



MSX Attitude Determination and Control Hardware

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Although APL has built over 50 satellites of various types since 1960, the Midcourse Space Experiment (MSX) satellite requires the most complex and demanding attitude control system of all. Precise pointing ability is combined with substantial agility. The system must be able to point in the direction of a test ballistic missile launch, follow the predicted missile trajectory (as the satellite proceeds in its own Keplerian orbit), and then receive closed-loop pointing instructions from the MSX optical and radio frequency sensors to follow the target as it proceeds on its ballistic trajectory. To meet this challenge, the MSX attitude control hardware is the most advanced in the industry. The reaction wheels are custom-designed to provide twice the torque capability of the Hubble Space Telescope wheels. A unique computer system integrates the attitude sensor data, provides solutions to the control laws with data from gyros and wheels, and directs torque commands to the four wheels every 0.5 s. This powerful onboard computational capability could not have been achieved 10 years ago.

INTRODUCTION

The mission of the Midcourse Space Experiment (MSX) is to gather data from, and evaluate the performance of, space-based scientific sensors as they measure the ultraviolet, visible, and infrared signatures from a ballistic missile or other background of interest. The mission requires precise pointing and stability of the line of sight to point the three science sensors that will gather data in the ultraviolet, visible, and long-wave infrared wavelengths: the Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI), a suite of ultraviolet and visible imagers and spectrographic imagers; the Space-Based Visible (SBV) instrument, a

sensor in the visible wavelengths; and the Spatial Infrared Imaging Telescope III (SPIRIT III), an imaging telescope sensor in the long-wave infrared.

The science sensors are pointed at a target in space by maneuvering the spacecraft via an onboard attitude determination and control system that uses hardware and computer software to accomplish its mission. This article describes the attitude determination hardware, which consists of sensors that

- Measure the Earth's magnetic field
- Determine the direction of the Sun relative to the spacecraft

- Detect the Earth’s horizon as seen by the spacecraft
- Determine the spacecraft orientation with respect to known star directions
- Indicate changes in the spacecraft attitude

In addition, we describe the hardware for effecting the attitude control solution: the electromagnetic torque rods, the reaction wheels, and the attitude computer.

The attitude determination and control software in the attitude processor is designed to control the attitude of the spacecraft. As in any control system, the attitude determination software computes the current attitude, compares it to the desired attitude (received from the spacecraft tracking processor), computes the torques required to control the spacecraft, and distributes commands to the appropriate torque generators so that the spacecraft can be maneuvered to the desired attitude.

ATTITUDE CONTROL AND DETECTION SYSTEM

Figure 1 depicts the components of the attitude determination and control system, and it shows the

interconnections of the sensors, processor, and activating mechanisms. Figure 2 is a cutaway view of MSX showing the placement of the four reaction wheels and the three electromagnetic torque rods in the electronics section of the satellite. The star camera and the two gyro assemblies are mounted at the top of the spacecraft on the optical bench. The two horizon scanners are also mounted near the top of the spacecraft on opposite corners. The magnetometer sensor is located at the end of the S-band antenna assembly. The digital Sun sensors, mounted on the exterior of the spacecraft, are not shown here.

The basic objective of the attitude sensors, the torquers, and the computers is to achieve the desired pointing with an accuracy of 0.1° at all times when tracking a moving target such as a test ballistic missile. Spacecraft vibrations that produce jitter are to be held to less than 1 arcsec.

Star Camera

Star cameras provide the most accurate absolute pointing information possible for a spacecraft attitude

