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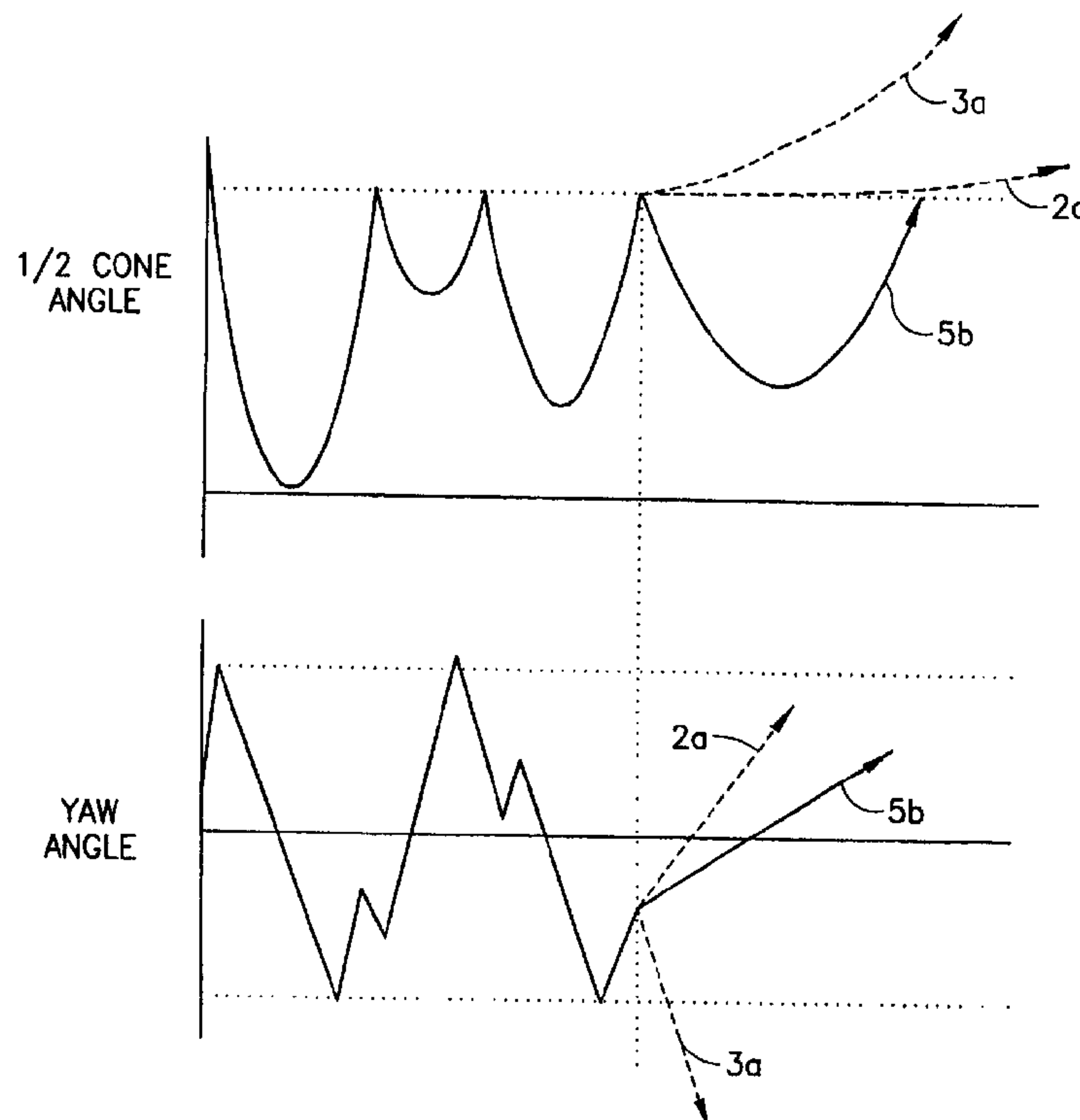
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(54) Titre : CONTROLE AU SOL DE L'ORBITE ET DE L'ATTITUDE D'UN VAISSEAU SPATIAL AU MOYEN D'UN CIRCUIT LOGIQUE DE SELECTION DE PROPULSEURS A ANTICIPATION ET DE GENERATEURS DE COUPLES MAGNETIQUES

(54) Title: EARTH BASED SPACECRAFT ORBIT AND ATTITUDE CONTROL USING A LOOK-AHEAD THRUSTER SELECTION LOGIC AND MAGNETIC TORQUERS



(57) Abrégé/Abstract:

A spacecraft ground loop controller (GLC), located on the Earth, interfaces with a satellite ground station receiving spacecraft telemetry from the downlink baseband equipment and automatically sending spacecraft commands through the command uplink baseband equipment to control the attitude of an orbiting spacecraft and achieve partial orbit control using commanded thruster firings and magnetic torquer polarity and magnitude. A cooperative approach of using all available thrusters, of both the primary and redundant strings, provides greater fuel savings.



