RAE-A Attitude Determination Ground Support System

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A disk-oriented programing system designed to support all attitude-dependent portions of The Radio Astronomy Explorer-A (RAE-A) mission is described. The RAE-A is a gravity-gradient-stabilized spacecraft characterized by four 750-ft-long experimental booms. Functions performed by the attitude support system, during both spin and despun mission phases, include reduction and calibration of telemetry data; determination, prediction, and command of spacecraft attitude; simulation of data for test purposes; and system maintenance. Design constraints imposed by mission requirements, spacecraft sensors, and existing ground support equipment (computers and tracking stations) are discussed. Summary descriptions of major program modules, their use and typical performance, are given. All significant atittude-related events, including apogee motor ignition and real-time observation of total spacecraft attitude during boom deployment maneuvers, are discussed.

Introduction

RADIO Astronomy Explorer-A (RAE-A, Explorer 38), a gravity-gradient-stabilized spacecraft designed to detect and measure various outer-space radio signals, was launched from the Western Test Range on July 4, 1968, by a 3-stage improved Delta booster vehicle, and the launch sequence closely followed nominal plans.[1,2] The launch vehicle placed the spacecraft in a near-nominal transfer orbit and spin-stabilized it at about 90 rpm. The apogee motor was later ignited on ground command to inject the spacecraft into a near 6000-km circular orbit. Following yo-yo despin to about 3 rpm, the spacecraft was further despun and oriented (approximately) by ground-command of an onboard magnetic control system.[3] Finally, four 750-ft antenna booms and a libration-damper boom were deployed in steps on ground-command for gravity-gradient capture; a dipole antenna was also deployed by ground-command.

Between launch and boom deployment, several critical attitude-related decisions were required at the Goddard Space Flight Center (GSFC). These decisions were formulated and executed using data supplied by the RAE Attitude Determination System (RAEADS). This ground support system, designed specifically for RAE-A, is a disk-oriented IBM System/360 programing package. It provides 3-axis attitude data as RAE-A acquires and transmits data from its circular, retrograde (102° inclined) orbit. READS also can provide 3-axis attitude determination in real time. This feature permits precise determination of near-optimum boom deployment time.

Presented as Paper 69-983 at the AIAA Aerospace Computer Systems Conference, Los Angeles, Calif., September 8–10, 1969; submitted September 5, 1969; revision received May 18, 1970. Work for this paper was funded under Contract Number NAS 5-10022 with the Computations Division, NASA Goddard Space Flight Center, in support of the Radio Astronomy Explorer Project.

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Spacecraft and Ground Systems

The spacecraft main body is cylindrical, approximately 36 in. in diam and 31 in. high, with four fixed solar paddles. Spacecraft total weight, excluding apogee motor, is ~380 lb. Experimental V-antennas are not shown in Fig. 1. At launch, the four 750-ft booms comprising the two V-antennas were wound on motor-driven reels. The booms were simultaneously payed-out (in steps) on ground-command as previously mentioned and as discussed later. Two onboard transmitters provide real-time and playback data transmission, at 400 and 10,000 bps, respectively, to STADAN ground stations via a telemetry and command antenna.

Mission characteristics required use of two types of onboard sun sensors. During the transfer orbit phase, with the spacecraft spin-stabilized, fan sun sensors were employed to measure the angle between the spacecraft spin axis and the sun-line. After despin, raw solar aspect sensor outputs replaced the fan sensor outputs in the telemetry stream; a total of eight solar aspect sensors are aboard RAE-A. As shown in Fig. 1, two sensors are mounted on each of four solar paddles; only one of the eight aspect sensors is used at a time. Outputs of these sensors permit resolution of the detected sun-line vector into any convenient spacecraft body frame.

Three mutually perpendicular magnetometers also are employed. The axis of one is directed along the spacecraft spin axis. These devices, together with the solar sensors, supply the data required for attitude determination during the transfer and operational orbit phases. In addition, cameras are used to record tip positions of the four long booms. A tip reflector on each boom appears as a circular area in the pictures. The pictures in which the Earth appears in the background also are used in an attitude backup system in RAEADS.

Attitude control prior to boom deployment was effected by an onboard, ground-commanded, magnetic control system comprising the foregoing magnetometers, an orthogonal set of three electromagnets, a magnetometer-driven "hysteresis generator" and associated electronics.[3]

Seven STADAN ground stations (Fairbanks, Rosman, Tananarive, Orroral, Winkfield, Barstow, and Santiago),

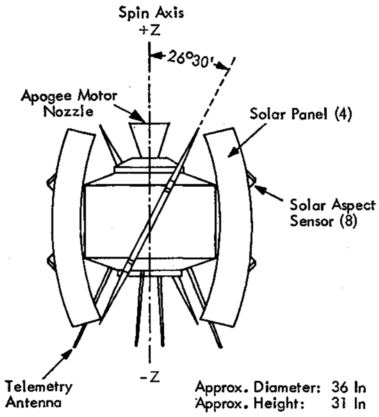

Fig. 1 RAE-A main body schematic.

coupled to GSFC by 48-kHz or 3-kHz data links, support RAE-A. Each station can transmit commands to it. All major functions are supported with backup systems. The GSFC Multi-Satellite Operations Control Center (MSOCC) is prime control center, and the GSFC Test Control Center (TCC) is its backup. Each is equipped with an SDS-930 computer for initial processing and conversion of data into engineering units as received from the ground stations. These computers provide quick-look status information, and generate raw attitude data tapes for the primary mission support computer—an IBM System/360 Model 95, with an IBM System/360 Model 75 as backup.

