THE DEVELOPMENT OF AN ATTITUDE SENSING SYSTEM FOR SMALL SATELLITES

Wedad A. Abdou and Sawat Tantiphanwadi

Globesat, Inc.
Logan, Utah

ABSTRACT

This paper describes the attitude sensing system developed by Globesat, Inc. for its gravity-gradient-stabilized satellites. Compactness, low cost, low power , and high performance were the main considerations of the system design. The sensor is based on a commercial CCD video camera for imaging the sun and the horizon. The images are digitized by a frame grabber and then processed for attitude computation. The system has a field of view of 90° X 360° and can determine attitude to 1° or better. Using the sun and nadir vectors as references, the orientation of the satellite with respect to the Earth is completely determined. The method used for the attitude calculations is outlined in this paper.

INTRODUCTION

Sensors which are currently used for spacecraft attitude determination have been developed mostly during the past two decades (Hatcher [1967], Fontana, et al., [1974], and Schmidtbaure, et al., [1973]). An informative summary on these sensors is included in a book edited by Wertz, [1985]. Of the various types of sensors which were designed originally for large spacecraft, sun and horizon sensors are the most widely used and are usually the most suitable for small satellite systems. The main reason for this is that the sun and the horizon are the brightest objects observed by near-earth satellites. This considerably simplifies the design of the system and reduces its power requirements which, consequently, results in a compact and inexpensive sensor.

Generally, most sensors consist of four basic units: the first scans the target, the second collects a signal from that target, the third detects the signal, and the fourth processes the signal and determines the orientation of the satellite. The scanning unit often incorporates mechanically moving parts. This adds to the complexity of the system and, therefore, should be avoided, if possible, in designing a sensor for a small satellite.

The unit for collecting the signal is often a lens system which focuses the signal on the detector. The cost and weight of this unit increases considerably with the resolution and accuracy of the sensor.

The detectors which are utilized with attitude systems are generally either optical or thermal in nature. Most of the developed sun sensors use a photocell (Analog sensors), or an array of photocells (Digital sensors). Infrared photodiode detectors, with high responsivity in the 15 µm spectral range, are often used with horizon sensors. In this spectral range the Earth has a nearly uniform intensity, while in the visible the large variation of the earth's albedo, from ~0.1 to ~ 0.80, and the rapid time fluctuation of its visual radiation result in a poorly defined horizon (Lyle, et al., [1971]).

Recently, solid-state charge-coupled device (CCD) technology has been transferred from the R&D environment to commercial production. The charge-coupled device is a semiconductor electronic structure which consists of tens or hundreds of thousands of photosensor elements. The light falling on each element creates an equivalent and unique electric charge packet which is stored at that element. Charge coupling, induced by voltage manipulation, is the collective transfer of these charge packets from each photosensor to the adjacent one. The resulting stream of electric charges is then delivered as a sequence of electrical pulses, the amplitude of each being directly proportional to the charge packet size generated in the corresponding photosite, and therefore, is also proportional to the intensity of the light falling on that photosite.

One of the significant advantages of the CCD image sensor is the precise knowledge of the photosensor locations with respect to one another. This is important in applications requiring data processing. Other important features of the CCD are its high quantum yield and the efficiency and high speed of its charge coupling process, which occurs without any significant loss of information. Various products of imaging systems equipped with CCD image sensors are now available in the market at reasonable prices. To date, these devices have not been fully utilized for the development of attitude sensors.

This paper describes an attitude system which utilizes a commercial CCD camera to sense the Sun and the horizon. The design of this system, and the method used to transform the output of the sensor into satellite attitude information, are outlined in the next following sections.

THE SYSTEM DESIGN

The main objective of the present design was to develop an attitude sensor, which utilizes a charge coupled device, with minimal cost and development time. Our design philosophy was, therefore, to use off-the-shelf, commercially available components, whenever possible.

The attitude system described in this paper consists basically of two units : A CCD imaging unit and an image processing unit. Figure 1 is a block diagram which illustrates the various components of these two basic units.

