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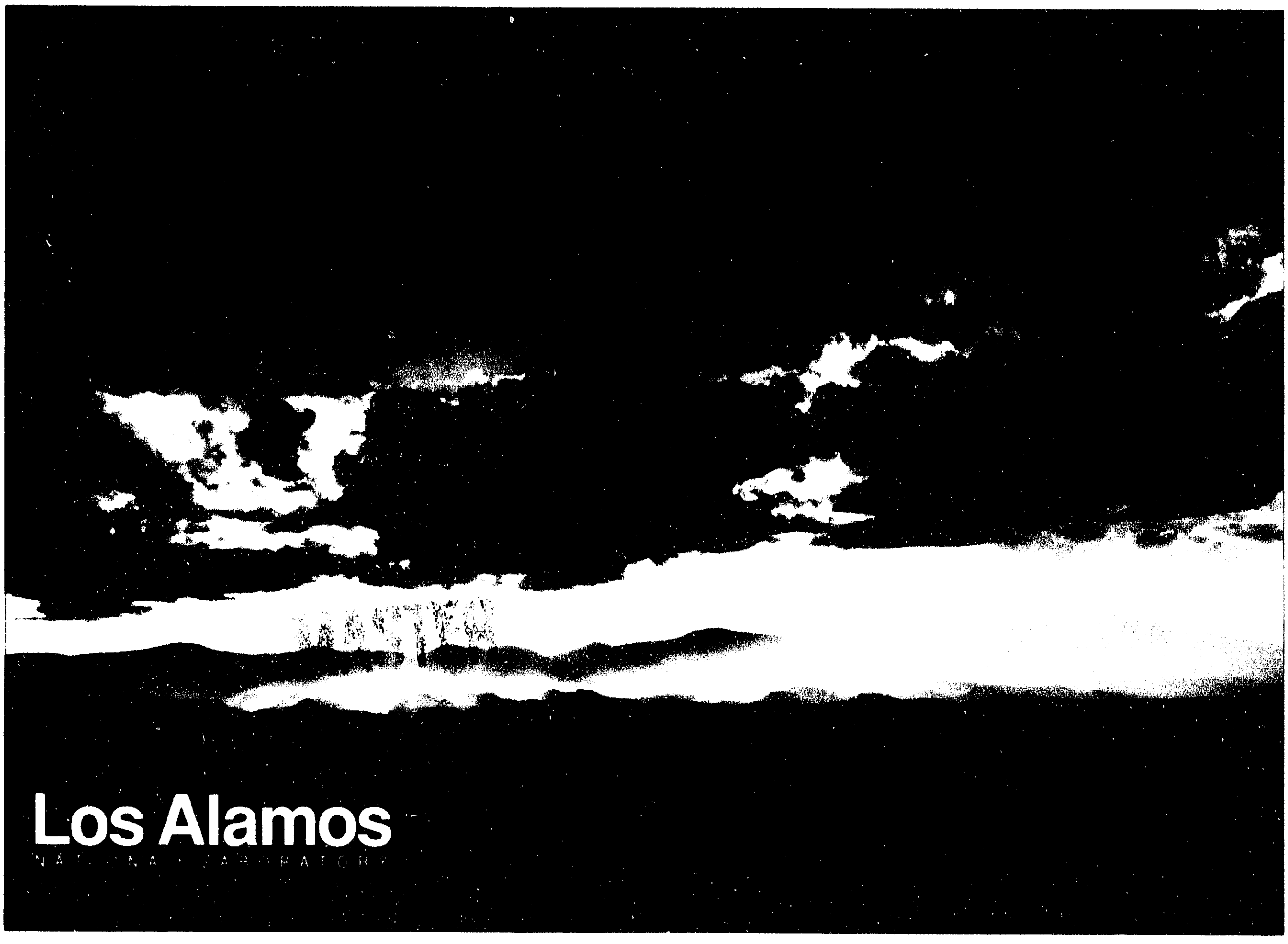

Photograph by Chris J. Lindberg

THE ALEXIS MISSION RECOVERY

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We report the recovery of the ALEXIS small satellite mission. ALEXIS is a 113-kg satellite that carries an ultrasoft x-ray telescope array and a high-speed VHF receiver /digitizer (BLACKBEARD), supported by a miniature spacecraft bus. It was launched by a Pegasus booster on 1993 April 25, but a solar paddle was damaged during powered flight. Initial attempts to contact ALEXIS were unsuccessful. The satellite finally responded in June, and was soon brought under control. Because the magnetometer had failed, the rescue required the development of new attitude control techniques. The telemetry system has performed nominally. We discuss the procedures used to recover the ALEXIS mission.

INTRODUCTION

ALEXIS is one of the first modern, sophisticated, miniature satellites. It was developed by a small skunks-work project at Los Alamos National Laboratory in collaboration with a startup aerospace company, AeroAstro Inc., and was launch-ready 3 years after its preliminary design review. Unfortunately, ALEXIS experienced a serious mechanical anomaly during launch. Though out of contact with ground controllers for two months, it was successfully rescued once contact was made. In a 113-kg package, ALEXIS includes a six-telescope ultrasoft X-ray array (the ALEXIS experiment), a broad-band VHF receiver and digitizer (BLACKBEARD), a digital processing unit (DPU), and a service bus (spacecraft). A major objective of the project was to develop the capability at Los Alamos to design, construct, integrate, launch, and fly capable but cost-effective small satellites. Experiments, spacecraft, and integration cost approximately $17 million. The ALEXIS spacecraft bus and experiment details, project documentation, design philosophy, integration and test history, and lessons learned during the development phase of ALEXIS are discussed in Priedhorsky *et al.* (1993a). The ALEXIS launch campaign, telemetry and power systems and lessons learned from the overall effort are discussed by Priedhorsky *et al.* (1993b).