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EARTH BASED SPACECRAFT ORBIT AND ATTITUDE CONTROL
USING A LOOK-AHEAD THRUSTER SELECTION LOGIC
AND MAGNETIC TORQUERS

ABSTRACT OF THE DISCLOSURE

A spacecraft ground loop controller (GLC), located on the Earth, interfaces with a satellite ground station receiving spacecraft telemetry from the downlink baseband equipment and automatically sending spacecraft commands through the command uplink baseband equipment to control the attitude of an orbiting spacecraft and achieve partial orbit control using commanded thruster firings and magnetic torquer polarity and magnitude. A cooperative approach of using all available thrusters, of both the primary and redundant strings, provides greater fuel savings.

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EARTH BASED SPACECRAFT ORBIT AND ATTITUDE CONTROL
USING A LOOK-AHEAD THRUSTER SELECTION LOGIC
AND MAGNETIC TORQUERS

BACKGROUND OF THE INVENTION

Field of the Invention:

The present invention relates to Earth satellite control systems and more particularly to a ground-based control system which interfaces with the satellite's ground station to automatically continue attitude control of a spacecraft in the event of momentum wheel failure.

Prior Art Problem to be Solved:

Various systems are known for the control of Earth-orbiting spacecraft or satellites involving the use of hardware and software for executing complex control algorithms that utilize on-board attitude control equipment such as momentum wheels, gyros, magnetic torquers, and strings of thrusters to maintain and alter the satellite's orientation and orbit. One example of system of this type is the ground loop automatic control system (GLACS) of Telestar of Canada. Pertinent features of this system are set forth in the attached pages identified at the lower left corner as 9 - 12.

However, problems are posed with such systems when there are failures in the proper operation of an on-board control device. In such event, the equipment and algorithms must be quickly adjusted to deal with the changed situation and maintain the satellite in its desired attitude and orbit. As the on-board control equipment and fuel are self-contained, the required adjustments should be efficient in execution.

Objects:

It is accordingly an object of the present invention to

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provide a system that allows the continued attitude control and simultaneous partial orbit control of a spacecraft in the event of momentum wheel failure with the novel and efficient use of thrusters, magnetic torquers and on-board gyroscopes.

SUMMARY OF THE INVENTION

The present invention involves a spacecraft controller system that is physically located on the Earth and interfaces with the satellite ground station receiving spacecraft telemetry from the downlink baseband equipment. This controller system automatically sends spacecraft commands through the command uplink baseband equipment using a ground loop control (GLC) which controls the attitude of an orbiting spacecraft, and achieves partial orbit control, using commanded thruster firings. It allows the continued attitude control of a spacecraft in the event of momentum wheel failure with the novel and efficient use of thrusters, magnetic torquers and on-board gyroscopes. A cooperative approach of using all available thrusters, of both the primary and redundant strings, provides greater fuel savings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a plot of the satellite's 1/2 cone angle.
Figure 2 is a plot of the satellite's yaw angle.
Figure 3 illustrates a set of earth-centered orbits with thruster vectors and the Sun orientation to the right.
Figure 4 is an illustrative plot of Elevation (deg) versus Azimuth (deg) for a non-circular pointing region.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

An automatic control system in accordance with the invention is composed of an Earth-based computer, including satellite control software, that interfaces with the satellite ground station receiving spacecraft telemetry

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from the downlink baseband equipment. The software includes estimators, controller algorithms, redundancy management routines, and communication routines. The estimators take sensor data as extracted from the telemetry frames and provide output estimates of the spacecraft attitude and rates (including yaw angle, for which no direct measurement is available). They also take data from the thruster torque table and provide thruster torque estimates. The yaw is determined using a gyrocompassing filter (kinetic or dynamic) driven by continuously running gyros. The controller algorithm takes the various estimates and produces thruster firing commands to maintain the spacecraft attitude within a defined pointing region. Other actuation devices, such as magnetic torquers, may also be used in the process, in which event, commands are also sent to control these other actuation devices.

Appropriate control torques are provided by thrusters, and magnetic torquers if available. If the momentum wheels are turned off, one wheel tachometer is reset such that the wheel speed measurement is zero. The other wheel tachometer is not reset, and reads the tachometer underspeed limit. The difference between the two measured wheel speeds allows the magnetic torquers to provide current output (control torque) with the polarity and magnitude being set by user command. Roll thruster torques are provided by manual thruster pulse commands available only in 10 ms quanta of pulse widths. Pitch/yaw thruster torques are provided by differentially setting commanded speed for each wheel, such that cycling through on-orbit wheel control mode will immediately effect a momentum unload pulse. The unload pulse is set by user command and can be less than 10 ms.

To achieve minimum fuel use, the standard roll, pitch, and yaw independent axis control is discarded. The attitude is controlled to a pointing polyhedron parameterized using the

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region's origin offset (with respect to the nominal antenna boresight), along with a series of (radius, polar angle) pairs. The region defines the -3dB coverage for the antenna beam pattern, and thus relates directly to communications performance. The definition of the pointing region includes as a subset the more traditional half-cone angle region, where the origin offset is zero and the radius is constant for all polar angles.

The spacecraft is set up in an automatic on-board thruster control mode which acts as a safety mode if commanding from the GLC should be interrupted. Sensor bias commands are sent periodically to the spacecraft to center the on-board mode deadband to the current attitude. These bias commands also serve as a GLC "heartbeat" that can be detected at the backup site and the absence of which indicates a problem at the primary site.

