

THE USE OF THE CONICAL SCAN EARTH SENSOR IN COMMUNICATION SATELLITE APPLICATIONS

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Introduction

Infra-red horizon sensors are almost universally used as the primary attitude sensor for pitch and roll on present day three-axis stabilized communication satellites. When used with a momentum wheel, yaw is also controlled without direct sensing. The application flexibility of the mechanically scanned Conical Earth Sensor, and its recent availability as a component designed for precision, long life performance have resulted in renewed interest in its use on communication satellites.

The Conical Earth Sensor will provide accurate on-orbit attitude sensing in pitch and roll. It can provide attitude sensing all the way from the shuttle orbit to synchronous for booster control, and is particularly attractive for multiple burn, multiple orbit transfer. It can provide accurate nadir sensing 100% of the time in the highly elliptical Molniya twelve-hour orbit. It can facilitate wide angle attitude sensing for antennae calibration maneuvers. It can be used in a static mode as a horizon crossing indicator for spacecraft that go up as spinners, and then for normal on-orbit sensing as a scanner. It can be readily hardened to both nuclear and laser threats, unlike static sensors that are highly susceptible to thermal transients. It has a simple, rugged, and stable construction that is not sensitive to resonance effects from other mechanical devices on the spacecraft such as momentum or reaction wheels.

Background

Scanning horizon sensors were first developed over twenty years ago for use as attitude sensors on low-orbit spacecraft, and have continued to be used in such applications since that time. When the communication satellite era began, static sensors and flexible pivot scanning sensors had been developed that were subsequently adapted to communication satellites. The primary concern about the mechanically driven sensor for communication satellites was the uncertainty over the lifetime achievable with the bearing technology of the day. That these concerns were unfounded is evident when one considers that essentially all present day communication satellites use mechanical bearings on momentum wheels, reaction wheels, or on despun platforms, and will continue to do so for the

foreseeable future. The promise of magnetically suspended bearings for low speed applications has faded--the victim of electronic and mechanical complexity on the one hand, and the proven success of today's bearing and lubrication technology on the other.⁽¹⁾

Description of Conical Earth Sensor

The optical configuration of the Conical Earth Sensor, hereafter referred to as the CES, is shown in Figure 1. All optical elements are made of germanium. The detector is an immersed bolometer, and ahead of the bolometer is a focusing lens. The wedge-shaped prism is the only rotating element, and deflects the image of the field of view by 45° . There is nothing particularly sacred about this angle, and other angles can be used for specialized applications. As the prism rotates, a conical scan path is generated with a 45° half cone angle. The germanium window has coatings that establish the optical passband at 14 to 16 microns and eliminate the penetration of energy at all other wavelengths. The window also hermetically seals the unit. A photograph of the sensor head and its separate electronics assembly is shown in Figure 2. An optical code wheel (not shown) that turns with the prism is used to determine the instantaneous position of the scan with respect to the spacecraft.

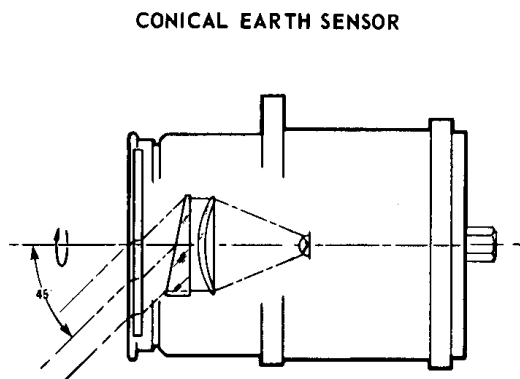


Figure 1



Figure 2

Mounting on the Spacecraft

For geostationary orbit operation, the CES is mounted on the spacecraft with its scan axis tilted down from the pitch axis at a tilt angle of about 40° , as shown in Figure 3. Figure 4 shows the geometric sensitivity to a roll attitude error as a function of the tilt angle in a synchronous orbit. Higher geometric sensitivity gives better signal to noise ratio.

