MAGSAT ATTITUDE DYNAMICS AND CONTROL: SOME OBSERVATIONS AND EXPLANATIONS

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ABSTRACT

The Magsat spacecraft was placed into an elliptical sun synchronous orbit on October 30, 1979. Before its reentry 7 months later, Magsat had transmitted an abundance of valuable data for mapping the Earth's magnetic field. As an added benefit, a wealth of attitude data for study by spacecraft dynamicists was also collected. Because of its unique configuration, Magsat presented new control problems. With its aerodynamic trim boom, attitude control was given an added dimension. Minimization of attitude drift, which could be mapped in relative detail, became the goal. Momentum control, which was accomplished by pitching the spacecraft in order to balance aerodynamic and gravity gradient torques, was seldom difficult to achieve. However, several interesting phenomena were observed as part of this activity. This included occasional momentum wheel instability and a rough correlation between solar flux and the pitch angle required to maintain acceptable momentum.

This paper presents an overview of the attitude behavior of Magsat and some of the control problems encountered. Plausible explanations for some of this behavior are offered. Some of the control philosophy used during the mission is examined and aerodynamic trimming operations are summarized.

I. Introduction

Managed by NASA's Goddard Space Flight Center, the Magsat spacecraft was a 3-axis stabilized spacecraft placed into a sun synchronous elliptic orbit of 350 X 560 km on October 30, 1979. During its lifetime which ended with reentry on June 11, 1980, Magsat met its scientific goals and also provided valuable information regarding spacecraft attitude dynamics and control in the low altitude flight regime. Goddard's Attitude Determination and Control Section (ADCS) was charged with the responsibility of daily attitude control operations and monitoring the health and safety of Magsat's semiautonomous control system. As a fallout from this activity and definitive attitude processing by the ADCS, an abundance of attitude data was accumulated. Continued analysis of this data is providing practical insight into such items as aerodynamic drift characteristics, drift minimization, and momentum control. Another benefit from this mission was the operational experience gained from controlling a spacecraft which had a large amount of control autonomy, yet still required 24-hour monitoring and numerous ground supplied control system updates.

Built by the Applied Physics Laboratory (APL), the Magsat spacecraft pictured in figures 1 and 2 utilized a SAS-C type bus. In flight, the spacecraft's Z axis (pitch axis) was nominally pointed near negative orbit normal (NON). Angular momentum provided by the body and a momentum wheel was directed along the -Z axis. In contrast to SAS-C, Magsat was given additional attitude control autonomy due to anticipated high aerodynamic torques. An Attitude Signal Processor (ASP) performed the onboard control system functions and required occasional updates via ground command by the ADCS. The ASP will be discussed in more detail later. Ground commanding of the spacecraft's magnetic coils for roll/yaw or momentum control served as a backup mode which was never required following initial ASP acquisition.

Activation of the spacecraft's magnetic coils for roll/yaw control or momentum dumping by either the ASP or ground command was not desired for two reasons. First, this activity corrupted science data gathered by the experimenter's magnetometer. Second, nutation was increased which had the potential for impacting fine attitude determination required by the experimenter. In order to achieve the goal of minimizing magnetic coil activity, several control capabilities were available and were utilized by the ADCS. As an aid to balancing yaw torques and thus Z-axis drift, a variable length aerodynamic trim boom was built into the spacecraft. The length of this boom was controlled by ground command and was adjusted on several occasions during the mission. Also available for drift control was the capability to target the spacecraft's Z axis to some point off negative orbit normal where the spacecraft might be better trimmed aerodynamically. It was suggested in prelaunch analysis that the Magsat spacecraft might be trimmed with its Z axis at a point between 2 to 4° above NON. While actual experience presented later will show that this trim point varied considerably throughout the mission, the importance here is that control requirements were flexible enough (and, in fact, necessary) to allow placing of the

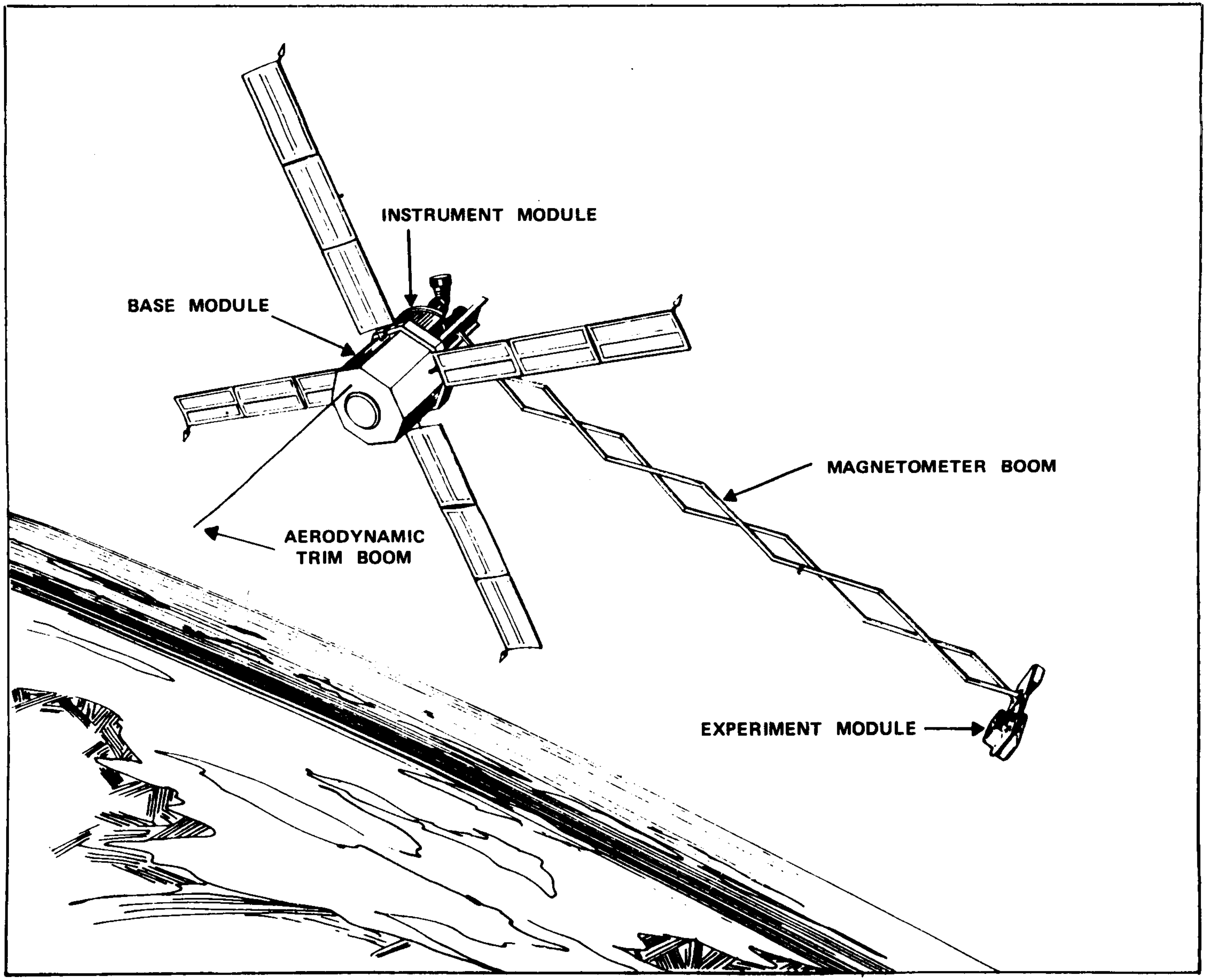


Figure 1. Artist's Conception of Magsat (reference 3)

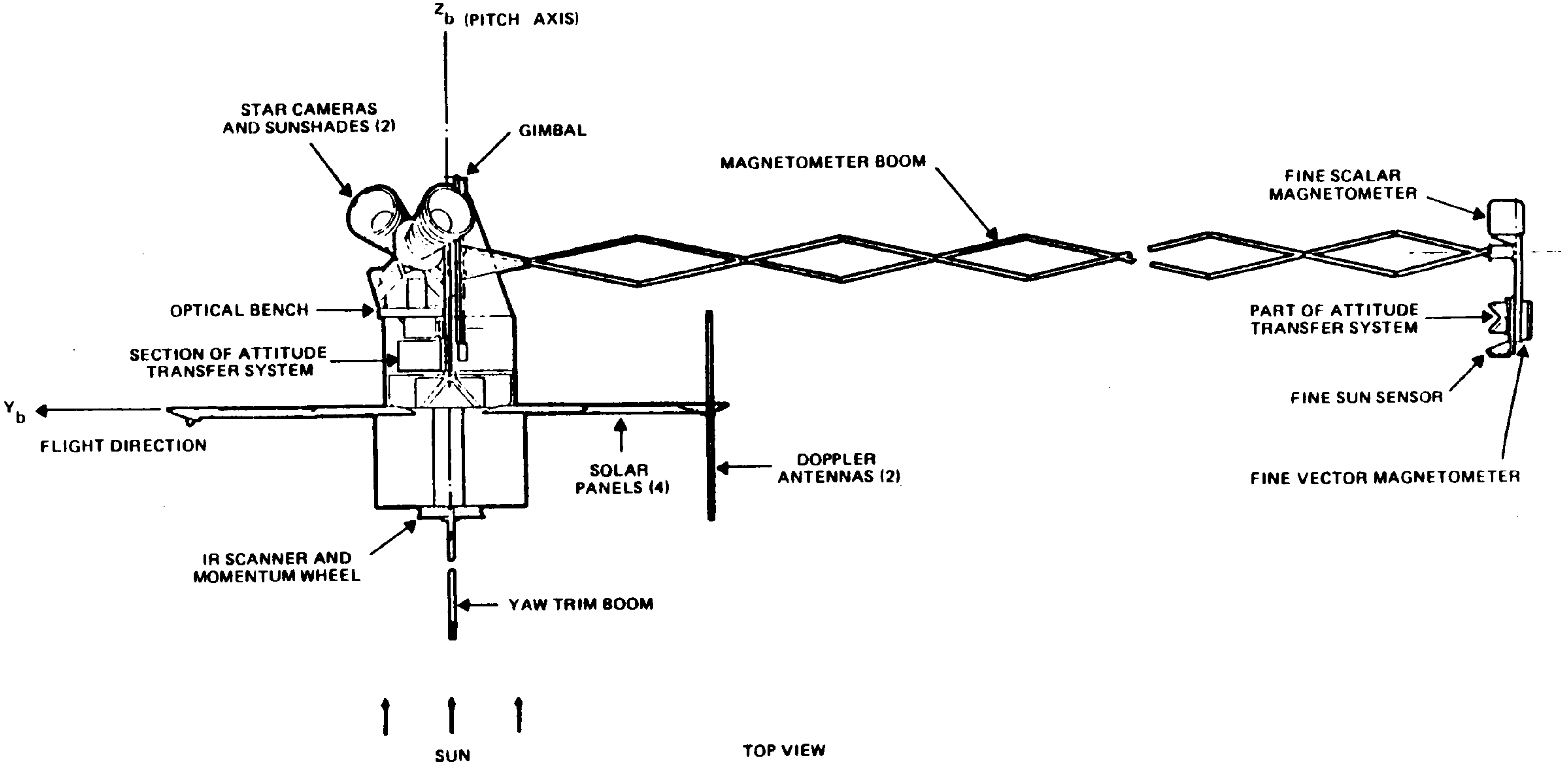


Figure 2. Magsat Orbital Configuration (reference 3)

spacecraft spin axis where roll/yaw control could be minimized. The amount of acceptable drift from the target attitude before ASP activation of control coils was also variable. By changing this control threshold, the drift could be highly restricted at the expense of control torques or given no tight bounds. Another major capability which aided in minimizing coil activity was associated with momentum control. On a near daily basis, the spacecraft's pitch was biased so as to alter the relative effects of the gravity gradient and aerodynamic torques on the spacecraft, thus affecting momentum build-up or loss.

