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Dynamic ground testing of the Skipper Attitude Control System

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Dynamic Ground Testing of the Skipper Attitude Control System

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Abstract

The evaluation of the Attitude Control System (ACS) for the Skipper spacecraft required the development of two complementary tools: a high fidelity numerical simulation program and a three axis air bearing table to experimentally evaluate the ACS hardware operating in a dynamic environment. The simulation program provides detailed evaluation of the controller's performance over entire orbits, allowing studies of varying sensor viewing conditions, aerodynamic effects and magnetic field variations. The air bearing table was used for functional, rather than calibrated testing of the integrated ACS. The table was first used as a platform for initial integration testing of the ACS sensors, electronics and computer system. The ACS maneuvers were then test-flown on the table. In doing so, several software errors and system-level problems were easily identified and corrected. A proposed method for estimating the inertia tensor of the spacecraft in flight was evaluated using air bearing test data. Data gathered from air bearing tests were used to evaluate the attitude determination software off-line. This proved necessary due to a need to examine the attitude resolution algorithm and the lack of a valid indoor GPS signal for nadir vector information.

Introduction

This paper describes the test system developed for and used in ground testing of the attitude control system for the Skipper spacecraft. The Skipper mission is designed to measure electromagnetic 'bow-shock' emissions in the ultra violet and visible spectrum in the earth's upper atmosphere. The Skipper spacecraft is unique in that it is built jointly by U.S. and Russian scientists and engineers, and is scheduled for launch on a Russian Molnia vehicle in December, 1995. During it's short thirty day mission, the spacecraft will change orbits ten times and undergo at least twelve slew maneuvers, placing a high demand on the spacecraft's attitude control system (ACS).

The ACS, along with the necessary test facilities was developed at the Space Dynamics Laboratory at Utah State University. Two separate tools were developed to test and verify the ACS. First, a dynamic simulation software program was developed to provide a detailed analysis of the dynamics, control, and viewing conditions of the spacecraft. Second, a three axis air-bearing table was built to allow integrated, functional testing of the ACS hardware and software under dynamic conditions.

The Skipper Attitude Control System

The Skipper spacecraft is designed as a minor-axis spin-stabilized system. For control, the spacecraft has four gas jet thrusters, one hydrazine precession thruster, a main hydrazine thrust engine and a torquer coil. Spin control is accomplished by using opposing pairs of gas thrusters, while nutational motion can be damped by firing co-linear pairs of gas thrusters. A 1 kg. hydrazine thruster is included for high rate precessional motion. The main hydrazine thruster is used for orbital transfer. The torquer coil, mounted along the spin axis of the spacecraft, is used throughout the flight to maintain nutational stability. Properly timed field-reversing commands are applied to the coil to greatly reduce its residual magnetic moment.

The body-fixed angular velocity vector is identified by three orthogonally mounted rate sensors. A fourth rate sensor mounted with components along each of the other three spin axes is included for redundancy. A 3 axis magnetometer is used to measure the magnetic field surrounding the spacecraft for nutation damping. An accelerometer is included for both nutational measurements and for orbit transfer control. Attitude sensors consist of a single horizon crossing sensor, two sun sensors, and a GPS receiver.

The flight control system uses a three-processor (68HC11) computer specifically developed for this mission. Each processor executes an independent function: Command and Control, Attitude Control, and Attitude Determination. The Command and Control processor is the supervisory controller for the spacecraft. It handles command sequencing, communications control and housekeeping duties. The Attitude Control processor is designed to execute at a 5 Hz rate, while the Attitude Determination processor runs asynchronously, dependent on the availability of data. The software for the Command and Control computer and the drivers for the Attitude Control and Determination processors are written in assembly code, while the attitude determination and control software is written in the "C" programming language.

The ACS software is divided into a time-critical attitude control function and a attitude determination functions, each residing on it's own processor. The attitude control software is divided into a parallel structure of ground-commanded maneuvers which supervise the sequential control of a series of tasks. The principal maneuvers are Nutation Maintenance, Precession, Orbital Transfer and Initialization. The attitude determination software is based on well-known cone intercept algorithms[1] combining horizon and sun crossing times and angles.

The Simulation Program

The SATSIM simulation program was developed to provide a detailed environment to study the interaction of the controller with the spacecraft dynamics. This program is based on the numerical integration package DIFFEQ, who's development has a long academic history, most recently by Dr. M. Van Der Ploeg at Iowa State University. SATSIM uses well established numerical integration algorithms (e.g., Adams Molton) in double precision format. 40 state and 140 other variables are currently used to describe the spacecraft's state, with variable step integration times bounded by the 0.2 second sampling rate of the controller. The integration duration is sufficient to cover a full orbit. SATSIM has a significant graphical interface capability, including 3D wire-frame animation of the spacecraft's motion. SATSIM allows the inclusion of the flight control software directly in the simulation, and provides an accurate model of the discrete-time controller implementation and asynchronous sensor inputs.