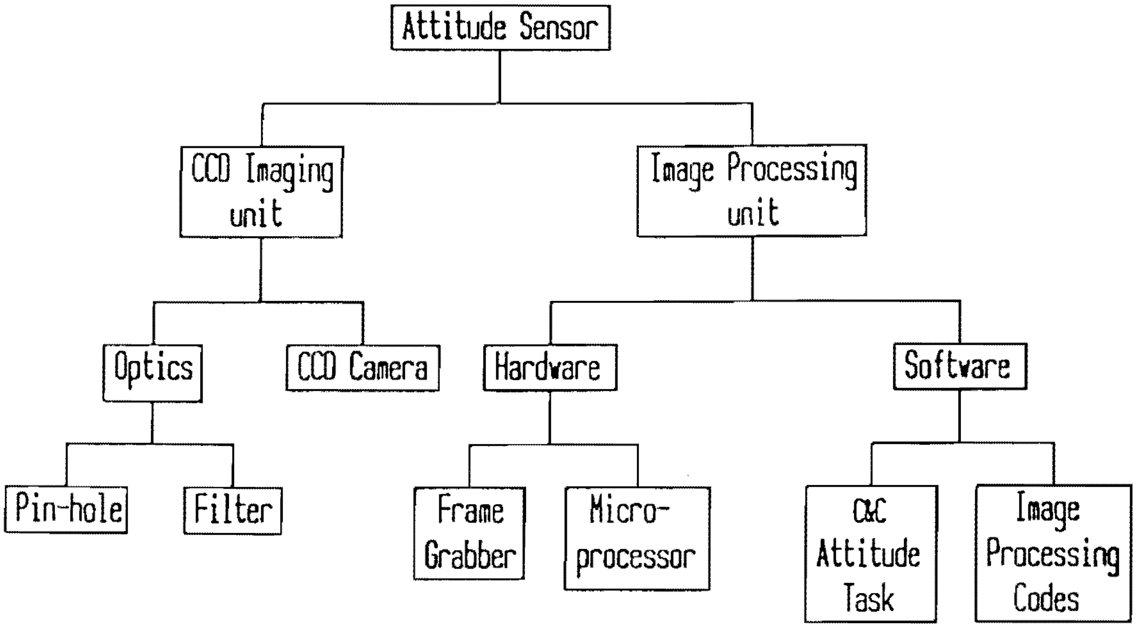

Figure 1. Attitude sensor block diagram

1. The CCD Imaging Unit

a. The Camera:

A commercial CCD, black and white, video camera was used for imaging the sun and/or the horizon. This camera, which was designed originally for industrial uses, is compact, rugged, and consumes low power. It is 13 cm X 4.4 cm X 2.9 cm in dimension and 240 gm. in weight. It withstands from 11 Hz to 200 Hz vibrations at 7G, and it has a shock resistance of up to 70 G. The camera operates at 12V DC and consumes 2.9 W. The sensor is a double-array CCD image sensor with 384 X 491 photosite elements, or pixels, each 23 μ X 13.4 μ in dimension. Since the camera was originally manufactured for industrial applications and not to fly in space some modifications were necessary. These were minor, however, and involved mainly the replacement of all electrolytic capacitors with suitable alternates.

b. The Optics:

The optical arrangement, to collect the light from the sun or the horizon, utilized simple pinhole optics. In visible light, a diffraction-limited pinhole has a minimum diameter of ~100 microns. In the present system, we use a pinhole with a diameter of 200 microns, laser drilled in the center of a stainless steel disk, 13 microns in thickness. The mount for the pinhole is designed from aluminum, etched to minimize any reflection, and designed to provide a 90^o X 90^o field of view. The use of the pinhole has considerably reduced the cost and weight of the system without compromising its accuracy.

Using a pinhole, rather than a lens, results in the spreading of the image around its edges due to the finite size of the pinhole. As will be seen later in this paper, the sun and the horizon images are of predetermined and simple geometrical shapes, and this spreading, which is related to the size of the pinhole, can be easily eliminated by the software during image processing. If a lens system were used instead, the software correction of aberrations would be more complicated.

The dynamic range of the CCD sensor is inadequate to accommodate both the solar and the Earth intensities, therefore, to avoid blooming in the sensor, a neutral-density filter has been used with the sensor when imaging the sun.

c. The Resolution and Field of View

The number of elements in the CCD currently being used, and the 90^o X 90^o field of view of the camera, permit a theoretical resolution of 0.2 to 0.3 of a degree for the attitude computation. In the future it will be possible to improve this resolution by using CCD sensors with more pixels. Although such devices are being developed at a fast rate, at the present time only linear devices with up to 3456 (7 µm X 7 µm) pixels, are, to our knowledge, available commercially.