The primary means of transferring raw attitude data from the SDS-930 to the System/360 is by means of magnetic tape. Since MSOCC is physically located one floor above the System/360 and TCC is about 2000 ft away in another building, the tapes are hand-carried from one location to the other. Each tape contained data taken in real time during a pass over a tracking station or playback data stored by an onboard tape recorder during a previous orbit and read out during the pass over the tracking station.

For the real-time monitoring of boom-deployment operations, raw data are transferred manually via a standard telephone link. This technique was, of course, susceptible to input data errors, since no smoothing was possible. Elapsed time between spacecraft readings and attitude determination was less than 2 min.

An important element of the over-all attitude determination process is the concurrently executed orbit determination effort, accomplished on IBM 7094 computers using tracking (interferometer) data received from ground stations. These data were supplied to RAEADS on magnetic tape and updated approximately once per week.

RAEADS Development

For RAEADS software design and development, functional requirements consistent with mission objectives, existing ground support equipment, and spacecraft onboard sensors, and telemetry equipment were determined, and a group of self-contained program modules and catalog procedures to perform these functions were designed. Each module was written with a well-defined, fixed external interface, so that each could be changed internally without impact on other modules, since 29 interfaces were involved. Each module consisted of a main program and one or more subroutines, some of which were common to more than one module. Where possible, programs previously designed for GSFC use with other spacecraft were adapted. Next, a disk-oriented operating system (program and data storage are in a direct-access disk storage device) was designed and developed, the first employed by GSFC in an attitude determination application.

The disk-oriented system approach reduces the required number of magnetic tapes, simplifies program setups, and allows more efficient management of intermediate data sets. As a result, effective near real-time mission support is possible by operating RAEADS in a multiprogram machine environment. Thus, in contrast to previous GSFC-supported satellite launches, RAE-A did not employ a dedicated computer for attitude determination. Finally, prelaunch tests and simulations were conducted to ensure proper program and system operation under nominal and off-nominal mission conditions.

System Description

The major functions performed by RAEADS (Fig. 2) are 1) reduction and calibration of spacecraft telemetry data, 2) attitude determination, 3) attitude prediction, 4) data simulation for prelaunch program checkout, and 5) system maintenance (e.g., transferring data sets onto tape). (Modules used only for simulation and test purposes are shown in broken lines.) Raw telemetry data recorded on magnetic tape by MSOCC are first processed by program RAEPRO, which reads and unpacks data records, calibrates sensor readings, performs time correlation, and creates attitude data sets (on disk or tape) which form the basis for attitude determination calculations.

Attitude Determination

Three attitude determination programs are employed. One (DYCON) is applicable only during the transfer orbit phase, when the spacecraft is spin-stabilized and attitude is specified in terms of spin-axis right ascension and declination relative to geocentric inertial coordinates. It employs a weighted least-squares approach using telemetered readings from the fan solar sensor and the spin-axis-mounted magnetometer. Spin-axis motion is approximated by quadratic polynomial time functions. The other two (TRIAD and DSOAP) are used during despun mission phases, when attitude is specified in terms of pitch, roll, and yaw angles relative to an orbital reference frame. The programs employ readings from any one of the eight solar aspect sensors and all three magnetometers. Program TRIAD implements a deterministic attitude-fixing method in which attitude angles are calculated point by point at each instant solar aspect sensor and magnetometer data are simultaneously available. "Moving arc" polynomial curve fitting is used to interpolate, smooth attitude angles and infer attitude angle rates. Smoothing intervals are varied in different mission phases as functions of spacecraft attitude frequency characteristics. For normal, nonreal-time monitoring, TRIAD operates on attitude data sets created on disk or tape by RAEPRO. For real-time monitoring, a simplified version of TRIAD is employed which allows raw sensor data to be entered manually point-by-point via the keyboard of a standard graphic display unit.

Program DSOAP/MAGCAP estimates attitude and attitude rate by direct search-optimized smoothing of redundant magnetometer, solar sensor, and camera data. Smoothing consists of a weighted least-squares curve fitting procedure in which the "trial" smoothing curves (i.e., functions of time) are generated by numerical integration (for different initial conditions) of the simultaneous set of nonlinear Euler differential equations. These equations model spacecraft rigid-body attitude motion according to gravity-gradient and magnetic control torques, including those due to the hysteresis damper. Selection of different initial conditions leading to trial smoothing curves is accomplished automatically by means of Powell's "conjugate directions" direct-search algorithm for numerical optimization of a function of several variables.[4]

