GLEN H. FOUNTAIN, FREDERICK W. SCHENKEL, THOMAS B. COUGHLIN,
AND CLARENCE A. WINGATE

THE MAGSAT ATTITUDE DETERMINATION SYSTEM

The Magsat mission required knowledge of the magnetic field orientation with respect to a geocentric coordinate system with an accuracy of better than 20 arc-seconds. Attitude sensors were therefore incorporated into the spacecraft. The design, construction, and verification of these sensors as a system became a major task of the spacecraft development.

INTRODUCTION

The Magsat mission requirement for measurements of the earth's magnetic field with an accuracy of 6 nanoteslas (1 nT = 10^{-9} Weber/m^2) root sum square (rss) per vector axis imposed a stringent requirement on the spacecraft's attitude determination system (ADS) of 14.5 arc-s (0.00028°) rss. The major sources of error in making such field measurements were the vector magnetometer, the satellite tracking system, and the ADS. The vector magnetometer measured the magnetic field at a given position in a geocentric coordinate system as determined by the satellite tracking network. The orientation of the field was determined by the spacecraft attitude sensors. Initial estimates of the errors associated with the vector magnetometer and the spacecraft tracking system required the errors caused by attitude measurement to be less than 4.5 nT rss; for the maximum field strength anticipated (i.e., 64,000 nT) the angular error inferred was 14.5 arc-s.

The design, fabrication, and verification of the ADS was one of the major challenges of the Magsat program. It is interesting, as a point of reference, to note that an angular measurement of 1 arc-s is equivalent to measuring the eye of a needle at a distance of 164 meters!

The Magsat ADS, shown schematically in Fig. 1, was a collection of sensors whose required accuracies were a few arc-seconds. These accuracies had to be verified by ground tests where component weight effects and thermal environments differed slightly from the flight conditions. From these measurements the instrument alignment and accuracies in orbit were inferred.

The ability to determine the attitude of satellites has been steadily improving. The Small Astronomy

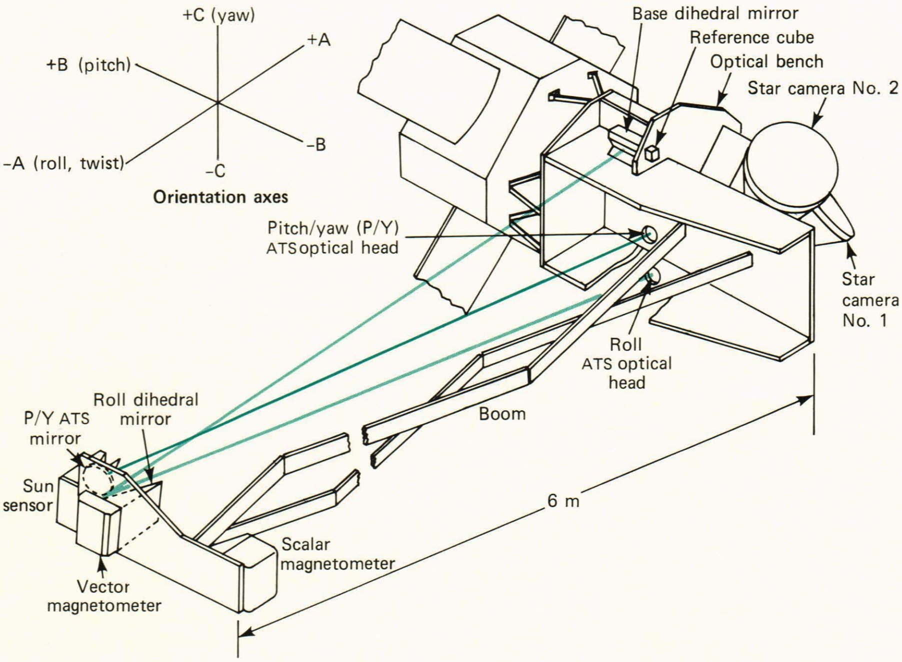

Fig. 1—The attitude determination system consists of two star cameras mounted on an optical bench, which also contains an attitude transfer system for relating the orientation of the star cameras to the vector magnetometer. The sun sensor (and a rate gyro located in the spacecraft) provides additional information to allow interpolation between star sightings.

