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A DESCRIPTION OF THE THRUSTER ATTITUDE CONTROL SIMULATION AND ITS APPLICATION TO THE HEAO-C STUDY

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Program Development

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16. ABSTRACT

During the design and evaluation of a Reaction Control System (RCS), it is desirable to have a digital computer program simulating vehicle dynamics, disturbance torques, control torques, and RCS logic. The Thruster Attitude Control Simulation (TACS) is just such a computer program. The TACS is a relatively sophisticated digital computer program that includes all the major parameters involved in the attitude control of a vehicle using an RCS for control. It includes the effects of gravity gradient torques and HEAO-C aerodynamic torques so that realistic runs can be made in the areas of fuel consumption and engine actuation rates. Also, the program is general enough that any engine configuration and logic scheme can be implemented in a reasonable amount of time.

The results of the application of the TACS in the HEAO-C study are given in the second half of the report, and a full understanding of the applicability of the TACS can be gained from studying these results.

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DEFINITION OF SYMBOLS

Symbol	Definition
$A_{i,j}$	elements of the direction cosine matrix
$\dot{A}_{i,j}$	rates of the elements of the direction cosine matrix
A_{0x}	attitude error gain in the X axis
A_{0y}	attitude error gain in the Y axis
A_{0z}	attitude error gain in the Z axis
A_{1x}	attitude rate gain in the X axis
A_{1y}	attitude rate gain in the Y axis
A_{1z}	attitude rate gain in the Z axis
A_{ref}	aerodynamic reference area
$C_{i,j}$	elements of the command matrix
C_{lcg}	aerodynamic coefficient
C_{mcg}	aerodynamic coefficient
C_{ncg}	aerodynamic coefficient
$D_{i,j}$	elements of the error matrix
D_{ref}	aerodynamic reference length
$\delta_{x,y,z}$	command torque
ϵ	deadband
η	vehicle angular position in orbit from initial position
$F_{i,j}$	RCS engines and level of thrust of each

DEFINITION OF SYMBOLS (Continued)

Symbol	Definition
F_{tx}	engine thrust in the X axis
F_{ty}	engine thrust in the Y axis
F_{tz}	engine thrust in the Z axis
$F_{x,y,z}$	forces in the X, Y, and Z axes
G	gravitational acceleration at altitude h
G_0	gravitational acceleration at sea level
h	altitude above sea level
$I_{x,y,z}$	principle moments of inertia
$I_{xy,xz,zy}$	cross products of inertia
$L_{x,y,z}$	lever arm on which each RCS engine acts about the X, Y, and Z axes
m	vehicle mass
$M_{ax,y,z}$	aerodynamic torque
$M_{gx,y,z}$	gravity gradient torque
$M_{tx,y,z}$	RCS engine torque
μ	gravitational constant
$M_{x,y,z}$	total torque about the X, Y, and Z axes
ORTHO 1, 2, 3	orthogonal correction parameter
P	period of vehicle's orbit

DEFINITION OF SYMBOLS (Concluded)

Symbol	Definition
π	Pi (constant)
$\psi_{x,y,z}$	attitude error in the X, Y, and Z axes
R_e	radius of the earth
ρ	density of the atmosphere at altitude h
R_s	distance from the earth's center to the vehicle center of mass
t	time
$\dot{\phi}_{x,y,z}$	vehicle angular rate about X, Y, and Z axes
$\ddot{\phi}_{x,y,z}$	vehicle angular acceleration about the X, Y, and Z axes
V_s	vehicle velocity in inertial space

TECHNICAL MEMORANDUM X- 64660

A DESCRIPTION OF THE THRUSTER ATTITUDE CONTROL SIMULATION AND ITS APPLICATION TO THE HEAO-C STUDY

SECTION I. INTRODUCTION

During the design and evaluation of a Reaction Control System (RCS), it is desirable to have a digital computer program simulating vehicle dynamics, disturbance torques, RCS logic, and control torques. The Thruster Attitude Control Simulation (TACS) is just such a computer program. The first part of this report is devoted to a description of the TACS, while the remaining portion is devoted to the results of the HEAO-C RCS performance study as a demonstration of the TACS applicability.

SECTION II. DESCRIPTION OF THE TACS COMPUTER PROGRAM

The TACS is a relatively sophisticated digital computer program that includes all the major parameters involved in the attitude control of a vehicle using an RCS for control. It includes the effects of gravity gradient torque and HEAO-C aerodynamic torques so that realistic runs can be made in the areas of fuel consumption and engine actuation rates. Also, the program is general enough that any engine configuration and logic scheme can be implemented in a reasonable amount of time; i.e., a major change is usually implemented in a few days.

A. Coordinate Systems

The TACS uses only two coordinate systems: a vehicle body system and a quasi-inertial system. The vehicle body coordinate system has its origin at the center of mass of the vehicle with the X_B body axis along the longitudinal axis of the vehicle, the Z_B body axis normal to the solar panel axis in the case of the HEAO, and the Y_B body axis completes the right-hand triad. The origin at the center of mass of the vehicle was chosen to implement the gravity gradient equations in an efficient manner.

The quasi-inertial coordinate system has its origin at the center of the earth. The X_S inertial axis can be assumed to be inclined 23.5 degrees from the earth's spin vector, while the Y_S and Z_S axes lie in the ecliptic plane. The Y_S and Z_S axes have no particular pointing direction, so the time of year of the orbit chosen, along with a particular vehicle orientation, is simulated by choosing the proper orbital inclination in the quasi-inertial system to give the desired orbital parameters. The method works well for runs of a few orbits; but if longer on-orbit times were to be studied, a coordinate system rotating once a year would have to be added.

B. Program Description

The TACS consists of four main divisions:

1. General Equations
2. Rotational Dynamics
3. Vehicle Dynamics
4. Translational Dynamics

Although it is not included as a separate division here, the TACS initialization procedure to ensure that all variables are initialized is rather lengthy and should not be overlooked. A flow chart of the entire program is shown in Figure 1 and the equations discussed are shown in Appendix A. It is believed that the most convenient way to discuss the TACS will be under the four divisions previously mentioned.

C. General Equations

There are five equations under this heading and each calculates elements that are used in one or more other sections of the program (Appendix A). Inertial position and velocity of the vehicle are calculated by the root-sum-square (rss) method for use in several other equations. The gravitational acceleration at altitude is calculated for orbital mechanics purposes and the final two calculations for vehicle altitude and position angle are performed primarily for the programmer's benefit.

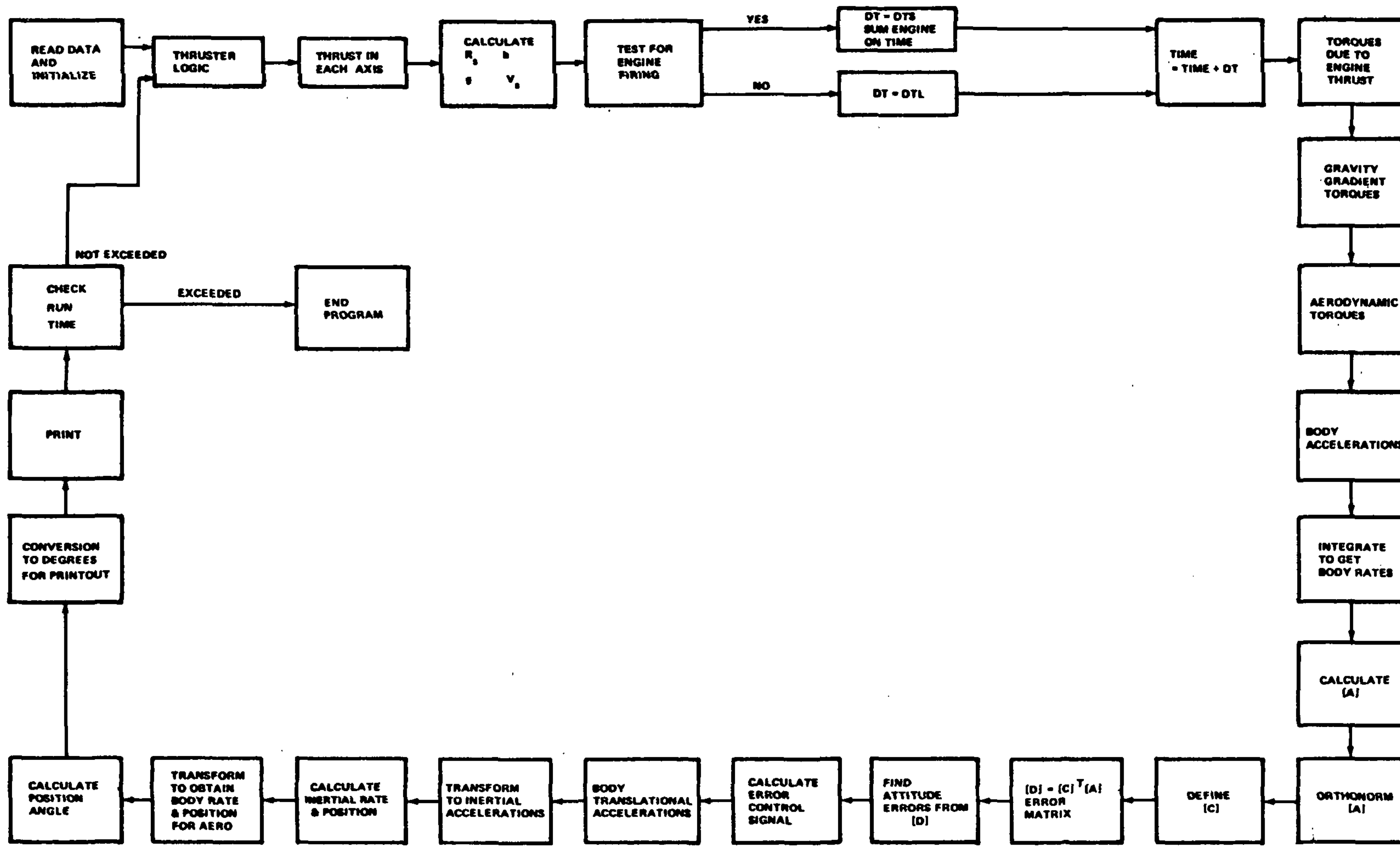


Figure 1. Flow chart for the thruster attitude control simulation.

D. Rotational Dynamics

In this section are calculated the gravity gradient torques, the aerodynamic torques, the thruster torques, vehicle angular acceleration and rates, and the direction cosine matrix. The gravity gradient equations were taken from Reference 1 where they are derived and explained in detail. The equations are valid only if the body coordinate system has its origin at the center of mass of the vehicle in orbit.

The torques caused by RCS engine firings are calculated simply by multiplying the thruster force by the corresponding lever arm(s). Since the equations for each axis are therefore relatively simple, it was decided to change them for each new engine configuration rather than try to write a general expression suitable for all configurations. The resulting savings in run time and program complexity more than make up for the small inconvenience.

The aerodynamic torques used in the TACS are valid only for the HEAO vehicles. Therefore, if any other vehicle is studied with the TACS and it is desired to include aerodynamic torques, the aerodynamic equations will have to be rewritten. The aero equations presently in the TACS were taken from Reference 2. They are written for the HEAO-A and HEAO-B vehicles, but it was felt they would be suitable at least for a preliminary study of the HEAO-C vehicle. The main drawback is that the effects of the orbit adjust stage (OAS) are not included. The aerodynamic torques are a function of the angle of attack and the roll angle so these parameters are fed into a group of aerodynamic coefficient equations derived by a curve fitting procedure. The resulting coefficients are modified according to center of gravity considerations and then these body aerodynamic coefficients are used in the aerodynamic equations. A more detailed analysis and discussion of the aero equations can be found in Reference 2.

The various vehicle torques are used to calculate the angular accelerations on the vehicle. These angular accelerations include equations simulating the effects of precession exhibited by a rotating body. The acceleration due to each source is integrated to obtain angular rates. Various methods of integration are used to produce the highest degree of accuracy. For instance, rectangular integration is absolutely correct for accelerations due to thruster torques whereas forward trapezoidal integration is suitable for the integration of accelerations due to gravity gradient torques. The rectangular integration is appropriate since the thruster firings are modeled with a perfect rectangular wave form of duration Δt.

