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ATTITUDE AND ORBIT CONTROL SYSTEM DESIGN FOR THE GLOBALSTAR TELECOMMUNICATIONS SATELLITE

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Abstract: The attitude and orbit control system (AOCS) for the Globalstar constellation of 48 low-earth-orbit cellular-telephone communication satellites is described. The attitude control system must point the antenna to the earth and rotate the satellite in a prescribed yaw-steering profile so that a single rotation about the solar-array axis can always keep the panels perpendicular to the sun. In addition, the AOCS must provide for safe holding in a sun-pointing mode and be able to control the satellite during orbit-change maneuvers.

Keywords: Globalstar, small satellite, communication, cellular telephone, yaw steering, attitude and orbit control

1. INTRODUCTION

The Globalstar worldwide satellite-based cellular telephone system consists of a configuration of 48 operational and 8 spare 450 kg earth-pointing satellites. The 48 operational satellites are at an altitude of 1414 km in eight orbital planes of 52 degrees inclination oriented every 45 degrees of right ascension along the equator. There are six satellites in each plane spaced every 60 degrees. The eight spare satellites will be maintained in 900 km phasing orbits ready to replace any satellite in the constellation should that become necessary. Figure 1 shows the configuration of a Globalstar satellite.

The satellite attitude is controlled to the standard orbit reference frame with the x-axis in the direction of the orbit velocity, the z-axis pointing to earth , and the y-axis oppositely directed to the orbital angular momentum vector. The satellite fixed coordinate system is identical to the orbital coordinate system when the roll, pitch, and yaw angles are zero. The solar array long axis is the body-fixed y-axis, and the solar array can be rotated 360 degrees about this axis.

In order to maintain maximum power at all times, the satellite attitude follows a yaw-steered profile. The satellite is rotated in yaw about the z-axis, and the solar array is rotated about its long axis such that the antenna boresight which is parallel to the z-axis always points to the earth and the solar array is always perpendicular to the sun (Figure 2). In order to avoid high rates when the sun is close to the orbital plane, the maximum yaw rate is limited to 5 deg/min. The attitude and orbit control system (AOCS) must maintain antenna pointing to a few tenths of a degree.

Space-Systems/Loral (SS/L) is the prime contractor for the Globalstar satellites, and Daimler Benz Aerospace (DASA) / Dornier Stellitensysteme GmbH (DSS) is the subcontractor for the attitude and orbit control system.

2. AOCS HARDWARE

The AOCS hardware must live for 7.5 years in the high radiation environment at 1400 km; and because 56 systems will be built, it must be inexpensive.

In addition to the sensors and actuators discussed below, the AOCS system is mechanized with a redundant digitial computer known as the OBPE (On-Board Processor Electronics). One half consists of a 1750A CPU, 64K RAM, 128K PROM, the sensor and actuator interfaces, and the telemetry and command logic. All equipment is cross strapped so that either half of the OBPE can talk to any sensor or any actuator.

2.1 The AOCS Sensors

The AOCS sensors consist of three EDO-Barnes analog sunsensor blocks, an infrared earth sensor consisting of three analog EDO-Barnes static heads, an Institut Förster three-axis fluxgate magnetometer on a short boom, and a Space-Systems/Loral dual GPS Tensor receiver.

The three-axis magnetometer furnishes two-axis body-fixed attitude rate; and with time and orbit information, it also furnishes two-axis attitude.

The three IR sensors are spaced 120 degrees about the vertical, and each is aimed at the earth's horizon. Two sensors are sufficient to give pitch and roll so that they are redundant for one failure.

The three sun-sensor complexes are mounted to give full 4π coverage except for a cone of radius 6 degrees about the ±y-axes. Each sun-sensor complex consists of six single-axis slit sensors, three primary and three redundant, such that one complex has a coverage of ± 64 degrees in the x-z-plane and ±84 degrees in the cross plane.

The GPS Tensor in addition to being a space-qualified navigation receiver is also a full three-axis attitude measuring device. Four GPS antennas are mounted on the anti-earth face of the satellite, and attitude is determined by the phase difference of the incoming satellite signals. Since the antennas are on the anti-earth side of the satellite, GPS attitude is only possible during earth pointing. In particular it cannot be used for initial acquisition. Because there is very little flight experience with the GPS receiver as an attitude detector apart from an experimental flight on DASA's CRISTA-SPAS in November '94, the AOCS system has been designed to only use GPS attitude initially as a backup.