One camera alone cannot completely determine satellite orientation. Therefore, a minimum of two cameras, one to sense the sun and the other to sense the Earth, are used for a complete attitude determination. A configuration of 4 cameras is sufficient to provide an attitude system with a 90° X 360° field of view. Figure 2. illustrates a Globesat GS100 satellite with 8 of these cameras configured around the satellite's 8 sides to provide, with redundancy, continuous 360° attitude coverage.

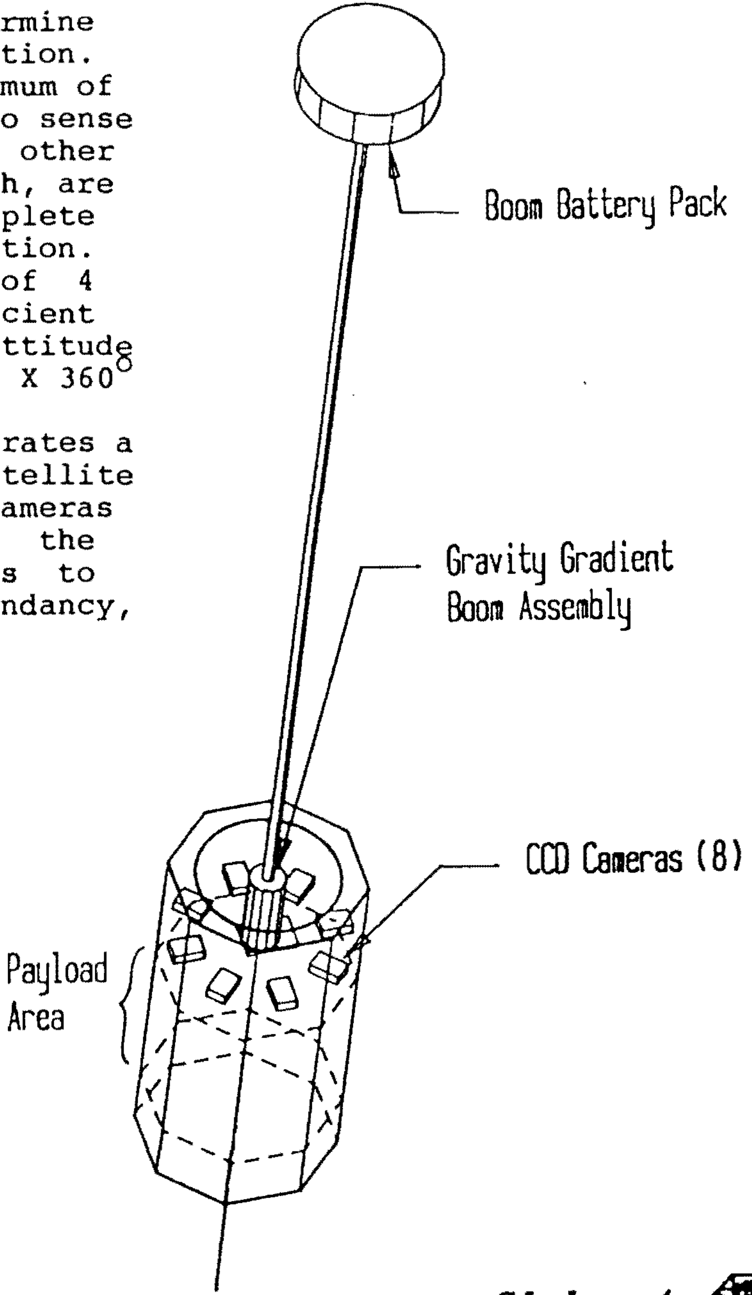

Figure 2.

GS-100

Globesat
Incorporated

2. The imaging processor unit

This unit has two main parts: the hardware part and the software part.

a. The Hardware:

This consists of two components: A frame grabber and a microprocessor. The frame "grabber" is a video digitizer board which obtains and digitizes a video signal from the camera in about 1/30 of a second. The board has 1024 X 1024 pixels X 8 bits of frame buffer, which provides switching between four video sources.