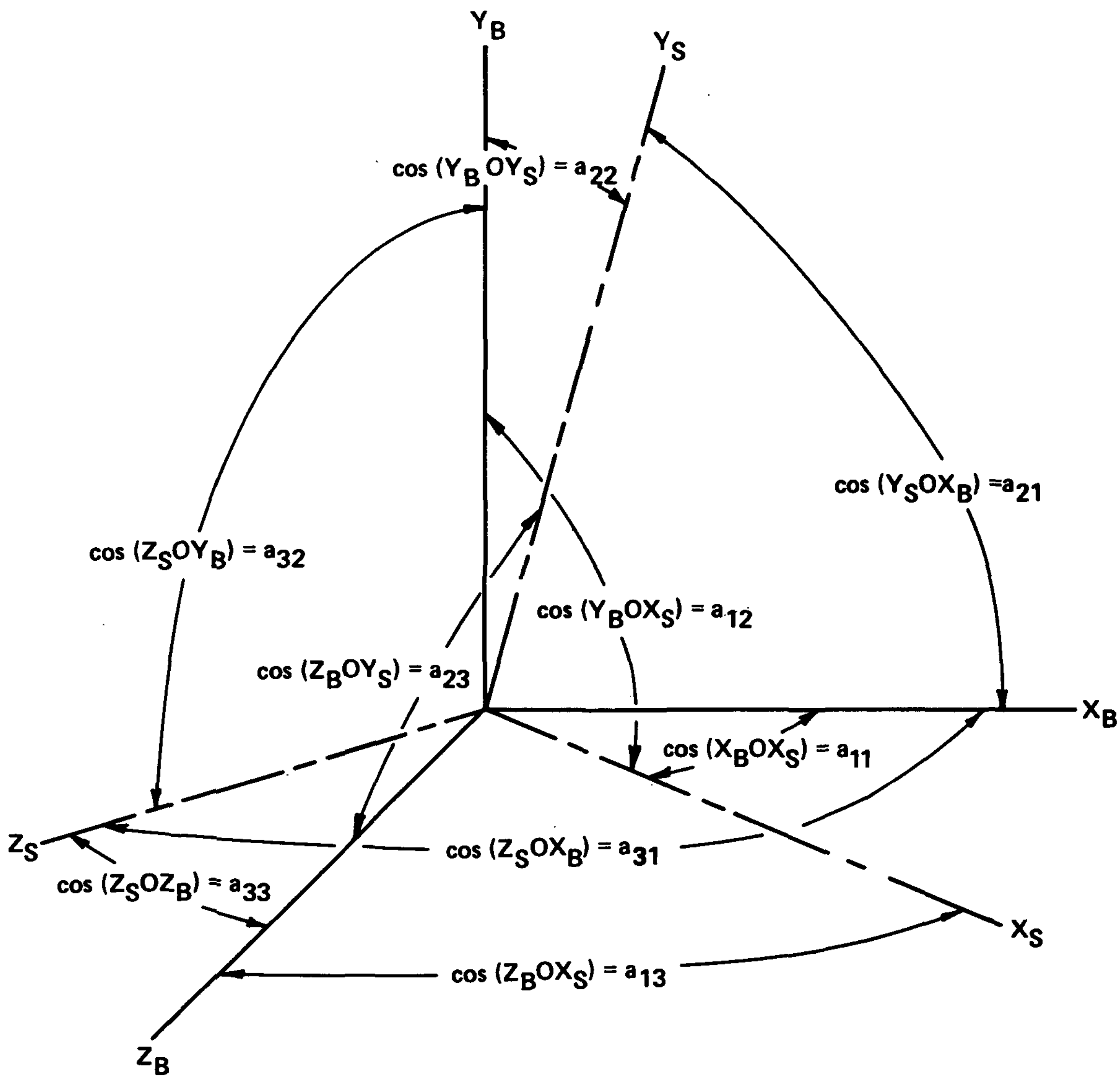
Direction cosines rather than Euler angles are used in the attitude determination of the vehicle to avoid the 90-degree angular rotation limit in one axis. The direction cosines, [A], are illustrated in Figure 2. The rates of change of the elements of the direction cosine matrix are determined from vehicle angular rates and previously calculated direction cosines. These new rates are then integrated to obtain new values for the direction cosines. Since the program is digital, a finite Δt must be used. Thus, there is some inaccuracy in obtaining the direction cosine rates to be integrated. Therefore, the direction cosine subroutine utilizes a simple ortho-normalization procedure to ensure that an overall drift of the direction cosines will not occur. A more detailed discussion of direction cosines can be found in Reference 3. It should be noted that the elements of the [A] matrix must be initialized accurately.

E. Vehicle Dynamics

The desired attitude of the vehicle is expressed with another direction cosine matrix, the attitude control matrix [C]. By multiplying the transpose of the attitude control matrix, $[C]^T$, times the direction cosine matrix [A], a third 3×3 matrix, [D], is obtained. By comparing the elements of this matrix with those of a comparable Euler matrix, appropriate terms can be chosen and combined to express the attitude errors. These errors are not absolutely correct but as the attitude error approaches zero, the deviation from the actual attitude error also approaches zero. Hence, for the small deadbands normally used during RCS control, the attitude errors generated are for all practical purposes correct.

If an attitude other than inertial hold is desired, the control matrix [C] will no longer consist of constant elements. Instead, trigonometric relationships will have to be used to express the elements. In addition, if the vehicle is required to spin about an axis, a spin angle will have to be introduced to express the desired vehicle attitude at each instant of time. The rate at which the spin angle changes will, of course, determine the spin rate of the vehicle.

Once the attitude errors are obtained, they are combined with the angular rates using suitable gains to obtain the control error signals or command torques. Presently the TACS uses a constant slope deadband, but it would be easy to implement other types of control laws. Using these command torques, the engine logic decides which engine or engines should be fired for a particular error. The logic equations in Appendix A are expressed only in general terms because engine logic normally changes between studies. The implementation of a particular logic configuration can be seen in the sample printout in Appendix B. The logic is that shown in Figure 3.



$$\begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} X_B \\ Y_B \\ Z_B \end{pmatrix}$$

Figure 2. Direction cosine rotations.

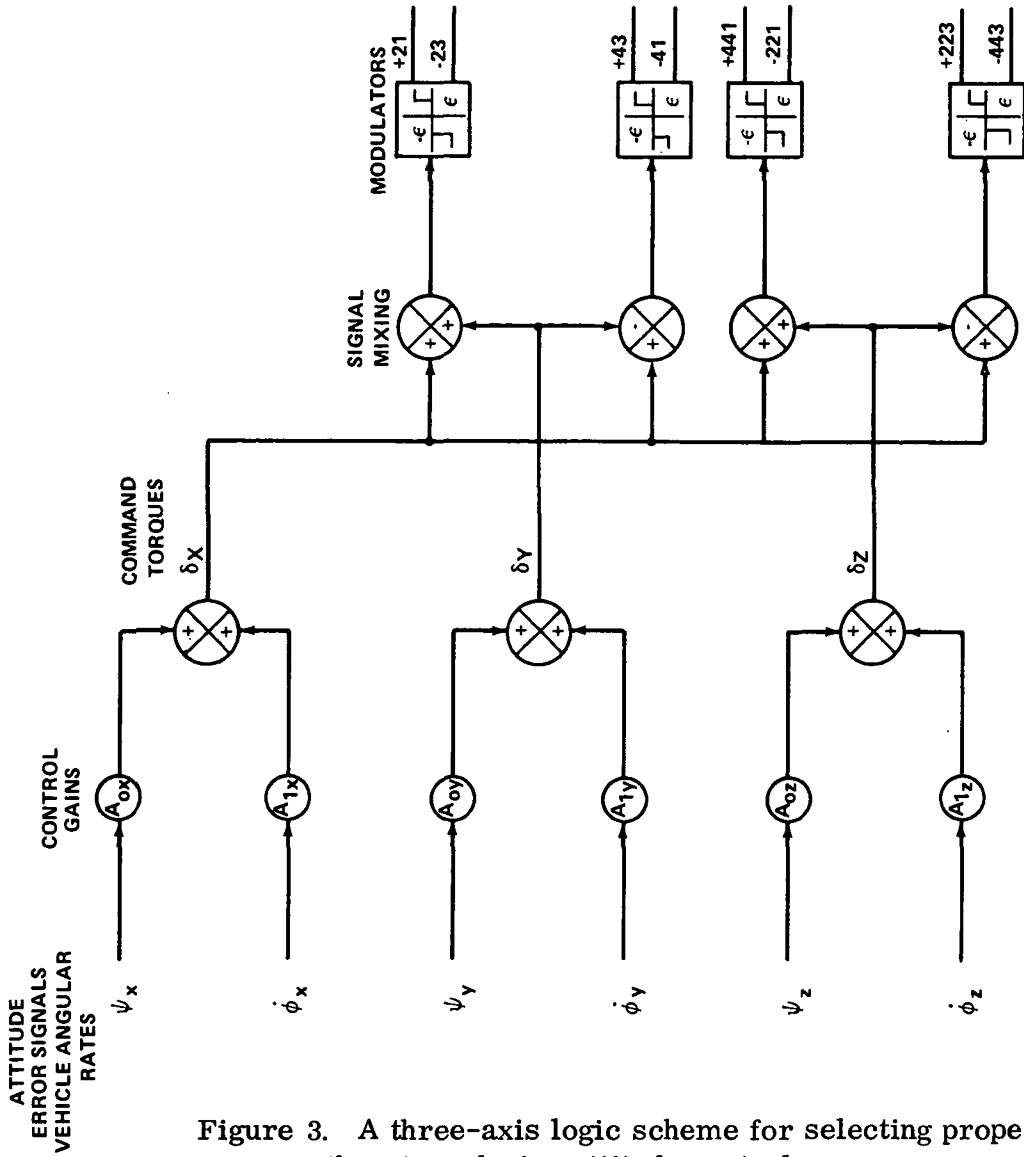


Figure 3. A three-axis logic scheme for selecting proper thrusters during attitude control.

F. Translational Dynamics

Since aerodynamic drag is ignored in the TACS, the only contributors to translational motion are thruster firings and gravity. The equations for force due to thruster actuations are simply summations per axis of the engine thrusting along the axes. Normally the engines are assumed to be aligned along the three axes, but if they are skewed at some angle, only a simple trigonometric relation needs to be added. These equations are changed for each new engine configuration to reduce program complexity and run time. The thruster forces are used to generate body translational accelerations which are transformed and combined with acceleration due to gravity to produce a total inertial acceleration. These translational accelerations are then integrated twice to obtain velocity and position in inertial space. Inertial velocity and position are then transformed to velocity and position in the body coordinate system. These transformed values are required in the gravity gradient and aerodynamic equations.

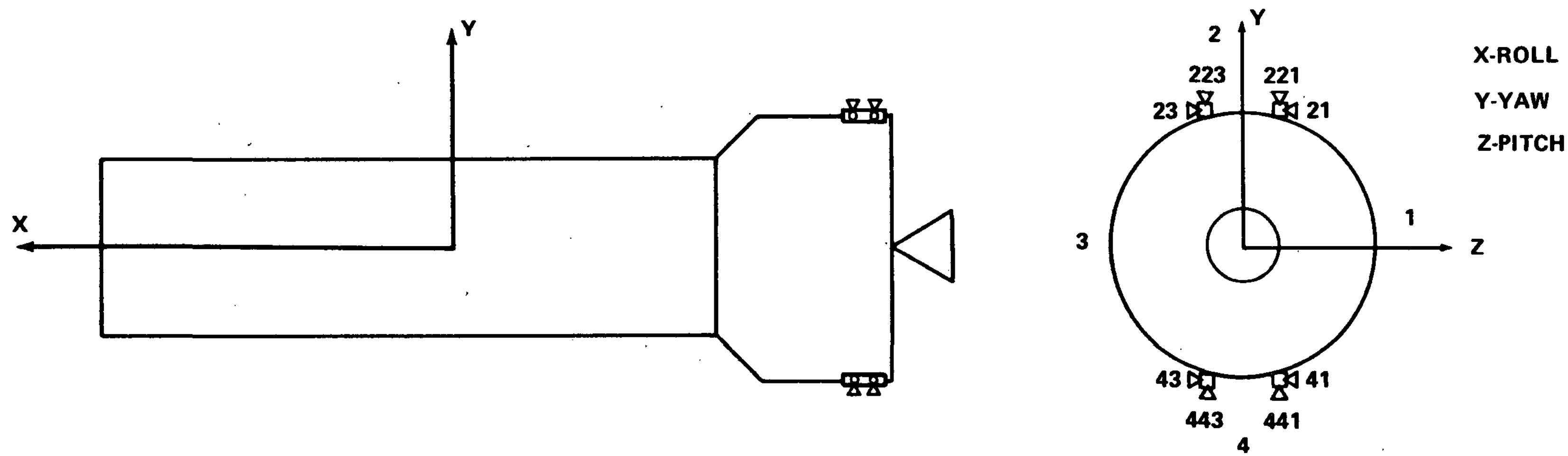
SECTION III. HEAO-C PERFORMANCE SIMULATION

The two primary HEAO-C vehicle requirements placed on the RCS are control moment gyro (CMG) momentum desaturation and attitude control. CMG desaturation requires by far the largest amount of fuel and is the primary driver in the selection of an engine configuration and control law. Since some attitude control is required of the RCS (one contingency mode may last 30 days), it was decided to perform an analysis from the RCS attitude control viewpoint. However, as presently baselined it should be remembered that the HEAO-C RCS depends upon CMG desaturation efficiency and not so much on performance in the RCS attitude control mode.

