Evolution of an Attitude Control System for Body-Stabilized Communication Spacecraft

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Improvements in attitude control system autonomy and beam pointing accuracy are reviewed. The ten-year history is based on the implementation and performance of geosynchronous satellites, which utilize a momentum biased concept to provide a body-stabilized spacecraft for the communication payload. Innovations and advances in microprocessor technology enabled the attainment of improved pointing and greater autonomy. Decreasing structural frequencies associated with ever larger solar arrays are accommodated by higher order filtering and control estimators; thus, stable and accurate control performance is attained during both normal and stationkeeping operations.

Introduction

THIS paper discusses the evolution of an attitude control system (ACS) for body-stabilized communication spacecraft in terms of design implementations and program applications. Twelve years have passed since body stabilization was proposed in terms of the momentum bias/magnetic torquing concept in order to provide three-axis attitude control for what was then "the next generation of communication satellites."[1] This concept was first demonstrated at the 1964 AIAA meeting in Washington, D.C.; and it was applied to the control of sun-synchronous meteorological spacecraft, including TIROS, more than five years prior to its geosynchronous use. This basic momentum bias approach has been successfully applied to geosynchronous spacecraft since 1975, and a series of evolutionary developments and improvements has been implemented in order to meet the technological challenges of the ever more stringent communication payload requirements. Taking full advantage of innovative ideas and the rapid advances in microprocessor technology enabled the attainment of improved pointing accuracy and greater autonomy in controlling the attitude of today's and tomorrow's geosynchronous communication satellites.

Initial Implementation

Satcom I, which was designed and built within a two-year period, was launched by NASA from the Kennedy Space Center on December 12, 1975 via a Thor-Delta 3914 launch vehicle. This spacecraft was the first frequency reuse, domestic commercial communication satellite. In order to match the available Thor-Delta launch capability while accommodating a payload of 24 cross-polarized 5-watt TWTA channels, it was essential to minimize bus weight and retain considerable functional support at the ground station. The ACS consumed 15 watts average on-orbit power and weighed 55.5 lb ($\sim$2.8% of GTO weight). This satellite utilized several innovations in the implementation of its attitude control system.[2] Most noteworthy of these advances were the application of the Dual-Spin Turn (DST) for attitude acquisition,[3] closed loop magnetic torquing for on-orbit roll/yaw control,[4-6] Product-Of-Inertia (POI) damping for nutation attenuation,[7,8] and thruster pulse modulation for efficient North/South stationkeeping.[9]

Satcom I was injected into the geosynchronous transfer orbit while spinning at 60 rpm about the maximum moment of inertia axis. The preoperational (spinning) mode attitude determination is accomplished by means of the sun-nadir angle cone-intersection method. Spin axis reorientations prior to and subsequent to injection into the geosynchronous drift orbit are accomplished by sun referenced rhumb line steering. Firing thruster pairs which are perpendicular to the spin axis achieve the desired precession without perturbing the orbit. Subsequent to apogee injection, the spacecraft momentum is reduced by about one order of magnitude and aligned with the orbit normal. The desired orthogonality of the pitch axis with respect to the orbit plane is attained by means of the DST, which is a passive acquisition maneuver requiring only the activation of the momentum wheel. Subsequent to passive nutation damping and final despin to the nominal on-orbit momentum level, solar arrays are deployed and the pitch loop is closed for pitch capture.

The Satcom I spacecraft is shown in Fig. 1, and the attitude control system is shown schematically in Fig. 2. A dual-scan oscillating Earth Sensor provides both pitch and roll information to the attitude control electronics. Momentum interchange between the Momentum Wheel Assembly and the spacecraft results in autonomous pitch capture and control. The pitch loop also attenuates nutation in response to filtered roll information via Product-Of-Inertia Damping.[10,11] By interacting a magnetic dipole with the magnetic field prevailing at geosynchronous altitude, roll attitude is maintained via closed loop action within prescribed threshold limits.[12] Simultaneously, the primary disturbance of solar torque is magnetically compensated by means of body and panel mounted bias coils. Under normal conditions, yaw attitude is inherently maintained by gyroscopic coupling with the roll axis. During North/South (N/S) stationkeeping, a fast response roll/yaw control utilizing off-pulse modulation of four north panel thrusters simultaneously corrects the orbit and maintains spacecraft attitude.[13] During this phase, relative yaw error with respect to the initial momentum vector attitude is provided by a rate-integrating gyro. East/West stationkeeping and pitch momentum adjustment are accomplished by means of ground commanded thruster pulses. All of these Satcom I attitude control modes performed their functions satisfactorily and within prescribed tolerances and, therefore, contributed to the successful operation during the intervening period of more than eight years.

