided by the U-shaped yoke. A ball bearing supports the left side of the optical bench. All motion control electronics resides at several locations inside the yoke. The azimuth drive, which also has 270 degrees rotational capability, also provides the structural support for the instrument. The interface to the spacecraft is a hexagonal base plate.

The solar calibration target has a granular surface that best can be described as a sand blasted surface. It reflects reduced, but controlled sunlight into the instrument: The instrument's sensing properties were carefully calibrated to the reflective properties of the solar calibration target.

The black body calibration target has a Martin Black coated saw tooth-like surface. It is intended to eliminate any reflected light so that the instrument can be calibrated against a perfectly black surface.

Optical Bench Assembly

The optical bench is shown in Fig. 2. In essence, it is a thin walled, hollow square tube structure. Baffles in front of the optical bench shield the internal optics from stray light. All structural parts of the optical bench assembly are made of Aluminum 6061-T6. The control electronics for the telescopes is mounted on two circuit boards located above and below the optical bench. A cross section through the optical bench, also showing one of the beam paths, is depicted in Fig. 3.

Each telescope is an independent unit that is inserted into the optical bench from the side. One of the twin telescopes is shown in Fig. 4. It mounts to the optical bench via two bi-directional and one uni-directional flexure, also visible in Fig. 4. Notice the absolute blackness of the Martin Black coating in the beam cavity.

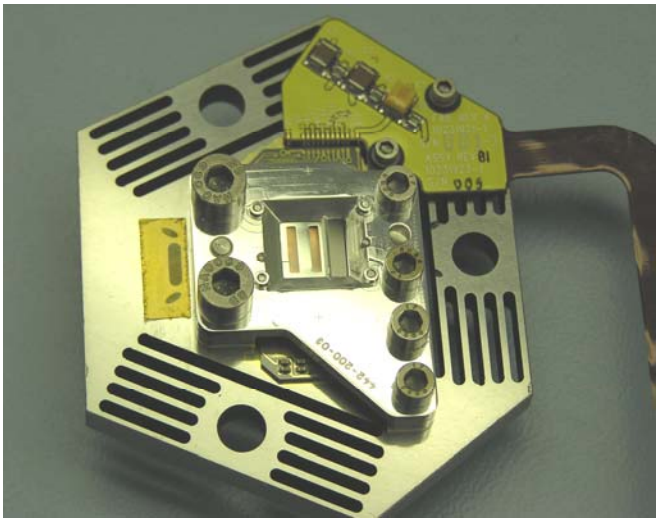


Fig. 5: The Focal Plane Assembly

The telescope consists of a structure, a focal plane assembly and a three mirror beam relay system. The mirrors are mounted directly to the structural blocks; fine-tune alignment capabilities are incorporated in the mounting provisions.

The focal plane detector arrays and filters are in the center of the focal plane assembly, shown in Fig. 5. The focal plane structure suspends itself through a series of flexures at its mounting locations to the telescope. Image processing takes place locally. The electronics board for it can be seen in the upper part of the focal plane in Fig. 5.