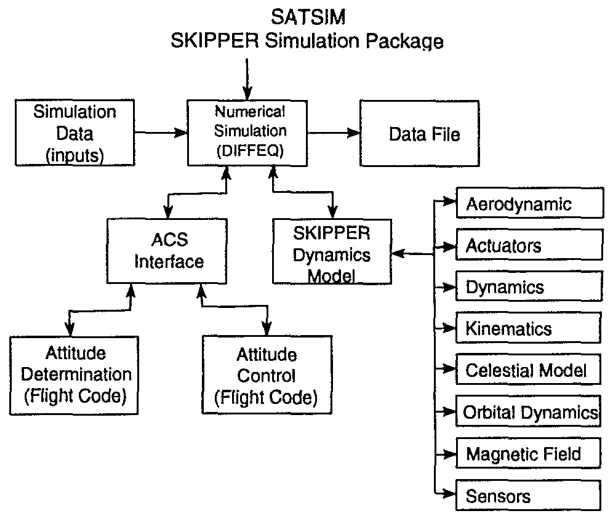

Figure 1: SATSIM Software Configuration

The Skipper simulation program was divided into several modules, as shown in Figure 1. The dynamics module contained the basic equations describing the spacecraft's rotational dynamics, including a hydrazine slosh mode. Atmospheric force and torque models were calculated as a function of the angle-of-attack and density, using standard techniques[2]. The actuator models were based on experimental data developed by Lavotchkin NPO for the Skipper thrusters. Kinematic transforms were developed to provide transforms between body-fixed, geocentric equitorial, earth-centered, earth fixed, heliocentric, and orbital plane coordinate systems. The orbital dynamics were based on a J6 gravitational model. The Celestial module provided information on the solar position, optical crossings of the earth (for the horizon crossing sensor), atmospheric density and a spherical harmonic model of the earth's magnetic field. An interface module was developed to emmulate the appropriate inputs and outputs between the controller and the sensors and actuators.

SATSIM was designed to be directly integrated with the flight code, and was used as a testbed for the development of this code. Simulation tests were used throughout the ACS system development to evaluate the ACS software. The software simulation tests were divided into the following subgroups: nutation damping, precession control, re-entry control, thruster burns, and attitude determination.

The SSACS Table

The Small Satellite Attitude Control Simulator (SSACS) air-bearing table, *shown in Figure 2*, was

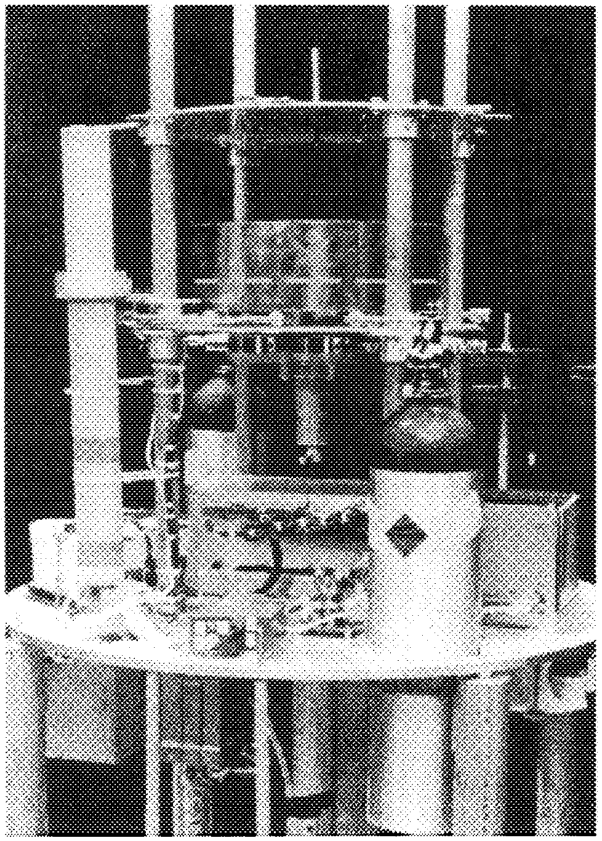

Figure 2: SSACS Air Bearing Table

built to mimic the torque-free attitude dynamics of the actual spacecraft in orbit. The table used for the Skipper simulations is a modified version of a previous table used for teaching and research[3]. It's role was to provide a functional testbed for evaluating the integrated ACS hardware and software. The table was not designed or intended to be an accurate, calibrated model of the spacecraft.

The air bearing allows motion of up to 45 degrees about the pitch and roll axes, while allowing nearly frictionless motion about the yaw axis. A safety ring was mounted around the top of the table to prevent motion of greater than 35 degrees from vertical.

