INTEGRATED SPACE EXPERIMENT SATELLITE (ISES) LOW COST STABILIZATION SUBSYSTEM PERFORMANCE

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ABSTRACT

On June 29, 1991 the ISES satellite was launched into a 450 nm polar orbit. The 183 lbs satellite is a 30 inch diameter, 16 inch high, 16-sided cylinder to provide Nadir-pointing stabilization for a helix antenna associated with the Radiation EXperiment (REX) payload of the satellite. The stabilization system uses a 20 ft gravity gradient boom, hysteresis rod damping, a 3-axis magnetometer, a sun sensor and torque coils. Through careful design of the gravity gradient boom and magnetic grooming of the satellite, excellent stability was achieved. The U.S. Air Force commended ISES as the best gravity gradient stabilized satellite. The satellite achieves about 5 degrees pointing error. From the performance of this satellite and potential further improvements that maybe possible, it maybe concluded that gravity gradient stabilization maybe applicable to a wide ranging set of low cost satellite applications.

THE ISES SATELLITE

The ISES satellite mission is to study ionospheric irregularities that disrupt radio signals. The satellite mission antenna is deployed from the bottom of the satellite. Successful performance of the mission requires that the peak pointing error should be less than 10 degrees.

The satellite is gravity gradient stabilized, it is 30 inches in diameter, 16 inches high, it weighs 183 lbs and uses a 20 ft gravity gradient boom with a 5 lbs tip mass and 2 orthogonal hysteresis damping rods. Attitude sensing is performed by a DSI 3-axis magnetometer and sun sensor, while active control is exercised with torque coils. The Z-coil is 65 ampere-turn-square meter. This is the 6th DSI satellite that flies a DSI gravity gradient boom of the same design. However, certain improvements were made to this boom that significantly improved stabilization system performance.

ISES, shown in Figure 1 during integration with the SCOUT launch vehicle at Vandenberg Air Force Base, was originally designed to support the Los Alamos ALEXIS spacecraft on top in a stacked configuration. It is for this reason that there is a 13" marman ring on top of the satellite. DSI was responsible for integration of ALEXIS and for the development of the launch vehicle interface and for integration of the stack to the PEGASUS launch vehicle. When delays in ALEXIS and PEGASUS forced substitution of a SCOUT launch vehicle, and flying alone, the marman ring on top of ISES was not removed, but was no longer needed.

ISES structure consists of 16 "stringers" (or vertical longerons) supporting heavily milled out top and bottom plates onto which all electronics are mounted. Mechanical interface with the launch vehicle is by a 23" diameter marman ring and V-band, severed by redundant bolt cutters activated at separation from the launch vehicle. Telemetry and command links use an 18-watt UHF transmitter and receiver with shared command and telemetry antennas. A digital processor performs stored scheduling, transmitter and receiver control, experiment and spacecraft telemetry data collection and formatting, sun sensor attitude computations, electric power management of spacecraft bus and experiment payload subsystems, pyrotechnic device control for releasing the deployables and communications with the ground station. In addition, the computer also performs magnetic damping calculations and controls the torque coils. The electric power system uses redundant NiCd batteries to provide 150 WH of energy storage, uses redundant, temperature-controlled, current and voltage limited battery charge regulators, and it employs computer-switched and monitored DC-to-DC converters to provide in excess of 150 watts of 28 volt power, 75 watts of +/-15 and 5 volt power. In addition, several other voltages are provided to the payload. Solar cells on each side and on the top of the satellite provide solar power to charge batteries and to operate the satellite electronics. All mechanical and electronics systems in the satellite were built in-house by DSI.

THE ISES STABILIZATION SYSTEM

The main component of the ISES stabilization system is the 20 ft gravity gradient boom. This boom consists of a 5 mil BeCu 2" wide flat spring coiled up into a 1.5" diameter coil. When released, the spring expands into a nearly solid tube, slightly tapered, about 1.25" in diameter at the base and 1" diameter at the top. The spring deploys from the inside out and forms a helically wound tube. The spring is tempered and lubricated with a solid lubricant. Making sure that the deployed tubular boom is as stiff as possible, a set of conical machined guides were installed to support the boom at the bottom and at the point where it exits the satellite. To control deployment of the spring, which is necessary to assure that successive layers of the helix should lay completely flat and tight against one another, a constant speed governor was designed to control deployment of a Kevlar line tied to the tip mass and deployed inside the helical tube. Thus, the Kevlar line became a central element of the deployed boom. A turn counter on the deployment spool measured the length and speed of the Kevlar line, and this data was telemetered to the ground to verify boom deployment. The entire deployment sequence takes 4 seconds.

