Effect of Orbital Inclination and Spin Axis Attitude on Wind Estimates From Photographs by Geosynchronous Satellites

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WASHINGTON, D.C.
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EFFECT OF ORBITAL INCLINATION AND SPIN AXIS ATTITUDE ON WIND ESTIMATES FROM PHOTOGRAPHS BY GEOSYNCHRONOUS SATELLITES

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ABSTRACT. Quantitative evidence demonstrates the serious effect of inclination and spin axis attitude on the accuracy of cloud vectors derived from the animation of pictures photographed by geosynchronous satellites. Orbital inclination causes the subpoint to move, while certain orientations of the spin axis cause the camera to change its orientation relative to the earth. Errors in the apparent cloud vectors due to subpoint motion are generally somewhat more serious than those due to changing camera orientation. In fact, effects of camera orientation can virtually be eliminated by maintaining the spin axis of the satellite normal to the orbital plane. On the other hand, orbital inclination, which is uncontrolled in existing geosynchronous satellites, steadily worsens with time; consequently, the errors of subpoint motion often approach the magnitude of the cloud vectors. In the future they will often exceed the magnitude of the cloud motions.

INTRODUCTION

Throughout the lifetimes of the Applications Technology Satellites, ATS 1 and ATS 3, the quality of picture animation has steadily deteriorated. Overall registration of successive images to each other has been impossible to achieve because distances between landmarks vary from picture to picture. As a consequence, land features as well as clouds are moving about in the animation. This distortion is steadily worsening so that registration is increasingly ineffective.

Since good registration cannot be achieved everywhere over the image, the quality of cloud motions or vectors as wind estimates is also impaired. In previous studies (Serebreny, Wiegman, and Hadfield 1970; Serebreny, Hadfield, Trudeau, and Wiegman 1969; and Hubert and Whitney 1971), comparisons of cloud vectors with nearby rawinsonde wind measurements showed that one was only a mediocre representation of the other. Although many diverse factors (Hubert and Whitney, 1971) affect this relationship, errors of measurement, such as imperfect registration, are among the most important. In hopes of improving the effectiveness of cloud motion vectors as wind estimates, a study was
undertaken to evaluate these errors of distortion and to develop a system for correcting them. It is the purpose of this paper to discuss the causes and to demonstrate the severity of the errors.

CAUSES OF DISTORTION

Two primary causes for relative distortion between pictures are subpoint motion and changing camera orientation relative to the subpoint.

Subpoint Motion (Orbital Inclination)

Geostationary satellites are truly stationary relative to the earth only when the orbit is circular, when the orbital period equals the rotation period of the earth, and when the orbital plane is in the equatorial plane of the earth. Once a geosynchronous orbit is obtained, circularity and period are easily maintained, but the orbital plane drifts slowly out of the equatorial plane. Because of the resulting orbital inclination to the equator, the satellite maintains only a quasi-stationary orbit. The subpoint oscillates meridionally about the equator (fig. 1). One complete oscillation takes 24 hours; the maximum excursions north and south of the equator reach latitudes equal to the inclination of the orbit. Since launch, the orbital inclinations of ATS 1 and ATS 3 have slowly increased, causing the subpoint to make correspondingly larger meridional oscillations about the equator. With subpoint motion, changing image perspective causes distortion changes between successive pictures of a sequence. Subpoint position is a sinusoidal function (appendix A) of time or mean anomaly (position of the satellite in the orbit); the most rapid changes in position occur at equator crossing and the least rapid at maximum latitudinal excursion. Distortion changes are most pronounced when the satellite is in the vicinity of the equator and least pronounced when it is at either maximum latitudinal excursion. (See fig. 1.)

Changing Camera Orientation (Spin Axis Orientation)

Camera orientation relative to the subpoint is changed by pitching and yawing of the satellite spin axis relative to the earth. Pitch (Allied Research Associates 1967) occurs whenever the spin axis is other than normal to the orbital plane, i.e., whenever the camera axis is not directed at the subpoint (fig. 2). In figure 1, where the spin axis is normal to the orbit, the pitch is everywhere zero. Otherwise, pitch varies sinusoidally with the orbital position of the satellite, reaching extremes equal to the angle formed by the spin axis and the orbit normal (fig. 2). A more detailed treatment of pitch is given in appendix B.

1In the present ATS and the future Geostationary Operational Environmental Satellite (GOES), this drift goes uncontrolled because of limited gas reserves.

