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GSTAR III Attitude for Inclined Geostationary Orbit

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The satellite GSTAR III is currently providing a multitude of communication services from its 3.9 deg inclined geosynchronous orbit. Nodal crossings are stationkept at 93°W longitude. North-south maneuvers are not implemented and the inclination is permitted to grow naturally. Daily sublatitude and longitude variations trace a "figure-eight" trajectory as seen from terrestrial observation points, requiring the ground antennas to track the satellite. Left uncompensated, the satellite radiative power footprint and associated radio-frequency polarization plane undergo 24-h cyclic variations. To minimize the daily radiative power variations, the spacecraft antenna boresight is kept targeted at the specified geographic location by programming the flight computer with appropriate roll and pitch bias increments. At later phases of mission life, when the signal polarization plane rotation is no longer acceptable, the momentum vector will be partially skewed in the direction of equatorial normal. At some stage, periodic thruster-assisted spacecraft yaw maneuvers will be required to reduce the polarization plane rotation. This paper describes the attitude maintenance procedures being used to support communication services from a non-nominal orbit.

Nomenclature

H = spacecraft momentum axis
i = inclination of orbit, deg
M = angle from ascending node to the satellite, deg
N = orbit normal vector
n = orbital rate, 15 deg/h
t = time past ascending node, h
Z' = spacecraft pitch axis
α = ratio of change in roll attitude to change in satellite latitude
δ_{lat} = excursion in satellite latitude, deg
δ_{lon} = excursion in satellite longitude, deg
ϕ_a = pivot offset commanded through the APE
ϕ_b = pivot offset commanded bypassing the APE
ϕ_m = maximum pivot offset over a day, deg
ϕ_l = pivot offset limit; 2 deg for GSTAR III
ϕ_t = total offset in satellite momentum wheel pivot, deg
ϵ = roll error due to pivot offset as sensed by the ESA
ψ = satellite yaw angle, deg

Introduction

THE GSTAR III is a three-axis-stabilized Ku-band repeater satellite that was targeted for operating at a geostationary orbital location over the continental United States. The onboard monopropellant hydrazine propulsion system was nominally designed to provide 10 to 12 years of stationkeeping operations.

GSTAR III ended up in an inclined 16-h orbit following its launch. The orbit has since been raised to a nominal 24-h inclined orbit, using onboard stationkeeping thrusters and available hydrazine fuel.[1,2] This recovery process, however, depleted most of the onboard propellant. Since north-south stationkeeping (inclination control) for a geostationary satellite consumes over 90% of its propellant budget, during GSTAR III's operational life only east-west stationkeeping is planned to control the eccentricity and east-west drift rate. There are no plans to control the inclination. This will effectively stretch out the satellite's useful life to over several years.

Although spacecraft longitude at the nodal crossings is maintained at the Federal Communications Commission assigned location of 93°W longitude, there is a daily variation in its latitude and longitude due to its nonzero inclination, with the variation in latitude being more pronounced. These variations require steering all ground antennas to track the satellite; they also require active spacecraft antenna boresight management to keep the effective isotropic radiative power (EIRP) within service specification. Active boresight management consists of providing continuous pitch and roll offsets in spacecraft attitude to keep the antenna boresight pointed at the optimum location and minimize the perturbation in antenna pattern and EIRP. Implementation of the tracking systems provides the necessary antenna pointing from terrestrial stations.

The remaining issue is the observed 24-h radio-frequency (RF) polarization plane oscillations caused by the orbit inclination. The inclination of the orbit translates directly into spacecraft yaw error at the ascending and descending nodes of its orbit. The effect is similar to the signal pattern of a nominally placed geostationary satellite that has a time-dependent yaw variation. For the purpose of GSTAR III operational description, such RF polarization plane deviations will be labeled "yaw error" or "yaw angle" throughout the paper for convenience.