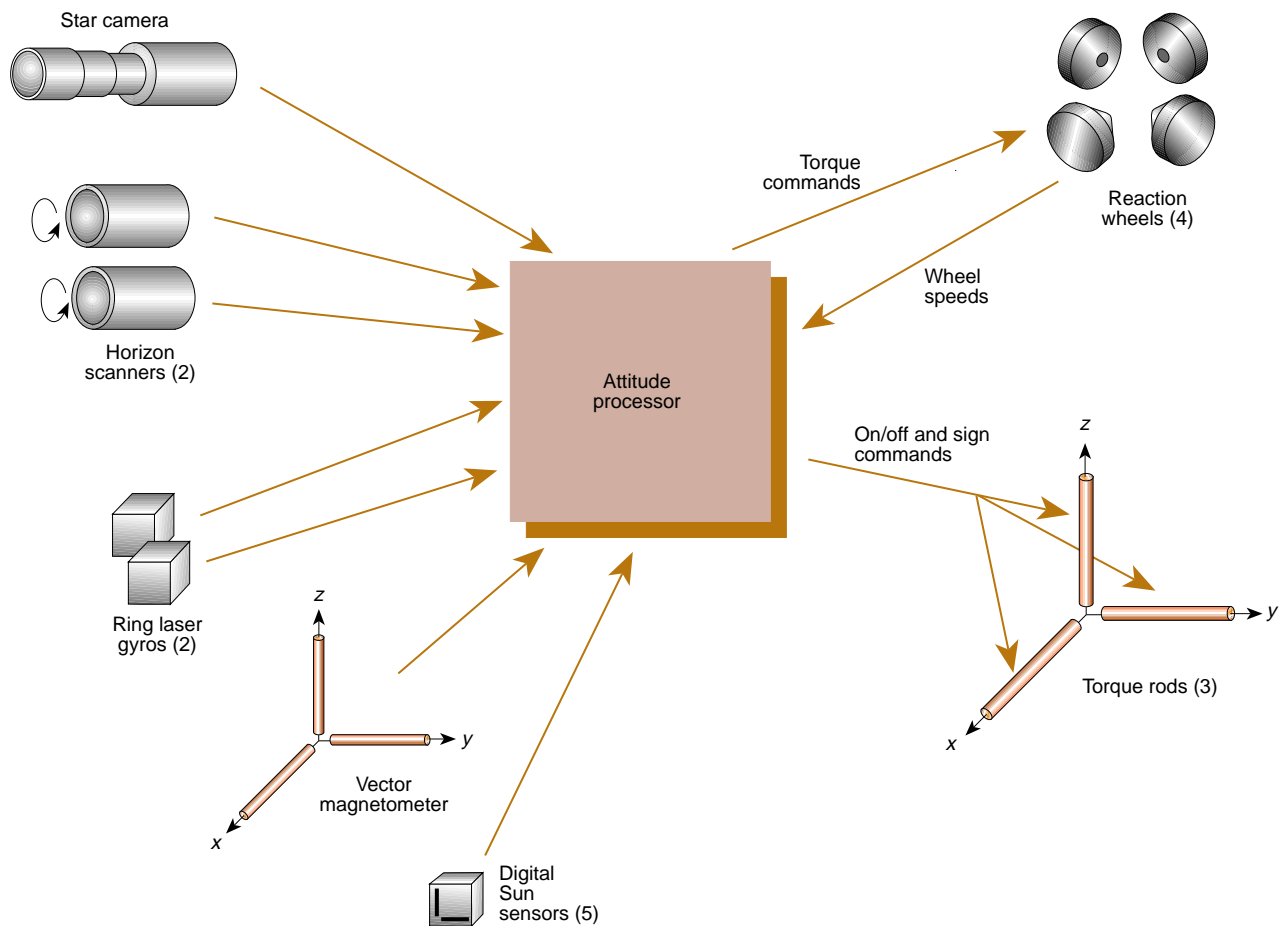


Figure 1. The components of MSX’s attitude determination and control system, showing the interconnections of the sensors, processor, and activating mechanisms.