The bearing was attached to an engineering copy of the spacecraft's deck plate, allowing the sensors to be mounted in the same location as in flight. The actual flight sensors were used, along with developmental versions of the flight computers and electronics. A N_2 gas thruster system was build specifically for this test, using two 2000 psi nitrogen tanks, a pressure regulator (set at 250 psi), solenoids and nozzles. The nitrogen tanks were mounted symmetrically about the center of mass to minimize the table off-balance as fuel was used. The inertia tensor of the table was scaled to be approximately one sixth that of the actual spacecraft. Data acquisition and telemetry also used near-flight versions of the hardware and software, including an S band antenna, even though the receiving antenna was less than two feet from the transmitting antenna. Timed execution uplink commands were sent using an umbilical cable, which was removed prior to the test. Power was supplied by four packs of lead-acid batteries at 28 volts. The wiring harness for the table was built from the same specifications as the flight harness.

Software was transferred between the SATSIM program and the SSACS table simply by recompiling the source code using a cross-compiler for the 68HC11. This code was then loaded into an EEPROM on the flight computer board. Telemetry data were converted into a format which could be read by the SATSIM program.

The table was placed inside an isolated chamber, shown in Figure 3, to minimize the effects of air currents. A theatrical light was used to model the sun. The earth was modeled by a metal disk 1 meter in radius. To provide an adequate thermal trigger for the horizon crossing indicator (HCI), the disk was painted black with thermal paint and heaters were mounted on the back to raise it's temperature to approximately 40 degrees C above the ambient temperature. The chamber was draped in black felt to prevent spurious infra-red triggers for the sensitive HCI.

Test Cell Integration

The SSACS table was used as the focal point for the integration of a majority of the Skipper bus electronics. A significant number of integration problems were identified and resolved easily, due to the existence of this system. For example, the digital filter algorithms used for the rate sensors and magnetometer were easily identified as too slow in software by simply observing the firing period of the thrusters. These algorithms were later re-written with more efficient code. Mundane but necessary throughput checks, such as verifying the sign of the rate sensor inputs or that the proper thrusters were fired when commanded were checked out. Note that these were preliminary checks; these tests were repeated on the final integrated spacecraft.

Sections of the ground support data handling were tested, including the PCM decommutator, data transfer network, and data format decoding programs. In addition, the SSACS tests required the subsystem designers to organize and prepare operational plans, setting the stage for later operational planning.