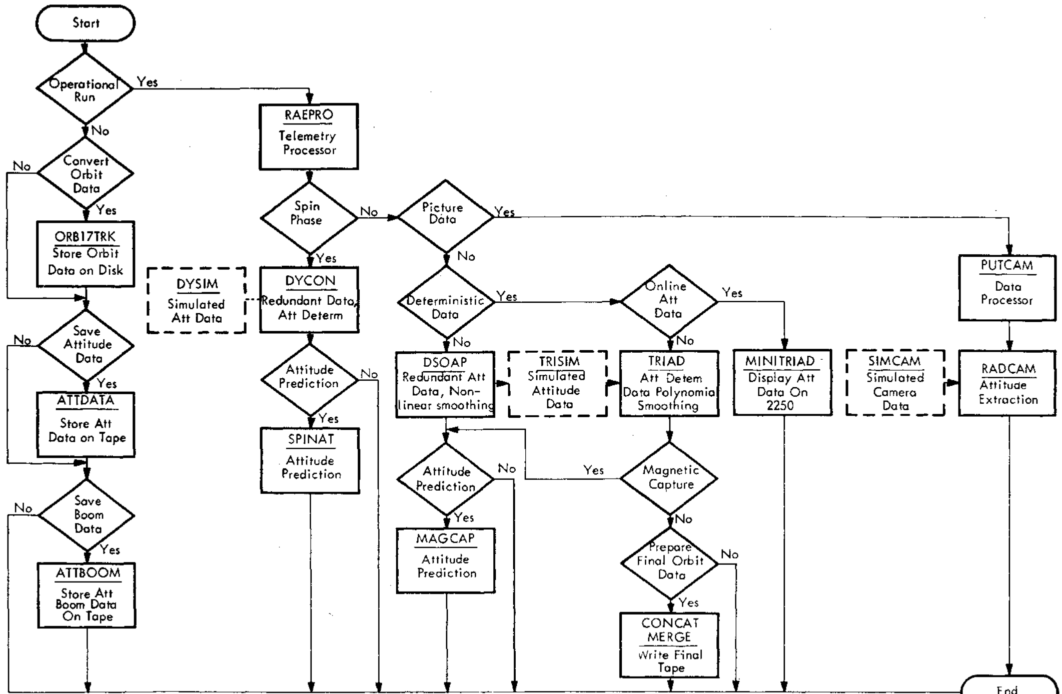

Fig. 2 RAEADS control flow.

In addition to providing attitude state estimation in the event of sensor failure, DSOAP was employed to estimate parameter values for an empirical model of the spacecraft magnetic control system hysteresis damper. A model of this damper was required to achieve attitude predictions over a 4-hr period.

Attitude Prediction

Attitude prediction and command/control in the spin phase are performed by program SPINAT. Spin-axis motion due to gravity gradient, magnetic bias, and magnetic control torques is obtained by rectangular integration of the motion equations for a rapidly spinning body. In addition to predicting attitude for specified (input) magnetic control coil settings, SPINAT is also used to calculate a magnetic control torque command sequence to give maximum spin-axis precession toward a specified (desired) spatial orientation. The calculated sequence takes account of the fact that all commands must be initiated and terminated when the spacecraft is within view of a tracking station.

Attitude prediction in the magnetic capture phase prior to antenna boom deployment is performed with program DSOAP by suppressing the direct-search option and specifying appropriate initial conditions. Mathematical details[5–8] are summarized in the Appendix.

Backups

Backup attitude information is provided by the four onboard cameras the primary purpose of which is to determine tip deflections of the highly flexible 750-ft antenna booms. From the pictures in which Earth appears in the background, a set of component values is determined which minimizes the weighted least-squares deviation between observed (computer-processed pictures) and predicted values for the Earth's limb points. Observed points are corrected for electronic and optical distortion. The resulting unit vector defines a multiplicity of spacecraft attitudes, but when combined with other sensor data, unique attitude solutions are obtained. A backup system is provided by a binary tape containing a separate system program in executable load module form in each file. These (binary tape) load modules are the same as those stored on disk except for their executable form. This approach obviates the need for a program library since all of the required subprograms are already linked directly with the main program.

System Integration

RAEADS data output (printer listings, disk data sets, and tape output) were used in RAE mission support by the Computation Division at GSFC. In addition, output data on tapes and/or disks were supplied to 1) the Mission and Trajectory Analysis Division for use in a) the RAE apogee motor ignition program RAEMOT[9] to determine ignition times to circularize the RAE transfer orbit and b) in a Westinghouse-developed system to aid boom and post-boom deployment calculations, and 2) the Spacecraft Integration and Rocket Sounding Division for use in an AVCO-developed system to determine boom deployment times and provide post-boom deployment support. Initially, RAEADS and these other programing systems were to be implemented on separate computers at GSFC. However, because of the enormous computing capacity of the System/360 Model 95, all programing systems used for RAE-A launch support were converted from tape to disk data sets and integrated on the same disk volume employed for RAEADS. The integrated system substantially reduced the required number of tapes