In addition, to assure boom stiffness, thermal conductivity from the sun-illuminated side of the boom to the side in the shade must also be maximized. This minimizes thermally-induced bending, which, because thermal heating periodicity is closely related to gravity gradient oscillation periodicity, could introduce thermal pumping, or reinforcement of oscillations by thermally-induced boom deflections.

The spring force that deploys the boom is a function of deployed length and, in particular, is very small at zero deployed length, rapidly building up to reach constant force by the time the boom is deployed 6". To provide the initial force to start the deployment sequence, a kick-off spring is used to initiate deployment. The entire deployment sequence is started by redundant pyrotechnic bolt cutters that sever a bolt that secures the tip mass to the satellite in the predeployed condition.

These design features were added as a result of a malfunction of a previous gravity gradient boom on TEX, launched in 1990. That boom was apparently not stiff enough and resulted in occasional large swings of the satellite. While we are not sure about the reasons for the occasional stabilization problems encountered on TEX, for it has been very stable for the last year, these design improvements were introduced to assure that each malfunction theory is countered.

The 3-axis magnetometer, the same design used on 11 DSI satellites, is used to provide detailed information on satellite attitude as a function of time, in conjunction with stored satellite telemetry samples from which the three magnetic field vector components as a function of time are displayed on the ground station displays. Figure 2 illustrates the x, y and z components of the Earth magnetic field during six orbits of ISES. The original display is in color, with the three components displayed as red, white and blue traces. The z component displays the characteristic nearly sinusoidal shape expected from a vertically stabilized satellite in a polar orbit. Near the equator the vertical component is near zero, at the poles it is a maximum, with a plus sign over the North pole and a minus sign over the South pole. Figure 3 shows the comparison between the z-axis magnetic field component computed from the Earth magnetic field model and measured on-board the satellite. In addition to providing an excellent measure of stabilization performance (by comparison with the magnetic field vector components computed from a spherical harmonic representation of the Earth magnetic field), the 3-axis magnetometer also provides accurate spin rate information during satellite despin immediately after release from the spin stabilized last stage of the launch vehicle.

The ISES sun sensor employs 7 solar energy detectors, 4 on opposite sides, 2 on top and 1 on the bottom of the satellite. These detectors are used to determine the sun elevation and azimuth angles in spacecraft coordinates by comparing the relative detector outputs from which the sun projection angles are computed on-board. Special algorithms are used to eliminate the effect of albedo and gravity gradient boom shadowing of some of the top solar cells. A black and white version of the color sun sensor attitude display of 6 ISES orbits is shown in Figure 4. To simplify interpretation of the sun sensor display, the sensor outputs are set to high values during umbra. The elevation angle display peak value is 90^{o}-Beta and its minimum value is the angle with which the sun illuminates the spacecraft bottom as it goes past the North pole, just before entering the umbra (or as it emerges from the umbra before reaching the South pole). The azimuth indicates spacecraft yaw, not controlled in a gravity gradient stabilized spacecraft.