Thrusters are fired singly or in pairs, as determined by the thruster selection algorithm. This algorithm propagates the dynamic model of the spacecraft attitude forward in time to find the thruster or thruster pair that results in the least fuel use rate before the spacecraft reaches the edge of the attitude pointing region, with the total thruster fuel use being weighted using the estimated time until next firing.

An orbit model, propagating from the last Orbit Determination result, determines the current orbit resulting from the commanded thruster activity. Since there will be a relatively large number of thruster firings each day, there will be sufficient thruster activity to allow East-West stationkeeping (EWSK), of both eccentricity vector and radial component control, on a continuous basis. That is, the thruster selection algorithm is biased to the selection of the appropriate thruster to accomplish both attitude control and an EW orbital correction in the

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desired direction. In this way, the need for separate EWSK maneuvers will be greatly reduced or completely disappear, saving overall fuel use. North-South Stationkeeping (NSSK) requires more thruster activity than the GLC will provide, but can still be helped by biasing the thruster selection algorithm in the desired North/South direction depending on the orbit inclination.

The GLC system of the invention may be made up of two fault tolerant computers which independently run the satellite control software. One of the computers is designated primary, and as such is authorized to send spacecraft attitude control commands. The secondary computer acts as a hot backup, running the satellite control software in parallel with the primary computer, but not actually sending commands. If the primary computer fails for any reason, logic in the secondary computer, or in an independent monitor unit, will transfer commanding authority immediately and automatically to the secondary computer.

The primary computer constantly sends commands to the spacecraft. Even if it is not required to send attitude control commands, the primary computer will send the periodic heartbeat commands which can be detected in telemetry and will imply the state of health of the command link. The backup computer can detect the heartbeat commands, and can infer failure of the primary computer if the heartbeat command disappears. Each computer also monitors an active status line in the other computer to detect computer failure.

The GLC system of the invention may be situated between the system operator computer and the baseband command transmitter so as to intercept all operator generated spacecraft commands. If the GLC controller is sending a command sequence, it will delay any non time-critical

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operator generated command for the duration of that sequence. The GLC computers communicate with the operator computers to receive parameter updates and send logger, warning, or alarm messages.

The GLC computers control switches in the baseband telemetry and command strings to switch to backup baseband equipment strings if a failure is detected in any baseband equipment unit. In this way, even though individual system components can fail, system redundancy is achieved and the GLC has a very high system availability.

If a backup ground station is available, a backup GLC unit can be located there and can monitor the primary site using a combination of the telemetered command carrier receiver signal strength and the telemetered command execute history of the heartbeat commands.

Attached are lists of items regarding features of the invention relating to and entitled CONTROL LAW, FUEL OPTIMAL THRUSTER SELECTION, YAW ESTIMATOR, ORBIT ESTIMATION AND CONTROL, and EAST/WEST ΔV SCHEDULE. These items illustrate the following features of the invention.

CONTROL LAW:

There are two methods of choosing thruster commands, i.e., fuel optimal and backup. The fuel optimal approach involves the steps of generating a list of feasible single/double fire commands and choosing the best command based on fuel efficiency and meeting the ΔV schedule generated by orbit control. A non-circular pointing region can be used. An illustrative plot of Elevation (deg) versus Azimuth (deg) for a non-circular pointing region is shown in Figure 4. The backup approach is only used if there is no fuel optimal solution and involves generating a list of single/double/triple fire commands based on rate/attitude switching curves, and choosing the command closest to meeting the ΔV schedule. And, Bang-Bang roll

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and yaw magnetic torquer commands are based on the rate/attitude switching curve.

FUEL OPTIMAL THRUSTER SELECTION:

A list of feasible thruster commands are generated, i.e., the 1/2 cone angle and yaw attitude is brought in bounds. Solutions are ranked by ratio of time in bounds and fuel use. The solution that best meets the ΔV schedule from orbit control is chosen. Illustrative 1/2 cone angle and yaw angle plots are shown in Figures 1 and 2.

YAW ESTIMATOR:

Yaw estimation is required in the absence of a yaw sensor. A ground based gyrocompassing yaw estimator may be used. The yaw attitude determination algorithm involves a 4th order Kalman filter using DSS, roll ES, and roll/yaw DIRA, and a 4th order Kalman filter ususing roll ES and roll/yaw DIRA. Transitions between the two filters are determined depending on Sun presence.

ORBIT ESTIMATION AND CONTROL:

An internal orbit model based on the last orbit determination and thruster commands issued by the control law is propogated. Using the daily averages of the internal orbit state, it is assessed as to how ΔV should be directed for the next day. Desired ΔV accumulations are scheduled for the control law to meet. Orbit control can be set to orbit neutral if no ΔV accumulation is desired.

EAST/WEST ΔV SCHEDULE:

Figure 3 illustrates a set of earth-centered orbits along with thruster vectors and the Sun orientation to the right. The thruster vectors are used to correct the satellite's eccentricity with respect to the Sun as shown.

It will be seen from the foregoing description that a ground loop automatic contol system is disclosed that provides an efficient and novel thruster selection and control logic and simultaneous east-west orbit and spacecraft attitude control. Additionally, yaw estimates are obtained more simply and more accurately.