2At the end of 1971 and after 5 years in orbit, ATS 1 reached an inclination of 4°; after 4 years, ATS 3 reached an inclination of 2°.
Figure 1.--Schematic view of the earth and ATS orbital plane. The satellite is shown at: A) the southernmost excursion, B) the equator crossing at ascending node, and C) the northernmost excursion. Descending node occurs at 180° around the orbit from position B. The subpoint oscillates about the equator between latitudinal extremes 1 and 3 which equal the inclination, i. The spin axis (represented by the heavy arrows) has a fixed orientation relative to the orbit. In this case, it is normal to the orbit so that the axis of the scanning camera is always aimed directly at the subpoint (zero pitch). Yaw varies from a negative maximum at B to zero at A and C.

Since the spin scan cameras aboard the ATS series scan only one raster line across the face of the earth with each rotation of the satellite, the pictures are not instantaneous views but are composed line by line over a period of time. The pictures are made up of about 2,000 such lines. The satellites spin nominally at 100 rpm, thus a single picture is generated in approximately 20 min. If the spin-axis changes pitch during that 20-min interval, the camera changes its orientation relative to the subpoint. The effect is to either stretch or to compress the image as shown in figure 3a.
Figure 2.--This schematic is identical to figure 1 except that the spin axis (heavy arrow) everywhere forms the angle, $\phi_{\text{max}}$, with the orbit normal. However, relative to a tangent plane at the subpoint, the spin axis varies its pitch sinusoidally around the orbit, reaching extremes equal to $\phi_{\text{max}}$ at A and C and zero at B. The camera changes direction of view as the spin axis changes pitch. By NASA convention, pitch is positive at A and negative at C. The camera is always moving relative to its immediate subpoint (except momentarily at A and C). In this case yaw is everywhere zero because the spin axis does not change its orientation relative to the subpoint meridian.

Naturally, the rate of change of pitch varies from picture to picture. These variations in turn cause variations in stretching (appendix B), thus introducing relative distortion from one picture to the next.

Yaw occurs whenever the spin axis is not parallel to the earth axis. Yaw then describes the rotation of the camera about its axis, relative to the subpoint meridian. In figure 1, it varies as a sinusoidal function of orbital position of the satellite, reaching extremes equal to the angle between the earth axis and the spin axis.

When a change occurs in yaw during the generation of a picture, distortion is produced. Successive scan lines swept across the earth form angles to each other as shown in figure 3b. The result is that
Figure 3a.—Schematic showing how an image may be compressed by a change in the pitch component of the spin axis during picture generation. The initial scan represents the first sweep across the earth when the satellite axis is in position I. If, at some time later (approximately 20 minutes for ATS), the spin axis has changed its position relative to the subpoint to position F as it scans the last line of the image, then the image will be composed of fewer scan lines than if the spin axis remained at position I throughout the picture generation. In other words, the apparent angle subtended by the earth will be smaller than if the spin axis had remained in position I. The apparent angle is reduced from the actual by the angle, $\Delta \phi$, between orientations I and F. If the spin axis pitches in the opposite direction during the scan interval, the image is stretched.

Figure 3b.—Schematic showing how an image may be twisted by a change in the yaw component of the spin axis during picture generation. The initial scan line is swept across the earth when the spin axis is in position I. If the spin axis changes to position F as it scans the last line of the image, then the last line will be at angle $\Delta \psi$, to the initial scan.

distances between scan lines on one side of the image are farther apart than the other. Since the rate of change of yaw also varies from picture to picture, relative distortion is produced.
Relative distortion, not absolute distortion, is the cause of errors in cloud vectors derived from the animated sequences. Fortunately, when orbital parameters and spin axis attitude are known, effects of both subpoint motion and camera motion can be described quantitatively. A computer program developed in the National Environmental Satellite Service (Doolittle 1969) permits generation of an accurate grid that contains the picture distortions resulting from the geometry of the system.

Availability of this gridding program suggested a procedure for obtaining the error accumulated during the sequence. The procedure has since been programmed, and it was used to derive the error fields presented in this report. Simply, the idea is as follows:

1. From orbital and altitude data, generate two grids representative of the first and last pictures of an animated sequence.