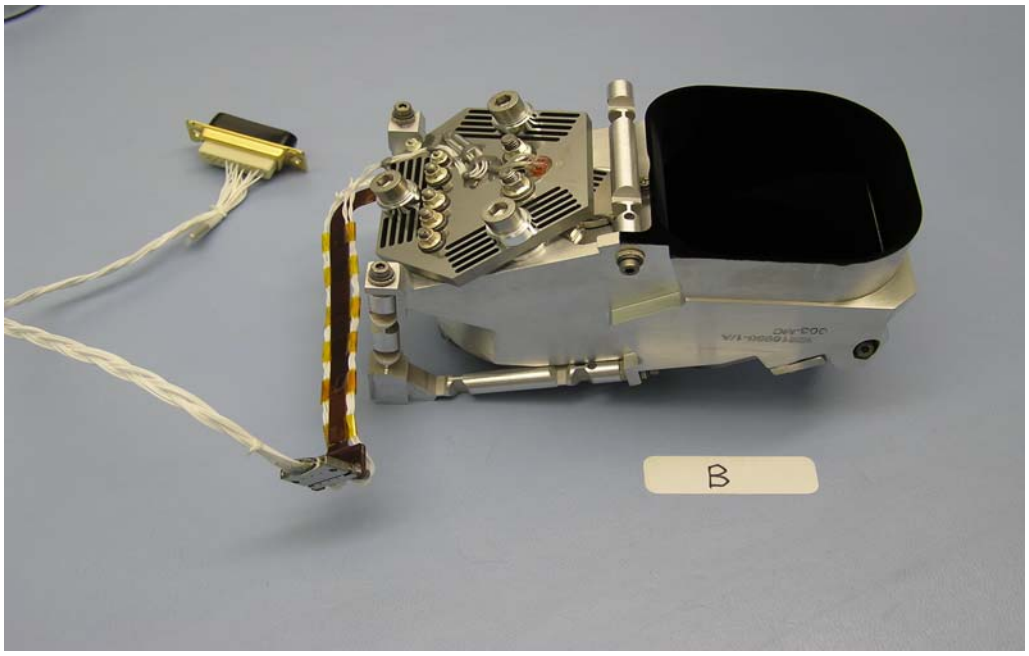
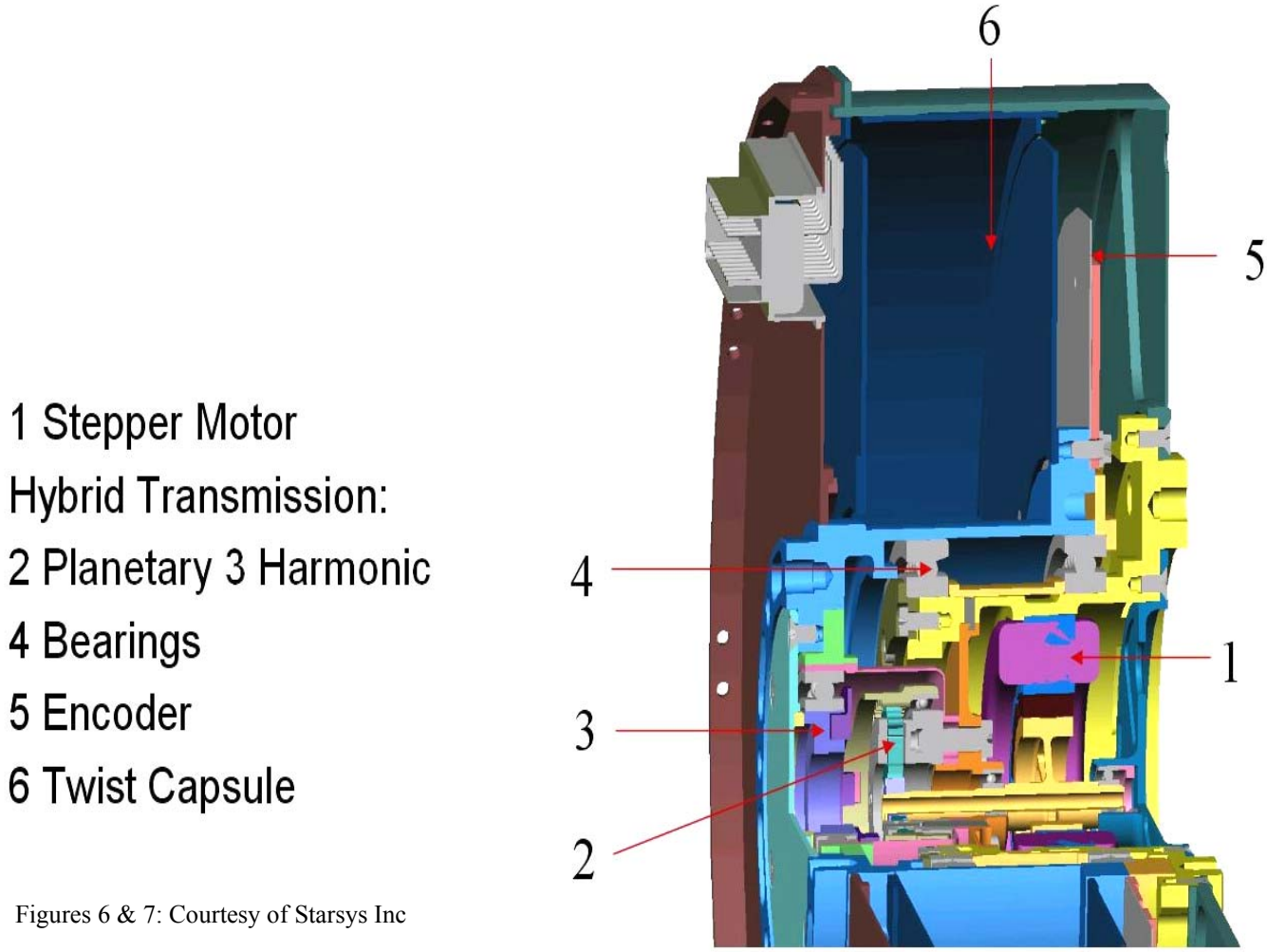