The microprocessor controls the operation and function of the frame grabber through read and write access to its internal registers. The grabbed frames, which contain the images of the sun and the horizon, are loaded into the microprocessor memory for processing and attitude computation.

b. The Software:

The software, which has been developed especially for this system, is divided into two main parts:

The first part, the attitude system task, is stored in the main command and control computer on-board the satellite. The attitude system task controls all the hardware and software functions of the system, and can be changed or modified from the ground.

The second part of the software is stored in ROM in the memory of the system's microprocessor. This part consists of four codes which perform the following functions :

1. Snapping a shot of the Sun or the horizon.
2. Processing the sun image, to locate its center, and calculating two angles of orientation for the sun vector in the satellite's coordinate system.
3. Processing the horizon image and calculating two angles of orientation for the nadir direction in the satellite's coordinate system.
4. Converting the above attitude information into three orientation angles for the satellite in the desired coordinate system.

There are two options for processing the images: on-board the satellite, or on the ground. The first option provides significant performance and cost saving. The second option is useful only at the beginning for checking the performance and accuracy of the system. The image-processing software was developed using the attitude geometry explained below.

METHODS OF ATTITUDE DETERMINATION

The attitude of the satellite is determined by calculating two orientation angles for each of the reference vectors, i.e., the sun and nadir vectors, in the sensor's coordinates. These (overdetermined) orientation angles, after being transformed into the satellite-fixed coordinates, are then transformed into three angles of rotation of the satellite in inertial, or any other, coordinate system. Since the present attitude system is designed for gravity-gradient or three-axis stabilized satellites, the coordinate system adopted by this work is the Roll-Pitch-Yaw (RPY) system. This is an orbit-defined system which maintains its orientation with respect to Earth, so that the yaw-axis is always parallel to the nadir direction and the pitch- axis is perpendicular to the plane of the orbit.

To transform the sensor's output into the desired attitude information, it is important to understand how the images of the sun and the horizon are formed by the sensor. This is a simple geometry problem which involves the satellite-sensor-sun and the satellite-sensor-Earth configuration.

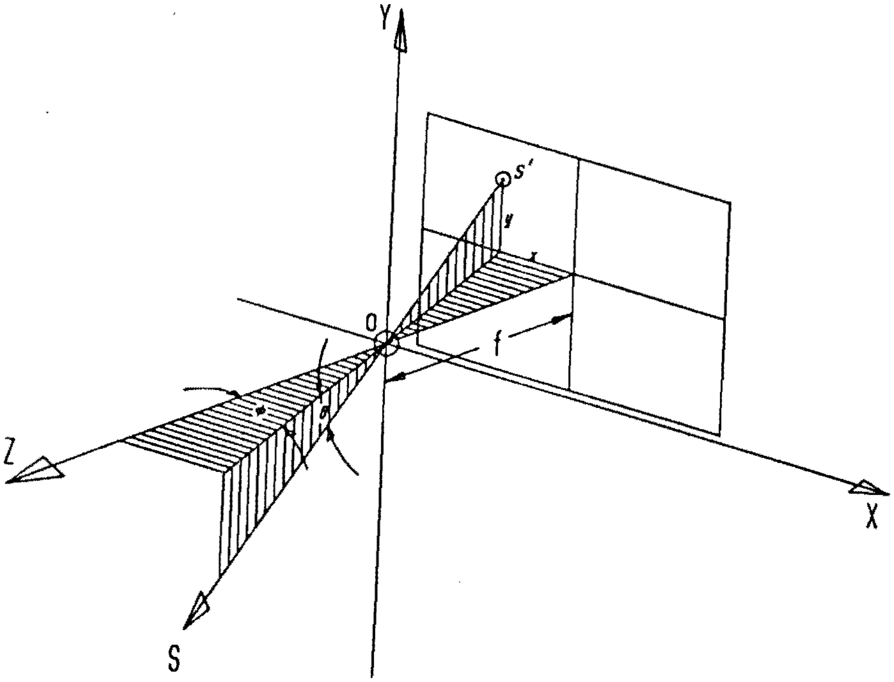

Figure 3. Geometry for sensing the sun.

