HIGH PRECISION ATTITUDE DETERMINATION FOR MAGSAT

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ABSTRACT

This paper describes the activities performed in connection with the production of a definitive, continuous, time history of the three-axis attitude of the Magsat spacecraft to a high precision. The development of a baseline system, during the prelaunch period, capable of processing nominal sensor data is discussed. Modification of the baseline system during the 5-month period following the launch to accommodate nonnominal sensor behavior is described. The operational implications of processing a large sensor data volume under stringent quality control and throughput requirements are also discussed.

Keywords: Magsat, Attitude Determination, Star Cameras, Inflight Sensor Alignment

1. INTRODUCTION

The Magsat Project is a joint National Aeronautics and Space Administration/United States Geological Survey (NASA/USGS) effort to measure near-Earth geomagnetic fields on a global basis as part of NASA's Resource Observations Program. Data obtained by the Magsat spacecraft will provide a more accurate measurement of absolute flux density and a finer definition of the perturbations in the magnetic field caused by the variations in composition and density of the Earth's mantle and crust. Specifically, the objectives of this mission are

- To obtain an accurate, up-to-date, quantitative description of the Earth's main magnetic field
- To provide data and a worldwide magnetic field model suitable for the USGS update and refinement of world and regional magnetic charts
- To compile a global scalar and vector crustal magnetic anomaly map
- To interpret the crustal anomaly map in conjunction with correlative data, in terms of geological/geophysical models of the Earth's crust

On October 30, 1979, the Magsat spacecraft was launched into a low elliptical, Sun-synchronous orbit by a four-stage Scout D solid-fuel launch vehicle from the Western Test Range in California. The initial orbital characteristics were

- Apogee--567 kilometers
- Perigee--347 kilometers
- Inclination--96.8 degrees
- Period--93.0 minutes
- Ascending node time--6 p.m.

This orbit gave almost 100 percent Earth coverage with 5.5 months of full sunlit orbits. Reentry occurred on June 11, 1980, after a mission lifetime of 7.5 months. (A mission lifetime of 4 to 8 months was required.) An artist's conception of the spacecraft in orbit is shown in Figure 1.

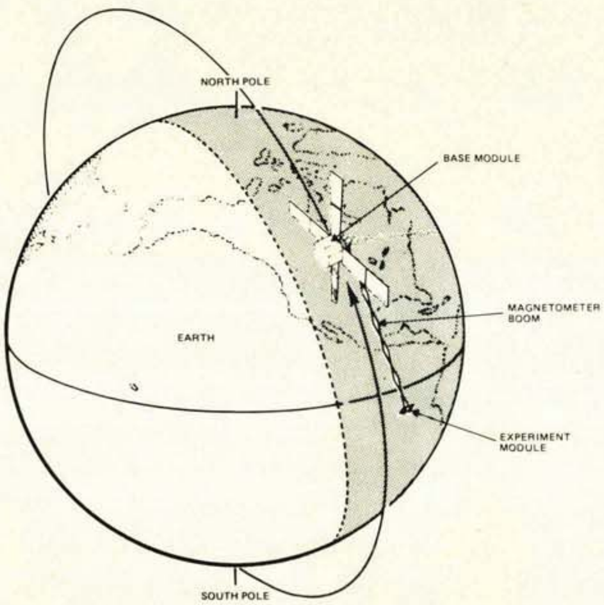

Figure 1. Artist's conception of Magsat

To meet the scientific objectives of the mission, a definitive, continuous, time history of the three-axis attitude of the experiment module was required to a precision of 20 arc seconds (one standard deviation) in each axis. The instrument or experiment module was attached to a 6-meter scissors boom that was connected to the base module (see Figure 2).

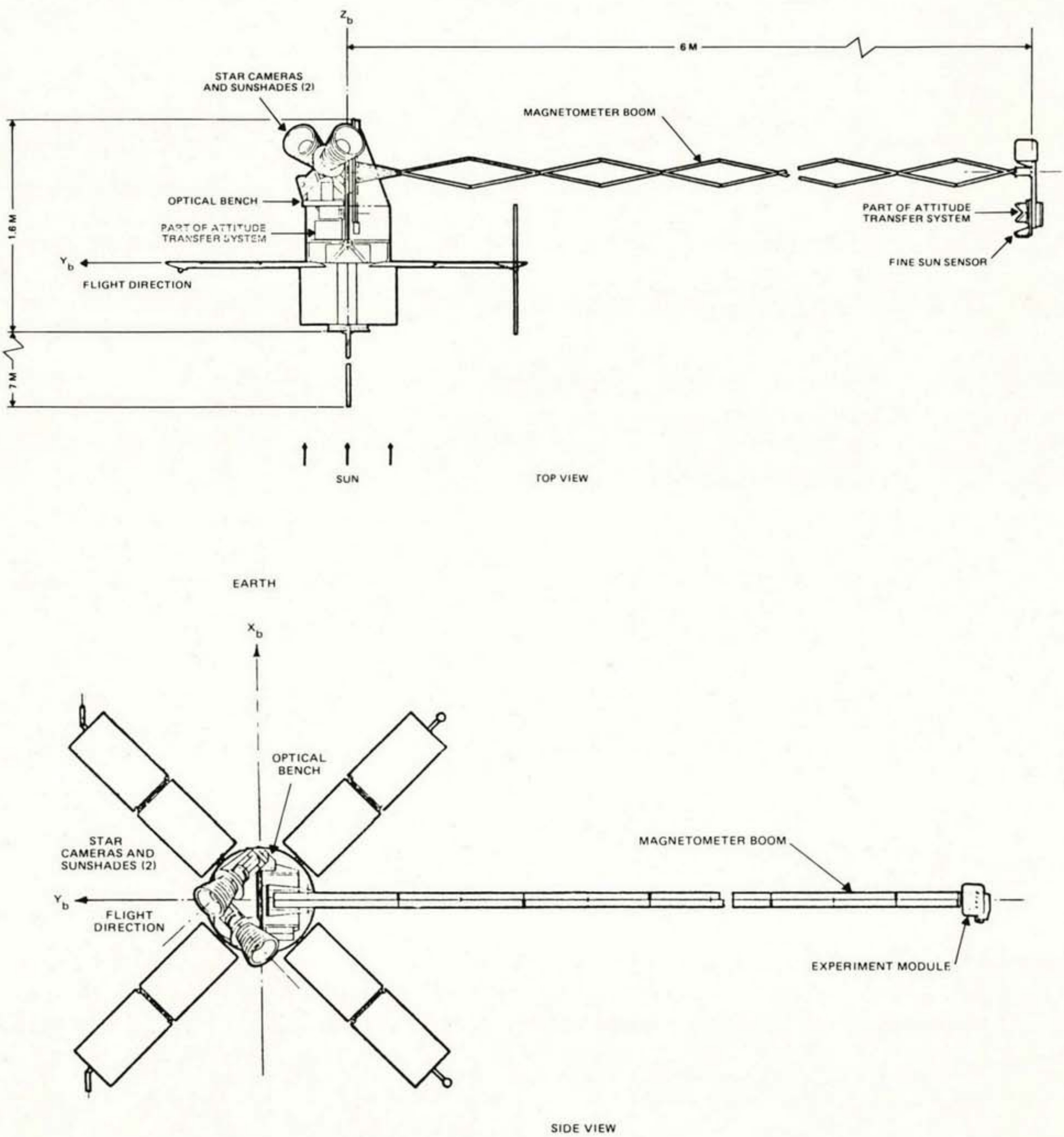

Figure 2. Magsat Spacecraft

To achieve this precision on a continuous production basis, a two-phase approach to the development of the attitude determination software system was adopted. In phase I, a baseline system, capable of processing nominal attitude data, was developed (see Ref. 1). The development and testing of the baseline system was completed before launch. In phase II, which could extend up to 5 months following the launch, the system was modified to accommodate the data characteristics and anomalies that were observed in the actual sensor data. The start of production processing was, therefore, scheduled to begin, at the latest, 5 months after launch. The production rate was to be maintained at a level sufficient for processing 5 months of sensor data in 5 calendar months. Thus, for a nominal 5-month mission, the entire activity was to be completed no later than 10 months following the launch.