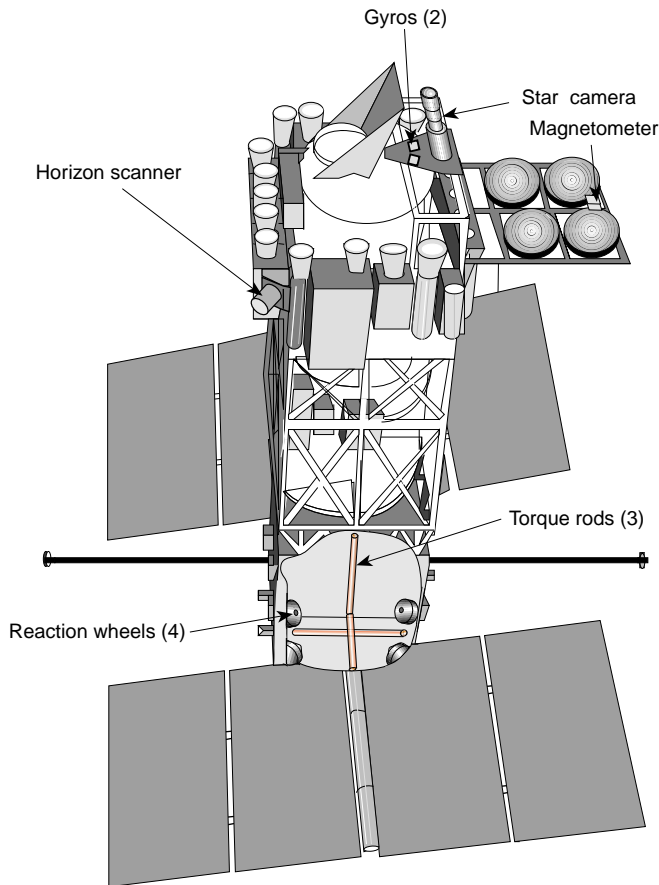


Figure 2. Attitude control components of the MSX satellite. Cut-away shows the placement of the four reaction wheels and the three electromagnetic torque rods; the star camera and the two gyro assemblies are mounted at the top of the spacecraft on the optical bench; the two horizon scanners are also mounted near the top of the spacecraft on opposite corners; and the magnetometer sensor is at the end of the S-band antenna assembly.

control system. Because there are so many stars in the celestial sphere, however, computer software is needed to identify them automatically and tell the satellite where it is pointed. The accuracy and autonomy provided by a star camera would be impossible without high-speed microprocessors for image processing and star identification.

Like a modern video recorder, the MSX star camera takes electronic "pictures." Figure 3 shows a cross section of the camera, which was designed and built for APL by Ball Corporation of Boulder, Colorado. Its primary components are a lens, a light-sensitive detector (a charge-coupled device or CCD), a microprocessor, and a power supply. The CCD is a chip of silicon, about 1.0×1.0 cm with 512×512 pixels

(picture elements). Starlight is absorbed for 0.1 s, then electronically read out to determine the star locations in the $8 \times 8^\circ$ field of view. The camera can detect stars as weak as 6th magnitude. The entire sky contains about 9000 stars of 6th magnitude or brighter; therefore, we are assured of having 3 to 5 stars in the field of view of the camera even in the least dense regions of space. The microprocessor in the star camera mathematically calculates the centroid location of up to 5 stars, and these centroid locations are relayed to the attitude computer for identification. The attitude accuracy is 5 arcsec.

The attitude control computer identifies stars by matching them with star locations in a catalog stored in the computer's memory. The APL-developed computer software first finds a pair of cataloged stars with the same separation as a pair of measured stars. When a pair of stars has been tentatively identified, an attitude is computed. If this identification is correct, other cataloged stars should overlay measured stars in that frame. Our software requires that at least three stars in the same field of view be matched with cataloged stars before the tentative attitude is accepted.

Ring Laser Gyros

In addition to the star camera, the MSX satellite uses two ring laser gyro (RLG) systems for attitude determination. Such RLGs are used on the latest commercial and military aircraft, but their use on MSX will be only the second such use in a satellite. The RLG systems for MSX were built for APL by Honeywell, Inc., of Clearwater, Florida. Each RLG system weighs 5.9 kg and