Figure 1 is an outline drawing of the ALEXIS satellite. A functional block diagram of the spacecraft and experiments is shown in Figure 2. The ALEXIS (Array of Low-Energy X-ray Imaging Sensors) experiment (Priedhorsky et al. 1988, Bloch et al. 1990) is an ultrasoft X-ray

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monitor that consists of 6 compact normal-incidence telescopes tuned to narrow bands centered on 66, 71, and 93 eV. The six ALEXIS telescopes are arranged in pairs and cover three overlapping 33° fields-of-view. The resolution of each telescope is limited by spherical aberration to about 1/2° diameter. During each rotation of the satellite, ALEXIS is to monitor the entire anti-solar hemisphere. ALEXIS is naturally not as sensitive as large-area, pointed telescopes like NASA's Extreme Ultraviolet Explorer, but will be uniquely sensitive to bright variable objects and the diffuse extreme ultraviolet background. While the ALEXIS experiment looks outward for astrophysical signals, BLACKBEARD looks at signals emitted near the Earth. BLACKBEARD is an radio frequency experiment designed to study distortion and interference effects on transient transionospheric VHF signals such as lightning and artificial pulses. A digital processing unit (DPU) services both experiments, compressing and formatting data before storage in the spacecraft. The spacecraft bus provides power, command and control, data storage, telemetry, and attitude control and determination in a spin-stabilized, solar-pointing orientation. Launch was provided by a Pegasus air-launched booster developed by Orbital Sciences Corporation under contract to the Air Force Space and Missile Systems Center.

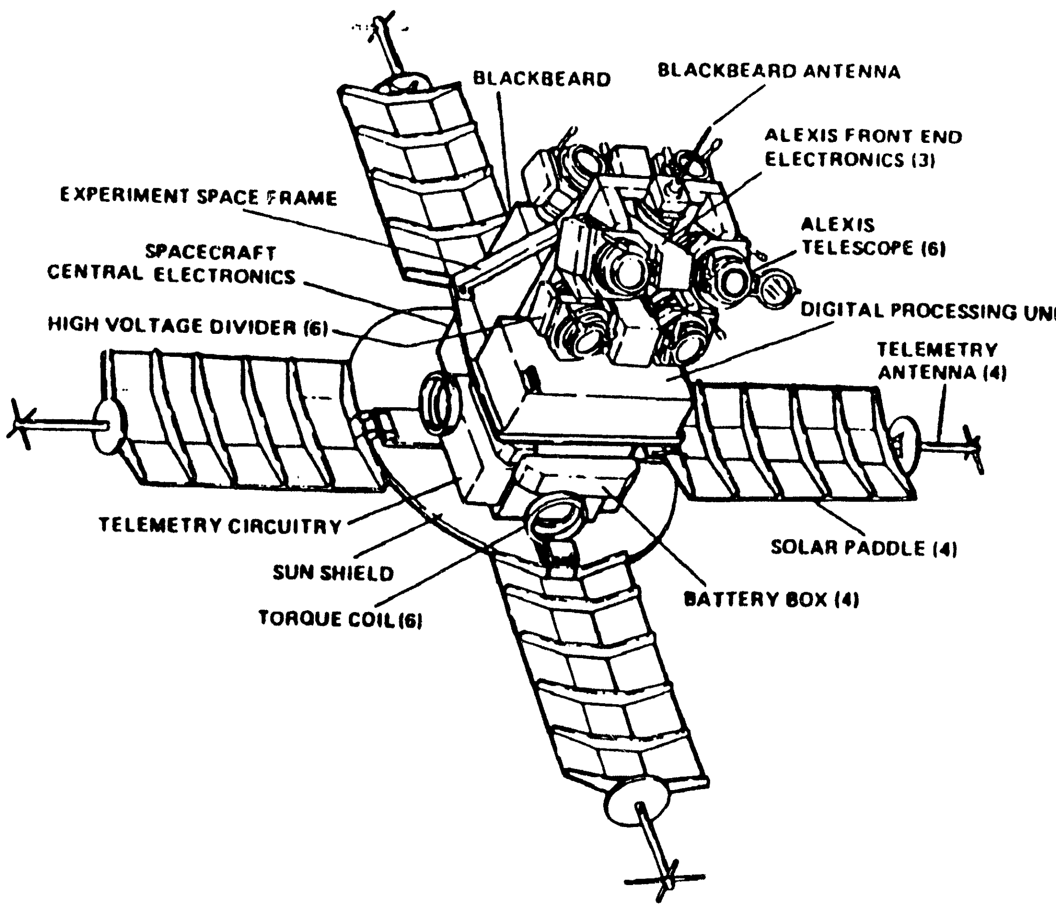

Fig. 1. The ALEXIS satellite in its on-orbit configuration The satellite height is 113 cm, base to antenna tip, and the spacing from solar paddle tip to paddle tip is 228 cm. The top BLACKBEARD antenna (shown) points opposite the Sun, and the satellite spins about the Sun-anti-Sun axis at 2 rpm.