The purpose of this paper is to describe the prelaunch planning and software development activities, the software modifications that were made during the 5-month startup period, the postlaunch analysis, and the definitive attitude production activities performed in support of the Magsat mission.

The spacecraft attitude hardware is described in Section 2. Section 3 details the prelaunch attitude determination software development activity. The software optimization for both nominal and nonnominal data situations is discussed in Section 4. The sensor alignment determination procedure and experience is described in Section 5. Operational aspects of data processing are discussed in Section 6. Finally, Section 7 presents conclusions.

2. SPACECRAFT HARDWARE

The Magsat spacecraft consisted of two distinct parts: the experiment or instrument module and the base module (see Figure 2). The experiment module contained the vector and scalar magnetometers and a precision Sun sensor. The base module contained the remaining attitude determination hardware and the data handling, power, communications, command, and attitude control subsystems to support the experiment module.

The experiment module was attached to the base module with a 6-meter scissors boom. The boom and the experiment module were deployed after the spacecraft attitude was stabilized in orbit. In this orientation, the boom always trailed the base module.

The attitude required for Magsat was the attitude of the experiment module rather than that of the base module. The requirement for 20-arc-second precision dictated the use of two star cameras and one precision Sun sensor. Only the Sun sensor, was sufficiently clean magnetically to be mounted on the experiment module; the star cameras had to be located on the base module. All three sensors were required for attitude determination. Because the sensors were separated by a boom that could not be made rigid, an attitude transfer system (ATS) was mounted onboard the spacecraft to measure the orientation of the base module relative to the experiment module. This provided the orientation of the star cameras relative to the precision Sun sensor.

The coordinate axes, X_b, Y_b, Z_b of the Magsat spacecraft body are shown in Figure 2. The nominal attitude was such that the X_b axis pointed at the Earth center, the Y_b axis pointed in the flight direction, and the Z_b axis pointed in the negative orbit normal direction. The X_b, Y_b, and Z_b axes are also referred to as the spacecraft yaw, roll, and pitch axes, respectively. Formally, yaw, roll, and pitch angles are defined by an ordered 1-2-3 Euler rotation from orbital coordinates to body coordinates, where the first rotation is the yaw angle, the second rotation is the roll angle, and the third rotation is the pitch angle. The orbital coordinate frame is defined such that X_o is the Earth center direction, Z_o is the negative orbit normal direction, and Y_o is in the direction of $Z_o \times X_o$ to form a right-hand system.

2.1 Star cameras and sun sensor

The primary attitude determination data were provided by two star cameras built by the Ball Brothers Research Corporation. The cameras tracked stars as dim as 7.0 visual magnitude (with a 10 percent probability of detection) to ensure the presence of at least two trackable stars at all times in their 8-degree-by-8-degree fields of view (FOV). The cameras systematically searched their FOVs to locate stars. Once a star was found, it was tracked for 32 seconds or until the star left the FOV. The search for other trackable stars was then resumed. The star cameras output two-axis positional information, in digitized form, on the displacement of the star image in the camera focal plane. This information is related to the orientation of the star in the camera reference frame, and forms the basis of the attitude determination. The measurement accuracy of the positional information was estimated before launch to be approximately 10 arc-seconds after systematic errors due to electro-optical effects had been removed.

The cameras were mounted at an angle of 58 degrees relative to the $+Z_b$ axis (see Figure 2) and 90 degrees in phase relative to each other, such that each scanned a small band on the celestial sphere while the spacecraft rotated at one revolution per orbit.

To provide additional attitude information, an Adcole Corporation fine Sun sensor (FSS) was mounted on the experiment module. This sensor, referred to as the precision Sun sensor earlier, provided two-axis Sun information to an accuracy of approximately 12 arc-seconds over a $\pm$32-degree FOV. Data from all three sensors were telemetered once every 0.25 second.

2.2 Gyroscope

A Northrup single-axis rate gyro was also part of the sensor complement, and it measured the pitch rate of the spacecraft base module. This rate was combined with the roll/yaw rates from the FSS to provide three-axis rate information in the star identification process. The precision of the instrument was $\pm$0.15 arc-second per second. The gyro data were also telemetered once every 0.25 second.

2.3 Attitude transfer system

The Attitude Transfer System (ATS) was an electronic and optical system built by the Barnes Engineering Corporation and was used to measure the three-axis orientation of the base module relative to the instrument module. As previously noted, the experiment module was mounted at the end of a 6-meter scissors boom that could not be made sufficiently rigid to ensure the fulfillment of the accuracy requirement.

After ground calibration, the ATS was presumed to be accurate to 4 arc-seconds in pitch and yaw and 8 arc-seconds in roll. The range of measurable displacement was: pitch and yaw, $\pm$3 arc-minutes; and roll, $\pm$5 arc-minutes. A gimbal system at the base-module end of the boom was used to move the instrument module into the above-mentioned ranges when required.

The star cameras and base module optical components of the ATS were mounted together on an optical bench. This bench was specified to maintain the relative alignment of the ATS and star cameras to 2 arc-seconds or better despite launch shock and environmental effects. The bench included heaters to maintain its temperature at 25 degrees Celsius $\pm$1 degree Celsius.

3. PRELAUNCH ATTITUDE DETERMINATION SOFTWARE DEVELOPMENT

3.1 Introduction

The design of the Magsat attitude determination software, designated as the Fine Definitive Attitude Determination (FDAD) system was driven by two major requirements: first to achieve continuous attitude determination to a precision of 20 arc-seconds or better, and second, to process, on an average, 1 day of spacecraft data in 1 calendar day or less. An additional requirement was to monitor routinely the health and performance of the attitude determination sensors in near-real-time. This section discusses the influence of these requirements on the software design.

A detailed analysis of these requirements led to the conclusion that a requirement to minimize the impact of intermittent computer failures was a major software design consideration. An interactive graphics capability was also deemed essential for quick identification and resolution of data anomalies.

To minimize the impact of computer failures, the software system was divided into four major independent subsystems. Each subsystem executed in a standalone mode and communicated the results of processing to other subsystems by means of disk data sets or magnetic tapes. Each subsystem possessed a reentry capability, i.e., in the event of computer failure, the processing could resume at the point it was halted rather than requiring initialization of the entire process.

The software contained an interactive graphics capability to permit maximum operator interaction for rapid online analysis of sensor and software performance. The system displayed data, at various stages of processing, in the form of plots and tables for easy detection of anomalies and recognition of correlations. Because display generation is time consuming, the user had the option to turn off any display that was not required.

The attitude determination function required data from at least one star camera. In the absence of any star camera data, the software contained a provision for the propagation of the last known attitude with rate information derived from the fine Sun sensor and gyro data.

3.2 FDAD software system

The FDAD system was partitioned into four main subsystems: the telemetry processor (TP), the data preparation subsystem (DPS), the segment processing subsystem (SPS), and the catalog processor subsystem (CPS) (see Figure 3). The first three subsystems processed the data sequentially, with the TP processing the input telemetry data and the SPS producing the final attitudes. The CPS was executed only as required by the SPS. The CPS extracted a reference band star catalog from the whole-sky star catalog SKYMAP. SKYMAP is a computer-based star catalog which contains positional and other information on stars up to 9.0 visual magnitude (Ref. 2).