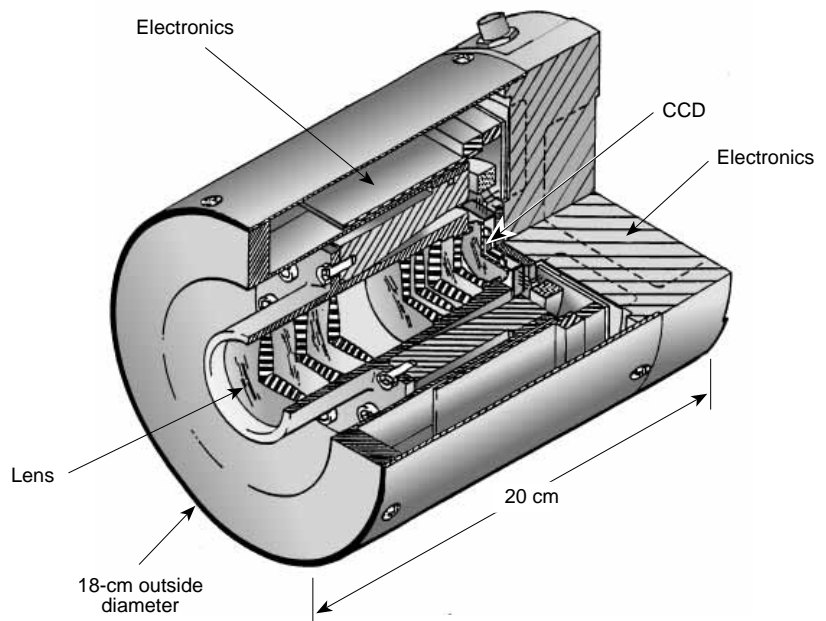


Figure 3. Cross section of the MSX star camera.

consists of an electronic assembly and three single-axis RLGs mounted orthogonally in one box. The basic unit of the RLG is a triangular block of glass about 5 cm on a side and 1.9 cm thick, with three internal passages connected in a triangle, as shown in Fig. 4. The internal passages are filled with helium and neon gas. Mirrors at the three corners reflect the laser light around the triangular internal path. The laser beams travel clockwise and counterclockwise, and the two beams interfere with each other to form interference "fringes." If the gyro rotates about its axis, these fringes move and are "counted" electronically. The counts are a measure of the rotation of the spacecraft. A computer accumulates all the rotations from the three orthogonal gyros, thereby tracking the relative changes in angular orientation of the spacecraft to an accuracy of 0.02°/h.

The electronics of the RLG system include a miniaturized digital computer that can perform 1.2 million operations per second. The computer accumulates the counts from the three orthogonal gyros, filters the data to remove certain known sources of error, and prepares a string of digital data that is sent to the attitude processor 20 times per second.

Reaction Wheels

The reaction wheels in the MSX spacecraft provide the necessary torque to change the attitude of the

spacecraft as needed. Each of the four reaction wheels is 46 cm in diameter and weighs 28 kg; the wheels were designed and built for APL by Honeywell, Inc., of Phoenix, Arizona. Figure 5 shows a wheel cross section. The three-phase brushless direct current motor provides torque to the wheel and is mounted under the web that supports the inertia rim. The electronics are mounted on circuit boards at three levels. Hall-effect sensors detect the angle of rotation of the central shaft and provide commutation signals for control of the motor current. The maximum torque output is 1.6 N·m and the speed range is ± 4500 revolutions per minute (rpm). The wheel is sealed with O-rings, and the interior is evacuated to eliminate air drag on the inertia rim. This arrangement also helps to keep the ball bearings clean during ground testing.

The speed of the reaction wheels depends on the operational mode and the maneuvering requirements of the spacecraft. Most of the time, the spacecraft will be in the "park" mode, and the wheels will spin at about 100 rpm. With the spacecraft in "track" mode, the wheels will accelerate to about 1000 rpm. Figure 6 shows computer calculations of the wheel speed variation that is required to track a ballistic missile. Wheel speeds reach their peak when the distance between MSX and the target is at a minimum and the angular attitude adjustments required for tracking are at a maximum. Marshall, Gunderman, and Mobley¹ give further details on the spacecraft's reaction wheels.