One method of inclined orbit operations has been developed by the COMSAT Corporation[3] that involves a fixed momentum offset. The scheme is simple to operate and does not require any special onboard attitude control hardware. This, however, does not provide active boresight control or address the issue of RF signal polarization plane rotation. Since the GSTAR series of satellites are designed with added attitude control system (ACS) capabilities that permit boresight retargeting in real time without having to reorient the system momentum, a different method has been developed for GSTAR III. This paper discusses various techniques employed with GSTAR III operations to compensate for the effects of inclination.

Orbit Dynamics

The net effect of the Earth's oblateness and luni-solar gravity causes the geosynchronous orbit pole to precess around a point that is 7.5 deg from the polar axis (equivalent inclination is 7.5 deg), with a complete rotation taking 55 years.[4] Linear-

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izing this orbital motion, about the current time, results in inclination growth of approximately 0.85 deg annually.

Satellite Location Drift

For GSTAR III, which has an inclined orbit with geosynchronous radius, the longitude at the nodes is maintained within a tolerance of ±0.05 deg at 93°W longitude. However, the net effect of inclination is a daily variation in both latitude and longitude, with a variation in latitude being more pronounced (the maximum latitude having the same value as the inclination). The excursion in longitude and latitude (resulting from inclination only) can be computed using the following equations:

$$\delta_{\text{lon}} = M - \tan^{-1}(\tan M \cos i)$$

$$\delta_{\text{lat}} = \tan^{-1}\left(\frac{\sin i \tan M}{\sqrt{1+\tan^2 M} \cos i}\right)$$

with

$$M = nt$$

Figure 1 shows the "figure-eight" excursion of the satellite over a 24-h period resulting from an inclination of 5 deg. The plot isolates the effect of inclination only and does not take into account the effect of eccentricity or longitudinal drift. GSTAR III eccentricity is maintained at its steady-state value of approximately 0.00035, which corresponds to a maximum longitudinal excursion of ±0.075 deg over a day. Inclusion of this effect would significantly alter the shape in Fig. 1, particularly in terms of longitude. It may be noted that the inclination of 5 deg has been chosen as an example to illustrate the dynamics of the satellite.

Attitude Control System

The spacecraft attitude is sensed by an Earth sensor assembly (ESA) in the mission mode and by gyros during stationkeeping maneuvers. The attitude control actuators are magnetic torquers, a servo-controlled momentum wheel assembly (MWA), and thrusters as needed. The onboard control logic is implemented through attitude processing electronics (APE). APE is a computing device built around RCA 1802 CPU firmware.

Pitch and Roll Offset

The unique feature of the ACS that permits active boresight management is the pitch and roll pointing capability. The design intent of the pitch and roll offset capability was to provide a means of optimizing the boresight pointing over a range of satellite location. In addition, the MWA pivot provides a means of trimming the alignment between the momentum vector and onboard sensors. The programmable roll and pitch offset system, using the APE table, was designed to maintain accurate spacecraft antenna targeting by compensating for thermally induced diurnal structural deflections. A table limit of ±0.5 deg was provided for this purpose. The APE table, however, has never been invoked to correct for structural deflections since none have been observed so far.

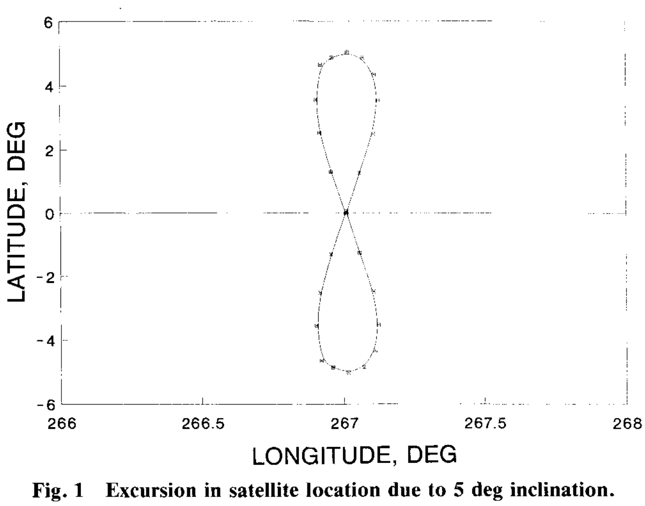

Fig. 1 Excursion in satellite location due to 5 deg inclination.