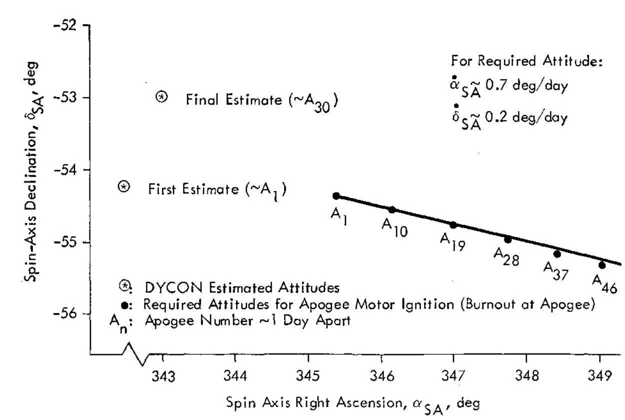

Fig. 3 Estimated and required RAE-A spin-axis attitudes.

and tape drives and allowed over-all system operation on one computer in a multiprograming environment.

Implementation of the integrated system required assignment of specific disk storage areas for individual programs and associated data sets. A special disk mapping routine was developed to list names and contents of data sets residing on the disk volume and the amount of remaining space. An over-all computer operating plan was established which resolved conflicts arising when several programs simultaneously required the same facilities (e.g., central utilization was provided for all launch support mission phases). Maintenance procedures were implemented and periodically executed to purge obsolete data sets, move out-of-date data sets to magnetic tape archives, copy disk volume contents to backup magnetic tape, test for defective tracks, and assign alternative ones.

Mission Support

Spin Phase

During the spin (transfer orbit) mission phase, programs RAEPRO and DYCON§ were continuously used to estimate spin-axis attitude from one or more passes of telemetry data. This estimate was then used to initialize program SPINAT for control-free attitude predictions at future times corresponding to successive transfer orbit apogees. These predictions were compared to the values required by the apogee motor to insert the spacecraft into the final (ideally, zero eccentricity) orbit. Since the comparison showed an excessive deviation between predicted and required attitudes,¶ program SPINAT was used to calculate an attitude control torque time history to drive the spin axis to within a specified tolerance of the required attitude. The whole procedure was repeated several times as improved attitude estimates were obtained; alternative control torque sequences were considered, and alternative values of desired attitude were calculated.

Figure 3 is a plot, on the α_{SA}, δ_{SA}-plane,** of the initial and final DYCON attitude estimates and the attitudes required for apogee motor ignition. Due to its high spin rate (92 rpm), RAE-A experienced negligible precession. Thus, as shown in Fig. 3, initial and final attitude estimates changed only slightly due to data accuracy improvement while required attitude (plotted in Fig. 3 as a function of one-day-apart apogee numbers) was changing significantly due to the changing ignition geometry induced by orbit nodal line progression. The difference between estimated and required attitudes was therefore increasing with time. (In Fig. 3, initial and final estimated attitudes correspond to required attitudes at about apogee 1 and 30, respectively.) When combined with data on sensitivity of final eccentricity to observed attitude deviations, the data of Fig. 3 implied that a preignition attitude reorientation maneuver was required to reduce the deviations to acceptable levels.

Execution of the preignition reorientation maneuver was made unnecessary by further analysis of data supplied by the apogee motor ignition program. By simply delaying ignition time by 68 sec, a reduction in final orbit eccentricity was achievable with the then current spacecraft attitude.†† Apogee motor ignition without a preignition reorientation maneuver was therefore recommended and successfully executed on July 7, 1968. The resulting eccentricity of 0.001 was well below the maximum allowable value dictated by boom depolyment dynamic constraints.

§ Although RAEPRO and DYCON are two distinct programs, they were run simultaneously in a so-called 2-step job to shorten computer turnaround time.

¶ Allowable deviation between actual and required attitudes was determined by program RAEMOT which evaluates the final in-orbit effects of deviations from nominal attitude at apogee motor ignition time.

** Symbols α_{SA}, δ_{SA} represent spin axis attitude-fixing angles right ascension and declination, respectively.

†† Spacecraft attitude was such that the radial component of orbital velocity prior to apogee nullified the corresponding attitude-induced component to final orbital velocity.[9]

Magnetic Capture Phase

After yo-yo despin (to about 3 rpm) and throughout the magnetic capture phase, monitoring of 3-axis attitude was performed using program TRIAD. Spacecraft magnetic capture approximately established the attitude state required for initializing antenna boom deployment. Mission plans required prediction of future attitude to within a few degrees accuracy for a period of ~4 hr (one orbital period). This predicted attitude history was to supply the initial conditions required by other simulation programs to compute the exact time to initiate boom deployment.

Attitude prediction in the magnetic capture phase was performed with program MAGCAP. Magnetic capture prediction accuracy was limited by difficulties encountered in simulating the damping effects of the onboard hysteresis generator. Because of approximations involved in its derivation, the hysteresis generator model was designed to include three "free" parameters[10] with numerical values adjustable by using DSOAP/MAGCAP to fit predicted model motion to observed (in-orbit) data. Values for these parameters were necessary to achieve the accurate attitude predictions required to support boom deployment. Due to the empirical nature of the hysteresis damper model, the unknown parameters could not be obtained in prelaunch analysis since data on actual system performance did not exist.