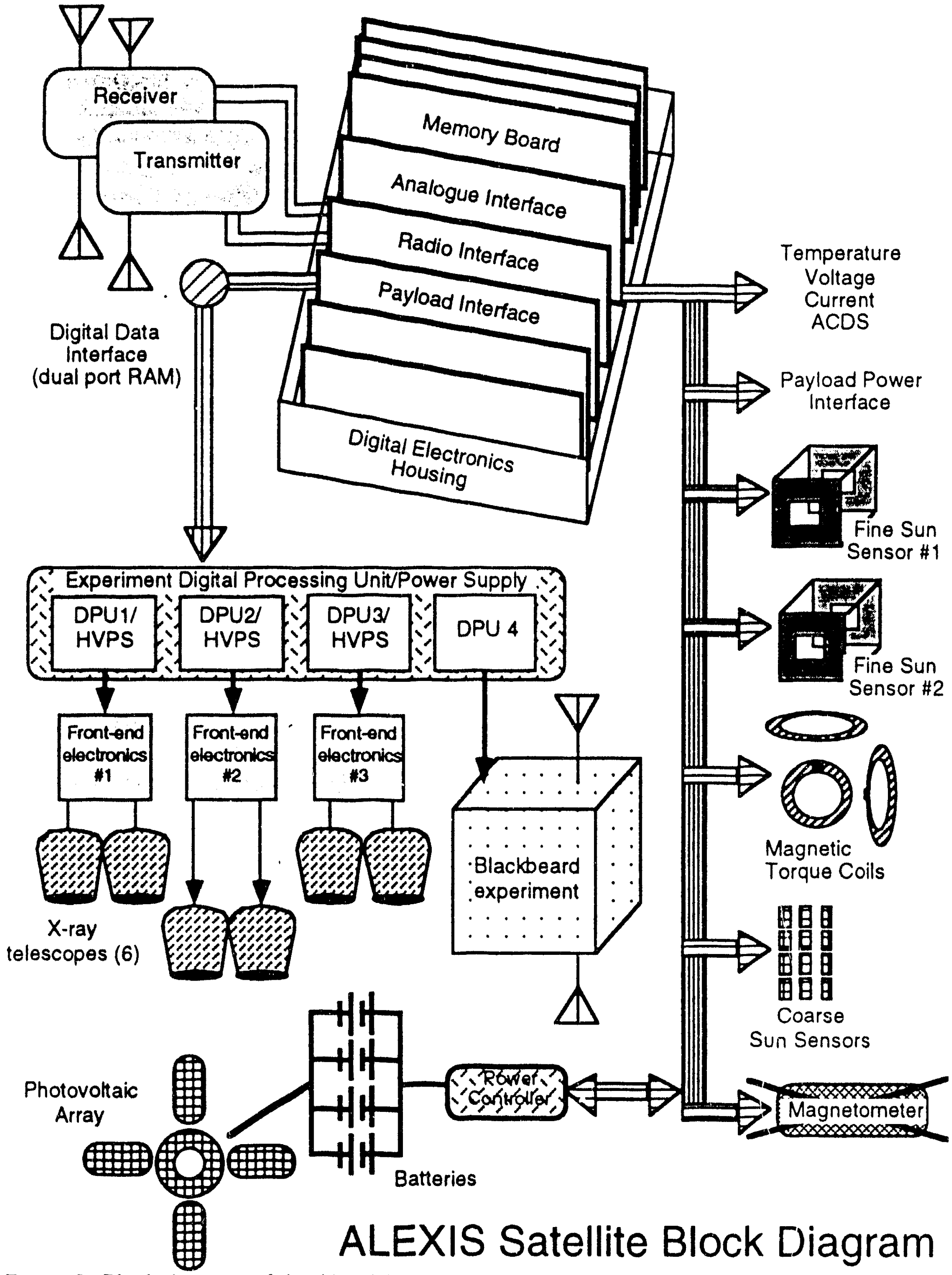

Figure 2. Block diagram of the ALEXIS spacecraft and experiments. The magnetometer, mounted on the +Y paddle, failed after launch.

The ALEXIS spacecraft is highly capable compared to previous miniature satellites. The spacecraft comprises only 40% of the total 113-kg mass, the rest being devoted to the BLACKBEARD and ALEXIS experiments, the DPU, and the payload space frame. Spacecraft functions consume less than 10 Watts, orbit-averaged, while the spacecraft is designed to provide 50 Watts of 28 V bus power to the payload, orbit-averaged. Payload data are recorded in a 96 Megabyte spacecraft mass memory at mean rates of 10 kilobits s^{-1}, with peak rates in excess of 100 kilobits s^{-1}. The ALEXIS system employs a "store-and-forward" architecture, passing data and commands between the spacecraft and a single ground station at Los Alamos. Commands are uplinked at 9600 bits s-1 and data are downlinked at 750 kilobits s^{-1} via a steerable 1.8-meter dish mounted on the roof of the Los Alamos Physics Building. The ground station is designed to receive data and transmit commands automatically without human intervention.

ALEXIS was launched by a Pegasus booster on 1993 April 25 into a 844 x 749 km orbit of 70° inclination. The Pegasus dropped from the wing of a B-52 bomber at 1356 UT. ALEXIS launch came at the end of a two-week field campaign at Edwards Air Force Base. Initial reports from the launch site indicated a perfect, nominal launch.

THE RESCUE OF ALEXIS

Initial attempts to contact the ALEXIS satellite after the April 25 launch were unsuccessful. The first passes over the Los Alamos ground station were on the evening of the 25th. Video taken from the second stage of the Pegasus booster became available before these passes. The video showed the ALEXIS +Y paddle to have prematurely unstowed. The paddle pivoted into the video field during a booster attitude maneuver. The back side of the paddle showed, proving that its lower hinge attachment to the bus had failed. The upper latch mechanism securing the paddle to the payload was designed to actuate via a hot wax plunger. This mechanism had either prematurely deployed or broken. The cause for the premature release, and the damage it caused, could not be deduced from the video, and is the subject of an anomaly investigation, whose report was released in early January, 1994. (The root cause of the anomaly was found to be a too-flexible bracket the held the solar paddle hinge assembly. The bracket on the paddle that failed was much more flexible than the other three brackets. Another contributing cause was some modifications that were made to the hot wax actuator mating plates which put additional stress on the tab that the actuators mated to.) The prolonged campaign to rescue the ALEXIS satellite is summarized in Fig. 3.

The ALEXIS team attempted contact April 25. ALEXIS did not respond. The dish was pointed using an ephemeris supplied from assets external to the ALEXIS team. We knew, however, that if the attitude system was disabled and ALEXIS did not lock on the Sun, contact would be delayed. ALEXIS would in that case not deploy its solar paddles until 20 hours after turn-on, and not turn on its receiver until 10 hours thereafter. Hopes were high for the evening passes of April 26, the first after the 30-hour time-out. ALEXIS did not respond. Suspicion grew that we had been tracking the wrong object. On the evening of April 27, the BLACKBEARD experiment team, using their ground equipment, detected the beacon from an attached payload on the Pegasus third stage and proved that we had been tracking the third stage instead of ALEXIS. The location and Doppler shift of the third stage were different enough that ALEXIS could not have responded. Once again, hopes were high for the passes on the evening of the 27th, as we tracked the correct object for the first time. ALEXIS did not respond. We now believe it likely that the batteries were dead by the 27th. If we had pointed properly on the 26th, there is a good chance that we could have contacted ALEXIS. The batteries would have been still charged from launch.

ALEXIS Rescue Timeline

1993	April 25:	Launch into 844 x 749 km orbit Pegasus video shows +Y paddle anomaly
	April 27:	First attempt to track correct object
	May 9-12:	Unsuccessful contact attempt from Vandenberg with 20-meter dish, 7 kWatt transmitter
May	April-: June	External assets show 4 paddles deployed. Paddle deployment implies CPU turned on.
	June 2:	ALEXIS transmits clock message. Message proves CPU, radio, batteries OK.
June	June:	Various false alarms
	June 30:	Housekeeping data received, status determined. Most systems nominal but magnetometer failed. Spin axis tilted nearly 90° to Sun.
	July 1:	Intermittent contact, commands impossible
	July 5:	Power conservation commanded
	July 8:	Batteries fully charged; DPU tested
	July 10:	Blackbeard experiment operations start
July	July 14:	Re-orientation begins, power situation improves
	July 22:	ALEXIS door opening begins
	July 25:	Spin axis pointed towards Sun
	July 26:	First high voltage operations
	July 29:	First spin-up completed

Figure. 3 Timeline of the ALEXIS rescue.