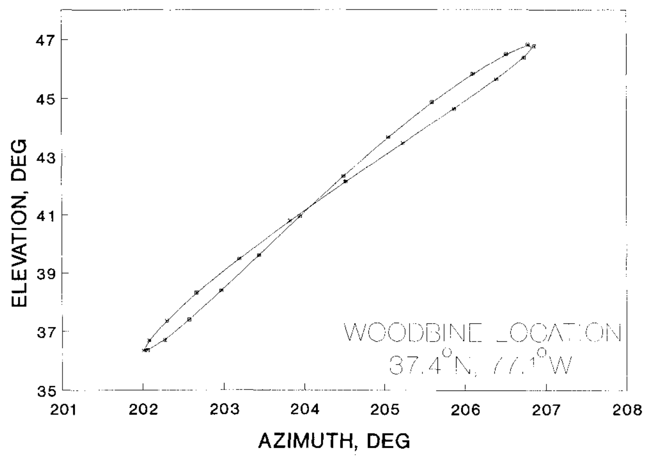

Fig. 2 Azimuth and elevation of GSTAR III from Woodbine, Maryland, for a 5 deg inclined orbit.

The pitch bias adjustment that accommodates up to a ±6 deg bias offset is achieved by summing a ground-commanded pitch bias demand with the measured pitch signal from the ESA. For roll biasing, the ACS incorporates a pivoting mechanism. When commanded, the spacecraft body is rotated about the roll axis by activating the gear mechanism against the gyroscopically stable MWA axis. Maximum available roll excursion is ±2 deg. As mentioned here, the biasing system can be automated up to ±0.5 deg by programming an APE resident roll and pitch data table, which targets the satellite antenna boresight to the specified zone.

This roll and pitch offset capability and the APE table offset system, as described throughout the paper, were successfully adapted to manage attitude requirements of GSTAR III in an inclined orbit. This allows the antenna boresight to be maintained at the target even though the satellite was not geostationary.

Operations

Successful GSTAR III service is based on finding effective solutions to three major issues normally associated with the geosynchronous inclined orbit operation of a commercial satellite system. The requirements are 1) for terrestrial antennas to track the satellite, 2) minimization of daily EIRP variations, and 3) compensation of RF polarization variations when needed. Operationally efficient procedures are in place to address all of the foregoing. The procedures for the operations are defined next.

Ground Antenna Tracking Requirement

A typical daily azimuth-elevation locus of GSTAR III is shown in Fig. 2. The plot represents a view from Woodbine, Maryland, and corresponds to an orbit inclination of 5 deg. Although the variations in azimuth and elevation are about 5 and 10 deg, respectively, the trace is fairly linear. Therefore, for smaller antenna (e.g., VSAT) applications, a single-axis tracking scheme can be feasible. Since the traces are computationally predictable, the tracking operation can proceed on an open-loop basis following an initialization and with infrequent updates.

The angular separation of GSTAR III from an adjacent geostationary satellite, located 2 deg apart in this case, is maintained or increased (Fig. 3). Therefore, it may be noted that the

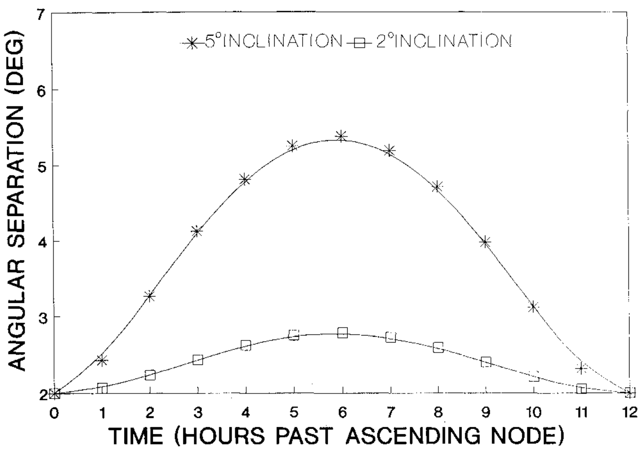

Fig. 3 GSTAR III angular separation from an adjacent geostationary satellite located 2 deg away.

