D22

N80 23517

THE MAGSAT MAGNETOMETER BOOM

James F. Smola, Wade E. Radford, and Marcus H. Reitz
The Johns Hopkins University
Applied Physics Laboratory

SUMMARY

A continuing requirement exists for lightweight extendable structures that can precisely position magnetically sensitive instruments safe distances from magnetic sources in a spacecraft. Presented herein is a brief description of one such device - The MAGSAT Magnetometer Boom System - and an overview of the major areas of concern that played dominant roles in its development. Weight, packaging volume, thermal distortion, mechanical misalignments, dimensional instability, launch environments, and low temperature functioning were areas that presented some formidable obstacles. The ways in which these obstacles were dealt with are offered here to those involved in the development of similar aerospace mechanisms with equally restrictive requirements.

INTRODUCTION

The need for a simple, lightweight, precisely alignable, virtually distortion-free, extendable structure capable of overcoming the stiffness of sizeable multiconductor electrical cabling arose during the development of the TRIAD (1972) satellite by the Johns Hopkins University's Applied Physics Laboratory. Similar devices - all of which utilized the scissors concept - were developed for GEOS-C (1975) and TIP II and III (1975, 1976). The experience acquired during these programs provided the background that was necessary for the undertaking that became the MAGSAT Magnetometer Boom.

MAGSAT's (Magnetic Field Satellite) mission was to provide global vector magnetic field data which would be used to create new maps of the earth's magnetic field and to detect large scale anomalies in the magnetic field for use in planning resource exploration strategy. Data collected during the spacecraft's low altitude phase following 5 months of expected life prior to reentry, was to be especially desirable for the latter objective. In addition to these principal objectives, the data was to be used for core/mantle studies, magnetospheric and ionospheric research, marine and other studies.

Measurements of the three vector components of the earth's magnetic field were the task of an ultrastable, high accuracy vector magnetometer and a pair of star cameras. Providing redundancy and an independent confirmation of total field magnitude were the roles of a companion instrument--a scalar magnetometer.

Magnetic contamination of the magnetometer sensors was avoided by locating the fairly magnetic star cameras on an optical bench in the spacecraft instrument module (I/M). The sensors of both magnetometers were mounted on a platform with passive and active temperature control, which was attached to the end of the magnetometer boom. Upon command the boom was to uncage and displace the sensor platform 6 meters distant from the (I/M). To satisfy requirements imposed by an Attitude Transfer System (ATS) which measured vector magnetometer tilt relative to the star cameras, the boom was to maintain the platform position such that the center of an ATS plane mirror, precisely attached to the backside of the vector magnetometer sensor, remained within a ±1.91 cm (±0.75 in) square target zone. This zone was centered on an optical axis defined by an ATS infrared light beam emanating from the I/M. In addition the plane mirror was to remain orthogonal to the optical axis within 3 arc minutes. (See ref. 1.)

SYSTEM DESCRIPTION

Figure 1 illustrates the MAGSAT spacecraft's operational configuration. Shortly after injection into a 96.76° inclination, 352 km by 561 km <u>sun synchronous</u> orbit, the spacecraft was three-axis stabilized with its Z-axis near the orbit normal and the magnetometer boom trailing aft. This orientation was maintained by an attitude control system consisting of a reaction wheel with an infrared horizon scanner, a three-axis magnetic torquing system, a pitch axis gyro system for pitch rate sensing, an attitude signal processor for semi-autonomous roll/yaw control, momentum wheel dumping and pitch loop dynamics compensation, and a second adjustable boom for aerodynamic trimming.

The magnetometer boom system consisted of a 14 link scissors boom, a three axis gimbal and the sensor platform (S/P). The S/P was connected to the I/M electrically with multiconductor cabling that was routed through the interior of each boom link. Two independent pyrotechnically actuated caging systems were used to contain and protect the boom and S/P in their stowed configurations during launch. The three-axis gimbal located at the boom base provided the boom with pitch, yaw, and roll capabilities of ±2°, ±2°, and ±5° for ATS acquisition. The drivers for each gimbal actuator, consisting of a 491 cycle square wave inverter powering

2 phase synchronous-hysteresis gearmotors coupled to gearboxes, provided average pitch, yaw, and roll scan rates of 30 arc sec/sec. A pair of tension springs attached to the drive base and I/M structure eliminated all unrestrained play in the gimbal actuator adjusting screws. Rotary potentiometers geared to the output shafts of each of these gearboxes were calibrated to give S/P angular orientation. (See Figure 2)

The boom drive consisted of a right and left handed ball screw which was similarly driven. A rotary potentiometer geared to the output shaft of the gearbox was calibrated to give boom length during deployment. Confirmation of total extension was given by a second pot made of non-magnetic materials and pinned to one of the boom hinges closest to the S/P. Total runout time was about 20 min.