2.2 The AOCS Actuators

The AOCS actuators consist of five Daimler-Benz Aerospace one-Newton monopropellant-hydrazine thrusters, four six-Nmsec Honeywell momentum wheels, and two 80 Am^2 Ithaco magnetic torque rods.

The thrusters are arranged with four on the -x-panel with their thrust vectors in the +x-direction, and one on the +x-panel with its thrust in the -x-direction. The thrust directions of the +x-thrusters are offset from the nominal center of mass so that they can also provide control moments. These thrusters are used for the transfer orbit from 900 km to 1400km, for station keeping, and for the initial acquisition and safe-emergency maneuvers. The single -x-thruster is for in-plane station keeping when negative thrust is required.

The four momentum wheels are arranged in a tetrahedral configuration and provide the yaw-steering profile during normal mode. Only three wheels are required for normal operation so that one wheel is redundant. The wheels are normally operated with zero momentum bias; but in the event of the loss of direct yaw measurement, the wheels may be operated as a momentum-biased system. This system is similar to the standard Whecon system, but the satellite rotates about the momentum bias vector to give the desired yaw-steering.

The magnetic torquers are used to unload the momentum wheels and are only on during normal mode.

2.3 AOCS Block Diagram

Figure 3 shows a block diagram of one half of the OBPE and the sensors and actuators. In addition to the AOCS system, the OBPE also manages the payload and handles the telemetry and command; and this is also shown in the block diagram.

3. AOCS MODES OF OPERATION

The AOCS has five modes of operation which are used for safe holding, establishing the operating orbit, establishing normal attitude-control operation, and for failure recovery. These modes may be entered automatically or manually by ground command. A general reprogramming capability also exists.

3.1 Safe-Emergency Mode

The safe emergency mode is the sun acquisition mode of last resort and points the spacecraft -z-axis to the sun and establishes an angular velocity of 0.5 deg/sec about the -z-axis with a minimum of prior information and equipment. The vehicle remains sun pointing until intervention by the ground. The only AOCS equipment which is used during safe-emergency is the OBPE, the sun sensors, and the thrusters. In particular no information is used from the safeguard memory (SGM), and it is not assumed that time and orbit information are available.

This mode is made up of the following steps: the solar arrays are rotated to the 180-degree position with the cells facing the spacecraft -z-axis, the reaction wheels are run down to zero speed, as soon as eclipse is exited three-axis rate is estimated and damped to less that one deg/sec using only sun-sensor measurements, the sun is searched for, a steady 25-degree depointing is established and the z-axis rate is set to 0.5 deg/sec with zero x- and y-axis rates.

3.2 *Sun-Acquisition Mode*

The sun-acquisition mode also acquires the sun and slews the arrays but with the difference that it uses time and orbit information and the magnetometer to facilitate the acquisition maneuver. The mode consists of the following submodes: wait during eclipse, sun search, pitch rotation, and sun pointing.

As soon as the vehicle exits the eclipse, the z-axis is aligned with the earth's magnetic field and the spacecraft is rotated about the z-axis until the sun is in the x-z-plane as indicated by the y-component of the appropriate sun sensor reading zero. The pitch rotation then drives the sun to the ±z-axis as desired, and a 0.5 deg/sec rate is established about the z-axis with the arrays oriented appropriately. The vehicle then remains sun pointing until ground intervention.

3.3 *Earth-Acquisition Mode*

The earth-acquisition mode is capable of acquiring the earth from any mode. It uses the sun sensors, the IR earth-sensor assembly, the magnetometer, and the GPS receiver as backup in the final earth pointing. In addition, it is assumed that time and orbit information are available. The actuators used are the momentum wheels, the Solar-Array Drive Assembly (SADA), and the thrusters.

This mode consists of earth search, earth capture, and fine earth poining. A rotation rate is first established which is guaranteed to find the earth in one revolution or less, and then the wheels are run up to the nominal bias momentum using the earth and sun sensors and/or the magnetometer. In the fine-earth-pointing mode roll and pitch are derived from the earth sensor or from the GPS receiver. Yaw is determined from the sun sensors or from the magnetometer with the GPS receiver as an option. The wheels are unloaded automatically with the thrusters, and the SADA and onboard software allow the array to automatically track the sun.