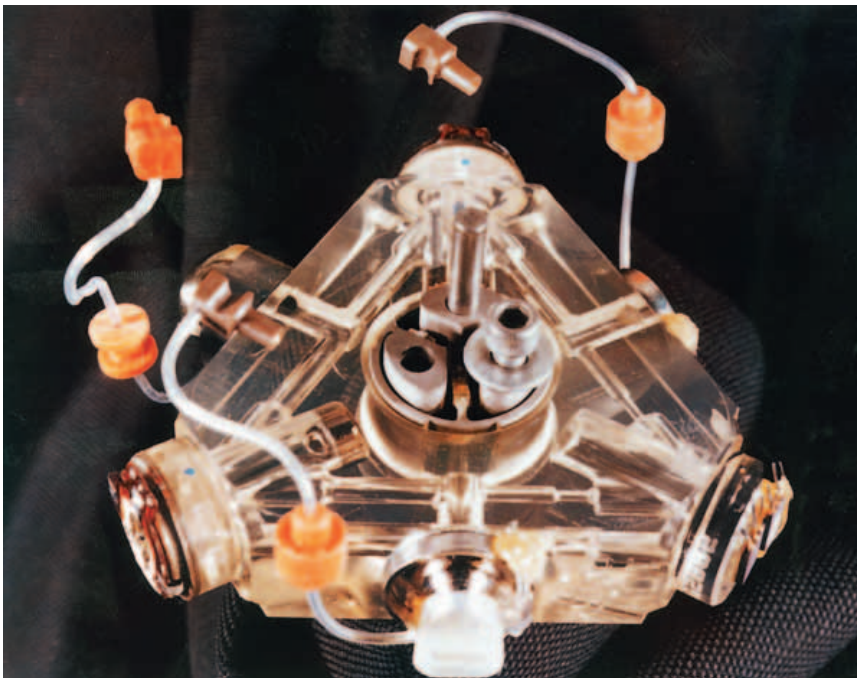


Figure 4. The basic unit of each ring laser gyro, a triangular block of glass about 5 cm on a side and 1.9 cm thick. Three internal passages are filled with helium and neon gas, and mirrors at the three corners reflect the laser light clockwise and counterclockwise around the triangular internal path. The two beams form interference fringes that are used to measure spacecraft rotation.

Sun Sensors

The direction of the Sun with respect to the spacecraft is determined by five digital solar attitude detectors (DSADs) designed and built for APL by the Adcole Company of Marlborough, Massachusetts. The DSADs provide conditioned data in two axes from each sensor, with an accuracy of $\pm 0.5^\circ$. The sensors are positioned on the spacecraft so that the Sun can be observed by one or more of the sensors, regardless of spacecraft orientation. The sensor most directly facing the Sun is selected by comparing the amplitude of the signal from each sensor. Once the proper sensor has been selected, the data are digitized by the electronics and sent to the attitude data processor.