Weight and thermal distortion dictated the use of graphite epoxy for the boom links. The basic link was 0.94 meters (37.125 in) long and measured 1.07 cm x 5.08 cm (0.42 in x 2.00 in) in crossection. Magnesium fittings were fastened to the ends and the center of each link with a semi-rigid epoxy to prevent interface cracking due to differential expansion. Each link was a hollow box with a .076 cm (0.030 in) thick wall and was covered internally and externally with an aluminum foil moisture barrier. (The hygroscopic nature of graphite epoxy is a source of dimensional instability). A final wrapping of aluminized Kapton* with an aluminum oxide overcoat was added for temperature control. The links were hinged to each other with pins that were forced through compliant undersized bushings which permitted rotation, but eliminated all unrestrained mechanical side play.

The aluminum foiled, graphite epoxy S/P was attached to the tip of the boom through a hollow graphite epoxy, box-like spacer and a "figure-eight" mechanism that enabled the S/P to translate while maintaining its attitude normal to the boom axis as the boom extended. Attached to the S/P with a kinematic suspension was the temperature controlled vector magnetometer base (VMB) which in turn had attached to it the vector magnetometer sensor, the remote plane and dihedral ATS mirrors, and a precision sun sensor. The kinematic suspension provided a compliant mount for the VMB and isolated it from thermally induced structural distortions that would be detrimental to the alignment of the vector magnetometer and the remote mirrors. The scalar magnetometer was attached to a 1.27 cm (0.50 in) thick epoxyglass thermal isolator which was fastened to the side of the graphite epoxy spacer.

The weight breakdown for the boom system is shown in Table 1.

*Kapton, polyimide film manufactured by E. I. duPont deNemours and Co. Inc.

AREAS OF MAJOR CONCERN

Although the precision scissors boom was a flight-proven concept, the remote, precisely aligned S/P was not. Magnetic considerations disallowed electrically powered adjusting mechanisms at the S/P end. Consequently S/P tilt adjustments could only be achieved by gimballing the boom at its base which caused the S/P to translate. This side effect coupled with the ATS's narrow field of view severely limited tilt adjusting capability. For this reason considerable engineering analysis and testing were necessary to demonstrate that the SCOUT launch environment, uncaging, deployment, thermal distortions and attitude control disturbances would not compromise the ability to achieve the precise alignments that were required.

The discussion that follows focuses on three major areas of concern that received considerable attention.

CONTROL OF THERMAL DISTORTION

The requirement here was to limit initial boom thermal distortion-due to broadside solar illumination - sufficiently to permit acquisition of the ATS remote mirrors by gimballing the boom at its base. Although the gimbals were adjustable ±2° in pitch and yaw and ±5° in roll, any tilting of the boom at its base would translate as well as rotate the remote mirrors. Since the target zone was ±1.91 cm (±0.75 in) square, any mirror tilting that was necessary for acquisition had to be achieved within 0.33° once the mirrors entered the target zone. This made the initial tilt angle of the mirrors and direction of tilt extremely important. If, for instance, the mirrors were perfectly centered within the target zone initially, acquisition would have to be achieved within 0.16° or 9.6 arc min.

The ±3 arc min requirement on mirror angle limited the permissible transverse offset of boom tip position to ±0.51 cm (±0.20 in) for simple mechanical misalignment and ±0.25 cm (±0.10 in) for misalignments caused by thermal distortion. It was important then that the system was free of play and that the boom elements were made of some material that was virtually immune to thermal distortion. (Active temperature control was ruled out because of the complexity required to implement it in the time that was available, and lack of sufficient electrical power).