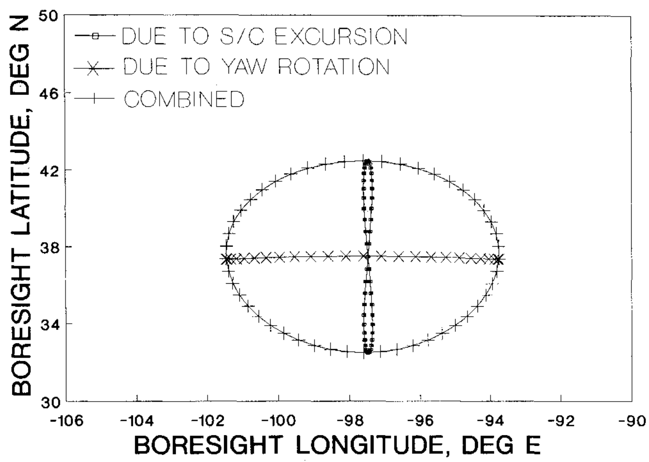

Fig. 4 Uncontrolled locus of antenna boresight for a 5 deg inclined orbit.

probability of interference with an adjacent satellite signal is decreased for GSTAR III service operations.

Spacecraft Antenna Boresight Pointing

The satellite excursion due to inclined orbit also results in a daily variation in the satellite antenna pattern. Part of this variation results from the linear displacement due to diurnal excursions in satellite location. In addition, the effective yaw rotation (discussed later) results in an oscillatory displacement of the antenna footprint. This is because the antenna boresight is located far north of the equator and a yaw rotation shifts the boresight in an east-west direction. Figure 4 shows the variations in boresight location for a 5 deg inclined orbit with a nominal boresight of 37.5°N and 97.6°W.

To minimize the variations in the antenna footprint on the ground, the spacecraft antenna boresight is pointed to the same spot on the Earth in the course of the excursion in spacecraft location. This is obtained by a series of spacecraft pitch and roll offset maneuvers completed as a function of time of day. Providing this roll and pitch offset, however, does not compensate for the yaw error resulting from inclination.

As described earlier, GSTAR III attitude can be offset up to a maximum of ±2 deg in roll and ±6 deg in pitch. GSTAR III can also accept a programmable roll and pitch offset commands up to a limit of ±0.5 deg and with a minimum interval of 12 min. The ratio of change in roll excursion to excursion in spacecraft latitude α is 0.127. Therefore, the roll and pitch table can be used to compensate for inclinations of up to 4 deg. With an extra set of manual commands per day for biasing roll and pitch offsets, this limit can be extended to 8 deg.

The appropriate roll offset can also be provided by skewing the spacecraft momentum vector H away from its nominal orbit normal orientation N, as shown in Fig. 5. The desired roll pointing can thus be obtained passively, without having to step through roll offset cycles on a daily basis. However, this method does not address the issue of observed yaw effects. In fact, the maximum daily yaw error is increased by the amount of skew.

Currently, GSTAR III is going through the roll and pitch offset cycle using the roll and pitch tables. The yaw angle is not being compensated for at this time. Preliminary link-budget estimates indicate that a yaw angle of up to 5 deg for projected service applications could be tolerated before a correction is required.

Yaw Pointing Error

The orbit inclination translates directly into the maximum yaw errors at the nodal crossings. For a spacecraft with its momentum vector perpendicular to the orbital plane (this includes the case where a roll and pitch table is being used), the yaw can be expressed as

$$\psi = i \cos nt$$

The maximum yaw would therefore be equal to the magnitude of inclination occurring at the nodal crossing times.

Maintaining the momentum vector skewed away from orbit normal, as described in the preceding section and Fig. 5, to provide the roll offsets without moving the pivot, results in a slightly larger yaw error at the nodes. The yaw profile for that case is given by

$$\psi = (1 + \alpha) i \cos nt$$

The term αi is the offset in roll required to compensate for the inclination.