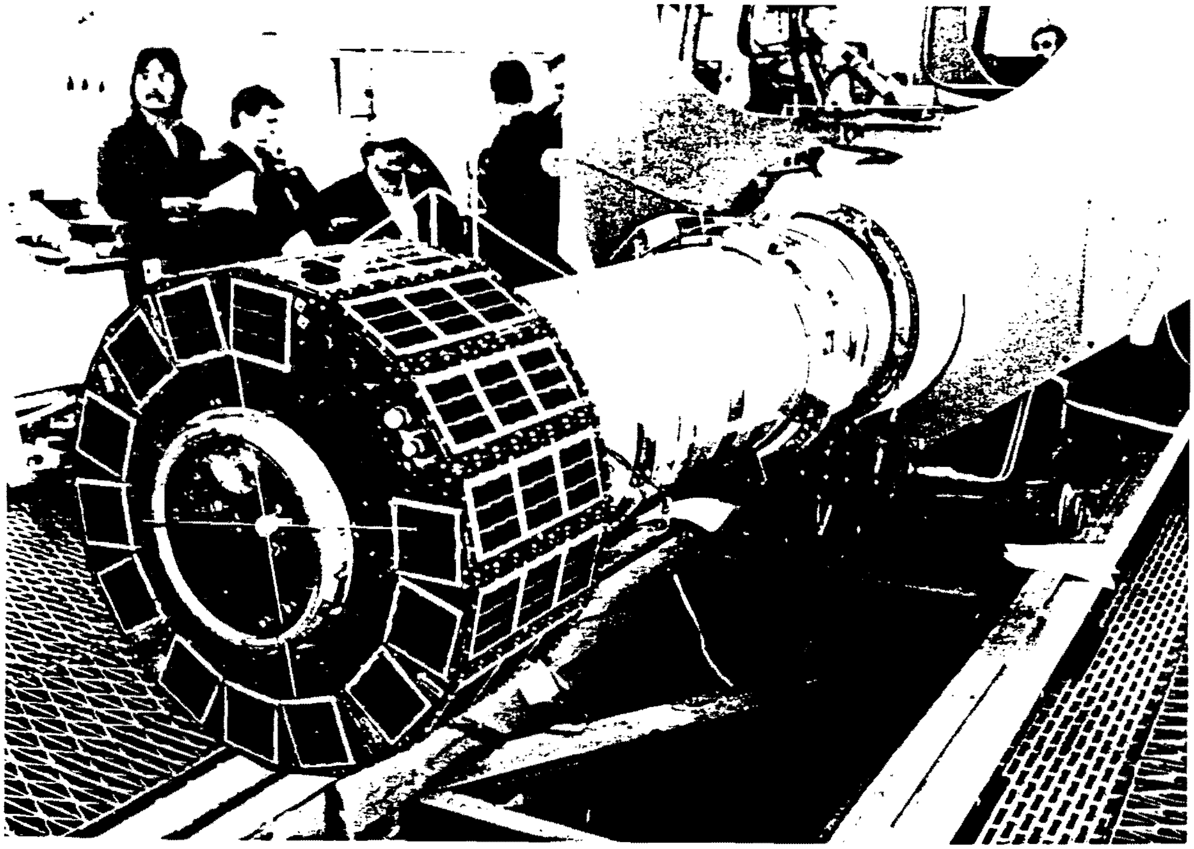

Figure 1. ISES Mated to SCOUT at VAFB

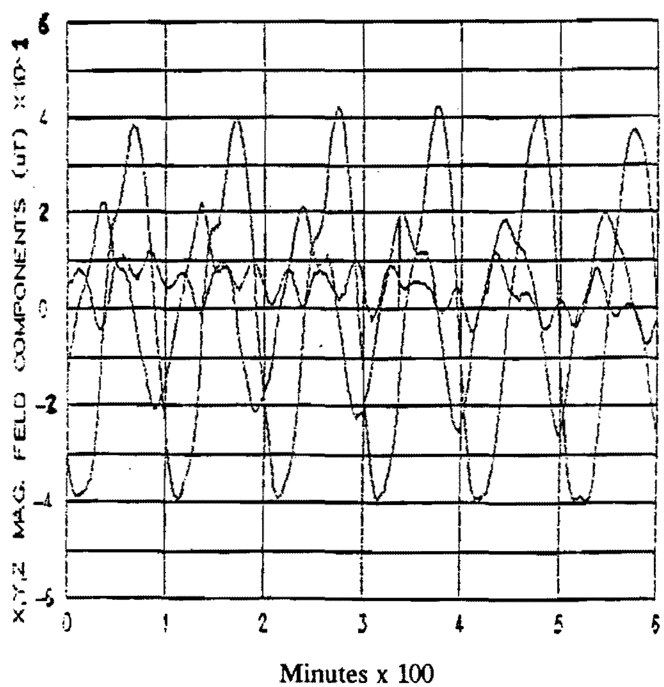

Figure 2. 600 Minutes of 3-Axis Magnetometer X, Y and Z Traces for 02-18-92 ending at 10:30 Zulu