Roll is computed by comparing the actual earth intercept angle with the expected intercept angle. The expected intercept angle is carried in memory as a digital word that can be trimmed if necessary to accommodate misalignment between antennae and the sensor if

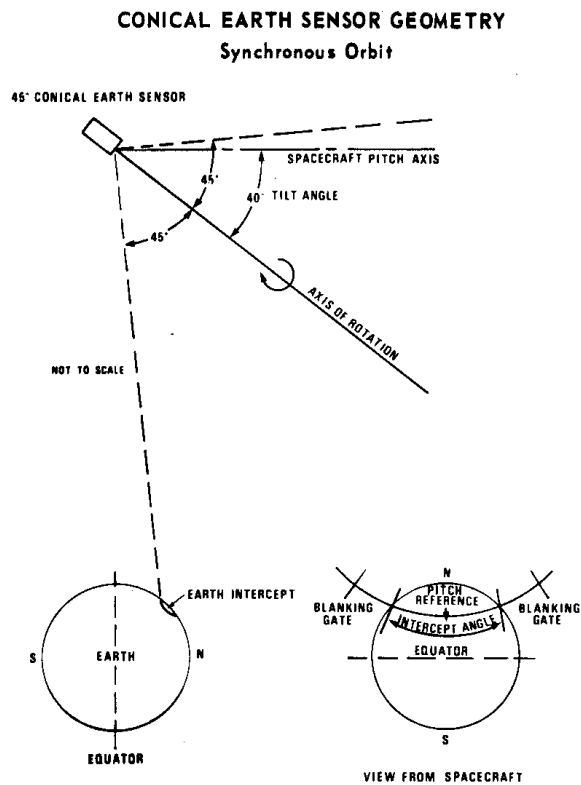


Figure 3

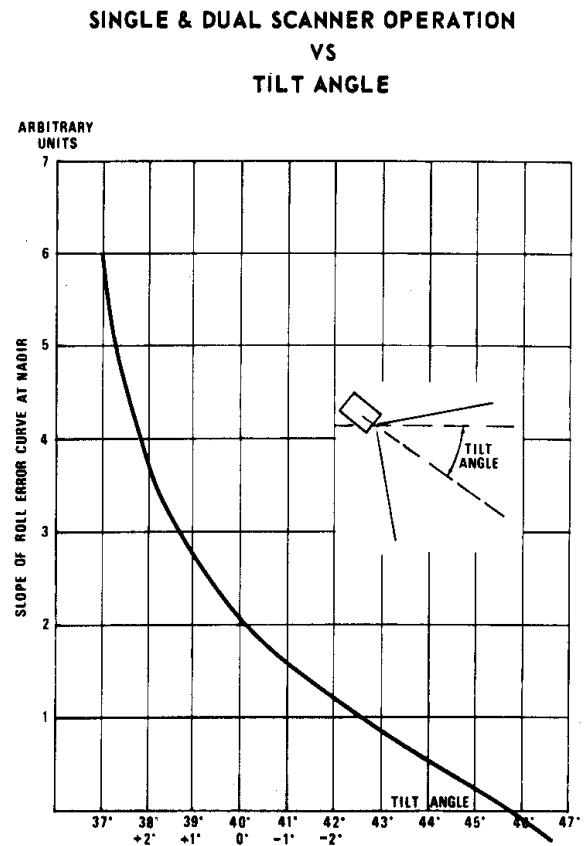


Figure 4

required. Eccentricity of .0004 produces a peak roll error of .003°, and is therefore not a factor.

Pitch is computed from the phase error of the earth signal relative to the optical reference on the CES. The optical reference pulse occurs at the center of the earth pulse when the spacecraft is nadir pointing.

Offset Pointing

A single CES has a wide offset capability in pitch. Figure 5 shows the pitch output that will occur as the spacecraft moves in pitch at roll null. As can be seen from Figure 6, the roll offset range for a single sensor is about $\pm 2^\circ$ at a tilt angle of 40° , using the criteria that the geometrical sensitivity must be at least unity. (See also Figure 4)

There is geometric coupling between pitch and roll as pitch offset increases to large angles. Figure 7 shows the roll null pointing error that will occur as a function of pitch offset if no correction to the roll bias is made. The roll bias setting can be changed by command for this purpose, or to trim out antenna misalignment as mentioned earlier.

