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ATTITUDE DETERMINATION USING DIGITAL EARTH PICTURES

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We at Computer Sciences Corporation have developed a computer program called PICATT, which stands for picture attitude determination. This paper describes the particular satellite to which this technique of attitude determination has been applied, describes the method of solution, and discusses the results that have been attained using the PICATT program.

The satellite to which we have applied the PICATT technique is the Applications Technology Satellite-3 (ATS-3), which has been operational since 1967. The mission characteristics of ATS-3 are as follows: It is in a geosynchronous, circular orbit, with very low eccentricity; currently the inclination is on the order of 5°. It is spin stabilized at approximately 100 rpm. The dominant torque on the spin axis is the solar radiation torque, which varies from 10 to 60 arc-seconds per day, depending upon the time of year.

Observable misalignments have developed between the ATS-3 principal axis of spin and the geometric axis of spin. This phenomenon was originally detected by Westinghouse Corporation, using a graphical technique for processing pictures. When Computer Sciences developed the PICATT program for ATS-3, we also detected the misalignments between the principal axes and the geometric axes. Due to the fact that there are misalignments between the principal and the geometric axes, there is a cross-coupling effect on the spin axis whenever an east-west stationkeeping maneuver is performed. ATS-3 is positioned at 70° west longitude, and east-west stationkeeping maneuvers are performed at approximately 3-month intervals; whenever one is performed, the attitude is perturbed.

The Soumi camera has a variable elevation that covers an approximately 18° field of view. At synchronous altitude, the earth subtends an angle of approximately 17.4°, and ATS-3 is able to view the entire earth when it is oriented properly. The elevation angle range covers 9° above the plane normal to the spin axis to 9° below the plane normal to the spin axis. The resolution of the camera, when it is pointing directly at the local vertical, or nadir, is approximately 3.7 km (2 n.m.). The spectral bandpass is 4720 Å to 6300 Å; hence, it is a visible system. The analog video signals are processed to form an image on a film, and the National Oceanic and Atmospheric Administration (NOAA) produces prints of the earth image. ATS-3 originally had the capability of taking a color photograph and was the first satellite to take a color photograph of the earth from synchronous altitude. Currently, the capability exists only for taking black-and-white, spin-scan, cloud-cover pictures. It is also possible to record the video signals onto a digital tape; these processed digital tapes are used for our attitude determination efforts.

The attitude control requirement for ATS-3 is to maintain the spin axis attitude to within 1° of orbit normal. More precisely, NOAA desires to take pictures of the earth 2.5 hours prior to high noon and 3.5 hours after high noon, for a total elapsed time of 6 hours, or one-quarter of an orbit. NOAA also wants to see 55° north latitude and above during this time interval.

As shown in figure 1, we use the standard celestial inertial coordinate frame, where the X_E axis points toward the vernal equinox and Z_E points toward the north celestial pole. Right ascension is measured in the conventional sense, counterclockwise from X_E. Declination is measured positive above the equatorial plane.