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CLAIMS

What is claimed is:

1. An Earth-based spacecraft ground loop controller (GLC) for controlling an Earth-orbiting satellite's on-board attitude control equipment, including momentum wheels, momentum wheel tachometers, gyros, magnetic torquers, and thrusters, in combination with a satellite ground station receiving spacecraft sensor data telemetry signals from the downlink baseband equipment and sending spacecraft commands through the command uplink baseband equipment, to maintain and alter the satellite's orientation and orbit, comprising:

means for interfacing with said satellite ground station to receive spacecraft telemetry data from the downlink baseband equipment and to send spacecraft commands through the command uplink baseband equipment; and

means, coupled to said interfacing means and responsive to telemetry data from an orbiting spacecraft indicating momentum wheel failure, for automatically sending spacecraft commands through the command uplink baseband equipment to control the attitude of said orbiting spacecraft and achieve partial orbit control using commanded thruster firings and magnetic torquer polarity and magnitude.

2. A controller as in claim 1 wherein said means for automatically sending spacecraft commands comprises:

a computer running satellite control software, and wherein said software comprises:

means for providing estimators;

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means for providing controller algorithms;

means for providing redundancy management routines; and

means for providing communication routines.

3. A controller as in claim 2 wherein said estimators comprise:

means for extracting sensor data from the telemetry data; and

means for using said sensor data to provide output estimates of the spacecraft attitude and rates and yaw angle.

4. A controller as in claim 1 further comprising:

means, in said spacecraft responsive to said commands when the momentum wheels are turned off, for resetting a first wheel tachometer such that the wheel speed measurement is zero;

means, in said spacecraft responsive to said commands, for using a second wheel tachometer to read the tachometer underspeed limit measurement; and

means, in said spacecraft, for using the difference between the first and second tachometer measurements to cause the magnetic torquers to provide current output to control torque and for setting the polarity and magnitude in response to said commands.

5. A controller as in claim 1 further comprising:

means, in said spacecraft responsive to said commands,

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for providing roll thruster torques by manual thruster pulse commands in 10 ms quanta of pulse widths.

6. A controller as in claim 1 further comprising:

means, in said spacecraft responsive to said commands, for providing pitch/yaw thruster torques by differentially setting a commanded speed for each wheel, such that cycling through on-orbit wheel control mode will immediately effect a momentum unload pulse; and

means, in said spacecraft responsive to said commands, for setting the momentum unload pulse.

7. A controller as in claim 6 further comprising:

means for setting the momentum unload pulse by user command.

8. A controller as in claim 1 further comprising:

means for discarding the standard roll, pitch, and yaw independent axis control; and

means for selecting thruster firing by propagating the spacecraft attitude forward in time for each candidate thruster to be fired, whereby fuel use is minimized or pointing performance is improved.

9. A controller as in claim 1 further comprising:

means for setting the current of a magnetic torquer of the spacecraft to select the commanded magnetic torquer polarity and magnitude; and

means for determining the magnetic torquer command

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selection as a function of the estimated attitude of the spacecraft.

10. A method for controlling an Earth-orbiting satellite's on-board attitude control equipment, including momentum wheels, momentum wheel tachometers, gyros, magnetic torquers, and thrusters, in combination with a satellite ground station receiving spacecraft sensor data telemetry signals from the downlink baseband equipment and sending spacecraft commands through the command uplink baseband equipment, to maintain and alter the satellite's orientation and orbit, comprising the steps of:

interfacing with said satellite ground station to receive spacecraft-momentum-indicative telemetry data from the downlink baseband equipment and to send spacecraft commands through the command uplink baseband equipment; and

in response to receiving spacecraft-momentum-indicative telemetry data from an orbiting spacecraft indicating momentum wheel failure, automatically sending spacecraft commands through the command uplink baseband equipment to control the attitude of said orbiting spacecraft and achieve partial orbit control using commanded thruster firings and magnetic torquer polarity and magnitude.

11. The method as in claim 10 wherein said step of automatically sending spacecraft commands comprises:

providing a computer running satellite control software, and providing said software with estimators, controller algorithms, redundancy management routines, and communication routines.

12. The method as in claim 11 wherein said estimators

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operate to take sensor data, as extracted from the telemetry data, and provide output estimates of the spacecraft attitude and rates and yaw angle.

13. The method as in claim 12 wherein said estimators' step of providing yaw angle output estimates comprises:

taking data, as extracted from the telemetry data, and applying a gyrocompassing filter thereto driven by continuously running gyros.

14. The method as in claim 12 wherein said estimators further operate to take data from the thruster torque table and provide thruster torque estimates.

15. The method as in claim 14 wherein said step of providing controller algorithms comprises:

taking said estimates of the spacecraft attitude and rates and yaw angle and thruster torque and producing thruster firing commands to maintain the spacecraft attitude within a defined pointing region.

16. The method as in claim 15 wherein said step of providing controller algorithms further comprises:

taking said estimates of the spacecraft attitude and rates and yaw angle and thruster torque and producing torquer commands to actuate and control said magnetic torquers to maintain the spacecraft attitude within a defined pointing region.

17. The method as in claim 10 further comprising the step of:

selecting thruster firings by propagating the dynamic

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model of the spacecraft attitude forward in time for each candidate thruster that may be fired to determine which thruster firing or combination of thruster firings provides minimum fuel use for a predetermined pointing performance.

18. The method as in claim 10 wherein said commanded thruster firings comprise the step of:

selecting said thruster firings by propagating the spacecraft attitude forward in time for each candidate thruster to be fired, whereby fuel use is minimized or pointing performance is improved.