SINGLE SCANNER OPERATION
PITCH OUTPUT
VS
PITCH OFFSET

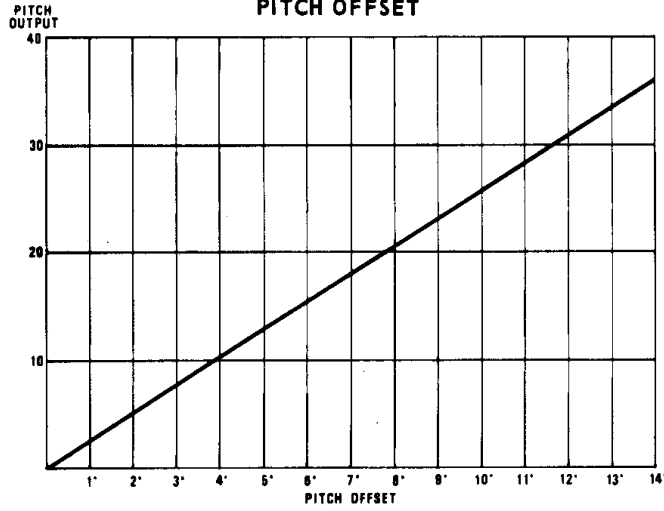


Figure 5

ROLL OUTPUT
VS
ROLL OFFSET
(40° TILT ANGLE)

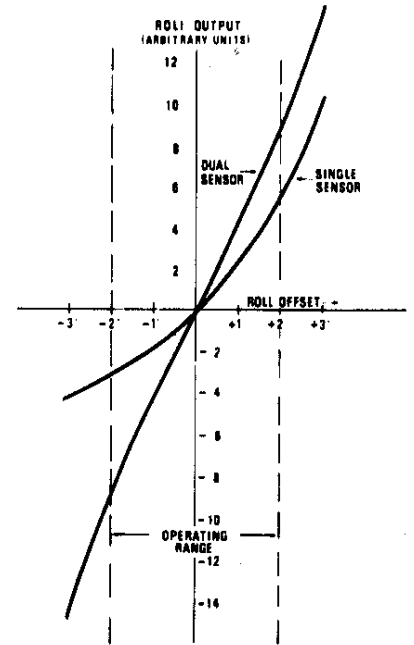


Figure 6

SINGLE & DUAL SENSOR OPERATION
ROLL NULL DIAS
VS
PITCH OFFSET
(40° TILT ANGLE)

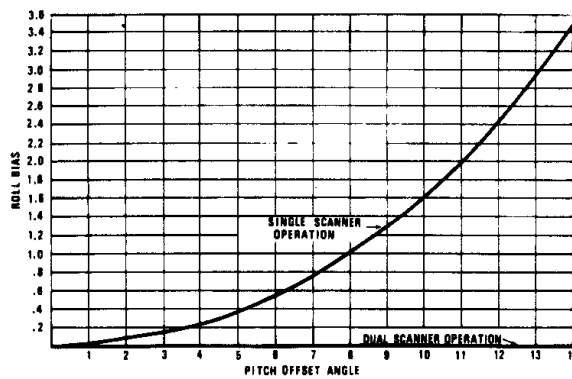


Figure 7

Sun Rejection

To conclude this discussion of the use of a single CES in a circular synchronous orbit, it is important to understand the implications of having the sun directly in the field of view of the sensor, a situation that will occur twice per orbit at certain times of the year.

To minimize the total number of orbits that the sun path intersects the scan path, a blanking gate near each horizon eliminates the effects of any hot object, including the sun, that is in the scan path in the blanked region. See Figure 3. The positions at which these blanking gates are set is a function of the spacecraft offset pointing requirements, and can be changed by command if required. This feature makes it possible to scan through hot objects on the spacecraft, such as antennae, without affecting performance.