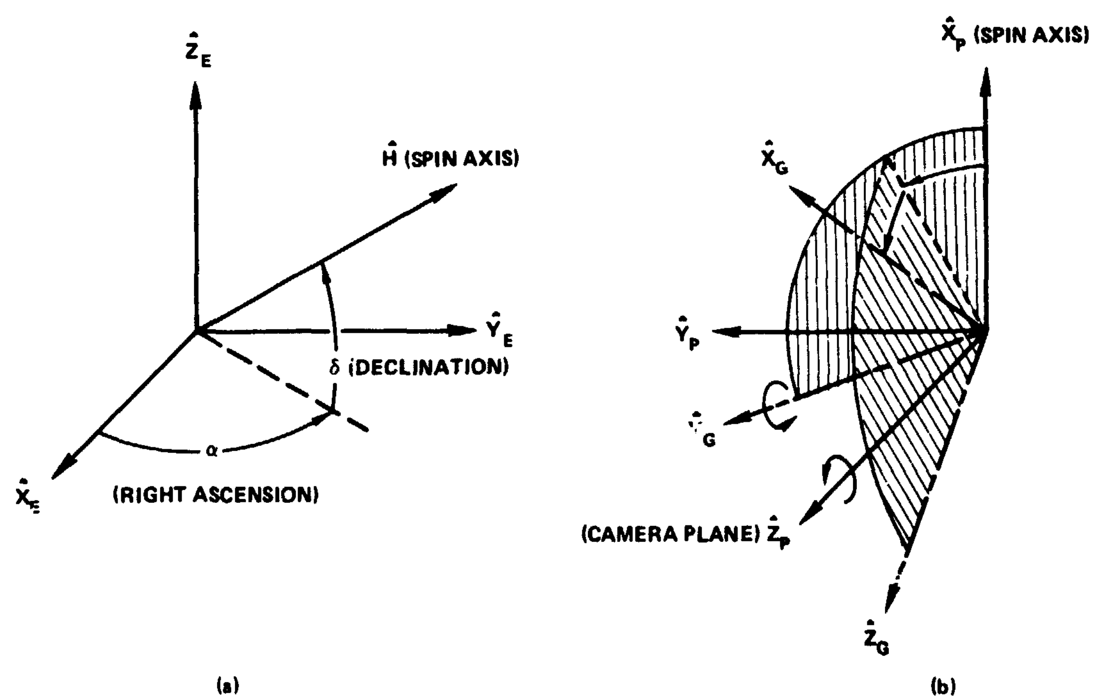

Figure 1. Coordinate systems. (a) Spin axis attitude angles; (b) principal and geometric axes.

As mentioned before, there are misalignments between the ATS-3 principal and geometric axes. These misalignments are described by two rotation angles: A geometric system is defined whereby the X geometric axis points along the symmetric axis of the spacecraft; the Z geometric axis points toward the plane of the camera on board ATS-3. We define the offset between the principal and geometric axes by first rotating around the Z principal axis through the angle ψ (which we call a skew misalignment angle) and then rotating about the Y geometric axis through the angle θ (which we describe as an offset misalignment angle).

As seen in figure 2, the reference pulse for ATS-3 is provided by the sun. Given the orbital and the spin axis characteristics, there is an angle, β, between the sun reference and the local vertical vector. This angle β and the time rate of change, $\dot{\beta}$, are precomputed and stored on the ground in the processing equipment. It should be remembered that the Soumi camera on ATS-3 is constantly on and scans the earth disk and the darkness of space as well. The digital processing occurs on the ground.