19. The method as in claim 10 wherein said commanded magnetic torquer polarity and magnitude are selected by setting the current of a magnetic torquer of the spacecraft, and further comprising the step of:

determining the magnetic torquer command selection as a function of the estimated attitude of the spacecraft.

20. The method as in claim 10 further comprising providing a measure of the attitude pointing performance by the steps of:

fixing a convex pattern on the ground to define a pointing region;

projecting a vector fixed in the spacecraft body coordinates to the ground; and

determining if said vector intersects the ground within the interior of said convex pattern defining the pointing region.

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21. The method as in claim 10 further comprising, when the momentum wheels are turned off, the steps of:

resetting one wheel tachometer such that the wheel speed measurement is zero;

using the other wheel tachometer to read the tachometer underspeed limit;

using the difference between the two measured wheel speeds to cause the magnetic torquers to provide current output (control torque) while setting the polarity and magnitude by user command;

providing roll thruster torques by manual thruster pulse commands in 10 ms quanta of pulse widths;

providing pitch/yaw thruster torques by differentially setting a commanded speed for each wheel, such that cycling through on-orbit wheel control mode will immediately effect a momentum unload pulse; and

setting the momentum unload pulse by user command.

22. The method as in claim 10 comprising the further step of discarding the standard roll, pitch, and yaw independent axis control to achieve minimum fuel use.