During the weeks after launch, data gathered from external assets indicated that all four solar paddles had extended. This implied that ALEXIS was not dead on arrival in orbit, but turned on and stayed on long enough to deploy the three undamaged solar paddles. This was our greatest cause for hope during the weeks that followed. On the chance that the telemetry system was damaged, we boosted the telemetry uplink. The nominal ALEXIS uplink goes out over a 20-Watt transmitter via a 1.8-meter dish. Using a traveling wave tube, we boosted the uplink power to 200 Watts without result. On May 9-12, we drove the spare portable ground station to Vandenberg Tracking Site to use a Space Command 20-meter dish and 7-kiloWatt transmitter. This gave a net advantage of 45 dB on the uplink and 15 dB on the downlink. Even if both receive antennae had been lost, the uplink signal should have been strong enough to make contact into a torn stub (the +Y solar paddle carried one of the two receive antennae, with the other on the -Y solar paddle). Frustratingly, ALEXIS did not respond. We retreated to Los Alamos and resumed nominal tracking procedures. A gloomy two months followed, but hardly a pass was missed. The night and weekend passes were eventually automated, and results checked the next morning.

On 2 June, ALEXIS spoke via a 15-second transmission. The ALEXIS transmitter turns on as soon as ALEXIS receives an uplink signal, but housekeeping data is transmitted only after a full acknowledgment between uplink and downlink. Until this acknowledgment, ALEXIS repeats a time packet word based on the spacecraft clock. The transmission consisted only of time packets, but was enough to prove that a) the transmission was, without a doubt, from ALEXIS, b) the processor, receiver, and transmitter were functional, and c) the batteries were functional, because the clock indicated that ALEXIS had run through the last orbital night. Hopes buoyed, and the ground station was staffed around the clock for the following passes. ALEXIS did not respond for four more weeks. The team occupied itself with various false alarms from Los Alamos and Vandenberg Tracking Site.

On June 30, ALEXIS transmitted a strong signal and stayed in contact for 4 minutes. The housekeeping data were complete and revealed the status of the satellite. ALEXIS was spinning about an axis nearly 90° from the Sun. All systems appeared functional except the magnetometer, which was flatlined. The transmission ceased after 4 minutes. A brief contact on July 1 returned a smaller set of housekeeping data. Because ALEXIS's solar arrays were approximately edge-on to the sun, they generated little power. Both the 30 June and 1 July contacts ended when the power code set the spacecraft into a power conservation mode ("nap"), which turned off the transmitter and receiver. Analysis of the housekeeping data showed that the spacecraft bus was drawing ~425 mA (~13 W), while the power system generated an orbit average of only 300 mA (~9 W). Aggravating the power situation was the fact that, with the magnetometer out, the attitude control code set the X and Y torque coils to maximum settings. As 225 mA of the bus draw was due to the torque coils, and nap mode turned off the torque coils, it seemed that ALEXIS would cycle in and out of nap mode. Contact would only be possible when the spacecraft was not in nap mode.

The top priority for the next contact was to minimize power consumption. This was done by sending a command to turn the torque coils off (to be exact, we set the gains in the attitude control code to zero), by keeping the contact short to minimize consumption by the 3-amp transmitter, and to command the receiver to remain off until the next pass over Los Alamos, rather than cycling 2 minutes off and 20 seconds on in its default mode.

These commands went up when ALEXIS next responded on July 5. Immediately, the power situation improved. The spacecraft draw was reduced to about 220 mA (~6.5 W), leaving an orbit-averaged surplus of 25 mA to charge each battery. Examination of an EEROM register showed that ALEXIS had cold started more than 20 times since launch, but probably turned off each time for lack of power. ALEXIS had cold started between June 30 and July 1, and again before the 5 July contact. Much of its live time was probably spent in a "nap" mode with the receiver turned off. After July 5 ALEXIS stayed on.

In succeeding passes, we gathered considerable data on the power system. Analysis of this early data was complicated by aliasing between the default 60-second sample rate and the nearly 60-second spin rate. This was remedied by increasing the sample rate. Power production varied dramatically during the spin period, due to the misalignment of the spin vector in the spacecraft body frame. During one rotation of the satellite the battery charge rate varied from 0 to 200 ma.

By July 8, the batteries were fully charged and 100-ma of excess current was available. By July 8 testing of the experiment digital processing units began, followed on July 10 by the first BLACKBEARD experiment operations. However, the power situation was marginal and perhaps deteriorating, and ALEXIS needed to be re-oriented towards to Sun. Telescope door opening was impossible with ALEXIS sideways to the Sun, because of the likelihood of damage to the thin filters. Now that we had regained reliable communication with the satellite, the attitude control problem was the next challenge.

The information gleaned from the first contacts with the spacecraft provided the basis for a scenario of what happened after launch. When the spacecraft was deployed from Pegasus, the lack of valid magnetometer readings prevented the autonomous attitude control system from working. With the magnetometer readings at a constant DC level, the control system would actuate the two radial coils (X and Y) at a maximum level in a vain attempt to spin the spacecraft up. In fact, the spacecraft was already spinning at 4 rpm about the Z axis from the impetus of the launch vehicle. The spacecraft was programmed to attempt to attain proper attitude within 30 hours. If the proper attitude had not been attained by this time, the solar arrays would be deployed and the spacecraft would attempt to make contact with the ground station. During the interval between separation and automatic paddle deployment the spacecraft entered a "flat spin" about a transverse axis. When the paddles deployed there was roughly an equal chance that the positive or negative Z axis would align with the spin vector. In yet another demonstration of Murphy's law, the spacecraft -Z axis ended up aligned with the spin vector and the spacecraft was facing almost exactly away from the Sun. Shortly thereafter the batteries discharged and the spacecraft became inactive.

SOLVING THE ATTITUDE CONTROL PROBLEM

The attitude control system for ALEXIS consists of a set of three, redundant, air core magnetic torque coils used as actuators, a suite of photo diodes used as coarse sun sensors, a pair of ±10° FOV fine sun sensors, a magnetometer and a horizon crossing indicator. Software running on the SC processor closed the loop with the intent of spinning about the major principal moment of inertia axis at a rate of 2 rpm. The spin axis was to be aimed towards the sun to keep the X-ray telescope array pointed away from the sun and maximize collected solar energy from the solar array.