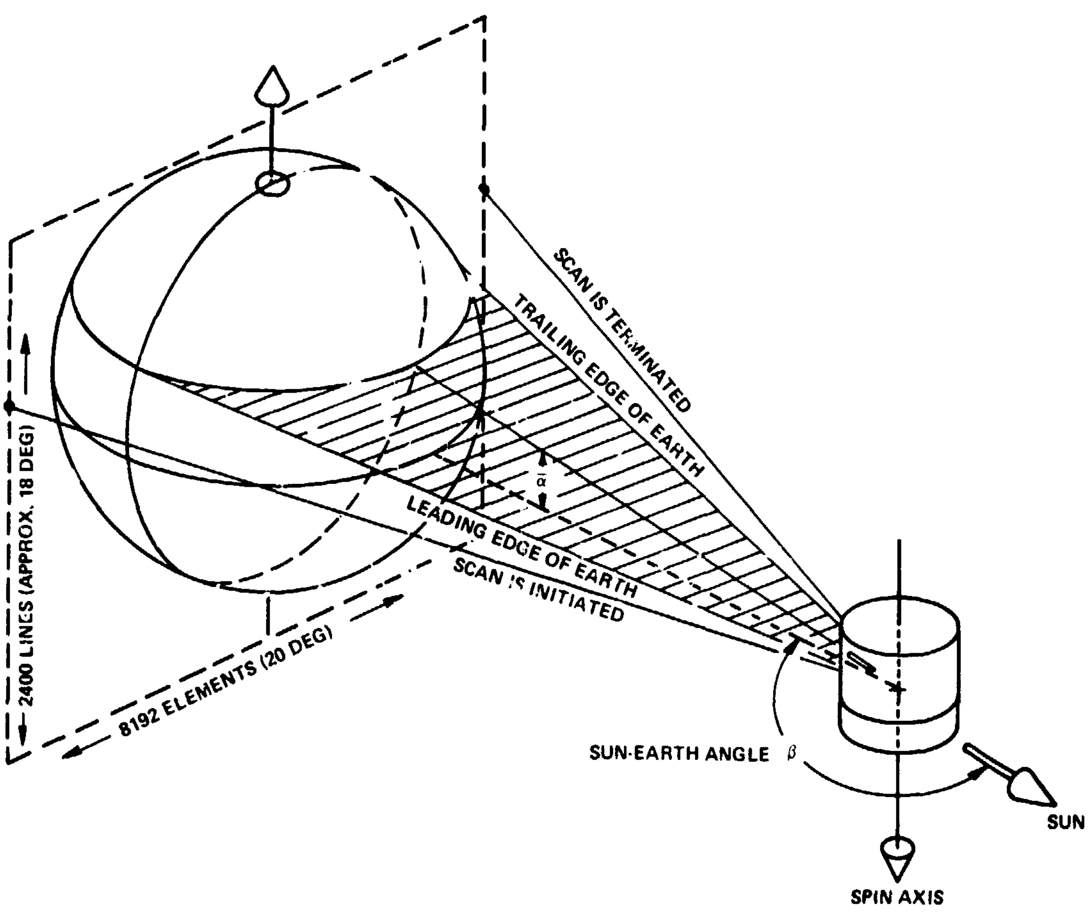

Figure 2. Camera scan geometry

Again referring to figure 2, the camera steps from 9° above the plane normal of the spin axis to 9° below the plane normal to the spin axis. For a typical elevation angle, $\bar{\alpha}$, the