FIG.1

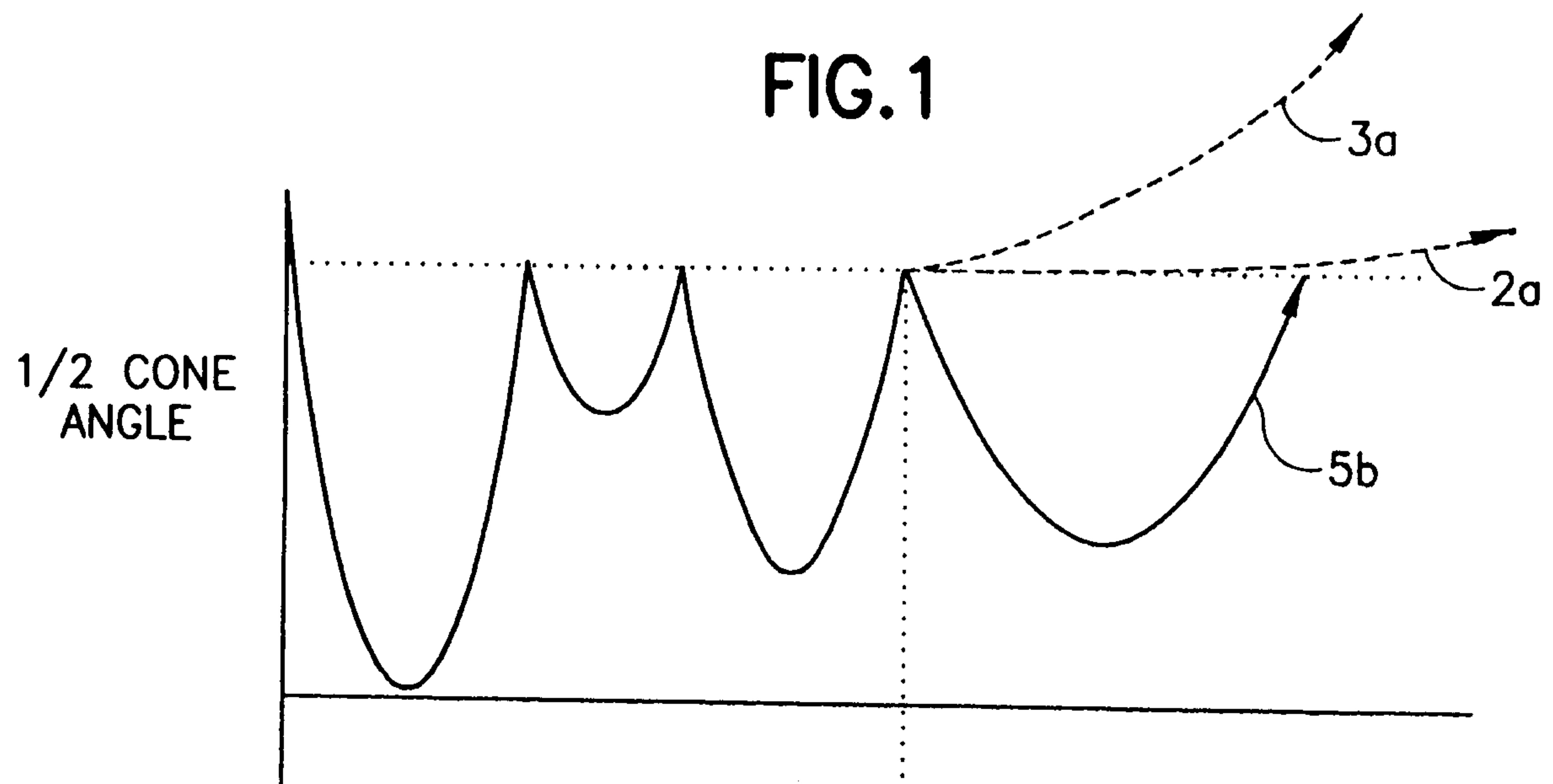
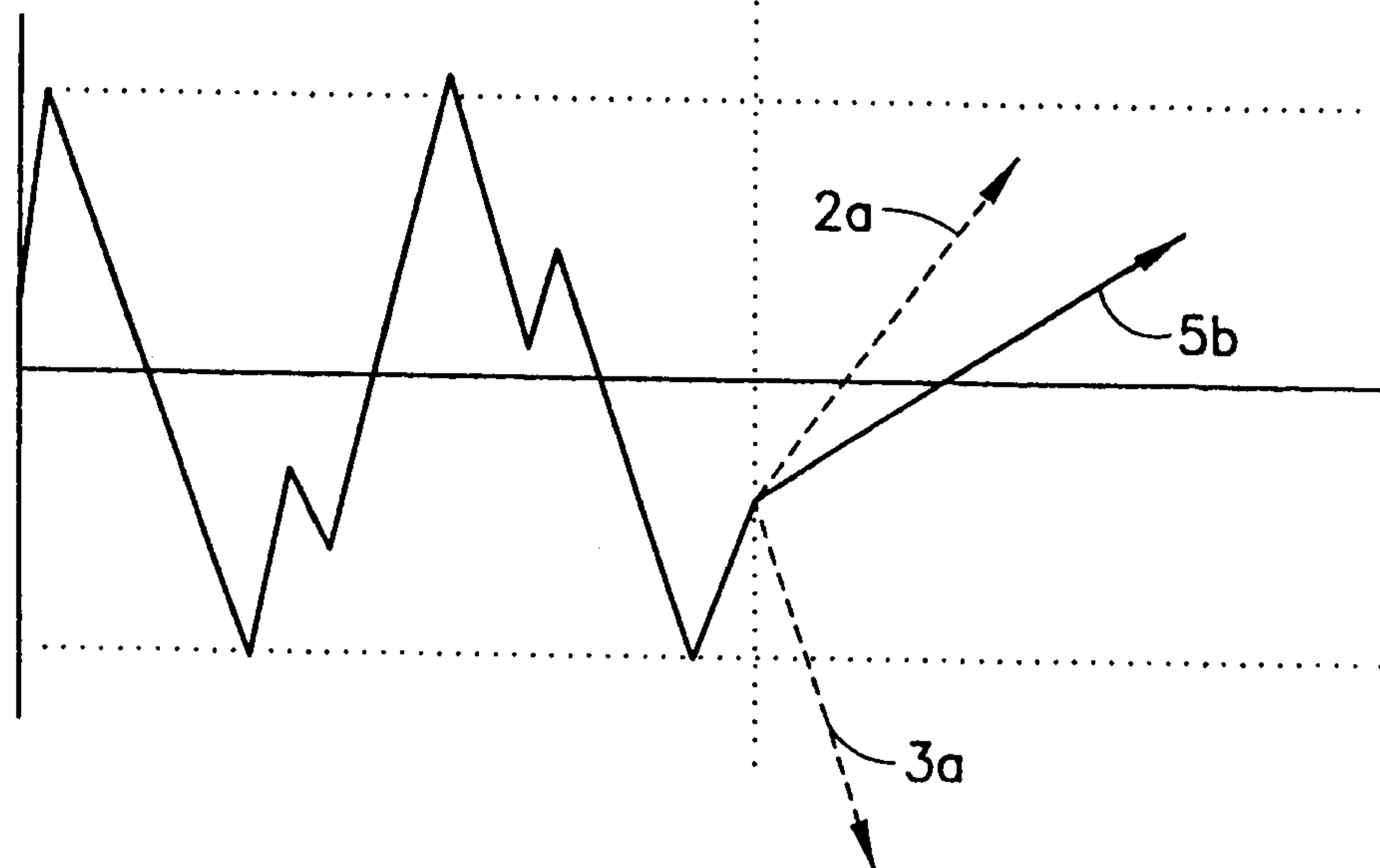
YAW
ANGLE