Program DSOAP/MAGCAP was thus used to estimate attitude, attitude rates, hysteresis damper parameters, magnetometer bias, etc. Different combinations of these quantities were employed in a series of computer runs, and comparisons were made on the residuals between measured and predicted values of the observables (sun and/or magnetometer readings). In addition, the time histories of attitude angles resulting from these estimates were compared with TRIAD-calculated values obtained during attitude monitoring for the same time period. Finally, 4-hr attitude predictions were made using the estimated hysteresis parameter values based on either DSOAP/MAGCAP estimates or TRIAD calculated values as initial conditions.

This sequence of operations was repeated with limited success several times over the 10-day period from July 12, 1968, until first boom deployment on July 22, 1968. Figure 4 illustrates attitude prediction accuracy typically achieved; it compares MAGCAP predictions with actual (measured) spacecraft attitude during a boom deployment exercise conducted on July 20, 1968. Pitch (β), roll (α), and yaw (γ) angles are plotted against time in the vicinity of 30-min-wide boom deployment windows.‡‡ Although each predicted attitude angle is slightly out-of-phase with its measured counterpart, prediction accuracy is sufficient to correctly predict window entry (i.e., whether an upcoming pass can be expected to yield a GO or NO/GO deployment situation). However, since boom deployment is possible only when angles (β,α,γ) are simultaneously contained within their respective windows (with near-zero values for each angle highly desirable), prediction accuracy is not sufficient to give reliable estimates of boom deployment time. This accuracy limitation is due primarily to the simulation difficulties characteristic of hysteresis phenomena and to the rather "loose" magnetic capture achieved by the spacecraft. Nonetheless, attitude predictions achieved by MAGCAP/DSOAP proved to be valuable boom deployment planning and monitoring aids.

‡‡ These attitude-limiting windows were established by prelaunch studies and are based on boom dynamic and station visibility constraints.[11]

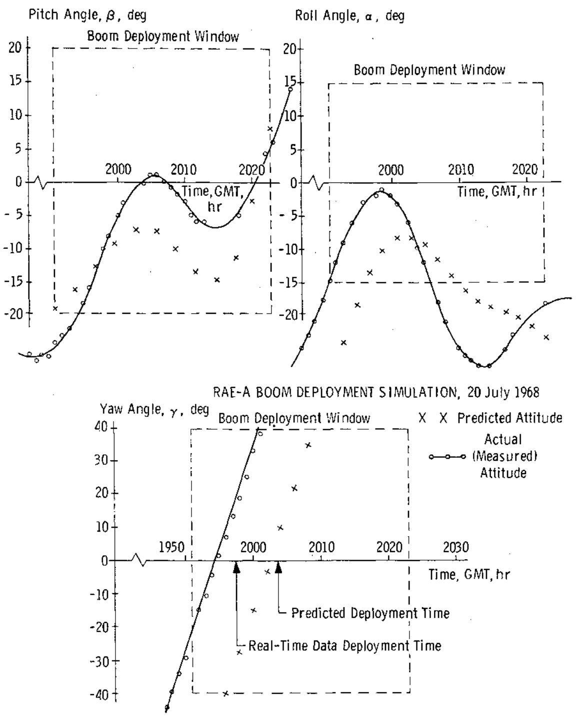

Fig. 4 Comparison of predicted and actual RAE attitude.

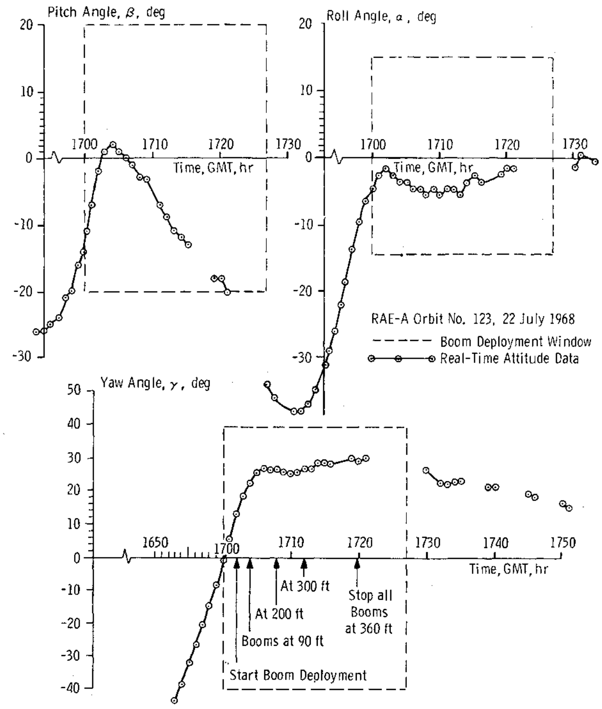

Fig. 5 Real-time attitude determination data during RAE boom deployment maneuver.