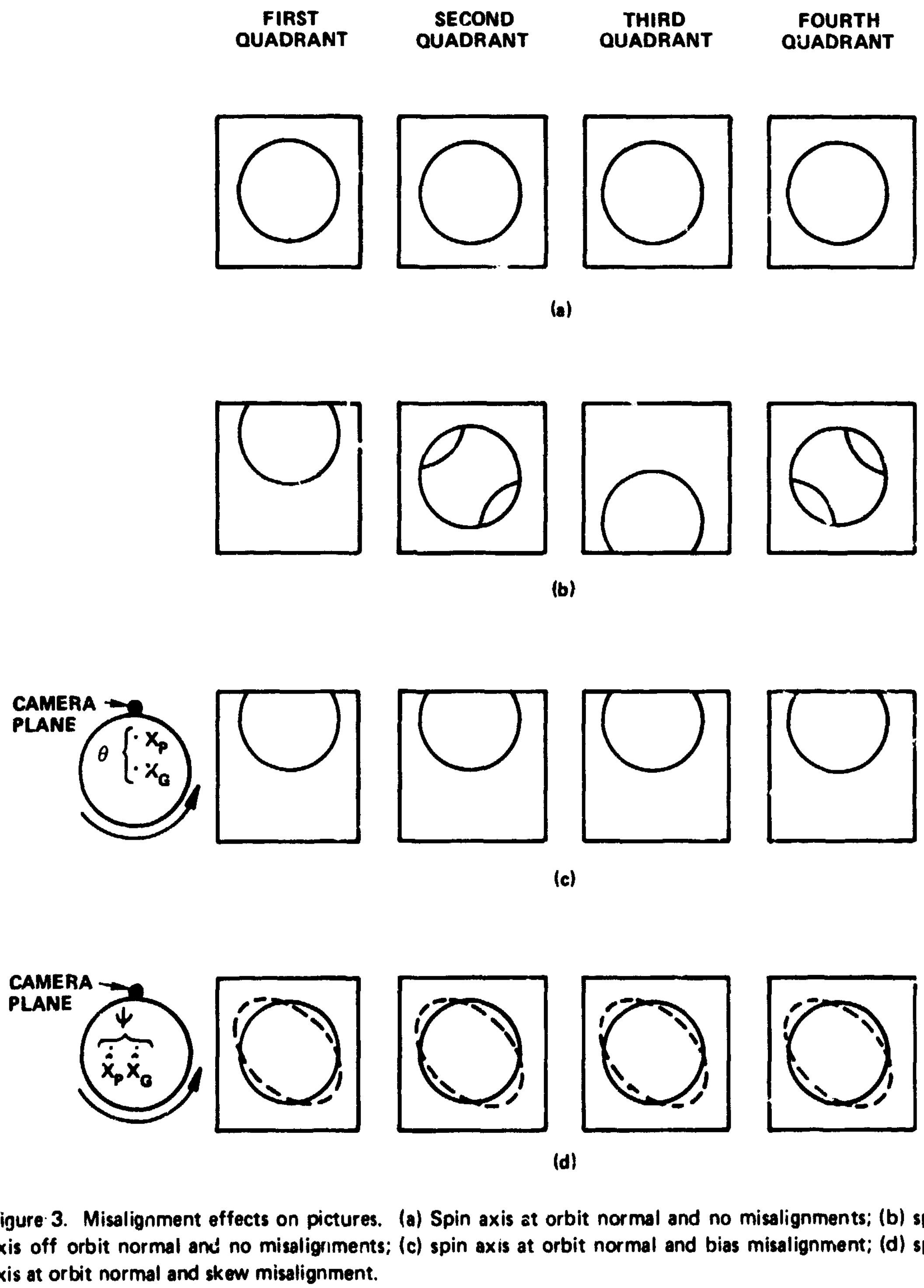

Figure 3. Misalignment effects on pictures. (a) Spin axis at orbit normal and no misalignments; (b) spin axis off orbit normal and no misalignments; (c) spin axis at orbit normal and bias misalignment; (d) spin axis at orbit normal and skew misalignment.

ground equipment initiates recording at a point which is a function of the precomputed angle, β, and the angular rate of change, $\dot{\beta}$. During the scan, the leading edge of the earth is observed as well as the entire earth disk. At the point where the trailing edge of the earth is observed, the scan is terminated. The spacecraft then rotates, the camera is stepped to the next discrete elevation angle, and the process is repeated.

The result is a matrix consisting of 2400 scan lines (corresponding to the 18° field of view) and 8192 samples per scan line (the analog signal is sampled 8192 times over the duration of the recording). The recording is synchronized with the spin rate such that a 20° scan is obtained. The matrix is searched by a preprocessor program called EDGE, and EDGE extracts either the leading edge of the earth or the trailing edge of the earth, depending upon which is the most sharply defined. Prior to high noon, we process the right earth edge. After high noon, we process the left earth edge. (Since this is a visible system, only one edge per picture is processed.)

The effects of spin axis orientation and misalignments are illustrated in figure 3 with four limiting cases. Case a depicts a purely circular synchronous orbit with the spin axis at orbit normal and no misalignments present between the principal and the geometric axes. In this particular case, we would see a perfectly centered earth throughout four points in the orbit, each separated by 90°. The effects of terminators are not illustrated in the figure. With a visible system, terminators would be present within these four pictures.

If no misalignments are present but the spin axis is perturbed off orbit normal (case b), the top of the earth would be cropped at one point in the orbit. The bottom of the earth would be cropped one half orbit later. One quarter and three quarters of an orbit later, the earth would be centered perfectly in the picture.

In case c, an orbit-normal attitude is represented, and a bias misalignment, θ, is present. It should be noted that if the total misalignment angle between the geometric axis of spin and the principal axis of spin is a biased misalignment, then the camera plane, the X-principal axis, and the X-geometric axis are all coplanar. With this particular geometry throughout the orbit, a constant cropping of either the north or the south of the earth within the frame would occur.

Finally, with case (d), an orbit normal attitude is represented, and the total misalignment angle is the skew misalignment angle ψ. In this case, there is a stretching of the earth, a distortion, because the angle β is computed by assuming that there are no skew misalignments. If there is a skew misalignment, recording will be sooner than desired at the top of the picture and later than desired at the bottom of the picture.

In general, the spin axis is not at orbit normal, and misalignments are present. The objective is to use the orbital information and then estimate the spin axis attitude angles as well as the misalignment angles ψ and θ.

The basic problem of estimation in PICATT can be outlined as follows:

PICATT Estimation Problem

Constants C

Ω	=	Right ascension of ascending node
$\bar{\omega}$	=	Argument of perigee
M	=	Mean anomaly
i	=	Inclination
$\bar{\alpha}$	=	Camera elevation angle
ϵ	=	Earth optical radius
τ	=	Spin period

State variables X

$\alpha, \delta, \psi, \theta$

Measurement Y

ω = Sweep angle from initiation of recording to earth edge

The standard orbital parameters are known constants. The semimajor axis and eccentricity are not included. PICATT actually does account for the complete orbital state in the mathematical model. At synchronous attitude, with a very low eccentricity, there is only second-order effect from those two parameters. We use the argument of perigee and the mean anomaly to describe the intrack position. In addition to intrack position, the inclination is also required to define the orientation of the local vertical relative to the spin axis. The camera elevation angle is also assumed to be exactly known, as is the earth optical radius (the angular width of the earth as viewed from synchronous altitude, approximately 17.4°) and the spin period (needed to convert the 8192 discrete digital counts to a sweep angle). These known parameters—the orbital information, camera elevation angle, earth optical radius, and spin period—are all assumed to be known with zero uncertainty.