Reference 5 suggests keeping the momentum vector perpendicular to the equatorial plane to eliminate the yaw error entirely, although it would still be necessary to provide the roll

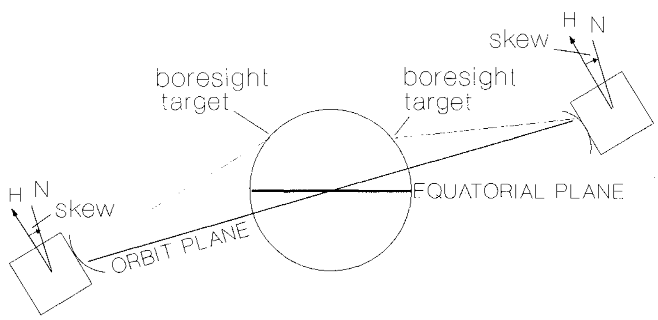

Fig. 5 Skewed momentum vector to compensate for roll.

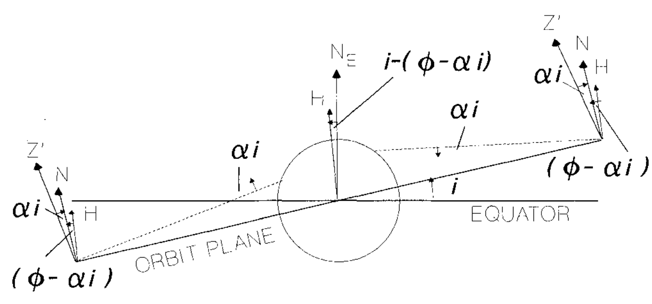

Fig. 6 Momentum vector skewed toward equatorial normal to compensate for yaw.

and pitch offset to keep the boresight pointed at the nominal location. This option would require a maximum pivot offset of $(\alpha+1)i$. On GSTAR III, since there is a physical limit ϕ_l of about 2 deg in pivot movement, the GSTAR III momentum vector could be maintained perpendicular to the equatorial plane only for inclinations smaller than 1.77 deg.

A compromise strategy has therefore been planned to reduce the maximum yaw error when the inclination becomes large, as shown in Fig. 6. It requires offsetting the momentum vector from its orbit normal orientation so that it approaches an equatorial normal orientation, the maximum allowed offset being $(\phi_l - \alpha i)$ degrees. Figure 7 shows the yaw error at the nodes, for this strategy, as a function of orbit inclination and compares this with yaw error at the nodes for the nominal case of momentum vector along the orbit normal. When the daily maximum yaw angle reaches 5 deg, the momentum vector is gradually shifted away from the orbit normal direction by the amount required to maintain the maximum yaw attitude at 5 deg. The magnitude of the momentum vector skew increases slowly with the increase in inclination until the pivot skew limit of ϕ_l is reached, which corresponds to the momentum vector offset of $(\phi_l - \alpha i)$. As shown in Fig. 7, this strategy can maintain the maximum yaw angles at nodes of 5 deg for an inclination of up to 6.3 deg. This is equivalent to an additional year and a half of operation.

The yaw profile resulting from this strategy will be

$$\psi = \left[(\alpha+1)i - \phi_m\right]\cos nt$$

for $i > 1.77$ deg. The pivot offset profile over a day will be

$$\phi = \phi_m \sin nt$$

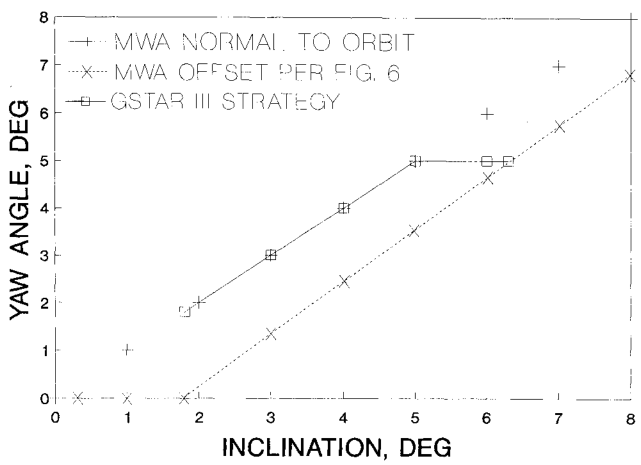

Fig. 7 Profile of GSTAR III maximum yaw angle.