Boom Deployment Phase

Because of the limited attitude prediction accuracy, the backup method of real-time 3-axis attitude determination became the primary support tool. This method used a modified version of TRIAD (MINI-TRIAD) to calculate attitude point-by-point from raw telemetry data. The raw data, obtained manually from the GSFC TCC, was telephoned to the computer room, copied manually, and typed into the System/360 Model 95. Raw input data consisted of time, three magnetometer readings, two solar sensor readings, and a sensor tag number. The computer instantly converted these numbers into spacecraft pitch, roll, and yaw attitude angles (as defined by the TRIAD coordinate frames and calculations), which were plotted manually for MSOCC. Observation of this current data in the vicinity of the predetermined deployment windows greatly facilitated the GO-NO/GO decision for boom deployment. The MINI-TRIAD procedure was practiced in three real-time simulations before actual boom deployment.

Results of employing MINI-TRIAD during the successful July 22 boom deployment maneuver are shown in Fig. 5. This figure gives real-time determined pitch, roll, and yaw angles as functions of time near the boom deployment windows.§§ Since successful boom deployment required that each attitude angle be simultaneously contained within its own window, the real-time data permitted precise determination of near-optimum boom deployment time. It is believed the event depicted in Fig. 5 is the first time the total attitude of a spacecraft was observed and monitored during an in-orbit boom deployment maneuver.

All anticipated dynamic effects of boom deployment (e.g., marked braking action on spacecraft yaw angle) were revealed-in real time-by the data given in Fig. 5. Mission command and control was thus effectively enhanced by the MINI-TRIAD procedure.

In addition to the initial boom deployment maneuver, the above procedure was used to monitor second boom deployment (to 450 ft on July 22), damper boom deployment (July 22), third boom deployment (to 600 ft on September 24), and final boom deployment (to 750 ft on October 8). These long periods between boom deployment were purposely provided to permit careful dynamic analysis of spacecraft behavior and to acquire experimental data consistent with intermediate antenna lengths. Real-time attitude data acquired during each of these maneuvers closely verified the responses predicted by a complete (flexible body) spacecraft simulation program.[11]

§§ In accordance with mission plans, first boom deployment was terminated when each boom was extended to approximately 360 ft.

Conclusion

The following major conclusions follow from experience acquired during development and successful application of RAEADS in support of the RAE-A mission.[12]

1) Use of a disk-oriented attitude determination system results in significant operational advantages such as elimination of tape drives (except for data input and archiving computation results), increased reliability, simplified program setups, and more efficient management of intermediate data.

2) Mission support over an extended period of time is feasible while working in an MVT environment (i.e., without a dedicated machine) provided proper priorities and job control are employed.

3) Sufficient communication and joint planning between attitude determination and other mission support groups involved in critical maneuvers (such as boom deployment) are essential to ensure that important problems are resolved or planned for well in advance.

4) Real-time 3-axis attitude determination proved very valuable during boom deployment maneuvers and is strongly recommended for support of future boom deployments.

Appendix: Mathematical Basis of Attitude Determination/Prediction Programs[5–8,10]

DYCON (Dynamic Cones) for Spin-Axis Attitude

Program DYCON employs a sequence of n cone angles θ_i ($i = 1, 2, \ldots, n$), measured at times t_i relative to inertial unit cones axes $\bar{U}_i$. Angles θ_i are a mix of angles between spin axis and sun line or magnetic field directions and $\bar{U}_i$ are corresponding sun or magnetic field directions. The $\bar{U}_i$ are taken as perfectly known (from standard field and sun models), and the θ_i are considered to have independent zero-mean errors. A slowly changing spin-axis orientation is then sought which lies closest to all conical surfaces (defined by $\bar{U}_i$, θ_i) simultaneously, in the sense of weighted least squares.

Using second-degree polynomial representations for spin-axis right ascension $\alpha(t)$ and declination $\delta(t)$, spin-axis attitude at any data time t_i is

$$\alpha_i = \alpha_0 + \dot{\alpha}_0(t_i - t_0) + \ddot{\alpha}_0(t_i - t_0)^2/2$$
$$\delta_i = \delta_0 + \dot{\delta}_0(t_i - t_0) + \ddot{\delta}_0(t_i - t_0)^2/2 \quad \text{(A1)}$$

Time t_0 is any convenient reference time within or at the end points of the data interval under consideration.

It is computationally convenient to regard $\cos\theta_i$ rather than θ_i as the observable; the equations of condition, which are to be satisfied simultaneously in the sense of weighted least squares of residuals in the $\cos\theta_i$, are then

$$\cos\theta_i = \bar{U}_i \cdot \bar{S} = X_i \cos\alpha_i \cos\delta_i + Y_i \sin\alpha_i \cos\delta_i + Z_i \sin\delta_i \quad \text{(A2)}$$

where α_i, δ_i are given by Eq. (A1); X_i, Y_i, Z_i are direction cosines of the ith locus cone axis vector $\bar{U}_i$ (in inertial coordinates) and $\cos\alpha \cos\delta$, $\sin\alpha \cos\delta$, $\sin\delta$ are corresponding direction cosines of unit spin-axis vector $\bar{S}$.