FIG.2

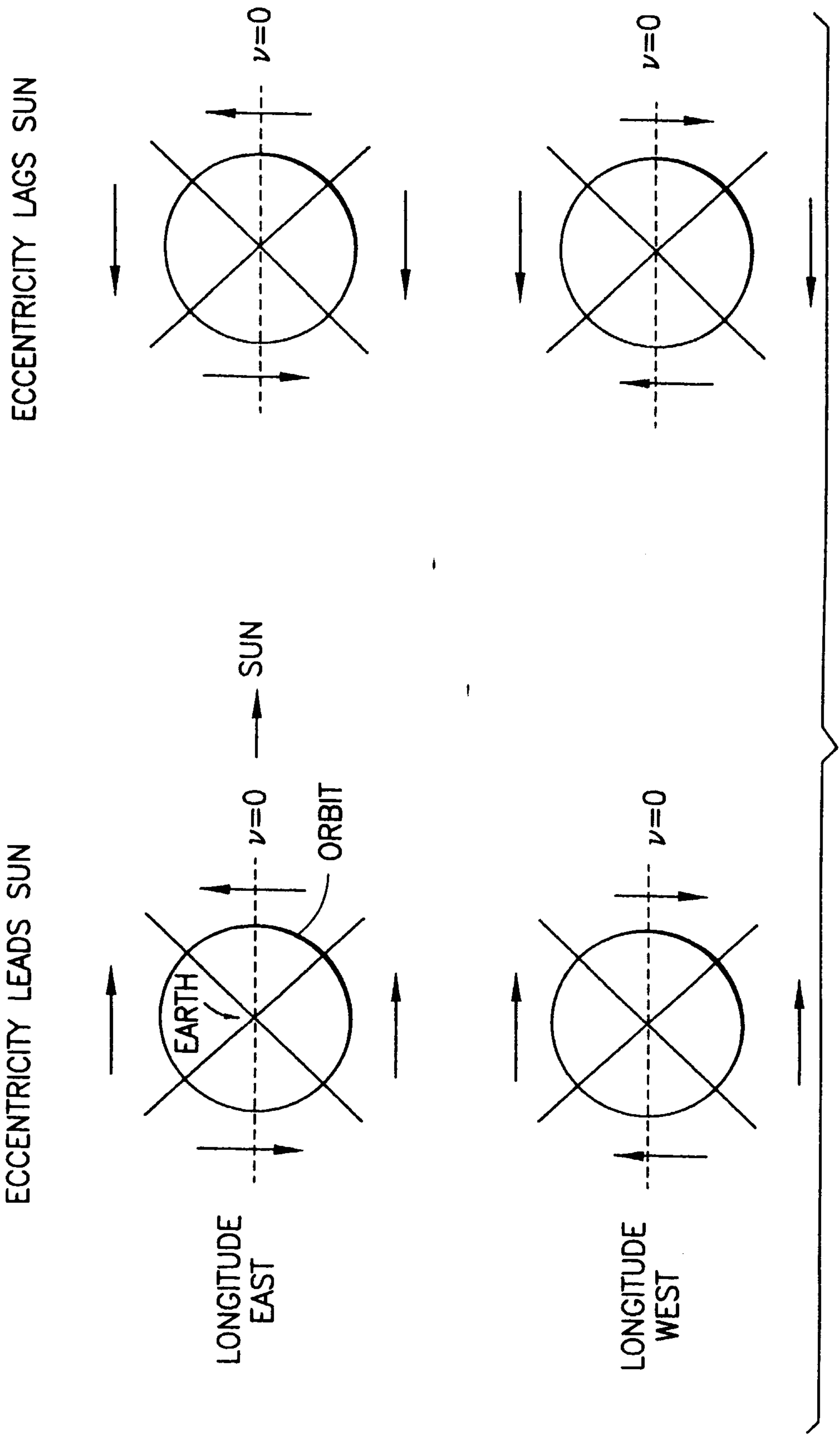


FIG.3

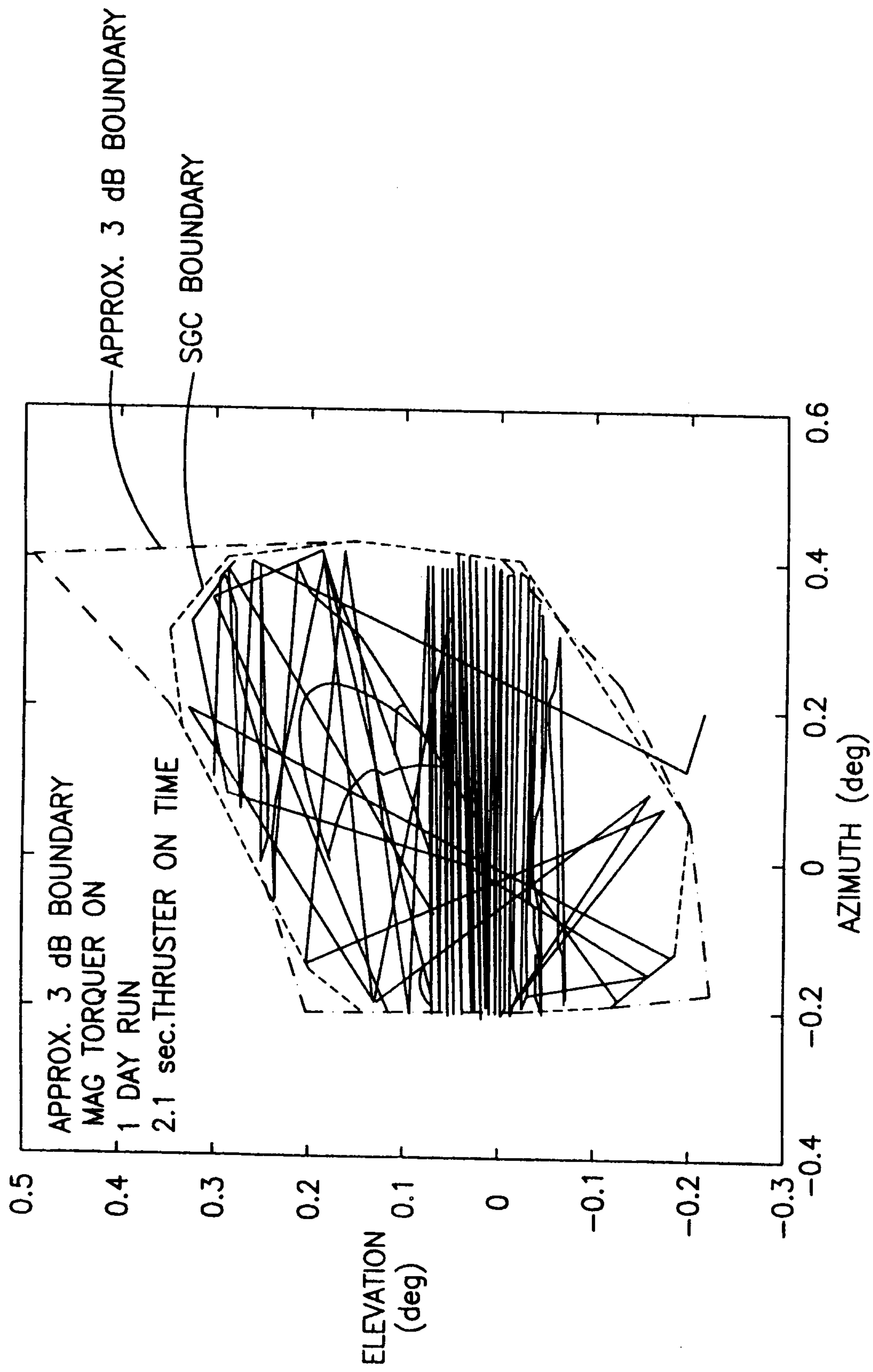