A. Baseline RCS Configuration and Control Law

The HEAO-C baseline RCS configuration is shown in Figure 4. It consists of four reaction engine modules each containing four reaction engines, two primary and two redundant. Four engines can control both pitch (rotations about Z_B) and/or roll (rotations about X_B) whereas the other four can control yaw (rotations about Y_B) and/or roll. The engines are numbered according to (1) the quadrant in which they are located, and (2) according to the direction they are pointing. Four of the engines have three identifying numbers rather than two. This is required since they are located in the same quadrant and point in the same direction. The third number is merely the quadrant they are nearest (not in). Hence each engine has its own identity and can be distinguished from the other seven.

Since the configuration lends itself so well to signal mixing, roll is mixed in with both pitch and yaw on all eight of the engines as shown in Figure 3 (see Figure 4 for the engine nomenclature). The resulting signal is routed through the modulators and then to the selected engine(s).



ERROR SIGNAL	21	221	223	23	41	441	443	43
+ PITCH						X	X	
– PITCH		X	X					
+ YAW	X				X			
– YAW				X				X
+ ROLL	X		X			X		X
– ROLL		X		X	X		X	

Figure 4. HEAO-C baseline RCS thruster configuration.

A straight line constant gain law was used with a gain ratio of five. Unless the roll error is exactly zero, this control law prevents two engine burns in a single axis at the same time. This, of course, allows longer burn times since only one engine will be performing vehicle control at any time. The longer burn times result in a higher I_{sp} and therefore more efficient use of the fuel. The signal modulators depicted in Figure 4 are merely a plus or minus deadband device with no attempt being made to enhance the signal for better efficiency.

B. Simulation Results

In all of the cases where the RCS was used for attitude control, the worst case orientation for gravity gradient was used. Therefore, the data presented depict the worst case fuel consumption and cycle rate in all cases unless otherwise noted.

Table 1 presents the results of the TACS study of the baseline HEAO-C. About half of the items listed were analyzed using hand calculations but they are included to complete the timeline. The first item studied was the separation of the HEAO from the launch vehicle with the resultant vehicle rates introduced on the HEAO. The TACS was initialized with the vehicle in the 140 by 250 n. mi. orbit with 3 degree/second rates on all three axes and the HEAO was immediately commanded to maintain attitude and null the rates. The fuel consumed, 7.45 lbm, includes that required for returning the vehicle to the same attitude as it had at the beginning of the burn, in addition to nulling rates, although the attitude hold may not be a requirement for the HEAO.

The next TACS application involved vehicle control in the insertion orbit of 140 n. mi. by 250 n. mi. Although nominally RCS control in this orbit, as well as the others, will not be a system driver, the contingency of about a 30-day stay in the 140 n. mi. by 250 n. mi. orbit will affect fuel consumption drastically if attitude is maintained within ±0.5 degree. The TACS analysis in this orbit indicated a fuel consumption rate of 0.244 lbm/orbit. Hence the nominal mission will require a maximum of 1.09 pounds of fuel in this orbit, but for the 30-day stay almost 115 pounds will be needed. The actual requirements should be less than those mentioned since vehicle attitude will vary with time; i.e., the worst case will not be maintained for 30 days. Also, it should be noted that a deadband of ±0.5 degree probably would not be needed and could be relaxed during this part of the mission.

TABLE 1. SIMULATION RESULTS FOR THE BASELINE HEAO-C

Event	Total Impulse (lb-sec)	Fuel Required at I_{sp} = 140 sec (lbm)	Worst Case Engine Cycling for an Engine	Comments
Null 3 degrees/second 3 Axes	1 043.8	7.45	30	Includes Attitude Control
Solar Acquisition (90 degrees about X and Y)	268.0	1.91	4	2 degrees/second Maximum Manuever Rate
Attitude Control in 140 × 250 n. mi. Orbit	153.6 16 082.0	1.09 at 4.5 Orbits 114.8 at 30 Days	319 or 31 500	0.244 lbm/Orbit
OAS Thrust Vector Misalignment During Burn to 205 × 250 n. mi.	1 079.5	7.71	150	7.5 minute Burn
Attitude Control in 205 × 250 n. mi. Orbit	33.49	0.239	70	0.239 lbm/Orbit for 1 Orbit
OAS Thrust Vector Misalignment During Burn to 250 × 270 n. mi.	804.1	5.74	112	5.58 minute Burn
Attitude Control in 250 × 270 n. mi.	51.0	0.364	106	0.242 lbm/Orbit for 1.5 Orbits
OAS Thrust Vector Misalignment During Burn to 270 n. mi. Circular Orbit	673.2	4.80	94	4.68 minute Burn
Attitude Control in 270 n. mi. Orbit until CMG's are up to Speed, End of Checkout and Acquisition of X-ray Reference	253.3	1.81	451	0.245 lbm/Orbit for 7.4 Orbits
CMG Momentum Dumping at 270 n. mi.	107 767	769.7	211 090	Only 52 750 Actuations per Engine are Expected
Totals	112 126.99 or 128 055.39	795.647 or 909.357	212 426 or 243 607	

The engine actuation rate could be extremely high in this orbit if the 30-day stay time is used. Extrapolating the worst case figures gives 31 500 cycles for one engine which is about one-sixth of the engine's rating. Again it must be noted that this is a worst case figure since a deadband of ±0. 5 degree was used. If the deadband were relaxed, the actuation rate would decrease appreciably. The nominal staytime of 4. 5 orbits requires only 319 actuations for a worst case engine, so no problem is anticipated if the nominal mission timeline is followed.

At the end of the stay period in the insertion orbit, the RCS will be used to acquire the proper vehicle attitude for the OAS burn into the 205 by 250 n. mi. orbit. The RCS will also be used to maintain vehicle attitude during the OAS burn. For both attitude acquisition and burn control, a 1080 lb-sec impulse will be required. This impulse determination was made without the use of the TACS.

Once the HEAO has been inserted in the 205 by 250 n. mi. orbit, the RCS will be used to maintain attitude control until the next OAS burn and nominally should require one orbit. During the orbit, only a 33. 5 lbf-sec impulse will be required. A total of 70 engine actuations will be required for the worst case engine.

After the HEAO has completed one orbit in the 205 by 250 n. mi. orbit, it must be positioned for an OAS burn into the 250 by 270 n. mi. orbit. The impulse required for attitude acquisition and OAS thrust misalignment management was found to be 804 lb-sec. If a single RCS engine is required to do all of the control during the OAS burn, it will be actuated a maximum of 112 times, a negligible amount compared to CMG desaturation requirements.

The vehicle will remain in this orbit for 1. 5 revolutions during which time the RCS will require a 51 lb-sec impulse to maintain the HEAO within the required deadband. At the end of 1. 5 orbits, the HEAO injection into a 270 n. mi. circular orbit will require an impulse of approximately 673 lb-sec impulse from the RCS. After the HEAO acquires the 270 n. mi. orbit, the RCS may be needed for 7. 4 orbits after which the CMGs will take over attitude control. RCS control for 7. 4 orbits will require an impulse of 253 lb-sec. The worst case engine can be expected to actuate 451 times during the 7. 4 orbits.

These last numbers can be used to obtain a worst case fuel consumption and actuation history in the case of a failure of the CMG; 253 lb-sec for 7. 4 orbits gives 34. 22 lb-sec per orbit at 270 n. mi. Since a 2-year mission will have about 11 000 orbits, an impulse budget of 379 842 lb-sec will be required. At an I_{sp} of 140 seconds this indicates a fuel requirement of 2713 pounds. This number is valid only if the HEAO remains in the worst case gravity gradient attitude for the entire mission (an unreasonable criteria), but it does place an upper limit on fuel requirements for a 2-year mission in the case of an early CMG failure. Also, the vehicle would be operating in a degraded mode as the above figures reflect a deadband of ±0.5 degree. The actuation history indicates that 61 actuations may be expected per orbit for a single engine as shown in Figure 5. If this number is extrapolated for 2 years, 677 100 actuations could be expected of a single engine. This exceeds by about a factor of four the present cycle lifetime of an engine but it must again be remembered that this is a worst case number and would actually be significantly smaller, perhaps even within the engine specifications.

A single run was made with the TACS to determine if a control system using only an RCS would be feasible for HEAO-C. A deadband of ±1 arc min was placed on all three axes and a 0.5-pound thrust level was used for the thrusters. This combination produced about 1600 actuations per orbit which would quickly exceed the cycle lifetime of present RCS thrusters. It was also felt that the I_{sp} would be so low as to preclude the RCS on a fuel weight basis. At this point it was decided to drop any further studies along this line.

Although CMG momentum desaturation is almost the exclusive RCS driver on the HEAO-C, a TACS study could not be performed since TACS does not include the necessary CMG equations. An analytical calculation showed that about 108 000 lb-sec input will ideally be required for the 2-year mission but the RCS configuration used will determine the actual amount of impulse and fuel required.

C. Alternate System

The alternate RCS configuration for HEAO-C is shown in Figure 6. The four reaction engine modules are retained from the baseline system but they are relocated to the positions shown. For identification, a two-digit number is used for each engine. The first digit of each number gives the quadrant the engine is in and the second digit tells the direction in which the engine is pointing.

Two control laws were tried for this alternate system. The first, shown in Figure 7, proved to be very undesirable from both actuation and fuel consumption viewpoints. Hence the second law, Figure 8, was devised.

