Attitude Determination Using Antenna Polarization Angles

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The attitude of a satellite is normally determined from Earth sensors, horizon sensors, and a sun reference. This paper discusses an alternate method of attitude determination using polarization-angle measurements of the normally radiated plane polarized radio frequency (RF) signal from the spacecraft. Simultaneous polarization-angle data, taken at geographically separated locations, contain sufficient information to determine the inertial orientation of the signal polarization at the time of observation. An iterative method, using the sensitivity of polarization-angle measurements to the radiating antenna, is used to determine the orientation. Since the RF signal polarization with respect to the spacecraft body axes is known, the spacecraft attitude can be determined.

Nomenclature

E = polarization angle error vector
P = inertial position vector of ground station
p = unit vector of P
S = sensitivity matrix of polarization angle to omni-antenna orientation
V = line of sight vector, ground station to spacecraft, inertial coordinates
v = unit vector of V
X = vector of corrections to α and δ
α = right ascension of omni antenna/spin axis
α_i = initial estimate of α
α_f = final estimate of α
δ = declination of omni antenna/spin axis
δ_i = initial estimate of δ
δ_f = final estimate of δ
ρ = polarization angle
ρ_n = estimated ρ at ground station n
ρ_{nm} = measured ρ at ground station n
σ = unit vector along spin axis

Introduction

IN the transfer orbit, momentum bias satellites are spin stabilized about the apogee kick motor (AKM) thrust axis. The inertial attitude of the satellite spin axis is normally determined from an Earth and a sun reference, the data being provided by a sun sensor and an Earth/horizon sensor.[1] The rotational motion of the satellite is used to scan the sun sensor and the horizon sensor. In the operational mode, the spacecraft is three-axis stabilized with the spacecraft momentum vector along the orbit normal (spacecraft pitch axis). Earth sensors onboard the spacecraft scan the Earth to determine the Earth chord width at two different sections, thereby providing the spacecraft pitch and roll information.

An alternate method of attitude determination would be to measure the polarization angle of a linearly polarized radio frequency (RF) signal from the spacecraft and thereby determine the inertial orientation of the emitting antenna. An antenna that would be convenient for this purpose is the omnidirectional antenna with which all spacecraft are equipped. The omni antenna of the spacecraft is aligned along the spin axis during the transfer orbit (launch omni antenna in Fig. 1). Therefore, determination of the omni antenna orientation from its signal pattern would be equivalent to determination of spin-axis attitude. Similarly, in the operational mode, the omni antenna is oriented along the spacecraft pitch axis (orbit omni antenna in Fig. 1). Therefore, determination of omni orientation would be equivalent to determination of roll and yaw attitude.

The polarization angle of the omni antenna measured at the ground station is a function of the spacecraft position relative to the station, and the omni antenna orientation. Determination of two variables, namely, right ascension and declination in the spinning mode, and roll and yaw attitude in the operational mode, would require simultaneous polarization-angle measurements from two well-separated ground stations. However, polarization-angle measurements from just one station can provide an estimate of only the spin-axis declination or the yaw attitude.

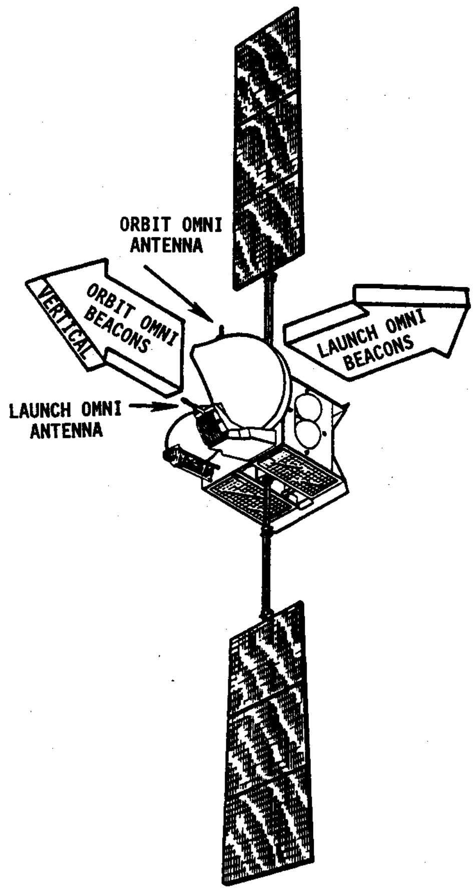

Fig. 1 Spacecraft omni-antenna locations and polarizations.