2. In the computer, simulate a registration of the first and last grids exactly like that used in the animated sequence.

3. Determine a difference field (error field) between grids at prescribed earth locations.

A number of registration procedures were tried, including best fits of two or more landmarks. It soon became clear that opinions of individuals differed as to what was a best fit of more than two landmarks, even when identical landmarks were used; therefore, simulation of picture registration in the computer was somewhat arbitrary and inaccurate. Finally, a system of using only two landmark points was adopted. This system prescribed superimposing all pictures on a primary point and then aligning them on a secondary point (fig. 4). Any two landmarks may be used but the same pair must be used throughout a sequence. Such a system not only simplifies the registration and causes less variation among individuals, but, equally important, it permits an easy and accurate simulation of grid registration in the computer. The result is a more accurate error field than given by any other procedures tried.

**ERROR FIELDS**

Subpoint motion and changing camera orientation can be examined separately, permitting examination of the individual error fields under various conditions. In reality, both error sources act simultaneously but in varying degrees of severity and either together or in opposition. This paper examines the effects of these error sources separately and in combination. Later, the effects of variations in registration are shown.
Figure 4.--Graphical simulation of grid registration performed by the computer. Two grids, one generated for a subpoint south of the equator (solid line) and the other for a subpoint north of the equator, represent the first and last pictures of an animated sequence of ATS pictures. In this case the grids are fitted on a primary point in Baja and aligned on a secondary point in Hawaii. The difference in position of like grid coordinates represents the vector error field that is subtracted from the observed cloud motions to obtain the actual cloud vectors.
Typical quasi-geosynchronous orbits are selected for all the examples presented herein. In most of the examples, orbital inclination is 2.5° meaning that the satellite subpoint migrates only 150 n. mi. to the north and south of the equator during a 24-hour period. In two cases orbits of 4° and 7° inclination are used to illustrate effects of different inclinations. In all cases a time interval of 2 hr 46 min is assumed for the animated sequence--an interval within the typical range of 2 to 3 hr. All error fields depict the changes in grids during this time interval as errors of direction and speed on the earth. These error vectors then represent the correction that must be applied (by vector subtraction) to the apparent cloud vectors derived from the animated sequence.

**Error Fields Due to Subpoint Motion**

Figure 5 shows a Mercator mapping of the worst error of subpoint motion that can occur with an inclination of 2.5°. Maximum effect of subpoint motion occurs whenever the satellite is in the vicinity of the equator because the subpoint changes most rapidly there. Note that since the registration is done by fitting on a point in Baja and aligning on a point in Hawaii, errors are smallest in the vicinity of these locations. Errors are as large as 30 kt within the useful portion of the image--the area within the ellipse. This ellipse is somewhat arbitrarily defined as the portion of the image within about 80 percent of the total radius of the image. The error vectors generally diverge from and rotate clockwise about the line of registration. Outside the 80-percent circle a large northerly component is observed in nearly all cases.

Because the satellite, in this case, moves from south to north, the area near the northern horizon becomes forshortened less with the lessening oblique view; thus the image size stretches. The reverse, a compression, occurs near the southern horizon.

If the picture series is taken across the descending node of the orbit, where the satellite is southbound across the equator, the resulting error field (fig. 6) is of nearly the same magnitude but opposite in direction to that at ascending node. There is convergent and clockwise motion about the line of registration, a shrinking of the northern portion of the image, and an expansion of the southern portion.

Figures 7 and 8 demonstrate the effect of increased orbital inclination on maximum error. All conditions used to generate figure 5 were maintained except orbital inclination--it was increased to 4° in figure 7, and to 7° in figure 8. Comparison of these 3 figures demonstrates how markedly the error increases with inclination. At 4° inclination the error in some

3 Effects of camera motion relative to the subpoint are zero since the grids are generated assuming an instantaneous scene rather than a 20-min generation period.
Figure 5.—Error field resulting from the maximum effect of subpoint motion northward across the equator. Orbital inclination is 2.5°. The subpoint moved along 149°W and across the ascending node from 0.8°S to 1.0°N in 2 hr 46 min. No effect of camera orientation relative to subpoint is included. Registration is on a fitted point (○) in Baja and on an aligned point (—•—) in Hawaii. Vector errors, given to the nearest degree and nearest knot, are mapped at 10° intersections on a Mercator projection. Arrows depict the direction of the error vectors and the isotachs depict the distribution of the speed field.
Figure 6.--Error field resulting from the maximum effect of subpoint motion southward across the equator. Orbital inclination and registration are identical to figure 5. Unlike figure 5 the subpoint moves southward along 149°W from 0.8°N to 1.0°S.
Figure 7.—Error resulting from maximum subpoint motion from 1.3°S to 1.6°N, when the orbital inclination is 4°. Registration and other conditions are the same as in figure 5.
Figure 8.--Error resulting from maximum subpoint motion from 2.2°S to 2.7°N when orbital inclination is 7°. Registration and other conditions are the same as figure 5.
locations is as large or larger than many cloud motions. At 7° inclination
the error field is much larger than most cloud motions.