From a control standpoint, Magsat's mission might be divided into three phases. First was an initial acquisition and trimming phase which took place the first 3 weeks of the mission. During this time, the spacecraft was placed into the ASP mode of operation, both the experiment and aerodynamic trim booms were deployed, and momentum control was established by biasing the spacecraft in pitch. This was also an active period of attempting to stabilize the spacecraft's drift with relatively frequent target changes and trim boom positioning.

Following this initial period was a time lasting roughly 4½ months which might be classified as the nominal operations phase. During this phase, control torques were kept to a minimum with active pitch biasing of the spacecraft and six trim boom operations. Magsat's target attitude remained nearly constant at a position 4^{o} above NON.

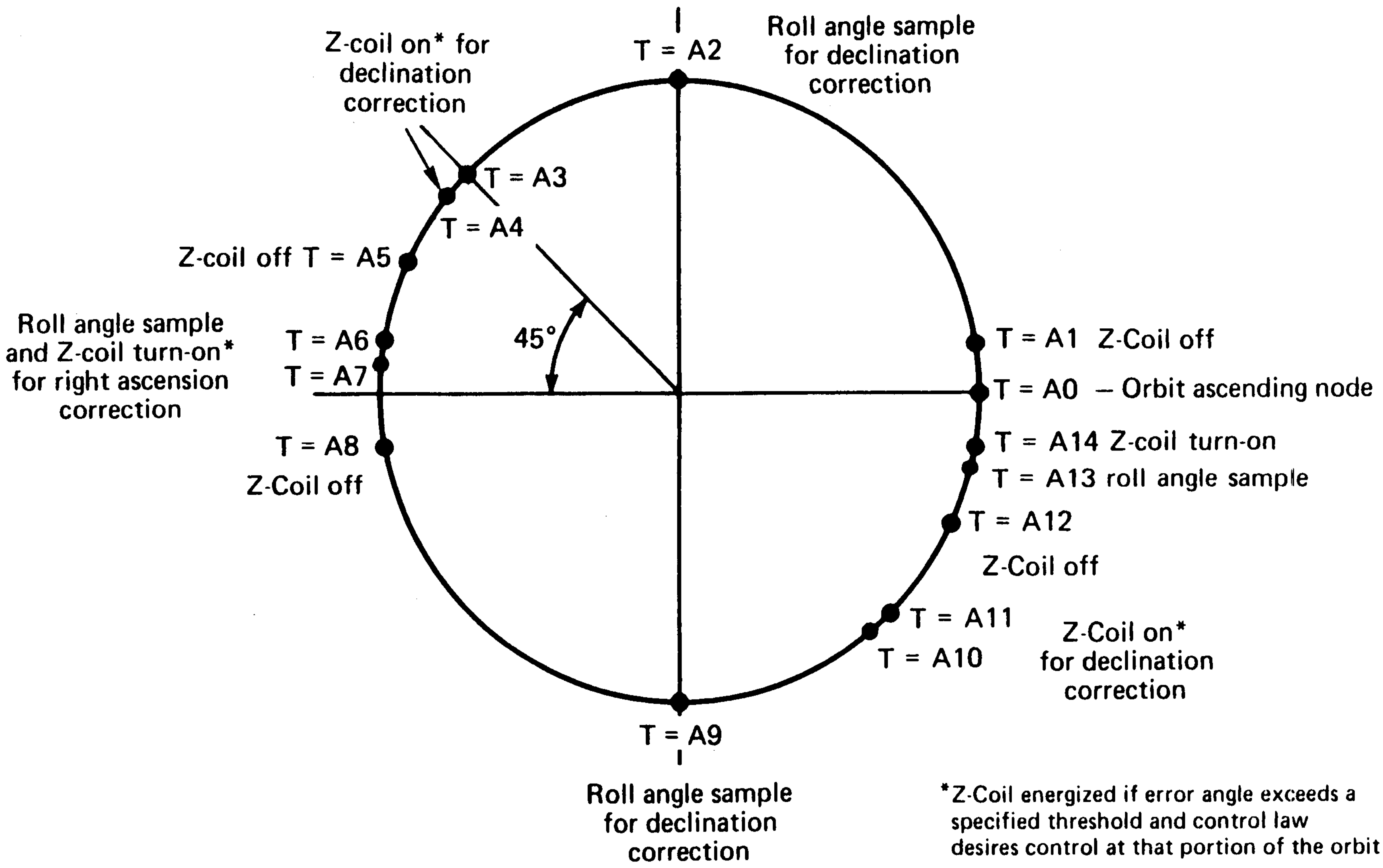
The final 2 months of the mission were not nominal by any standard. Originally designed as a 5-month mission, orbit decay was less than predicted, thus giving the spacecraft an additional 2 months of life. This resulted in two complications. First, the orbit had time to precess enough so that the spacecraft encountered increasingly larger periods of darkness which had not been anticipated under the prelaunch mission plan. The second complication was that the Sun angle increased so as to create problems in fully charging the spacecraft's battery. These two factors necessitated a Project Office decision to move the spacecraft's target attitude roughly 10^{o} to improve solar array position relative to the Sun. While the ASP successfully maintained the spacecraft Z axis at this off-nominal target roughly 6^{o} below NON, the spacecraft drift and relative frequency of control torques increased drastically. Also as a result of the low power conditions that existed, a considerable amount of full orbit attitude data was lost due to tape recorder turn-offs. The off-nominal target was held until 2 weeks before reentry when it was decided that drift had to be reduced to insure successful attitude control during Magsat's final days. At that time the Z axis target attitude was returned to a point 4^{o} above NON. Attitude drift and control activity benefited considerably. Approximately 27 hours before spacecraft reentry, the target attitude was changed due to Sun sensor calibration limitations to a point 2^{o} above NON. The subsequent increase in drift could not be corrected by the ASP resulting in a nonrecoverable loss of attitude control 20 hours before reentry.

The primary intent of this paper is to summarize some of the dynamics and control phenomena observed by the ADCS during Magsat's 7-month mission. Specifically, items associated with roll/yaw control and momentum control are discussed. Where possible, flight data is presented and actual flight experience is compared to prelaunch expectations. Postmission analysis by the ADCS is continuing with emphasis being placed on obtaining a more thorough understanding of the nature of Magsat's aerodynamic trim point and in studying flexible boom dynamics.

II. The Attitude Signal Processor (ASP)

As mentioned before, the ASP performed the onboard control system functions and required periodic updates via ground command by Goddard's Attitude Determination and Control Section. While the ASP is not the subject of this paper, its general operation and capabilities should be summarized. For a detailed description, the reader is directed to references 2 and 3.

Pitch control was maintained with a momentum wheel tied into a control loop which included an Ithaco IR scanner, a filter, and a gyro. While pitch control was active throughout the spacecraft's orbit, activities associated with roll/yaw control and momentum dumping were keyed to 14 control points in the spacecraft's orbit referenced from the ascending node. These control points are depicted in figure 3. Of these 14 control points, four were roll sample checks, two were momentum checks and the remaining eight were points for possible magnetic coil commands by the ASP. Roll samples were taken by the IR scanner at the poles and nodes and indicated to the ASP any attitude error from a ground supplied target attitude. Note that a roll error at the poles represents a declination error from negative orbit normal. Likewise, a roll error at the nodes represents a right ascension error from negative orbit normal. If the ASP determined that the Z axis had precessed beyond some ground supplied threshold from the target attitude then the Z axis coil was commanded on at an appropriate torque zone. Right ascension torque zones were located around each node while declination torque zones were located between 22° and 40° in latitude. The duration of the Z coil on time was a ground supplied parameter but was typically 5 minutes. A similar procedure was followed for momentum control. If the speed of the momentum wheel exceeded the nominal speed of 1500 rpm by some ground supplied threshold (usually 200 rpm), spin/despin coils were commanded on. The duration of the coil on time for momentum dumping could be as high as 40 minutes. This outline of roll/yaw and momentum control represents the nominal operational ASP mode. Certain variations in roll/yaw, pitch and momentum control existed, but will not be covered here. One operational restriction which should be noted is that the spacecraft had to be maintained within 12° in roll in order to avoid an IR scanner failure due to calibration limitations. If this occurred, the pitch control loop was disabled and had to be reactivated by ground command.



*Z-Coil energized if error angle exceeds a specified threshold and control law desires control at that portion of the orbit

Figure 3.

Magsat Orbit Positions for ASP Observations and Control (reference 1)

Nineteen ASP parameters were uplinked to the spacecraft on a near daily basis. Most frequently changed were the spacecraft's orbital period, ASP clock correction, pitch bias, and percent Earth values used for roll determination. It should be pointed out that the spacecraft's target attitude was controlled with the percent Earth values. Other parameters which were changed, but with less frequency were the thresholds used by the ASP to determine the necessity for momentum dumping or roll control. Loads to the ASP were generated on tape and quality assured by the ADCS. These tapes were hand carried to Goddard's Multi-satellite Operations Control Center (MSOCC) for uplink to the spacecraft at a scheduled station pass. Although a minimum of one ASP load could usually be expected each day, updates to the pitch bias and orbit related parameters were not regularly scheduled events, but were the result of an attitude control analyst's decision to improve ASP performance. Changes in target or control threshold parameters, however, always followed consultation with the Magsat Project Office.

III. Momentum Control

Although conceptually easy to understand, momentum control activities often presented some perplexing problems operationally. Because automatic momentum dumping could result in coil activity for as long as 40 minutes, it was very desirous, and became a goal to eliminate the necessity for automatic dumping through proper biasing of the spacecraft in pitch. This approach to controlling momentum was advanced early in the mission planning by the APL and during most of the mission was handled with success by the ADCS. By pitching the spacecraft, the magnitude of the gravity gradient and aerodynamic torques could be altered so as to affect a wheel speed change advantageous to momentum control. An average of one pitch bias update was uplinked to the spacecraft each day. While this exceeded the APL's estimate of one every two days, there were periods of up to 4 days in which there were no pitch bias changes. As a measure of the success of this approach to momentum control, the spin/despin coils were inactive between November 10, 1979, and May 15, 1980. During much of the mission the primary control function was one of fine tuning the bias. Wheel speed changes were usually held to less than 5 rpm/orbit. Nominal changes in the pitch bias were on the order of .1-.2°.