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This paper discusses this alternate method of spacecraft attitude determination using antenna polarization-angle measurements. This strategy was successfully implemented to determine the yaw attitude of GSTAR III during its recovery effort and it has been presented, with operational details, in Ref. 2.

Antenna Polarization Angle

The polarization of the antenna can be defined as the polarization of the wave it radiates. In the far field of the antenna the radiated wave may be considered to be a uniform plane wave and the polarization of the antenna is the same as that of the plane wave.[3]

The omni antenna on most communication satellites is a biconical antenna with a toroidal beam (Fig. 2). This omnidirectionality is in the horizontal plane whereas the polarization in the far field, with the coaxial feed shown in Fig. 2, will be vertical, that is, parallel to the axis of symmetry of the omni antenna.[3-5] Therefore, this polarization angle, measured at a ground station, can be defined as the angle between the orthogonal projections of the omni antenna (spacecraft spin axis in the transfer orbit mode, and spacecraft pitch axis in the three-axis mode) and the ground station local vertical onto the plane perpendicular to the antenna-spacecraft line of sight.

If $\boldsymbol{P}$ is the inertial position vector of the ground station, and $\boldsymbol{V}$ is the line of sight vector from the ground station to the spacecraft, the respective unit vectors $\boldsymbol{p}$ and $\boldsymbol{v}$ are given by

$$\boldsymbol{p} = \boldsymbol{P}/|\boldsymbol{P}|$$

$$\boldsymbol{v} = \boldsymbol{V}/|\boldsymbol{V}|$$

The unit vector along the spin axis is given by

$$\boldsymbol{\sigma} = \begin{bmatrix} \cos\delta \cdot \cos\alpha \\ \cos\delta \cdot \sin\alpha \\ \sin\alpha \end{bmatrix}$$

Defining intermediate values as

$$\boldsymbol{n} = \boldsymbol{v} \times \boldsymbol{s} \qquad \text{and} \qquad \boldsymbol{m} = \boldsymbol{v} \times \boldsymbol{\sigma}$$

expressions for the angle Θ are obtained as

$$\cos\Theta = (\boldsymbol{n} \cdot \boldsymbol{m})/(|\boldsymbol{n}|\ |\boldsymbol{m}|)$$

$$\sin\Theta = (\boldsymbol{n} \times \boldsymbol{m}) \cdot \boldsymbol{v}/(|\boldsymbol{n}|\ |\boldsymbol{m}|)$$

The polarization angle ρ is related to the angle θ by the following relationships:

$$\rho = \theta \quad \text{for} \quad 0 \leq \theta \leq 90 \text{ deg}$$

$$\rho = \theta - 180 \quad \text{for} \quad 90 \text{ deg} \leq \theta \leq 270 \text{ deg}$$

$$\rho = \theta - 360 \quad \text{for} \quad \theta \leq 270 \text{ deg}$$

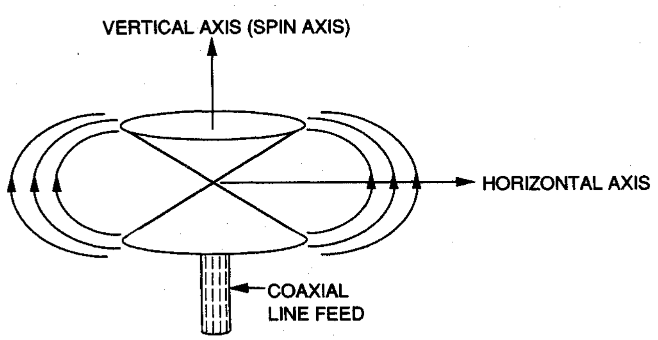

Fig. 2 Biconical omni-antenna.

Measurement of Antenna Polarization Angle at Ground Station

The polarization of the radiated field from an antenna may be determined by measuring the received signal voltage with a linearly polarized receiving (secondary) antenna as its polarization is rotated in direction through 360 deg.[4] Since the omni antenna is linearly polarized, the measurement should yield two maxima and two nulls. The polarization would be in the direction corresponding to the maxima. In practice, the direction of the nulls should be determined, since the direction of nulls can be measured more accurately than that of the maxima, and the maxima will rotate by 90 deg from the nulls.

This polarization-pattern method is described in detail in Ref. 5. Reference 5 also describes another possible option, called the liner-component method. In this method two fixed linearly polarized antennas mounted at right angles measure the two perpendicular components of the incoming wave; by connecting both antennas to a phase comparator, the phase angle can be determined. The polarization then can be determined from this information.