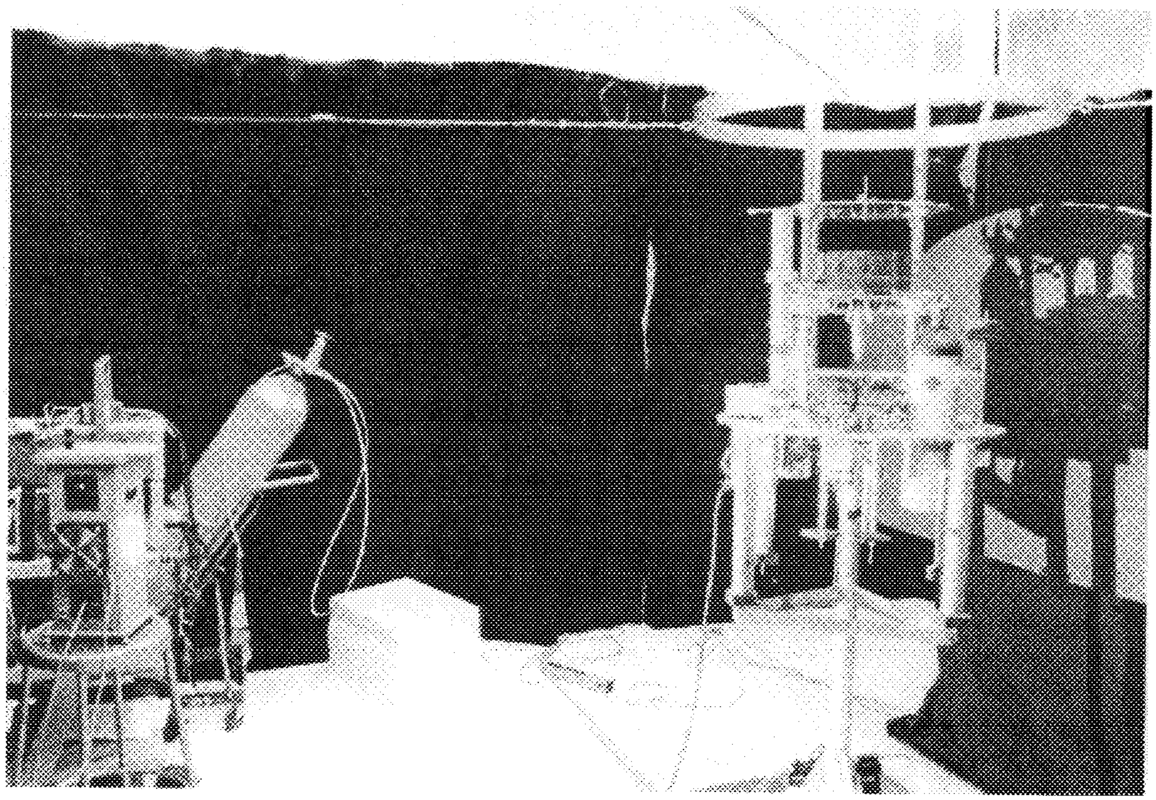

Figure 3: SSACS Table Test Cell

Balancing and Dynamic Identification

The mass properties of the SSACS table proved to be as critical as those of the actual spacecraft. The center of mass (CM) of the SSACS table must be aligned with the center of rotation (CR) of the bearing to avoid gravitational moments and products of inertia. Coarse balancing was based on an initial mass distribution estimate. Fine balancing was achieved by manually adjusting lead screws. After extensive trial and error efforts, the most effective balancing method first balanced the two horizontal axes over the CR with the CM slightly below the CM. The CM was then raised until the oscillatory period of the table proved effectively long (e.g. 1 minute).

The SSACS table was not spin balanced. The products of inertia caused by both uneven mass distribution and CM offsets created a significant shift in the spin axis of the table from the nominal symmetrical axis. A manual procedure to reduce this was developed, where the offset was first approximately estimated, then reduced by iterative balancing and mass addition. Considerable skill and patience were required. An automated balancing system[4] would greatly speed up this process.

The SSACS table provided a platform for experimentally testing a parameter identification algorithm to determine the inertia tensor in flight. An estimate of the inertia tensor was generated based on an initial mass distribution model for comparison.

The effects of the inertia tensor can be extracted directly by identifying the coefficients of Eulers equation:

$$I\dot{\overline{\omega}} + \overline{\omega} \times I\overline{\omega} = \overline{M}_{Thrusters} + \overline{M}_{Aero}$$

where:

I is the Inertia tensor;

$\overline{\omega}$ is the body-fixed angular velocity vector;

$\overline{M}_{Thrusters}$ is the moment vector generated by the thrusters;

$\overline{M}_{Aero}$ is the atmospheric drag moment developed by the spinning motion $[-B\omega_x^2, 0, 0]^T$;

For a specific observation at time t_i, Euler's equations can be partitioned in terms of the coefficients of the Inertia tensor and the drag coefficient B as:

$$\Phi_i \Theta = \overline{M}_{Thrusters_i}$$

where:

$$\Phi_i = \begin{bmatrix} \dot{\omega}_x & \omega_x\omega_z & -\omega_x\omega_y \\ -\omega_y\omega_z & \dot{\omega}_y & \omega_x\omega_y \\ \omega_y\omega_z & -\omega_x\omega_z & \dot{\omega}_z \\ -\dot{\omega}_y + \omega_x\omega_z & -\dot{\omega}_x - \omega_y\omega_z & \omega_y^2 - \omega_x^2 \\ -\dot{\omega}_z - \omega_x\omega_y & \omega_x^2 - \omega_z^2 & -\dot{\omega}_x + \omega_y\omega_z \\ \omega_z^2 - \omega_y^2 & -\dot{\omega}_z + \omega_x\omega_y & -\dot{\omega}_y - \omega_x\omega_z \\ \omega_x^2 & 0 & 0 \end{bmatrix}_i^T$$

and

$$\Theta = \begin{bmatrix} I_x & I_y & I_z & I_{xy} & I_{xz} & I_{yz} & B \end{bmatrix}^T$$

The angular rate values come directly from the rate sensors. The derivatives $\bar{\dot{\omega}}$ can be estimated by a soothing procedure which averages the filtered data both forwards and backwards through the filter:

$$f(s) = \frac{s}{(\tau s + 1)^4}$$

The set of observations of Φ_i and $\overline{M}_{Thrusters_i}$ are adjoined in a columnwise fashion to form the arrays Φ and $\overline{M}_{Thrusters}$. The least squares soution for Θ is:

$$\Theta = (\Phi^T \Phi)^{-1} \Phi^T \overline{M}_{Thrusters}$$

or:

$$\Theta = \begin{bmatrix} 1.99 \\ 2.58 \\ 2.70 \\ 0.001 \\ 0.029 \\ -0.063 \\ 0.0018 \end{bmatrix} kg\, m^2$$

These values correspond well with the values determined from the mass budget. Note that the ratio of the product of inertia to the moment of inertia on the SSACS table is an order of magnitude greater than that expected on the actual spacecraft. This method will be used in flight to monitor the spacecraft inertia tensor as it changes due to the loss of hydrazine propellant.

Maneuver Testing

The Skipper spacecraft is inherently unstable, requiring an active nutation damping system consisting of a torquer coil damper, backed up by cold gas damping, if necessary. Tests indicated that large nutational angles caused by physically bumping the table while spinning were reduced by the gas jet system. Evaluation of damping with the torquer coil proved more difficult, as the nominal magnetic field in the test chamber was aligned along the coil's axis, minimizing the effective torque from the coil. Torquer coil damping is based on a trigger signal using input from the magnetometer, which in turn is effectively saturated by the torquer coil. The controller uses a store-and-forward approach for the torquer coil trigger signal to avoid this problem. The trigger signal is recorded for one cycle with the torquer coil off. This signal is then cyclically repeated to provide the trigger signal for nutation damping for several cycles. The store-and-forward process is continually repeated. SSACS table tests demonstrated that the store-and-forward scheme worked, despite saturation of the magnetometer.

