MAGNETIC ATTITUDE CONTROL SYSTEM FOR SPINNING SMALL SPACECRAFT

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A magnetic Attitude Control Subsystem (ACS) designed for minimum power, weight, and cost is presented. The ACS subsystem was designed and built by ITHACO for the Small Communications Satellite Cluster (SCSC), integrated by Defense Systems Incorporated for the Defense Advanced Research Projects Agency. The basic spacecraft configuration is a flat cylinder, having a mass of 22.7 Kg with a diameter of 47.2 cm and 17.0 cm height. Hardware for the ACS design includes a two-axis magnetometer, two TORQRODs™, a Horizon Crossing Indicator and the host microprocessor.

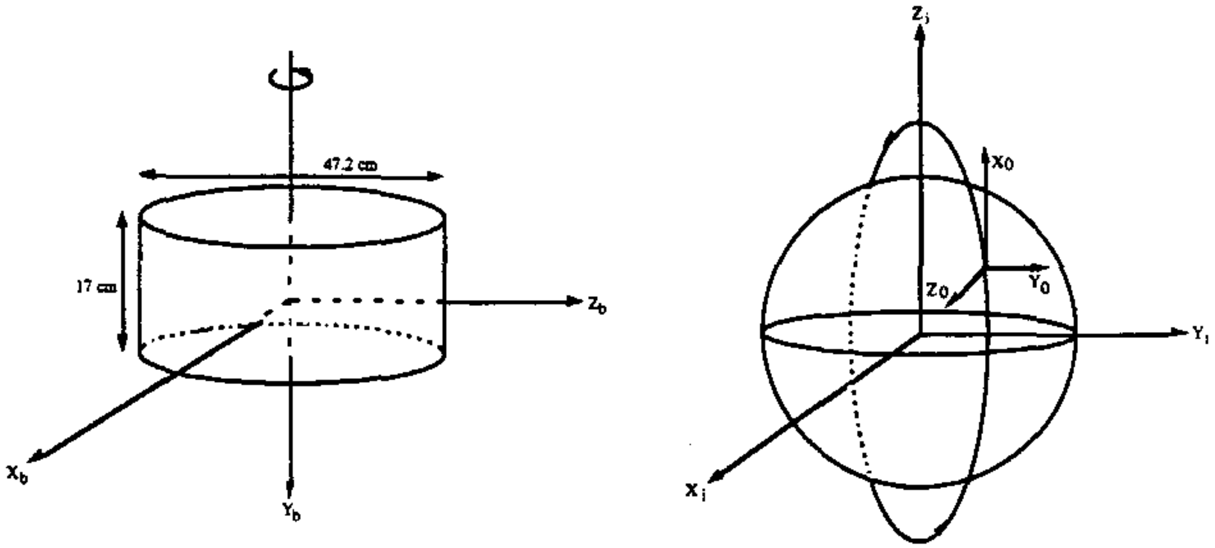
During acquisition mode, the ACS spins up and stabilizes the spacecraft with a spin rate of 3 RPM (within 10%) and the spin-axis to within 5° of the orbit normal. Simulation results show that the above objectives can be achieved with the 1 Am^2 TORQRODs within 4 orbits with total ACS orbital average power consumption of 190 mW and total ACS mass of 0.428 Kg.

INTRODUCTION AND PRELIMINARIES

A magnetic ACS has been designed and built by ITHACO Inc., for the Small Communication Satellite Clusters (SCSC) - known as MICROSAT, integrated by Defense System Inc. for Defense Advanced Research Projects Agency (DARPA). The objectives were to design and build a low cost, low weight, and low power magnetic ACS for seven small spacecraft each of which having a mass of 22.7 Kg (50 lbs). Each spacecraft has a flat cylindrical configuration with a diameter of 47.2 cm and 17.0 cm height. These spacecraft are spin-stabilized to be launched in circular orbit with an inclination of 82° for a communication mission. All seven spacecraft will be launched to an altitude of 741 Km (400 nmi) by PEGASUS in a single launch mission. In normal mode the spacecraft will be spinning about the cylindrical axis (maximum moment of inertia) at 3 RPM with the spin axis parallel to the orbit normal. The performance requirements for the magnetic ACS are to maintain the spin rate within 10% of 3 RPM and the spin vector within 5° of the orbit normal.

Figure 1 illustrates the configuration of the SCSC satellites with the body fixed coordinate system. The Y_b-axis (axis coincident with the cylindrical axis) is designated as the spin axis and will be normal to the orbit plane. The other two axes (X_b and Z_b) are arbitrarily chosen perpendicular to the Y_b-axis with the origin of the coordinate system at the center of gravity (CG). The other two coordinate systems, i.e., Earth centered inertial system (X_i,Y_i,Z_i) and the orbiting reference coordinate system (X_o,Y_o,Z_o) used for simulations and performance verification are shown in the same Figure 1.

This paper describes the control algorithms, attitude determination procedures, hardware requirements and their functions, power requirements, masses etc. for the SCSC spacecraft. Results of the computer simulations of the spacecraft attitudes in the presence of various disturbance and control torques are presented.



Body Coordinate System

Orbital And Inertial Coordinate System

FIGURE 1

MODE OF OPERATIONS AND ACS HARDWARE

During the mission the spacecraft will be operating in either of two modes: Acquisition or On-Orbit mode. After the launch from PEGASUS, the spacecraft will have arbitrary orientation (most likely zero roll and 90° yaw) with no significant spin rate. The acquisition mode will spin up the spacecraft to within 10% of 3 RPM and re-orient the spin vector such that it aligns itself close to the orbit normal. Acquisition mode will also be turned on when certain tests for on-orbit mode operations fail. The on-orbit mode maintains the spin rate within 10% of the 3 RPM and holds the spin vector within 5° of the orbit normal.

The hardware required for the magnetic ACS in both modes of operation are a few lightweight, non-moving parts designed for very low power consumption. The ACS needs only a two-axis magnetometer and two small 1.0 Am^2 TORQRODs™ for acquisition mode, and additionally one horizon sensor for on-orbit mode for the mission. The magnetometer senses the Earth's field to provide information to the control algorithms. The Horizon Crossing Indicator (HCI) provides the roll error, the only additional information needed by the on-orbit control algorithm. TORQRODs™ are activated or deactivated to apply control torques to the spacecraft based on the above information provided by the magnetometer and the HCI. In addition to the above hardware, a low power control electronics assembly on its own printed circuit board and installed in the host spacecraft microcomputer is required for processing the signals and commands. The spacecraft layout of Figure 2 shows the physical locations and orientation of the ACS hardware for proper functioning. The two TORQRODs™ are to be parallel to the two sensitive axes of the magnetometer. One is aligned parallel to the spin axis (Y_b-axis) for spin vector precession and the other is perpendicular to this (Z_b-axis) for spin rate control. The HCI has been mounted on the surface of the spacecraft such that its Line-Of-Sight (LOS) is tilted 60° away from the Y_b-axis. The functional block diagram of magnetic ACS in Figure 3 shows the flow of signal processing and commands during the operational modes.