Presented as Paper 84-1839 at the AIAA Guidance and Control Conference, Seattle, WA, Aug. 20-22, 1984; submitted Dec. 6, 1984; revision received Aug. 8, 1985.

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Greater Autonomy

Since that auspicious beginning, there has been a steady evolutionary process of improving the attitude control performance. Much emphasis has been placed on making the spacecraft more autonomous, which not only eases the work load at the ground station but also minimizes the chance of command error. Table 1 summarizes this history in terms of control functions requiring ground commands or being autonomous. As indicated in the table, new functions were introduced over the years. Some of these developments were motivated by the need to improve pointing performance and accommodate lower structural frequencies. On the other hand, some functions were eliminated when new improved design concepts made the original purpose superfluous.

The initial magnetic roll/yaw control implementation[12] utilized a body-mounted yaw bias coil and a solar panel bias coil for open-loop torque compensation. These coils, which supplemented the primary roll magnetic torquer of the closed-loop control, required occasional adjustment via ground commands in order to optimize performance with changing seasons. Starting with Anik-B launched in December 1978, the orientation of the closed-loop dipole in the roll/yaw plane was optimized, negating the need for the two previously utilized supplementary bias coils.[14]

The on-orbit active nutation damping of Satcom I and II is accomplished by pitch momentum wheel torquing. In response to a filtered roll signal, which is combined with the pitch error signal, the wheel generates a damping torque which is transmitted into the transverse plane via a deliberately provided product-of-inertia. Since this damping process inherently couples the nutation oscillation into the pitch axis during the attenuation process, spacecraft operators enable this action only as required, i.e., subsequent to large disturbances such as those that might be induced by thruster operation. Beginning with Satcom IIIR, launched in November 1981, the magnetic attitude control loop was enhanced with nutation damping capability.[15] This damping process does not couple into the pitch axis and, therefore, does not need to be inhibited at any time. Greater autonomy once again results from this design improvement.

Secular disturbance torques about the pitch axis and stationkeeping interactions cause a deviation from the desired pitch momentum bias range. The nominal north/south orientation of the geosynchronous magnetic field precludes the use of this medium for pitch torquing. The Satcom I design requires ground commanded adjustments by means of thruster pulses in order to maintain the pitch momentum within the acceptable operating limits.[2] Starting with Satcom IIIR, this function has been automated in microprocessor firmware, providing autonomous momentum adjust control. Usually this correction is performed concurrent with the North/South stationkeeping maneuver.

Table 1 Command requirements of attitude control functions

SPACECRAFT	YEAR OF LAUNCH	PITCH CAPTURE & CONTROL	MAGNETIC ROLL/YAW CONTROL	PANEL BIAS COIL COMMAND	YAW BIAS COIL COMMAND	POI DAMPER ENABLE/DISABLE	MAGNETIC ACTIVE NUTATION DAMPER	MOMENTUM ADJUST PULSE COMMANDS	SOLAR ARRAY SLEWING FOR N/S S/K	INITIATE/TERMINATE N/S S/K	THRUSTER PULSE CONTROL N/S S/K	BIAS TORQUE SELECT N/S S/K	INITIATE/TERMINATE E/W S/K	THRUSTER PULSE COMMANDS E/W S/K	PIVOT ACTIVATED NUTATION DAMPER
SATCOM I	'75	A	A	G	G	G	•	G	G	G	A	•	G	G	•
ANIK B	'78	A	A	+	+	G	•	G	G	G	A	•	G	G	•
SATCOM IIIR	'81	A	A	+	+	O	A	A	G	G	A	•	G	A	•
SATCOM V	'82	A	A	+	+	O	A	A	+	G	A	•	G	A	•
GSTAR	'84	A	A	+	+	O	A	A	+	G	A	O	G	A	O
SATCOM Ku	'85	A	A	+	+	O	A	A	+	G	A	A	G	A	A
STC/DBS	'86	A	A	+	+	O	A	A	+	G	A	A	G	A	O