3.4 *Orbit-Correction Mode*

The orbit-correction mode covers four mission requirements: the orbit raising maneuver from the 900-km phasing orbit to the 1414-km operational orbit , in-plane orbit corrections approximately every six weeks, and inclination corrections a few times in the mission lifetime and deorbit to 1500 km at the end of the mission.

During this mode the primary attitude actuators are the four +x-thrusters. The full nominal thrust of four Newtons is required for burns of many hours duration so the attitude torques are applied by off modulation. During this phase the thrust level decays due to tank blowdown, and the control system must accomodate this. Full three-axis sensing is required by this mode, and this is provided by the sun sensors and the magnetometer in addition to the IR earth sensor. Also the GPS receiver is available as a backup. The SADA maintains array pointing to the sun in so far as the geometrical constraints allow it.

3.5 *Normal Mode*

The normal mode maintains the roll and pitch angles nominally at zero and executes the required yaw-steering profile as a function of sun angle, and the SADA rotates the array to the sun in a manner consistent witht he yaw angle. The yaw-angle is maintained by changing the speed of the momentum wheels, and the wheels are automatically unloaded by the magnetic torquers. The thrusters are not used during normal mode.

The wheels can be normally operated with zero momentum bias and continuous yaw measurement from either the GPS attitude receiver, the sun sensors, and/or the magnetometer. In the event of a failed GPS receiver and inadequate magnetometer accuracy (due to being near to the magnetic poles), the wheels can also be operated with a momentum bias to hold the yaw accuracy during eclipse or colinearity (sun overhead) when the sun sensors cannot give a yaw measurement. In this case yaw steering is maintained by rotating the momentum bias vector in the spacecraft. Due to the orbit motion a yaw error during this time becomes a roll error and is detected and corrected by the IR earth sensor. As soon as the vehicle exits eclipse the accumulated yaw error is corrected to zero by the sun sensors. The magnetic unloading loop only functions when yaw measurement is available. In normal mode it is possible for any one of the four wheels to fail in either the zero-momentum or the biased-momentum modes, and for normal operation to continue on three wheels.

For in-plane orbit correction, yaw-steering cannot be used since the x-axis must be maintained in the orbit plane during the thruster firings. The sun is within ± 12 degrees of the orbit plane approximately every six weeks so that during this time the AOCS reverts to a yaw-equal-zero mode to avoid unacceptably high yaw rates. The in-plane orbit correction can then be done at any time when the sun angle is less than ± 12 degrees with manual thrust command for short pulses within the normal mode.

For the details of the yaw-steering control sytem, see Brüderle et al.

4. SEQUENCE OF EVENTS

After separation from the launch-vehicle dispenser the spacecraft prepares to enter the sun-acquisition mode (SAM) since time and orbit information are stored in the OBPE at launch. The magnetometer boom is deployed immediately after separation, and the deployed status of the boom is verified from the magnetic field measurements. The thruster catalytic-bed heaters are turned on; and if the satellite is not in eclipse, the sun acquisition is completed. Once the 0.5 deg/sec rate has been established about the -z-axis, the solar arrays are deployed; and the satellite waits for ground intervention through the earth or anti-earth telemetry and command antennas.

As soon as the ground has verified the health and status of the satellite, the earth acquisition mode is commanded. Once the earth has been acquired, a series of in-orbit tests are performed to further verify health and status and to calibrate certain AOCS functions.

When the in-orbit tests have been completed and as soon as the orbit phasing is correct, the orbit-raising maneuver is completed with a series of burns and the satellite enters normal mode.

5. ASPECTS IN ATTITUDE AND RATE DETERMINATION

With the exception of the safe-emergency mode, time and orbit information are always available; and the earth vector, the sun vector and the magnetic field vector can all be computed in either the inertial or the orbit frame. The magnetic field vector can always be measured without any field-of-view restrictions; the sun vector can be measured with only insignificant field-of-view restrictions; and the earth vector can be measured over a fairly large field of view in the earth pointing modes. With the exception of only a short colinearity interval for the sun and earth vectors, three axis attitude can be computed from any two of the three vector measurements. From the ROSAT experience (Kaffer et al.), it has been learned that the magnetometer can provide excellent attitude measurement accuracy. Three-axis GPS attitude is available when the S/C is earth pointing. From these many measurement sources, it can be seen that there is considerable redundancy and flexibility in the attitude determination.