Satellites SAS-1 and -2 made measurements with accuracies of a few arc-minutes. Large complex satellites such as the Orbiting Astronomical Observatory (OAO) made angular measurements of 1 arc-min. SAS-3 was the first small spacecraft to attempt to make measurements in the sub-arc-minute range, but only after in-flight calibration. It was for that mission that a "strap down" star camera for high accuracy attitude determination was developed. Analysis of the in-orbit performance of SAS-3 indicated that the star cameras had the inherent accuracy to provide primary attitude data for Magsat.[1] However, to meet the entire Magsat attitude requirements, significant changes in the SAS-3 design were required, including better ground calibration, a more stable structure, and additional angular (or rate) sensing to interpolate between star sightings.

The three rotations chosen to describe the angular orientation of the vector magnetometer are roll, pitch, and yaw. As shown in Fig. 1, these rotations are measured about a set of body-fixed axes that would nominally be aligned to the spacecraft velocity vector (roll), the orbit normal (pitch), and the local vertical (yaw). For the sun-synchronous orbit chosen for Magsat, the pitch (B) axis also pointed in the general direction of the sun. For each of these axes, a detailed error budget was determined. The error budget established in November 1977 for each axis had the form shown in Table 1.

Table 1

ERROR BUDGET FOR VECTOR MAGNETIC FIELD MEASUREMENT

	arc-s		*nT*
Vector magnetometer			3.8
Attitude determination			
Star camera	11		
Attitude transfer system	5		
Optical bench	4		
Subtotal (rss)	13	→	4.1
Satellite position error			1.7
Total error (rss)			5.8

STAR CAMERAS

The two star cameras that provide the primary attitude determination data were built by the Ball Brothers Research Corp., based on the SAS-3 star camera design. Each camera consisted of a Super-Farron objective lens that focused an 8 by 8° star field onto the photocathode of an image-dissector tube. The image dissector consisted of a photomultiplier with a small aperture in front of the first dynode and a gradient-free drift space between the aperture and the photocathode on which the optical image was focused. Deflection coils steered electrons from a given portion of the photocathode surface through the aperture. By programming the deflection current the entire area of the photocathode was scanned for the presence of star images. Figure 2 shows the scanning pattern for the Magsat cameras.