G GROUND COMMAND
A AUTONOMOUS
O OPTIONAL
\+ NO LONGER REQUIRED
• NOT AVAILABLE

Until 1982, body-stabilized spacecraft referred to in this paper utilized a solar array offset along the yaw axis. This design feature permitted the use of a single Solar Array Drive (SAD) for the required counterrotation of both the north and south solar array with respect to the earth oriented spacecraft body. However, prevailing plume interactions during N/S stationkeeping necessitated the reorientation of this array into the pitch/yaw plane. With the launch of Satcom V, the implementation of a centered array, utilizing two SADs, enabled the execution of the inclination adjust maneuver for any array angle, obviating the need for ground commanded solar array slewing prior and subsequent to thrusting. Since the pulse modulated N/S stationkeeping mode has always been autonomous, it is now only necessary to enable appropriate thrusters, corresponding catalytic heaters, and the gyro in order to perform this maneuver. The concurrent maintenance of three-axis attitude and bias momentum is completely automatic.

As the size of communication spacecraft and solar arrays grew over the years, structural modes continued to drop to ever lower frequencies. For example, the total solar array area

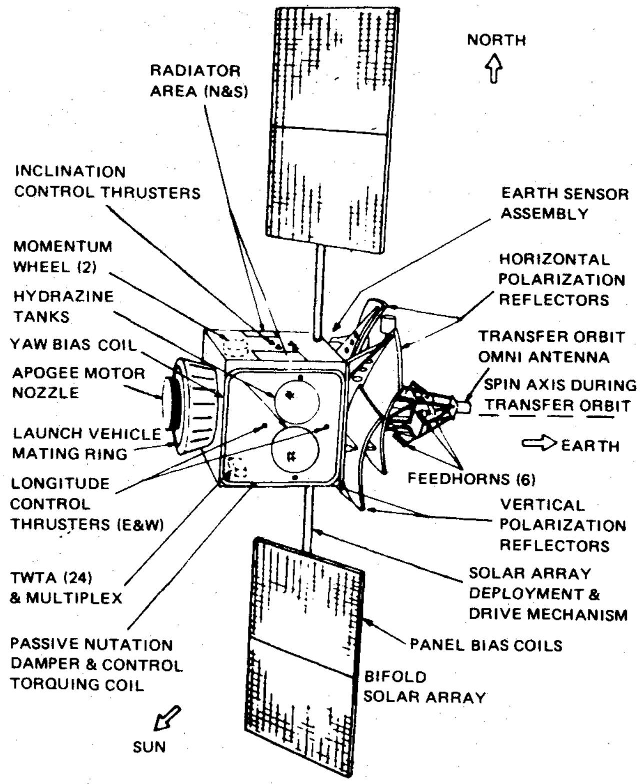

Fig. 1 RCA Satcom I—launched in 1975.

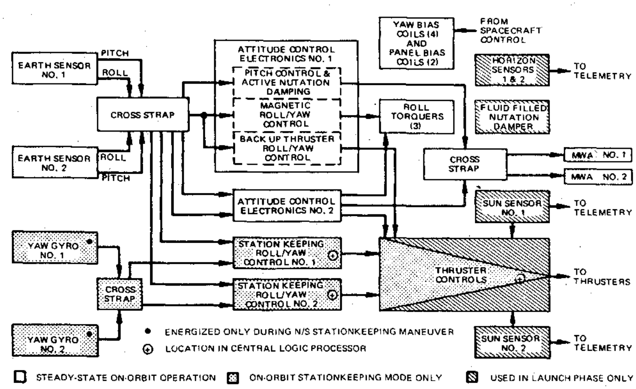

Fig. 2 Attitude control system for RCA Satcom I.