ROLL ERROR ESTIMATION FOR ON ORBIT MODE

The estimated roll error required by the on-orbit control law is determined from a single HCI. This sensor, as indicated in the previous section, is located on the spacecraft surface with the LOS tilted 60° away from the Y_b-axis. The HCI scan geometry as the spacecraft spins is shown in Figure 4. The purpose for the selection of this tilt angle was twofold: (i) To let the HCI LOS view the Earth's surface for a significant part of the spin period so that the Earth time pulse width (i.e., the difference between the leading edge and the trailing edge times) is significantly larger than the corresponding pulse widths of the Sun and Moon. This will help in rejecting the Sun and the Moon interference in case they show up in the HCI's Field-Of-View (FOV) during a scan; (ii) To have enough range for roll error estimation (in both positive and negative directions) to be computed for on orbit control law operation. Computation of the roll error with one HCI requires spacecraft altitude information. Since the performance requirement is modest (< 5°) a slight error in altitude can be accommodated. The altitude reference may be adjusted by ground command. Nominally, assuming everything is normal and there is no Sun and Moon interference, the roll error is estimated from the timed Earth pulse width using a simple linearized formula as

$$\varphi = C_1 * [2.0 * \pi * \Delta t/T_s - C_2]$$

Where φ = estimated roll error in radian
Δt = difference between the current leading and trailing edge times
= TE - LE
TE = Trailing edge time
LE = Leading edge time
T_s = spacecraft's spin period
C_1 = 0.7496
C_2 = 2.0937