Linearizing in the usual way about an initial state estimate $\hat{\alpha}_0, \ldots, \hat{\ddot{\delta}}_0$ (the "hat" notation indicating estimate) then gives

$$\begin{bmatrix} \Delta\alpha_0 \\ \cdot \\ \cdot \\ \cdot \\ \Delta\ddot{\delta}_0 \end{bmatrix} = [G^TK^{-1}G]^{-1}[G^TK^{-1}] \begin{bmatrix} \rho_i \\ \cdot \\ \cdot \\ \cdot \\ \rho_n \end{bmatrix} \quad \text{(A3)}$$

Weighting matrix K in Eq. (A3) is the $n \times n$ diagonal covariance matrix of errors in the observables, and matrix G is the $n \times 6$ matrix of partials of observables (considered as $\cos\theta_i$) with respect to state, evaluated about the estimated state; ρ_i represent residuals given by the estimated attitude.

For high spacecraft spin rates the spin axis is inertially stabilized over long intervals and attitude angles $\alpha(t)$ and $\delta(t)$ can be taken as constant*; the dimension of the state vector to be estimated is then reduced from six to two. The DYCON state vector can be augmented to permit estimation of spin-axis-directed magnetometer bias; procedures for circumventing spin-axis singular points ($\delta = \pm 90°$) are also provided in DYCON.[13]

SPINAT (Spin-Axis Attitude Prediction Program)

With the spacecraft spin-stabilized, unit spin-axis vector $\bar{S}(t)$ may be taken as coincident with the spacecraft total angular momentum vector and spacecraft total angular momentum magnitude may be taken as spin angular momentum. Prediction of spin-axis attitude at some future time $t = T$, from any inputted initial attitude state $\bar{S}(t_0)$ at time $t = t_0$, then follows directly by numerical integration as

$$\bar{S}(T) = \bar{S}(t_0) + (I_s\omega_s)^{-1} \int_{t_0}^{T} \bar{L}(\tau)d\tau \quad \text{(A4)}$$

where I_s, ω_s represent spin-axis moment of inertia and spin rate and vector $\bar{L}$ represents the net (disturbance and, when applicable, command) torques acting on the spacecraft. Spin-axis attitude is assumed to remain constant over the integration interval $t_0 < t < T$†; the above equation thus periodically "updates" spin axis attitude to keep account of its slowly-changing behavior.

The primary disturbance torque is that due to gravity gradient effects; for an axially-symmetrical, spin-stabilized spacecraft, this torque $\bar{L}_g$ is given by

$$\bar{L}_g = -3\mu(I_s - J)[\bar{S}\cdot\bar{R}][\bar{S} \times \bar{R}]/R^5 \quad \text{(A5)}$$

where $\bar{R}$ represents the current spacecraft position vector (available from an orbit determination process), J is spacecraft transverse moment of inertia and μ is the usual constant GM.

Magnetic control torques $\bar{L}_M$ result from interaction of a (ground-commanded) onboard magnetic dipole moment $\bar{M}$ with the Earth's magnetic field vector $\bar{B}$ according to

$$\bar{L}_M = \bar{M} \times \bar{B} \quad \text{(A6)}$$

where vector $\bar{B}$ is available from standard field models as a function of spacecraft orbital position vector $\bar{R}$.

When a reorientation maneuver is to be planned, SPINAT determines (by the above equations and built-in logic) portions of upcoming orbits that provide sufficient (and correctly directed) spin-axis motion when a dipole moment of fixed level and approximately fixed duration‡ is applied. All admissible orbital portions are then compared to the observation periods of each (inputted) station comprising the RAE ground network; the dipole on-time period is then stretched or shortened (by built-in logic) to match it to the appropriate observation periods. A ground station schedule for issuing ON/OFF dipole commands to RAE is thus made available.

TRIAD (TRI-Axis Attitude Determination)

Program TRIAD employs spacecraft measurements of the unit sun vector ($\bar{P}$) and local magnetic field vector ($\bar{B}$), made in a body-centered ($\bar{x},\bar{y},\bar{z}$) frame, and values of these vectors calculated in an ($\bar{i},\bar{j},\bar{k}$) orbit reference frame. At any time point t_k at which measurements ($P_x,P_y,P_z;B_x,B_y,B_z$) and components ($P_i,P_j,P_k;B_i,B_j,B_k$) are simultaneously available, an orthogonal set of unit vectors ($\bar{P},\bar{Q},Z$) using both body-frame (measured) and orbit-frame (calculated) components is formed as $\bar{P} = \bar{P}, \bar{Q} = \bar{P} \times \bar{B}/|\bar{P} \times \bar{B}|$, $Z = \bar{P} \times \bar{Q}$. Attitude matrix [A] is then computed as

$$[A] = [\bar{P}\bar{Q}Z]_{x,y,z}[\bar{P}\bar{Q}Z]^T{}_{i,j,k} \quad \text{(A7)}$$

and, using the definition of matrix $[A]$, RAE-A attitude angles (β,α,γ) are directly calculated from the elements of $[A]$.