of Satcom I is 75 ft, whereas that of Satcom K is 280 ft. Simultaneously, payload pointing requirements became more and more precise. Therefore, the need arose for an ACS which could accommodate low structural frequencies (approximately 0.1 Hz fixed base) while simultaneously providing improved pointing. For the nonpropulsive mode which prevails more than 99.5% of in-orbit time, the momentum interchange and magnetic torque precession control are quite capable of satisfying these two more stringent requirements. For stationkeeping and, in particular, during the N/S maneuver, this dual goal was satisfied by linearizing the thrust-pulse modulation, i.e., making the pulse width proportional to the attitude errors. To further reduce errors while remaining within the bandwidth constraint imposed by the structural modes, an onboard observer-derived trim torque continuously removes offsets during the orbit adjust period. Although these stationkeeping attitude control algorithms are more sophisticated than in the original Satcom I design, the 1985/86 Series 4000 (Satcom KuBand) and the Satellite Television Corporation (STC/DBS) spacecraft perform this control phase with complete autonomy. For the first Satcom spacecraft, the East/West (E/W) orbit adjust was accomplished by means of ground commanded thruster pulses alternating with ground activated backup roll control. Beginning with the 1981 spacecraft, the desired number of stationkeeping pulses is stored and executed automatically, while the concurrent attitude control pulses are provided autonomously.

For the Series 3000 (SPACENET, GSTAR, American Satellite) satellites which became operational in 1984 and 1985, the previously fixed pitch momentum bias wheel is mounted on a platform which is able to pivot about the roll axis with 4.5×10^{-3} degree steps. This permits bias and long-term roll pointing error compensation as will be discussed subsequently. Combining this feature with rate signals available from rate-integrating gyros enables the implementation of a very effective nutation damper. This Pivot Actuated Nutation Damper (PANDA) generates damping rates of 50 and 8 deg/h after the Dual-Spin Turn and during normal on-orbit operation. The PANDA feature is implemented as an autonomous on-board loop for spacecraft scheduled for late 1985 and beyond. This will permit the elimination of the cross-coupling product-of-inertia damper, which has been carried only for optional use since 1981.

Thus, within a period spanning one decade, an evolutionary process has substantially increased the autonomy of the ACS and concurrently improved the beam pointing accuracy. Figure 3 graphically depicts the inverse relationship between ACS functions requiring ground commands and those performed in an autonomous manner. Except for ground command initiation and termination of stationkeeping maneuvers, the control of this series of body-stabilized communication spacecraft is now performed exclusively on board via closed-loop action. The full utilization of modern microprocessor technology was an important facilitator towards such a desirable independence from the ground station. The ACS which accomplishes this performance improvement (Fig. 4) consumes 40 watts average on-orbit power, weighs 82.6 lb ($\sim$2% of GTO spacecraft weight), and is completely redundant. The system includes the components required for all mission phases including those used exclusively in the preoperational (orbit achievement) mode. Ground overrides and ground logic control loops are available as backups to the various redundant autonomous control modes.

Improved Pointing Accuracy

Accurate pointing of the antenna beam is, of course, the primary function of the ACS of a communication satellite. The various sources which affect this pointing accuracy include tolerances due to attitude determination, attitude control, component alignments, orbital position, maneuver transients, eclipse induced disturbances, quantization limits, and thermal distortions. For each spacecraft axis, these errors are subdivided into bias and long- and short-term time categories. Then the pitch, roll, and yaw RSS of each of these three subsets is determined. Pitch and roll attitude errors translate into E/W and N/S beam pointing errors, respectively. Yaw errors represent a rotation about the local vertical which is manifested as a rotation of the antenna beam. This rotation couples with E/W and N/S in proportion to the line-of-sight angle relative to satellite nadir. This relatively small yaw contribution is then statistically combined with the pitch and roll tolerances to arrive at the overall E/W and N/S pointing accuracy. The overall accuracy is defined by the arithmetic sum of the bias, long-term, and short-term subtotals. In-orbit control performance over the years has correlated well with prelaunch predictions. While the control error could be determined from the attitude sensor date, analysis of the communication payload performance was required to demonstrate that the attitude determination accuracy also satisfied prelaunch predictions.