The loss of the magnetometer during launch rendered the on-board autonomous attitude control system ineffective. As mentioned in the previous section, for over eight weeks the satellite operators were not able to establish or maintain contact with the spacecraft as it remained in a completely unfavorable attitude with respect to the sun and was thus unable to generate any power from its solar array. We now believe that the brief transmission on June 2 was the result of Earthshine providing a partial charge for the batteries. Finally in late June 1993 the spin axis drifted to an attitude in which some energy was generated and regular contacts began. A series of improvised ground based commands to the magnetic coil actuators brought the satellite to a favorable sun aspect and normal mission operations were begun.

During the design phase of the ALEXIS an extensive software simulation program was written to exercise, test and evaluate the performance of the attitude control system. While the on-board software was rendered useless by the unavailability of the magnetometer data the original simulation software has proven to be very valuable for the initial improvised attitude control schemes and later, more robust and automatic control methods.

The simulation code consisted of an orbital position model, based upon the SGP4 algorithm, an 8th order earth magnetic field model, numerical integration to solve the SC dynamics, environmental disturbance torque's, including gravity gradient, residual magnetic moments, aerodynamics and solar radiation pressure, models for all SC sensors and actuators and the actual flight attitude control system code.

Spacecraft housekeeping data from the contacts on June 30 and July 1 provided us with important information about the attitude situation. Readings from the coarse Sun sensor (CSS) array indicated that the spin period was on the order of 53 seconds, that the spin axis was skewed in the body frame by approximately 18° (probably due to mis-location of the damaged solar paddle), that the spin direction was almost retrograde from the intended direction and that the spin vector was nearly perpendicular to the Sun. The horizon crossing indicator (HCI) was functional, but the magnetometer was not.

When the situation on the satellite had been assessed the flight software routines in the simulation programmed were (with regret!) deleted and a simple command parser substituted. Commands to slew the spin axis towards the sun were invented, typically by trial and error, and the simulation ran to determine the effects of these commands. When an effective set of commands was ready they were uploaded to the SC for execution. This improvised system was adequate to regain control of the SC attitude but the generation process was labor intensive and time consuming.

Spin rate maintenance was managed in a similar way. While axis precession required command rates on the order of four times the orbital rate, spin rate maintenance would require command bandwidth on the order of the spin rate. To get around having to determine spin phase angle and uploading a large number of commands we uploaded a new piece of SC processor code for spin up maneuvers. This code would automatically check the status of the horizon crossing indicator to determine optimum coil switching times and the ground based commands need only indicate to the SC the optimal times to utilize this code and the appropriate coil polarities, again at about four times the orbit rate.

Once the SC was maneuvered to a reasonable attitude with respect to the sun and a nominal spin rate restored we had the time to devise a ground based control system that was easier to use. Again the original simulation program was pressed into service, the simple command parser was converted into an automatic command generator and the output files were converted into a form that was almost directly ready for upload to the SC. The satellite operators need only maintain the ephemeris of the SC in the simulation, specify the current SC attitude, the desired attitude and the time to start the maneuver, the rest of the process is automatic. This new system, dubbed "AutoPilot" has been in use since September 1993 with great success.

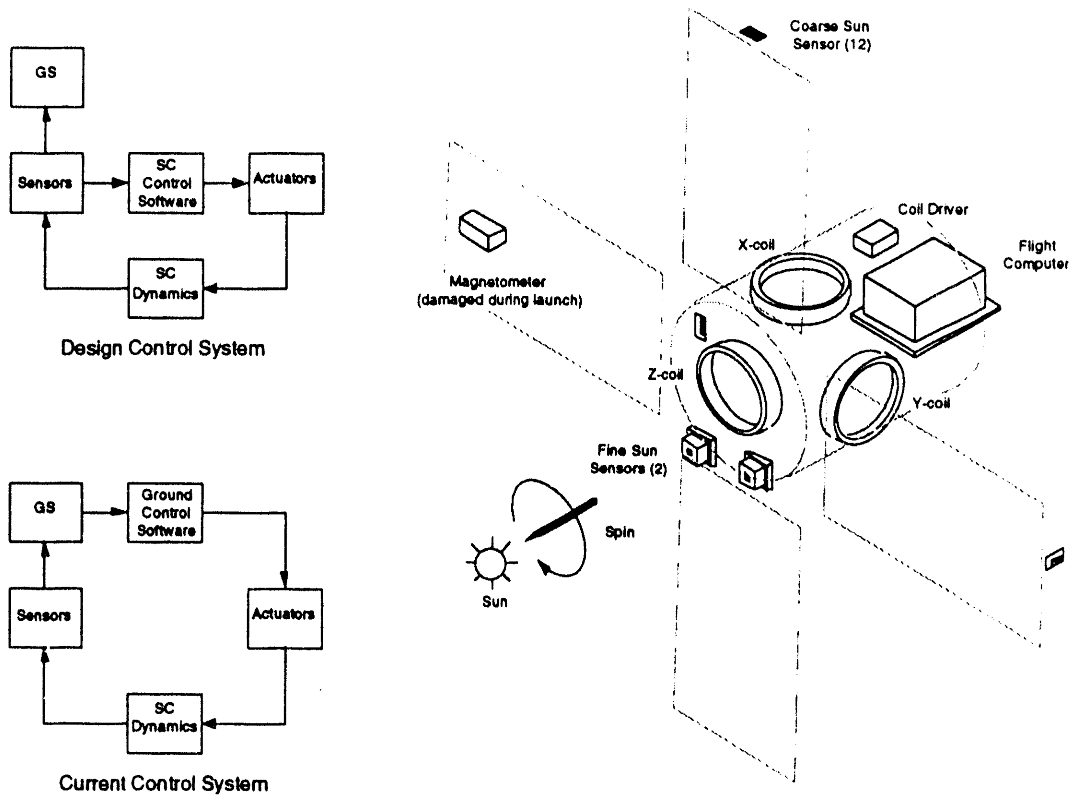

Figure 4. The left side of the figure shows the block diagrams of the attitude control system as designed, and the final implementation after launch to compensate for the missing magnetometer. The right side contains a block diagram of the major elements of the ALEXIS spacecraft attitude control system.