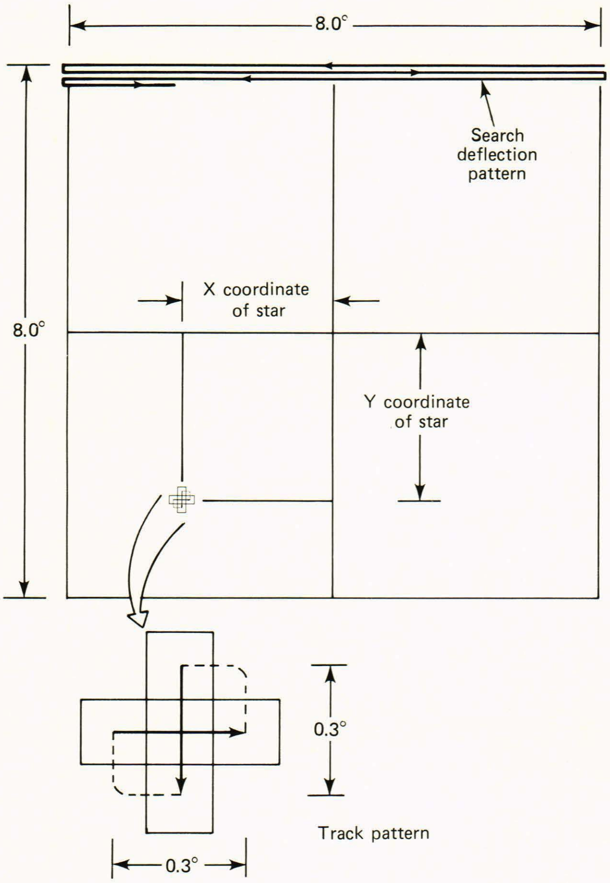

Fig. 2—When searching for a star, the camera field is searched in a left-to-right, right-to-left pattern. If an illuminated area is detected during the scan pattern, the camera will automatically initiate a small cruciform scan about the center of the illuminated area. If the illuminated area moves in the field of view, the camera automatically recenters the cruciform scan and tracks it. The deflection coil currents required to keep the aperture centered on the illuminated spot are direct measures of the star coordinates.

The cameras were designed to detect stars as dim as 6.0 visual magnitude with a probability of 0.98. In fact the cameras were typically tracking stars as dim as 7.2 visual magnitude. This guaranteed that several detectable stars were in the camera's field of view at all times.

The cameras were mounted on the spacecraft in such a way that both swept the same circle on the celestial sphere while the spacecraft rotated at one revolution per orbit. This circle was 32° off a great circle to minimize the effect of both sun and earth albedo interference. As each camera swept out its circle, the stars appearing in its field of view were tracked for a specific time. The tracking time was commandable between 4 and 128 s; for Magsat a time of 30 s was selected. After the 30 s period (or loss of track caused by the star falling outside the camera's field of view), the camera was commanded to break lock and search for another star. In this manner a "snapshot" of stars was located in the camera field of view.

Like most real devices the camera outputs were not truly linear or independent. As a result there were variations from an idealized linear response of several arc-minutes. The camera's ultimate accuracy was achieved by calibrating these effects during ground tests and removing them during post-flight data processing. Each observed position, once these effects were removed, was accurate to 10 arc-s or better with respect to the camera optical axis.

ATTITUDE TRANSFER SYSTEM

The transfer of each observed star position to the vector magnetometer depended on the accuracy of the attitude transfer system (ATS). The system, built by the Barnes Engineering Corp., measured the relative orientation of the vector magnetometer with respect to the star cameras via two optical systems that measured the rotational angles of pitch, yaw, and roll. Both optical systems used a 125 Hz, 50% duty cycle, modulated infrared beam at 930 nanometers to perform the optical measurement. This allowed both optical filtering and a synchronous detection scheme to eliminate effects of interfering light sources such as sun or earth albedo.

The simplest system was one that measured the pitch and yaw angles of the vector magnetometer with respect to the optical bench. The pitch/yaw transceiver generated at the transceiver exit pupil a 1.8 cm square beam that was reflected by the flat mirror mounted on the vector magnetometer platform. The return beam formed a square image in the focal plane of the transceiver 0.03 cm on a side. When perfectly collimated, the image was centered on two split detectors as is shown in Fig. 3. Pitch or yaw rotations of the vector magnetometer platform produced displacements of the image. The two detectors were oriented so that, to first order, the pitch sensor was insensitive to yaw motion and the yaw sensor was insensitive to pitch motion. A 1 arc-s rotation in either pitch or yaw produced displacement of the image on the order of 1.3×10^{-4} cm, which generated an output in the appropriate split detector. The maximum angular rotation, allowed to keep the pitch/yaw system within its linear region, was ± 3 arc-min. A second constraint on the pitch/yaw system was the allowable translation of the vector magnetometer. If the flat mirror translated more than ± 1.9 cm, the collimated beam would be vignetted or possibly not returned to the pitch/yaw transceiver.

The roll system was much more complicated. It was, in essence, trying to measure the rotation (twist) about the line of sight of the optical system. The measurement was made by generating an off-axis collimated beam that produced a pseudo-yaw signal as a function of roll rotations. The roll optical system is illustrated in Fig. 4. A transceiver was located on the optical bench but was displaced from the roll axis. The collimated signal was transmitted to a dihedral mirror on the magnetometer platform that reflected the beam to a second dihedral mirror on the optical bench. From this base dihedral mirror the beam was reflected back on itself to the transceiver.