The situation is somewhat different for the safe-emergency mode where only sun-sensor measurements are available, and the rate derivation is not trivial. The derivation of the rate, $\boldsymbol{\omega}_c$, perpendicular to the sun direction is obtained by differentiation of the unit-vector sun-sensor measurement, $\mathbf{s}$:

$$\boldsymbol{\omega}_c = \dot{\mathbf{s}} \times \mathbf{s} \tag{1}$$

The scalar component of the angular velocity parallel to the sun vector, c, can be calculated from

$$\boldsymbol{\omega} = \boldsymbol{\omega}_c + c\mathbf{s} \tag{2}$$

and

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega} + \mathbf{h}) = \mathbf{T} \tag{3}$$

where $\boldsymbol{\omega}$ is the spacecraft angular rate, $\mathbf{I}$ the moment-of-inertia tensor, $\mathbf{h}$ is the wheel angular momentum and $\mathbf{T}$ the thruster torque vector. A second degree vector equation can be derived for c by computing the derivative of $\boldsymbol{\omega}_c$ which is possible due to the practically noiseless sun sensor.

$$\mathbf{s} \times \mathbf{d}_2\, c^2 + \mathbf{s} \times (\dot{\mathbf{s}} + \mathbf{d}_1)\, c = \mathbf{s} \times (\mathbf{I}^{-1}\,\mathbf{T} - \mathbf{d}_0 - \dot{\boldsymbol{\omega}}_c) \tag{4}$$

where $\mathbf{d}_0$, $\mathbf{d}_1$, and $\mathbf{d}_2$ are vectors which arise when equation (2) is substituted into equation (3). The solution of equation (4) for the sun component of the rate, c, is the key to safe-emergency mode sun acquisition with only sun-sensor information. It is important to note that the final depointing of the -z-axis is required to maintain the observability of c.

6. FAILURE DETECTION, ISOLATION AND RECOVERY (FDIR)

The AOCS is designed to automatically detect and recover from a specified list of failures. All FDIR functions can be configured by ground command initially.

Failure detection is on three levels: the equipment level, by consistency check, and by limit check. On the equipment level the magnetometer is checked by the earth's magnetic field strength, the wheels by the wheel model in the control loop, the SADA by the position sensors, and the GPS receiver by its internal health status. There are consistency checks for the sun sensors and the earth sensors. These checks consist of comparing the primary and redundant sun sensors, comparing the three earth vectors computed from two of the IR sensors, and comparing the computed sun, earth, and magnetic field vectors with the measured ones. The consistency checks are the most powerful means for failure detection. The limit checks involve timeout and performance-error checks.

Failure isolation is automatic for failure detection at the equipment level. In the case of a failure in the consistency checks, comparing the calculated vectors with the measured ones will usually isolate the failures. There are some failures, however, especially from the limit checks, which cannot be isolated.

Recovery is achieved by switching sensors or actuators in the event of an isolated equipment failure. In the event of an

OBPE problem, the computer can either do a warm start or a cold start. A warm start is usually triggered by an OBPE interrupt or by the watchdog signal. It requires about one second, and an attempt is made to continue in the last running mode by the reestablishment of the AOCS tables. If a cold start is made, the OBPE is switched off and the same or the redundant OBPE is switched on. In either start up condition, critical parameters are retained in an independent memory area of the main processor, and an attempt is made to reenter the last active mode. If this memory is not available the safe-emergency mode is always entered.

The OBPE also monitors earth presence, sun presence, and thruster activity independently of the main processor. In case of anomalous data, equipment switching is triggered automatically.