Initialization tests were performed to identify start-up errors and evaluate the spinup and detumbling algorithm. Unlike the tumbling motion experienced by the actual spacecraft on release from the launch vehicle, the SSACS table could only support very low off-spin axis velocities. To test the combined detumble and spinup algorithm, off-spin axis velocities were added by physically bumping the table. Full sequence tests of spinup with no off-spin axis angular velocities were used to evaluate the initialization maneuver along with the initialization of the on-board digital filters. The results of one initialization test are shown in Figure 4. In this plot, the spacecraft is spun up from an initially stationary position to it's design spin rate of 1.57 rad/sec. The spacecraft then undergoes a five minute coast period, where the controller identifies the offset angular rate components due to the residual products of inertia on the spacecraft. At 500 seconds, the controller is re-activated and quickly returns the table to it's rotational state. Note that the controller needs to continually spin-up the table in response to aerodynamic drag acting on the spin rate.

Initialization tests were followed by rhumb line precession control tests, where the cold gas thrusters fire a specified period after a sun crossing trigger (Figure 5), The orbital transfer tests were run through to check the controller sequencing, even though there was no main thruster simulation and the accelerometer was saturated.

Attitude Determination

The evaluation of the attitude determination (AD) subsystem was divided into two parts: verification of the proper input signals from the sun sensor and HCI, and evaluating the attitude solutions from these inputs. The reason for evaluating the solutions off-line was that the appropriate inputs of the sun and nadir vectors, typically determined by an internal ephemeris table plus GPS receiver inputs, did not correspond with the vectors from the sun and horizon models. The vectors from these models were directly programmed into a non-flight version of the software for evaluation.

The SSACS table tests demonstrated that the sun and horizon crossing sensors were providing the correct inputs into the AD processor. Sun crossing times from both sun sensors and the cross-in and cross-out times from the HCI were repeatable and corresponded to the appropriate geometric positioning of the test cell. The nutational motion of the table was readily discernible from the sun sensor angles. The heated metal disk used for the horizon model provided an excellent trigger for the HCI. However, the HCI would occasionally trigger off a worker in the cell. Figure 6 shows the resulting sensor angles developed from the sensor crossing times, along with their actual geometric values.

A modified version of the flight software was used for off-line analysis. This program used measured values for the nadir and sun vectors plus a correction factor to the sun angle to compensate for the parallax generated by having the sun 0.5 m. away. This approach also allowed checking on the resolution algorithm which selected the appropriate solution out of up to four potential solutions.

The attitude was correctly estimated over a series of tests with the sun and horizon mounted in eight separate arrangements. However, the nutational motion of the table caused by a combination of products of inertia and the offset of the CM introduced a significant variation in the sun and HCI input data, which was reflected in the attitude solutions, despite time averaging of these input signals. These variations caused attitude estimates to vary by up to 2.0 degrees. Figure 7 shows the resulting attitude solution of the spin axis from an experimental test. Note that for declinations near 90 degrees, large variations in the right ascension have little effect on the solution. In this figure, the variation of the right ascension over a 70 degree range results in only a difference of 3.5 degrees in the final vector solution, which was a realistic variation for this test.

No independent method of determining the attitude of the table was developed, preventing the calibration of the approach. In all cases, the solution found that the spin axis was within 12 degrees of the nominal vertical orientation.

Conclusions

The combination of the SATSIM software simulations and the SSACS table dynamic tests provided complementary tools for the evaluation of the Skipper ACS system.

Dynamic software simulation is standard practice for this type of ACS analysis. While not unique to this simulation program, the following software simulation features proved to be useful. First, the inclusion of the actual flight software in the simulation allowed workstation-level debugging techniques to be applied to the code. Second, the primitive 3D animation provided a better "feel" to the spacecraft's motion during simulations, as opposed to time histories of euler angles or quaternions. (Future modifications will include solid model animation with earth and sun viewing conditions). Third, flight data was converted into a format directly compatible with the simulations, allowing for a single data storage and presentation package.

Dynamic air bearing table tests are not typically done in other ACS tests, although they have been used in the past[5,6]. We found several advantages in this type of testing. The table provided a convenient ACS integration platform. The dynamic sensors, such as the rate sensors, could be easily excited. Further, these signals (e.g., ω_y and ω_z plus the sun and horizon crossing triggers) were inherently properly correlated. The table also provided an excellent test platform to examine the initialization of the rate sensor filters and how they compensate for the off-axis products of inertia. The interaction between actuators and sensors is directly produced. For example, the effects of the torquer coil on the magnetometer-based store-and-forward nutation damping trigger were observed. The table was also used to monitor the transitions between maneuver states in the spacecraft. Finally, since large portions of the ACS mission were test flown in the laboratory, issues with operations and telemetry were addressed earlier in the project.