The scheme is quite simple, at each step in the simulation the software determines the difference between the simulation spin vector and the target spin vector. From this a desired torque is computed and the code determines if a coil command setting exists in the current magnetic field situation to generate the desired torque. If such a setting exists it is written to the command file otherwise no command is generated. Hysteresis and gain reduction is applied as the simulated attitude approaches the target to prevent dithering and hunting with attendant excessive command generation.

Spin up maneuvers are handled in a similar way, as the simulation proceeds it is determined if it would be effective to enable the small uploaded program to generate spin up torques, if so these commands are written to the output file.

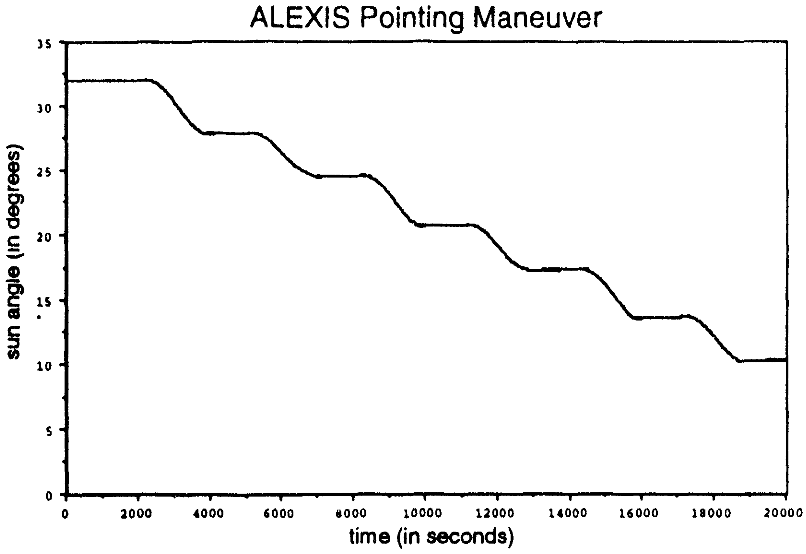

Figure 5. Typical time history of an ALEXIS spin axis maneuver which brought the spin axis closer to the Sun.

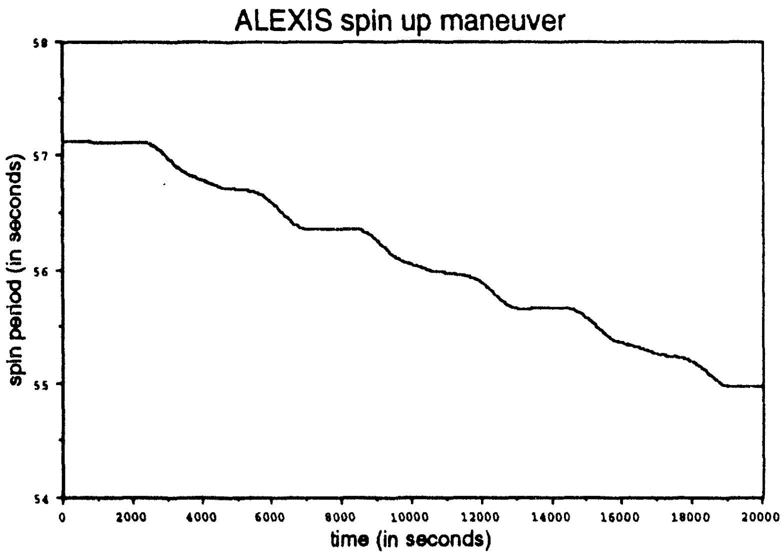

Figure 6. Typical time history of an ALEXIS spin-up maneuver which uses the HCI instead of the broken magnetometer to determine the phasing of the torque coil activity.

The attitude control problem for ALEXIS can be considered solved at this point, except for minor maintenance when the occasional bug crops up. The code is easy to use and effective enough that no additional work is deemed necessary. Axis move and spin up maneuvers are generated about every five days, often enough to keep the sun in the fine sun sensor FOV and the spin rate within about 1 second of the desired period. Figure 5 shows the typical time history for an attitude maintenance move, and Figure 6 shows the time history of a typical spin-up maneuver.

INITIAL EXPERIMENT RESULTS

First experiment operations were scheduled for the secondary BLACKBEARD experiment, because of its less demanding power and attitude requirements. The BLACKBEARD payload is designed to make radio frequency observations in the VHF band. It consists principally of two selectable monopole antennas, a band-selectable receiver, and a broadband (150 MS/s) digitizer. Other components of the payload include narrowband channels, a broadband trigger circuit, and a simple photodiode.

The primary mission of the BLACKBEARD experiment is to measure the effects of the ionosphere on the propagation of impulsive radio signals such as those that might emanate from lightning or possibly from an electromagnetic pulse (EMP) from a nuclear device. Part of the experiment is to transmit a calibration pulse from the ground and record its time-domain signature on the spacecraft, to measure the filtering effects of the ionosphere. The calibration pulse is well characterized by ground-based and other satellite measurements. It is of approximately 20 nanoseconds duration, with a peak effective radiated power (ERP) of about 1 Gigawatt, and most of the radiated energy in a band from 100 to 200 MegaHertz. The facility is called the Los Alamos Portable Pulser (LAPP).

The antennas on BLACKBEARD are subresonant monopoles with little directionality. When the broadband digitizer is running, it consumes 30 Watts of power. However, only a few seconds of operation are required to arm, stabilize, and trigger it. On average, the power consumption is quite low. These two facts contributed to scheduling the BLACKBEARD operations early in the mission. On our third try, we optimized out timing and gains. BLACKBEARD succeeded in detecting a LAPP pulse. Subsequently, we acquired several more pulses in a row, giving us high confidence in our timing and sensitivity.

Tests of the ALEXIS telescope electronics show that on-orbit performance is unchanged from before launch. All six telescope doors have been opened, even though they were sealed much longer than planned due to the launch mishap. High voltages have been turned on, and count data obtained for all six telescopes. All six telescopes are now returning data on a regular basis, using up most of the spacecraft downlink. Telescope backgrounds are significantly above pre-launch predictions for portions of the orbit. The source of these backgrounds is as yet unexplained. However, we believe that astrophysically useful data are being returned over ~10% of each orbit. Proper analysis of telescope data awaits development of attitude solutions that take into account the modified spin axis and failed magnetometer (See next section).