Each mode is recovered in a different manner; but in general, the modes with more complex logic and equipment sets will switch to simpler, safer modes if problems are detected. For example, if time and orbit information are not available, every mode switches to the safe-emergency mode. The safe-emergency mode recovery is done with a switch of the OBPE. If the transition time is exceeded, the sun-acquisition mode switches to the safe-emergency mode. If at least three wheels are not available or if the transition time is exceeded, the earth-acquisition mode switches to the sun-acquisition mode. If the errors are too large, the orbit-correction mode switches to the earth-acquisition mode. The normal mode switches to the earth-acquisition mode if at least three wheels are not available or if the errors are too large. These mode switches continue until performance is achieved or all the way to safe sun acquisition if required.

7. CONCLUSION

The digital Attitude and Orbit Control System for the Globalstar satellites is a simple inexpensive robust system with a 7.5-year lifetime. It does not use gyros, and in the normal mode the only external-torque actuators are the magnetic torque rods which are used to unload the momentum wheels. In addition, it has a variety of self monitoring features to maintain satellite safety.

With more attitude data from GPS tests, future generations of the Globalstar AOCS could eliminate some of the sensing equipment. In principle with eight antennas the GPS attitude receiver could replace all of the AOCS sensors, but safety and redundancy probably require that the magnetometer and the sun sensors be retained.

Because of the large number of satellites, a very large number of AOCS components will be purchased. This has resulted in an intense competition among the suppliers with the consequence that the price of some components has been drastically reduced and entirely new components such as the EDO-Barnes analog earth and sun sensors have been developed.

8. REFERENCES

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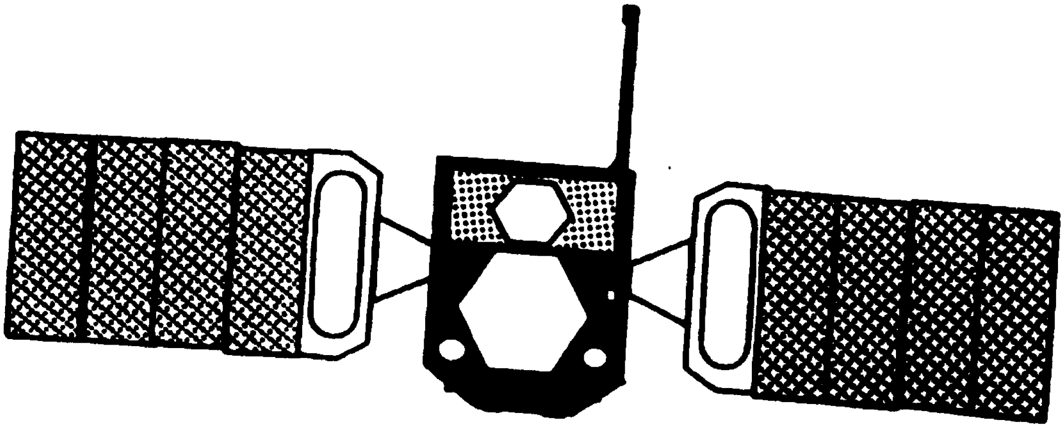

Figure 1: The Globalstar satellite showing the earth face and the four antennas. The magnetometer boom can be seen at the top, and four solar-array panels are on each side