A covariance matrix subroutine is included in TRIAD.[14] This matrix, useful as a mission analysis aid, quantitatively describes the error-amplifying effects of orbital geometry on basic sensor measurement errors. "Moving-arc" quadratic polynomial curve fitting is employed to smooth the calculated angles and to infer attitude rates.[8] The TRIAD method is based on procedures first reported by Black.[15]

DSOAP/MAGCAP (Direct Search Optimal Attitude Program/Magnetic Capture Phase)

Taking the RAE ($\bar{x},\bar{y},\bar{z}$) body frame as a principal moment-of-inertia frame, Euler's equations of (rigid-body) rotational motion can be written

$$\dot{\omega}_x' = A\omega_y'\omega_z' + C_x' + D_x'$$
$$\dot{\omega}_y' = B\omega_z'\omega_x' + C_y' + D_y' \quad \text{(A8)}$$
$$\dot{\omega}_z' = F\omega_x'\omega_y' + C_z' + D_z'$$

* This was the situation found to exist throughout the RAE-A transfer orbit mission phase.

† This and the previously stated SPINAT assumptions hold for reasonably long periods (e.g., up to one orbital period in the absence of control torques).

‡ Prelaunch studies indicated that an RAE-A dipole on-time of ~25 min provides near-maximum spin-axis motion for most RAE-A orbits.

where $C_x' \equiv c_x/I_x, \ldots, D_z' \equiv d_z/I_z$

$$A \equiv (I_y - I_z)/I_x,\ B \equiv (I_z - I_x)/I_y,\ F \equiv (I_x - I_y)/I_z \quad \text{(A9)}$$

Symbols I, c, d respectively represent moment-of-inertia, control torque, and disturbance torque about the subscripted axes and $\omega_x', \omega_y', \omega_z'$ are body frame components of spacecraft total (inertial) angular velocity. These components are given by

$$\omega_x' = \omega_x + \omega_0 s\gamma c\alpha,\quad \omega_y' = \omega_y + \omega_0 c\gamma c\alpha$$
$$\omega_z' = \omega_z - \omega_0 s\alpha \quad \text{(A10)}$$

where ω_0 represents orbital angular velocity and $(\omega_x,\omega_y,\omega_z)$ are the components of $(\bar{x},\bar{y},\bar{z})$-to-$(\bar{\imath},\bar{\jmath},\bar{k})$ relative angular velocity.

Since $\dot{\omega}_x,\dot{\omega}_y,\dot{\omega}_z$ (as well as, in general, $C_x, \ldots, D_z$) are functions of attitude, equations expressing attitude angle rates as functions of $\omega_x,\omega_y,\omega_z$ must be coupled to the above formulations. These equations, obtainable directly from geometrical considerations, are,

$$\dot{\beta} = (\omega_x s\gamma + \omega_y c\gamma)/c\alpha,\quad \dot{\alpha} = \omega_x c\gamma - \omega_y s\gamma$$
$$\dot{\gamma} = \omega_z + (\omega_x s\gamma + \omega_y c\gamma)s\alpha/c\alpha \quad \text{(A11)}$$

The significant disturbance torque for RAE rigid-body attitude prediction purposes is that due to gravity gradient effects, $\bar{d}_g$. This torque is resolved into the $(\bar{x},\bar{y},\bar{z})$ frame by means of angles (β,α,γ) as

$$d_{g_x} = 3\mu c\alpha c\beta(s\gamma s\beta + c\gamma s\alpha c\beta)(I_z - I_y)/R^3$$
$$d_{g_y} = 3\mu c\alpha c\beta(s\gamma s\alpha c\beta - c\gamma s\beta)(I_x - I_z)/R^3 \quad \text{(A12)}$$
$$d_{g_z} = 3\mu(-c\gamma s\beta + s\gamma s\alpha c\beta)(s\gamma s\beta + c\gamma s\alpha c\beta)(I_y - I_x)/R^3$$

Attitude control torques for RAE are generated by an onboard magnetic control system, as indicated earlier.

Spacecraft RAE employs an onboard "hysteresis generator" to supply the (preboom deployment) damping torques required for magnetic capture and detumble attitude control. The difficulties of accurate digital simulation of hysteresis phenomena required an empirical approximation of RAE hysteresis damping effects in program MAGCAP.[10] The area A of a hysteresis loop can be approximated as

$$A = K|B_{\max} - B_{\min}|^3 \quad \text{(A13)}$$

where, for cyclic motion of the spacecraft x (or y) axis, $B_{\max}$ and $B_{\min}$ are the sensed maximum and minimum of the component of Earth magnetic field vector $\bar{B}$ along x (or y). The value of constant K depends on the shape and gain options in the damper. The approximation given by Eq. (A13) is the basis of the RAE damper simulation.

Since attitude angle set (β,α,γ) is a Euler angle set, it is subject to singularity limitations. An α-triggered subroutine designed to circumvent the (β,α,γ) singularity is provided in MAGCAP.[16]

With its direct-search-optimization algorithm, MAGCAP/DSOAP automatically adjusts an input set of initial conditions (and/or spacecraft parameters) to fit predicted attitude time histories optimally to spacecraft-acquired measurements. Three-axis attitude and attitude-rate estimates based on direct-search-optimized smoothing of measurement data are thus generated by MAGCAP/DSOAP.

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