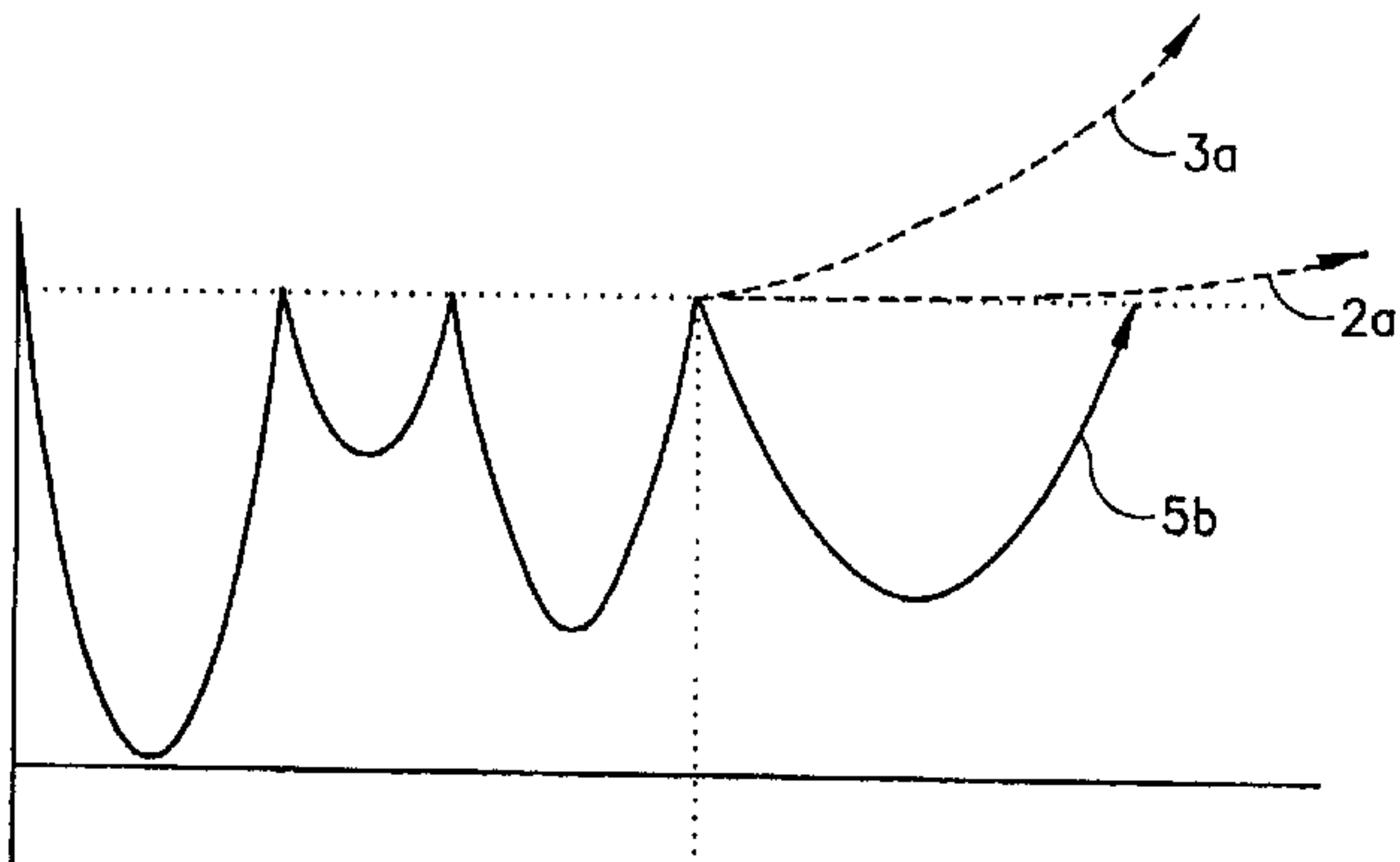


FIG. 4

1/2 CONE
ANGLE



YAW
ANGLE