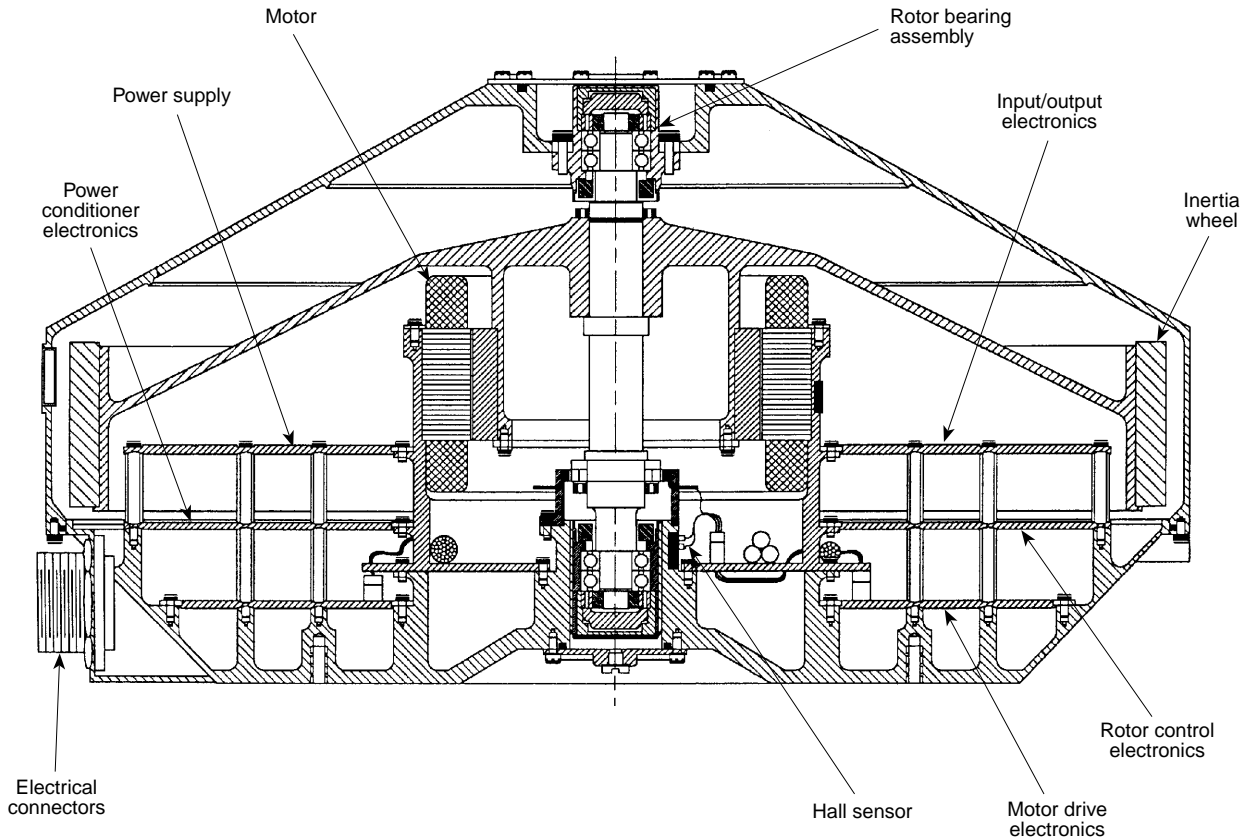


Figure 5. Typical cross section of an MSX reaction wheel. The motor provides torque to the wheel and is mounted under the web that supports the inertia rim. The electronics are mounted on circuit boards at three levels. Hall-effect sensors detect the angle of rotation of the central shaft and provide commutation signals for control of the motor current.

Horizon Scanners

Horizon scanners on the MSX spacecraft are the principal means for directly determining the orientation of the spacecraft with respect to the Earth. The scanner uses an infrared sensor to detect the temperature difference between the Earth and space. The horizon scanner consists of a mechanism for scanning a cone centered on the instrument's boresight, associated optics, a radiance detector (thermistor), and

signal processing electronics. The scanner scans the Earth looking for horizon crossings (i.e., the edges of the warm Earth against the cold background of space). The instrument sends a serial digital message containing two angles per scan to the attitude data processor. The scan cone radius is 45°, and the scan rate is 4 rpm.

The MSX satellite uses two identical horizon scanners, which were built for APL by the Barnes Engineering Division of the EDO Corporation, Shelton,

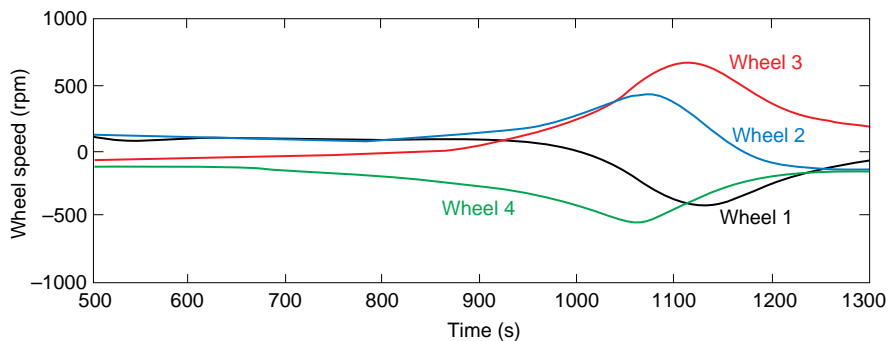


Figure 6. Predicted speed variation of the reaction wheels during a typical tracking maneuver.

Connecticut. The scanners are mounted on the spacecraft such that the scan cones intersect the horizon on opposite sides of the Earth when the spacecraft is in the park mode. During normal spacecraft maneuvering, the Earth and space will be seen by at least one of the sensors to provide the necessary data for determining spacecraft orientation. The accuracy of pitch and roll angles from the horizon scanner is about $\pm 0.1^\circ$.

Torque Rods

Three electromagnetic torque rods in the MSX spacecraft are used primarily to control (dump) excess spacecraft angular momentum. The torque rods can also be employed in attitude control where a high rate of maneuvering is not required. The torque rods were designed and built for APL by ITHACO, Inc., of Ithaca, New York. Applying current to a torque rod coil creates a magnetic field, which interacts with the Earth's magnetic field to generate small torques on the spacecraft. This action is like a magnetic brake to the spacecraft angular motion. By selectively turning on one or more rods, the excess angular momentum can be removed from any spacecraft axis. Each torque rod is 0.9 m long, 2.5 cm in diameter, and weighs 2.7 kg. Each rod can produce a magnetic dipole strength of $100 \text{ A}\cdot\text{m}^2$ and a torque of $0.005 \text{ N}\cdot\text{m}$.