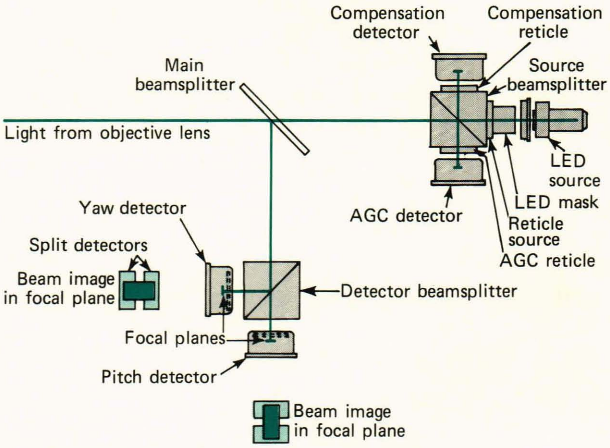

Fig. 3—The light-emitting diode (LED) of the attitude transfer system generates an infrared signal that is formed into a square image by the LED mask at the focal plane of the objective lens. The source beamsplitter diverts a small amount of the transmitted and received energy to the compensation and automatic gain control detectors, which stabilize the sensor performance. The majority of the returned signal is diverted to the pitch and yaw detectors by the detector beamsplitters. There the image formed by the LED mask is focused on the two silicon cells in each detector. Yaw motion causes the beam image to move along the horizontal axis of each detector, producing a change in the differential output of the yaw detector while leaving the output of the pitch detector unchanged. Pitch motion causes the image to move along the vertical axis of the detector, producing change in the output of the pitch detector.

In its simplest form the dihedral mirror on the magnetometer platform can be thought of as reflecting the transmitted image onto a circle whose radius is defined by how far the transceiver is off the roll axis. As the magnetometer dihedral mirror rotates, the transmitted image moves around the circle, producing a pseudo-yaw motion. In fact, the two dihedral mirrors could be flat mirrors tilted at the appropriate angles and produce the same result, but both pitch and yaw motion of the magnetometer would corrupt the roll measurement. The dihedral mirrors are insensitive to rotations about the ridge line. Thus the dihedral mirror on the magnetometer platform effectively decoupled yaw from the roll measurement and the decoupled pitch motion of the base dihedral mirror.

The transmitted roll image was focused onto another split detector in the transceiver that detected the pseudo-yaw motion. In this case, how-

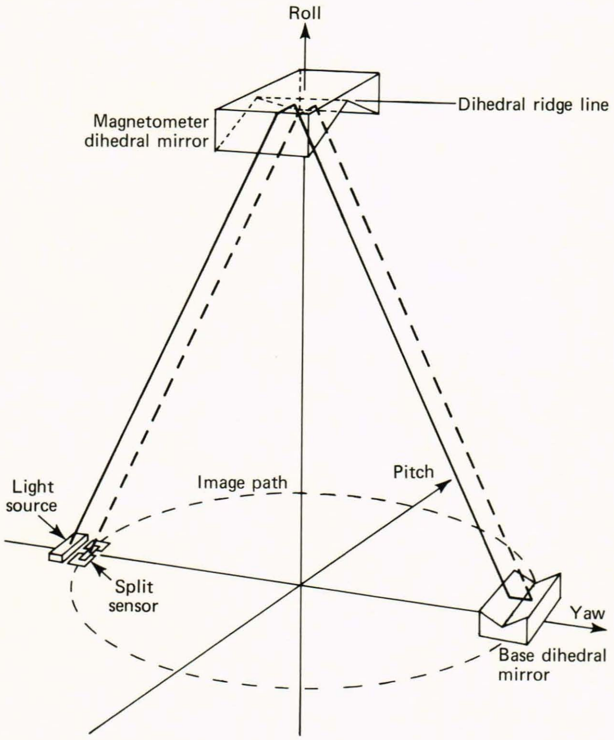

Fig. 4—The roll system transceiver generates a collimated beam that is reflected by the magnetometer dihedral mirror. As the dihedral mirror rotates about the roll axis, the reflected beam traces out a circle in the pitch/yaw plane. The base dihedral mirror causes the reflected beam to be returned to the transceiver when the magnetometer dihedral ridge line lies in the roll/yaw plane. For small roll rotations, the returned image is translated parallel to the pitch axis (as a yaw rotation would produce in an autocollimator), which is measured by the split detector.