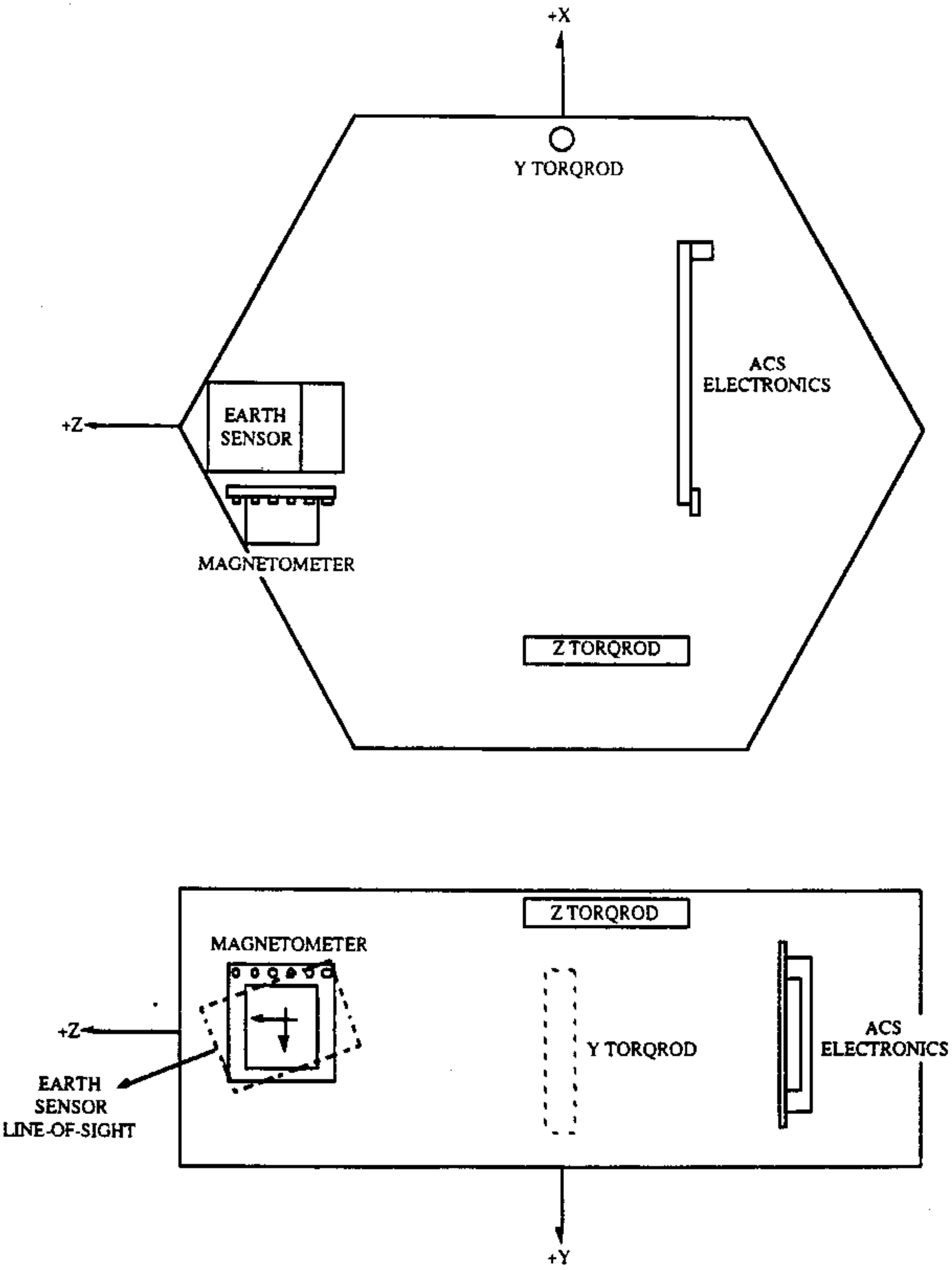


FIGURE 2
TYPICAL MICROSAT LAYOUT

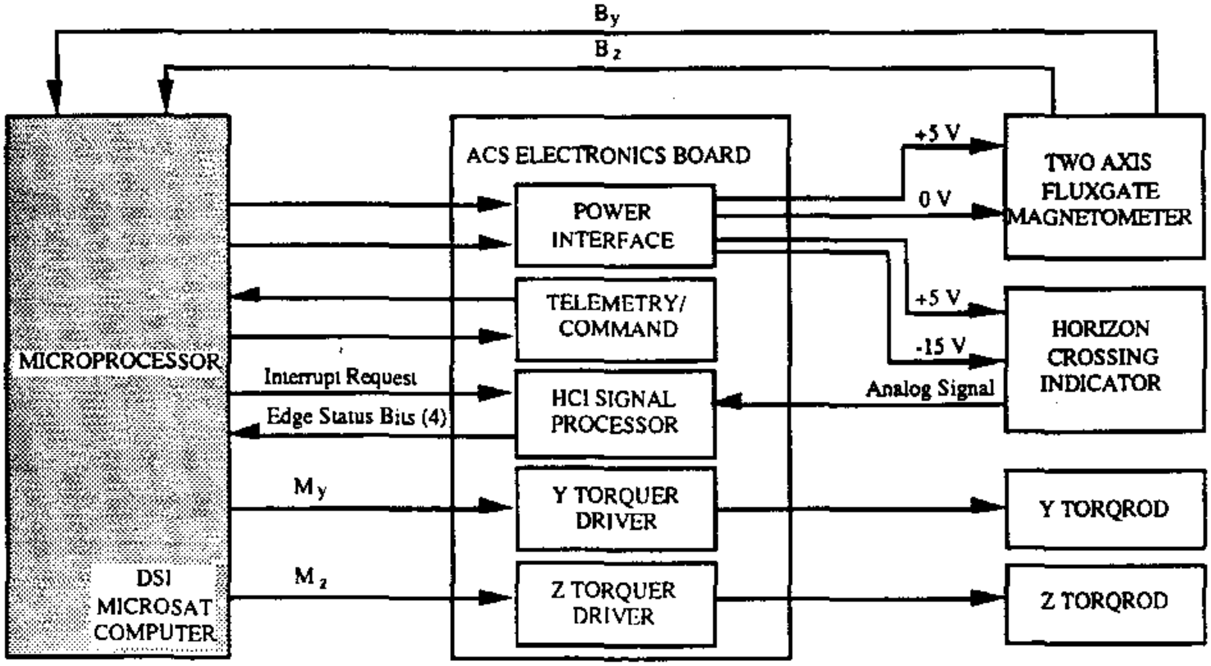


FIGURE 3
ATTITUDE CONTROL SUBSYSTEM BLOCK DIAGRAM

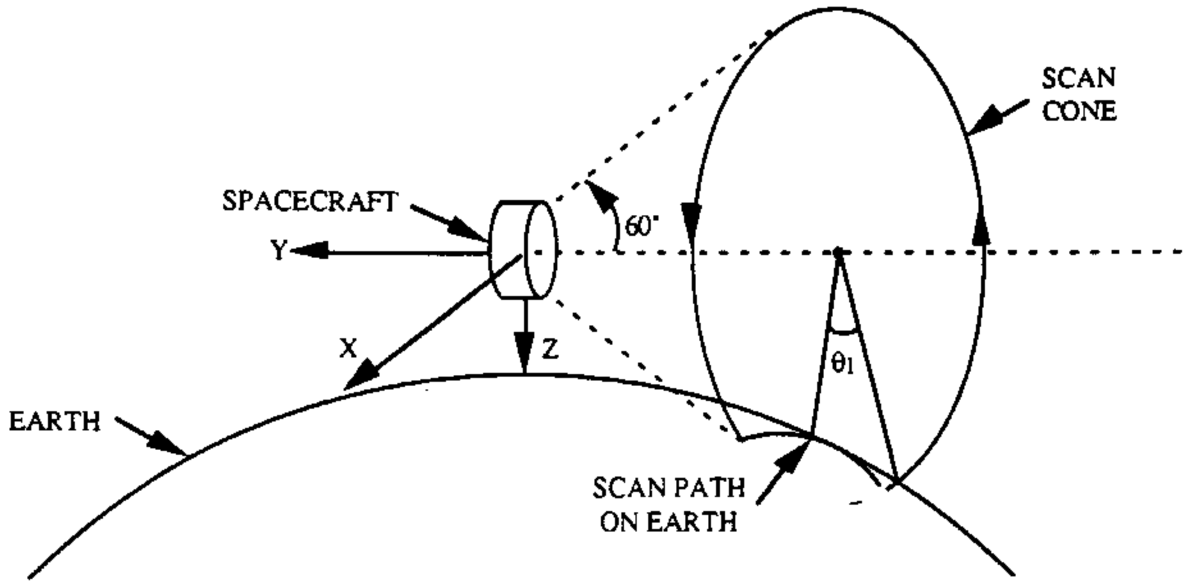


FIGURE 4
SPACECRAFT/HORIZON SENSOR SCAN GEOMETRY

ROLL ERROR ESTIMATION FOR ON ORBIT MODE (Continued)

The constants C_1, C_2, which are dependent on the HCI tilt angle and spacecraft's altitude, are uplinkable parameters. These can be changed by ground command if it is necessary to do so. The spin period T_s is calculated from:

T_s = $k * T_s + NTs * (1.0 - k)$
NTs = latest spin period computed
= [(TE - TEP) + (LE - LEP)] / 2.0
LEP,TEP = Previous leading and trailing edge times.
k = 0.8 , weighting factor which is uplinkable.

CONTROL ALGORITHMS

The control algorithms have two tasks to perform; maintain the spin period of the spacecraft and maintain the spin axis orientation within 5° of the orbit normal. The acquisition mode assumes that the spacecraft is spinning at any arbitrary rate below about 7 RPM and is oriented in any arbitrary attitude. The HCI may or may not be viewing the Earth. The on-orbit mode assumes that the HCI can view the Earth throughout the orbit and relies on the HCI data for fine pointing control and timing of ACS operations throughout each spin of the spacecraft.

The two-axis magnetometer is used in both modes. In order to simplify the hardware, there is no provision for magnetic compensation of the TORQROD™ to magnetometer interference. Instead, the TORQRODs™ are turned off by software prior to initiation of a sample measurement from the magnetometer.

Since minimum power consumption has a high priority on such small spacecraft, the TORQRODs™ were specially wound for high efficiency. To minimize resistive losses, HEX FET drivers switch the TORQROD™ windings to the battery voltages under control of the host computer. Operation of the TORQRODs is three state, ON+/OFF/ON-. As a result, very little power is wasted in the electronics.

The HCI is used only in the Normal mode. It is powered down during acquisition mode when TORQROD™ duty cycles are expected to be high. The HCI is a simple instrument with one infrared detector accompanied with a single operational amplifier preamp. The signal processing electronics uses low power, low voltage amplifiers in a simple signal processing scheme optimized for low power and modest accuracy.