In contrast to pictures taken when the satellite is in the vicinity of
the equator, those taken at the most northerly or southerly excursion of
the satellite suffer virtually no error (not shown) because of subpoint
change. Near or at either maximum excursion, latitudinal changes of the
satellite are too slight to produce appreciable error.

Error Field Resulting from Changing Camera Orientation

Whenever a picture sequence is centered in time on maximum pitch, the
greatest errors caused by variations in rate of change of pitch occur.
This error is isolated in figure 9 for a case in which the maximum positive
pitch is 2.5°. (Maximum pitch is rarely numerically greater than the
orbital inclination). The first picture of the sequence, beginning
before maximum positive pitch, is compressed as shown in figure 3a; the
last picture, taken after maximum pitch, is stretched. The net result,
shown in figure 9, is a stretching over the period of animation.

Maximum negative pitch is reached 180° around the orbit from maximum
positive pitch. If a picture sequence is centered on this event, the net
error (fig. 10) is a compression effect.

Similarly, maximum errors caused by variations in the rate of change of
yaw occur when a picture sequence is centered on an event of maximum yaw.
This error is isolated in figure 11, in which the maximum yaw is 2.5°.
Clearly, the effects of yawing produce far less error than effects of
either pitching or subpoint motion.

In the hypothetical cases just described, the maximum errors of sub-
point motion are isolated from errors of camera orientation so that each
could be examined individually. In practice, any combination of errors
can occur, depending upon the orientation of the spin axis and the
position of the satellite in orbit. For example, the worst errors of
pitching can occur simultaneously with the worst errors of subpoint motion.
Figure 12 depicts such a situation during the northbound equator crossing
(ascending node). The error is essentially a vector sum of the errors of
figures 5 and 9. Generally, the error becomes worse and the vectors
undergo directional changes.

Comparison of figure 5 with 9 (or figure 6 with 10) demonstrates that
errors caused by subpoint motion are somewhat more serious than those
caused by changes in camera orientation so long as the maximum pitch
stays within reasonable limits. Ideally, most errors caused by camera

4Pitch effects are isolated from subpoint motion when the maximum pitch
of the spin axis occurs simultaneously with either of the two extreme
latitudinal excursions (fig. 2).
Figure 9.—Error resulting from maximum variations in rate of change of pitch from beginning to end of an animated sequence. Orbital inclination is 2.5° but virtually no subpoint motion exists because the satellite is at its most southerly excursion. The time interval of 2 hr 46 min is nearly centered on occurrence of maximum positive pitch of 2.5° (camera pitched to its southern extreme). Registration is identical to that in the previous figures.
Figure 10.--Error resulting from maximum variations in the rate of change of pitch before and after maximum negative pitch of 2.5°. Unlike figure 9, the camera is pitched to its northern extreme during the sequence interval; therefore, the first image is stretched and the last is compressed, resulting in a net compression. The satellite is also at the maximum northern excursion at the time of maximum pitch. Otherwise, conditions are the same as for figure 9.
Figure 11.—Error resulting from maximum variations in the rate of change of yaw alone before and after a maximum yaw of 2.5°.
Figure 12.--The maximum error possible by combining the maximum subpoint and pitching effects. It is, in effect, a combination of fields from figures 5 and 9; maximum positive pitch occurs exactly at ascending node.

Orientation can be eliminated if pitch is maintained at zero (i.e., the spin axis is maintained normal to the orbital plane). Under this circumstance, effects of yawing continue to exist and occur simultaneously
with subpoint motion, but effects of yawing produce much less error than any of the other effects. Fortunately, since the spin axis can be controlled, the effects of changing camera orientation can be minimized. Unfortunately, orbital inclination cannot be controlled for either ATS 1 and ATS 3 nor will it be controlled for the geosynchronous satellites of the near future, such as GOES (Geostationary Operational Environmental Satellite).