To eliminate error due to the sun, the presence of the sun in the field of view near the horizon is detected automatically prior to the time that an output error results. When the sun is detected, the last valid information from that horizon is held in memory, as is the roll output, for as long as the sun is present. If the spacecraft contains a pitch momentum wheel, a single CES will enable the control system to continue to operate normally with the sun in the unblanked region near the horizon. Because of the inertial stiffness due to the momentum wheel, disturbance torques cannot change the roll attitude during the short period (about one hour maximum) that the sun is in the scan path, and therefore this outage of roll data will have no effect on the roll/yaw control performance of the spacecraft. Accurate pitch sensing and control is maintained utilizing information from the horizon that is not interfered with by the sun.

For spacecraft without a pitch momentum wheel, a second CES may be required when the sun is present.

Dual Sensor Operation

In most applications Conical Earth Sensors are used in pairs, not only for redundancy, but also because of the additional capabilities provided. A pair of CES' makes it possible to provide accurate nadir offset sensing 100% of the time for a three-axis spacecraft in any useful orbit, including highly elliptical orbits such as transfer orbits or the twelve-hour Molniya orbit. Figure 8 shows a pair of CES' in a back-to-back configuration that provides accurate attitude information from well below shuttle altitude to above synchronous. No intervention from the ground or commendable modes are required. The geometric performance is good over this entire altitude range. Figure 8 shows the roll geometric sensitivity from below the shuttle orbit to above synchronous for a pair of back-to-back scanners at 40° tilt angle. Altitude effects completely cancel. This plot shows the relative signal output from a pair of CES's per degree of roll motion at nadir as a function of height

above the earth's surface, and this plot is roughly proportional to the output signal to noise ratio. Pitch performance at null is not affected by altitude.

For super synchronous applications, the altitude range can be extended by using a larger tilt angle.

Attitude Computation

Roll is computed as the difference between the earth intercept angles of the two sensors, and pitch as the phase of the earth signal with respect to the vertical reference on the sensor. Figure 9 illustrates this, and the simple computations required.

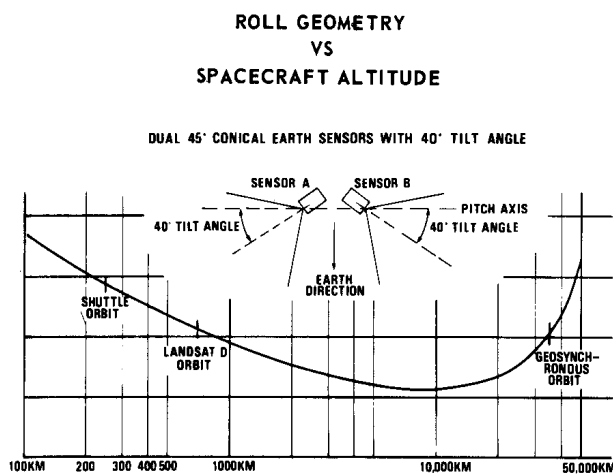


Figure 8

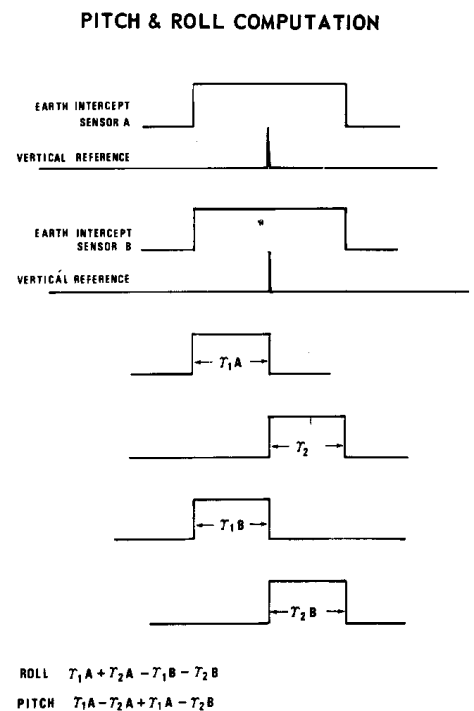


Figure 9

The use of back-to-back sensors eliminates the null offset in roll at large pitch offsets, as shown in Figure 7. This configuration also provides generally superior roll offset pointing performance, as seen in Figure 6. There is a very linear $\pm 2^\circ$ roll offset range where performance will not be degraded.