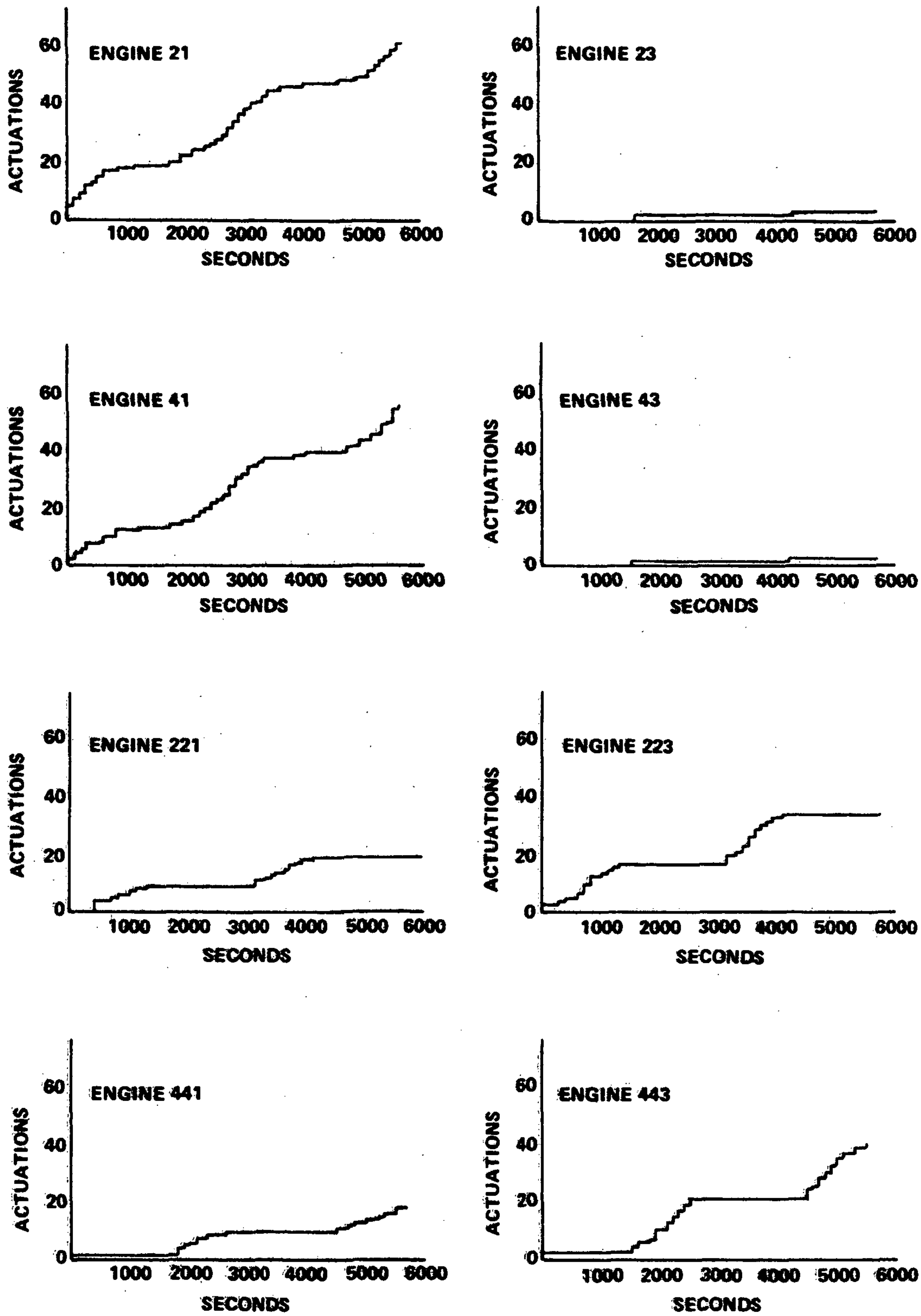
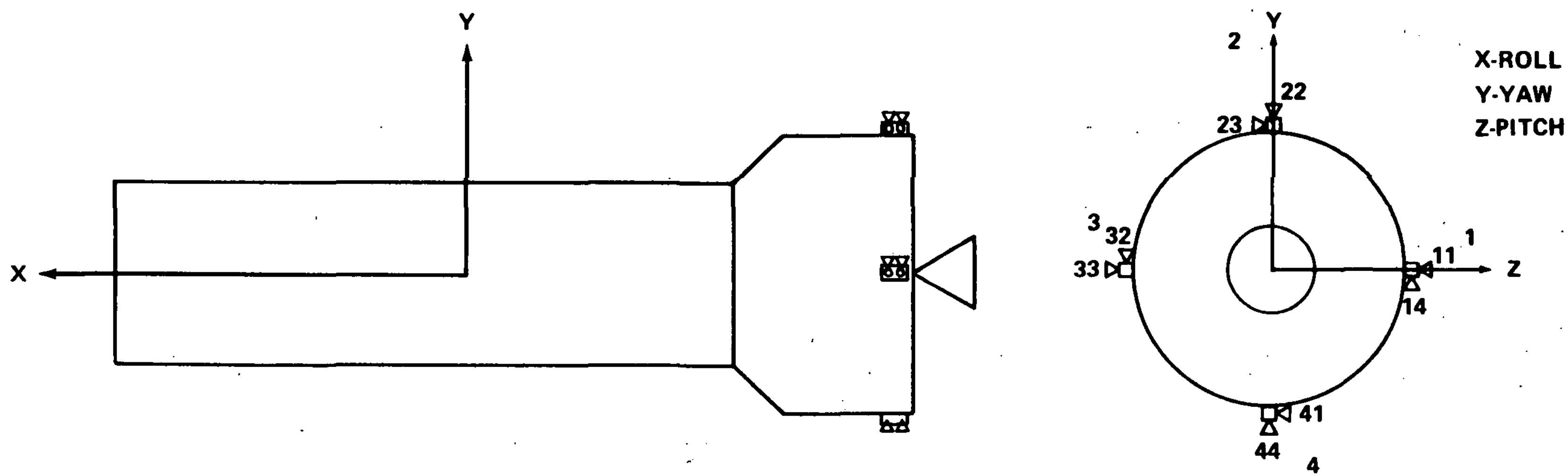


Figure 5. Typical thruster actuation history for the baseline HEAO-C.



ERROR	11	14	22	23	32	33	41	44
+ PITCH		X						X
− PITCH			X		X			
+ YAW	X						X	
− YAW				X		X		
+ ROLL		X			X			
− ROLL				X			X	

Figure 6. The alternate thruster configuration for the HEAO-C.

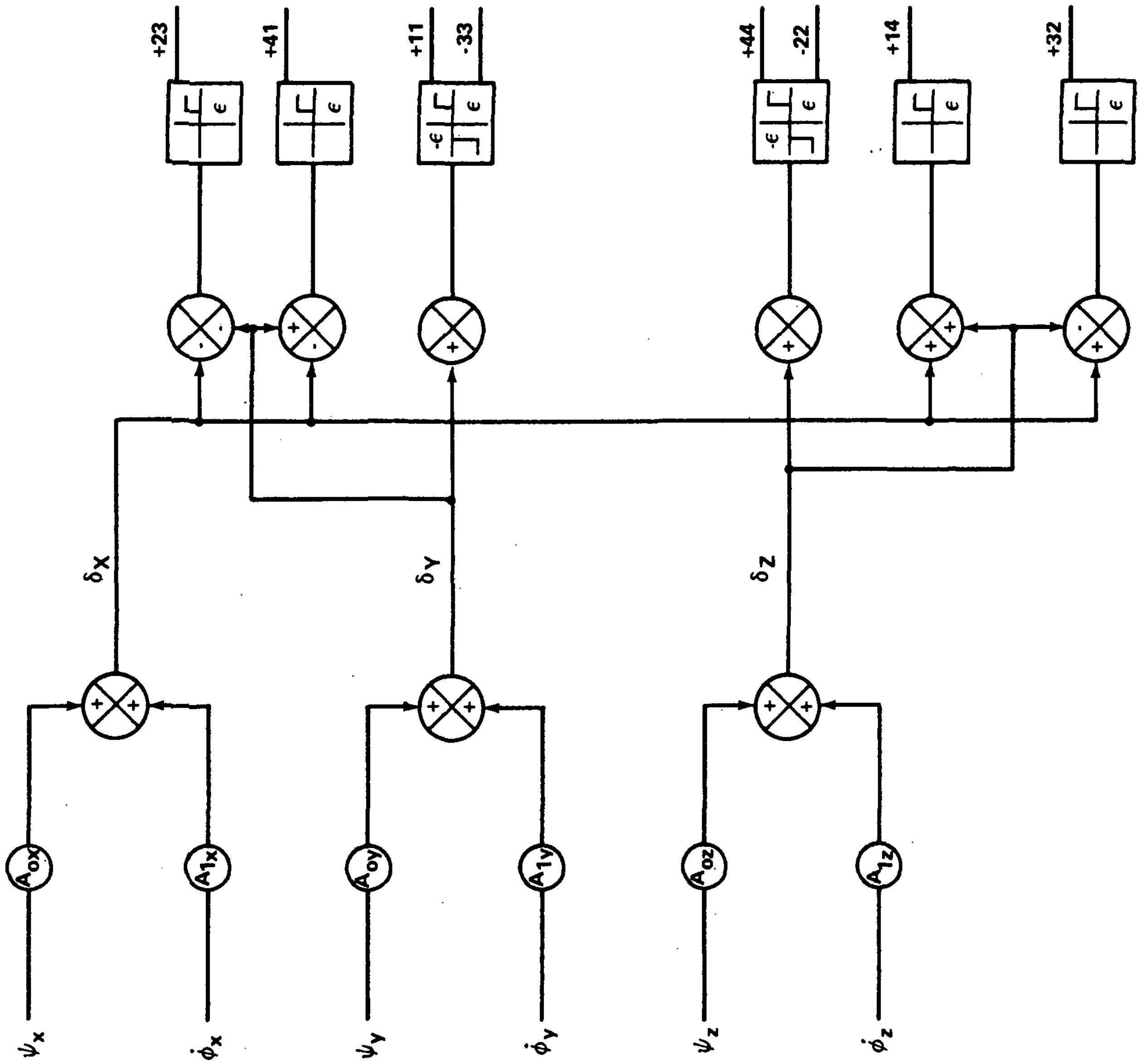


Figure 7. An unsuitable control law for the alternate HEAO-C RCS.

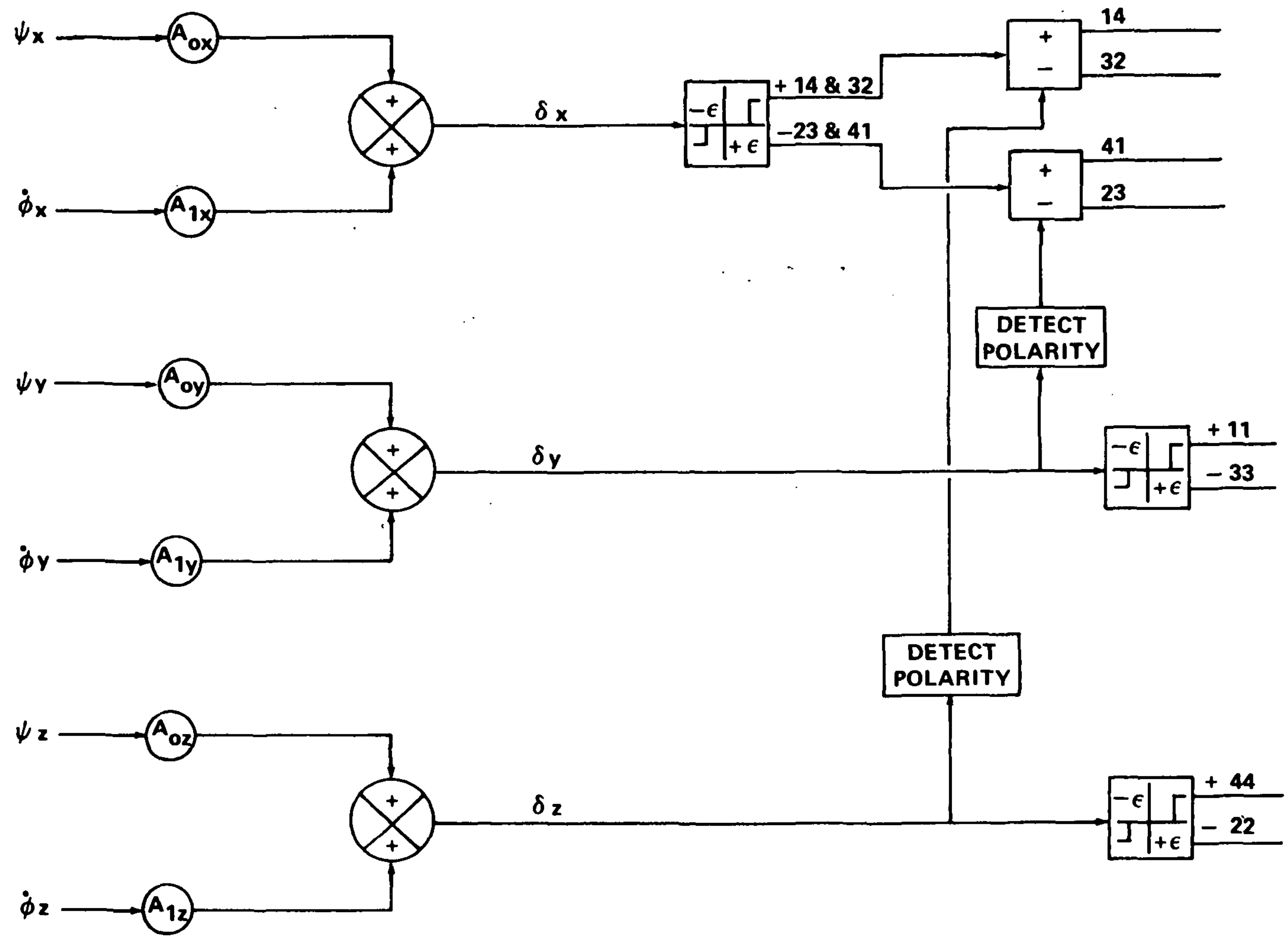


Figure 8. The final control law used in simulating the alternate HEAO-C RCS.

Pitch and yaw are controlled with the radial engines so there is no roll control when either pitch or yaw is being corrected. Roll is controlled with the tangential engines where two of the four engines available are chosen depending on the polarity of the roll error signal. Only one engine is finally used, though, depending upon the polarity of any error in pitch or yaw. Hence, roll is partially coupled to pitch and yaw in that only one engine will be used at any one time for roll control depending on which roll engine of the two selected will best help pitch or yaw. Only when the roll error has exceeded the deadband, however, will a roll engine be actuated. This law proved to be much more efficient than the first law tried, therefore, it was used for the TACS study of the alternate RCS system.