A four-parameter state variable array includes the right ascension (α), declination (δ), the skew misalignment angle (ψ), and the bias misalignment angle (θ). The precession of the spacecraft due to solar radiation torque is ignored because picture information is obtained over only a quarter of an orbit. In other words, 6 hours of information, rather than 24 hours, is obtained. Over the computational period in which the pictures are taken, it is assumed that α and δ are inertially fixed.

Finally, the measurement Y is the sweep angle from the initiation of the recording to the detection of either the leading edge or the trailing edge of the earth. This measurement is obtained by converting the edge counts to an angle of sweep, using the spin period, τ.

PICATT uses the weighted least-squares batch filter with memory and requires knowledge of the Bayes matrix, Λ_0^{-1} (the inverse covariance matrix of error and the initial state estimate):

$$\hat{x}_{i+1} = (A_i^T W^{-1} A_i + \Lambda_0^{-1})^{-1} [A_i^T W^{-1} y_i + \Lambda_0^{-1} \bar{x}_i]$$

where

x_i = $X - \hat{X}_i$

$\bar{x}_i$ = $X_0 - \hat{X}_i$

y_i = $Y - f(\hat{X}_i, C)$

A_i = $(\partial f/\partial X)_i$

W^{-1} = Weighting matrix

Λ_0^{-1} = Bayes matrix

The x_i is the residual between the unknown true state and a current best estimate of the state; $\bar{x}_i$ is the residual between the initial state estimate and the current best estimate of the state; y_i is the residual between the measured sweep angle Y and the predicted sweep angle, which is a function of our current best estimate of state as well as the known constants. The A matrix is the matrix of partial derivatives of the observation equation, and W is the weighting matrix. In PICATT, the data are weighted as a function of the computed standard deviation of the residuals between the measured and observed sweep angles.

How well does PICATT work? Prior to the development of the PICATT program, the operational attitude determination program for ATS-3 was the ATBAY program, which used sun sensor information and polarization angle measurements (POLANG). The problem with ATBAY was the POLANG. Real-time Faraday rotation measurements normally were not available. In addition, the stations tended to have biases that could not be estimated. It was felt that this was no better than a 1° accuracy system.

Prior to the development of the PICATT program, we would perform an attitude maneuver on ATS-3 at approximately 2-month intervals. That was a very inefficient procedure as far as performing attitude maneuvers—trying to erect the spin axis to orbit normal and then finding out that the spin axis actually precessed in some other direction. As a result, we were maneuvering approximately every 2 months. With the advent of the PICATT program, the requirements for maneuvering ATS-3 have been reduced to a frequency on the order of one maneuver every 8 months. Because of the increased accuracy of PICATT, the efficiency has been significantly improved as far as the attitude control.

The following is a comparison between the ATBAY program and PICATT, for the time period covering August 1970 to December 1971. During this time, we were not receiving pictures on a weekly basis as we are now, so we did not have a large volume of PICATT solutions. Normally, the ATBAY solutions were computed out of phase. For this statistical study, we selected spin axis attitude estimates at points that are separated by no more than 1 or 2 days between ATBAY and PICATT. With this ground rule, there were 11 samples. The residuals are the differences between ATBAY and PICATT. It is assumed that PICATT is correct. Listed below are the mean (μ) and the standard (δ) deviations for these 11 samples:

	μ	δ
Right ascension	0.512	13.486
Declination	−0.195	0.225
Pointing error	0.496	0.302

The most important characteristic is the pointing error. With this statistic, the mean is almost 0.5° with a standard deviation of 0.3; 8°. The sum of the mean and standard deviation approach the 1° total error in the sun sensor/polarization angle method of attitude solution.

This is a relative comparison: To find out the actual operational results on ATS-3, an intermediate computational program called the latitude scan program is used. This program takes the orbital information, the attitude and bias state estimate (α and δ as well as the misalignment angles ψ and θ), and predicts the latitude that will be scanned in the center of the picture as a function of time of day.