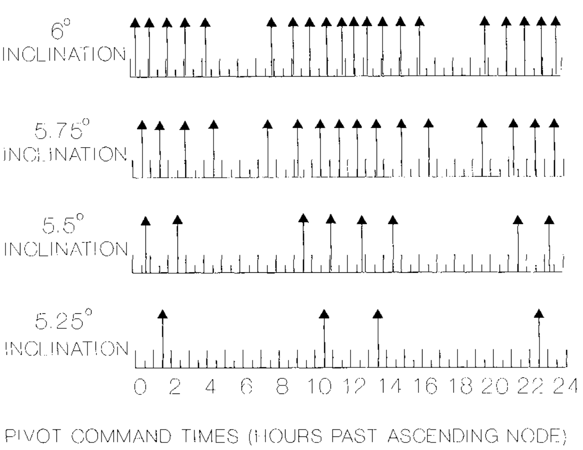

Fig. 8 GSTAR III pivot command frequency.

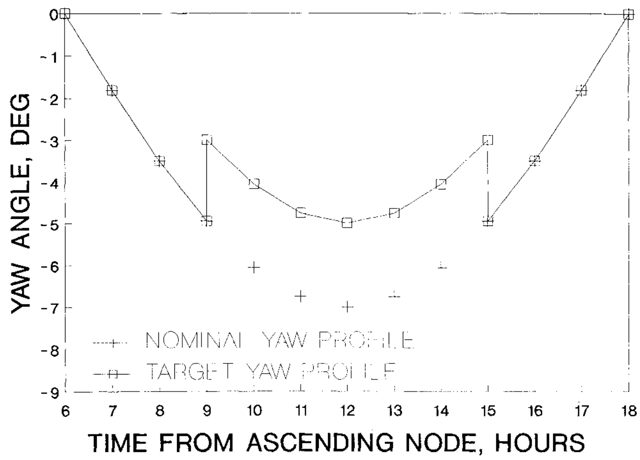

Fig. 9 GSTAR III yaw profile at descending node for 7 deg inclination.

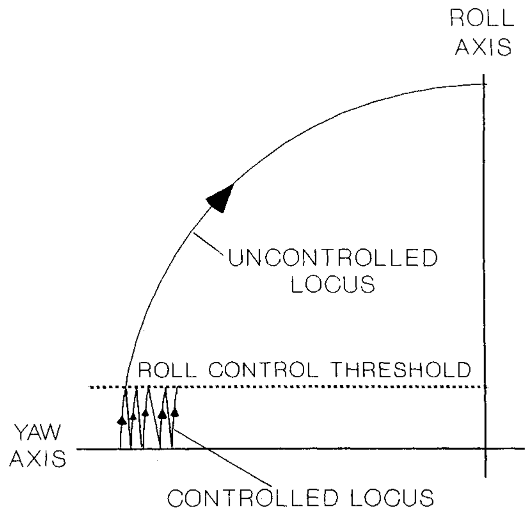

Fig. 10 Phase-plane plot of yaw-roll error vector.

The roll error due to offset in the spacecraft Z' axis with respect to the orbit normal N (Fig. 6), detected by the ESA, will be

$$\epsilon = \alpha i \sin nt$$

When the roll and pitch offset commands are sent through the roll and pitch table, the onboard APE implement them as commanded biases, and the magnetic torquers onboard maintain the spacecraft at this new attitude.