The study followed the same timeline as was used for the baseline study with the results shown in Table 2. Fuel consumption and actuation rates are larger than they were in the baseline system. This was expected since the baseline configuration allows single engine burns to efficiently control two axes. However, it is felt that the alternate system would be the better system for the HEAO-C since long single engine burns would be allowed when dumping momentum. A modification to TACS to include the CMG equations is being considered and will probably be added at a later date.

D. Conclusion

The TACS has been shown to be a valuable tool in the performance studies of vehicles using an RCS for attitude control. It has been demonstrated that various RCS configurations and logic schemes can be implemented in a short time so that a detailed tradeoff study can be made of various candidate systems. For the HEAO-C in particular, the simulation is very comprehensive in that aerodynamic torques are included in addition to the gravity gradient torques. However, if aerodynamic torques are desired for any other vehicle, the equations for that vehicle will have to be substituted for the HEAO-C aerodyanmic equations since the ones now in the TACS are applicable only to the HEAO.

The TACS was used primarily to determine fuel consumption and engine actuations. For the alternate system, two control laws were considered. The first of these was shown to be somewhat less efficient as compared to the law finally used. Hence, it is seen that the TACS can be used to aid the selection of a particular RCS configuration, choose a control law for that configuration, and finally, allow a performance study of the chosen configuration.

TABLE 2. SIMULATION RESULTS FOR THE ALTERNATE HEAO-C RCS

Event	Total Impulse (lb-sec)	Fuel Required at I_{sp} = 140 sec (lbm)	Worst Case Engine Cycling for an Engine	Comments
Null 3 degrees/second 3 Axes	1 043. 8	7. 45	30	Includes Attitude Control
Solar Acquisition (90 degrees about X and Y)	268. 0	1. 90	4	2 degrees/second Maximum Manuever Rate
Attitude Control in 140 × 250 n. mi. Orbit	165. 9 17 374. 0	1. 18 at 4. 5 Orbits 124. 1 at 30 Days	675 or 70 632	0. 263 lbm/Orbit
OAS Thrust Vector Misalignment During Burn to 205 × 250 n. mi.	1 079. 5	7. 71	150	7. 5 minute Burn
Attitude Control in 205 × 250 n. mi. Orbit	36. 55	0. 261	146	0. 261 lbm/Orbit for 1 Orbit
OAS Thrust Vector Misalignment During Burn to 250 × 270 n. mi.	804. 1	5. 74	112	5. 58 minute Burn
Attitude Control in 250 × 270 n. mi. Orbit	54. 4	0. 38	144	0. 259 lbm/Orbit for 1. 5 Orbits
OAS Thrust Vector Misalignment During Burn to 270 n. mi. Circular Orbit	673. 2	4. 80	94	4. 68 minute Burn
Attitude Control in 270 n. mi. Orbit Until CMGs are up to Speed. End of Checkout and Acquisition of X-ray Reference	266. 9	1. 90	1 058	0. 258 lbm/Orbit for 7. 4 Orbits
CMG Momentum Dumping at 270 n. mi.	107 767	769. 7	422 180	Typically 105 545 Actuations per Engine are Expected
Totals	112 159. 35 or 129 367. 45	801. 02 or 923. 94	424 593 or 494 550	

APPENDIX A

EQUATIONS DERIVED TO IMPLEMENT THE THRUSTER ATTITUDE CONTROL SIMULATION

0.0 General Equations

0.1 $$R_s = \sqrt{X_s^2 + Y_s^2 + Z_s^2}$$

0.2 $$g = g_0 R_E^2/R_s^2$$

0.3 $$h = R_s - R_E$$

0.4 $$V_s = \sqrt{\dot{X}_s^2 + \dot{Y}_s^2 + \dot{Z}_s^2}$$

0.5 $$\eta = 2\pi t/P$$

1.0 Rotational Dynamics

1.1 $$M_{gx} = \frac{3\mu}{R_s^5}\left[\left(I_z - I_y\right)Y_B Z_B + I_{zy}\left(Z_B^2 - Y_B^2\right) + I_{xy}X_B Z_B - I_{xz}X_B Y_B\right]$$

1.2 $$M_{gy} = \frac{3\mu}{R_s^5}\left[\left(I_x - I_z\right)X_B Z_B + I_{xz}\left(X_B^2 - Z_B^2\right) + I_{zy}X_B Y_B - I_{xy}Y_B Z_B\right]$$

1.3 $$M_{gz} = \frac{3\mu}{R_s^5}\left[\left(I_y - I_x\right)X_B Y_B + I_{xy}\left(Y_B^2 - X_B^2\right) + I_{xz}Y_B Z_B - I_{zy}X_B Z_B\right]$$

1.4 $$M_{Tx} = \sum L_x F_x$$

1.5 $$M_{Ty} = \sum L_y F_y$$

1.6 $$M_{Tz} = \sum L_z F_z$$

1.7 $$M_{Ax} = \frac{1}{2} \rho V_s^2 A_{ref} D_{ref} C_{lcg}$$

1.8 $$M_{Ay} = \frac{1}{2} \rho V_s^2 A_{ref} D_{ref} C_{mcg}$$

1.9 $$M_{Az} = \frac{1}{2} \rho V_s^2 A_{ref} D_{ref} C_{ncg}$$

1.10 $$M_x = M_{gx} + M_{Tx} + M_{Ax}$$

1.11 $$M_y = M_{gy} + M_{Ty} + M_{Ay}$$

1.12 $$M_z = M_{gz} + M_{Tz} + M_{Az}$$

1.13 $$\ddot{\phi}_x = \frac{M_x}{I_x} + \left[\left(I_y - I_z\right) \dot{\phi}_y \dot{\phi}_z + I_{xz}\left(\dot{\phi}_x \dot{\phi}_y + \ddot{\phi}_z\right)\right] / I_x$$

1.14 $$\ddot{\phi}_y = \frac{M_y}{I_y} + \left[\left(I_z - I_x\right) \dot{\phi}_x \dot{\phi}_z + I_{xz}\left(\dot{\phi}_z^2 - \dot{\phi}_x^2\right)\right] / I_y$$

1.15 $$\ddot{\phi}_z = \frac{M_z}{I_z} + \left[\left(I_x - I_y\right) \dot{\phi}_x \dot{\phi}_y + I_{xz}\left(\ddot{\phi}_x - \dot{\phi}_y \dot{\phi}_z\right)\right] / I_z$$

1.16 $$\dot{\phi}_x = \int \ddot{\phi}_x \, dt$$

1.17 $$\dot{\phi}_y = \int \ddot{\phi}_y \, dt$$

1.18 $$\dot{\phi}_z = \int \ddot{\phi}_z \, dt$$

1.19 $$\dot{A}_{11} = A_{12}\dot{\phi}_z - A_{13}\dot{\phi}_y$$

1.20 $$\dot{A}_{12} = A_{13}\dot{\phi}_x - A_{11}\dot{\phi}_z$$

1.21 $\dot{A}_{13} = A_{11}\dot{\phi}_y - A_{12}\dot{\phi}_x$

1.22 $\dot{A}_{21} = A_{22}\dot{\phi}_z - A_{23}\dot{\phi}_y$

1.23 $\dot{A}_{22} = A_{23}\dot{\phi}_x - A_{21}\dot{\phi}_z$

1.24 $\dot{A}_{23} = A_{21}\dot{\phi}_y - A_{22}\dot{\phi}_x$

1.25 $\dot{A}_{31} = A_{32}\dot{\phi}_z - A_{33}\dot{\phi}_y$

1.26 $\dot{A}_{32} = A_{33}\dot{\phi}_x - A_{31}\dot{\phi}_z$

1.27 $\dot{A}_{33} = A_{31}\dot{\phi}_y - A_{32}\dot{\phi}_x$

1.28 $A_{ij} = \int \dot{A}_{ij}\, dt$

ORTHO NORMALIZATION

1.29 $A_{21} = A_{13}A_{32} - A_{12}A_{33}$

1.30 $A_{22} = A_{11}A_{33} - A_{13}A_{31}$

1.31 $A_{23} = A_{12}A_{31} - A_{11}A_{32}$

1.32 $A_{31} = A_{12}A_{23} - A_{13}A_{22}$

1.33 $A_{32} = A_{13}A_{21} - A_{11}A_{23}$

1.34 $A_{33} = A_{11}A_{22} - A_{12}A_{21}$

1.35 $\mathrm{ORTHO}_1 = \sqrt{A_{11}^2 + A_{12}^2 + A_{13}^2}$

1.36 $\mathrm{ORTHO}_2 = \sqrt{A_{21}^2 + A_{22}^2 + A_{23}^2}$

1.37 $\mathrm{ORTHO}_3 = \sqrt{A_{31}^2 + A_{32}^2 + A_{33}^2}$

1.38 $A_{ij\ \mathrm{corrected}} = A_{ij}/\mathrm{ORTHO}$

2.0 Vehicle Dynamics

2.1 $$[C] = \begin{vmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{vmatrix} \equiv \text{Control Matrix}$$

2.2 $$[D] = C^T A$$

2.3 $$\psi_x = \frac{1}{2}(D_{32} - D_{23})$$

2.4 $$\psi_y = \frac{1}{2}(D_{13} - D_{31})$$

2.5 $$\psi_z = \frac{1}{2}(D_{21} - D_{12})$$

2.6 $$\delta_x = A_{0x}\psi_x + A_{1x}\dot{\phi}_x$$

2.7 $$\delta_y = A_{0y}\psi_y + A_{1y}\dot{\phi}_y$$

2.8 $$\delta_z = A_{0z}\psi_z + A_{1z}\dot{\phi}_z$$

THRUSTER LOGIC

2.9 $$F_{ij} = f\left(\delta_x, \delta_y, \delta_z, \epsilon\right)$$

3.0 Translational Dynamics

3.1 $$F_{Tx} = \sum F_x$$

3.2 $$F_{Ty} = \sum F_y$$

3.3 $$F_{Tz} = \sum F_z$$

3.4 $$\ddot{X}_B = F_{Tx}/m$$

3.5 $$\ddot{Y}_B = F_{Ty}/m$$

3.6 $$\ddot{Z}_B = F_{Tz}/m$$

3.7–3.9
$$\begin{bmatrix} \ddot{X}_s \\ \ddot{Y}_s \\ \ddot{Z}_s \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} \ddot{X}_B \\ \ddot{Y}_B \\ \ddot{Z}_B \end{bmatrix} \begin{matrix} - gX_s/R_s \\ - gY_s/R_s \\ - gZ_s/R_s \end{matrix}$$

3.10 $$\dot{X}_s = \int \ddot{X}_s dt$$

3.11 $$\dot{Y}_s = \int \ddot{Y}_s dt$$

3.12 $$\dot{Z}_s = \int \ddot{Z}_s dt$$

3.13 $$X_s = \int \dot{X}_s dt$$

3.14 $$Y_s = \int \dot{Y}_s dt$$

3.15 $$Z_s = \int \dot{Z}_s dt$$

3.16–3.18
$$\begin{bmatrix} \dot{X}_B \\ \dot{Y}_B \\ \dot{Z}_B \end{bmatrix} = \begin{bmatrix} A_{11} & A_{21} & A_{31} \\ A_{12} & A_{22} & A_{32} \\ A_{13} & A_{23} & A_{33} \end{bmatrix} \begin{bmatrix} \dot{X}_s \\ \dot{Y}_s \\ \dot{Z}_s \end{bmatrix}$$

3.19–3.21
$$\begin{bmatrix} X_B \\ Y_B \\ Z_B \end{bmatrix} = \begin{bmatrix} A_{11} & A_{21} & A_{31} \\ A_{12} & A_{22} & A_{32} \\ A_{13} & A_{23} & A_{33} \end{bmatrix} \begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix}$$

APPENDIX B

AN EXPLANATION OF THE SYMBOLS USED IN THE DIGITAL PROGRAM TACS AND A REPRESENTATIVE PRINTOUT OF TACS

SYMBOL	DEFINITION
A (i,j)	elements of the direction cosine matrix
AO	attitude error gain
A1	angular rate gain
AD (i,j)	rate of change of the elements of the direction cosine matrix
ADP (i,j)	value of AD(I,j) during the previous computation cycle
ALT	altitude of the vehicle in nautical miles
AMASS	mass of the vehicle
APOGEE	apogee of the orbit
AREF	aerodynamic reference area
ARUN	conversion of RUN into seconds
AT	the aerodynamic angle of attack
ATIME	a time used in the print loop to determine how often to print
AXIS	one-half the major axis of the orbit
C (i,j)	elements of the command matrix
CA	aerodynamic coefficient
CAO	aerodynamic coefficient