Attitude Geometry for sun sensing:

Figure 3 illustrates the geometry for the sun sensing. X_s, Y_s, and Z_s with the pinhole at their origin, represent the sensor's coordinates. The optical axis, or boresight, of the sensor is along the Z_s-axis and perpendicular to its focal plane, X_s-Y_s. The pinhole is at a distance, f, from the focal plane. The sensor is mounted on the satellite so that, at perfect alignment, its three axes are parallel to the satellite's fixed coordinates. SO represents a ray coming from the sun's center through the pinhole, forming an image S' on the sensor's focal plane. From the coordinates, x_s and y_s, of S', the elevation and the azimuth angles of the sun vector, θ and ϕ respectively, are determined, where:

$$\theta = \mathrm{Tan}^{-1}\,(y_s/f) \tag{1}$$

$$\phi = \mathrm{Tan}^{-1}\,(x_s/f) \tag{2}$$

Assuming perfect alignment of the sensor with the satellite, these two angles are also the orientation of the sun vector in the satellite's fixed coordinates. At the same time, these two angles represent two rotations for the satellite with respect to the sun vector: ϕ about its Y_s-axis and, θ about its X_s-axis. The rotation about the Z_s-axis is not, however, determined by the sun sensor, and will be determined, with respect to the nadir direction, by the horizon sensor as explained below.

Attitude Geometry for Horizon Sensing:

The geometry used for the horizon sensing is illustrated in figures 4-a and 4-b. X_s, Y_s, and Z_s represent the sensor, or the satellite, coordinate system, and X, Y, and Z, in which, for convenience, the Y-axis is parallel to the nadir direction, represent the reference coordinate system.

For simplicity of illustration, it is assumed in figure 4 that the satellite is gravity-gradient stabilized, and therefore, the two sets of coordinates coincide with each other. ρ is the angular radius of the Earth at the satellite's altitude. At 500 km., ρ is $\sim 68^\circ$. As illustrated in figure 4-b, the light rays, reflected by the horizon in the direction of the pinhole, lie on the surface of a cone with half an angle equal to ρ. Part of this light, which is within the field of view of the sensor, falls on the focal plane to form the horizon image.

The horizon's image is, therefore, described by the equation of the conic section resulting from the intersection of the focal plane and the image cone as illustrated by figure 4-b. This equation, in the XYZ coordinate system, is therefore given by:

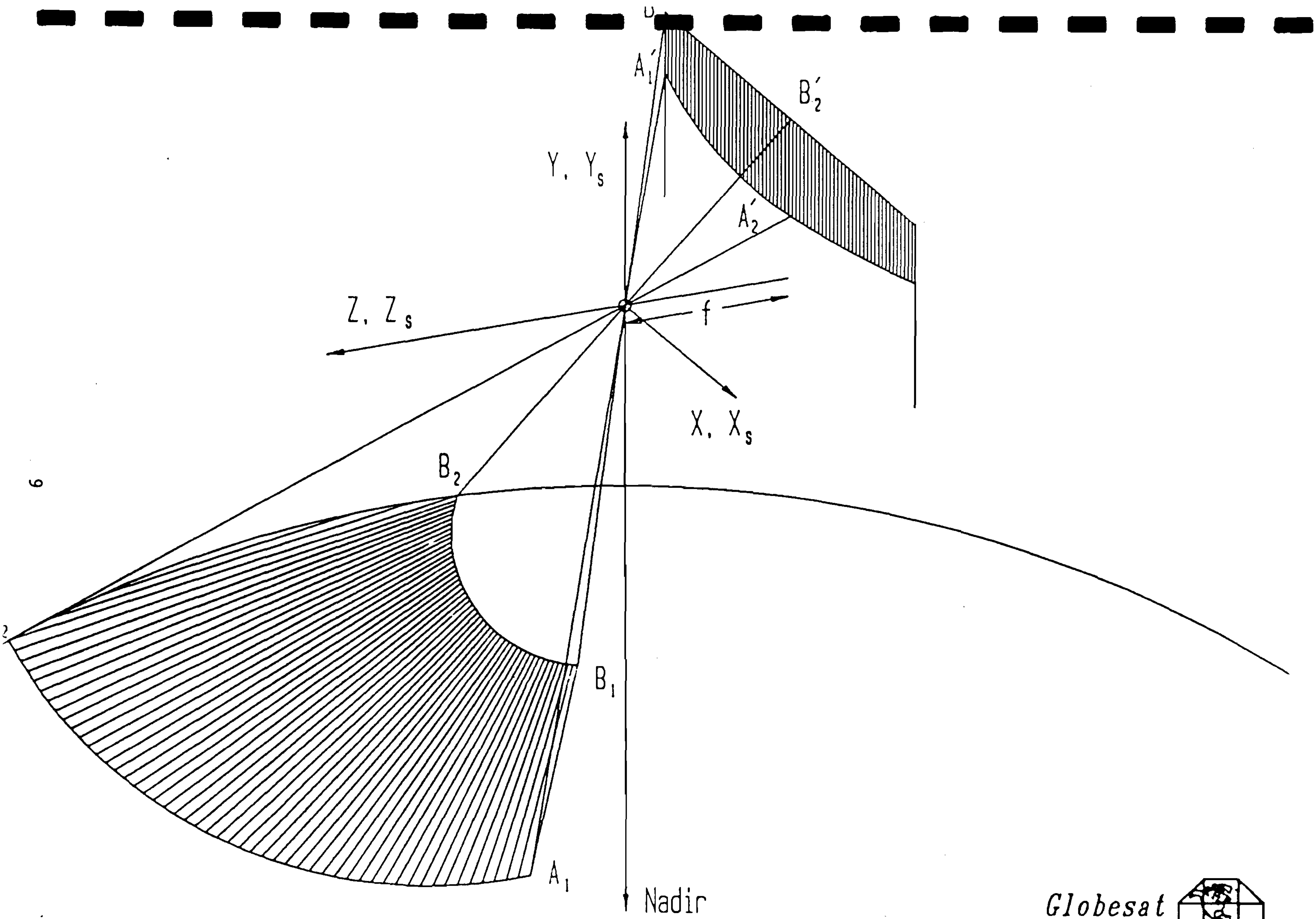

Figure 4-a. Geometry for sensing the horizon.