Figures 5 and 6 depict the E/W and N/S beam pointing improvements as a function of spacecraft launch dates. During most of the on-orbit time (more than 99.5%), the normal (nonpropulsive) performance governs. The remainder of the time is defined by the accuracy which prevails during the thruster mode (stationkeeping and momentum adjust maneuvers). By means of on-orbit ACS and payload calibrations, which take place primarily in the preoperational phase, pitch bias errors always could be removed. This results in the first (E/W) improvement in pointing accuracy shortly after the launch of Satcom I. The N/S improvement of 1978 (Anik-B) uses on-orbit calibration to detect misalignments of the Earth Sensor with respect to the Momentum Wheel. It corrects these misalignments by a biasing technique. It is appropriate to observe at this point that, beginning with Anik-B, the optimization of the magnetic dipole orientation in conjunction with a reduced control threshold improves both roll and yaw pointing performance.[14] In the normal mode, skewed magnetic torquing controls simultaneously roll and yaw attitude in response to roll error; i.e., the control provides desirable orbital yaw damping.

With the launch of the Series 3000 spacecraft in 1984, substantial pointing performance improvements are realized, particularly in the stationkeeping mode. The utilization of an all-digital attitude control logic, as implemented in the redundant Attitude Processing Electronics (APE), permits the application of more sophisticated algorithms and filtering techniques. As a result, the short-term errors prevalent during stationkeeping are significantly reduced in comparison to the prior capability.

For all spacecraft discussed herein, the ACS is referenced to the Earth Sensor and the payload antenna is rigidly mounted

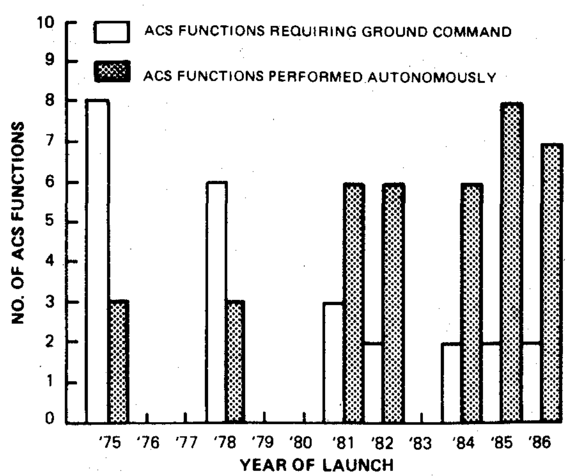

Fig. 3 Increased ACS autonomy.