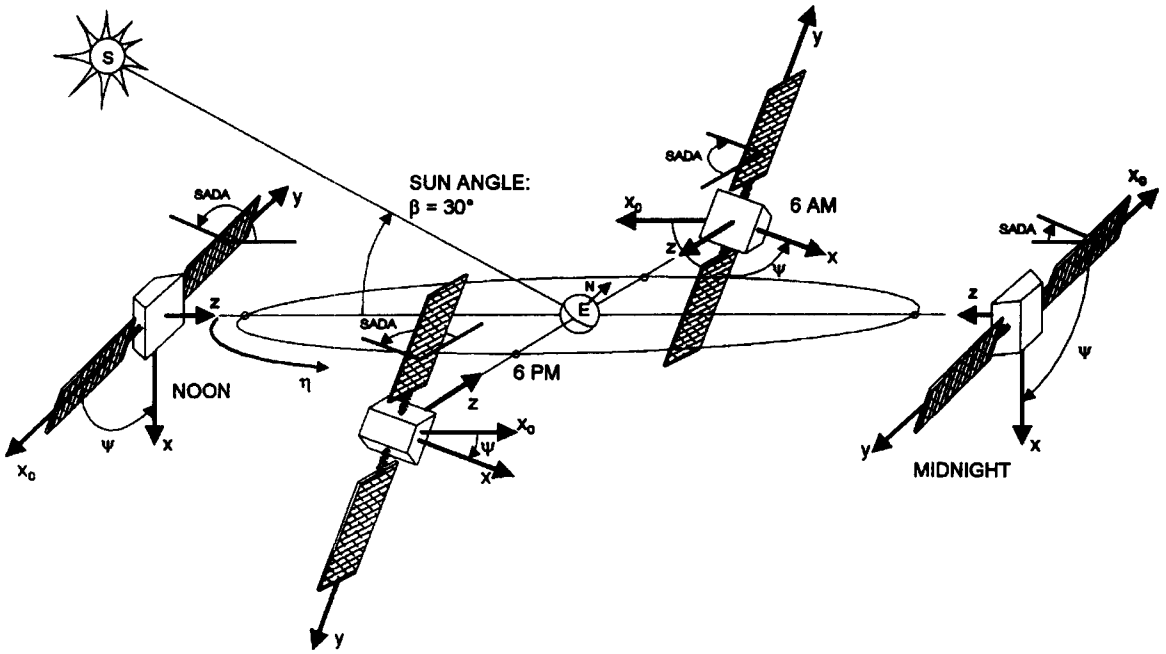

Figure 2: Yaw Steering at Four Places in Orbit

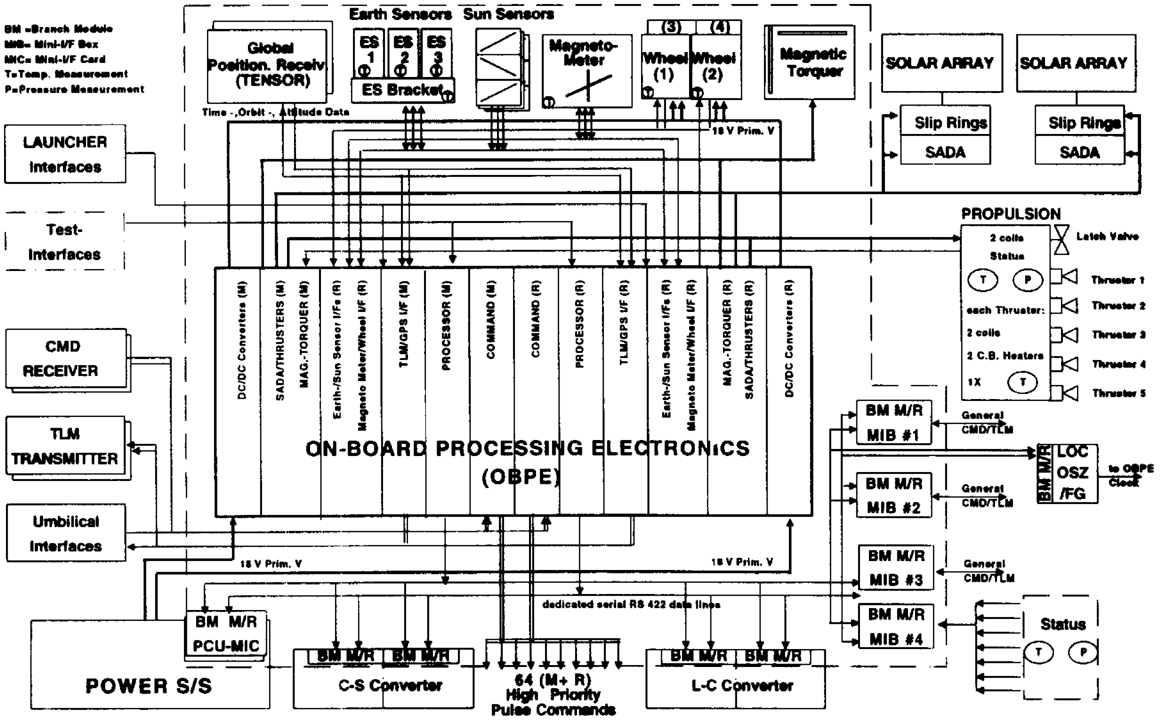

Figure 3: Overall AOCS Blockdiagram