Effects of Registration on Error Fields

Thus far, extreme conditions of subpoint motion and satellite attitude have been examined, but all at a fixed registration. What happens when the registration is varied? Figure 13 shows the error field due to subpoint motion resulting from a registration different than that used in figure 5. A point in the New Hebrides is fixed (primary point) while alignment is made on a second point in the Baja area. Clearly, this change in registration drastically alters the central portion of the error field (compare with fig. 5). This comparison demonstrates the critical role played by the registration; subpoint motion and changing camera orientation produce the errors, but registration controls their distribution and magnitude.

VERIFICATION

The same program used to derive the error fields is designed to automate the correction of apparent cloud vectors. This automation was one of the objectives of this study because manual correction of the cloud-vectors is very time-consuming. As input, the program requires orbital elements, satellite attitude, picture times, points of registration, and the end points (from the first and last pictures) of the cloud motions. Apparent cloud motions are then corrected, rectified, and located as the actual cloud vectors on the earth.

Even though the foregoing procedure for determination of error may seem sound, some independent evidence of its validity is required. One way is to compare measured cloud vectors both before and after correction with the rawinsonde observations. Such a test was performed on a sample of cloud measurements taken from ATS 1 data during 5 days of June 1970. Results of the comparisons are shown in figure 14. After correction, directional difference from the rawinsondes is improved only slightly (fig. 14a) over that before correction. About 20 percent of the data were improved by more than 5°. On the other hand, after correction nearly all the data show at least some improvement in speed (fig. 14b) and vector (fig. 14c) difference; about 50 percent of the data were improved by 5 kt or more in both instances.

Speed improvement played the dominant role in the vector correction because of the nature of the cloud motions and the area investigated. Cloud measurements were made in the tropical Pacific, particularly south of the equator where the low cloud motions were typical easterlies. The error fields on the 5 days studied, while not exactly like those of figure
Figure 13.—Error field resulting from change in registration. All conditions except registration are identical to figure 5. A point in the New Hebrides (O) is fitted and a point in Baja (—) is aligned. Note the ring of minimum error about 30° of great circle arc from the subpoint; this peculiarity is a geometrical quirk of the assumed conditions.

5° are very similar. Since both apparent motions and errors are easterly, the error field reduces the speed component of the initial cloud vectors with little change of direction. In other areas or for other cases, directional correction may be more significant.
Figure 14a.--Comparison of direction difference between ATS and rawin observations before and after correction of cloud vectors.

b.--Comparison of speed difference between ATS and rawin observations before and after correction of cloud vectors.

c.--Comparison of vector difference between ATS and rawin observations before and after correction of cloud vectors.
While significant improvement is made in the relationship between rawinsonde data and cloud vectors, the magnitude of the improvement is not as great as the magnitude of the correction. This seeming discrepancy does not necessarily indicate that error fields are inadequate. Many factors affect the accuracy of both satellite-derived cloud motions and rawinsonde data (Hubert and Whitney 1971). Correction for one of these factors will not necessarily improve the relationship to the full extent.

Inaccuracy in the error field will occur when there are inaccuracies in the specification of either the orbital elements or the attitude. A few experiments were conducted to examine the effects of orbital and attitude inaccuracies. In one experiment the right ascension of the ascending node was changed by $1^\circ$ during a period of maximum subpoint motion. The resulting error field (not shown) changed by only 1 kt or less from that of the original (fig. 5). In another experiment an error of $10^\circ$ introduced in the orbital position of the satellite (mean anomaly) caused an alteration of 1 kt or less in the original error field of figure 5.

Regarding attitude inaccuracies, an increase of $0.5^\circ$ in maximum spin axis pitch ($0.5^\circ$ decrease of declination) over that of figure 9 generally alters the error field by less than 2 kt; nowhere does it change more than 4 kt. A change of $10^\circ$ in the right ascension of the spin axis produces changes in the error field (not shown) of generally no more than 1 kt from that of figure 9.

It seems then, that only very serious inaccuracies in orbital and attitude data can materially affect cloud vector corrections.

**DISCUSSION AND CONCLUSIONS**

The quantitative evidence presented here demonstrates the serious effect of subpoint motion and changing camera orientation on the accuracy of cloud vectors derived from the animation of geosynchronous satellite pictures. In many cases the errors approach or even exceed the magnitude of the actual cloud vectors, especially those derived from low cloud motion. Often too, the directions of the errors vary greatly from those of the cloud motions. As a result, apparent (uncorrected) cloud vectors are drastically altered from those of reality.