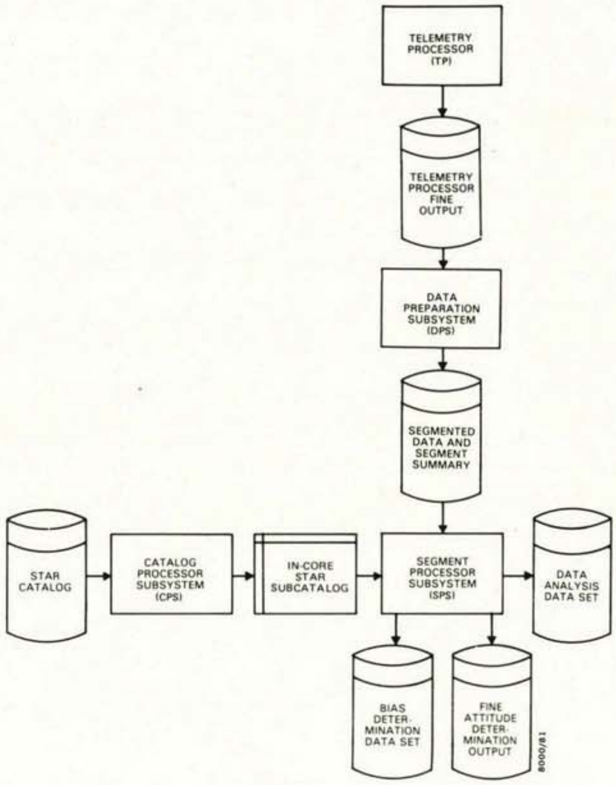

Figure 3. Magsat Fine Definitive Attitude Determination (FDAD) system internal data flow

3.2.1 Telemetry Processor. The functions of the TP were to unpack the sensor and time data from the incoming telemetry stream and to write this data onto a TP fine output data set which was then read by the DPS.

3.2.2 Data preparation subsystem. The functions of the DPS were: conversion, correction, editing, and calibration of raw sensor data. These functions ensured that the calibrated sensor data were consistent and were of the highest possible precision. To provide continuous data, the DPS interpolated gyro and FSS data whenever these data were not available. The output from the DPS subsystem consisted of sensor data arranged in a form suitable for attitude determination. The output data set was referred to as the segmented data and the segment summary data set. The computation of the star observation vectors from the camera data involved conversion from digital counts to angular measure. These converted angles were corrected for field distortion, sensor temperature variations, observed intensity, and the presence of magnetic fields. These corrections were calculated using low-order polynomials derived from ground test data (Ref. 3). The FSS angles were computed from the telemetered data according to an algorithm supplied by the manufacturer. The angles were then corrected for distortion in the sensor FOV. Again, low-order polynomials based on the ground test data were used to effect these corrections.

The DPS grouped the data in specified units called segments. The size of a segment had to be large enough to contain sufficient star camera data to permit star identification (three or more stars) but was limited by the amount of available core storage. The nominal segment contained 128 seconds of data.

3.2.3 Segment processing subsystem. The basic function of the SPS was to compute the spacecraft attitude using observations from at least two of the three attitude sensors--the two star cameras and the FSS.

To reduce the star camera data to a form in which it was usable for attitude computation, it was necessary to identify the stars tracked by the cameras with stars from a reference catalog. The star identification method was based on a pattern recognition technique. A spacecraft motion model was used to reduce the star observations to a "snapshot" at an epoch, and the pattern of observed stars was matched with a pattern of stars in the reference catalog. Initially, one pair of observation stars was identified with a pair of reference stars. To be so identified, the angular separation of the observed star pair was required to be within the distance error tolerance of 0.03 degree of the angular separation of the catalog star pair. In addition, at least one other star was required to be identified with a reference star after it was paired with the original two observations. Using this triplet of stars, the identification of the remaining observations was attempted.

This method can sometimes lead to misidentifications. The incidence of misidentification can be minimized provided that the number of observations in the snapshot is high (five or more) and that the estimated attitude is close (within 1 degree) to the true attitude. The former condition was a determining factor in deciding upon the length of a segment.

3.3 Attitude determination algorithms

Two methods were used to compute the attitude. The first method, called QUEST (Ref. 4) required that at least two of the three sensors, the FSS and the two star cameras, have valid data. The second method, the motion model, used data from one of the three sensors and the gyro rate information to provide a continuous time history of the spacecraft attitude. The attitudes were computed once every 0.25 second.

QUEST is an optimal algorithm which computes a best estimate of the spacecraft attitude on the basis of minimization of a quadratic loss function. Given a set of reference unit vectors, $V_1, \ldots, V_n$, and a set of corresponding observation unit vectors, $W_1, \ldots, W_n$, QUEST finds the optimal attitude matrix A such that $A V_i = W_i$, i = 1, n. The loss function to be minimized is

$$\mathscr{L}(A) = \frac{1}{2} \sum_{i=1}^{n} a_i \; W_i - A V_i{}^2$$

where $\sum_{i=1}^{n} a_i = 1$

The QUEST algorithm is computationally economical because high accuracy is achieved without explicitly solving the complete eigenvalue problem. When only one of the three primary sensors has valid data, the motion model is used. The motion model also requires valid gyro data. The last determined QUEST attitude is propagated using rate information from the valid sensor and the gyro until valid data are again available from two or more sensors.

3.4 Prelaunch software testing

Before launch, the FDAD system software was tested to ensure the integrity of each subsystem and to verify the interfaces both between the subsystems and with the spacecraft telemetry stream. The testing was accomplished by executing a number of software acceptance tests that were designed to verify the analytical and functional capabilities of the software. Data for these tests were obtained from a software simulator. The simulator generated telemetry data containing simulated data from all the attitude determination sensors with data characteristics that varied from perfect sensor data with no noise or spacecraft motion to sensor data with noise 10 times the specification value and spacecraft motion 5 times faster than that expected. Processing the simulated data helped identify and resolve problems in the FDAD system.

The spacecraft data generated during integration and testing of the spacecraft were used to verify the stripping of the telemetry data from the telemetry stream and to provide an additional check on the sensor calibration functions. Significantly, the spacecraft data verified the orientation of the sensors as implemented in the FDAD system.

4. POSTLAUNCH SOFTWARE OPTIMIZATION

As previously noted, the first 5 months following the launch were used to fine tune the FDAD system using actual sensor data. Two types of activities were undertaken during this period. First, selected data passes were processed and the results were examined in detail to optimize the various input control and editing parameters. Second, anomalous data conditions were identified and procedures were developed to circumvent the problems posed by these data. This section describes these two types of activities.

4.1 Optimization of input control and editing parameters

The input parameters that needed optimization controlled processing in the DPS and SPS subsystems. Optimization was to be effected to satisfy two divergent requirements. The requirement to achieve 20 arc-second precision dictated that only the highest quality sensor data be accepted for attitude determination. However, the requirement to generate a continuous time history of the attitude called for accepting as much sensor data as possible.

4.1.1 Optimization of DPS input control and editing parameters. The DPS input control and editing parameters determined the limit of data validity, the time intervals over which data could be considered linear, and the choice of data calibration coefficients. Editing parameters were determined by examination of inflight data. Time intervals were determined by comparing results from the processing of inflight data of varying time lengths and noting the times over which deviations exceeded the precision limits. The calibration coefficients for all sensors except the star camera were obtained from the manufacturer's documentation.