Prior to measuring the polarization angle, the antenna has to be calibrated, and the biases in each of the antennas relative to their true polarization removed. This can be accomplished by pointing each antenna at a known spacecraft. Geosynchronous spacecraft, which are essentially stationary relative to the ground antennas and with their attitude well defined, provide good reference for calibration measurements. To determine the station bias, the measured polarization for such test cases should be compared with calculated predictions. This bias determination should be repeated several times, and the refined bias should be used with all subsequent measurements to determine the actual polarization angles. Figure 3 shows such a polarization-angle prediction for an operational omni antenna (antenna aligned along the orbit normal), for a geosynchronous satellite located at different longitudes with respect to a ground station. As expected, polarization angle is 0 deg for spacecraft with same longitude as the ground station.

Reference 2 describes the details of polarization-angle measurement done on ground during the GSTAR III recovery effort. The accuracy of antenna-axis computation is dependent on the accuracy of the actual polarization-angle measurements. In addition, the particular spacecraft-station geometry also determines the sensitivity of the measurements to the spin-axis orientation. The sensitivity matrices computed in the course of this method, as shown in Table 1, would determine the actual error in spin-axis measurements corresponding to errors in polarization-angle measurements.

The polarization measurements made in Ref. 2 were sufficiently accurate to determine spacecraft yaw attitude within the mission requirement of about 5 deg. However, obtaining accurate polarization measurements turned out to be the most difficult part of the exercise. Inaccuracy in ground equipment measurement was a primary reason for this, since ground stations were not required to measure polarization angle with

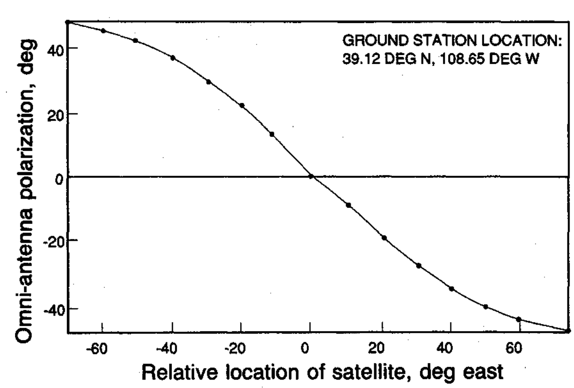

Fig. 3 Omni-antenna polarization angle for geosynchronous locations relative to a ground station.

Table 1 Spin-axis attitude determination

Parameters, deg	Initial	After first iteration	After second iteration	After third iteration
Estimated α	230	235	239.113	238.598[a]
Estimated δ	-2	-4.5	-7.79	-7.819[a]
Polarization angle at Grand Junction	-52.023	-55.059	-58.848	-51.8104
Polarization angle at Guam	13.209	10.512	7.082	7.0696
Error in polarization angle	6.786 6.138	3.75 3.44	-0.038 0.0121	-0.00044 -0.0038
Sensitivity matrix, S	$\begin{bmatrix} -0.106 & 0.99 \\ -0.0343 & 1.0233 \end{bmatrix}$	$\begin{bmatrix} -0.114 & 0.997 \\ -0.03 & 1.008 \end{bmatrix}$	$\begin{bmatrix} -0.12 & 1.003 \\ 0.032 & 1.001 \end{bmatrix}$	

[a]Converged to this solution; the solution from sun and horizon sensor was $\alpha = 238.73$, $\delta = -7.86$.

a high degree of accuracy during normal operations. In addition, the signal from the omni antenna was also unreliable. The large size of the spacecraft in relation to the antenna size as well as the sizeable projections can modify the omni pattern. It was found that polarization angles measured for the omni were less reliable than those measured for the reference horn antenna. The horn antenna also emmitted a linearly polarized signal, with a known offset in polarization from the omni antenna, and therefore spacecraft attitude could still be determined.

Determination of Omni Orientation and Spin-Axis Attitude

In the transfer orbit, the omni antenna is aligned along the spacecraft spin vector. Therefore, determining omni antenna orientation is equivalent to determining the spin-axis attitude. This attitude determination algorithm uses the simulataneous polarization angle measurements ρ_{1m} and ρ_{2m} at two stations to converge to the actual spin-axis orientation α_f and δ_f, starting with an initial estimate α_i and δ_i.