The two CES's can also be placed at right angles to each other and tilted by 45° in order to expand the offset operating range in roll to at least $\pm 5^\circ$. In this configuration, pitch is computed from one sensor, roll from the other. In general, however, this is a less favorable configuration from the output noise and accuracy standpoint. It also reduces the pitch

offset range to the same $\pm 5^\circ$. This configuration could be of interest in very high orbits, i.e., up to 5 X synchronous.

Horizon Crossing Indicator Mode

Many three-axis communication satellites are launched as spinners and go into a three-axis mode after the orbit is circularized. The CES is the only earth sensor that can provide earth sensing during normal operation as a three-axis spacecraft, and double as a horizon crossing indicator (HCI) for spacecraft that are spinning during the transfer orbit. Since virtually all such spacecraft use separate sensors for these two modes, a considerable cost savings can result through use of the CES. Furthermore, as an HCI, the CES can be stepped by command to virtually any angle relative to the spin axis, regardless of which on-orbit axis the spacecraft spins around during the transfer orbit.

Figure 10 illustrates a spacecraft that is inertially oriented as a spinner during the transfer orbit, then does a 90° pitch maneuver into its normal on-orbit configuration after the apogee burn and orbit circularization has been achieved. Figure 10 (a) shows the normal on-orbit configuration. Figure 10 (b) shows the spacecraft at several positions during the transfer orbit. The beam position can be placed at any point in the normal scan path, and stepped around in 3° increments by command. The fan patterns in this figure illustrates the available positions, and shows that the sensor can be pointed to an appropriate point on the earth from any position during the transfer orbit. Once the sensor is set to a particular position, it scans out a cone due to the rotation of the spacecraft. The only place where the sensor cannot be used effectively is the region where the spacecraft spin axis aims at the earth, because the geometric sensitivity is zero at that point. Both sensors can be used at the same or different angles. Note in the figure that when the spacecraft reaches apogee, the two sensors can be aimed symmetrically on each side of nadir.

Use on Dual Spin Spacecraft

On dual-spin spacecraft, the Steerable Horizon Crossing Indicator (SHCI) mode can be used to track the spacecraft attitude during the transfer orbit. SMS, for example, uses six separate fixed sensors to get less coverage than a pair of CES could do in an SHCI mode at a considerable cost savings.

Pedigree

The optical, mechanical, and electronic technology for the CES is derived from over fifteen years of experience with Scanwheels^(R) twenty-five of which are in orbit, some up to twelve years. The Scanwheel, first developed for Nimbus 4 and first flown in 1969,