The aerodynamic model of the Magsat spacecraft used in simulations and both prelaunch and postmission analysis decomposes the spacecraft into ten elements. While its accuracy is questionable, it is useful in showing general trends and in providing theoretical estimates of torque magnitude as shown in figure 4. Aerodynamic torques were addressed in several technical memos before launch and formed an integral part of the control philosophy. Intuitively, these torques can be expected to exhibit the largest daily variations due to the wide range of altitude dependent atmospheric variables. Successfully predicting these variations and their effect on the required pitch bias for momentum control does not appear practical. Plots of the pitch bias and averaged daily flux as given in figure 5 appeared to show some rough

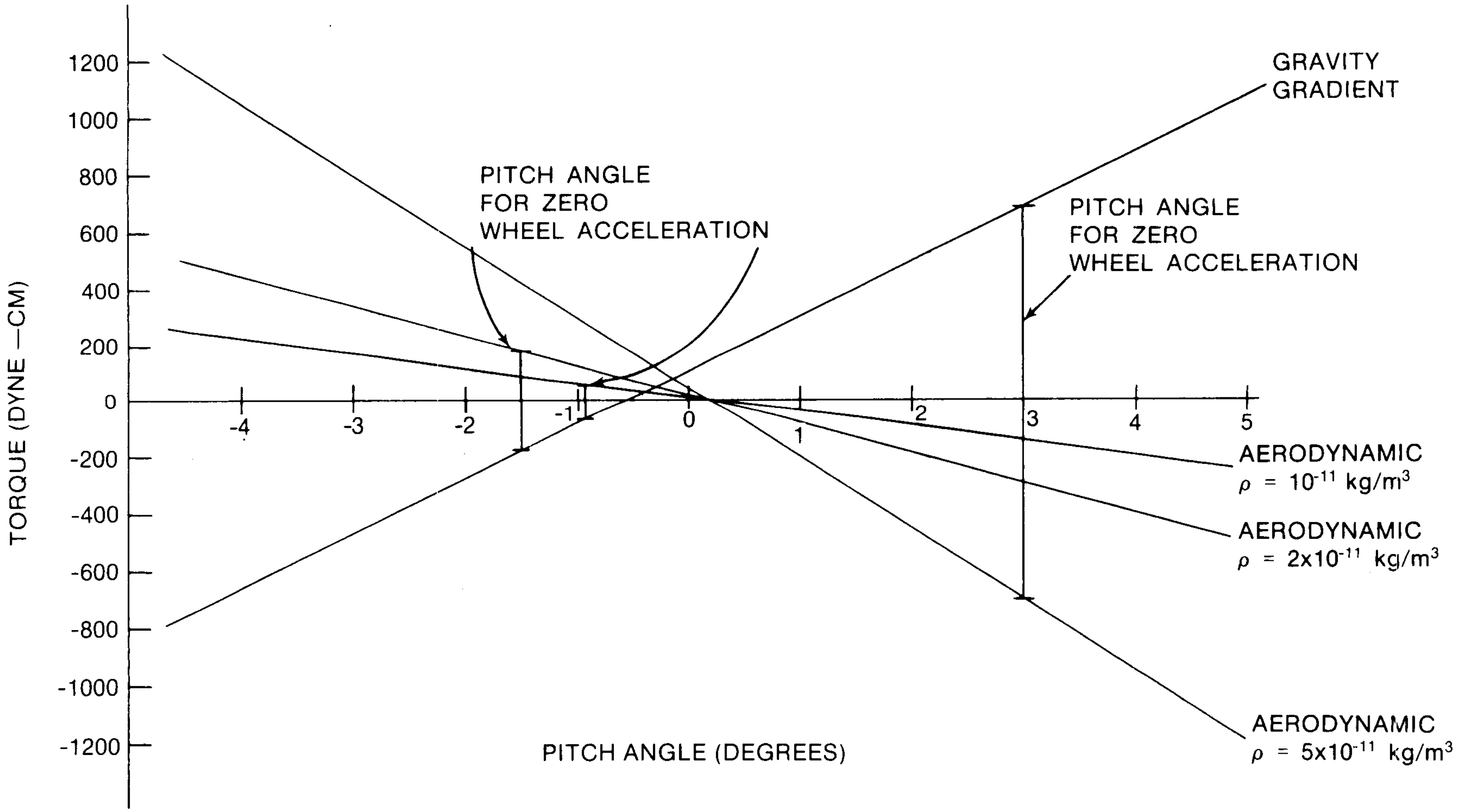


Figure 4.

Aerodynamic and Gravity Gradient

Torques Versus Pitch Angle

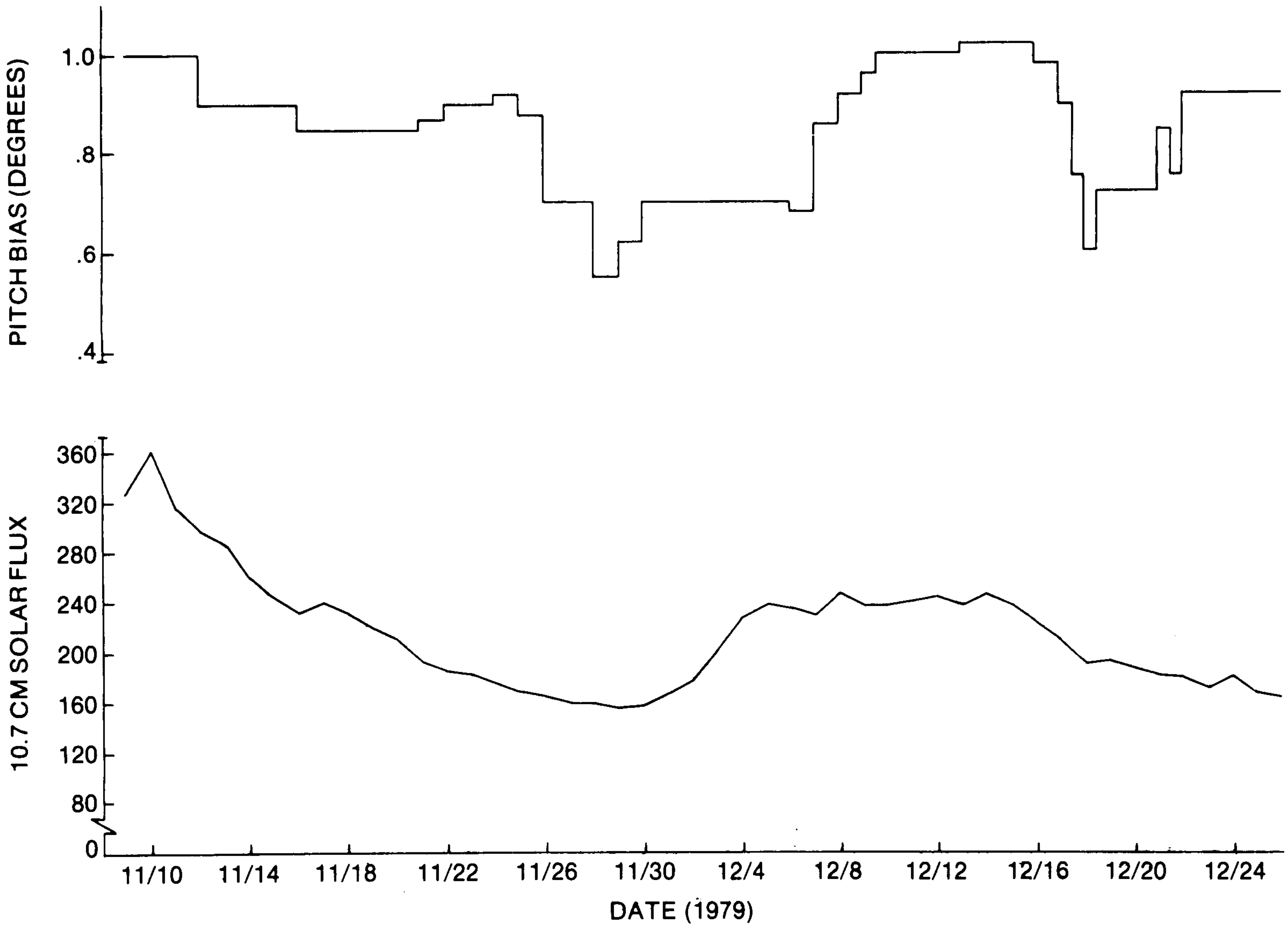


Figure 5. Pitch Bias and Solar Flux History

(November 8 - December 28, 1979)

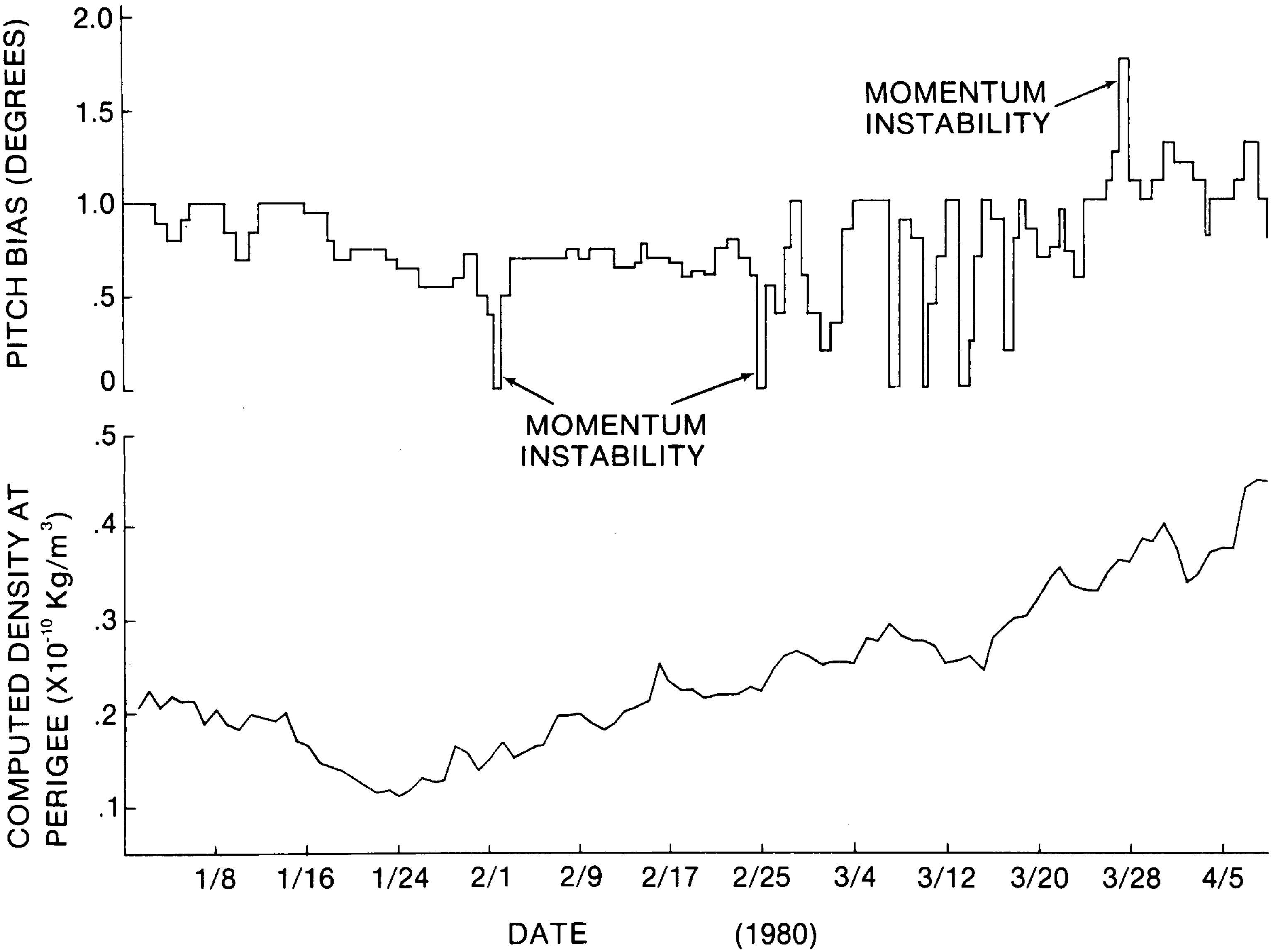


Figure 6. Pitch Bias and Computed Density History

(January 1 - April 15, 1980)

correlation early in the mission. A 28-day cycle associated with the pitch bias activity was evident and was phased similar to the Sun's 28-day cycle. However, this correlation did not hold true nor did the pitch bias history show any likeness to the nature of the atmospheric density at perigee computed using a flux dependent Jacchia model (figure 6).