SYMBOL	DEFINITION
CF_{ijk}	engine on time (cumulative)
CL	aerodynamic coefficient
CLCG	aerodynamic coefficient
CN	aerodynamic coefficient
CNO	aerodynamic coefficient
CONV	a conversion factor equal to the number of degrees per radian
CSM	aerodynamic coefficient
CSMCG	aerodynamic coefficient
CSMO	aerodynamic coefficient
CSN	aerodynamic coefficient
CSNCG	aerodynamic coefficient
CVX	aerodynamic coefficient
CY	aerodynamic coefficient
D (i,j)	elements of the attitude error matrix
DB 1, 2, 3	three deadbands available for use (multiples of epsilon)
DELTX, Y, Z	command torques derived from attitude error and angular rate signals
DELTYO	main engine command torque
DELTZO	main engine command torque
DREF	aerodynamic reference length

SYMBOL	DEFINITION
DT	time increment
DTL	normal time increment
DTS	time increment during engine burn (equal to minimum on time)
EPDX, Y, Z	angular rate due to inertial cross coupling
EPDDX, Y, Z	angular acceleration due to inertial cross coupling
EPDDXP, YP, ZP	value of EPDDX, Y, Z during the previous computation cycle
EPSLN	deadband value for attitude control
ETA	angular position of vehicle in orbit relative to an arbitrary reference point
F_{ijk}	engine name and thrust level during a computation cycle
FMTX, Y, Z	total torque due to engine burns
FMXCG, YCG, ZCG	torque due to aerodynamics
FPDX, Y, Z	angular rate due to engine torques
FPDDX, Y, Z	angular acceleration due to engine torques
FTX, Y, Z	total engine thrust in each axis
G	gravitational acceleration at altitude h
GO	gravitational acceleration at sea level
GIX, Y, Z	principal moments of inertia
GIXY, XZ, ZY	cross products of inertia

SYMBOL	DEFINITION
GMGX, Y, Z	gravity gradient torques
GMU	gravitational constant
GMULT	gravitational parameter used in calculating gravity gradient torques
GPDX, Y, Z	angular rate due to gravity gradient and aero torques
GPDDX, Y, Z	angular acceleration due to gravity gradient and aero torques
GPDDXP, YP, ZP	values of GPDDX, Y, Z during previous computation cycle
H	altitude above sea level
$IACT_{ijk}$	number of engine actuations for each engine
ISUM 1, 2	parameter used to determine if an engine has fired (for printout purposes)
J_{ijk}	logic element in engine firing logic
NISUM 1, 2	parameter used for engine actuation printout purposes
ORTHO 1, 2, 3	an orthogonalization parameter
PDX, Y, Z	vehicle angular rates
PDDX, Y, Z	vehicle angular accelerations
PERIGEE	perigee of the orbit
PERIOD	period of the orbit
PHI	aerodynamic roll angle

SYMBOL	DEFINITION
PI	π, constant
PPDX, Y, Z	values of PDX, Y, Z during previous computation cycle
PRINT	determines the time between print cycles
PSIX, Y, Z	attitude error signals
Q	initialization constant to avoid dividing by a DT of zero during the first computation cycle
RDT	ratio of DT to the previous DT
RHO	atmosphere density at altitude h
RS	distance in inertial reference system from the center of the earth to the center of mass of the vehicle
RUN	sets the time the vehicle will orbit
T, T1, T2	the RCS thrust level, T, and two multiples of it, if needed
TEST	used to choose between normal DT and minimum on time DT
TIME	time (vehicle, not real time)
TMX, Y, Z	sum of gravity gradient and aerodynamic torques
TT1, 2	parameter used in calculating engine on time
VPDX, T, Z	initial angular rates
VS	vehicle velocity in the inertial reference system
XB, YB, ZB	body axes