Two sets of star camera data calibration coefficients were available. One set (designated MIT) came from the manufacturer's documentation and covered a 6-degree-by-6-degree portion of the FOV. The second set (designated CSC) was obtained by Computer Sciences Corporation (CSC) by processing the manufacturer's ground test data. This set of coefficients was applicable to the entire 8-degree-by-8-degree FOV. Extensive tests with actual sensor data showed that the CSC coefficients led to more consistent attitude results. Furthermore, the larger FOV covered by these coefficients made it possible to use the star data that were close to the edges of the FOV. Therefore, the CSC coefficients were chosen for use in production processing.

4.1.2 Optimization of SPS input control and editing parameters. The SPS input control and editing parameters consisted of data editing parameters, gyro drift rate computation parameters, star identification control parameters, attitude computation control parameters, and quality assurance parameters.

The purpose of the SPS data editing parameters was to discriminate between valid and spurious star camera data. Most of the spurious data arose because the lit Moon was in the FOV or in close proximity to the FOV of the cameras. The frequency of the gyro drift rate computation had to be high enough to meet the desired 20 arc-second precision requirement without imposing any undue computational burden. After an exhaustive study of the growth of error in the drift rate, it was decided that the drift rate would be updated once every 1.8 hours. For star identification, three control parameters needed optimization:

- Window Size--The radius of the circle within which the candidate stars for matching an observation were to be found. The window size depended on the accuracies of the initial attitude estimate and the motion model.
- Distance Error Tolerance--The allowable error in angular separations between the observed star pair and the corresponding catalog star pair.
- Percentage of Snapshot Stars Identified.

These parameters were frequently adjusted during production processing, as required, to maximize the number of identified stars.

4.1.3 Optimization of attitude computation control parameters. The input control parameters in the attitude computation function were the statistical weights assigned to the attitude sensor observations. A good weighting scheme was needed to combine the sensor observations in an optimal fashion for attitude computation. A procedure, based on the QUEST algorithm, was developed for inflight estimation of the sensor accuracies. This was used to provide the weighting scheme. The inflight estimate of the sensor error variance was 9.2 arc-seconds for star camera 1, 8.0 arc-seconds for star camera 2, and 11.2 arc-seconds for the fine Sun sensor. These numbers are comparable to the manufacturer-estimated values of 8, 7, and 12 arc-seconds for star camera 1, star camera 2, and the fine Sun sensor, respectively. The quality-assurance tests were designed to flag the data segments in which the quality of attitude solutions was suspect. The attitude computation algorithm, QUEST, generated a residual, which was a measure of the accuracy of computed attitudes. The segments in which the average QUEST residual was greater than 30 arc-seconds, the average QUEST residual for any sensor combination was greater than 100 arc-seconds, or the segments with 5 or more observations in which the percentage of identified stars was less than 60 were automatically flagged for further checking.

4.2 Postlaunch software optimization-nonnominal conditions. Three major nonnominal situations were encountered in the attitude sensor data: 'jumps' in the ATS roll, loss of a large volume of star camera data, and shadow data. The ATS roll jumps occurred only during the first 9 days after activation of the ATS and, more specifically, only after magnetic torquing. The most serious problem was star camera data loss, which occurred in almost every orbit. For many orbits, this affected as much as a third of the orbit; thus approximately 30 percent of the data lay in the star camera data loss region. The shadow data occurred during the last 38 days of the mission. For up to 30 minutes of each orbit during this time, the spacecraft passed through the Earth's shadow. This resulted in the loss of FSS data and low-power conditions which required that the star cameras be turned off.

Another anomalous condition, related to the alignment of attitude sensors, was also discovered. Attempts at inflight alignment of sensors showed that the alignment varied in time by an amount that would not allow the 20-arc-second precision requirement to be satisfied without frequent changes in the alignment correction. This problem is discussed in Section 5. In this subsection, only the afore-mentioned nonnominal situations are discussed.

4.2.1 ATS roll jump. Anomalous, periodic jumps in the ATS roll angle data were discovered shortly after launch. These jumps were found to occur for a period of up to several hours after each torquing maneuver. At times, the jumps became as large as 200 arc-seconds. The cause of these jumps was never discovered. The jumps stopped occurring approximately 1 week after launch and were never detected again. It was recognized, however, that if attitudes were to be computed from the first week's data, a method was needed to edit and smooth the ATS roll angles.

The editing procedure that was developed used an updated default value for the ATS roll angle. At the start of processing, a default value, which corresponded to the first good roll data, was chosen. Then, during processing, roll values deviating from the default by more than 30 arc-seconds were replaced by either interpolated or updated default values. Every 32 seconds the average of the good roll angles was computed, and if it deviated from the current default value by less than 60 arc-seconds, it was adopted as the new default value which was then used for subsequent processing.

This procedure was found to be very effective. As an illustration, a large jump in the input ATS roll counts is shown in Figure 4. The corresponding roll angles at the end of processing are plotted in Figure 5. As is evident from the illustrations, the roll jump has been almost entirely eliminated.

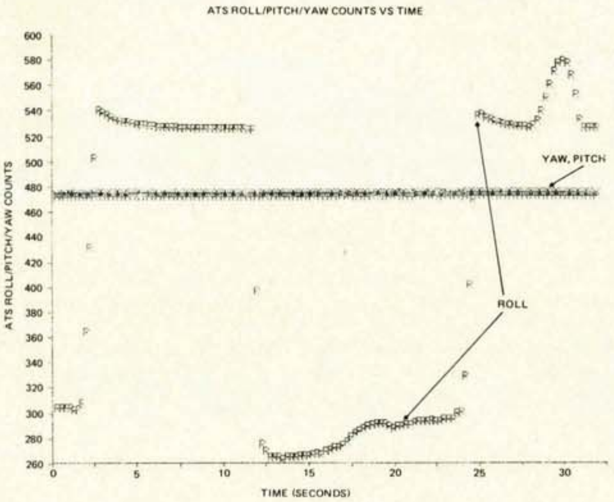

Figure 4. ATS angles during roll jumps

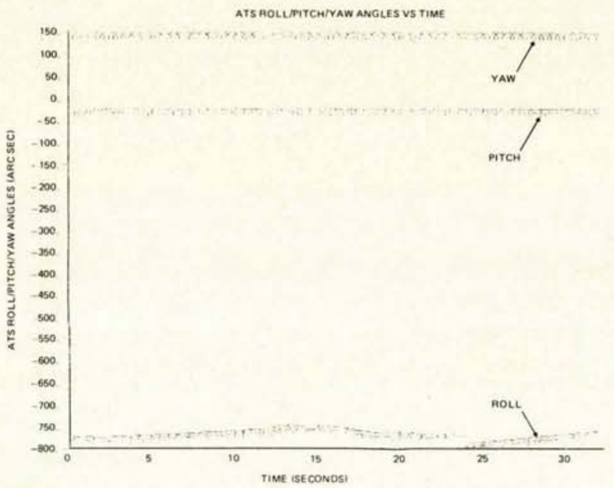

Figure 5. ATS angles after editing

4.2.2 Star camera data loss. During a large fraction of most orbits, when the star cameras were not shielded from the Sun by the base module, the Magsat star cameras were not able to properly track the stars in the FOV. This problem was observed immediately after launch and was ultimately traced to inadequate Sun shades on the cameras. At first, only a few minutes of data in each orbit were affected. The problem increased in severity as the mission progressed and, at times, as much as 30 percent of the data were affected. Figure 6 shows the distribution of star observations or track points for a normal segment. Figure 7 shows the same distribution during a problem segment. Only one star was tracked in this segment. Figure 8 shows the number of identifiable stars in both cameras for each segment during a typical data-loss day.