Gravity gradient and aerodynamic torques act in opposite directions which makes possible the use of these torques for momentum control. It must be kept in mind that the purpose was to balance net orbital torques. Variations over the orbit in wheel speed could be expected due to the altitude dependent aerodynamic torques. (Altitude variations in gravity gradient torques were relatively small). The orbital variation in the wheel speed was nominally less than 15 rpm, but went higher than 100 rpm when the pitch bias was increased to 8° late in the mission. The magnitude and direction of the torques were such that to spin up the wheel the spacecraft was pitched in a negative sense when average orbital gravity gradient torques dominated during the first 6 months of the mission and a positive sense when average orbital aerodynamic torques dominated at the end of the mission. The transition period in which the relative roles of the gravity gradient and aerodynamic torques reversed was one of two noteworthy items observed as part of momentum control activities. This period occurred 6½ months into the mission with the spacecraft in a 270 km X 365 km orbit and lasted 2 weeks. During this time the momentum could not be controlled by biasing the spacecraft in pitch. The reason for this can be shown both theoretically and graphically. Tossman of the APL described the average orbital torque about the pitch axis as:

$$T = K_0 + K_{GG} P + K_{AERO} P$$

where K_0 = torque at zero pitch

$K_{GG} = \partial T_{GG} / \partial P$

$K_{AERO} = \partial T_{AERO} / \partial P$

P = pitch angle

T_{GG} = average orbital gravity gradient torques

T_{AERO} = average orbital aerodynamic torque

Theoretical results show that the coefficients K_{GG} and K_{AERO} are linear and of opposite sign over the range of pitch bias angles used operationally (figure 4). By defining K_{AERO} and K_0 as coefficients derived from average torques over an orbit, orbital variations in these coefficients are avoided. Solving for the pitch angle required to balance the two torques results in the following expression:

$$P = -K_0/(K_{GG} + K_{AERO})$$

As can be readily seen, when K_{GG} and K_{AERO} approach each other in magnitude (but still of opposite sign) torque control using pitch biasing becomes no longer effective. Also, depending on which torque dominates, the spacecraft must be pitched in opposite directions to achieve, for example, an increase in momentum.

Returning to the available wheel speed data during the mission and the pitch bias history, it is instructive to determine actual values for the coefficients K_{AERO} and K_{GG}. The sum of these two coefficients, $K_{GG} + K_{AERO}$ is plotted in figure 7 for the period between January 1 and May 1, 1980. The results do not clearly show what might intuitively be expected but do reflect the randomness and variability of the spacecraft's aerodynamics. A gradual decline in $K_{GG} + K_{AERO}$ would be expected as the aerodynamic torques gradually increase in importance. This, however, is not obvious from the flight data. Unfortunately, definitive values for $K_{GG} + K_{AERO}$ beyond May 1, 1980, cannot be easily determined. This is due to a scarcity of good data resulting from poor spacecraft health and the fact that with the higher pitch biases used, it is difficult to determine with some confidence the net wheel speed acceleration.

The transition period is depicted graphically in figure 4. Plotted are average gravity gradient torques and aerodynamic torques over an orbit versus pitch angle. Three theoretical curves are featured for the average aerodynamic torques corresponding to conditions found throughout the mission. As the mission progressed, the magnitude of these torques increased, thus effecting the magnitude of the slope of the aerodynamic torque curves given in figure 4. This plot shows graphically the proper pitch angle for zero torque about the pitch axis (and thus, no acceleration in the momentum wheel) and also the trend towards a more negative pitch as aerodynamic torques gain in relative importance. Figure 4 also shows the need for a positive pitch when this torque dominates the system.

One surprise associated with the transition period was how rapid the aerodynamics changed. In the 1-week period immediately preceding the loss of momentum control, the required pitch bias increased from 2^{0} to its operational limit of 8^{0}. Previous to that time momentum control activity had been relatively stable with pitch biases ranging between $.5^{0}$ and 2^{0}.

Once it was concluded that wheel speed had been lost, the pitch bias was returned to zero. This was done to reduce orbital variations in the wheel speed caused by orbital variations in the aerodynamic torque. Without the momentum control capability with pitch biasing, automatic momentum dumping using electromagnetic coils occurred several times a day. Some degree of control over the momentum was achieved by biasing the spacecraft pitch following the 2-week transition period. It should be pointed out that this was approximately 1 week before spacecraft reentry and time did not permit the establishment of tight control over the momentum which was exhibited during the first 6½ months of the mission. Nevertheless, there was a reduction in momentum dumping activity the last week of the mission by biasing Magsat's pitch.

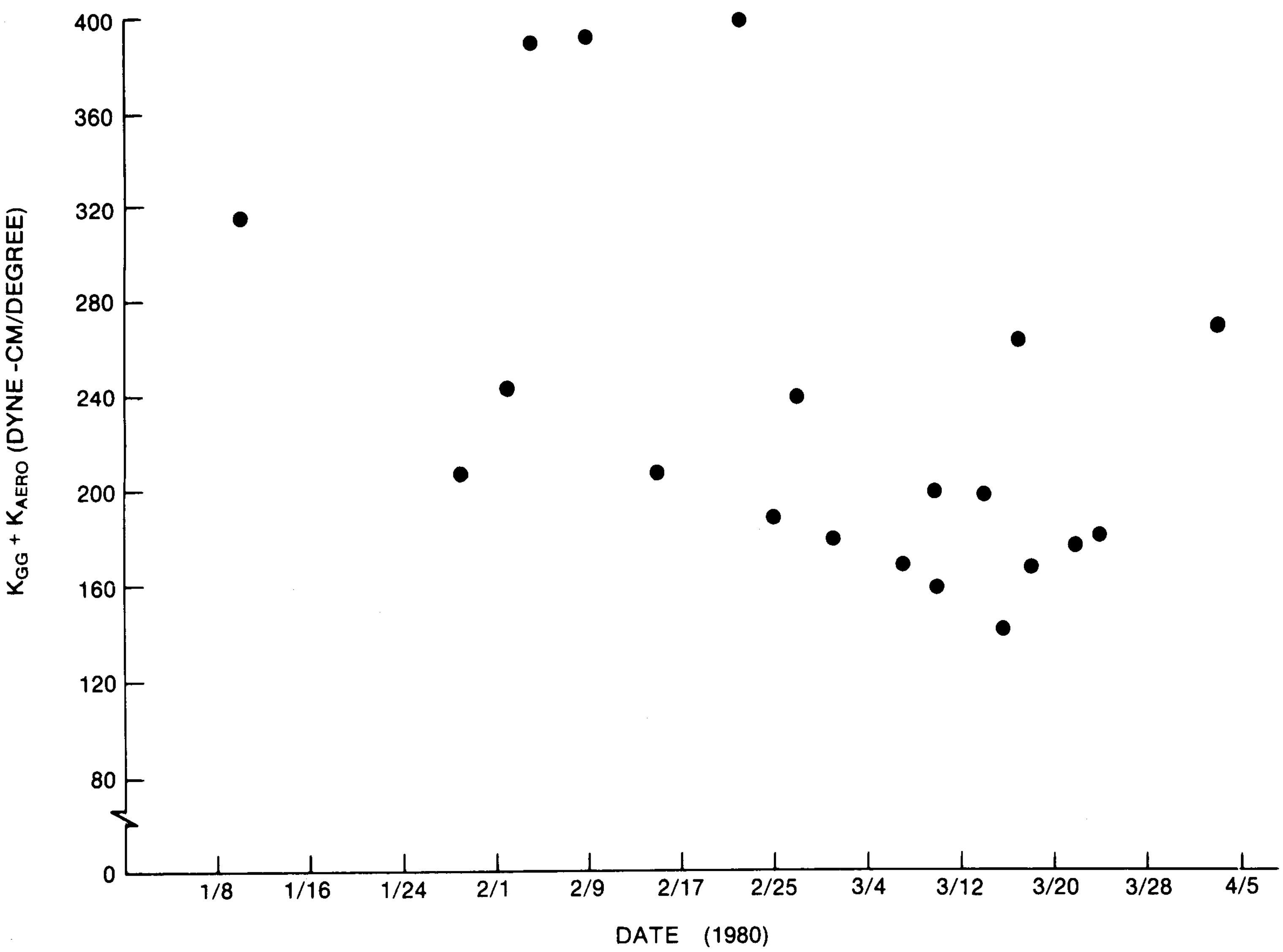


Figure 7. $K_{GG} + K_{AERO}$ Estimated from Wheel Speed and Pitch Bias History

A second noteworthy phenomenon associated with momentum control was occasional instability in the momentum. This required more active monitoring of the momentum wheel speed and numerous ASP loads with large pitch bias changes to bring the momentum back under control. At least three periods of wheel speed instability were encountered during the mission. These periods can be observed in figure 6 as sudden changes in the required pitch bias following a period of relatively small pitch bias changes. This feature was characterized by a rapid rise or fall in the wheel speed as high as 30 rpm per orbit requiring large, immediate changes to the pitch bias to avoid spin/despin coil activity. Thus far, there has been no confirmation that a sudden change in atmospheric conditions affecting aerodynamic torques caused these rapid changes in the wheel speed. This does, however, appear to be the only plausible explanation. There also has not been any consistent correlation found between these periods of wheel speed instability and significant changes in the spacecraft Z axis drift. This might be expected since Z axis drift should be affected by large changes in aerodynamics which might suddenly change spacecraft momentum. A rough correlation can be found for one case around March 25, 1980. On that day, the spacecraft drift suddenly increased from 2^{o}/day to 8^{o}/day. At that time, there was also a larger than nominal drop in wheel speed. The importance of the occasional momentum instability is that it illustrates the need for active monitoring of a spacecraft such as Magsat while in low altitude flight. Real time monitoring and near real time response was often necessary to avoid magnetic coil activity. This phenomenon also adds evidence to the extreme variability of atmospheric conditions.

IV. Spacecraft Drift

Drift minimization became the most challenging aspect of Magsat's control activities. The goal was to eliminate all attitude control torques by using the trim boom and by properly adjusting relevant ASP parameters for attitude target placement. Of course, this goal was not achieved. However, with the exception of the few weeks following launch when active trimming operations were underway and the final 9 weeks of the mission when the spacecraft had to be held at an off-nominal attitude, the number of control torques was below most prelaunch expectations. In fact, there were periods in excess of 2 weeks in which there were no control torques. These periods can be seen in a histogram of the attitude control torques given in figure 8. Part of this success must be attributed to the fact that a 6^{o} control threshold was used during most of the mission rather than the 2^{o} bounds suggested before launch. This allowed more overall drift, but did not jeopardize control or safety of the spacecraft. Prelaunch estimates of the control torque activity were as high as three torques per day with a control threshold of 2^{o}.

The daily Attitude Determination and Control Section role in drift control was one of processing a minimum of one orbit of playback data to track the spacecraft Z axis drift in right ascension and declination coordinates. Decisions regarding trim boom operations and target changes were made by the Attitude Determination and Control Section following consultation with the Magsat Project Office and on occasion, the Applied Physics Laboratory. In general, there was considerable caution by all organizations involved during the early