APPROACHING THE ATTITUDE DETERMINATION PROBLEM

The attitude knowledge requirement for ALEXIS is 0.25°, which is driven by the angular resolution of the x-ray telescopes. The ALEXIS design has a magnetometer, an infrared earth horizon crossing indicator (HCI), and two fine sun sensors (FSSs) providing attitude information sufficient to satisfy the knowledge requirement. The HCI and FSSs provide measurements accurate to 0.1° while the magnetometer's accuracy is only about 1° due to uncertainties in the earth's magnetic field. An optimal filter using the nonlinear rigid-body dynamic model (an extended Kalman filter) was designed to determine the attitude using the FSSs, the HCI, and the magnetometer during orbit day. With an accurate attitude fix at the beginning of orbit night, the HCI and magnetometer are sufficient to meet the knowledge requirement during orbit night since disturbances are not large. Twelve coarse sun sensors (CSSs), each with an accuracy of 5° and a 180° field of view, are mounted to the spacecraft for recovery in the event of an anomaly such that at least one CSS is on every face in both stowed and deployed configurations. The inclusion of these CSSs in the design proved to be prescient as the mission unfolded.

Evidently the magnetometer electrical connection was broken during the launch incident. The spacecraft was designed for autonomous attitude control but the on-board control system depends on the magnetometer, so without it the attitude control loop must be closed on the ground and the attitude determination must be accomplished using only the HCI and sun sensors. The attitude is still completely observable during orbit day, but with only HCI information available during orbit night it is not. During initial recovery operations the Sun was not in the 10° filed of view of the FSSs, so the CSSs were used with the HCI to determine the attitude to sufficient accuracy that the control loop could be closed and commands uploaded to the spacecraft's magnetic torquers. This process was repeated over several weeks to carefully bring the spacecraft to the desired state (spinning with spin vector and solar arrays pointing at the sun and instruments anti-sun).

Without the magnetometer the original sophisticated attitude determination filter needed revision. Also, it was better suited to achieving the accuracy necessary for the science requirements in good time than for obtaining the less accurate but more timely knowledge needed to pilot and recover the spacecraft. It had not been designed for piloting the spacecraft in close-to-real time.

"Hammer and Screwdriver" Method

For initial spacecraft recovery a deterministic method was quickly formulated that yields a fix for the spin vector using data at one instant of time. This method was dubbed the "hammer and screwdriver" method. It's advantages are its simplicity and its relative ease of implementation. It requires no detailed knowledge of the spin vector orientation in the spacecraft coordinate system and uses the HCI data and a spin vector to sun vector angle from the CSS data. The method involves the computation of the intersection points of a small circle and a great circle on the celestial sphere. The disadvantage of this method is that it produces two solutions for the spin vector orientation and the correct one of the two must be guessed at through dead reckoning or other information. Reproduced in Figure 7 is the original notes on the formulation of the method.

The hammer and screwdriver method was probably instrumental in achieving full (except for the magnetometer) spacecraft recovery because it came on line so quickly. Usually it is apparent which of the two possible solutions is correct and the maneuvers based on this determination usually produced the desired effect. However, at times the correct solution is not discernible from the two possibilities or neither choice is accurate; on occasion maneuver results indicated that the assumed solution was wrong because the maneuver result was not the one predicted or desired. Since maneuvers were prudently performed in small increments these occasional missteps were not catastrophic. However, clearly a better determination method was needed even for piloting so that mission operations could commence and be conducted efficiently and safely.

Implementation of the final 0.25° accuracy optimal filter was not imminent, especially with the automation necessary for piloting, so an interim method was needed. Speed of implementation was still a major factor. It was decided to try a batch algorithm using a simple kinematic model of the spacecraft spinning about its major axis.