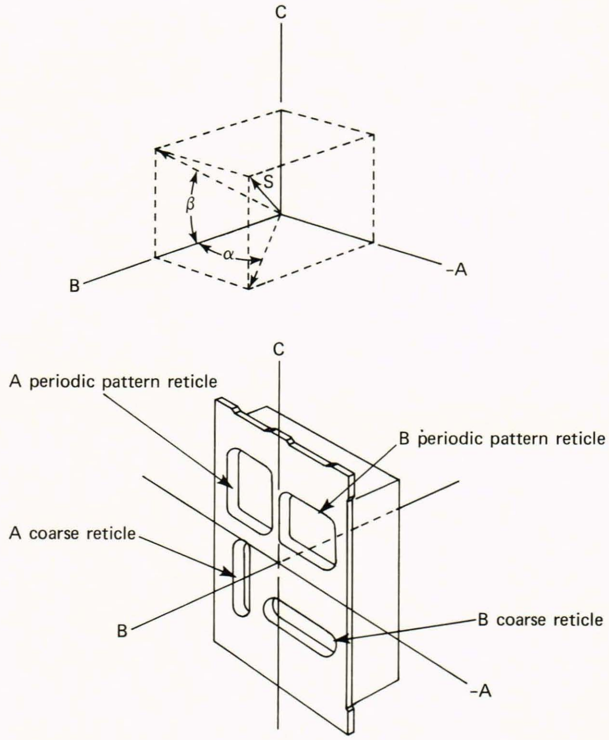

Fig. 5—The precision sun sensor resolves the orientation of the sun line into two angles (α and β) in the sensor coordinate system by means of the A and B reticle assemblies. The periodic patterns determine the α and β angles with a precision of 2 arc-s in a 2.2° repeating pattern. The coarse reticles determine which one of the 2.2° segments (in the 32° field of view) actually contains the sun line.

ever, the pseudo-yaw motion for a 1 arc-s roll rotation was only 1×10^{-5} cm. In addition, because the roll rotation appeared as a yaw motion, actual yaw rotations between the transceiver and the base dihedral mirror appeared as roll motion and, unfortunately, at an even more sensitive level than the true roll rotation. This put a very stringent requirement on the Magsat optical bench and required the rotation about the line connecting the transceiver and the base dihedral (yaw) in the plane of the bench to be less than 0.2 arc-s if such motion was to affect the roll measurement by less than 2.5 arc-s. This effect was noted during ground calibration of the roll system. Measurements taken with the spacecraft in two configurations that reversed gravity-induced distortion in the optical bench produced significant changes in the roll output. This 1 g bias was removed by the roll system calibration.

PRECISION SUN SENSOR

The precision sun sensor (see Figs. 5 and 6), manufactured by the Adcole Corp., was the only primary attitude sensor that was sufficiently clean