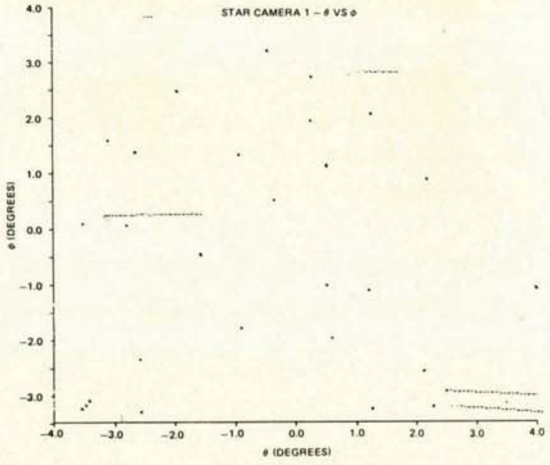

Figure 6. Distribution of star camera observations during normal segment

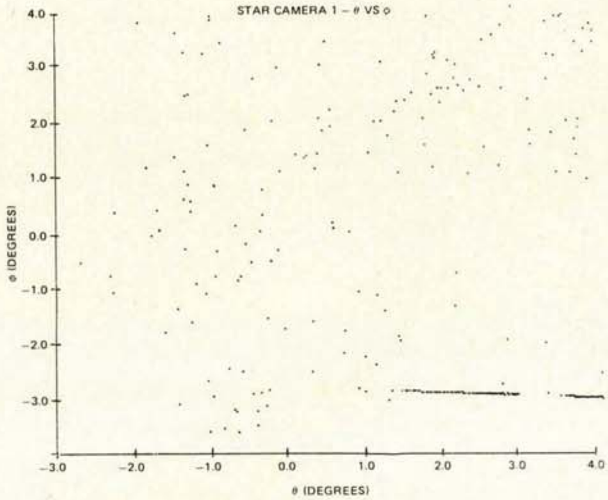

Figure 7. Distribution of star camera observations during star camera data loss segment

The star camera data-loss problem was serious. As previously noted, the data loss region accounted for up to 30 percent of the available data. Because a loss of data of this magnitude would have very seriously impacted the scientific output of the mission, a method was developed to recover these data.

The method chosen to recover these data was to save a triplet from a good segment for use in a segment in the data-loss region. To compensate for errors resulting from gyro drift, the observation vectors constituting the triplet were updated using the following equation:

$$W_i = A_f \; A_Q \, A_0^{-1} \, V_i, \; i = 1, 3$$

where V_i = observation vector in inertial coordinates at the start of the segment

A_0 = atttitude matrix (spacecraft to inertial frame) at the start time, t_0

A_Q = attitude matrix that goes from time t_0 to time t_f (final time) in the spacecraft frame

A_f = attitude matrix (spacecraft to inertial frame) at t_f

W_i = adjusted observation vector at the end of the segment

Through this equation, the observation vectors were adjusted to reflect the current spacecraft attitude. If a segment contained enough star observations to permit formation of a triplet, one member of the old triplet was replaced by a star observation in the current segment. This procedure enabled formation of triplets with well separated vertices--an important criterion in triplet formation. Approximately 95 percent of the data within the data-loss region were recovered using this method.

4.2.3 Shadow data. During the final 38 days of the mission, Magsat passed through the Earth's shadow at regular intervals of increasing duration. This resulted in the lack of fine Sun sensor data as well as low-power conditions. The latter necessitated turning off the star cameras for the duration of the shadow region and for several minutes on either side of this region.

Because no attitudes could be computed when the satellite was in shadow, to save processing time, the input module of the DPS was modified to ignore shadow data. In addition, the DPS output module was modified to ensure proper segmenting at the pre/postshadow interface. These modifications reduced the time needed for DPS processing by nearly one-third.

The shadow data alone created no problem for processing through the SPS; however, during the shadow days, the star camera data-loss problem also occurred. As stated earlier, this problem was serious. Figure 9 is marked at the locations at which the shadow data has been removed. At these locations, a new initial attitude estimate had to be provided and a new triplet of stars to be used in the star camera data-loss region had to be identified in the short time before the start of the data-loss region. Fortunately, the method of selecting a triplet discussed earlier usually resulted in the choice of a triplet that recovered most of the data from the data loss region.

5. SENSOR ALIGNMENT DETERMINATION

Previous experience had shown that the mounting alignment of the attitude sensors could change due to launch shock and could vary throughout the mission lifetime due to changing conditions onboard. Therefore, an alignment utility was developed prelaunch to perform inflight alignment of the star cameras and the FSS. The utility determined the alignment matrix of a sensor relative to the experiment module by minimizing, in a least-squares sense, the angular separations between observation vectors from the sensor, over many observations, and the corresponding rotated reference vectors.

The alignment procedure required a spacecraft attitude which, of course, was dependent on the assumed sensor alignments. The alignment procedure was, therefore, an iterative one. The ground-measured alignments were used to compute the spacecraft attitude. Next, this computed attitude was used to refine the alignment estimate. This procedure was repeated until the changes in sensor alignments from one iteration to the next were less than 1 arc-second. Earlier, ground measurements of sensor alignments had shown that star camera 2 exhibited