The thermal problem narrowed the field of materials down to a very few. The goal was to find a material whose coefficient of thermal expansion (CTE) would remain very close to zero over a temperature range of 0°C to 40°C. Once other considerations such as weight, strength stiffness and availability were thrown in, the only material that remained suitable was graphite fiber reinforced plastic (graphite epoxy).

Design analysis concluded that graphite epoxy GY 70/X30 (co-cured foil, 0, 54, -54, -54, 54, 0, foil) would be the optimum selection. The average CTE for the 14 links in the MAGSAT boom was $+0.34 \times 10^{-6}/^{\circ}C$.

The thermal coating selected to control link temperatures and temperature gradients in the presence of the solar and earth infrared environments was vapor deposited aluminum with an Al_2O_3 overcoat on a Kapton substrate. It was attached to the aluminum moisture barrier with an acrylic, pressure sensitive adhesive. The coatings 0.11/0.16=0.69 ratio of solar absorptance to infrared emittance was chosen to give link equilibrium temperatures close to 25°C. This temperature was dictated by the fact that all mechanical alignments would be done and checked at room temperature.

Thermal distortion tests conducted in the NASA/GSFC solar simulator on a four link version of the flight boom provided temperature data that was fed into a NASTRAN model of the test boom. Tip deflections in pitch, yaw and roll that evolved were then compared against those measured during the test. Satisfactory correlations gave a high degree of confidence in the NASTRAN model of the flight boom which was three times as long. This model indicated that the transverse and angular displacements of the S/P due to boom thermal distortion would be well within the ATS allowable range.

UNCAGING, SEPARATION, AND EXTENSION

The fact that the boom and sensor platform were to trail behind the I/M and base module in orbit made stowing for launch rather elaborate. To preserve mechanical alignments and to prevent the 7.03 kg (15.5 lb) S/P from transmitting sizeable launch loads into the more delicate boom structure, two independent caging systems were provided. The S/P was held securely by two separate chains of latches each consisting of three latches interconnected by two pullrods. Pyrotechnic piston-type actuators were used to open each latch chain by command.

A second caging system consisting of two "T-rods" strapped the folded boom links and drive base securely to the vertical bulkhead of the I/M. The lower ends of these T-rods were inserted into anchor posts that were mounted to the same vertical bulkhead.

Two pyrotechnically actuated pullrods beneath the drive base pinned each T-rod to its anchor post. An adjustable nut at the other end of each T-rod was then torqued to preload the folded boom at two points 0.59 m (23.25 in) apart to 1067.6 nt (240 lbs). The preload was required to keep the boom links and gimbal actuators from chattering and to prevent the links and drive base from rolling over when subjected to side loads during vibration testing and launch. Boom uncaging preceded S/P uncaging in the boom deployment scenario.

The stowed system abounded with potential hangups. Multilayer insulation in regions of tight clearance and extremely cold temperatures at separation gave great cause for concern. Eight 150 ohm 7.5 watt resistors were attached to the drive base to provide about 15 watts of heat which kept the drive mechanism in a temperature range that would prevent it from loading up and possibly seizing due to differential contraction. The heat also kept the drive lubricants in an acceptable operating range.

Since the boom system was located in an external cavity which was shadowed from the sun prior to uncaging not much more could be done simply to keep certain parts from growing very cold. Temperature predictions for link ends that protruded from the cavity were as low as -70°C. Telemetry indicated that cavity side wall temperatures dropped to -6°C while the drive base dropped to -10°C at the time of heater turn on. After 100 minutes of preheating the drive base temperature reached 13°C, after which the S/P was uncaged. Boom extension followed.

Early in the development effort there was great concern over the ability of the boom to overcome the stiffness of the multiconductor cabling that was routed through the interior of each boom link and across 16 hinges. This cable consisted of 52 electrical conductors insulated with Durad-coated Teflon* and woven into a flatpack. Two such flatpacks ran between the S/P and I/M. With so much cabling present, it was feared that cable stiffness would become a critical factor at temperatures as low as -70°C. Cold temperature tests demonstrated that the increased stiffness of the cable was manageable. Torsion springs operating at each link pivot were of sufficient capacity to overcome cold cable stiffness as well as hinge frictional moments.

*Durad, fluorocarbon polyimide, manufactured by Haveg Industries, Winooski, Vermont
Teflon, tetrafluoroethylene, manufactured by E.I.duPont deNemours Co. Inc.