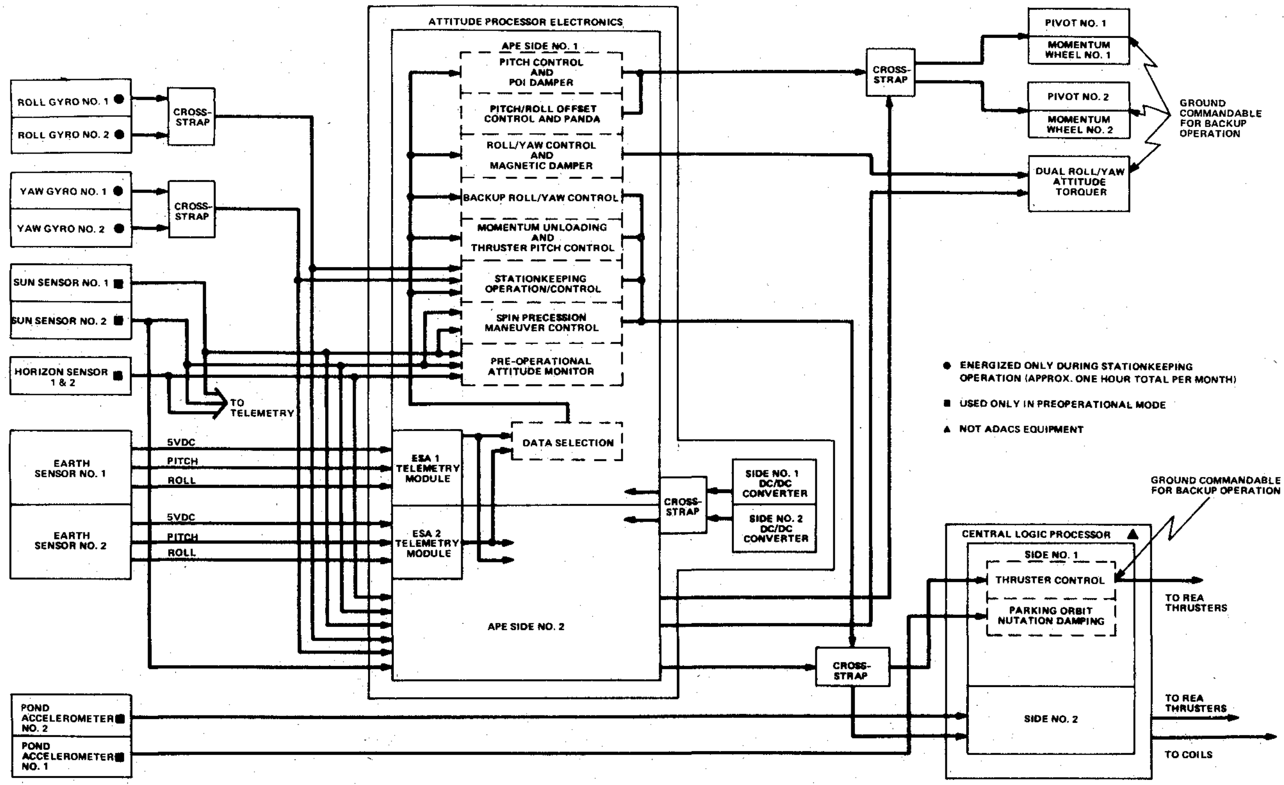

Fig. 4 Attitude control subsystem for Satcom Ku-band.

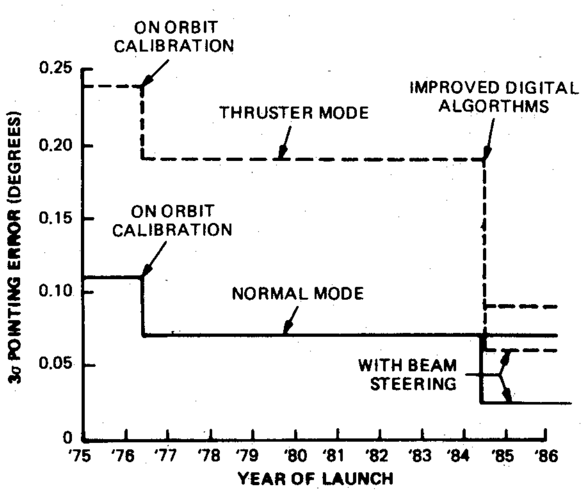

Fig. 5 East/West beam pointing accuracy.

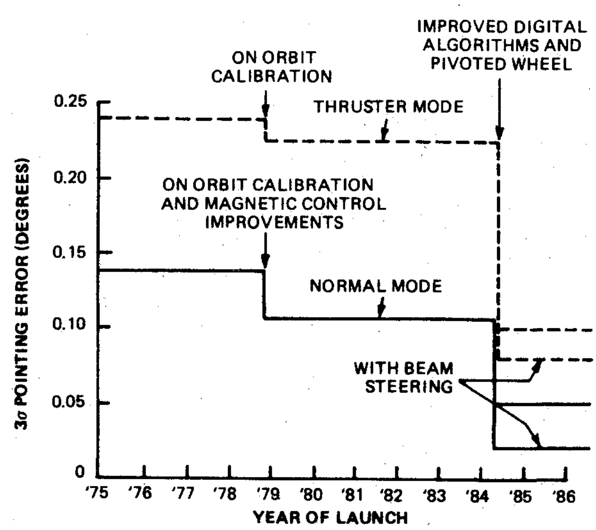

Fig. 6 North/South beam pointing accuracy.