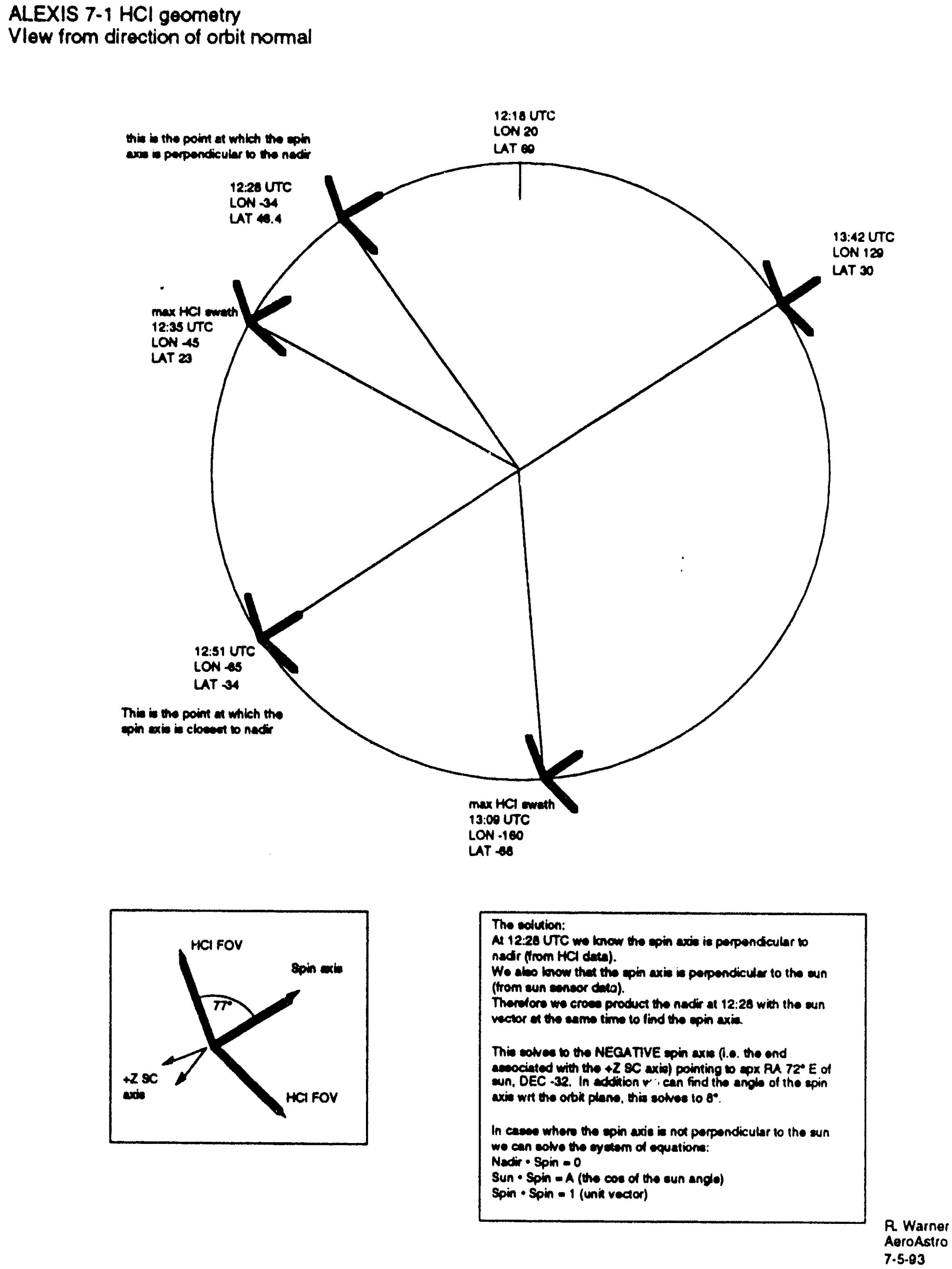

Figure 7. Original notes by Richard Warner of AeroAstro, Inc. outlining the initial "Hammer and Screwdriver" solution which determined where the spin vector of the ALEXIS spacecraft was pointed after spacecraft communication was established in early July 1993.

Kinematic Batch Estimator

The batch estimator assumes that the spin vector is fixed in inertial space over the time corresponding to the batched data. This is a reasonable assumption over short periods of time since the disturbance torques are small, for example a batch over 7 minutes of data yields a fit acceptably accurate for piloting. The objectives of the estimator are to find the right ascension and declination of the spin axis in inertial space, the spin phase at the reference time corresponding to the first CSS data point, the orientation of the spin axis in the body frame. The spacecraft was designed for the spin axis to be aligned with the spacecraft Z axis, but the severing of the structural connection to one of the four solar panels during the launch incident (it is still attached by its electrical harness and providing power!) has caused a change in the inertia tensor such that the spin axis is about 16° from the Z axis.

The batch estimator could not rely on the FSSs, at least not initially. While the spacecraft attitude was much improved and generally sun pointing, it was not yet controllable so precisely that the sun was in the FSSs fields of view. The batch estimator would have to rely on the HCI and the CSSs.

After parsing the HCI and CSS data, the first step in the batch procedure is to determine the spacecraft spin period, since the kinematic model in the batch estimator requires this parameter as an input. This is accomplished by performing a FFT of the detrended CSS data for one of the CSSs that sees a large amplitude change in sun incidence over one spin period. For example, with the spacecraft Z axis pointed generally toward the sun the +X sun sensor might be used to obtain the spin period.

For the batch estimator the CSS data must be filtered to minimize earth albedo effects. These effects tend to be negligible during orbit day entry and exit. The filtering is simply done manually by choosing CSS data from these times.

The cost function that is optimized by the batch job consists of two components, one for several relevant CSSs and one for the HCI. The CSS observation model is simply the signal strength of the CSS per the kinematic model including the current values (within the optimization loop) of the parameters defining the spin vector orientation. The observation model for the HCI is the nadir angle at earth entry and exit (at which points the HCI registers), again per the kinematic model. The HCI observation model also depends on the spacecraft position, obtained using a NORAD SGP4 propagator of the most current NORAD ephemeris for ALEXIS (the parallax for the CSSs versus orbit position is negligible). The cost function then consists of the sum of the squares of the differences between the observation model and the respective observation for each time point, with the CSSs and the HCI receiving approximately equal weighting (a least squares optimization).

The kinematic batch estimator is implemented in software using Matlab. The cost function is minimized by starting at a reasonable orientation guess (usually using the previous fix results) and searching for the local minimum using either of two algorithms. The two optimization algorithms are those contained in the Matlab functions "fmins", which uses a simplex search method, and "fminu", a quasi-Newton gradient method. Usually either of these algorithms converges to a local minimum that is evidently the global minimum (since the resulting fix makes physical sense). On occasion one has not converged but then the other always has. The algorithms are quite robust to the initial guess, usually converging even when the initial guess is in the opposite direction of the parameter space.

A formal, rigorous analysis has not been performed to establish the accuracy of the kinematic batch estimator. However, from the fit quality and the results of maneuvers based on it the apparent accuracy of the estimator is on the order of several degrees. Maneuvers based on the batch estimator have produced results consistent with predictions in all cases.

The kinematic batch estimator has allowed the spacecraft to be piloted accurately enough to routinely perform mission operations. However, while its accuracy could be improved to provide attitude knowledge that meets the science requirements in some cases, in general it is inherently not sophisticated enough to meet the attitude knowledge specification of 0.25°. For example, it cannot model nutation or disturbance torques. Toward that end, work continues on implementing an optimal filter using the nonlinear rigid-body model.

Extended Kalman Filter

The Kalman filter will use Euler's equations to dynamically model the spacecraft as a rigid body. The most significant disturbance torque is gravity gradient, which is of course deterministic and can be modeled accurately. Solar radiation and aerodynamic torques are also being modeled. Residual magnetic dipole torques are also modeled although less accurately.

The extended Kalman filter for ALEXIS is conventional for orbit day. However, during orbit night only the HCI is available and the attitude is not fully observable. The filter will use the state estimate at orbit night entry with the HCI to propagate the solution as well as possible over orbit night. Preliminary analyses indicate that the 0.25° attitude knowledge specification will be obtainable over the entire orbit with detailed disturbance torque modeling.

While it is hoped that a rigid body model will be adequate, and this approach is being attempted first, because the damaged solar panel is attached only by its electrical umbilical its connection to the spacecraft is quite flexible and this flexibility may need to be modeled in the estimator. Also, the ALEXIS inertia tensor has changed form nominal and changes somewhat with time because of the loose panel. While it may be possible to achieve the desired accuracy with a new nominal inertia matrix calculated using the best available information, and while this approach should be taken first, it may prove necessary to perform a sophisticated time-dependent identification of the ALEXIS inertia properties based on the sensor data and command response.

The implementation of the extended Kalman filter is expected to occur shortly and confidence is high that the science attitude specification will be met. Even so the ALEXIS attitude determination has turned into a much more interesting problem than anyone expected.

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