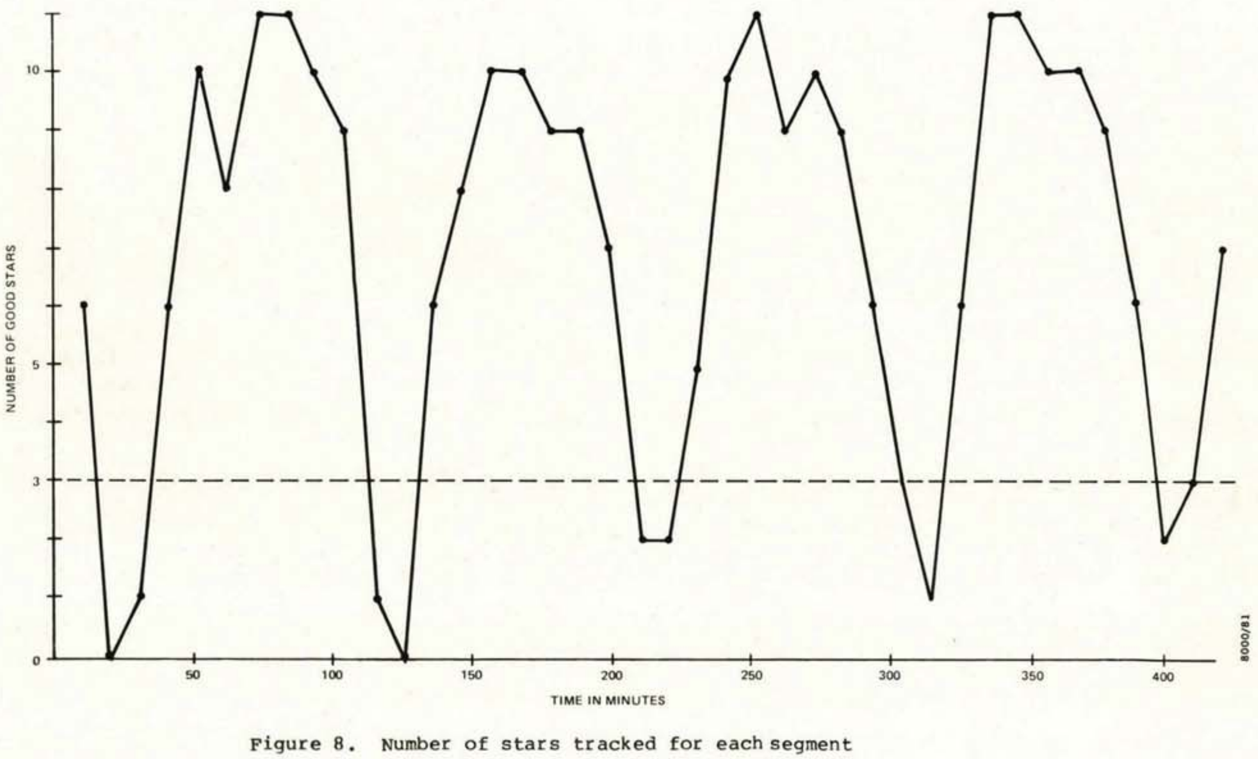

Figure 8. Number of stars tracked for each segment

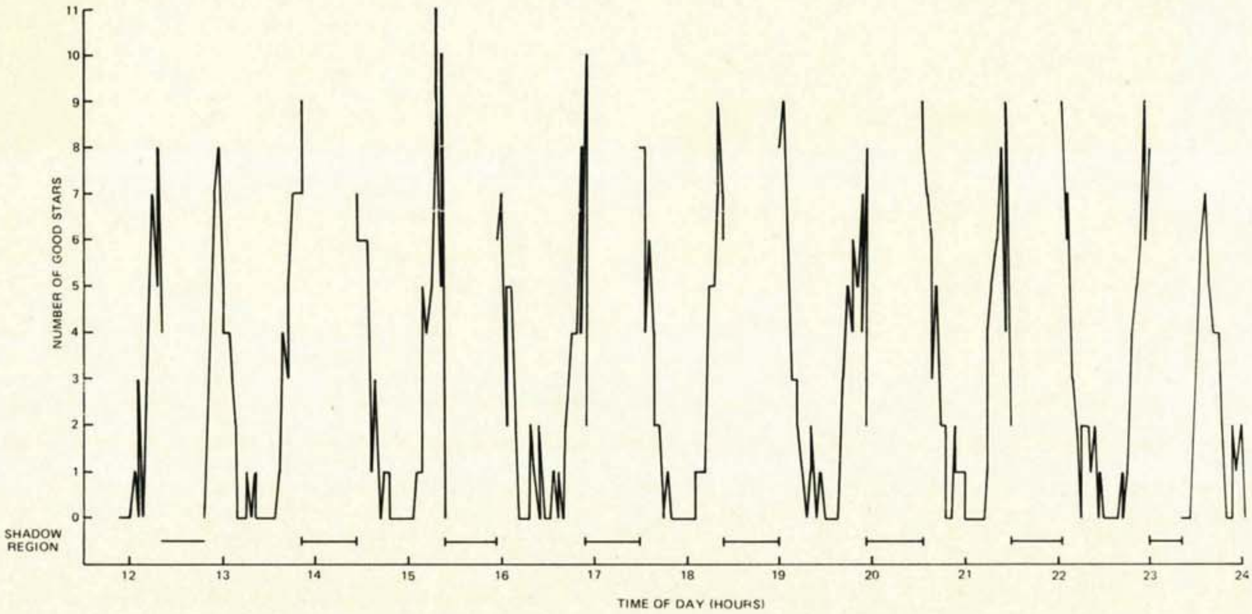

Figure 9. Number of stars available for star identification during shadow day

very consistent results under repeated measurements. Therefore, this sensor was chosen as the primary sensor and attempts were made to refine the alignments of star camera 1 and the fine Sun sensor. Details of the alignment determination sequence are shown in Figure 10.

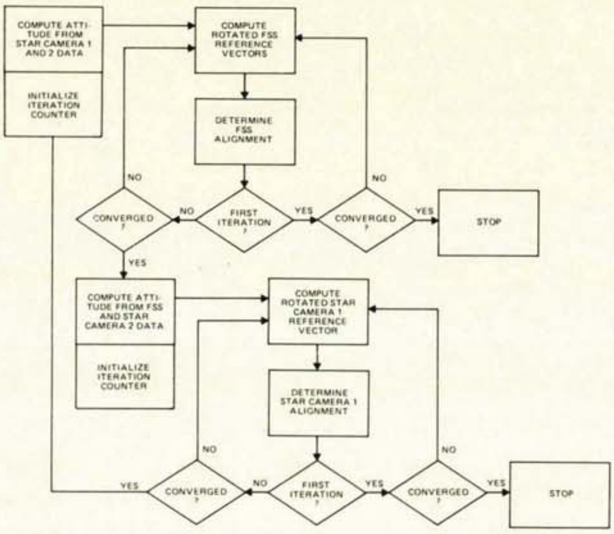

Figure 10. Inflight Sensor Alignment Determination Procedure

Initial results from implementation of this inflight alignment procedure revealed that the direction of the boresight of star camera 1 had changed by 11 arc-seconds and that the direction of the boresight of the FSS had changed by 220 arc-seconds. The former value was within the expected alignment tolerance of 10 arc-seconds; however, the latter was approximately four times the expected alignment tolerance of 50 arc-seconds. The 220-arc-second discrepancy in the alignment of the FSS was composed of a 53 arc-second yaw misalignment, a 51 arc-second pitch misalignment, and a 202 arc-second roll misalignment. Because the ATS roll-jump anomaly was of the same magnitude, data before and after a roll jump were processed through the alignment utility to determine whether it caused the FSS misalignment. No correlation between the ATS roll jumps and the FSS misalignment was established. The ATS was used to measure the rotation between the star cameras and the FSS. Unlike the star cameras and the FSS, the misalignment of the ATS, if any, could not be determined. After the experimentally measured magnetic field at the experiment module was compared with the modeled magnetic field, however, 150 arc-seconds of the 220 arc-second misalignment was attributed to the ATS.

Once the ATS misalignment problem was resolved, the time variation in the sensor alignments was studied using data from November 10, November 21, and December 5, 1979. The FSS sensor boresight changed by 30 arc-seconds from November 10 to November 21 and by 5 arc-seconds from November 21 to December 5. Because of the 30-arc-second change, the decision was made to compute sensor alignments periodically. The alignment determination procedure, being iterative, was time consuming. After an analysis of the changes in sensor alignments and their effect on attitude precision, a compromise solution of recomputing sensor alignments once every 7 days of data was adopted.

Surprisingly, the FSS boresight continued to move relative to the experiment module on which it was mounted (Figure 11). In this figure, the positions of the FSS boresight are plotted as projected onto the plane perpendicular to the ground-calibrated boresight.

In addition to this gradual movement, several large changes occurred between successive FSS boresight orientations. For example, from December 5, 1979 to December 12, 1979, the FSS boresight orientation changed by 30 arc-seconds. Similar large changes were observed between March 17, 1980 through March [illegible], 1980, and March 19, 1980 through March 26, 1980, April 14, 1980 through April 21, 1980, and