PRE-LAUNCH MECHANICAL ALIGNMENTS

The objective here was to bring the remote mirrors mounted on the S/P into the fields of view of the ATS pitch/yaw and roll optical heads and then to bring them into the linear region of the ATS by fine adjustment. How this was to be accomplished with a 6.02 m separation between them was not immediately apparent at the outset. A way had to be found to eliminate the one-g bias which would overwhelm any boom system biases that might be present.

The idea that turned out to be the best of those proposed was one that utilized a pair of 6.1 m long water troughs - Figure 3. Specially designed floats with gimballed pulleys were attached to the boom link pivots. The idea here was to simulate a zero-g condition in a plane parallel to the plane of the water. Remote mirror transverse and/or angular offset could then be corrected by gimballing the boom at its base and/or introducing shims at the VMB-S/P interface. The boom system was installed in a special fixture which was attached to a rotary table, the purpose of which was to rotate the boom into its pitch and yaw-planes for orthogonal plane zero-g measurements and adjustments. With the aid of an autoreflecting telescope, a theodolite, and numerous mirrors to measure the transverse and angular offset of the plane remote mirror, the data in Table 2 was generated.

Tests I and V were the baseline and final tests. Tests II through IV (not shown) were performed to check alignment repeatability following numerous boom extensions and retractions, removal of the boom from and its reinstallation in the flotation system, and vibration testing. These test results indicated that errors introduced by the test system were slight and that the aligned boom system had sufficient margin to accommodate the remote mirror tilting and displacement that could be expected from thermally induced structural distortions. Following this the boom system was installed in the I/M and aligned for flight.

The boom was extended from 1.52 m to fullout and back 30 times during alignment testing at room temperature and never exhibited any functional abnormalities whatsoever. Complete retractions were not easily achievable due to limitations imposed by the flotation system. Consequently only 10 total extensions and retractions were performed.

OPERATIONAL PERFORMANCE

MAGSAT was launched on 30 Oct 79. By 1 Nov 79 the spacecraft attitude was stabilized and at 23:27:53UT, following S/P uncaging, the magnetometer boom was extended. Telemetry in the form of potentiometer readouts - converted to boom length - of the drive screw rotations and the angle between the last hinged set of links, indicated that the boom extended properly. The final readings were practically identical to the readings obtained during the deployment tests. ATS telemetry surprisingly indicated that the remote mirrors were within sight of the ATS optical heads. This obviated the need for extensive gimbal searching for ATS acquisition. The following day slight gimbal adjustments were made to bring the remote mirrors into the linear range of the ATS. Subsequent gimbal adjustments were unnecessary.

Figure 4 - one orbit of data 28 days into mission life - shows ATS roll, pitch, and yaw angles relative to orbital time and boom link temperatures as measured by thermistors attached directly opposite one another on a boom link. The plots indicate that the remote mirrors were oscillating slightly in pitch, yaw, and roll, but well within the ±180 arc sec pitch and yaw and ±300 arc sec roll limitations of the ATS. These oscillations had periods approximately equal to the spacecraft orbital period. Interestingly the boom link temperatures exhibited this same characteristic. The variations in temperatures were caused primarily by the once per orbit coning of the solar vector. Their magnitudes were functions of the boom link angle relative to the sun which was established by the link angle relative to the boom axis and the seasonal variation of the solar vector. The near cyclical coincidence of these curves led to the inference that the boom was being thermally excited at the orbital frequency.

Bulk temperatures ran somewhat hotter than expected. The design goal - about 25°C - was exceeded by temperatures that ran as high as 32°C early into mission life. Twenty-four and 43 days later, readings as high as 38.6°C and 40.5°C were observed and were representative of a general uptrend that started shortly after boom extension. This is symptomatic of degradation in the link thermal control surface.

Hot-to-cold side temperature differences cycled with bulk temperatures and typically fell into the 2.0°C to 2.5°C range. Analysis predicted a range of 4.0°C to 4.6°C.

CONCLUDING REMARKS

The ability of this boom system to maintain the precise position and angular inclination required of the sensor platform is an endorsement of the concept and the special precautions that were exercised to guarantee its successful utilization.

REFERENCE

1. Mobley, F. F.; Eckard, L. D.; Fountain, G. H.; and Ousley, G. W.: MAGSAT - A New Satellite to Survey the Earth's Magnetic Field. Johns Hopkins paper presented at IEEE INTERMAG Conference (Boston), Apr. 21-23, 1980.