Magnetometer

A three-axis vector magnetometer measures the three components of the Earth's magnetic field (x , y , and z). The function of the magnetometer is twofold: to determine when the magnetic torque rods should be turned on and off to correct for excessive spacecraft angular momentum (momentum dumping) and to provide attitude data during the park mode operation. The magnetometer outputs (X , Y , and Z) are voltages that are proportional to the magnetic field at each sensor coil.

The MSX three-axis vector magnetometer was designed and built for APL by the Schonstedt Instrument Company of Reston, Virginia. The system consists of an electronics unit and a sensor head containing three sensing coils. To avoid the magnetic effects from the spacecraft, the sensor head is mounted at the end of the S-band antenna platform that extends out from the spacecraft. The sensor is driven through a long cable by an electronics unit mounted within the spacecraft. The accuracy of the magnetometer data is within 1% of the true magnetic field of the Earth.

Computer

The MSX attitude processor was designed, built, and programmed by APL. It consists of two MIL-SPEC 1750 microprocessors, each with 500K words (16 bits each) of random access memory (RAM) and 256K words of electrically erasable programmable read-only memory (EEPROM). When power is turned on, the attitude software is copied from EEPROM to RAM, and then the software executes out of RAM. One processor interfaces with the spacecraft and the attitude hardware. This processor contains all of the interface software that collects the attitude sensor data, sends the commands to the attitude actuators (wheels and torque rods), processes commands from the ground, and outputs telemetry. The other processor contains the attitude determination and control software. Every 0.5 s it receives attitude sensor data from the interface processor, determines the present attitude, compares it with the desired attitude, and calculates the actuator commands required to correct any errors.

SENSOR AND INSTRUMENT ALIGNMENT

All attitude sensors and scientific instruments on the MSX spacecraft must be mechanically aligned so that the orientation of the instruments with respect to a spacecraft reference can be determined precisely. If the attitude control system is to maneuver and point the spacecraft accurately, and if the scientific instruments are to provide reliable information, precise data on the mechanical orientation of the various sensors and instruments (for example, the star camera and the digital Sun sensors) must be determined. Alignment is also performed on mechanical, moving structures of the spacecraft to ensure correct positioning of the moving part or repeatability of a movement.

Theodolites are used to make the alignment measurements. An optical cube is mounted on each instrument, and the instrument boresight is referenced to this cube. All instrument boresights are then referred to spacecraft coordinates by optically mapping their cubes into a master cube using theodolites. All narrow field-of-view instruments were adjusted by shimming and shifting their mounting feet until they were coaligned with SPIRIT III, the prime science instrument.

The boresight orientations of the attitude sensors were inserted into the computer software. The total allowed error of 0.1° includes structural and thermal distortions, as well as initial alignment errors and tracking errors. Actual alignments are better than 0.03° .

POWER CONSUMPTION OF THE ATTITUDE CONTROL SYSTEM

The power consumed by the attitude control system is given in the following tabulation:

	Typical power (W)
Star camera (1)	11
Horizon scanners (2; both on)	11
Ring laser gyros (2; one on)	14
Digital Sun sensors (5)	0.5
Reaction wheels (4)	80*
Electromagnetic torque rods (3)	5
Vector magnetometer (1)	1
Attitude processors (2; one on)	24
Total	146.5

*Wheel power consumption can vary dramatically when rapid wheel acceleration or deceleration is required during rapid maneuvering. In fact, with rapid wheel deceleration, the wheels return power to the spacecraft. Under extreme wheel acceleration, a wheel can draw up to 800 W for brief periods (only 10–30 s) during peak maneuver acceleration. The number of 80 W is more representative of the typical satellite quiescent conditions.

SUMMARY

The attitude control system hardware is integrated into the MSX spacecraft. The reaction wheels, ring laser gyros, infrared horizon scanners, star cameras, Sun sensors, magnetometer, and torque rods were assembled on the MSX structure and electrically connected to the satellite power system and the attitude control computer system. The hardware has been tested extensively with the attitude software, including simulated in-orbit dynamics, and the system is ready for launch.

REFERENCE

- ¹Marshall, T., Gunderman, T., and Mobley, F., "Reaction Wheel Control of the MSX Satellite," American Astronautical Society Guidance and Control Conf., Paper No. AAS 91-038 (Feb 1991).

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