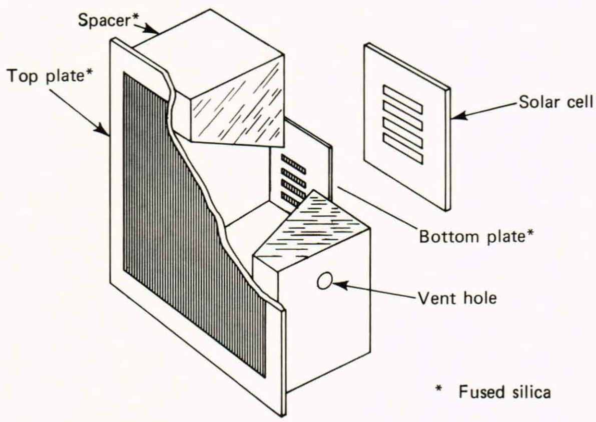

Fig. 6—The periodic pattern reticle assemblies consist of two thin, fused, silica plates separated by a fused silica spacer. Four photocells are located beneath the bottom plate. A periodic grating deposited on the lower surface of the top plate has equal-width lines and spaces with a grating period *w*. The bottom plate has four identical periodic patterns deposited on the upper sun-facing surface, with the same grating period as the upper plate. However, each of these four lower patterns is displaced by one-quarter of the grating period. When combined, these four periodic patterns form a 4-phase filter for light reaching the photocells beneath the four patterns.

magnetically to be mounted near the vector magnetometer. The sensor optical system resolved the angle between the sun line and a sensor coordinate system into two angles with a resolution of better than 2 arc-s and an accuracy of 12 arc-s root mean square (rms) based on preflight calibration. The sensor optics contained two reticle assemblies for each angle measurement. Each assembly consisted of one periodic pattern reticle and one coarse angle reticle. The periodic pattern reticle provided angular information with 2 arc-s resolution over repeated angular periods of 2.2°. The coarse angle reticle determined which of the periodic patterns the sun line was in over a range of ±32°.

The periodic pattern reticle acted as a 4-phase filter for the incident sunlight with a spatial distribution of intensity. The position of the intensity distribution, and consequently the amount of light transmitted by the 4-phase grating to the photocells, was a function of the sun angle. As the sun angle moved in the plane perpendicular to the grating lines, the output of each of the 4 photocells varied sinusoidally with a period of 2.2° and with each cell in phase quadrature. The sensor electronics converted the photocell outputs to digital data.

By combining the periodic pattern reticle outputs with the coarse pattern reticle outputs, which unambiguously determine the angles α and β with a resolution of 1°, the sun angle could be determined with a resolution of 2 arc-s.

Like most other highly accurate sensors, small imperfections in the system created nonlinearities in the actual sensor output. For the sun sensor, these nonlinearities were caused by a number of factors such as the flatness of the grating substrates, the photocell spectral response, the skew (misalignment) between the input and output gratings, and the thickness of the grating patterns. Analysis by the Adcole Corp. resulted in a transfer function dependent on higher order harmonics of the fine reticle period that reduced the errors to the level of 12 arc-s rms.

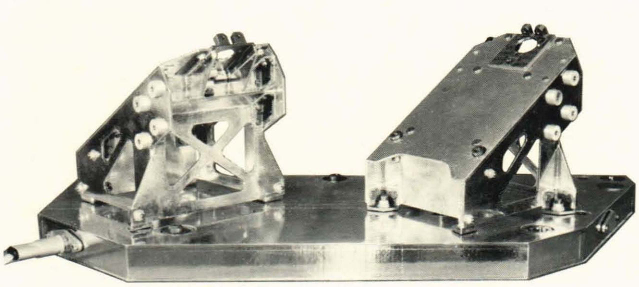

Fig. 7—The Magsat optical bench shown here was fabricated by the Convair Division of General Dynamics. The inclined planes on the top surface hold the star cameras. The ATS components are mounted on the underneath side as illustrated in Fig. 1. The silver-like surface of the structure is the aluminum moisture barrier.

OPTICAL BENCH REQUIREMENTS

For the ADS to function, the attitude sensors had to be connected by means of extremely stable structures. The spacecraft optical bench (Fig. 7) and the magnetometer platform were designed and built to hold the alignment of the system elements mounted on them to deflections of 1 to 2 arc-s during orbital operations. In addition, they could suffer no alignment changes during the launch and prestabilization phases of the mission. Severe weight constraints, in conjunction with the thermal, structural, and magnetic requirements, led to the choice of graphite-fiber reinforced epoxy (GFRE) for the construction of both structures. Active temperature control was necessary to meet thermal deflection objectives. The optical bench was attached to the spacecraft by means of a kinematic mounting arrangement to prevent significant deflection caused by spacecraft bending.