The estimated spin-axis orientation α_i and δ_i is used to calculate the polarizations angles ρ_1 and ρ_2 for the two stations. The difference between ρ_n and ρ_{nm}, n being the station identifier, is the error that is to be nulled in order to arrive at α_f and δ_f. The sensitivity matrix S is determined by perturbing the angles α_i and δ_i one at a time; the linear equation shown below is obtained:

$$E = SX$$

where

$$E = \begin{bmatrix} \rho_1 - \rho_{1m} \\ \rho_2 - \rho_{2m} \end{bmatrix}$$

$$S = \begin{bmatrix} \dfrac{\partial \rho_1}{\partial \alpha} & \dfrac{\partial \rho_1}{\partial \delta} \\ \dfrac{\partial \rho_2}{\partial \alpha} & \dfrac{\partial \rho_2}{\partial \delta} \end{bmatrix}$$

$$X = \begin{bmatrix} \Delta\alpha \\ \Delta\delta \end{bmatrix}$$

Solving for the correction vector, $X = S^{-1} E$, the updated values of α and δ are obtained

$$\alpha_{\text{new}} = \alpha_i + k . \Delta\alpha$$

$$\delta_{\text{new}} = \delta_i + k . \Delta\delta$$

Table 2 Spacecraft and station geometry

Parameter		Values
Time		9/11/88, 20:19:00 GMT[a]
S/C[b] Position, km	X	-34537.08
(ECI[c] coordinates), km	Y	24810.84
	Z	-137.02
S/C Latitude, deg		-0.186
Longitude, deg		208.614
Grand Junction		
Latitude, deg		39.12
Longitude, deg		-108.65
Polarization angle, deg		-58.81
Guam		
Latitude, deg		13.417
Longitude, deg		144.44
Polarization angle, deg		7.07

[a]Greenwich mean time [b]spacecraft [c]Earth-centered inertial

The gain k is used in order to limit the correction applied to initial estimates to a reasonable level for cases of very high sensitivity.

This iteration is repeated until the error vector E is reduced to an acceptable level, making the value of α and δ converge to the actual spin-axis orientation α_f and δ_f.

In the three-axis stabilized mode, the preceding exercise would be equivalent to determining the spacecraft pitch-axis orientation, since in that mode the omni antenna is aligned along the pitch axis.

Application of the Procedure in Spinning Mode

This section is an exercise in explicitly determining the spin axis of spacecraft based on theoretically determined polarization measurements at two stations.

The algorithm already discussed is used here to determine the spin-axis orientation of GSTAR III just prior to the AKM burn. Table 2 shows the spacecraft position at the time, along with the location of the two ground stations used for the polarization-angle measurements, Grand Junction, Colorado, and Guam. Table 2 also indicates the omnipolarization angle measured at the two ground stations. These readings imply no error in measurements.

To solve for the actual spin-axis attitude, an initial estimate of the 230 deg in right ascension and -2 deg in declination is assumed, as shown in Table 1. This initial estimate results in polarization-angle error of 6.78 and 6.14 deg for Grand Junction and Guam, respectively. The algorithm described in the preceding section nulls this error in an iterative way, ultimately converging to the actual spin-axis orientation. Table 1

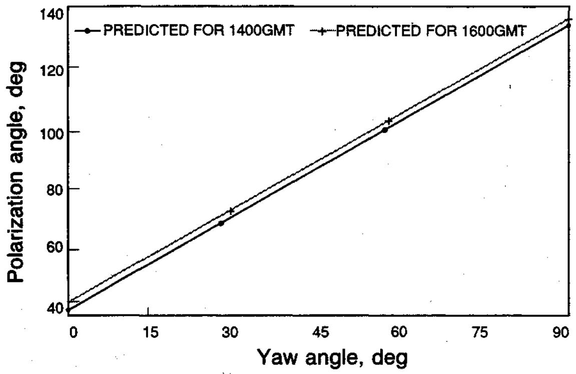

Fig. 4 Predicted omni-antenna polarization angle during yaw precession maneuver.

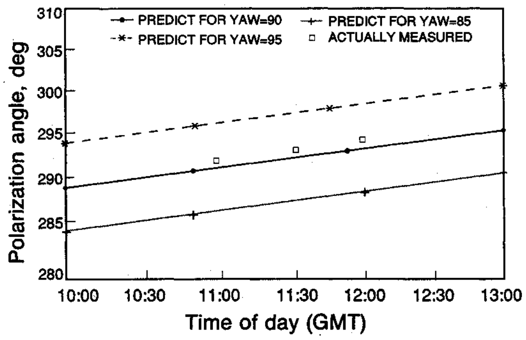

Fig. 5 Reference horn polarization angle during a GSTAR III maneuver.

shows the sensitivity matrix, the correction required, and the error in polarization angle, for each iteration. After three iterations, the error in polarization angle is reduced to 0.00044 and 0.00038 deg, showing that the process has converged. The right ascension and declination corresponding to this iteration are 238.598 and -7.819 deg, respectively, which is the spin-axis orientation determined from polarization-angle measurements. The spin-axis orientation actually determined from the spacecraft horizon sensors and the sun sensor was 238.73 deg in right ascension and -7.86 deg in declination.