ACQUISITION MODE

In the Acquisition mode, the ACS relies on the magnetometer for attitude information and on the TORQRODs™ for momentum management. The acquisition process relies upon a variation of the well known "minus B-dot" magnetic control law [Reference 1]. In a conventional three-axis magnetic acquisition, each TORQROD™ is driven according to the negative derivative of the measured magnetic field along the TORQROD™. The result is a damping of motion relative to the external magnetic field surrounding the spacecraft. The Y_b axis TORQROD™ operates using this control law to force that TORQROD™ to drive toward an orientation where little or no motion relative to the Earth's magnetic field is detected. For the high inclination SCSC orbit, the terminal orientation of the Y_b axis TORQROD™ is along the orbit normal. The field derivatives required for control law. Implementation are computed as follows:

$$\dot{B}_i(t) = [B_i(t) - B_i(t - \Delta t)] / \Delta t$$

where $\Delta t = 2.0$ sec and $B_i(t)$ is the field along axis i, $i = Y_b, Z_b$

ACQUISITION MODE (Cont'd)

The Z_b TORQROD™ also uses the "minus B-dot" law if the spin rate is above the 3 RPM ±10% range. Should the spacecraft be spinning at say 6 RPM, the Z_b TORQROD™ will use the law to reduce the spin rate to 3 RPM. In the more likely event that the spin rate is low or zero, the polarity of the control law is reversed (plus B-dot) for the Z_b TORQROD™. Thus, instead of driving the spin period down, the spin period is driven up until it reaches the 3 RPM operating range.

Determination of the spin period is made in the software by examining successive samples of the Z_b-axis magnetometer. A several minute history is maintained and periodically examined for zero crossings. If there are none or those observed are not at 10 second intervals, the software operates the Z_b TORQROD™ in either the plus B-dot or minus B-dot mode to drive the spin period back to the desired 3 RPM rate.

The ACS is required on MICROSAT because an orbit trim capability is required for each spacecraft. The ACS is then required in order to orient the nozzle. Since there are only two TORQRODs™, the magnetics behave like a two pole DC motor which will run in either direction once it gets started. Rather than provide extra hardware, the spacecraft are carefully built so that no matter which way the rotation starts, the final state in normal mode will be a stable mode allowing proper operation of the on orbit ACS and the orbit adjust thruster. The key is proper orientation of the HCI, the nozzle, the TORQRODs™ and the choice of the proper control law.

NORMAL ON-ORBIT MODE

Normal on-orbit control law assumes that the spacecraft is spinning near its 3 RPM operating range and that it is aligned to with several degrees of the orbit normal so that the HCI can view the Earth throughout a scan. The acquisition law has operated for sufficient time that the spin is relatively smooth, i.e., the nutation angle is small.

The spin period is determined by examining a historical record of HCI horizon crossing signals. The software sorts out short pulses and spurious pulses to determine when the Earth is being scanned. By recording the time (LE) of the leading edge crossing and the time (TE) of the trailing edge crossing, the time that the HCI was looking along the orbit normal / nadir plane (t_{nad}) can be determined by: $t_{nad} = (LE + TE) / 2.0$. Once successive regular t_{nad} times are observed, the spin period can be established and the spacecraft orientation can be determined.

The on-orbit control law relies upon measurements of the Earth's magnetic field approximately along the velocity vector, along the nadir vector, and along the spacecraft Y_b axis (orbit normal). These measurements are phased to the spin period of the spacecraft and to the normal/nadir pointing times. For example, once the spin period is known, the Z_b-axis magnetometer axis can be sampled 3/4 of a turn after the last normal/nadir time and again at the next anticipated normal/nadir time. The two measurements are the B_{xh} and B_{zh} field measurements respectively. These measurements are combined with the roll calculation from the HCI to produce control signals to the Y_b TORQROD™.

Nutation damping is accomplished by sampling the Y-axis magnetometer eight times per turn of the spacecraft. Every eighth of a turn, the Y_b-axis magnetometer is read and applied to the same minus B-dot control law used for acquisition.

A unique feature of the ACS is the removal of the requirement for a preferred direction of rotation. The acquisition law leaves the spacecraft spinning and with the angular momentum vector aligned with the orbit momentum vector. What is not deterministic is whether the HCI is viewing out the positive side of the orbit or out the negative side of the orbit. In practice, we anticipate that some of the seven satellites will be oriented one way and some the other. By phasing all of the on orbit ACS operations to the HCI t_{nad} pointing times, the on orbit ACS algorithms are equally stable in either orientation.

In order to obtain the dual terminal condition situation, there were constraints placed upon the relative orientation of the HCI, the TORQRODs™, the magnetometer axes and the thruster nozzle. The nozzle is located on the opposite rim of the spacecraft from the HCI. The HCI is mounted in the (Y_b, Z_b) plane of the spacecraft. Relative orientation of the Y_b-axis TORQROD™ and the Y_b-axis magnetometer are determined at the time of construction of the spacecraft. The minus B-dot acquisition law is independent of the HCI orientation. It forces 3 RPM and drives the angular momentum to the negative orbit normal. That same law in the normal on orbit mode, operating in the same way, reduces nutation damping regardless of the orientation of the HCI.

The magnetometer is sampled at 3/4 of a spin period and again one full spin period after a nadir/normal time. Thus, whether the HCI is viewing left or viewing right, the magnetometer sample will represent the magnetic field approximately along the velocity vector and along the nadir vector. Thus the B terms in the control law are sensed relative to the orbit and do not change polarity regardless of whether the spin up occurs at 180° yaw or at 0° yaw. The HCI polarity does reverse, thus the polarity of the computed roll error reverses from one state to the other. However, the Y_b-axis TORQROD™ also reverses. Since two negatives make a positive, the resulting control torques are in the proper direction.

Orbit trim thrusting is also direction independent since the thruster is aligned with the HCI. Thrusting after 1/4 turn reduces the orbit energy while thrusting after 3/4 turn increases it.

Maintenance of the spin period requires use of the Z-axis TORQROD™. In the normal on-orbit mode, the sampled B_{xh} and B_{zh} fields are used to determine the proper time to switch the Z_b-axis rod. Each spin period is divided up into four quadrants representing 1/4 turns. The Z_b-axis TORQROD™ is switched on in the two quadrants where it is most orthogonal to the B-vector, thus resulting in efficient generation of torque along the Y_b axis of the spacecraft.

Based on T_s and t_{nad} four time quadrants are defined as in Figure 5 for each spin period to turn on Z_b-axis TORQROD™. These quadrants are as follows:

$$
\begin{aligned}
Q_1 &= (t_{nad}, t_{nad} + T_s / 4) \\
Q_2 &= (t_{nad} + T_s / 4, t_{nad} + 2.0 * T_s / 4) \\
Q_3 &= (t_{nad} + 2.0 * T_s / 4, t_{nad} + 3.0 * T_s / 4) \\
Q_4 &= (t_{nad} + 3.0 * T_s / 4, t_{nad} + T_s)
\end{aligned}
$$

Let the Z_b-axis field measurements be B_{xh} when time

$$t = t_{nad} + 3.0 * T_s / 4$$

i.e., when Z_b-axis is along the velocity vector, and B_{zh} when time

$$t = t_{nad} + T_s$$

i.e., when the Z_b-axis is in nadir direction.