The pivot offset command will therefore be sent in two parts

$$\phi = \phi_a + \phi_b$$

where the first part

$$\phi_a = \alpha i \sin nt$$

will be sent through the automated roll table via APE. This will make the APE roll offset and the ESA roll offset identical, enabling the magnetic torquers to maintain the desired offset. The remaining offset command

$$\phi_b = (\phi - \alpha i)\sin nt$$

will be sent bypassing the APE. Sending this offset command (which makes the pivot position follow the sine curve representing the roll offset requirement) will have a big operational impact since sending pivot commands directly to the satellite is not automated. The frequency of pivot commands is a function of the amount of pivot offset required and the tolerance in pointing error. Figure 8 shows the command frequency required to keep the roll pointing within ±0.1 deg for different inclinations. Thus, the frequency of commanding, particularly at inclinations approaching 6 deg, could be an operational constraint, requiring yaw reduction using thrusters.

Thruster-Assisted Yaw Reduction

If reducing yaw reduction by the momentum vector offset and pivot commands described here is not feasible, it may be necessary to shift the momentum vector during nodal crossings by using thrusters. This will require four sets of maneuvers per day: two to move the momentum vector away from orbit normal orientation as the nodes approach and two to reset the orientation to orbit normal once past the nodes. Figure 9 shows the yaw profile for a satellite with an inclination of 7 deg as it approaches the descending node. As discussed earlier, the nominal yaw profile will have a maximum yaw angle of 7 deg. To keep the yaw angle from exceeding 5 deg, yaw maneuver 1 would shift the momentum vector away from its orbit normal orientation, by a magnitude of 2 deg in this case, and yaw maneuver 2 would restore the orbit normal orientation. This sequence would have to be repeated at every nodal crossing.

Reorienting the momentum vector effectively introduces a spacecraft yaw error. Over time, this yaw translates into roll error (for uncontrolled motion, yaw error completely translates into roll error in 6 h), which needs to be corrected. GSTAR III has a feature that automatically activates the appropriate roll control thruster to remove roll when a certain threshold is reached. This feature has to be activated between the two yaw maneuvers to keep roll error to within 0.1 deg. Figure 9 shows that for an inclination of 7 deg requiring a yaw maneuver of 2 deg, the roll control mode will be activated for about 6 h, during which time a total of 3.1 deg in roll will have been removed. Figure 10 illustrates the mechanics of yaw error being transformed into roll error and the roll error being removed by roll control thruster. This is a rather inefficient method of removing yaw error and only about 0.1 deg in yaw will have been removed compared to 3.1 deg in roll. However, this turns out to be a very desirable mode for this operation, since yaw offset will be maintained and the roll error kept within limits. The use of this strategy to reduce yaw at the nodal crossings is constrained by fuel availability.

Conclusions

GSTAR III, currently in an inclined geosynchronous orbit, has its nodal crossings' longitude maintained within a tolerance of ±0.05 deg about its assigned location at 93°W, without regulating its inclination. The nonzero inclination will produce a daily variation in spacecraft sublatitude and sublongitude trace. In the course of these excursions, the spacecraft antenna boresight is kept pointed at the same spot on Earth by programming the GSTAR III attitude to provide a series of daily pitch and roll offset maneuvers. Providing pitch and roll offsets, however, does not correct the yaw error that also results from the inclination. Therefore, when the yaw error becomes unacceptably large, the GSTAR III momentum vector is planned to be tilted toward an equatorial normal orientation and maintained in that attitude, while the pitch and roll offsets are simultaneously applied. This procedure will reduce the yaw error and extend the operational life of the satellite. In addition, the yaw angle can be controlled by using thrusters to appropriately tilt the momentum vector when approaching the nodal crossings and resetting it to the orbit normal configuration once past the nodes.

The techniques described in this paper are for a satellite that was not designed to operate in an inclined geosynchronous orbit. The GSTAR III ACS flexibility and robustness have permitted the adaptation of the existing design to inclined orbit operations. If a satellite is actually designed for inclined orbit operation, the operating procedure can be vastly simplified. As an example, if the pivot limit on GSTAR III was extended to 9 deg (instead of the existing 2 deg limit), if the APE table for pitch and roll offset was operational up to ±1 deg (instead of the existing ±0.5 deg limit), and if direct commands to the pivot could be automated, GSTAR III could be operated in an equatorial normal orientation up to an inclination of 8 deg. This would have totally eliminated the RF polarization plane rotation, and the boresight pointing could be automated through its operational life. The impact on the operations would have been negligible.

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