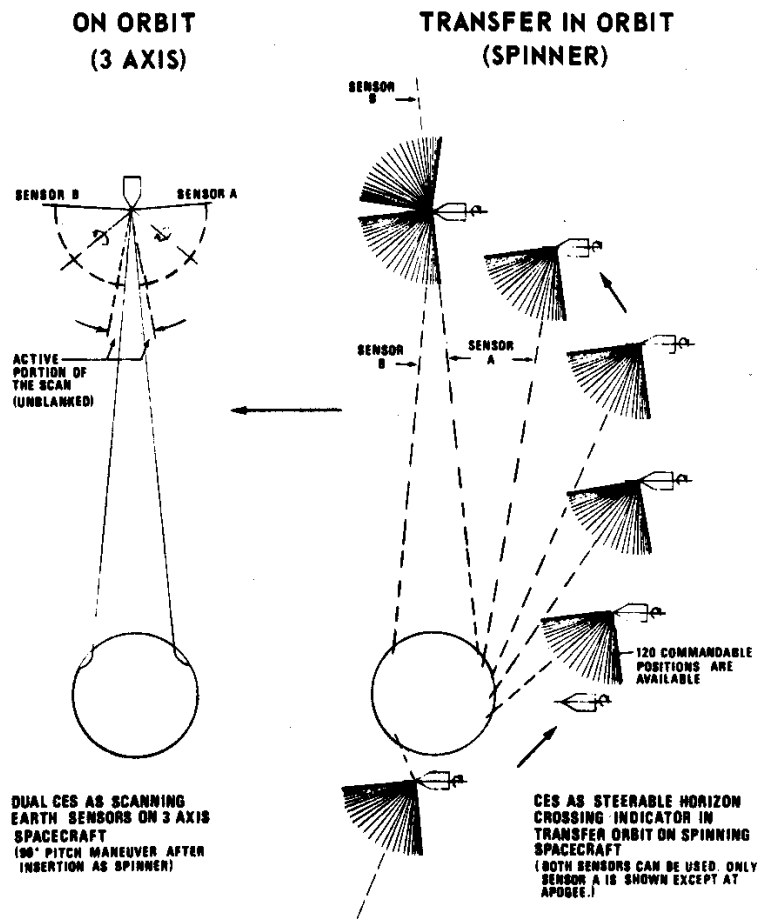


Figure 10A

Figure 10B

combines the Conical Earth Sensor and momentum-reaction wheel functions into a single package. There are no known Scanwheel failures after 138 unit-years of operation in orbit.

The CES mechanical configuration was developed for the USAF on the SCATHA Program. A pair of these sensors have been operating successfully in orbit for nearly three years in a steerable horizon indicator mode on that spacecraft. The CES described in this paper is a close derivative of the SCATHA sensor, and has been delivered to three low-orbit programs: SPACELAB, the USAF Teal Ruby Spacecraft, and LANDSAT D.

Accuracy

The primary error source in any well-designed earth sensor results from the variability of earth radiance as a function of season, latitude, and weather⁽²⁾. The position of the horizon is stable in the 14 to 16 micron band, and is not a factor in the error budget. This passband also minimizes radiation variability effects.

In the scanning mode, the CES uses a shape sensitive horizon locator that accurately measures the position of the horizon in the presence of these radiance variations. The CES will achieve $.05^\circ$ 3 sigma attitude determination accuracy at geosynchronous altitude, including the effects of wide temperature variations and other environmental factors.

In the horizon crossing indicator mode, the horizon locator finds the center of the convolution of the horizon with the field of view, independent of crossing angle, spin rate, or altitude. This feature facilitates the use of the CES as a steerable HCI by eliminating the need for ground corrections of the sensor data. In this mode, the sensor accuracy varies from about $.1^\circ$ 3 sigma in very low orbits, to $.05^\circ$ 3 sigma at geosynchronous altitude.

Radiation Hardening

The CES is probably better suited to radiation hardening than any other earth sensor configuration. Static sensors, for example, are sensitive to thermal transients that can result from laser impulses. The coatings on the CES window are arranged such that the 14 micron cut-on filter is on the front surface, and this filter is highly reflective to lower wavelengths.

Performance Summary

AS SCANNING SENSOR:

Tilt Angle	40°
Accuracy 3 sigma	$< .05^\circ$ (geosynchronous) $.10^\circ$ (250 Km)
Power	5 Watts
Weight	4.5 lbs.
Sample Rate	4 per second
Optical Passband	14.1 micron to 16 micron
Maneuver Range	$\pm 2^\circ$ Roll ± 14 Pitch
Orbit Altitude Range	< 200 Km to 45,000 Km
Number of Sensors Required	Circular Orbit 1 Elliptical Orbit 2 (+1 for redundancy)

AS A STEERABLE HORIZON CROSSING INDICATOR:

Power	Add .5 Watts
Weight	Add .5 lbs.
Step Size	3° (There are 120 positions that the sensor can be aimed)
Stability & Accuracy of Step	± 1 minute
Spin Rate Range	10:1 Anywhere between 1 RPM and 200 RPM

References

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- 2 Barnes, M. B., Craig, S., Haskell, A., The Miranda (X4) Infra-Red Experiment: Design, Performance and Earth Radiance Measurements, Journal of the British Interplanetary Society, Vol. 33, PP. 52-65, 1980