Fig. 4: The MCS Telescope



Figures 6 & 7: Courtesy of Starsys Inc

Fig. 6: Cross Section through the Elevation Joint

JOINT DRIVES

Both rotating joints [6] combine an actuator and a twist cap section in a compact design. Its actuators are identical but the output bearing configuration is different: The azimuth joint has a hub extension so that its bearings could be spaced further apart, enabling to support the more severe launch loads at the base of the instrument. Fig. 6 shows the elevation joint with its output bearings spaced close together. The motor is a two-phase, brushless stepper motor with redundant windings and a detent section, acting as launch lock. Its stall torque is .012Nm. The transmission is comprised of a planetary gear stage, followed by a harmonic drive. The overall gear ratio is 297:1. The step rate is 0.1 degrees/step with a pointing accuracy requirement of less than +/-0.25deg. As encoder serves two sets of diodes that determine two distinct output positions. The load bearing structural sections of the azimuth drive are made of Titanium. Weight saving measures drove the elevation joint structural parts to be made from lightweight AlBeMet material instead, having a density of 2.1g/cm³ and yield strength of 11.7kg/mm².

The twist cap chamber contains six printed circuit flex cables that can coil-in or unroll to enable the electrical wiring to transition from the stationary to the rotating section. For longevity reasons, a clock spring type flex cable arrangement was chosen over the rolling type arrangement. The life time cycle accumulation will be 3.5 million cycles. Each flex print has 14 electrical traces for a total of 78 power and signal traces and 6 grounding traces.

THREMAL CONTROL

The allowable operating temperature for the instrument is from -20degC to +55degC. Exception: due to the high viscosity of the Pennzane lubricant in the actuators (see below), the operating temperatures of the actuators had to be restricted to be between +5degC and +55degC. A total of 9 heaters ensure adherence to the minimal temperatures for

all operating and cold start conditions. Heaters are either actively controlled through the instrument's control electronics, i.e. for the focal planes, electronics and actuators, or passively by the spacecraft.

POWER CONSUMPTION

Subsystem peak power consumption is 16W for electronics and imaging, 15W for actuators, 20W for operational heaters and up to 30W for survival heating. The average power consumption during normal operations is approximately 15W.

4. SCANNING STRATEGIES

The instrument utilizes its elevation drive for regular scanning operations: An observational sequence lasts 34 seconds and starts with limb viewing in a polar orbit cross directional direction for 16 seconds. Thereafter, it positions itself to look straight down to the Martian surface to acquire nadir data for four second. This is followed by rotating upwards to view black space for two second to re-calibrate. The sequence then completes by returning to the limb position. Over the scheduled life time of this instrument, the instrument will perform 3.5 million such scanning sequences.

The thermal imaging sensors are re-calibrated approximately once per 113 minute orbit by pointing the instrument at the on-board calibration surfaces. On occasion, other viewing patterns are also chosen, i.e. viewing ahead or looking back. Such viewing pattern involves moving the azimuth drive.

No sensing takes place while the instrument re-positions itself. Thus, every repositioning of the instrument means downtime for science gathering. To minimize slewing times, all motions are executed with maximum constant accelerations over the 1st half of any motions, followed by maximum constant deceleration over the 2nd half of the motion.