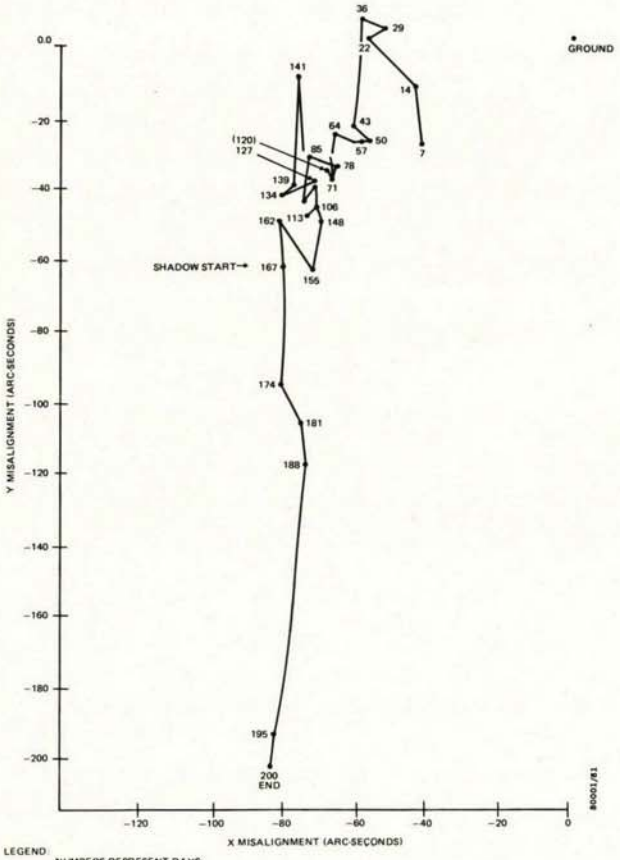

Figure 11. FSS boresight position relative to ground-calibrated position

May 5, 1980 through May 12, 1980. Although the exact cause of these abrupt changes is not known, some evidence implies that these changes are correlated to sudden shifts in the ATS and/or the star camera 1 photocathode temperatures (see Figures 12 and 13).

On April 14, 1980, the spacecraft entered the Earth's shadow for part of its orbit. This shadow period, which became more pronounced with time, caused a dramatic decrease in all sensor temperatures. Although the boresight of star camera 1 continued its steady drift away from the ground position during this period, the changes in FSS boresight were even more sudden and of greater magnitude. The change in the FSS boresight position from April 14, 1980 through April 21, 1980, was about 40 arc-seconds and from May 5, 1980 through May 12, 1980, was over 80 arc-seconds.

The alignment computations proved to be an ongoing postlaunch activity due to the changing sensor alignments throughout the mission. These changes were radical enough to require calibrations weekly and whenever severe sensor temperature shifts occurred. In all, 30 misalignment sets (FSS, SC1) were computed for the 199-day mission. An examination of the uncertainties in alignment determinations showed that the accuracy of computed sensor alignments was 15 arc-seconds or better.

6. OPERATIONAL CONSIDERATIONS IN ATTITUDE DATA PROCESSING

The Magsat mission requirement to generate a definitive, continuous, time history of the three-axis attitude to a high precision had major operational implications. First, a large volume of attitude data (11.66 megabytes/day) were to be received and processed through the attitude system, and an equally large volume (8.76 megabytes/day) of the attitude results were to be transmitted to the experimenters.

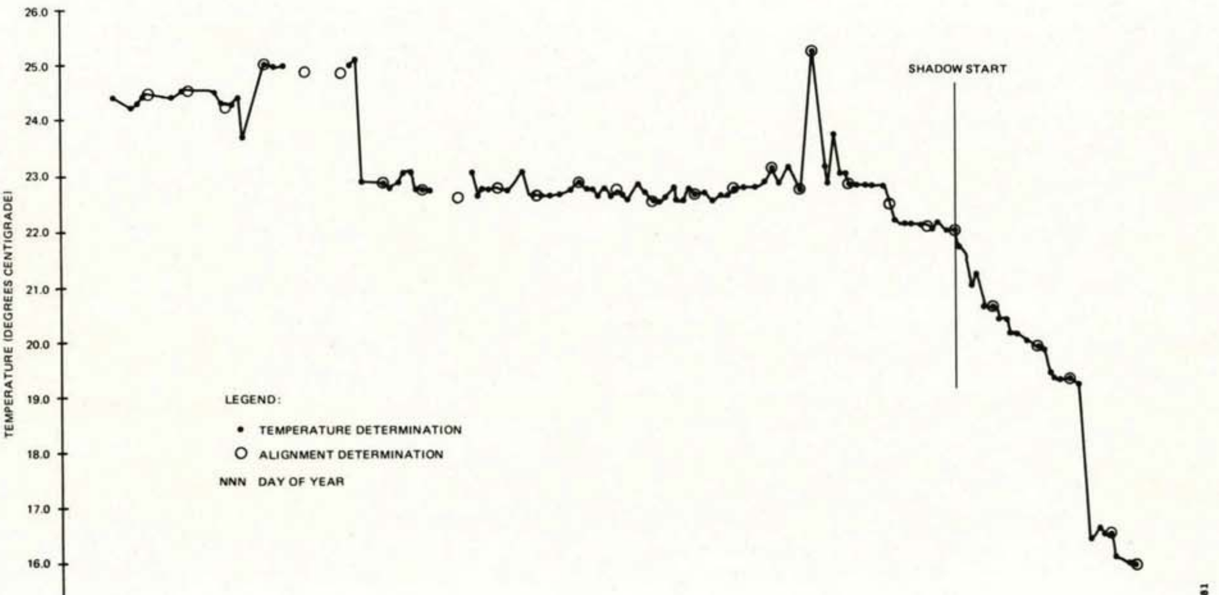

Figure 12. ATS temperature (^{o}C versus time)

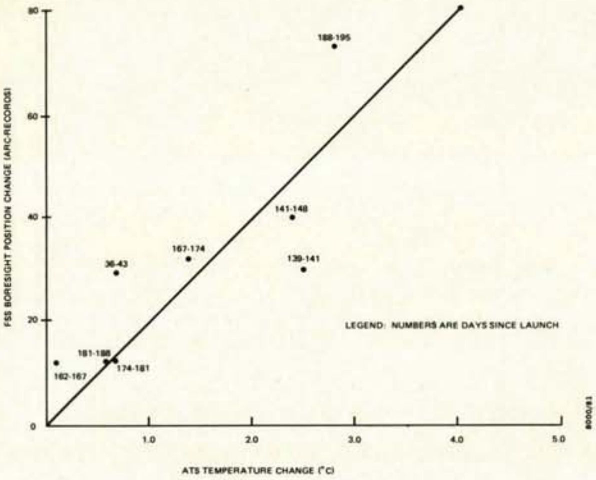

Figure 13. FSS Boresight angular change versus ATS temperature change

Second, the commitment to process 5 months of sensor data within 5 calendar months necessitated that an average production rate of 1 day of sensor data in 1 calendar day be maintained. The precision requirement dictated that strict quality assurance controls be exercised. In this section, some operational aspects of the attitude data processing activity are discussed.

6.1 Computer Resources

The attitude data were processed at the NASA/ Goddard Space Flight Center on the IBM S/360-95 computer. The computer was nominally available 24-hours per day, 5-days per week. However, computer failures were experienced sporadically. The load modules and the input, output, and ancillary data were stored online and required almost 75 megabytes of storage space.

6.2 Data Processing Plan

The processing plan called for the execution of two jobs in parallel continuously and, resources permitting, occasionally a third job. The nominal plan was to process data in 12-hour blocks. A 12-hour block of data processed through the DPS or SPS was defined as a unit. Because the processing through the TP was twice as fast as through the DPS or SPS, one 12-hour block of data processed through the TP was assigned a value of 0.5 unit. Thus the processing of 1 day (24 hours) of sensor data through the TP, the DPS, and the SPS required the processing of five units. This led to the requirement to process 35 units per week. Figure 14 shows the actual production rate that was achieved.

Early in the production phase, the goal of 35 units was not achieved because of lack of familiarity with the system on the part of software operators, as well as the need to attend to the health and safety problems of the spacecraft. Later, for several weeks, lack of adequate computer resources prevented the realization of the goal of 35 units per week. However, in the final phase of production period, the production goals were easily achieved. Overall, 200 days of sensor data were processed in 190 days.