Even for an inclination as small as $2.5^\circ$, errors of subpoint motion are too large to be ignored except near maximum latitudinal excursions. Orbital inclinations of existing geosynchronous satellites (ATS 1 and 3) continue to deteriorate since they are not controlled. At inclinations greater than $2.5^\circ$, errors increase; at $4^\circ$ inclination they are much worse than at $2.5^\circ$. At $7^\circ$ most errors can be as great as 20 to 80 kt over most of the image.
Errors caused by changing camera orientation are significant, but generally smaller than those of subpoint motion. Errors caused by pitching are much greater than those caused by yawing. Changing camera orientation may either increase or decrease the effect of satellite motion since each operates independently. Fortunately, attitude of the spin axis is, unlike inclination, controlled; thus, the errors of camera orientation need not worsen with time as do those of subpoint motion. Ideally, the spin axis should be maintained at a position normal to the orbit; then all error due to pitch would be eliminated.

Inaccuracies in orbital and attitude data can cause inaccuracies in the calculated error field. However, virtually no inaccuracy is suffered when the following limitations are satisfied:

The right ascension of ascending node is known to about 1°.

The mean anomaly is known to about 10°.

The declination of the spin axis is known to about 0.5°.

The right ascension of the spin axis is known to about 10°.

The computer program discussed in this report has been extended to automate the correction of apparent cloud vectors. The evidence suggests that this scheme improves the quality of the cloud vector data. Yet, as the errors become larger with time, they will approach and exceed the magnitude of the cloud vectors themselves. Thus, even though the errors are systematic, the cloud motions will become increasing suspect.

The future GOES will be deliberately launched into a slightly inclined orbit of perhaps 1.5° to permit the orbital plane to drift back into the equatorial plane before again drifting out and worsening. This procedure should maintain small inclinations for a longer period than was experienced with the ATS series.
ACKNOWLEDGEMENTS

The efforts of Leroy Herman who successfully programmed this procedure are particularly appreciated. By linking his existing programs for calculating cloud vectors with the gridding program developed by Russell Doolittle of DAPAD, and by adding new logic for deriving error fields, he provided a single totally automated procedure for obtaining final cloud vectors from the raw measurements of the animation.

Thomas Babicki provided invaluable aid in the seemingly endless experimentation and testing of this program. Emmett Bragg also assisted in this area. Leonard Hatton prepared the figures for presentation; Gene Dunlap provided the photographic work. Forrest Dishman typed the manuscript and Olivia Smith and Zelda Licausi, the draft versions.
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APPENDIX A

EFFECT OF ORBITAL INCLINATION ON SUBPOINT POSITION

By reference to figure 15, the latitude of the subpoint for any satellite, including one at geosynchronous altitudes, is defined by

\[ \sin L = \sin i \sin A, \]

where \( L \) is latitude,

\( i \) is orbital inclination, and

\( A \) is mean anomaly of the satellite, i.e., the angular position of the satellite in its orbit as measured from ascending node.

The rate of change of latitude is given by the time derivative of eq (1) and is

\[ \frac{dL}{dt} = \sin i \sec L \cos A \frac{dA}{dt}. \]

Eq (2) may be greatly simplified by the following considerations: \( i \) is small, \( \sec L \) is positive and equal to 1 within 1% up to angles of 10°, and \( \frac{dA}{dt} = \frac{\pi}{720} \) min\(^{-1}\) since the satellite revolves about the earth once every 24 hr. Therefore, the latitudinal change rate (if \( i \) is expressed in deg) becomes

\[ \frac{dL}{dt} = \frac{\pi}{720} i \cos A. \]

The latitude of the subpoint changes most rapidly at the equator and most slowly at the northernmost and southernmost excursions.
Figure 15.--Depiction of the satellite orbit and spin axis in the celestial system. Definitions of the angles and symbols appear in the text.
APPENDIX B

EFFECT OF PITCH ON THE IMAGERY OF SPIN SCAN CAMERAS ABOARD GEOSTATIONARY SATELLITES

Pitch of the spin axis is by NASA definition, the angle, \( \phi \), formed by the spin axis and the projection of the spin axis on a plane normal to the satellite position vector (fig. 15). Pitch is expressed by the function

\[
\cos(90 - \phi) = \cos (90 - \phi_{\text{max}}) \cos (90 - \theta)
\]

which reduces to

\[
\phi = \arcsin[\sin \phi_{\text{max}} \sin(\lambda - \Lambda)] \quad (4)
\]

where \( \phi_{\text{max}} \) is the angle between the orbit normal and the spin axis,

\( \Lambda \) is the mean anomaly of the satellite,

\( \lambda \) is the angle from ascending node to the location where the pitch is zero and about to become negative, and

\( \theta \) is the orbital position angle of the satellite as measured from the point where pitch is zero and about to become negative.