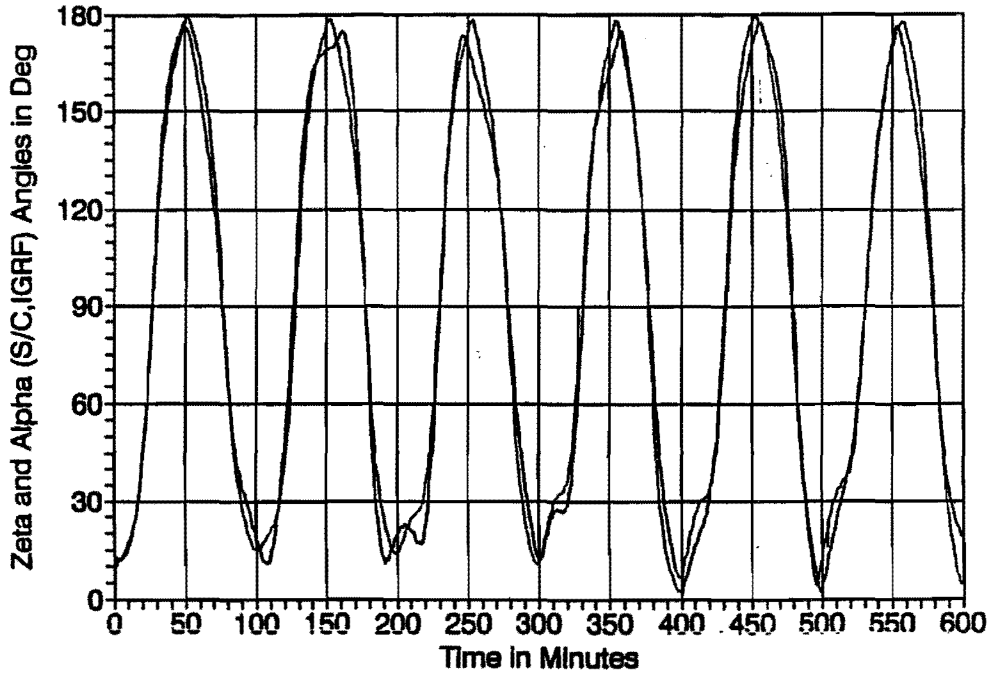

Figure 3. ISES Attitude Angles (B to Z-Axis) on 07-28-91 at 10:00 Zulu
Libration Sigma = 5.2°