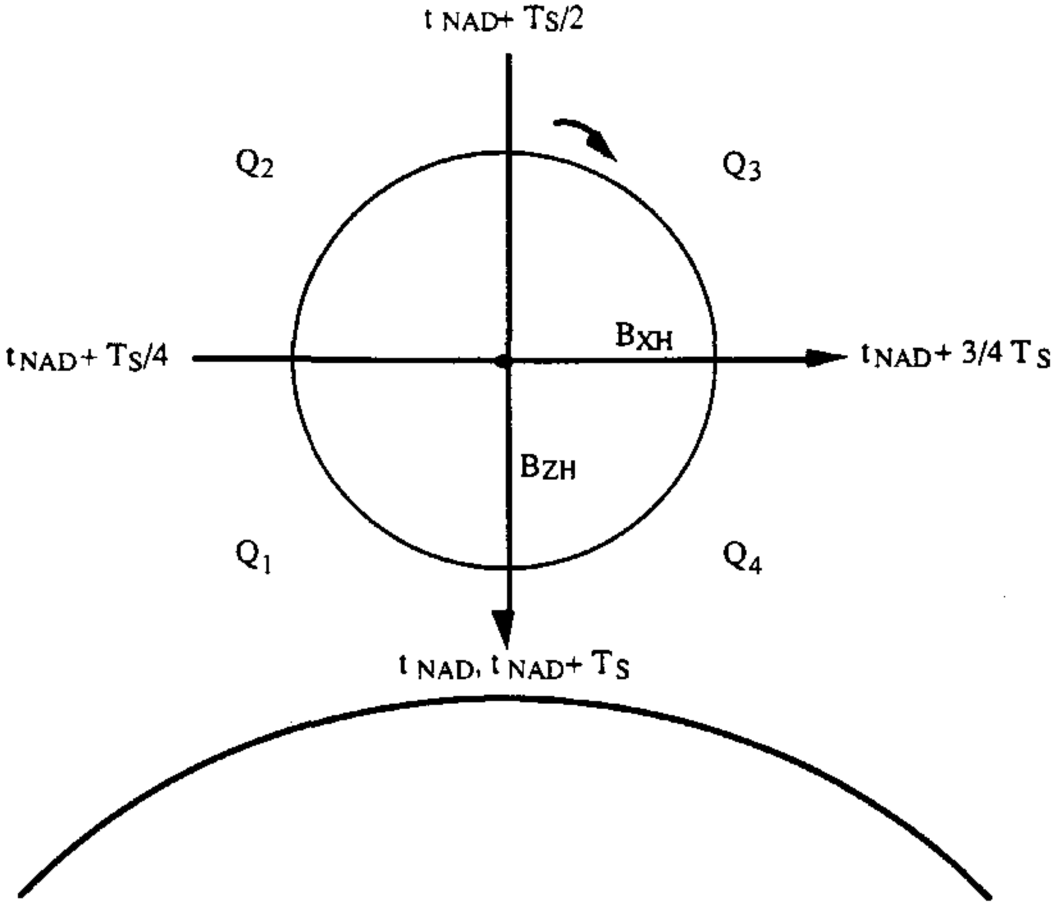


FIGURE 5
ON-ORBIT Z-AXIS TORQROD™ TURN ON/OFF QUADRANTS

NORMAL ON-ORBIT MODE (Cont'd)

The Z_b-axis TORQROD™ is turned on to produce the dipole M_z to spin down the spacecraft's rate according to the following table:

Sign of		M_Z in Quadrant (Am^2)			
B_{XH}	B_{ZH}	Q_1	Q_2	Q_3	Q_4
+	+	+1.0	0	-1.0	0
+	-	0	-1.0	0	+1.0
-	+	0	+1.0	0	-1.0
-	-	-1.0	0	+1.0	0

If either B_{xh} or B_{zh} is too small (say <10%) with respect to the other, then the dipole is set to zero due to some uncertainty associated with the polarity. To increase the spin rate of the spacecraft the polarities of M_z in the above table are reversed.

For precession control the control law to activate Y_b-axis TORQROD™ to produce dipole M_y is defined as [Reference 1] :

$$D_{My} = -K_1 * (B_{xh} * \varphi + B_{zh} * \varphi) - K_2 * \dot{B}_y$$

where B_{xh}, Bzh and φ have been defined before.

$\dot{B}_y$, the derivative of the Y-axis magnetometer samples, is computed every 2.5 secs. K_1, K_2 are two constants which have values of 1.0×10^5. The first two terms in this law precesses the spin vector while the third one damps nutation.

The precession dipole generated along Y_b-axis is as follows:

$$M_Y = \begin{cases} -1.0 \text{ Am}^2 \text{ if } D_{MY} < -\varepsilon \\ +1.0 \text{ Am}^2 \text{ if } D_{MY} > \varepsilon \\ 0 \text{ otherwise} \end{cases}$$

Where $\varepsilon = 0.05 \text{ Am}^2$

COMPUTER SIMULATION AND PERFORMANCE

The spin rate and the spin vector precession control of the MICROSAT spacecraft were simulated on a computer using the commercially available ACSL simulation package to asses the ACS capabilities. A top level block diagram of the simulation program is presented in Figure 6. The program allows for selection of the moment of inertia matrix, initial attitudes and rates, control gains, orbital parameters, order of the spherical harmonics for field generation etc. The disturbance torques included the aerodynamic drag, solar pressure, gravity gradient torque, and magnetic residual dipole torques. The MICROSAT simulations were run under the following assumptions:

- Orbit Precession
- Earth's Rotation
- Magnetometer noise standard deviation = 36 nT
- Magnetometer Resolution = 25 nT
- Geomagnetic field order = 8
- Spacecraft released from PEGASUS with zero spin rate and 90° yaw
- Equator as the simulation starting point

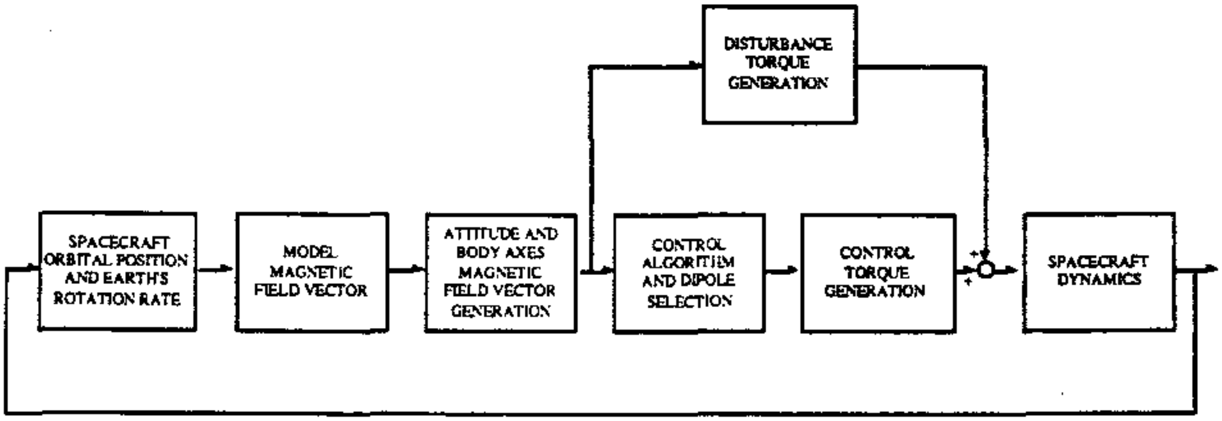


FIGURE 6
SIMULATION BLOCK DIAGRAM

COMPUTER SIMULATION AND PERFORMANCE (Cont'd)