The SSACS table used for the Skipper test was a modified version of one previously developed by the Mechanical and Aerospace Engineering department at Utah State University for teaching and research in spacecraft ACS systems. Due to this, the cost of developing the table and test cell was relatively low. The development cost of such a table and test cell is probably close to the development costs of a more traditional hardware-in-the-loop emulator.

The SSACS table was primarily used for functional testing of the ACS. There were several physical and programmatic reasons why the table was not developed as a calibrated, accurate simulator. First, the table was balanced both statically and dynamically by hand. This not only introduced a slight gravitational moment, but the effects of the product of inertia terms on the table provided a significant coning motion. Secondly, the aerodynamic drag due to the spinning motion caused the spin rate to decay rapidly, which in turn caused the spinup algorithm of the controller to repeatedly kick in. Unlike the actual spacecraft, the table is prevented from tumbling randomly, as it is expected to do on release from the launch vehicle. Also, the aerodynamic torques violate the torque-free motion expected of the satellite in space. The table is unable to simulate the nutational instability problem resulting from a transfer of energy about the spin axis to fluid motion (the homogeneous vortex mode of the hydrazine propellant). Finally, the optical targets (earth and sun models) were only approximately defined, introducing error into the attitude determination tests.

The software simulation allows for a full range of orbital test conditions to be investigated. The hardware testing verifies communications and timing conditions, and allows the mission to be effectively test flown in the laboratory. The combination of the two methods provides a rational, inexpensive test program for the ACS system.

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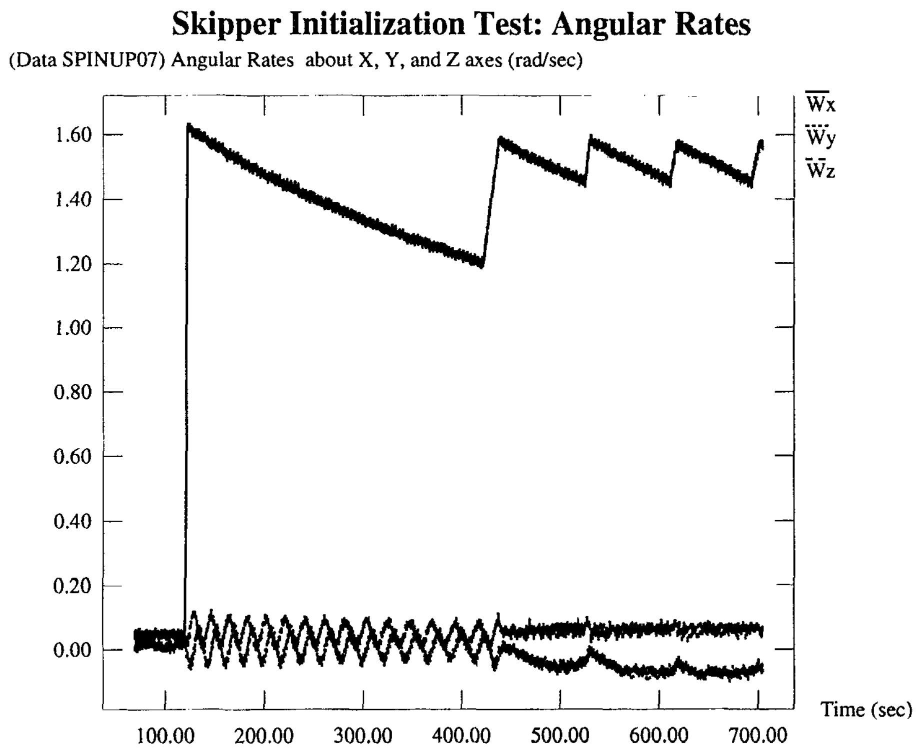