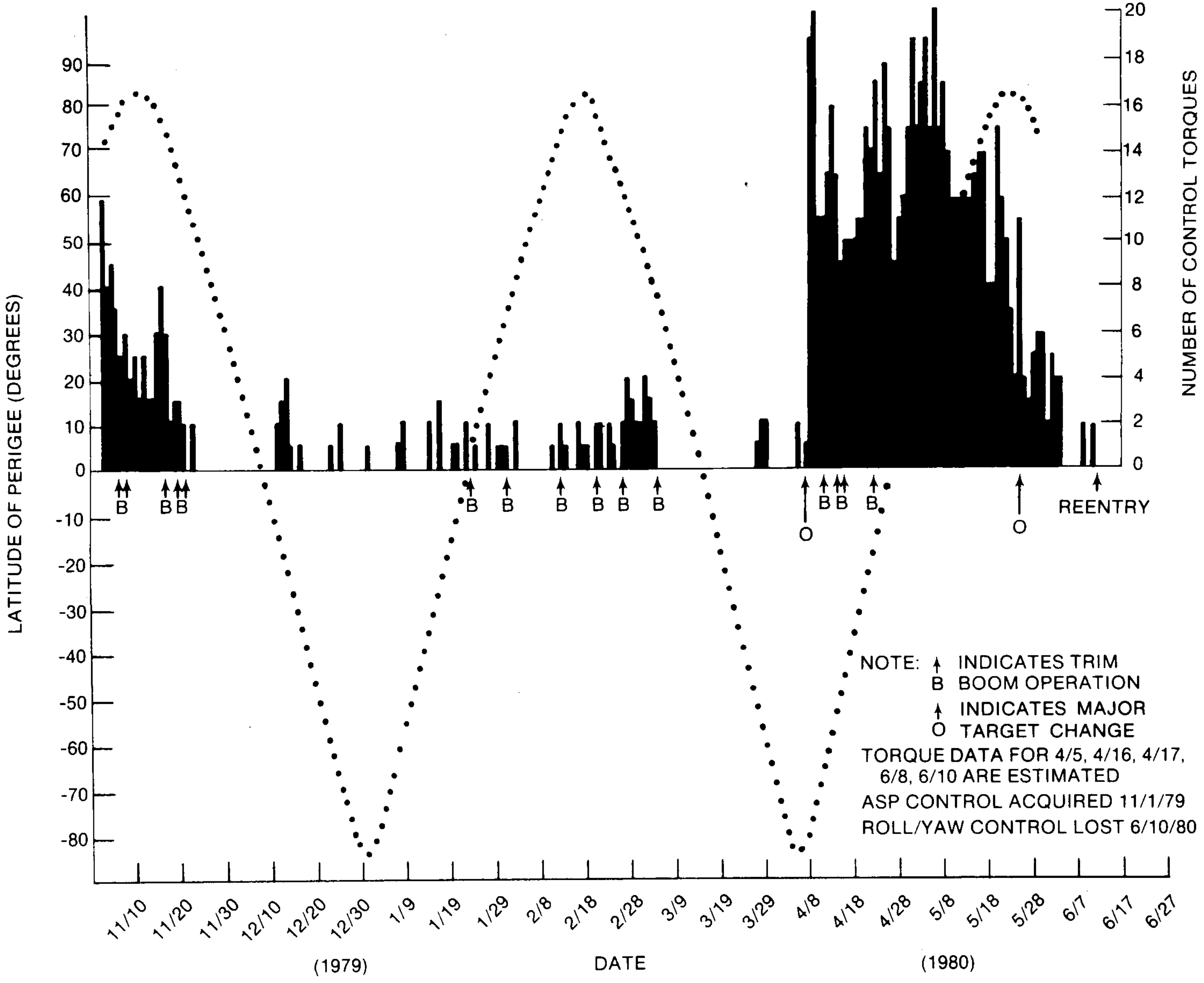


Figure 8. Roll/Yaw Control Torque Histogram and Perigee History for the Magsat Mission

months of the mission towards overuse of the aerodynamic trim boom and in actively changing the spacecraft target attitude. This initial conservatism was the result of several factors. First was the uncertainty in the physical reliability of the trim boom system following a large number of extensions and retractions. A second factor was the lack of experience in controlling a spacecraft such as Magsat with its unique configuration and control capabilities. Although the amount of prelaunch analysis by both the Applied Physics Laboratory and the Attitude Determination and Control Section was considerable, large uncertainties in modeling aerodynamic effects seemed to demand a certain degree of hesitancy in making changes to trim boom length or target location until more experience and confidence could be gained with these operations.

Use of definitive data can now give a more complete picture of Magsat's drift characteristics. As predicted by simulations conducted by the Applied Physics Laboratory, Magsat's drift track is characterized by two distinct circular motions as illustrated in figure 9. One circular track which is traced out over an orbit is of varying size, but typically around 1^{o} in diameter. This orbital motion can be attributed primarily to variations in the aerodynamic torques as the spacecraft travels through its orbit. While gravity gradient torques were present and affected roll/yaw torques, their effect appears to be of lesser importance when compared to aerodynamic torques. If the spacecraft were properly trimmed such that total environmental torques averaged over the spacecraft's orbit were zero then the orbital drift circle was closed. If the net torque was nonzero, then in addition to the orbital drift track, the spacecraft's Z axis would also precess about a larger, secondary circle with a period ranging between 4-7 days. The size of this circle varied, but was typically observed to be between $2\text{-}6^{o}$ in diameter. Figure 10 is another example of this secondary Z axis precession. The orbital motion has been removed for clarity. In figure 10, not only can the circular drift track be observed, but also the consequence of drifting outside the control bounds as specified by the ground supplied target attitude and control threshold. Both a right ascension and declination control torque are shown.

The center of the secondary circle was referred to in prelaunch analysis and during the mission as the spacecraft trim point. While the location and uniqueness of this trim point is still being studied, the apparent trim point during the mission was not stationary, although it always remained above negative orbit normal in declination. The Applied Physics Laboratory predicted that net orbital Z axis motions would center about a preferred trim point. The desirability by the Z axis to remain above NON has been attributed to superrotation of the atmosphere. Dynamic analysis by Tossman (references 4 and 5) indicated that minimum attitude perturbations would exist if Magsat flew into the relative wind. Thus, Magsat wanted to fly at a biased declination angle, directed into the westerly wind caused by atmospheric superrotation. In effect, this superrotation of the atmosphere introduces a "side" component of wind which is variable in direction and magnitude as the spacecraft passes through its orbit. Figure 11 shows the X, Y, and Z components of the spacecraft wind vector in spacecraft body coordinates