By the right-hand rule, the spin axis vector points with a southward component since the satellite spins so as to scan from west to east. Negative pitch by NASA convention (Allied Research Associates 1967) occurs when the spin axis vector has a component pointed toward the earth, i.e., when camera is directed north of the orbital plane.

The parameters \( \phi_{\text{max}} \) and \( \lambda \), by reference to figure 15, are described by the following functions:

\[
\cos \phi_{\text{max}} = \cos i \cos (90 + \delta) + \sin i \sin (90 + \delta) \cos P
\]

or

\[
\cos \phi_{\text{max}} = -\cos i \sin \delta + \sin i \cos \delta \sin (\text{RA}_S - \text{RA}_N) \quad (5)
\]

and

\[
\cos (90 + \delta) = \cos i \cos \phi_{\text{max}} + \sin i \sin \phi_{\text{max}} \cos \lambda
\]

or
\[
\cos \lambda = \frac{-\sin \delta - \cos i \cos \phi_{\text{max}}}{\sin i \sin \phi_{\text{max}}} \tag{6}
\]

where \( i \) is orbital inclination,
\( \delta \) is declination of the spin axis (it is negative),
RA is right ascension (subscripts SA and AN refer to spin axis and ascending node, respectively), and
\( P = 180 + \text{RA}_{SA} - (\text{RA}_{AN} - 90) \).

All parameters needed to determine \( \phi \) by means of eq (4), (5), and (6) are given in orbital element data and spin axis attitude data for ATS 1 and ATS 3.

The rate of change of pitch, the time derivative of eq (4), is given by
\[
\frac{d\phi}{dt} = -\sin \phi_{\text{max}} \sec \{ \arcsin [\sin \phi_{\text{max}} \sin(\lambda-A)] \} \cos (\lambda-A) \frac{dA}{dt}.
\]

Remembering that \( \frac{dA}{dt} = \frac{\pi}{720} \) min\(^{-1} \) and that the secant term is nearly 1, even up to \( \phi_{\text{max}} = 10^\circ \), this equation becomes
\[
\frac{d\phi}{dt} = -\frac{\pi}{720} \sin \phi_{\text{max}} \cos (\lambda-A).
\]

During a 20 min interval of picture generation, the change (in degrees) of camera angle relative to the subpoint is closely approximated by
\[
\Delta\phi = -5 \sin \phi_{\text{max}} \cos (\lambda-A) \tag{7}
\]
since \( \lambda-A \) changes by only 5°.

The rate of change of pitch itself varies with time, thus causing a compression or expansion of the image throughout the course of a movie prepared from geosynchronous satellite pictures. Figure 16 demonstrates how the error accumulates. The net line expansion is expressed by
\[
\Delta N_\phi = (\Delta \phi_F - \Delta \phi_I) \frac{N}{\gamma} = (\Delta^2 \phi) \frac{N}{\gamma}, \tag{8}
\]
where \( N \) is the number of lines making up the image
\( \gamma \) is the angle of view
F is the subscript referring to the final image, and
I is the subscript referring to the initial image.
Figure 16.—A schematic demonstrating the changing distribution of scan lines resulting from variations in the rate of change of pitch. Consider that the plane of the paper is normal to the satellite position vector. The dashed lines represent the tracks of scans 1 and 2000 of the initial picture, I, in a given series of pictures. Solid lines are the tracks of the final picture of the series. In picture I the earth is scanned with more lines than it is in picture F. Since the ground equipment always displays the scan lines at a constant interval, then picture I is expanded and picture F is compressed, resulting in a net compression of $\Delta N_\phi$ lines from first to last pictures.