Figure 4: Test Results: SSACS Table Spinup Test

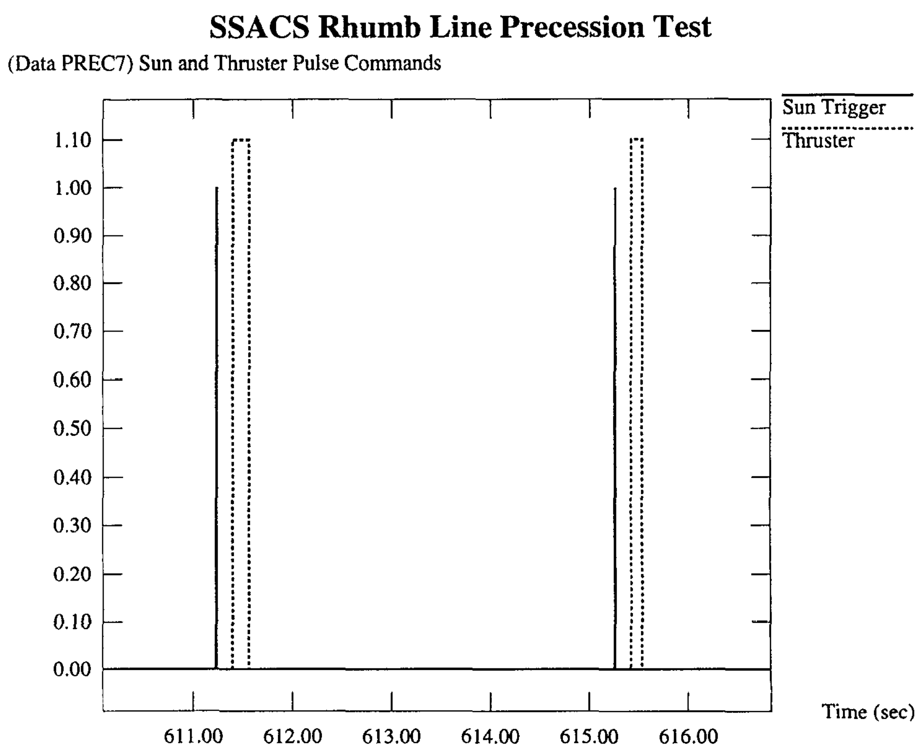

Figure 5: Test Results: SSACS Table Precession Test

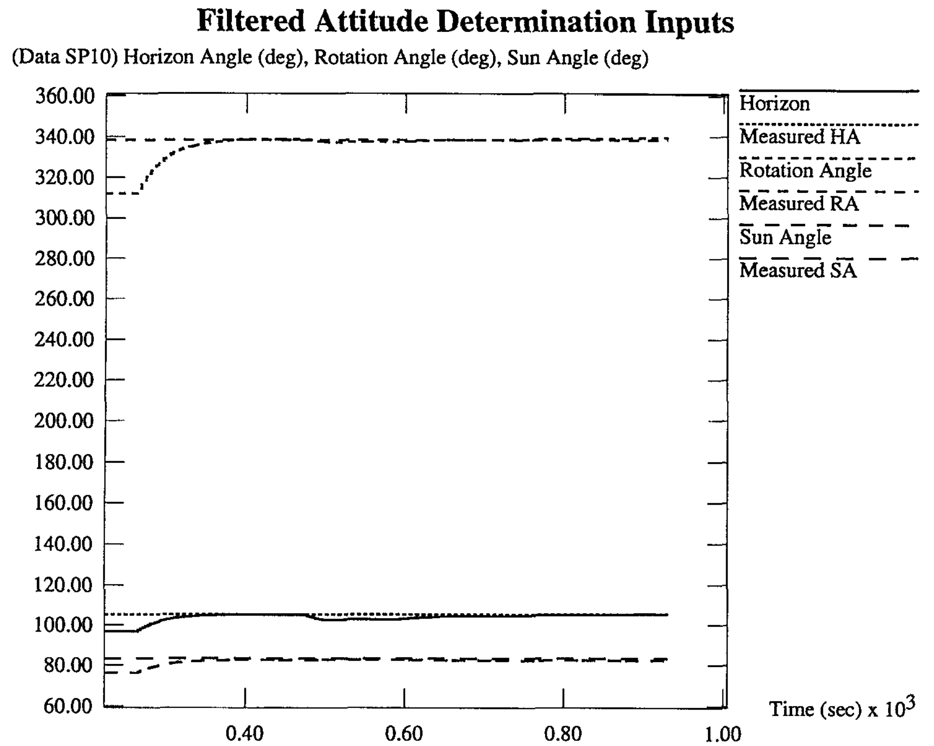