5. MOTOR DRIVE ISSUES

Today's high resolution optical telescopes require sturdy and vibration free platforms. MRO's HiRISE instrument fits this category. Maximizing acceleration rates and employing stepper motors for MCS conflict with those requirements. Disturbance torque limitations were thus imposed for this instrument: the instrument is not allowed to emit disturbance torques to the spacecraft that exceed 0.02Nm for the elevation axis and 0.04Nm for the azimuth axis. To keep within these limitations, MCS's rotational acceleration rates were chosen under consideration of the load inertia about each axis so that maximal acceleration rates can be achieved without exceeding the above limiting disturbance values. The actual maximal acceleration rates are 25deg/sec² for the azimuth drive and 42deg/sec² for the elevation drive. The maximum rotational velocity ramps up to 26.3deg/sec for both drives.

Higher frequency vibrations originate from the stepping actions of the motors. They are most severe at motor start/stop. In spite of attempts to dampen the structure, the emitted high frequency vibrations were still too severe to be tolerated. Micro stepping motor control was thus implemented. At low speeds, the motor driver ramps the currents of the two motor phases in a quasi-sinusoidal fashion, rather than by discrete square waves. At higher speeds, the current input per motor step switches to a few discrete micro steps. The number of micro steps diminishes as the motor approaches maximum speed. Evaluations of images taken in-flight by the high resolution HiRISE camera revealed that some image jitter could still be detected that seems to originate from stepper motor vibrations of the MCS instrument. An operational constraint was thus issued that restricts MCS movements during image taking when the Telescope operates in its high resolution mode.

6. CRITICAL DESIGN ISSUES

The quest for limiting mass, the operational demand to operate at maximal acceleration rates, and the requirement to survive 3.5 million operational cycles, were the primary design drivers and optimization criteria.

New, miniaturized sensing technologies and an extremely compact design enabled to reduce the mass and size of this instrument to less than half of what a previous similar instrument [7] was. Some exotic materials, like Al-Li 2297 and AlBeMet, were also used to minimize the weight of structural parts. Parts were sized to approach their limiting allowable stress values as closely as possible, but under inclusion of life time factors for parts that operate under fluctuating loads. In an effort to keep parts wear to a minimum, some match drilling was also performed, enabling a nearly perfect in-line alignment of the entire gear train.

Even with that, the participating engineers had considerable concern that the life test might reveal that the joint could not survive the equivalence of multiple years of simulated continuous space operations under the rather severe operational conditions. But the life test joint performed well, it is still being used occasionally, long after its life test was completed.

Of particular concern was the survivability of the flex tapes over the required high number of bending cycles, the longevity of the lube under the high contact pressures in the

transmission, as well as parts wear in the drive train over their life cycles. Life test results of these most critical elements are briefly described in the Section 7.

DESIGN LESSONS LEARNED

The Al-Li material achieves weight savings of 5% over the comparable strength Al 7075-T7351 material. Its drawbacks are that there is very limited supply and suppliers of this material, making it somewhat difficult to obtain proper raw material; and the chips that are generated during metal forming need to be handled separately because of the hazardous Lithium content. This material was successfully used at JPL for large space structures, achieving substantial weight savings. For this instrument, which weighs only a few kilograms, the weight savings didn't amount to much while the effort to deal with this material was substantial. Al-Li materials are thus not recommended for use in quantities not exceeding a few kilograms.

The drawback of AlBeMet is that special ventilation is needed during chip formation because it emits toxic gases. That requires fabricating such pieces in specialized workshops, of which there are only a few, all of them having substantial backlogs of work. In general, it is advisable not to use AlBeMet for single edition pieces, for even the slightest modification requires returning the piece to the manufacturer. Working with AlBeMet delayed the completion of the drive units by several months and was a substantial cost driver.

Match drilling might have extended the life of the transmission by quite some amount but should otherwise be avoided for (needless to say) it is a cost driver. It definitely should not be used in conjunction with exotic materials, like AlBeMet: One late braking modification, requiring returning a subassembly to the specialized manufacturer for match drilling some other parts to AlBeMet pieces, caused the overall schedule to slip by two months.