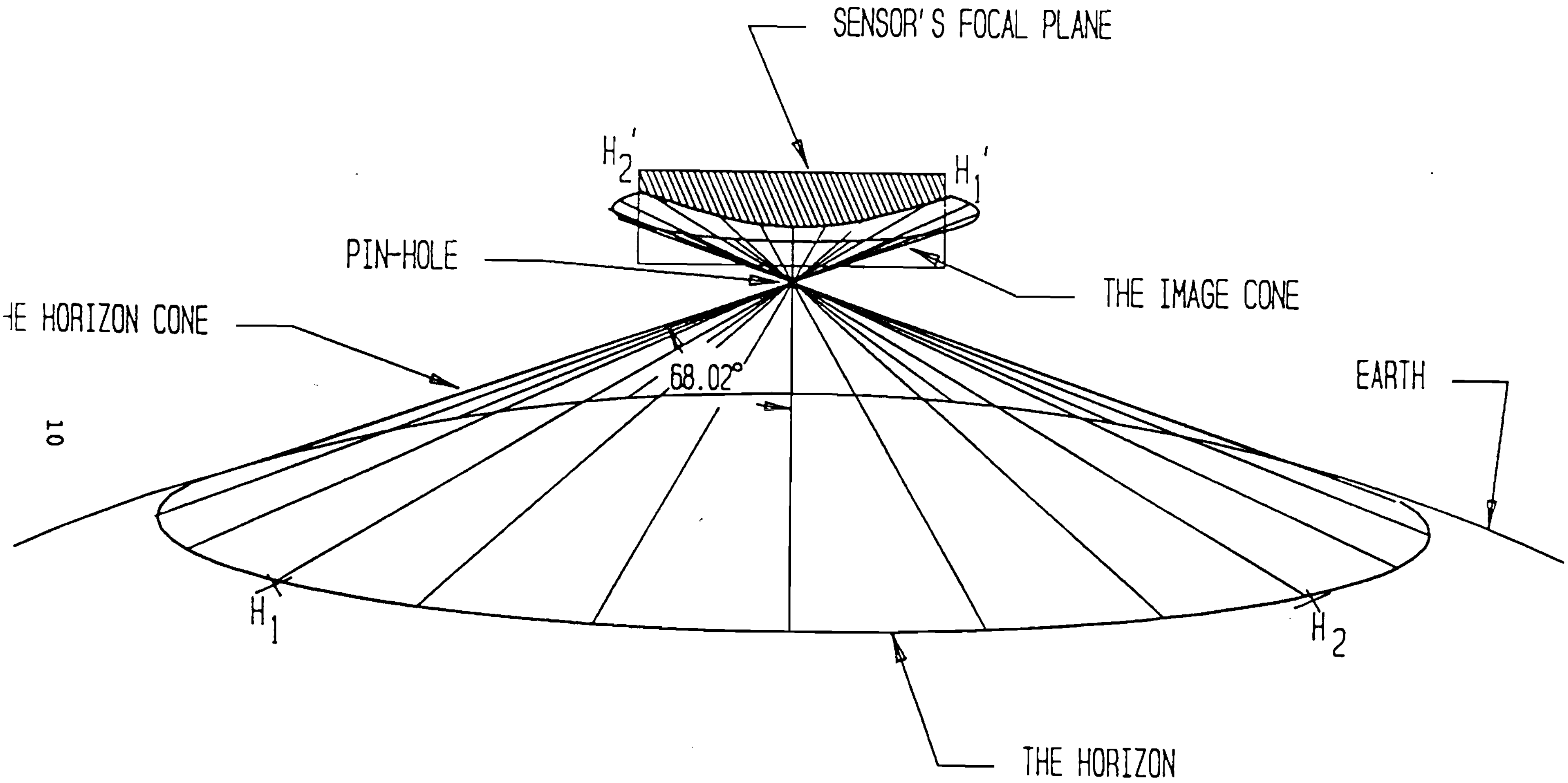

Figure 4-b. Geometry for sensing the horizon.

Globesat
Incorporated

$$z = -f \tag{3}$$

and,

$$x^2 + z^2 = y^2 \tan^2 \rho \tag{4}$$

In this gravity gradient stabilized configuration, the transformation equation between the x, y, and z coordinates and the sensor's or the satellite's coordinates, x_s, y_s, and z_s is :

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix} \tag{5}$$

where the first matrix on the right-hand side is the attitude, or the direction cosine matrix.
If the satellite rotates an angle α about its Z_s-axis and an angle β about its X_s-axis, the transformation between the two coordinate systems becomes:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix} \tag{6}$$

where the first two matrices on the right hand side of equation 6 represent the rotation about the Z_s and the X_s axes, respectively. Due to the symmetry illustrated by figure 4, the rotation about the Y_s-axis cannot be determined by the horizon sensor. The angles α and β also describe the orientation of the nadir direction in the satellite's frame of reference. Solving equations 4, 5, and 6, the equation of the horizon's image in the sensor's coordinates, x_s and y_s is obtained in the form,

$$A\,x^2 + B\,y^2 + C\,x_s\,y_s + D\,x_s + E\,y_s + F = 0 \tag{7}$$

which corresponds to a conic section. The coefficients A, B, C, D, E, and F are functions of α and β, which describe the orientation of the nadir direction in the satellite's frame of reference. The image taken by the horizon sensor is processed to determine the coordinates x_s and y_s along the horizon's image, and with a least square fit, the above coefficients, and therefore, the angles α and β are calculated. For fields of view less than 2ρ, equation 7 will always represents a hyperbola.

Knowing the orientation of both the Sun and Earth in the satellite's frame of reference and, at the same time, the position of the Sun, Earth, and the satellite with respect to each other, the attitude of the satellite could be determined.

Atmospheric effect and albedo variations are effects which have to be taken into consideration during the processing of the horizon's image. The first results in a band, ~5 pixels in width, along the horizon's image, which exhibits a gradually decreasing intensity. The second effect is diminished during the selection of the set of points (x_s, y_s).

REFERENCES

1. Fontana, R., R. Baldassini, and G. Simoncini," Attitude Sensors Review and General Applications," Vol. 2 of Study Detection and Estimation Techniques Applied to Attitude Measurements of Satellites, ESRO, ESRO-CR(p)-551, April 1974.

2. Hatcher, Norman M.," A Survey of Attitude Sensors for Spacecraft," NASA SP-145, 1967.

3. Schidthbauer, B., Hans Samuelsson, and Arne Carlsson, "Satellite Attitude Control and stabilization Using On-Board Computers," ESRO, ESRO-CR-100, July 1973.

4. Wertz, James R., Spacecraft Attitude Determination and Control, Reidel Publishing Company, Boston, 1985.

5. Lyle, Robert, James Leach, and Lester Shubin, Earth Albedo and Emitted Radiation, NASA SP-8067, July 1971.