The parameters used for the simulations are the following:

- Inertia Matrix = $\begin{bmatrix} 0.3964 & -0.00652 & 0.01900 \\ -0.00652 & 0.5692 & -0.00185 \\ 0.01900 & -0.00185 & 0.3483 \end{bmatrix}$ Kg-m^2
- CP-CG offset = [0.0, 1.1, 0.0] cm
- Magnetic Residual dipole = 0.05 Am^2
- Atmospheric density = 2.6364×10^{-14} Kg/m^3
- Solar flux = 4.5×10^{-6} newton/m^2

To test the performance of the magnetic ACS, simulation runs were made for both the acquisition and on orbit control modes. Figure 7 to Figure 9 show the spin rate and roll/yaw plots in acquisition mode. Figure 7 indicates that the spin rate builds up to 3 RPM in about two orbits while during the same period the roll/yaw errors settle within 10° as the plots of Figure 8 and Figure 9 indicate.

The roll/yaw plots for the on orbit mode in Figure 10 and Figure 11 show that with initial yaw of 11° attitude errors are reduced to about 4°.

ACS SIZE, MASS AND POWER SUMMARY FOR MICROSAT

The minimal hardware requirements and their low power consumption, light weight and small size for MICROSAT magnetic ACS components makes it low cost and attractive for the small satellites. The specifications for all the hardware are as follows:

Component	Mass (g)	Size (cm)	Power(max) (mwatt)	Power(Average) (mwatt)
Magnetometer	60	8.9 x 5.3 x 2.5	30	20
HCI	92	5.6 x 4.2 x 4.7	90	60
TORQROD(2)	8 (x 2)	1.3 x 12.7	250 (x 2)*	30 (x 2)**
Electronic Assemblies	120	19.9 x 11.4 x 0.1	50	50
TOTAL	428		620*	190