The selected material was superior to the other materials (such as aluminum or beryllium) in strength and stiffness ratios and in coefficient of thermal expansion, and it is not magnetic. It has some unique properties that require special care but are tractable. GFRE consists of graphite fibers lying in a single plane, held together by resin. The desirable properties of GFRE exist only in the fiber plane. Normal to the plane, the thermal properties of GFRE degrade, approaching those of epoxy. By using an egg crate construction technique degradation of the anisotropic properties was reduced.

Another factor considered was hygroscopicity. Strains caused by water absorption by GFRE during satellite construction and testing can approach 100 μm/m and can produce deformations far exceeding those caused by thermal sources. Critical alignments of bench-mounted components, performed when the bench had a high moisture content, were likely to change in orbit as the moisture was released in vacuum. This undesirable property was reduced to tolerable levels by the application of a moisture barrier to the external surfaces of the optical bench. The moisture barrier consisted of 0.017 mm aluminum foil bonded to the GFRE.

A comparison of the critical alignment goals and the expected thermal deflections of the satellite structure when in orbit indicated that the bench should be attached to the structure in a manner that would not introduce bench bending. This analysis led to a kinematic arrangement for attaching the bench to the spacecraft. Of the three attachments, one restricted all three translational degrees of freedom and the other two restricted the three rotational degrees of freedom without introducing additional translational constraints.

Even with the use of GFRE, the requirement for temperature control was reasonably stringent. For the optical bench, which was 3.8 cm thick and had a maximum separation between any two components of 66 cm, a temperature gradient through the bench of 0.5°C would produce a deflection of 1 arc-s. In addition to controlling the bench temperature, it was necessary to maintain each of the bench-mounted components at a constant temperature. The basic approach taken was to prevent large temperature gradients by minimizing heat flow within the bench. The bench was first enclosed in its own multilayer thermal blanket within the spacecraft to reduce heat transfer by radiation to its surroundings. Second, the five components and three mounting points that must penetrate the blanket were heated to 25.0 ± 0.2°C. Third, thermal connections between the bench and the heater-controlled surfaces had relatively high thermal resistance.

The three spacecraft attachment fittings were designed to minimize heat flow between the bench and the spacecraft structure by controlling the temperature to 25°C through the use of thermostatically controlled heaters. Thermal resistance introduced between the bench and the spacecraft reduced the required heater power substantially. Also, in those few cases when the temperature of the structure was greater than 25°C, the heat flow into the bench was limited by the resistance.

Because the optical components (i.e., the two ATS optical heads, the base dihedral mirror, and the two star cameras) have direct heat leaks to space, they had to be directly controlled to the desired temperature. In addition, they had to be mounted so that precise alignment was maintained through all mission phases. Thus titanium, a material with low thermal conductivity, was used for the joints between the bench and each component. A heater placed directly on the bottom of each component served the dual function of preventing heat flow from the bench and controlling the component's temperature. This design resulted in a bench with minimal thermal gradients through and across the bench. Post-launch data show that gradients were less than 0.1°C.

SYSTEM VERIFICATION AND PERFORMANCE

The Magsat attitude determination system was a composite of individual units that had to be assembled into a calibrated system. Each of the sensors was tested and calibrated by its manufacturer to various levels depending on the manufacturer's facilities and the ability of that particular component to operate without assembly into the spacecraft. Verification of the primary attitude system was performed at the Calibration, Integration, and Alignment Facility at the NASA/Goddard Space Flight Center. Tests were performed to determine the alignments of the star cameras and the ATS components to an optical reference mounted on the spacecraft optical bench. The star camera calibration algorithms generated by the Massachusetts Institute of Technology's Center for Space Research, based on the calibration data furnished by the Ball Brothers Research Corp., were verified. The calibration of the ATS system related the sensor outputs to the angular relationships between the spacecraft optical bench reference cube and a reference cube on the vector magnetometer (see Fig. 1). The alignments between the precision sun sensor and the vector magnetometer were also measured at this time, but no verification of the Adcole calibration of the sun sensor was performed.