SYMBOL	DEFINITION
XCG	distance from center of mass to geometrical center along X axis
XDB, YDB, ZDB	rates in body axes
XDDB, YDDB, ZDDB	accelerations in body axes
XDDSF, YDDSF, ZDDSF	transforms of body accelerations to inertial reference system
XDDSG, YDDSG, ZDDSG	acceleration due to gravity in inertial reference system
XDDSP, YDDSP, ZDDSP	values of XDDSG, YDDSG, ZDDSG during the previous computation cycle
XDS, YDS, ZDS	vehicle velocity expressed in the inertial reference system
XDSP, YDSP, ZDSP	values of XDS, YDS, ZDS during the previous computation cycle
XIMP	absolute value of disturbance impulse in X axis
XS, YS, ZS	inertial axes
YCG	distance from center of mass to geometrical center along Y axis
YIMP	absolute value of disturbance impulse on vehicle in Y axis
ZCG	distance from center of mass to geometrical center along Z axis
ZIMP	aboslute value of disturbance impulse on vehicle in Z axis

```
      PROGRAM TACS
      DIMENSION N1(4),N2(4),N3(4),N4(4),N5(4),N6(4),N7(4),N8(4),N9(4)
      DIMENSION AD(3,3),A(3,3),ADP(3,3),C(3,3),D(3,3)
      READ  67,N1,RE,N2,GO,N3,AMASS,N4,PI,N5,CONV,N6,T,N7,FO,N8,GIX
      PRINT 67,N1,RE,N2,GO,N3,AMASS,N4,PI,N5,CONV,N6,T,N7,FO,N8,GIX
      READ  67,N1,GIY,N2,GIZ,N3,GIZY,N4,GIXY,N5,GIXZ,N6,YCL1,N7,YCL2
      PRINT 67,N1,GIY,N2,GIZ,N3,GIZY,N4,GIXY,N5,GIXZ,N6,YCL1,N7,YCL2
      READ  67,N1,ZCL1,N2,ZCL2,N3,X1,N4,X2,N5,X3,N6,X4,N7,X5,N8,X6,N9,X7
      PRINT 67,N1,ZCL1,N2,ZCL2,N3,X1,N4,X2,N5,X3,N6,X4,N7,X5,N8,X6,N9,X7
      READ  67,N1,X8,N2,X9,N3,Y2,N4,Y4,N5,Y6,N6,Y8,N7,Z1,N8,Z3,N9,Z5
      PRINT 67,N1,X8,N2,X9,N3,Y2,N4,Y4,N5,Y6,N6,Y8,N7,Z1,N8,Z3,N9,Z5
      READ  67,N1,Z7,N2,RS,N3,XB,N4,YB,N5,ZB,N6,XS,N7,YS,N8,ZS,N9,XDS
      PRINT 67,N1,Z7,N2,RS,N3,XB,N4,YB,N5,ZB,N6,XS,N7,YS,N8,ZS,N9,XDS
      READ  67,N1,YDS,N2,ZDS,N3,XDDS,N4,YDDS,N5,ZDDS,N6,EPSLN,N7,DELTYO
      PRINT 67,N1,YDS,N2,ZDS,N3,XDDS,N4,YDDS,N5,ZDDS,N6,EPSLN,N7,DELTYO
      READ  67,N1,DELTZO,N2,PDX,N3,PDY,N4,PDZ,N5,GPDX,N6,GPDY,N7,GPDZ
      PRINT 67,N1,DELTZO,N2,PDX,N3,PDY,N4,PDZ,N5,GPDX,N6,GPDY,N7,GPDZ
      READ  67,N1,FPDX,N2,FPDY,N3,FPDZ,N4,PDDX,N5,PDDY,N6,PDDZ,N7,GPDDX
      PRINT 67,N1,FPDX,N2,FPDY,N3,FPDZ,N4,PDDX,N5,PDDY,N6,PDDZ,N7,GPDDX
      READ  67,N1,GPDDY,N2,GPDDZ,N3,A0,N4,A1,N5,DTS,N6,DTL,N7,APRINT
      PRINT 67,N1,GPDDY,N2,GPDDZ,N3,A0,N4,A1,N5,DTS,N6,DTL,N7,APRINT
      READ  67,N1,RUN
      PRINT 67,N1,RUN
      READ 500,CF11,CF12,CF14,CF21,CF22,CF23,CF32,CF33,CF34,CF41,CF43,CF
     144
      READ 500,CF55,CF56,CF58,CF65,CF66,CF67,CF76,CF77,CF78,CF85,CF87,CF
     188
   67 FORMAT (1X,4A4,2X,F15.5)
  500 FORMAT (12F4.1)
      DO 501 I=1,3
      DO 501 J=1,3
      A(I,J)=0.0
  501 AD(I,J)=0.0
      A(1,1)=-1.0
      A(1,2)=0.0
      A(1,3)=0.0
      A(2,1)=0.0
      A(2,2)=-1.0
      A(2,3)=0.0
      A(3,1)=0.0
      A(3,2)=0.0
      A(3,3)=1.0
      XIMP=0.0
      YIMP=0.0
      ZIMP=0.0
      XDDSG=0.0
      YDDSG=0.0
      ZDDSG=0.0
      TUMBLE=0.65219785/CONV
      DELTX=0.0
      DELTY=0.0
      DELTZ=0.0
      Q=-2.
      TIME=0.0
      ATIME=0.0
      PRINT=0.0
      DT=0.0
      TEST=0.0
      GMU=0.39860379E+15
      ETA=0.0
```

```
      APOGEE=250.0
      PERIGEE=140.0
      AXIS=(2.*RE+1852.*(APOGEE+PERIGEE))/2.
      PERIOD=2.*PI*SQRT(AXIS*AXIS*AXIS/GMU)
C
C
      CF221=0.0
      CF223=0.0
      CF441=0.0
      CF443=0.0
      PDX=FDX/CONV
      PDY=FDY/CONV
      PDZ=FDZ/CONV
      PDDX=PDDX/CONV
      PDDY=PDDY/CONV
      PDDZ=PDDZ/CONV
      GPDX=GPDX/CONV
      GPDY=GPDY/CONV
      GPDZ=GPDZ/CONV
      GPDDX=GPDDX/CONV
      GPDDY=GPDDY/CONV
      GPDDZ=GPDDZ/CONV
      FPDX=FPDX/CONV
      FPDY=FPDY/CONV
      FPDZ=FPDZ/CONV
      DELTYO=DELTYO/CONV
      DELTZO=DELTZO/CONV
      EPSLN=EPSLN/CONV
      NISUM1=0.0
      NISUM2=0.0
      ARUN=RUN*60.0
      VPDX=PDX
      VPDY=PDY
      VPDZ=PDZ
      DB1=EPSLN
      DB3=DB1
      DB2=1.5*DB1
      T1=T
      T2=10*T
      EPDX=0.0
      EPDY=0.0
      EPDZ=0.0
      EPDDX=0.0
      EPDDY=0.0
      EPDDZ=0.0
      H=RS-RE
      ALT=H/1852.
      RHO=1.9522523E-08*EXP(-ALT*.041755)
      XCG=4.826
      YCG=-.005718
      ZCG=-.06538
      DREF=2.5399
      AREF=3.1415926*DREF*DREF/4.0
      XDB=0.0
      YDB=7807.73
      ZDB=0.0
C
      IACT21=0.0
      IACT23=0.0
      IACT41=0.0
      IACT43=0.0
      IACT221=0.0
```

```
      IACT223=0.0
      IACT441=0.0
      IACT443=0.0
      IACT11=0.
      IACT22=0.
      IACT33=0.
      IACT44=0.
      IACT14=0.
      IACT23=0.
      IACT32=0.
      IACT41=0.
C
   69 CONTINUE
C     LOGIC CONFIGURATION 1 (ONE)...
      J21=(DELTX+DELTY-DB1+100.)/100.
      J221=(-DELTX-DELTZ-DB1+100.)/100.
      J223=(DELTX-DELTZ-DB1+100.)/100.
      J23=(-DELTX-DELTY-DB1+100.)/100.
      J41=(-DELTX+DELTY-DB1+100.)/100.
      J441=(DELTX+DELTZ-DB1+100.)/100.
      J443=(-DELTX+DELTZ-DB1+100.)/100.
      J43=(DELTX-DELTY-DB1+100.)/100.
      F21=J21*T
      F23=J23*T
      F41=J41*T
      F43=J43*T
      F221=J221*T
      F223=J223*T
      F441=J441*T
      F443=J443*T
      FTX=0.0
      FTY=F441+F443-F221-F223
      FTZ=F23+F43-F21-F41
      PTEST=TEST
      TEST=F21+F23+F41+F43+F221+F223+F441+F443
      RS=SQRT(XS*XS+YS*YS+ZS*ZS)
      G=GO*(RE/RS)*(RE/RS)
      H=RS-RE
      VS=SQRT(XDS*XDS+YDS*YDS+ZDS*ZDS)
      PDT=DT
      IF(Q) 57,57,133
  133 IF(TEST)56,56,55
   55 DT=DTS
      ISUM1=0.0
      ISUM2=F21+F23+F41+F43+F221+F223+F441+F443
      NISUM1=NISUM1+ISUM1
      NISUM2=NISUM2+ISUM2
      TT1=DT/T1
      TT2=DT/T2
      CF21=CF21+(F21*TT1)
      CF23=CF23+(F23*TT1)
      CF41=CF41+(F41*TT1)
      CF43=CF43+(F43*TT1)
      CF221=CF221+(F221*TT1)
      CF223=CF223+(F223*TT1)
      CF441=CF441+(F441*TT1)
      CF443=CF443+(F443*TT1)
      GO TO 57
   56 DT=DTL
   57 Q=2.
      TIME=TIME+DT
      HDT=DT/2.0
```

```
      IF(PDT)134,134,135
  135 RDT=DT/PDT
      GO TO 136
  134 RDT=0,0
  136 CONTINUE
      FMTX=1,5*(F23-F21)+1,485*(F41-F43)+,233*(F443-F223)+,376*(F221-F44
     11)
      FMTY=6,567*(F23+F43-F21-F41)
      FMTZ=6,567*(F221+F223-F441-F443)
      IACT21=((9,9-DT+PDT)/10,)*J21+IACT21
      IACT23=((9,9-DT+PDT)/10,)*J23+IACT23
      IACT41=((9,9-DT+PDT)/10,)*J41+IACT41
      IACT43=((9,9-DT+PDT)/10,)*J43+IACT43
      IACT221=((9,9-DT+PDT)/10,)*J221+IACT221
      IACT223=((9,9-DT+PDT)/10,)*J223+IACT223
      IACT441=((9,9-DT+PDT)/10,)*J441+IACT441
      IACT443=((9,9-DT+PDT)/10,)*J443+IACT443
      GMULT=3,0*GMU/(RS*RS*RS*RS*RS)
      GMGX=GMULT*((GIZ-GIY)*YB*ZB+GIZY*(ZB*ZB-YB*YB)+GIXY*XB*ZB-GIXZ*XB*
     1YB)
      GMGY=GMULT*((GIX-GIZ)*ZB*XB+GIXZ*(XB*XB-ZB*ZB)+GIZY*YB*XB-GIXY*YB*
     1ZB)
      GMGZ=GMULT*((GIY-GIX)*XB*YB+GIXY*(YB*YB-XB*XB)+GIXZ*ZB*YB-GIZY*ZB*
     1XB)
      XIMP=XIMP+DT*ABS(GMGX)
      YIMP=YIMP+DT*ABS(GMGY)
      ZIMP=ZIMP+DT*ABS(GMGZ)
      FPDDX=FMTX/GIX
      FPDDY=FMTY/GIY
      FPDDZ=FMTZ/GIZ
      GPDDXP=GPDDX
      GPDDYP=GPDDY
      GPDDZP=GPDDZ
      PHI=ATNB(YDB,ZDB)
      CVX=XDB/VS
      IF(ABS(CVX)-1,)8,7,8
    8 AT=PI/2,-(CVX+CVX*CVX*CVX/6,+3,*CVX*CVX*CVX*CVX*CVX/40,+15,*CVX*CV
     1X*CVX*CVX*CVX*CVX*CVX/336,)
      GO TO 10
    7 AT=0,0
   10 CONTINUE
      CA0=5,77121*COS(AT)-1,75706*COS(3,*AT)-,40363*COS(5,*AT)-,08961*CO
     1S(7,*AT)+,04889*COS(9,*AT)
      CN0=6,77165*SIN(AT)-,96271*SIN(3,*AT)-,34303*SIN(5,*AT)+,02238*SIN
     1(7,*AT)+,00889*SIN(9,*AT)
      CSM0=14,88051*SIN(AT)-1,6028*SIN(3,*AT)-,54178*SIN(5,*AT)+,00297*S
     1IN(7,*AT)-,01482*SIN(9,*AT)
      CA=CA0
      CN=CN0*COS(PHI)
      CY=-CN0*SIN(PHI)
      CL=0,0
      CSM=CSM0*COS(PHI)
      CSN=-CSM0*SIN(PHI)
      CSMCG=CSM+CA*ZCG/DREF-CN*XCG/DREF
      CSNCG=CSN-CY*XCG/DREF-CA*YCG/DREF
      CLCG=CL+CY*ZCG/DREF+CN*YCG/DREF
      ALT=H/1852,
      RHO=,2068E-05*EXP(-,3805E-06*(ALT*ALT*ALT-,7774E03*ALT*ALT+,2911E0
     16*ALT))                                                          NOMINAL
      Q=,5*RHO*VS*VS
      FMXCG=Q*AREF*DREF*CLCG
      FMYCG=Q*AREF*DREF*CSMCG
```

```
      FMZCG=Q*AREF*DREF*CSNCG
      TMX=GMGX+FMXCG
      TMY=GMGY+FMYCG
      TMZ=GMGZ+FMZCG
      GPDDX=TMX/GIX
      GPDDY=TMY/GIY
      GPDDZ=TMZ/GIZ
      EPDDXP=EPDDX
      EPDDYP=EPDDY
      EPDDZP=EPDDZ
      EPDDX=((PDX*PDY+PDDZ)*GIXZ-(GIZ-GIY)*PDY*PDZ)/GIX
      EPDDY=((GIZ-GIX)*PDZ*PDX+(PDZ*PDZ-PDX*PDX)*GIXZ)/GIY
      EPDDZ=((GIX-GIY)*PDX*PDY+(PDDX-PDY*PDZ)*GIXZ)/GIZ
      EPDX=EPDX+DT*(EPDDX+((EPDDX-EPDDXP)/2.)*RDT)
      EPDY=EPDY+DT*(EPDDY+((EPDDY-EPDDYP)/2.)*RDT)
      EPDZ=EPDZ+DT*(EPDDZ+((EPDDZ-EPDDZP)/2.)*RDT)
      FPDX=FPDX+DT*FPDDX
      FPDY=FPDY+DT*FPDDY
      FPDZ=FPDZ+DT*FPDDZ
      GPDX=GPDX+DT*(GPDDX+((GPDDX-GPDDXP)/2.)*RDT)
      GPDY=GPDY+DT*(GPDDY+((GPDDY-GPDDYP)/2.)*RDT)
      GPDZ=GPDZ+DT*(GPDDZ+((GPDDZ-GPDDZP)/2.)*RDT)
      PPDX=PDX
      PPDY=PDY
      PPDZ=PDZ
      PDX=FPDX+GPDX+VPDX+EPDX
      PDY=FPDY+GPDY+VPDY+EPDY
      PDZ=FPDZ+GPDZ+VPDZ+EPDZ
      PDDX=FPDDX+GPDDX+EPDDX
      PDDY=FPDDY+GPDDY+EPDDY
      PDDZ=FPDDZ+GPDDZ+EPDDZ
      DO 58 I=1,3
      DO 58 J=1,3
   58 ADP(I,J)=AD(I,J)
      AD(1,1)=A(1,2)*PDZ-A(1,3)*PDY
      AD(1,2)=A(1,3)*PDX-A(1,1)*PDZ
      AD(1,3)=A(1,1)*PDY-A(1,2)*PDX
      AD(2,1)=A(2,2)*PDZ-A(2,3)*PDY
      AD(2,2)=A(2,3)*PDX-A(2,1)*PDZ
      AD(2,3)=A(2,1)*PDY-A(2,2)*PDX
      AD(3,1)=A(3,2)*PDZ-A(3,3)*PDY
      AD(3,2)=A(3,3)*PDX-A(3,1)*PDZ
      AD(3,3)=A(3,1)*PDY-A(3,2)*PDX
      DO 59 I=1,3
      DO 59 J=1,3
   59 A(I,J)=A(I,J)+DT*(AD(I,J)+(AD(I,J)-ADP(I,J))*RDT/2.)
C
      A(2,1)=A(1,3)*A(3,2)-A(1,2)*A(3,3)
      A(2,2)=A(1,1)*A(3,3)-A(1,3)*A(3,1)
      A(2,3)=A(1,2)*A(3,1)-A(1,1)*A(3,2)
      A(3,1)=A(1,2)*A(2,3)-A(1,3)*A(2,2)
      A(3,2)=A(1,3)*A(2,1)-A(1,1)*A(2,3)
      A(3,3)=A(1,1)*A(2,2)-A(1,2)*A(2,1)
      ORTHO1=SQRT(A(1,1)*A(1,1)+A(1,2)*A(1,2)+A(1,3)*A(1,3))
      ORTHO2=SQRT(A(2,1)*A(2,1)+A(2,2)*A(2,2)+A(2,3)*A(2,3))
      ORTHO3=SQRT(A(3,1)*A(3,1)+A(3,2)*A(3,2)+A(3,3)*A(3,3))
      A(1,1)=A(1,1)/ORTHO1
      A(1,2)=A(1,2)/ORTHO1
      A(1,3)=A(1,3)/ORTHO1
      A(2,1)=A(2,1)/ORTHO2
      A(2,2)=A(2,2)/ORTHO2
      A(2,3)=A(2,3)/ORTHO2
```

```
      A(3,1)=A(3,1)/ORTHO3
      A(3,2)=A(3,2)/ORTHO3
      A(3,3)=A(3,3)/ORTHO3
C     THE C MATRIX IS THE GUIDANCE MATRIX AND THE POSITION ERRORS ARE OBTAINED
C     FROM THE D MATRIX.
C
C     ZB ALONG ZS,  YB IN ORBITAL PLANE,  XB PEP,
      C(1,1)=-1.0
      C(1,2)=0.0
      C(1,3)=0.0
      C(2,1)=0.0
      C(2,2)=-1.0
      C(2,3)=0.0
      C(3,1)=0.0
      C(3,2)=0.0
      C(3,3)=1.0
      DO 60 I=1,3
      DO 60 J=1,3
   60 D(I,J)=C(1,I)*A(1,J)+C(2,I)*A(2,J)+C(3,I)*A(3,J)
      PSIX= 0.5*(D(3,2)-D(2,3))
      PSIY=0.5*(D(1,3)-D(3,1))
      PSIZ= 0.5*(D(2,1)-D(1,2))
      DELTX=A0*PSIX+A1*PDX
      DELTY=A0*PSIY+A1*PDY
      DELTZ=A0*PSIZ+A1*PDZ
      DELTYO=DELTY
      DELTZO=DELTZ
C
C     ,,,,,,..................................
      XDDB=FTX/AMASS
      YDDB=FTY/AMASS
      ZDDB=FTZ/AMASS
      XDDSP=XDDSG
      YDDSP=YDDSG
      ZDDSP=ZDDSG
      XDDSF=A(1,1)*XDDB+A(1,2)*YDDB+A(1,3)*ZDDB
      YDDSF=A(2,1)*XDDB+A(2,2)*YDDB+A(2,3)*ZDDB
      ZDDSF=A(3,1)*XDDB+A(3,2)*YDDB+A(3,3)*ZDDB
      XDDSG=-G*XS/RS
      YDDSG=-G*YS/RS
      ZDDSG=-G*ZS/RS
      XDSP=XDS
      YDSP=YDS
      ZDSP=ZDS
      XDS=XDS+DT*XDDSF+DT*(XDDSG+((XDDSG-XDDSP)/2.)*RDT)
      YDS=YDS+DT*YDDSF+DT*(YDDSG+((YDDSG-YDDSP)/2.)*RDT)
      ZDS=ZDS+DT*ZDDSF+DT*(ZDDSG+((ZDDSG-ZDDSP)/2.)*RDT)
      XS=XS+HDT*(XDS+XDSP)
      YS=YS+HDT*(YDS+YDSP)
      ZS=ZS+HDT*(ZDS+ZDSP)
      XB=  A(1,1)*XS+A(2,1)*YS+A(3,1)*ZS
      YB=  A(1,2)*XS+A(2,2)*YS+A(3,2)*ZS
      ZB=  A(1,3)*XS+A(2,3)*YS+A(3,3)*ZS
      XDB=A(1,1)*XDS+A(2,1)*YDS+A(3,1)*ZDS
      YDB=A(1,2)*XDS+A(2,2)*YDS+A(3,2)*ZDS
      ZDB=A(1,3)*XDS+A(2,3)*YDS+A(3,3)*ZDS
      ETA=(VS*DT/RS)+ETA
      ATIME=ATIME+DT
      IF(ATIME-PRINT) 69,70,70
   70 ATIME=0.0
      PRINT=APRINT
      DEG1=ETA*CONV
```

```
      DEG2=PSIX*CONV
      DEG3=PSIY*CONV
      DEG4=PSIZ*CONV
      DEG5=DELTX*CONV
      DEG6=DELTY*CONV
      DEG7=DELTZ*CONV
      DEG8=PDX*CONV
      DEG9=PDY*CONV
      DEG10=PDZ*CONV
      DEG11=AT*CONV
      DEG12=PHI*CONV
      PRINT 600,TIME,XS,XB,DEG5,TMX,GMGX,G,YS,YB,DEG6,TMY,GMGY,H,ZS,ZB,D
     1EG7,TMZ,GMGZ,VS,XDS,DEG2,DEG8,FTX,RS,YDS,DEG3,DEG9,FTY,DEG1,ZDS,DE
     2G4,DEG10,FTZ,PERIOD
  600 FORMAT(//,(1X,4HTIME,2X,F12.3,5X,2HXS,4X,F12.3,5X,2HXB,4X,F12.3,5X
     1,5HDELTX,1X,F7.3,5X,3HTMX,3X,F12.6,5X,4HGMGX,F12.6,/,1X,1HG,5X,F12
     2.3,5X,2HYS,4X,F12.3,5X,2HYB,4X,F12.3,5X,5HDELTY,1X,F7.3,5X,3HTMY,3
     3X,F12.6,5X,4HGMGY,F12.6,/,1X,1HH,5X,F12.3,5X,2HZS,4X,F12.3,5X,2HZB
     4,4X,F12.3,5X,5HDELTZ,1X,F7.3,5X,3HTMZ,3X,F12.6,5X,4HGMGZ,F12.6,/,1
     5X,2HVS,4X,F12.3,5X,3HXDS,3X,F12.3,5X,4HPSIX,2X,F12.3,5X,3HPDX,1X,F
     69.5,5X,3HFTX,3X,F12.3,/,1X,2HRS,4X,F12.3,5X,3HYDS,3X,F12.3,5X,4HPS
     7IY,2X,F12.3,5X,3HPDY,1X,F9.5,5X,3HFTY,3X,F12.3,/,1X,3HETA,3X,F12.3
     8,5X,3HZDS,3X,F12.3,5X,4HPSIZ,2X,F12.3,5X,3HPDZ,1X,F9.5,5X,3HFTZ,3X
     9,F12.3,5X,6HPERIOD,F8.2))
      PRINT 601,DEG11,DEG12,FMXCG,FMYCG,FMZCG
  601 FORMAT(23X,5HALPHA,2X,F11.4,5X,3HPHI,4X,F11.4,5X,5HFMXCG,F12.6,5X,
     15HFMYCG,F12.6,5X,5HFMZCG,F12.6)
      PRINT 6358,XIMP,YIMP,ZIMP
 6358 FORMAT(1X,10HX IMPULSE=,E11.4,5X,10HY IMPULSE=,E11.4,5X,10HZ IMPUL
     1SE=,E11.4,/)
      IF (NISUM1)1000,1000,1001
 1001 PRINT 1005,CF11,CF14,CF22,CF23,CF32,CF33,CF41,CF44
 1005 FORMAT(1H0,5HCF11=,F6.3,8H    CF14=,F6.3,8H    CF22=,F6.3,8H    CF23=
     1,F6.3,8H    CF32=,F6.3,8H    CF33=,F6.3,8H    CF41=,F6.3,8H    CF44=,F
     26.3)
      PRINT 7359,IACT11,IACT22,IACT33,IACT44,IACT14,IACT23,IACT32,IACT41
 7359 FORMAT(1X,5HACT11,I5,8H    ACT22,I5,8H    ACT33,I5,8H    ACT44,I5,9H
     1     ACT14,I5,9H     ACT23,I5,9H     ACT32,I5,9H     ACT41,I5)
 1000 IF (NISUM2)1003,1003,1004
 1004 PRINT 1006,CF21,CF23,CF221,CF223,CF41,CF43,CF441,CF443
 1006 FORMAT(1H0,5HCF21=,F6.3,8H    CF23=,F6.3,8H   CF221=,F6.3,8H   CF223=
     1,F6.3,8H    CF41=,F6.3,8H    CF43=,F6.3,8H   CF441=,F6.3,8H   CF443=,F
     26.3)
      PRINT 7358,IACT21,IACT23,IACT41,IACT43,IACT221,IACT223,IACT441,IAC
     1T443
 7358 FORMAT(1X,5HACT21,I5,8H    ACT23,I5,8H    ACT41,I5,8H    ACT43,I5,9H
     1    ACT221,I5,9H    ACT223,I5,9H    ACT441,I5,9H    ACT443,I5)
 1003 CONTINUE
      NISUM1=0
      NISUM2=0
 2047 CONTINUE
      IF(TIME-ARUN)69,73,73
   73 STOP
      END
```