The original plan was to process data through

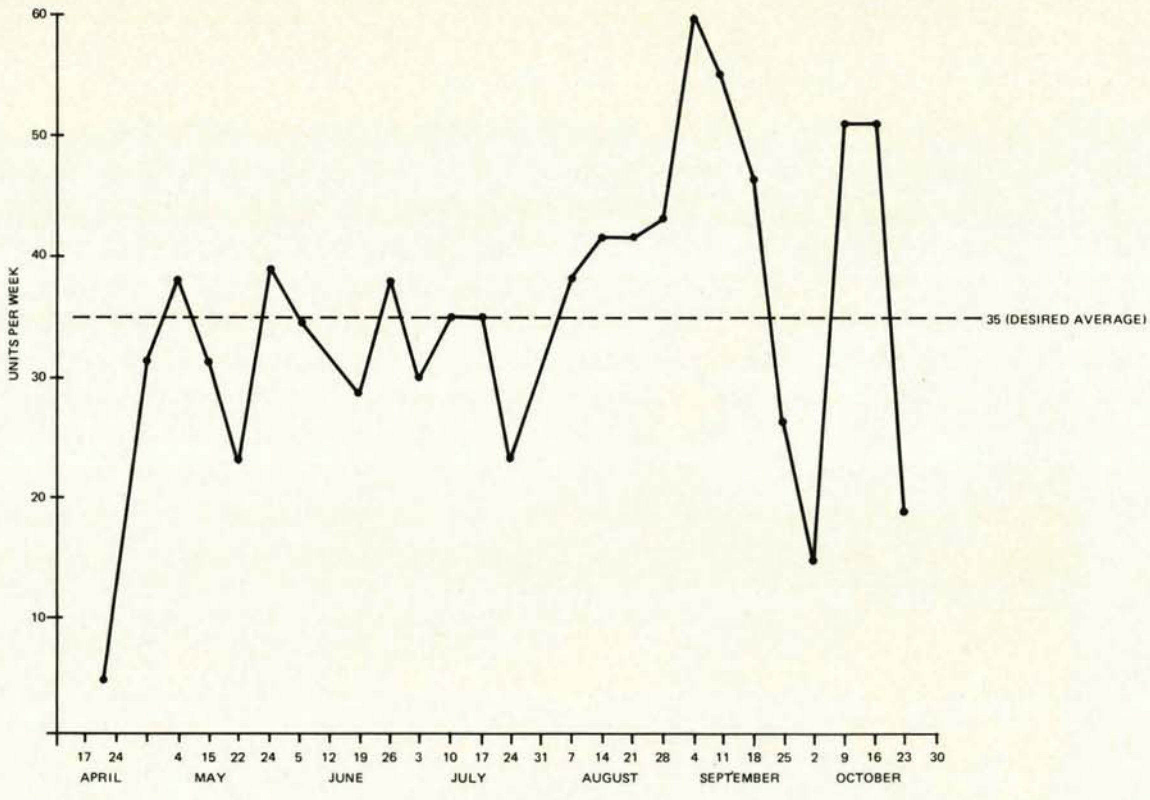

Figure 14. Magsat Attitude Data Processing Rate

the TP, archive the output on magnetic tapes, and then to process data sequentially through the DPS, and the SPS subsystems. These plans were revised because of the unresolved sensor alignment problems discussed in Section 5. The TP was run on the attitude telemetry data, and these data were archived to magnetic tapes, as originally planned. Telemetry processing of the data was started about 4 months before the start of DPS and SPS processing to get ahead on the production processing. A software modification was made to the DPS subsystem to shift the sensor alignment-related computations entirely to the SPS subsystem. The DPS subsystem was then executed on the archived TP output. The DPS output was also archived to magnetic tapes. This enabled DPS processing to proceed in parallel with analytical efforts to resolve the sensor alignment problems. After the alignment problems were resolved, the SPS subsytem was executed on the archived DPS output tapes. The archiving of DPS output added a burden of approximately 25 percent to the time required for processing through the DPS subsystem.

The attitude results were to be transmitted to the experimenters over a computer-to-computer data link. However, this approach had to be abandoned due to computer scheduling problems; instead, archived tapes of the attitude results were delivered to the experimenters.

6.3 Quality Assurance

The quality assurance of the attitude results was a significant activity during the production phase. Critical quality assurance parameters were routinely computed and used to automatically flag data segments where accuracy of the attitude solutions was suspect. Hard copy printouts of these parameters were regularly checked to determine whether any systematic trends or biases were present. As previously noted in Section 4, the attitude computation algorithm QUEST generated a residual which was a measure of the attitude accuracy. A summary of this residual for a typical 3-day period is shown in Table 1. The number of attitude solutions upon which the average and the standard deviation of the residual are based is also shown in Table 1. Note that only 8 percent of the attitude solutions had residuals greater than 20 arc-seconds.

Table 1. Attitude Solution Residual Summary

METHOD	RESIDUAL (ARC-SECONDS)	STANDARD DEVIATION OF RESIDUAL	NUMBER OF ATTITUDE SOLUTIONS	PERCENT ABOVE 20 (ARC-SECONDS)	DAY
FSS, SC1, SC2	12.84	5.81	2,000	12.2	325
FSS, SC1	9.49	14.65	2,000	8.5	325
FSS, SC2	5.01	3.61	2,000	0.25	325
SC1, SC2	10.72	7.12	2,000	10.90	325
FSS, SC1, SC2	15.04	7.59	2,000	21.7	326
FSS, SC1	6.37	5.12	2,000	2.4	326
FSS, SC2	7.97	5.16	2,000	1.0	326
SC1, SC2			0		
FSS, SC1, SC2	12.74	6.99	2,000	14.2	328
FSS, SC1	5.99	4.49	1,063	1.2	328
FSS, SC2	6.98	7.07	1,395	3.2	328
SC1, SC2			0		
		TOTAL	18,458	8 PERCENT	

8000/81

In addition, line printer plots of the attitude results were checked for consistency and for continuity of results. Whenever, any problems were discovered, the affected data were closely scrutinized, and, if possible, were reprocessed. The system allowed the affected attitude results to be replaced by the reprocessed attitude results.

7. CONCLUSIONS

The goal of generating a definitive, continuous, time history of the three-axis attitude of the Magsat spacecraft to a precision of 20 arc-seconds (one standard deviation) in each axis was successfully realized. About 200 days of attitude sensor data were processed in 190 calendar days, thus exceeding the throughput requirement of processing 1 day of sensor data in 1 calendar day. The sensor alignment determination activity proved to be an ongoing postlaunch activity because of the changing alignments and their deleterious effect on attitude precision. This activity also entailed considerable expenditure of resources.

The two-phase approach to the development of the attitude determination software proved to be extremely valuable; unanticipated data anomalies were easily accommodated and, at the same time, the system was not burdened with software dealing with every potential contingency. This reduced the software development cost because the system complexity was well matched with the system needs. This also reduced the time required to develop a fully operational system. Another advantage of this approach was that the attitude solutions delivered to the experiments were of uniformly high quality, from the very beginning, because of the experience gained during 5 months of postlaunch data evaluation.

Experience on previous missions had shown that, if the production processing is initiated immediately after the launch, the attitude solutions may not benefit from a full understanding of the sensor data characteristics until after the lapse of a learning period. The authors firmly believe that the two-phase approach was critical to the success of this effort. An equally important factor responsible for the overall success of this project was the close cooperation between all groups involved in support of the Magsat mission. These groups included experimenters, spacecraft and sensor builders, spacecraft control personnel, ground data processing personnel, and attitude determination personnel. Close interaction between the attitude determination personnel and the experimenters led to timely resolution of many problems bearing on sensor alignments and attitude solution quality.

8. ACKNOWLEDGMENTS

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