TABLE 1 - BOOM SYSTEM WEIGHT BREAKDOWN

Link Structure	2.72 kg	6.00 lbs
Drive Ass'y	2.93	6.45
Gimbal Actuators (3)	3.09	6.82
Caging Subsystems	1.13	2.50
	9.87 kg	21.77 lbs
Inverters (2)	0.62	1.37
Electrical Subsystem	0.76	1.68
	1.38 kg	3.05 lbs
Sensor Platform Ass'y	7.03	15.50
Boom Cable	2.72	6.00
	9.75 kg	21.50 lbs

TABLE 2 - ALIGNMENT TEST RESULTS

TEST NO.	MIRROR TILT ANGLE(1) (arc min)	MIRROR POSITION OFFSET(2) (cm)	TRANSVERSE DISPLACEMENT TO CORRECT MIRROR TILT (cm)	SUM OF POSITION OFFSET AND TRANSVERSE DISPLACEMENT(3) (cm)
A. Rotary Table at 0° (Pitch)				
I	+.75	0	-.128	-.128
V	+1.12	0	+.191	+.191
B. Rotary Table at 180° (Pitch)				
I	+1.87	+.064	+.317	+.381
V	-4.12	+.128	-.699	-.571
C. Rotary Table at 90° (Yaw)				
I	+3.75	0	+.635	+.635
V	-1.12	+.381	-.191	+.191
D. Rotary Table at 270° (Yaw)				
I	-4.87	+.128	-.826	-.699
V	-.75	+.191	-.127	+.064

(1) Mirror is normal to ATS optical axis when tilt angle is 0.0 arc min.

(2) Mirror is centered on ATS optical axis when position offset is 0.0 cm.

(3) Operation of the pitch (or yaw) gimbal to produce a displacement of this magnitude reduces tilt angle to zero and leaves this position offset. Size of target zone for position offset is ±1.91 cm in both pitch and yaw.

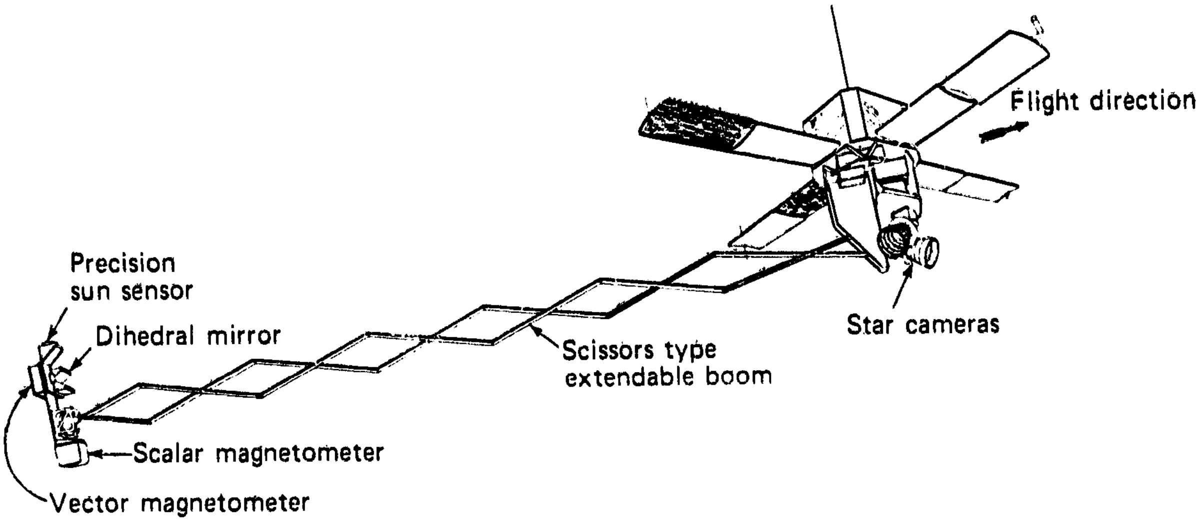

Figure 1.- MAGSAT orbital configuration.