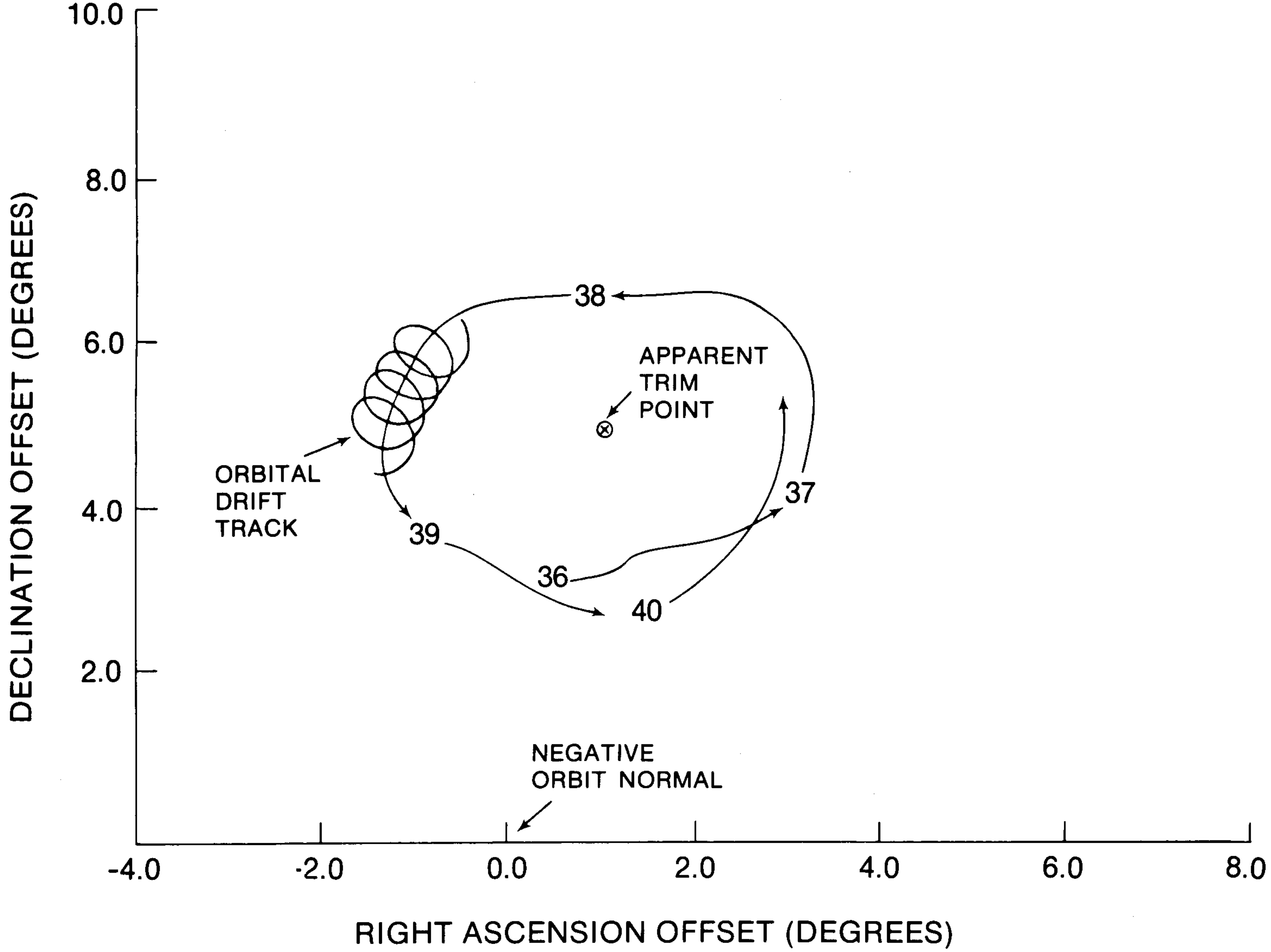


Figure 9. Z Axis Drift for Days 36-40 (February 5-9), 1980

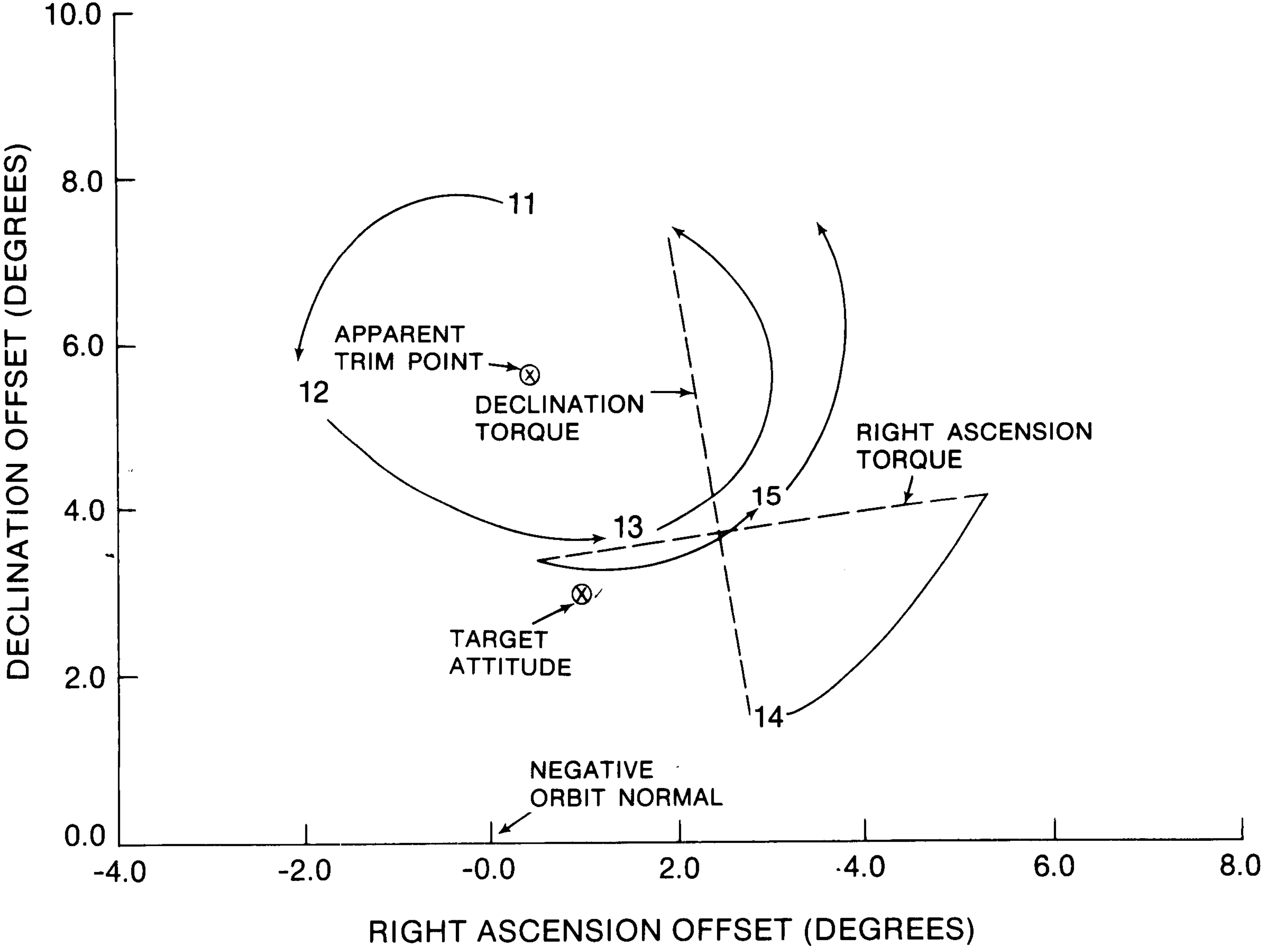


Figure 10. Net Orbital Drift for Days 11-15 (January 11-15), 1980

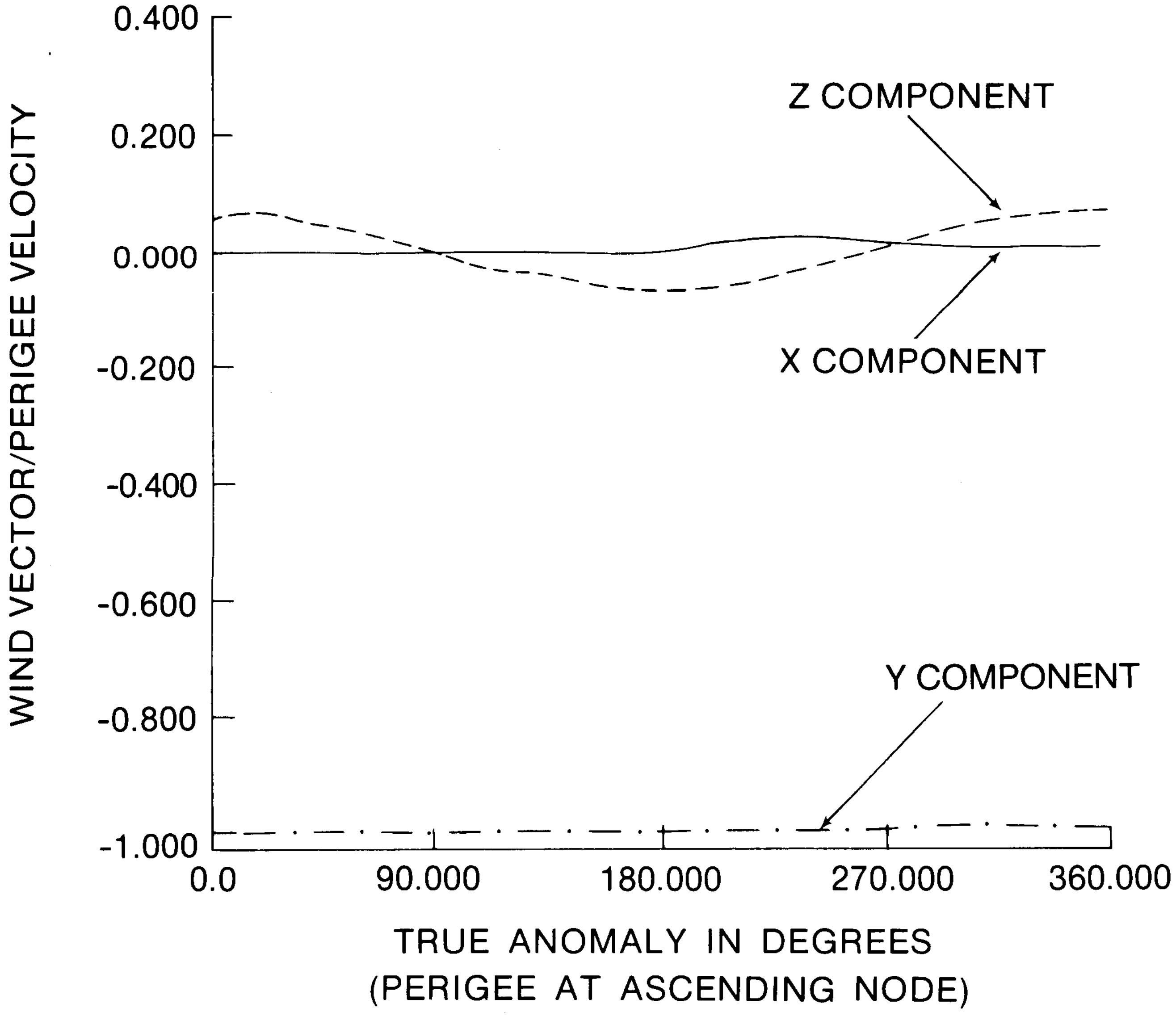


Figure 11.

Normalized Wind Vector for Magsat Targeted

At Negative Orbit Normal (Early Mission Orbit) which were calculated for a Magsat orbit with the target attitude at NON. These components are normalized with respect to the spacecraft velocity at perigee. As can be seen, a considerable component of the wind vector is present in a direction parallel to the pitch axis. With Magsat's relatively large (.28 m) center of mass-center of pressure offset along the roll axis, density variations due to the orbit's eccentricity, and superrotation, significant variations in the yaw torque could be expected. Simulations show that the Z component of the wind vector is significantly reduced by targeting above NON. This results in yawing the spacecraft into the relative wind.

The significant point here is that no matter how far the spacecraft was placed from the trim point, the precession of the Z axis was always such that it circled a trim point located above negative orbit normal. Generally speaking, the larger the circle of precession, the higher the drift rate. The Applied Physics Laboratory believed that a viable control approach for reducing drift would be to determine the trim point by tracking the Z axis precession over a period of days and then maneuver the spacecraft to that target. Subsequently, the net orbital Z axis motion as predicted by the Applied Physics Laboratory's simulations would precess less than 1^{o} from this point. Although this approach was tried, it was abandoned primarily because the drift bounds was increased to 6^{o} and this significantly reduced control torques to a more tolerable level. When the Applied Physics Laboratory's suggested control approach was tried, two problems were evident. First, maneuvering the spacecraft to a specific target to within 1^{o} was not a simple task. This type of maneuver was accomplished by closing the drift threshold to force the ASP to automatically torque the spacecraft to the desired target. The coarseness of the control system and coupling of right ascension motion with declination maneuvers and vice-versa did not permit accurate placement of the spacecraft's Z axis. This can be seen in figure 10. A second problem was that the desired target was dynamic. This was suspected in prelaunch analysis, but no estimates of the target's variability were made. Figure 12 shows the location of the apparent target attitude determined from the drift tracks during various periods of the mission. At one time it was postulated that the target location was a function of the latitude and altitude of perigee. This cannot yet be substantiated, although the target appears to want an offset in right ascension when perigee is at the poles. One period of operation does seem to validate the findings of the Applied Physics Laboratory's simulations. Between March 5-27, 1980, a very stable drift period existed. The net orbital drift track for 5 days during this period is given in figure 13. During this time the spacecraft remained close to its trim attitude, never precessing away from this point by more than 1^{o}.

Concerning the size of the control threshold relative to control torque frequency, evidence certainly suggests that a further reduction in the number of control torques may have been achieved by using larger control threshold. An example of this can be seen in figure 10. The Z axis precession was following what appears to be a stable circular track about a trim point before

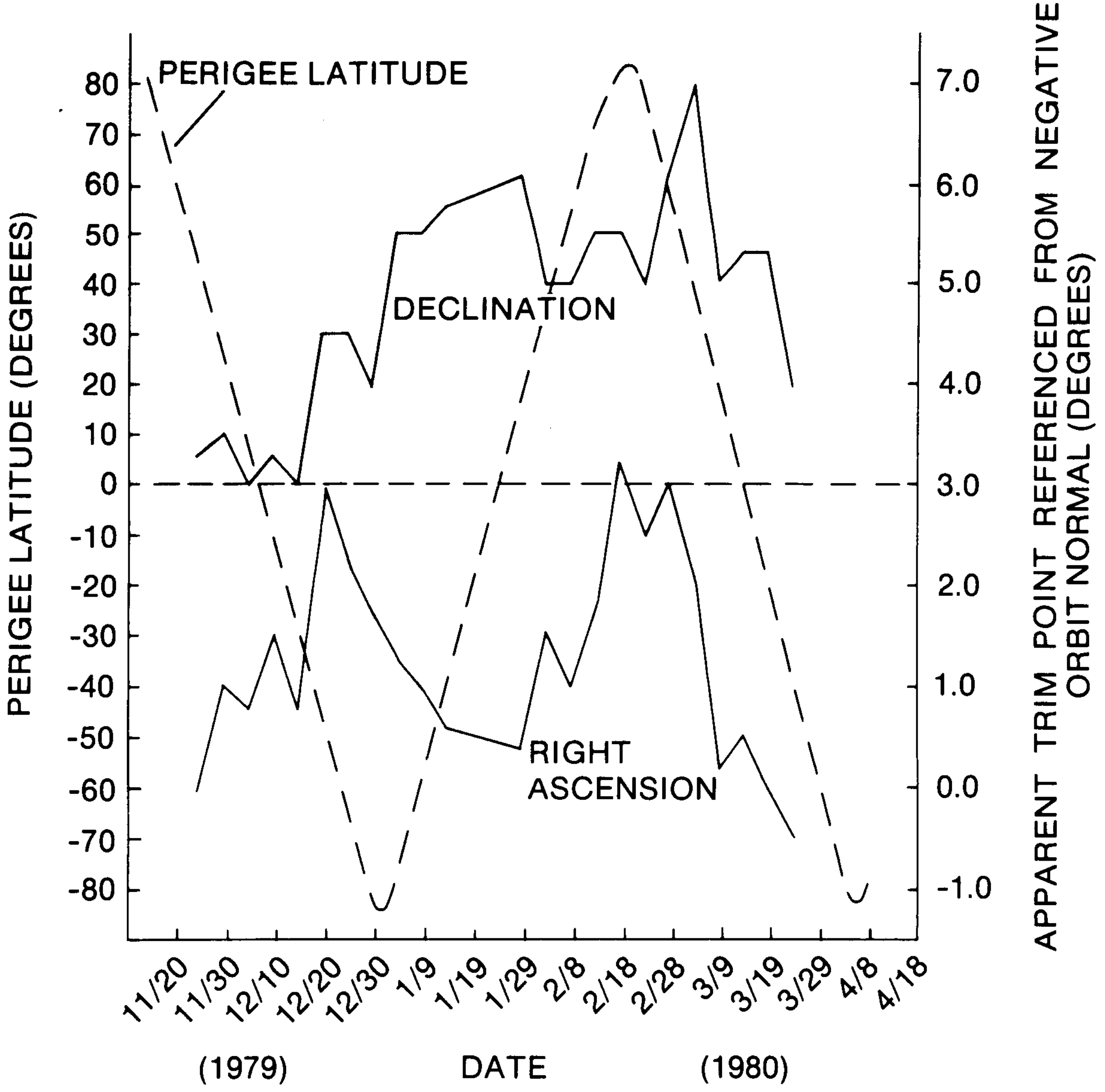


Figure 12.