RB	METER	6378244,79993
GO	M/S/S	9,79800
MASS	KG	7209,40000
PI	RAD	3,14159
CONV	DEG/RAD	57,29580
T	N	22,24000
FO	N	0
GIX	N*M*S**2	3902,43000
GIY	N*M*S**2	94246,38000
GIZ	N*M*S**2	94974,75000
GIZY	N*M*S**2	0
GIXY	N*M*S**2	0
GIXZ	N*M*S**2	0
YCL1	M	0
YCL2	M	0
ZCL1	M	0
ZCL2	M	0
X1	M	0
X2	M	-4,97840
X3	M	0
X4	M	-4,97840
X5	M	0
X6	M	0
X7	M	0
X8	M	0
X9	M	0
Y2	M	-1,36150
Y4	M	1,38170
Y6	M	0
Y8	M	0
Z1	M	1,46050
Z3	M	-1,28270
Z5	M	0
Z7	M	0
RS	M	6637524,79993
XB	M	-4693438,79504
YB	M	0
ZB	M	4693438,79492
XS	M	4693438,79492
YS	M	0
ZS	M	4693438,79492
XDS	M/S	0
YDS	M/SEC	-7807,73000
ZDS	M/S	0
XDDS	M/S/S	0
YDDS	M/S/S	0
ZDDS	M/S/S	0
EPSLN	DEG	,50000
DELTYO	DEG	0
DELTZO	DEG	0
PDX	DEG/SEC	,01000
PDY	DEG/SEC	,01000
PDZ	DEG/SEC	,01000
GPDX	DEG/S	0
GPDY	DEG/S	0
GPDZ	DEG/S	0
FPDX	DEG/S	0
FPDY	DEG/S	0
FPDZ	DEG/S	0
PDDX	DEG/S/S	0
PDDY	DEG/S/S	0

```
PDDZ     DEG/S/S            0
GPDDX    DEG/S/S            0
GPDDY    DEG/S/S            0
GPDDZ    DEG/S/S            0
A0                    1,00000
A1       SEC          5,00000
DTS      SEC           ,02500
DTL      SEC           ,50000
APRINT   SEC        100,00000
RUN      MIN         45,00000

TIME              0   XS     4693438,795   XB    -4693438,795   DELTX    ,050    TMX        ,004185   GMGX         0
G             9,047   YS               0   YB               0   DELTY    ,050    TMY        ,186209   GMGY    ,186209
H        259279,996   ZS     4693438,795   ZB     4693438,795   DELTZ    ,050    TMZ        ,032854   GMGZ         0
VS         7807,730   XDS              0   PSIX             0   PDX    ,01000    FTX              0
RS      6637524,798   YDS      -7807,730   PSIY             0   PDY    ,01000    FTY              0
ETA               0   ZDS              0   PSIZ             0   PDZ    ,01000    FTZ              0   PERIOD 5506,04
                      ALPHA      90,0000   PHI        90,0000   FMXCG    ,004185    FMYCG  -0,000000    FMZCG    ,032854
X IMPULSE=            0    Y IMPULSE=        0    Z IMPULSE=        0

TIME        100,300   XS     4661297,334   XB    -4690242,729   DELTX  -0,001    TMX        ,004363   GMGX    ,000254
G             9,046   YS     -781327,073   YB      817359,964   DELTY    ,430    TMY        ,185552   GMGY    ,183339
H        259960,279   ZS     4661297,293   ZB     4625948,889   DELTZ    ,447    TMZ        ,000081   GMGZ  -0,031979
VS         7806,943   XDS      -640,141    PSIX        -0,006   PDX    ,00085    FTX              0
RS      6638205,079   YDS      -7754,269   PSIY          ,434   PDY  -0,00085    FTY              0
ETA           6,759   ZDS      -640,142    PSIZ          ,447   PDZ  -0,00005    FTZ              0   PERIOD 5506,04
                      ALPHA      84,8390   PHI        94,6555   FMXCG    ,004108    FMYCG    ,002213    FMZCG    ,032060
X IMPULSE= 1,3236E-02    Y IMPULSE= 1,8576E 01    Z IMPULSE= 1,6642E 00

CF21=  ,150   CF23=    0  CF221=    0  CF223=    0   CF41=  ,100   CF43=    0  CF441=    0  CF443=  ,125
ACT21    6    ACT23    0  ACT41     4  ACT43     0   ACT221    0   ACT223   0  ACT441    0  ACT443    5

TIME        200,450   XS     4565523,450   XB    -4590155,803   DELTX    ,003    TMX        ,004317   GMGX    ,000481
G             9,040   YS    -1550818,031   YB     1577164,071   DELTY    ,404    TMY        ,179785   GMGY    ,175518
H        262000,978   ZS     4565523,315   ZB     4531673,784   DELTZ    ,269    TMZ      -0,030677   GMGZ  -0,060463
VS         7804,579   XDS     -1270,193    PSIX          ,045   PDX  -0,00831    FTX              0
RS      6640245,778   YDS      -7595,027   PSIY          ,408   PDY  -0,00080    FTY              0
ETA          13,506   ZDS     -1270,194    PSIZ          ,285   PDZ  -0,00320    FTZ              0   PERIOD 5506,04
                      ALPHA      80,3065   PHI        99,4596   FMXCG    ,003836    FMYCG    ,004267    FMZCG    ,029785
X IMPULSE= 5,0380E-02    Y IMPULSE= 3,6581E 01    Z IMPULSE= 6,3323E 00

CF21=  ,225   CF23=    0  CF221=    0  CF223=    0   CF41=  ,150   CF43=    0  CF441=  ,025  CF443=  ,125
ACT21    9    ACT23    0  ACT41     6  ACT43     0   ACT221    0   ACT223   0  ACT441    1  ACT443    5

TIME        300,550   XS     4407575,830   XB    -4444421,407   DELTX  -0,027    TMX        ,004086   GMGX    ,000672
G             9,031   YS    -2298793,454   YB     2285463,866   DELTY    ,403    TMY        ,169590   GMGY    ,163767
H        265371,032   ZS     4407575,563   ZB     4377404,672   DELTZ  -0,187    TMZ      -0,058243   GMGZ  -0,084677
VS         7800,677   XDS     -1881,863    PSIX        -0,015   PDX  -0,00236    FTX              0
RS      6643615,832   YDS      -7332,624   PSIY          ,398   PDY    ,00098    FTY              0
ETA          20,244   ZDS     -1881,864    PSIZ        -0,158   PDZ  -0,00590    FTZ              0   PERIOD 5506,04
                      ALPHA      76,1142   PHI       104,2502   FMXCG    ,003413    FMYCG    ,005823    FMZCG    ,026435
X IMPULSE= 1,0845E-01    Y IMPULSE= 5,3591E 01    Z IMPULSE= 1,3633E 01

CF21=  ,275   CF23=    0  CF221=    0  CF223=    0   CF41=  ,200   CF43=    0  CF441=  ,025  CF443=  ,125
```

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APPROVAL

A DESCRIPTION OF THE THRUSTER ATTITUDE CONTROL SIMULATION AND ITS APPLICATION TO THE HEAO-C STUDY

By Larry B. Brandon

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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