Figure 6: Test Results: SSACS Table Horizon Angle, Rotation Angle and Sun Angle

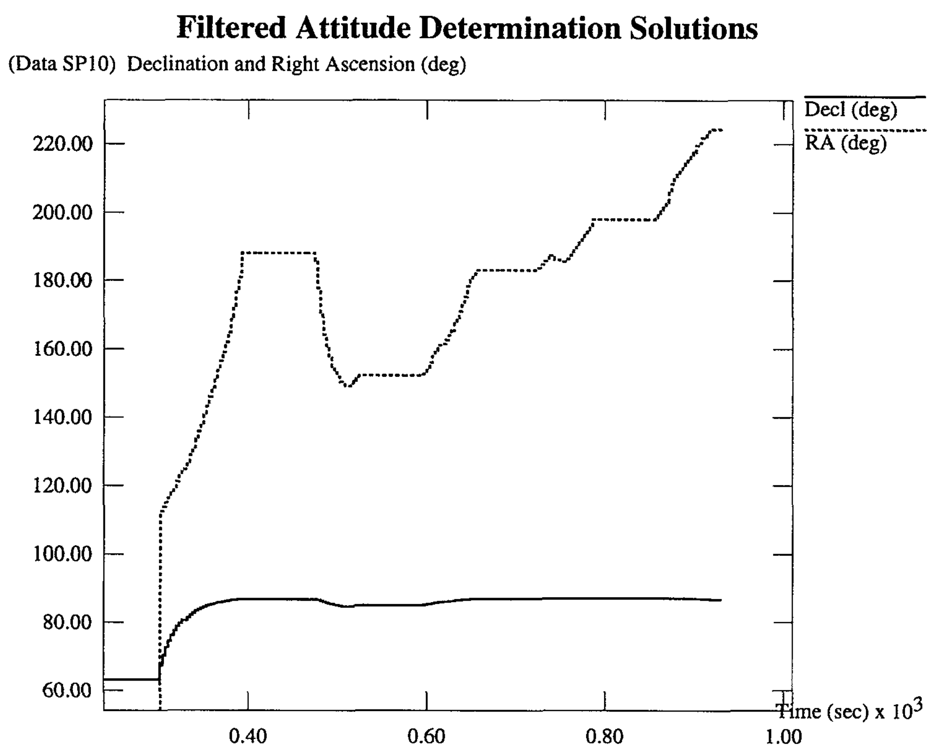

Figure 7: Test Results: Right Ascension and Declination Estimates

Fig. 2

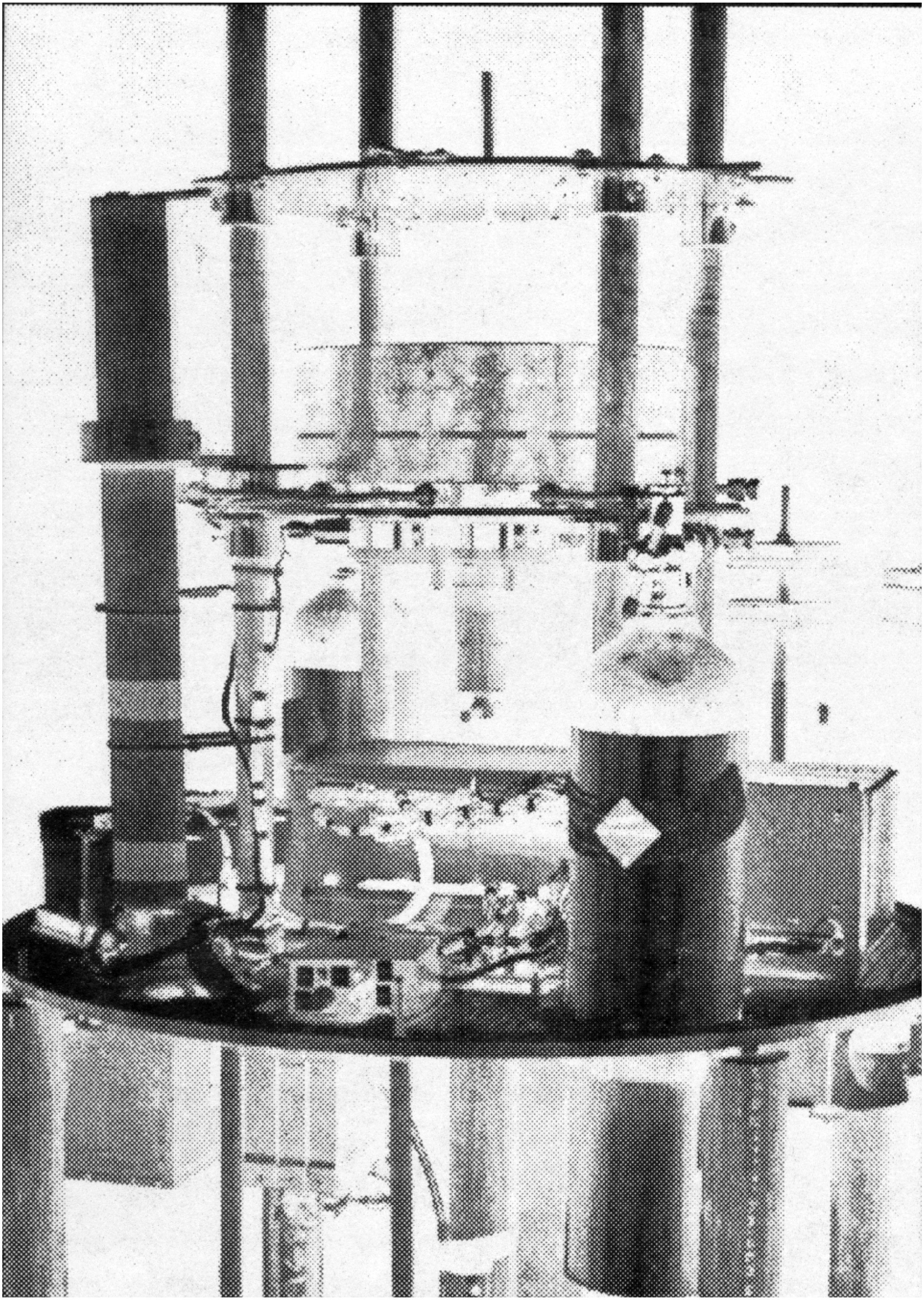

Fig. 3