The first scale on figure 4 represents right ascension, which ranges from 0° to 360°. Time of day can be related to right ascension in inertial space, since the earth is moving 360° in one day. Likewise, local high noon as a function of time of year can be correlated as a function of right ascension. The solid line indicates a prediction for observing the maximum north latitude scanned on the pictures as a function of time, using the PICATT state estimate and the orbit parameters. The portion that is fairly flat indicates that the camera is scanning over the top of the earth. The sharply curved portions indicate that the camera is scanning into the earth disk. The triangles represent latitudes which have been read off gridded weather pictures. It should be remembered that not only do we get the digital pictures, but we can also obtain a corresponding print by processing the video signals from the camera.

It is seen that, the farther the spin axis is located from orbit normal, the more the scan cuts into the earth. At the point that the scan starts cutting into the earth, seeing lower and lower, and approaching the 55° north latitude limit, the better observability we have as far as the correctness of the PICATT solution is concerned. From the figure, it is seen that we are predicting very accurately where the cutoff occurs between the point where we scan over the top of the earth and the point where we start cutting into the center of the earth. Normally, we find that right ascension is the most difficult parameter to define; we usually detect a bad solution by finding a horizontal shift in the prediction. We generally get fairly good agreement on the vertical scale or latitude.

It has been indicated previously that cross-coupling of attitude perturbations with the east-west stationkeeping maneuvers occurs. The last stationkeeping maneuver was performed December 5, 1973. Figure 5 presents the ATS-3 state since then. There is a general trend in right ascension and declination with some scatter. There is even more scatter in the total

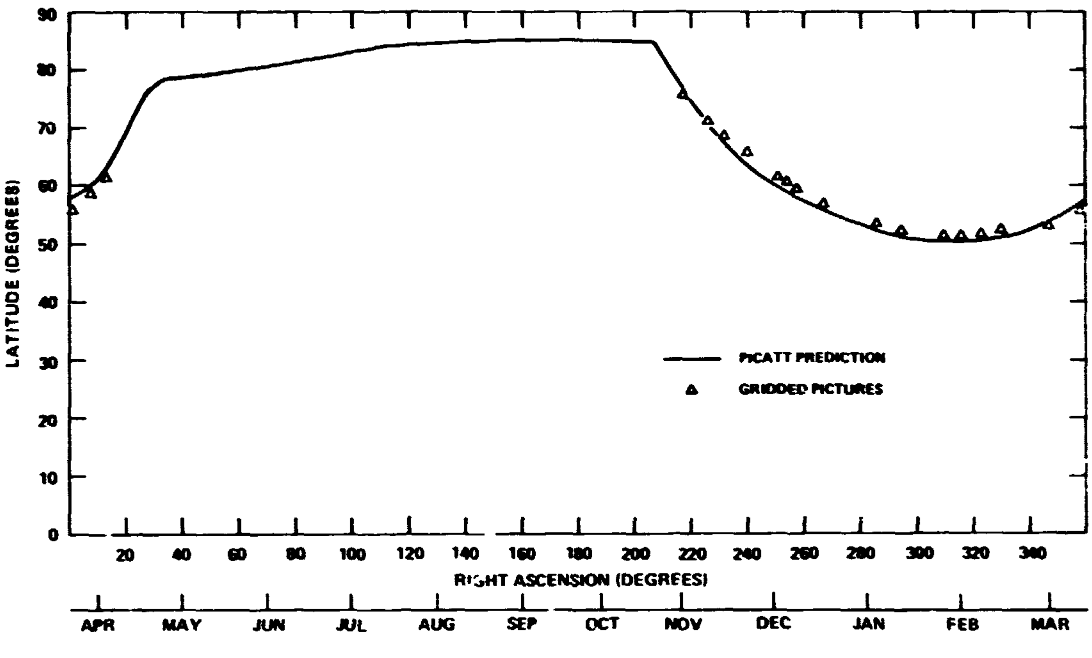

Figure 4. Typical latitude scan plot.

misalignment angle, as seen in figure 6 (total misalignment angle being the included angle between the geometric axis of spin and the principal axis of spin). The problem illustrated is traceable to the fact that we get only a quarter orbit of information, and the spin axis is fairly close to orbit normal. Being close to orbit normal, the PICATT program has difficulty relating the bias misalignment angle, θ, to the declination state, δ. There is a trade-off between θ, which is the primary contributor toward the total misalignment angle, and the declination, δ.

We currently are obtaining erratic results, this would improve if we were to have information over a full orbit. Of course, being a visible camera system, we cannot get that information over a full orbit. Included in figure 6 is a statistical study on the misalignment information. We are predicting a mean misalignment of 0.348° with a standard deviation of 0.112° and a total misalignment angle on the order of 0.5°, although earlier in the development of the PICATT program, it appeared that the misalignment angle was on the order of 1°. Every time an east-west stationkeeping maneuver is performed, more fuel is used and the misalignments change.