Apparent Magsat Trim Point Determined From Definitive Data

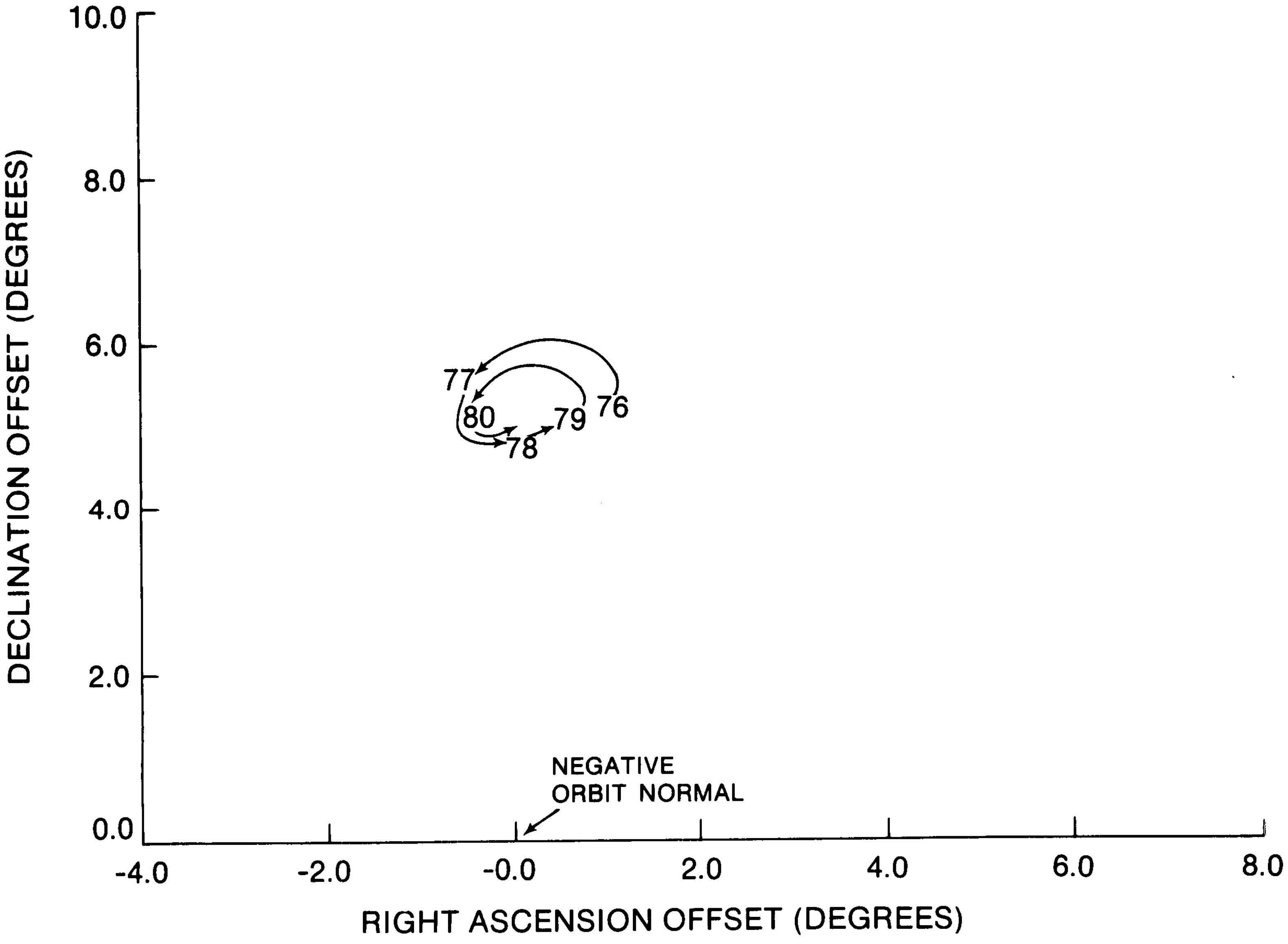


Figure 13.

Net Orbital Drift for Days 76-80 (March 16-20), 1980 it crossed the control threshold. Had the threshold been larger, the precession would have probably continued on the track pattern established. Figure 10 shows that two control torques would have been averted since coupling from the first (declination) torque necessitated a second (right ascension) torque. The main reason for not opening the threshold further was the 12° roll restriction with the IR horizon scanner had to be respected. It should also be kept in mind that real time data available during the mission could not supply analysts with the complete picture of the drift tracks which are now available from definitive data.

The importance of the aerodynamic trim boom cannot be minimized. In fact, the trim boom was a vital, if not essential tool for reducing drift. Sixteen boom operations were performed during the mission including 10 which took place following an initial 3-week period of trimming during Magsat's early mission phase. Boom operations have been marked on the histogram of control torques given in figure 8 so that the effectiveness of the trim boom can be clearly seen. Boom operations on November 20, 1979, and March 4, 1980, were followed by extended periods of nearly 3 weeks with low drift and no control coil activity. Perhaps the best example of what trim boom operations can accomplish can be seen in figure 14. Presented are drift tracks for 2 to 3 orbits on 4 days in late November 1979 with four different trim boom positions. Net orbital drift was significantly reduced.

Because of orbit eccentricity and variations in the spacecraft attitude, the yaw torque was always variable over the orbit regardless of the boom length. The general approach to trimming with the boom was to assume an imbalance in the yaw torque could be corrected only when the spacecraft was at perigee. Thus, when perigee was at either pole, boom extensions or retractions could be made to change yaw torque which would affect declination drift. Likewise, changes with perigee at the equator were made to reduce right ascension drift. While in practice the above approach proved adequate, the general lack of experience in working with a trim boom necessitated a certain degree of trial and error with this operation. Although a large degree of confidence was placed in the direction of boom change, the magnitude of these changes to affect an increase or decrease in yaw torque was always questionable. Typical changes in boom length were 25 cm. Some prelaunch analysis suggested that command sequences for extending or retracting the boom should be in 2 cm increments (reference 4).

Current postmission analysis is involved in a more detailed examination of the aerodynamic effects using definitive attitude data which is now available, and also critiquing drift control operations with the spacecraft's aerodynamic trim boom. Here, it is instructive to point out the nature of the drift patterns observed. Also, rather than take a theoretical approach to explaining how drift might be reduced, periods of relatively low drift can be examined with special attention to the trim boom configuration and target attitude which provided low drift. Two periods of low drift are summarized below. One period corresponds to a very stable drift period beginning around March 5 and lasting until March 27, 1980. During this period, perigee was located at or near the descending node. The second period covers the first week in January 1980 when perigee was at or near the

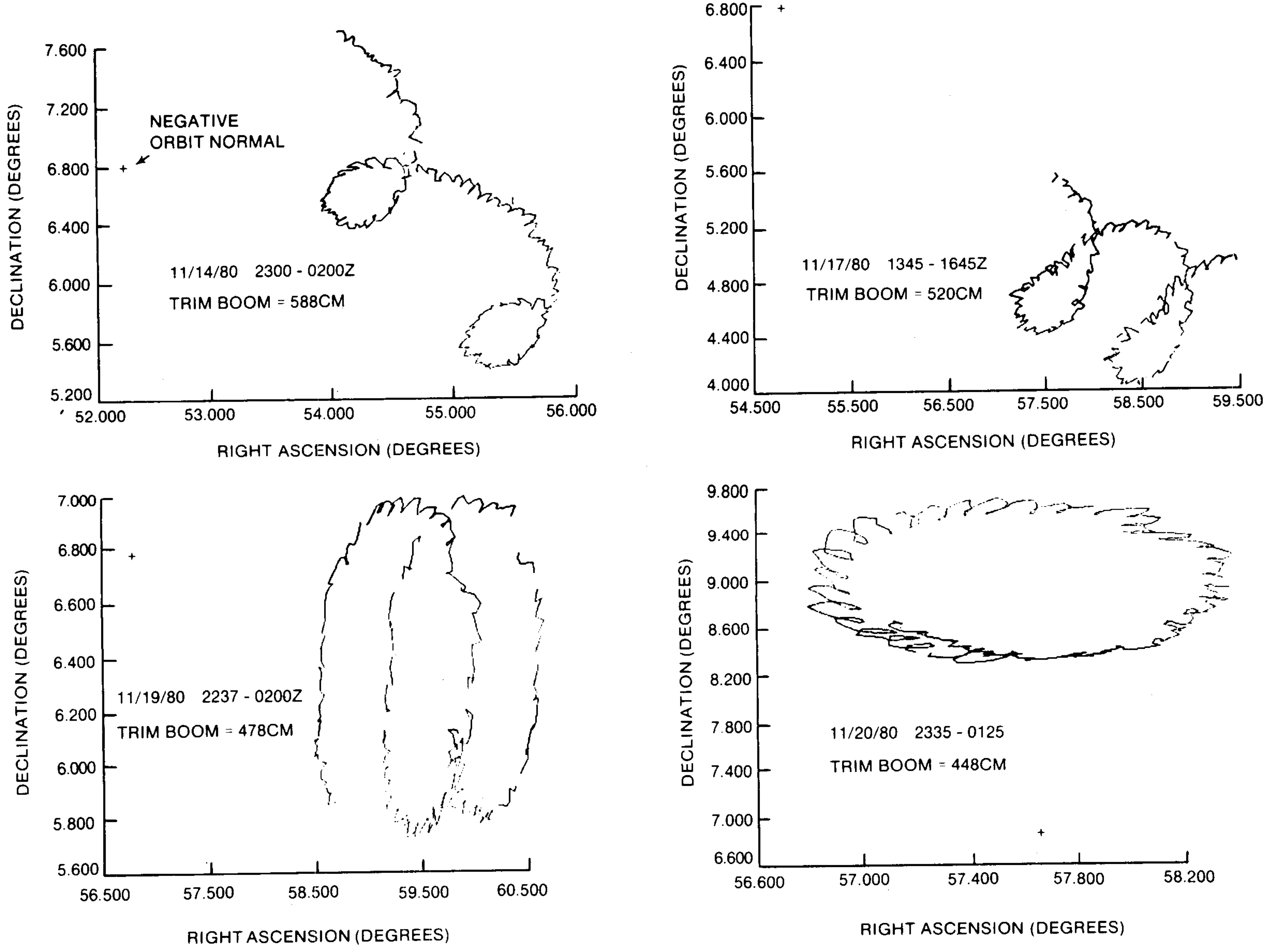


Figure 14.

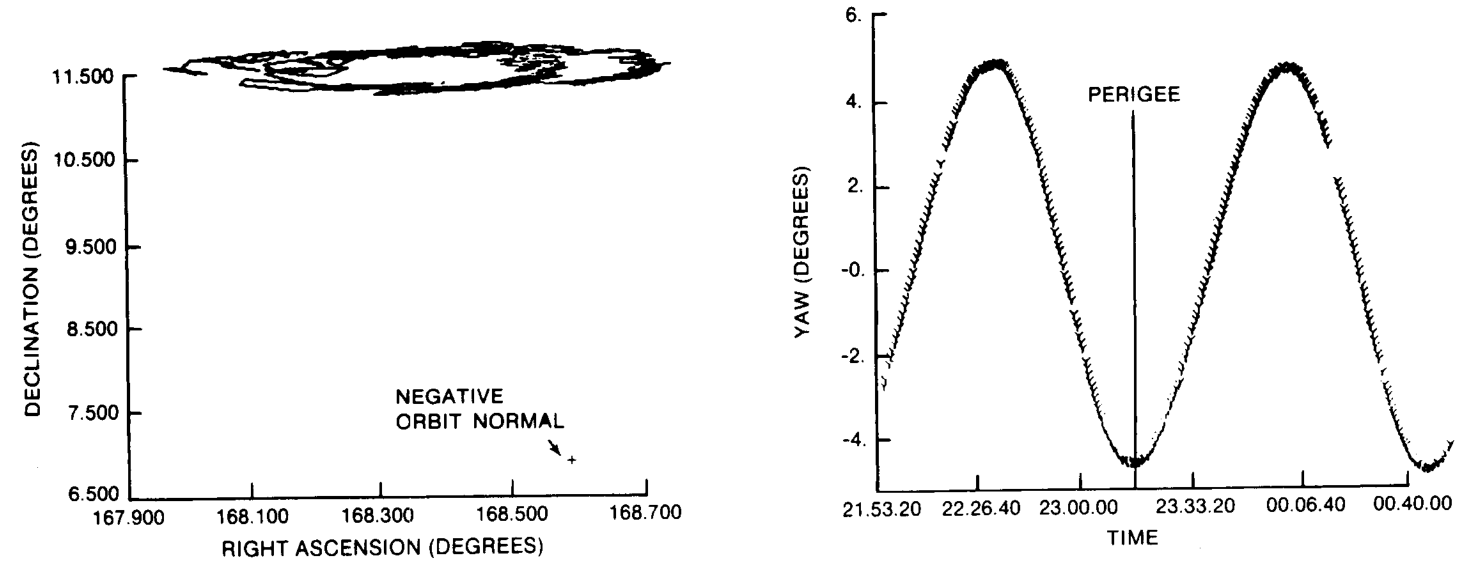
Orbital Drift for Four Trim Boom Lengths in November 1979

South Pole. Examination reveals the existence of different conditions for minimal drift as perigee altitude and location change.