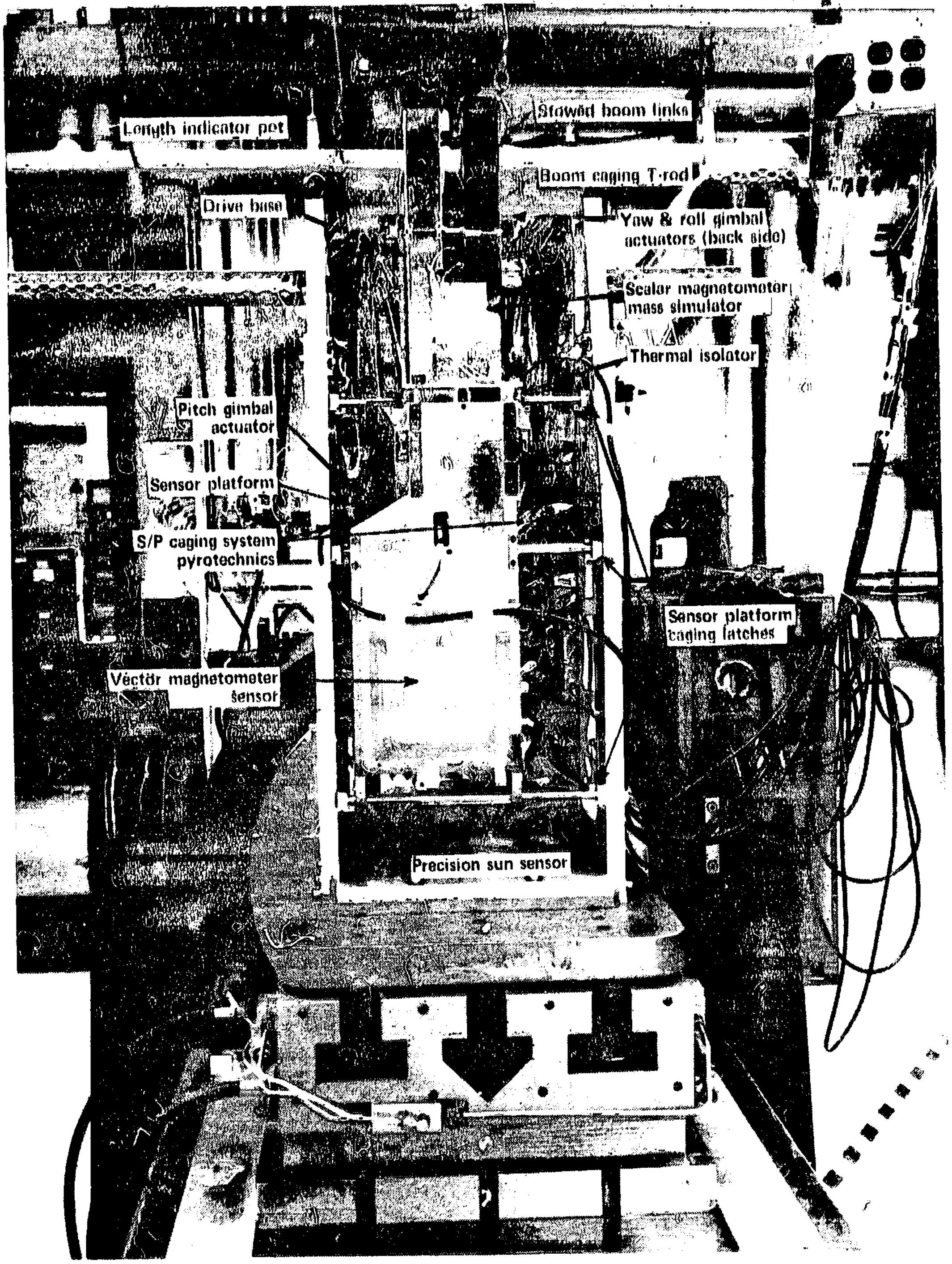

Figure 2.- Magnetometer boom system.