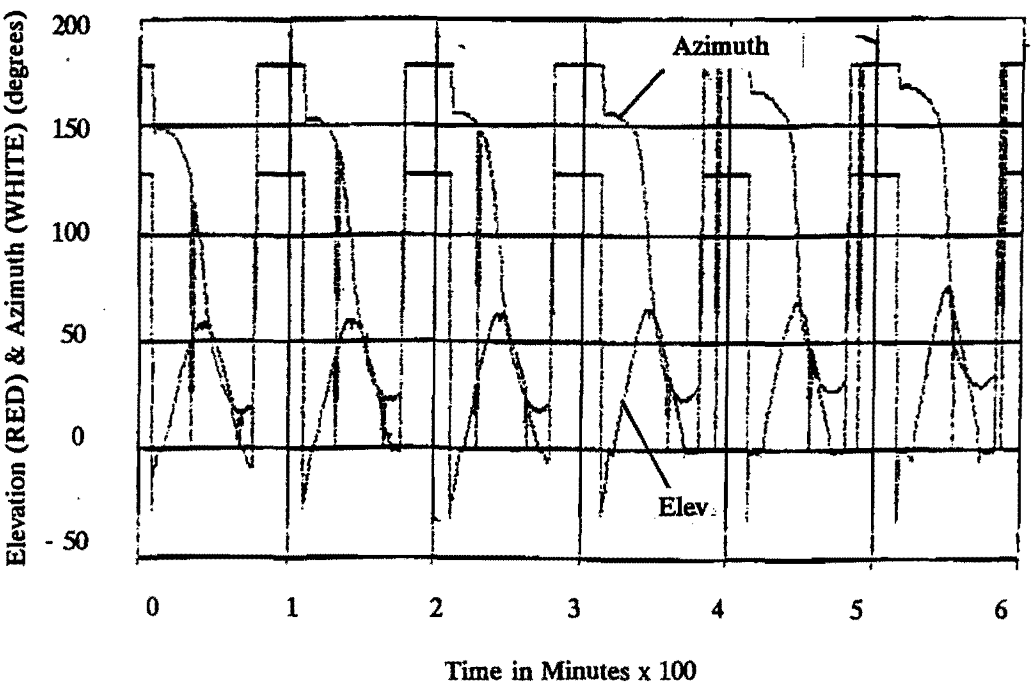

Figure 4. ISES Sun Sensor Elevation and Azimuth Angle versus Time Output During Six Orbits on 02-18-82, ending at 10:30:00 Zulu

INITIAL DESPIN

The SCOUT launch vehicle last stage is spin stabilized. Just prior to separating the satellite the SCOUT despins the last stage with a Yo-Yo despin mechanism that may leave the spacecraft spinning at as much as 3 rpm. In the case of ISES the residual spin at separation was 2.2 rpm. Hysteresis rod damping is used to despin the satellite to 0.2 rpm which, for ISES, was the highest angular velocity for deploying the gravity gradient boom so as to achieve gravity gradient capture. Angular deceleration rate was about 0.12 rpm per day, taking nearly three weeks to despin to the point where the boom could be deployed.

If the satellite is allowed to despin much below 0.2 rpm then it will go into a flat spin and, eventually, begin to tumble. Because we developed a procedure for deploying the gravity gradient boom in a manner so as to have a high probability that the satellite should stabilize right side up on the first try, it is important not to let the satellite despin too much before the boom is deployed. Since polar launches from VAFB are to the South, the satellite will initially spin with its Z axis pointing South. By commanding boom deployment to occur near the South pole, the slowly spinning satellite is already oriented in a Nadir pointing manner when the boom is deployed, resulting in rapid gravity gradient capture with the satellite right side up. This was, in fact, the procedure implemented with ISES that resulted in stabilization right side up.

Should the satellite stabilize upside down, however, it can readily be inverted with the powerful Z-coil, which can invert the satellite despite the fact that the pitch moment of inertia has been increased by a factor of 30 as a result of deploying the boom. The maneuver to invert the satellite is performed by a high level ground command that is programmed to execute the maneuver at a longitude such that the orbit plane is nearly the same as the plane defined by the two lines from the magnetic and the geographic North poles to the center of the Earth. If the Z coil is energized while the satellite is in this plane, the resulting maneuver will be a pure pitch. Otherwise an undesirable roll also results. The maneuver is centered about the magnetic equator and consists of a pitch acceleration, followed by a constant pitch rate coast, and terminated by an equal pitch deceleration. The entire inversion maneuver takes place over a 25 minute interval. During this maneuver the 3-axis magnetometer is sampled at a high rate, and the resulting telemetry when read out at the Ground Station is used to confirm the success of the maneuver.

LIBRATION DAMPING

Initial magnitude of Pitch and roll oscillations (librations) of the gravity gradient stabilized spacecraft, after the boom was deployed, was about 29°. Pointing error and librations then decayed with a time constant of 7.1 days until the spacecraft settled down with librations of about 5.4°. This is shown in Figure 5. Over the last year the peak libration amplitude varied somewhat, sometimes reducing to about 4°, at other times increasing to over 6°. Using the sun sensor data, over the last year we saw a steady reduction in yaw, sometimes resulting in essentially no yaw for large fractions of a day. The flexible stored telemetry commands permit monitoring the satellite attitude behavior with precision.