Assuming the maximum pitch, $\phi_{\text{max}}$, is 2.5°, the worst variation of pitch change that can occur during a 2 hr 46 min movie is $\Delta^2\phi = .155^\circ$. This result comes of applying eq (7) to the first and last pictures of the movie and taking a difference. Then, since $N/\gamma$ is nominally 2000/15 lines per deg for the ATS spin scan camera, the maximum net expansion or compression, by virtue of eq (8), is $\Delta N_\phi = 30$ lines.
EFFECT OF YAW ON THE IMAGERY OF SPIN SCAN CAMERAS ABOARD GEOSTATIONARY SATELLITES

Yaw, by NASA definition, is the angle, \( \psi \), formed by the projections of both the earth axis and the spin axis on a plane normal to the satellite position vector. Referring again to figure 15, yaw is expressed by

\[
\sin \psi = \frac{\sin(180 + RASA - RA_s)}{\sin(90 - \phi)}
\]

where \( RA_s \) is the right ascension of the satellite. Right ascension of the satellite may be expressed by

\[
RA_s = RA_{AN} + \arctan (\tan \alpha \cos \iota)
\]

or, since \( \iota \) is a small angle

\[
RA_s = RA_{AN} + \alpha
\]

Therefore, the expression for yaw may be reduced to

\[
\sin \psi = \cos \delta \frac{\sin (A + RA_{AN} - RASA)}{\cos \phi}
\]  

(9)

The rate of change of yaw is the rather cumbersome equation

\[
\frac{d\psi}{dt} = \frac{\cos \delta}{\cos \phi \cos \psi} \left[ \frac{\pi \cos (A + RA_{AN} - RASA) + \sin (A + RA_{AN} - RASA) \tan \phi \frac{d\phi}{dt}}{720} \right]
\]  

(10)

Fortunately, the second term is usually negligible. Pitch (\( \phi \)) and yaw (\( \psi \)) occur out of phase with one another so that when \( \psi \) is a maximum, \( \phi \) is near if not zero; and when \( \psi \) is zero, \( \frac{d\phi}{dt} \) is near if not zero. Also the spin axis is usually maintained nearly parallel to the orbital normal so that both \( \tan \phi \) and \( \frac{d\phi}{dt} \) are small; their product is very small.

Therefore, as a general rule only the first term is significant.

During a 20-minute picture, the change of yaw (in degrees) is very closely approximated by

\[
\Delta \psi = 5 \frac{\cos \delta \cos (A + RA_{AN} - RASA)}{\cos \phi \cos \psi}
\]  

(11)

Equation (11) represents the amount the camera rotates about its axis, relative to the earth, during the course of generating a single picture.

Just as in the case of pitch, the rate of change of yaw itself varies with time causing the scan lines from the first to the last pictures to form angles with one another. Figure 17 shows how net error accumulates between the two images. At the right and left hand margins of the image the net accumulated error in scan lines, \( \Delta N \psi \), may be expressed as
Figure 17.—A schematic demonstrating the changing distribution of scan lines on the earth resulting from variations in the rate of change of yaw. The plane of the diagram is normal to the satellite position vector. The dashed lines represent the tracks of scans 1 and 2,000 of the initial picture, I, showing that the spin axis is yawing counterclockwise during picture generation. The scan lines of the final picture were rotating in the opposite sense. The result is that on the right, the earth is scanned with more lines in picture I than in picture F. Therefore, the final image of the earth undergoes a net compression of $\Delta N_\psi$ lines. At the left the image undergoes a net expansion of an equivalent number of lines. The length of scan lines (image width) is assumed equivalent to the spacing of 2,000 scan lines.

$$\Delta N_\psi = 2000 \sin \left[ \frac{\Delta \psi_F - \Delta \psi_I}{2} \cdot \frac{\pi}{180} \right] = 2000 \sin \left[ \frac{\Delta^2 \psi \cdot \pi}{360} \right]$$

or since $\frac{\Delta^2 \psi \cdot \pi}{360}$ is small

$$\Delta N_\psi = 17.45 \Delta^2 \psi \quad (12)$$

Assuming a maximum yaw, $\psi_{\text{max}}$, of 2.5° and applying eq (11) to the first and last pictures of a movie, the worst variation in yaw change that can occur over 2 hr 46 min is $\Delta^2 \psi = 0.1406°$. Therefore, applying eq (12),
$\Delta N_\psi = 2.5$ lines of compression on one side of the image (left side of figure 17) and 2.7 lines of expansion on the other. This error is nearly an order of magnitude less than the effect of pitch.

As a consequence of this examination of pitch and yaw, it is desirable to maintain the spin axis normal to the orbit. Such an orientation eliminates the effects of pitch and permits only the minimal effects of yaw on the geostationary imagery.
(Continued from inside front cover)


NESCTM 21 Reserved.


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