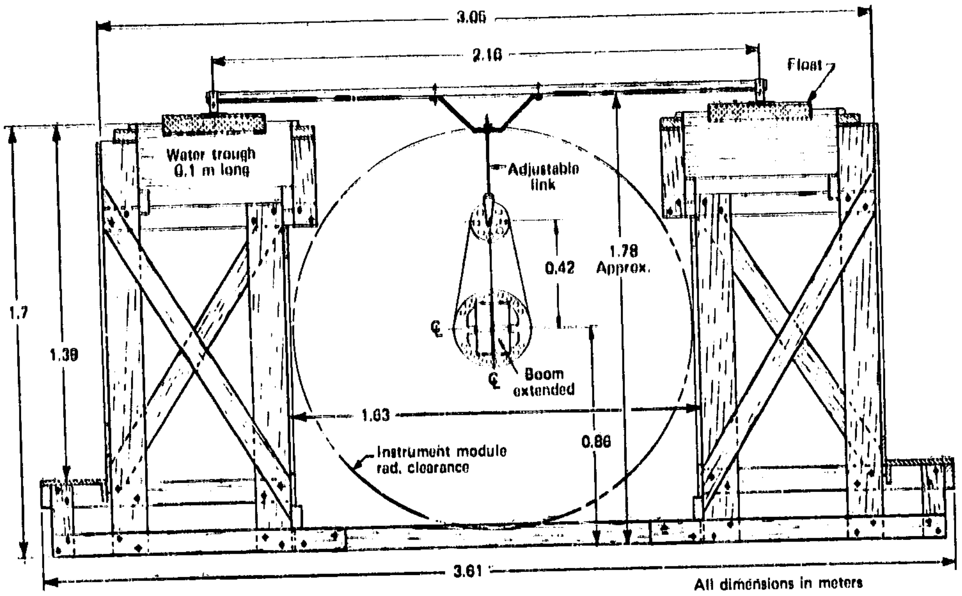

Figure 3.- MAGSAT boom flotation system.

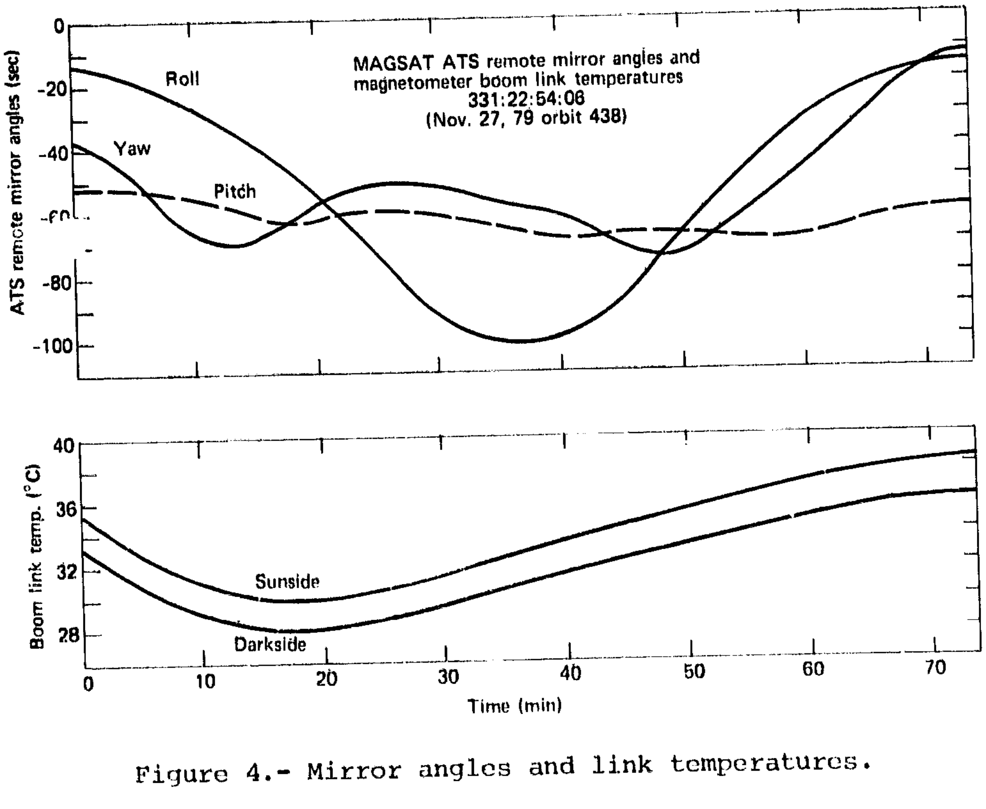

Figure 4.- Mirror angles and link temperatures.