The flexure induced in the bench by the weight of the components was measured by making all alignment measurements with the spacecraft B axis both up and down (i.e., ±1 g). The measurements indicated that star camera No. 1 moved 9 arc-s and star camera No. 2 moved 30 arc-s because of weight reversal. The ATS pitch/yaw system moved less than 3 arc-s, but the roll system changed by 70 arc-s because of the sensitivity of the roll output to yaw rotation between the roll transceiver and the base dihedral mirror. Changes of 10 arc-s in the sun sensor alignment were measured when the vector magnetometer plate assembly was flipped to reverse the weight loading. The final calibration of the system used these measured changes to determine the relative alignments when in space. The weight loading effect was removed by averaging the difference in alignment in the ±1 g cases.

A second set of alignment measurements was made after the spacecraft had been exposed to environmental testing. Residual changes caused by environmental stress were less than 3 arc-s for the ATS and star camera No. 2. Changes in star camera No. 1 were slightly larger, reaching 10 arc-s.

The data from the various attitude sensors were used as inputs to a computer program developed by the Computer Sciences Corp., that generated three-axis attitude information at 0.25 s intervals.[2] The program computed the attitude for each 0.25 s interval based on the sensor data available. If both cameras were tracking identified stars, the magnetometer orientation was computed using the two star sightings and ATS data. If only one star camera was tracking an identified star, the second vector required for an attitude solution was derived from the sun sensor data. If neither star camera was tracking an identified star, a motion model was used to interpolate between valid star tracks. This motion model determined the right ascension and declination of the B axis from sun sensor data and the rotation (pitch) about the B axis by integrating the output of the pitch axis gyro.

The attitude determination program was capable of making certain self-consistency checks to ascertain the validity of the data and the stability of the system throughout the mission. One major check was the determination of biases in the system from data sets in which all three sensors generated valid data simultaneously. These bias determinations, computed from data taken early in the mission, indicated that the two star cameras were within 6 arc-s of the prelaunch alignment measurements. Differences between the attitude as computed by the star cameras, the ATS, and the sun sensor were larger than expected (based on ground testing). Since the star camera alignment did not appear to have changed, the discrepancy appeared to lie either in the ATS or the sun sensor. Further analysis, using a least squares fit of the observed magnetic field data, determined the distribution of the error. The best fit of the data to a model of the earth's field indicated that the major discrepancy of 200 arc-s in roll was due to the ATS (i.e., the precision sun sensor measures the roll angle correctly). Likewise, a smaller yaw discrepancy of 55 arc-s was associated with the sun sensor. The sources of these errors in the individual instruments have not been determined.

In time, the input of each sensor varied over a large portion of its range; i.e., the sun moved in a circle about the B axis during each orbit of the spacecraft, the ATS angles varied, and many stars were tracked over the entire field of view. During such a period of time, variation in the difference between a reference vector (determined by star camera No. 2, the ATS, and the sun sensor) and the same vector determined solely by star camera No. 1 was computed to be 5 arc-s root mean square (rms).[3] This variation was a measure of the system noise and the ability of all sensor transfer functions to remove the system nonlinearities.

Computations of system biases were performed several times during the mission life. Variations in system alignments were small, but with some drift that was correlated with temperature changes. A failure of the heater on one of the star cameras in December 1979 caused a shift of 6 arc-s. The data set of attitude measurements for the Magsat mission has good internal consistency and, with resolution of the observed bias, the system has an absolute accuracy of 20 arc-s rms.

REFERENCES

[1]R. L. Cleavinger and W. F. Mayer, "Attitude Determination Sensor for Explorer 53." AIAA Paper 76-114, *Proc. 14th Aerospace Science Meeting* (1976).

[2]D. M. Gottlieb *et al.*, *MAGSAT Fine Aspect Baseline System Overview and Analysis,* Computer Science Corp. Document CSC SD-78-6067 (1978).

[3]F. Van Landingham, personal communications (March 1980).