The PICATT program has been extremely successful, as far as maintaining the attitude on ATS-3 within the given requirements. I think that the program has more capability if it can be used on a satellite that has digital earth pictures over a complete orbit. This is possible with the Synchronous Meteorological Satellite-A (SMS-A), launched May 16, 1974, which has an infrared capability and takes pictures over the complete orbit. We expect SMS to get much more consistent estimates of the misalignment angles as well as the attitude angles, α and δ.

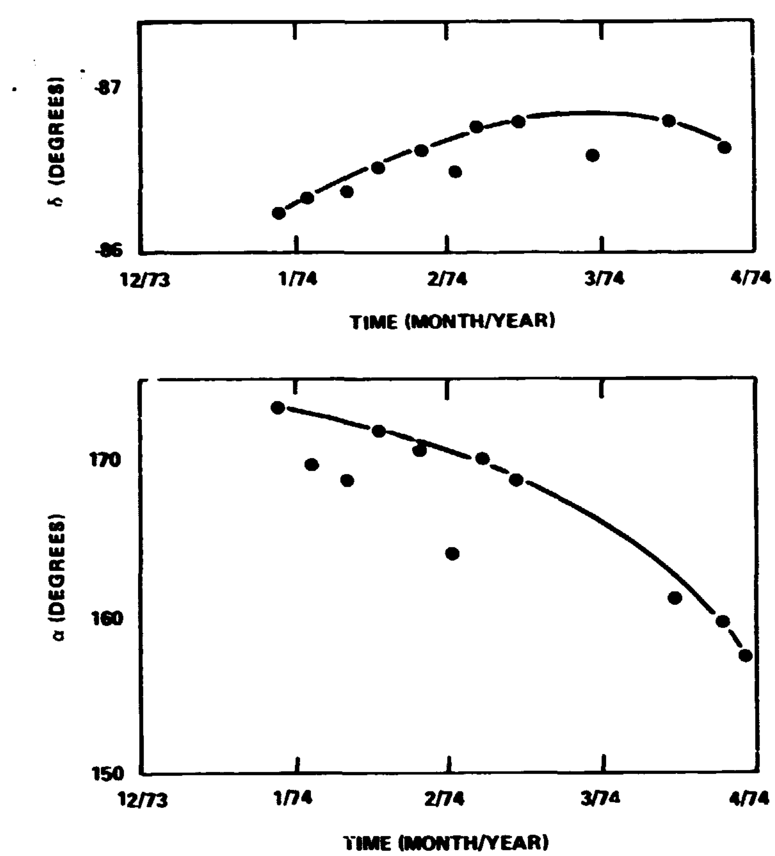

Figure 5. ATS-3 attitude time-history following December 5, 1973, stationkeeping maneuver.

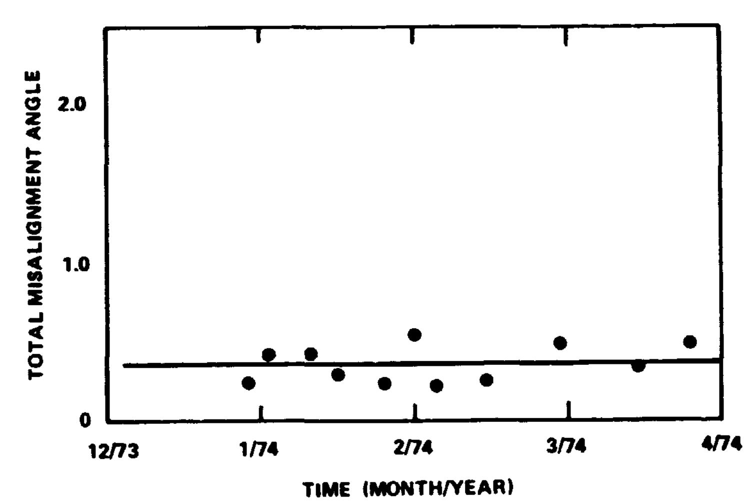

Figure 6. ATS-3 Misalignment time-history following December 5, 1973, stationkeeping maneuver. (Misalignment angle statistics: μ = 0.348°, σ = 0.112°.)