to the bus structure; thus, correct spacecraft bus orientation is nominally equivalent to achieving correct antenna pointing. However, certain effects contributing to the beam pointing error such as antenna misalignments and thermal distortions of the bus structure and/or the reflector are not observable by the earth sensor and are, therefore, not inherently corrected by the ACS. For the STC/DBS spacecraft, the deployable antenna and the Earth Sensor are installed on a precision mounting plate, thereby avoiding thermal distortion effects of the bus on the pointing accuracy.

Since the ultimate objective is the antenna beam pointing of the communication payload, additional features have been provided to increase the pointing accuracy of the antenna itself for spacecraft launched in 1984 and subsequently. Based upon on-orbit calibration with Earth stations, it was always possible, starting with Satcom I, to compensate for E/W biases caused primarily by the alignment tolerances of the antenna and the Earth Sensor. This function is accomplished by offsetting the reference index pulse of the pitchloop in 0.01 deg increments. For the 4000 Series spacecraft, the pivot-platform mounted Momentum Wheel provides a similar degree of freedom in the N/S direction with an offset pointing resolution of 4.5×10^{-3} deg.

By utilizing the Beam Optimization Steering System (BOSS) developed for GSTAR, satellite E/W and N/S antenna pointing may not only be refined by vernier bias adjustments but can be corrected for small diurnal or seasonal deviations as well. Power ratio measurements of alternately switched signals from the communications and reference horn antenna[16] need to be conducted at several widely separated unmanned Earth stations. These stations have to be located where the communication antenna beam gain is changing rapidly as a function of displacement and where the reference horn antenna pattern is much less sensitive to pointing offsets because of its broader beam width. The remote station data is automatically transmitted to and processed at the satellite operations control center. Vernier pitch and roll attitude corrections are subsequently formatted for uplink to the satellite. These data are stored and time tagged in the on-board memory of the APE which can generate up to 128 vernier attitude steps per axis per orbit. These steps adjust the pitch loop index pulse and/or the wheel pivot position. Updates of the stored schedule may occasionally be implemented to adjust for seasonal effects. Although closed-loop RF tracking could be provided for body-stabilized momentum biased spacecraft, the BOSS approach avoids the continuous dependence on the operational ground station as implied by the tracking scheme. Furthermore, BOSS permits corrections not only for antenna boresight errors but also for distortions of the antenna pattern, including those in the fringe areas. Figures 5 and 6 depict the improvement of spacecraft pointing performance made possible by the utilization of BOSS. During the prevalent normal mode, the BOSS-enhanced ACS attains beam pointing within 0.02 to 0.03 deg. This performance includes BOSS bias measurement errors and thermal noise effects in ground measurements.

Conclusion

Greater spacecraft autonomy and improved pointing precision represent the two primary improvements which evolved during the past decade. In addition, the momentum biased satellite performance was enhanced by making the attitude control compatible with a wide range of spacecraft mass properties and structural flexibility. Decreasing structural frequencies associated with ever larger solar arrays are being successfully accommodated by higher order filtering and estimators, thus assuring stable and accurate attitude control performance during both normal and stationkeeping operations.

The evolution towards greater spacecraft autonomy, tighter beam pointing accuracy, and compatibility with a wide range of mass properties has significantly enhanced the performance of body-stabilized momentum biased satellites. This process will continue in order to satisfy the ever more challenging requirements of tomorrow's geosynchronous communication satellites.

Acknowledgments

The author would like to thank those personnel of the RCA Astro-Electronics technical staff who participated in the evolution and successful implementation of the ACS described in this paper. Special thanks are extended to Stephen M. Fox who reviewed and prepared the presented pointing performance data.

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