Attitude determination from polarization angles provides a more accurate determination of the spin-axis declination as compared to the right ascension. Therefore, this method can be used in a complementary fashion with the attitude determination using sun and Earth/horizon reference, since the latter is less accurate in determining the spin-axis declination, due to relative insensitivity of the sun angle to declination.

An examination of the sensitivity matrix S in Table 1 shows that in the spinning mode, there is almost a 1:1 relationship between polarization angle and declination of the spin axis. Extended into the three-axis stabilized mode, this relationship would also exist between yaw angle and the polarization measurement. This turns out to be a very useful property because it allows data from only one station to be used to estimate declination without explicitly solving for the spin axis as shown previously. In most cases, this obviates the need for simultaneous polarization measurements from two ground stations.

Application to Three-Axis Attitude Determination

As described in Ref. 2, polarization angles have been successfully used during the GSTAR III recovery operations to determine spacecraft yaw angle. The recovery scenario required the spacecraft to be yawed 90 deg from normal operating attitude for the burns to be executed. Because the onboard Earth sensors do not indicate the yaw attitude, yaw had to be estimated from the polarization angle.

In the course of actual application, it was not necessary to explicitly solve for the orientation of the omni antenna. Because of the almost 1:1 relation between yaw attitude and polarization measurement, polarization-angle measurement from one ground station was sufficient to give an estimate of the yaw angle.

The yaw procession maneuver required keeping continuous track of the yaw angle. Although the yaw rate gyro provided an accurate estimate of the yaw angle, it saturated part way through the maneuver. The precession maneuver was completed using the chart shown in Fig. 4, which displays expected polarization angle corresponding to yaw angle. With gyro data unavailable, this chart provided the only reference for estimating yaw angle.

During the actual burns, the polarization angles measured at stations were compared with the prediction charts (Fig. 5) showing expected measurements corresponding to the time of burn for different yaw attitudes. Figure 5 also shows an actual set of measurements taken during a certain burn that confirmed the yaw attitude to be within 2 deg of the desired yaw angle of 90 deg. Comparison with measurement prediction charts provided a quick fix on the yaw attitude, and did not require explicitly solving for spacecraft attitude. These prediction charts were also corrected for any known or measured biases, both on the spacecraft and at the stations.

As noted, the difficult part of implementing this method of attitude determination was getting accurate polarization measurements at ground stations. Quite often the omni antenna signal was noisy and its polarization measurement data was frequently corrupted with the multipath effects, such as change of phase due to reflections from spacecraft body. The polarization of the reference horn antenna was successfully used instead. A possible reason for this omni antenna data inadequacy was that the spacecraft/ground antenna was not specifically designed to accurately measure the polarization. However, using the reference horn antenna, it was possible to get an accuracy of within 5 deg, which was the mission requirement for GSTAR III recovery. This accuracy could possibly be improved if a large number of measurements were available and a filtering scheme implemented to reduce the errors and uncertainties.

Conclusions

The orientation of a spacecraft antenna emitting plane polarized radio frequency signal can be determined from its polarization angle reading at the ground stations. With the orientation of the antenna relative to the spacecraft axes known, the spacecraft attitude, both in the spinning mode and the three-axis mode, can therefore be determined. An explicit solution for the spin-axis attitude, or roll/yaw attitude would require simultaneous polarization measurements from two well-separated ground stations. However, measurement from one station only provides an estimate of spin-axis declination, or the yaw attitude.

This method of spin-axis attitude determination may be used to complement the more accurate method of attitude determination using sun and horizon sensor. This can provide a quick fix on the spin-axis attitude before an attitude file can be taken and processed for the more accurate measurement. This method can also be a backup attitude-determination scheme in case of problems with the primary attitude-determination method.

In the three-axis stabilized mode, this method can complement the roll/pitch determination using the Earth sensors. This provides an estimate of the spacecraft yaw attitude, which is not directly available from the Earth sensors.

Acknowledgment

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