7. LIFE TEST RESULTS

The azimuth drive life test unit was required to accumulate 3.5 million 80 degree (typical, some up to 270 degrees) cycles. Test conditions were: Nitrogen environment under ambient pressure with temperatures ranging from -2degC to +60degC at speeds of up to 45deg/sec. The acceleration rates switched between plus and minus 25deg/sec², the load inertia was equivalent to the actual azimuth load. Thus, the test conditions were considerably harsher than the flight units will ever experience where only the elevation drive has to survive the large number of cycles, but with a load that is only ¼ of the life test unit inertia, and a top speed of only 26.3deg/sec.

The following observations were made at the end of the life test:

FLEX TAPES

Due to concerns about the survivability of the flex tapes over the required number of flex cycles, an early life test was undertaken to validate the design: at the half time inspection, some flex tape shavings were found in the chamber. The cause was traced to a somewhat pointed edge that was not fully de-burred, enabling the split housing sidewall edges to cause some abrasion at one side of several tapes, but none of the electrical traces were affected yet. This edge was properly de-burred, resulting in no additional abrasion over the second half of the life test. As a design pre-caution, all six cables use their outermost trace facing this housing wall as grounding trace. Thus, even if the wear had cut into one of these traces, the instrument's functioning would not have been affected. The flex cable life test set up can be seen in Fig. 7.

Fig. 7: Flex Cable Life Test Set-Up

For the azimuth joint life test, extra care was taken to ensure that all tape contacting surfaces were absolutely smooth. This time, the tapes survived the life test remarkably well, far beyond expectation: all electrical traces were still intact and no cuts or cracks or other damage was found on any of the tapes. Some of the side surfaces of the flex prints looked polished but not worn; the top/bottom surfaces showed some dull spots (previously shining) from tapes rubbing each other, but no wear. Lessons learned: Under proper conditions, especially regarding smoothness of sidewalls, flex tape bending radii not below 4cm and flexing in one direction only: printed circuit flex tapes could potentially survive 10 million cycles.

LUBRICATION

Due to longevity requirements, Pennzane was the obvious choice as lubricant. Unfortunately, Pennzane's viscosity increases dramatically at only moderately cold temperatures. The cold cycles for the life test were thus set to the relatively benign temperature of -2degC. At 2.3

million cycles, the actuator experienced difficulties running at top speed. After determining that a slight degradation of the lubricant was the most likely cause, cold testing was resumed at +3degC. That slight increase in temperature, which causes the lube's viscosity to decrease, proved to be all that was necessary to compensate for the lube's increase in drag due to aging: the life test completed without any further incident. Examining the lube after the life test showed color alterations from brown to black. Chemical analyses, however, revealed that the lube had retained its lubrication properties and thus was still good for use. In fact, this joint is still being used and performs flawless within the updated, narrower temperature range that sets the new lower temperature limit at +5degC. Lessons Learned: Pennzane has the longevity required for long duration deployments under heavy load conditions, provided it is allowed to operate at sufficiently warm temperatures, preferably above 0degC. For intermittently running applications that require cold starts, sufficient heating power must thus be provided to pre-heat the mechanisms.

MECHANICAL COMPONENTS

Since the joint is still being used, it could not be disassembled completely, restricting more elaborate post life test analyses. Visual inspections revealed that neither gears, bearings or the harmonic drive show any signs of deformation or wear. This is remarkable, given the high actual stresses, the large number of load cycles, and severe impact loads that included driving into the hard stops at full speed during acceptance testing. Lessons learned: adhere to design practices and guidelines and choose proper operating conditions and lubricants to establish a solid foundation for mechanical survivability.

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BIOGRAPHY

Bruno Jau is a Member of the Technical Staff at the Jet Propulsion Laboratory. He earned a Ph.D. in ME from the University of Southern California and a MS degree in ME from Michigan State University. His undergraduate work was done in Switzerland.

His areas of expertise are solid mechanics, mechanisms, CAD and manufacturing. He gained professional experiences in corporate, R&D, consulting and University environments, including a position as a Professor at Texas A&M University. Principal research activities include the development, design and implementation of electromechanical systems and space instruments. He has published over 30 articles in these areas.

Dr. Jau joined JPL in 1985 and has worked in Robotics and Mechanical Engineering Sections since then. He was responsible for the mechanical development of several space flight instruments. He also developed, designed and implemented a variety of robotics prototypes, including an anthropomorphic telerobot system with a four fingered hand.

ACKNOWLEDGMENT

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