* with 100% duty cycle
** with 12% duty cycle for on orbit mode

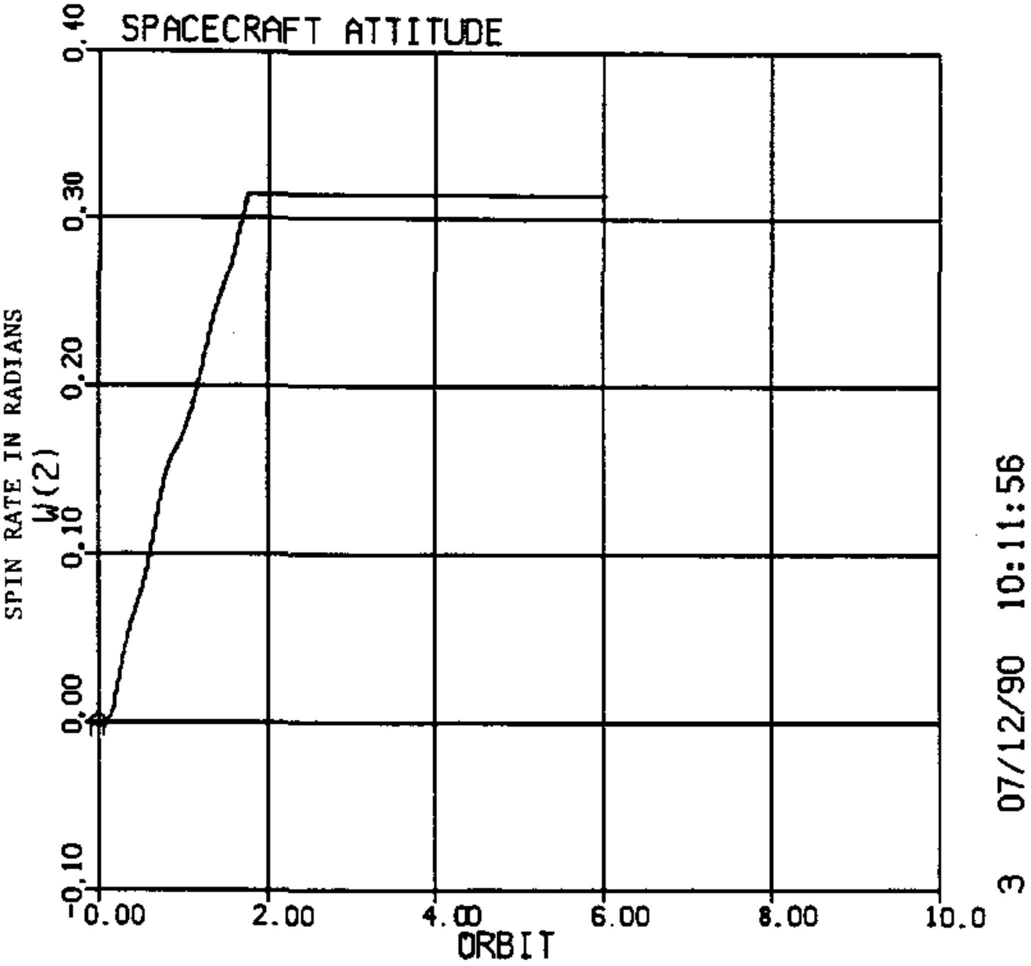


FIGURE 7
SPIN RATE, ACQUISITION MODE
RATE BUILDS UP TO 0.314 RAD/SEC (3 RPM) IN TWO ORBITS

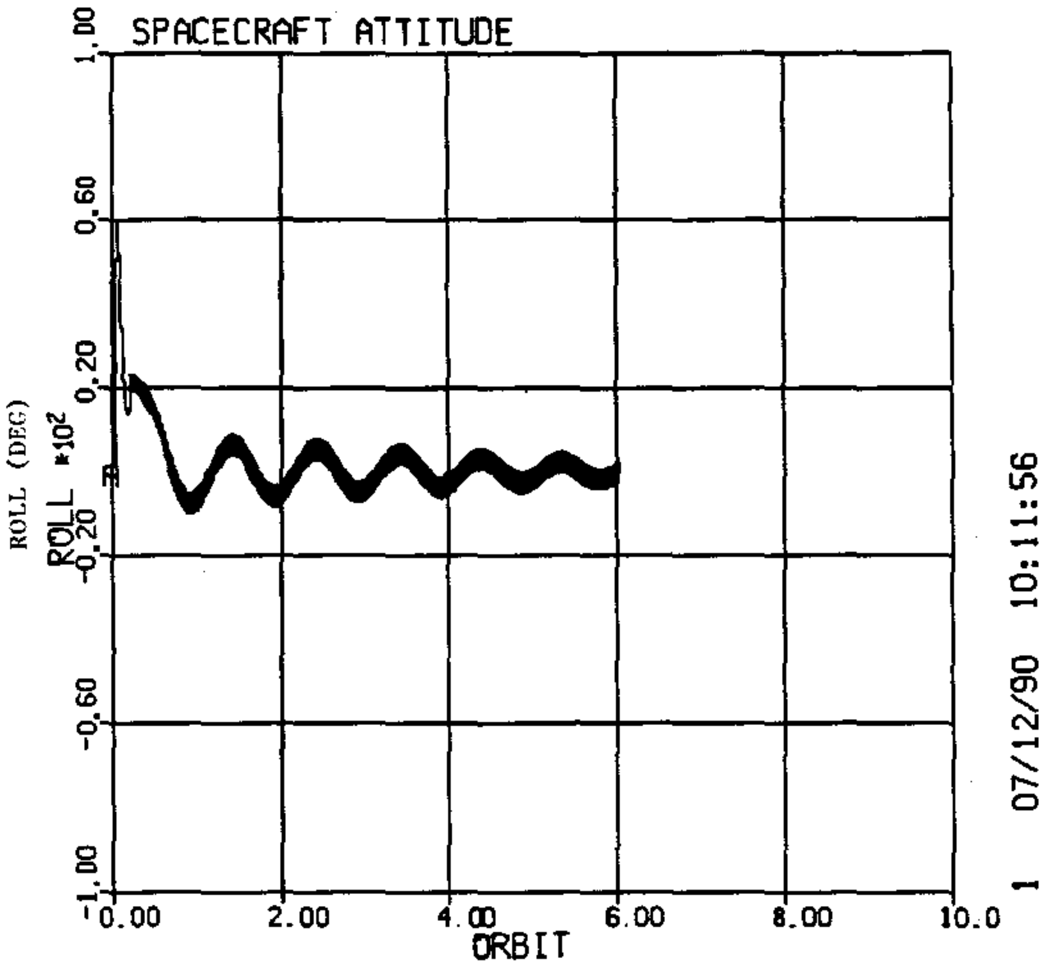


FIGURE 8
ACQUISITION MODE
ROLL SETTLES WITHIN 10° IN TWO ORBITS

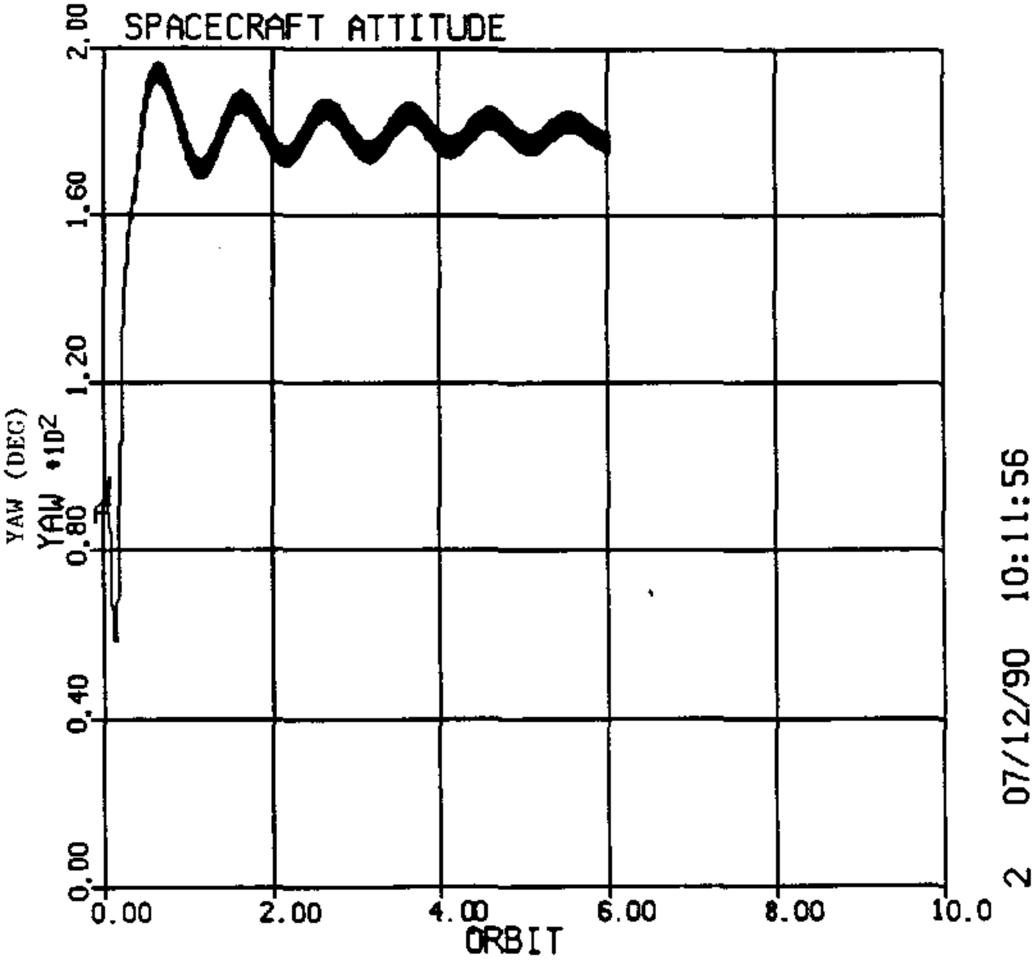


FIGURE 9
ACQUISITION MODE
YAW SETTLES WITHIN 10° IN TWO ORBITS

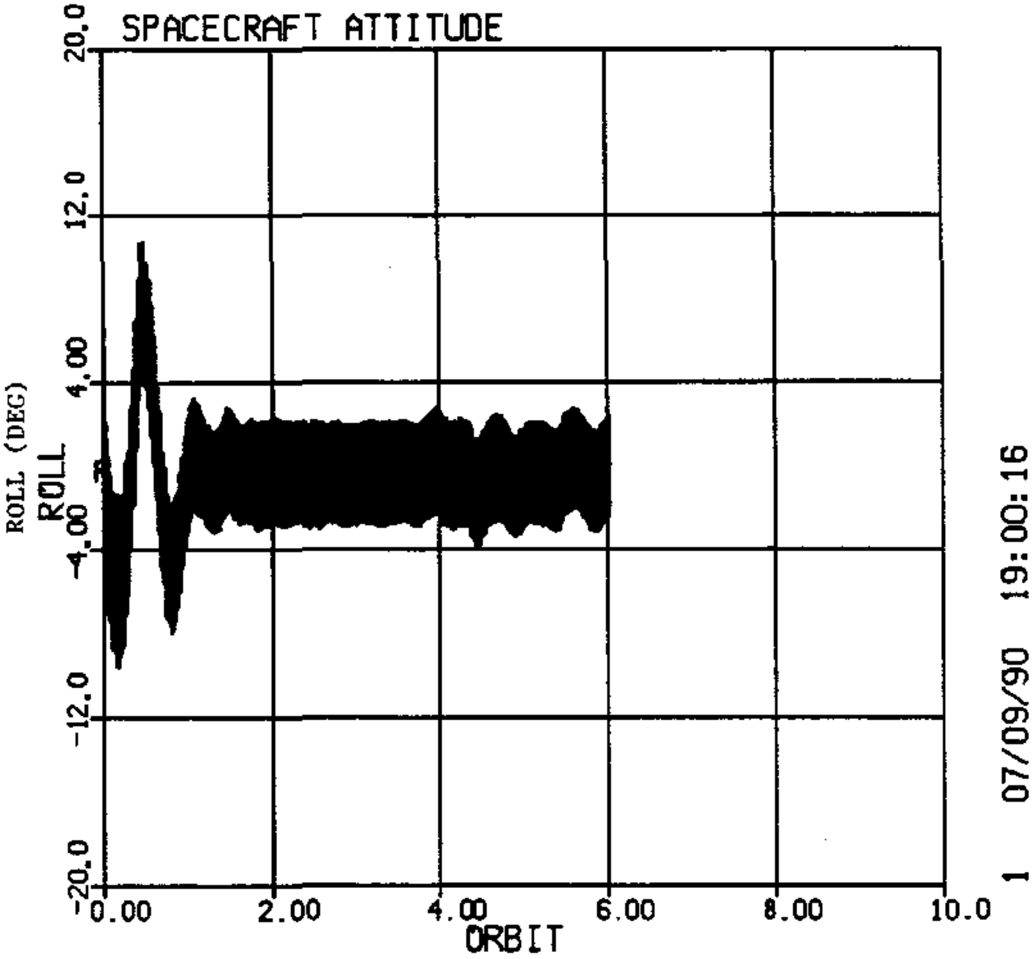


FIGURE 10
ON-ORBIT MODE
ROLL ERROR SETTLES WITHIN 4° IN ONE ORBIT
MEETING THE SPECIFICATION OF 5°

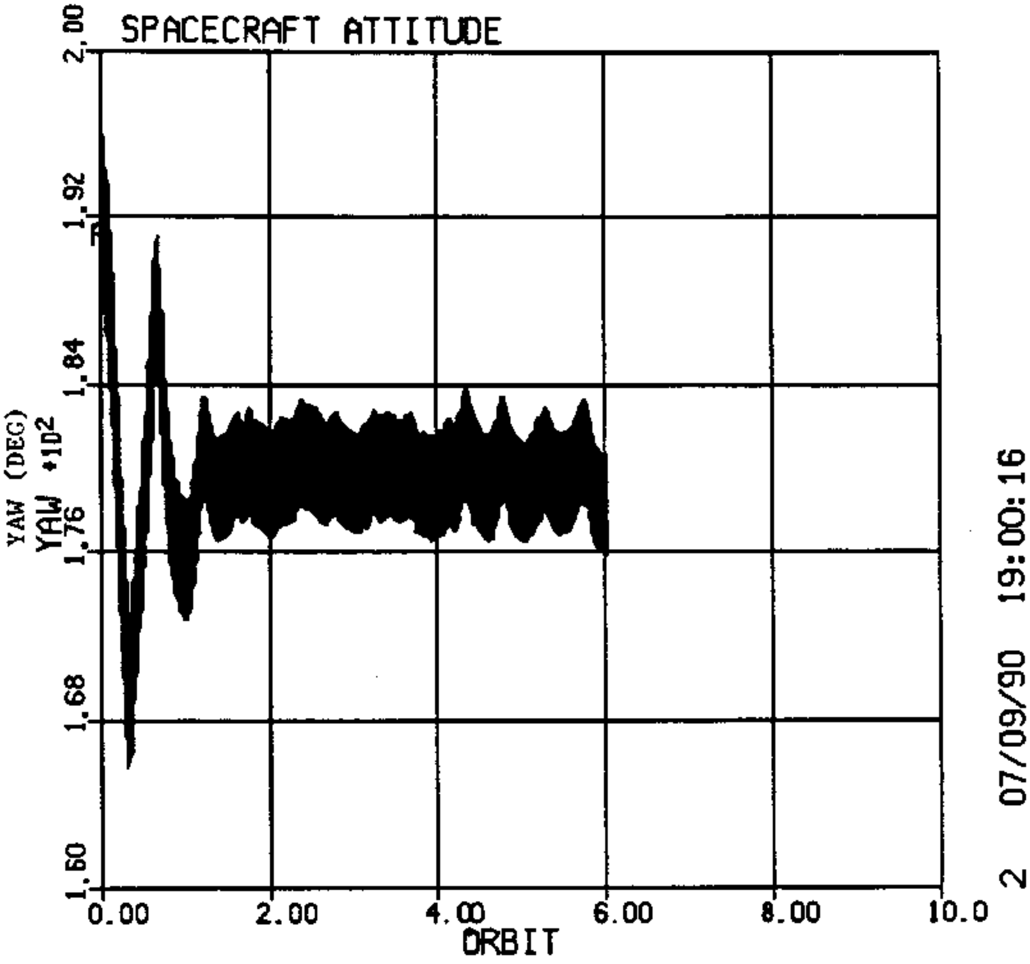


FIGURE 11
ON-ORBIT MODE
YAW ERROR SETTLES WITHIN 4° IN 1.5 ORBIT
MEETING THE SPECIFICATION OF 5°

CONCLUSIONS

The magnetic ACS for the small spin stabilized MICROSAT spacecraft is described. The ACS relies upon proven magnetic momentum management techniques to accomplish its mission. The primary features of the ACS are the minimum amount of hardware (approximately 0.5 Kg total mass) and the minimum average power consumption (less than 200 milliwatts exclusive of power consumed by the spacecraft host computer). The results of simulation studies show that the ACS can capture control of the spacecraft and achieve the mission pointing requirements of 3 RPM and spin axis alignment of better than 5° to the orbit normal within four orbits from the anticipated initial conditions.

REFERENCES

1. A. Craig Stickler and K.T.Alfriend, An Elementary Magnetic Attitude Control System, AIAA Mechanics and Control of Flight Conference, 1974, AIAA Paper No. 74-923.