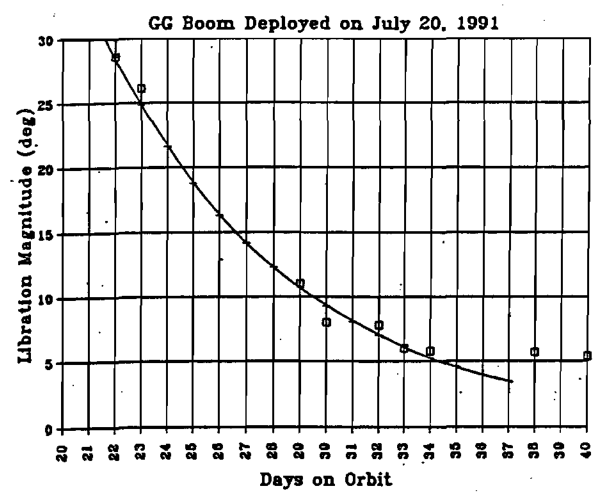

Figure 5. ISES Libration Amplitude Decay

Simulation of the gravity gradient stabilization system, using a model of the Earth magnetic field and the magnetic properties of the hysteresis rods, coupled with the spacecraft dynamics, provided a very accurate model of spacecraft stabilization behavior. Among other things the simulation program exhibited the importance of magnetic grooming of the spacecraft. Residual spacecraft dipole moments definitely result in increased libration magnitudes. For this reason, ISES was magnetically groomed and its residual magnetic moment was cancelled with the addition of a small permanent magnet. Magnetic grooming was accomplished in a Helmholz coil at GSFC.

ACTIVE MAGNETIC DAMPING

To further improve the stabilization performance of gravity gradient stabilized spacecraft, ISES also contained an active magnetic damping system. This system was based on the premise that if the spacecraft on-board magnetic field vector components exhibit a derivative much different than the derivative of the calculated Earth magnetic field components, based on a model of the Earth magnetic field, then the spacecraft must be pitching or rolling at a rate different than that which would correspond to a stable, Nadir-pointing spacecraft. This modified B-dot law was implemented by the following steps:

- o the spacecraft contained a Latitude and Longitude propagator. This was based on uplinking Equator crossing time and by on-board computation of instantaneous Latitude and Longitude.
- o on-board computation of the Earth magnetic field vector components as a function of time.
- o computation of the calculated magnetic field vector component derivatives.
- o on-board measurement of the Earth magnetic field vector components in spacecraft coordinates.
- o computation of the measured derivatives.
- o comparison of the calculated and measured field component derivatives.
- o this produced the vector error between computed and measured derivatives.
- o application of the error vector to the excitation of torque coils to induce angular velocities to counter the libration errors.

This algorithm effectively damps out residual librations to reduce the remaining pointing error. The algorithm was implemented in the on-board computer and tested in the Helmholz coil. The satellite was "flown" in the Helmholz coil by varying the simulated Earth magnetic field to correspond to the field seen by a spacecraft on orbit, Nadir pointing with a stabilization error of variable amplitude oscillations. Monitoring the torque coil excitation response of the spacecraft, its ability to damp out libration errors could be assessed. While this system performed as expected in ground testing, an unfortunate software error that only permitted the algorithm to function in the test mode, prevented its employment on orbit. Fortunately the performance of the ISES gravity gradient stabilization system even without this active damping subsystem was excellent, resulting in the best stabilization performance of any gravity gradient stabilized system, according to the Air Force.

CONCLUSION

Gravity gradient stabilization is the least expensive spacecraft Nadir pointing stabilization system. While years ago gravity gradient stabilization was used often, increased pointing accuracy requirements of most present-day spacecraft missions make the use of gravity gradient stabilization less frequent. Since recent studies indicate that the majority of spacecraft applications require Nadir pointing accuracies of only 1-2 degrees, the improved accuracy potential of gravity gradient stabilization by spacecraft magnetic grooming, use of very stiff and thermally conductive booms and active magnetic damping may result in gravity gradient stabilization performance sufficient to satisfy a large fraction of spacecraft applications, resulting in a significant reduction in small spacecraft cost. Further research to better understand the origin of disturbance torques would also benefit gravity gradient stabilization system performance improvements.

ACKNOWLEDGEMENTS

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