The March period is interesting because it was a time during the mission with very low drift (less than 2^o net drift per day) and perigee located near the descending node. The trim boom was retracted 25 cm to 489 cm immediately preceding this period. Figure 15 shows right ascension, declination and yaw versus time for two Magsat orbits on March 17, 1980. Time of perigee crossing is also marked. Plots of these parameters for other orbits during this March period are nearly identical. The plots seem to contradict what was once advanced prelaunch as a possible drift control philosophy, namely to balance out yaw torques completely at perigee. Instead, as the right ascension plot in figure 15 shows, the spacecraft undergoes maximum drift due to yaw torque at perigee. Thus, what becomes important is not simply the balancing of drift at one point in the orbit, but to affect the drift at perigee in a way such that net orbital motion is reduced. Here, the high torques at perigee are adjusted to zero out the torque over the orbit. As can be seen in figure 15, the right ascension versus declination plot is a closed circle indicating little net orbital drift.

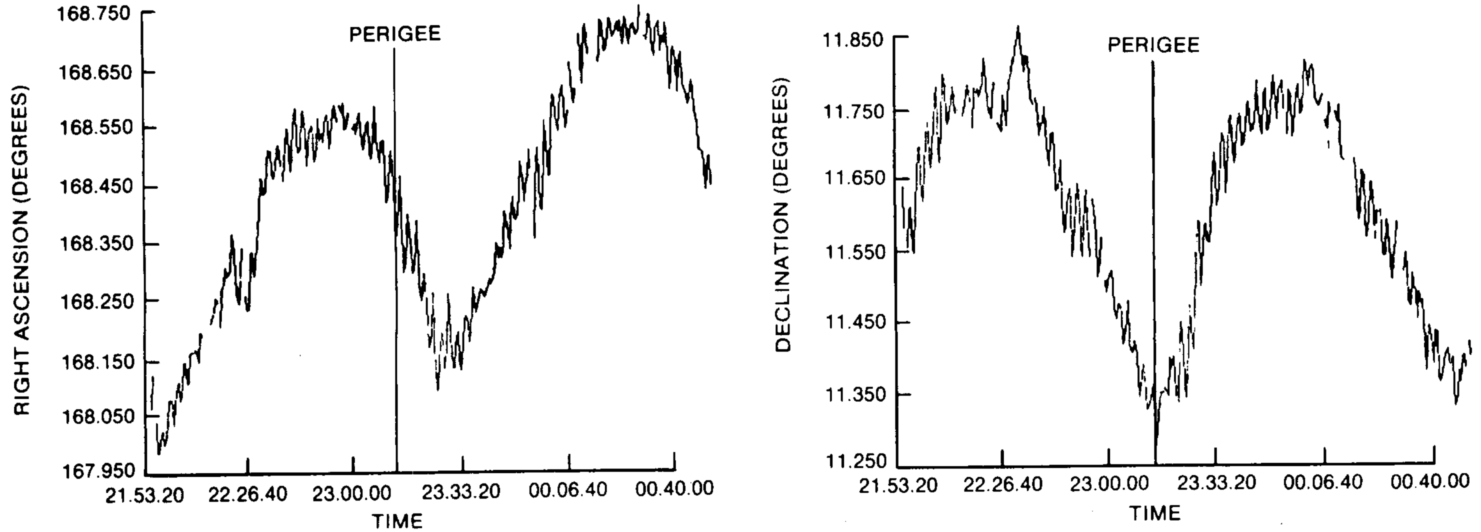
During this period, the Z axis precessed in a circle about a relatively stable trim point located 5^o above negative orbit normal with little right ascension offset. The diameter of this circle was less than 2^o and was traversed in approximately 4 days (figure 13). Note that since the trim point was located directly above negative orbit normal in declination that the maximum yaw angle was at perigee.

The second study case with representative plots given in figure 16 is taken from early January 1980. Although not as nice as the stable period in March, Magsat's drift during this January period was less than 3^o per day and was relatively free of control torques. The Z axis precessed about a trim point 5.5^o above negative orbit normal in declination with a period of 5 days and traced out a circle with diameter of 4^o. The trim boom length was 448 cm. Unlike the March period, perigee was near the South Pole during early January. With the trim point still above negative orbit normal in declination and only a small offset in right ascension, the yaw angle was not at its maximum value at perigee. Unlike the March period, there is drift in both right ascension and declination at perigee. Here, a balance in the yaw torque appears to occur near maximum yaw with both declination and right ascension drifts near minimum. The implication of this simple examination with perigee at the South Pole is that balancing the torque at maximum yaw is a valid, if not optimum control approach rather than balancing the torque at perigee. This perhaps shows the significance of torques due to high yaw angles near the nodes (where superrotation effects are largest) relative to torques at perigee when perigee is at a pole. Certainly this is a simplistic conclusion which will be examined in more detail. The eccentricity of the orbit, latitude of perigee, variation of aerodynamic effects with altitude and target placement (which will effect the phasing and magnitude of yaw) must be considered further.



R.A. VS. DECLINATION WITH N.O.N.

YAW VS. TIME



RIGHT ASCENSION VS. TIME

DECLINATION VS. TIME

Figure 15.

Orbital Drift for Two Orbits on March 27, 1980

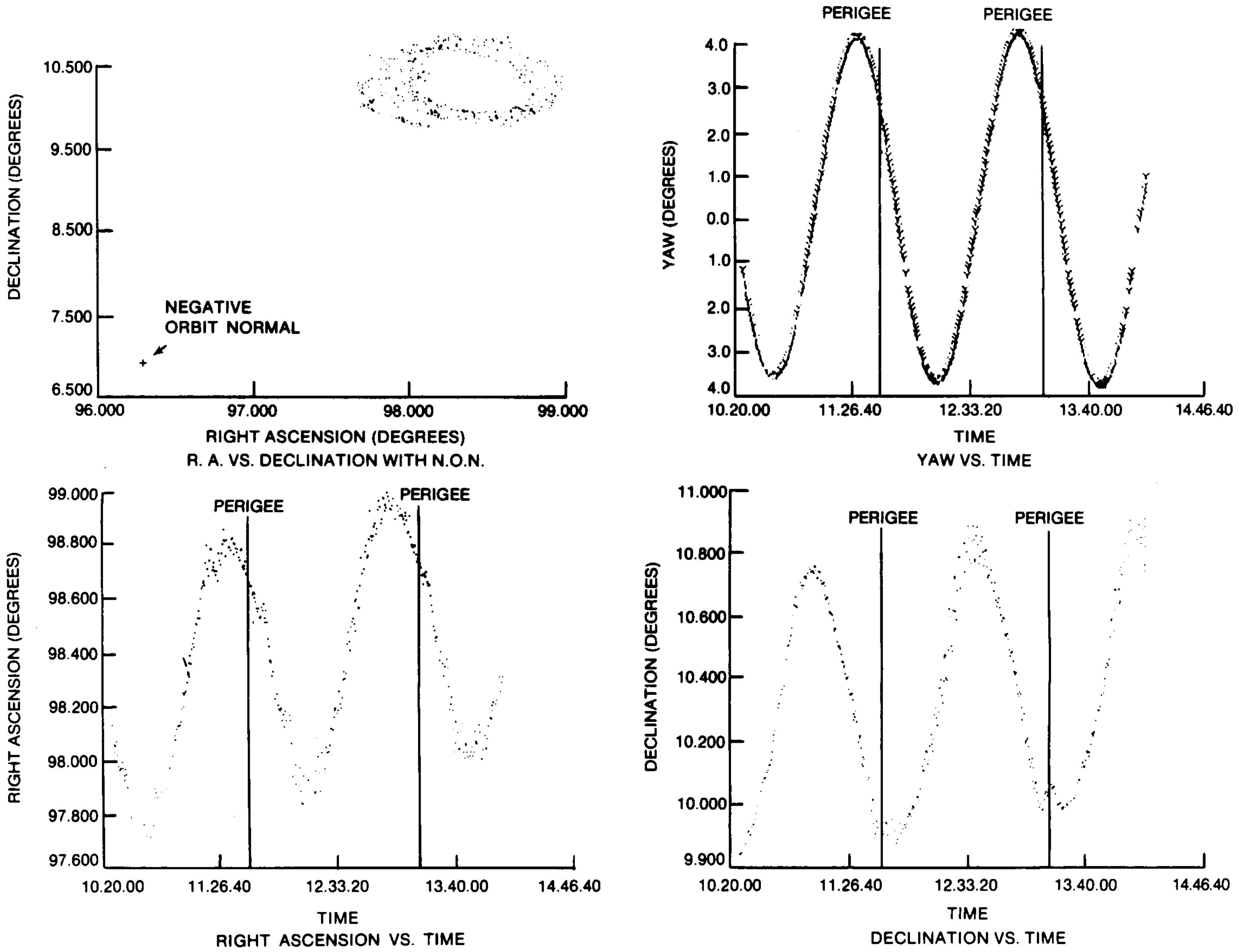


Figure 16.

Orbital Drift for Two Orbits on January 1, 1980

V. Closing Remarks

While analysis is continuing, some abstract conclusions can be drawn regarding the attitude control of Magsat. First, the ASP was essential for successful completion of the Magsat mission. Ground control, especially during the closing months of the mission, would have most likely been met with frustration and failure. Although drift was often low and manageable when the spacecraft was properly trimmed, this state was always achieved as a result of active adjustment of various ground supplied ASP parameters and the aerodynamic trim boom. In terms of performance, the ASP successfully satisfied all onboard control requirements. During times of high drift activity, the ASP displayed its effectiveness by maintaining Magsat within its prescribed control bounds. Ground control would not have been able to respond in time to violations of these control bounds. The importance of active ground monitoring of spacecraft attitude health and safety has been shown. The effectiveness of the ASP must be attributed, in part, to successful ground support.

Any optimum control philosophy for Magsat must be complex. The effects of boom length and perigee location on the spacecraft's trim point are not fully understood. At least two sets of conditions may exist for minimizing drift. Studies of the uniqueness and stability of the trim point are currently underway.

References

1. Applied Physics Laboratory, Johns Hopkins University, SDO 5146, "Magsat Spacecraft Description", March 1979.

2. Applied Physics Laboratory, Johns Hopkins University, BCE-T-0781, "Final Description of the Magsat Attitude Signal Processor Microcomputer Subsystem Command and Telemetry Words", T. Zaremba and D. Klein, revised September 1979.

3. Computer Sciences Corporation, CSC/SD-78/6077UD1, "MAPS/Magsat Attitude System Functional Specifications and Requirements Appendixes B and C - Attitude Signal Processor Ground Support Software (MAGSAP)", July 1979.

4. Applied Physics Laboratory, Johns Hopkins University, S4A-2-123, "Magsat Postlaunch Aerotrim Boom Length, Declination Bias and Pitch Bias Angle Selection Algorithms", B. Tossman, August 15, 1979.

5. Applied Physics Laboratory, Johns Hopkins University, S4A-2-060, "Magsat Z-Axis Stabilization in the Presence of Atmospheric Rotation", B. Tossman, March 23, 1975