ATTITUDE ERRORS DUE TO MISALIGNMENTS IN CONICAL SCANNING EARTH SENSORS

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A b s t r a c t . Infrared horizon sensors are accurate instruments employed in satellites for Earth referred sensing and attitude control. These optical devices are affected in accuracy by several sources of errors. One of these sources, namely the misalignment between the rotating axis and the optical axis of a conical scanning horizon sensor, has been mentioned in the literature but hasn't being studied in sufficient detail. This paper aims to model and to study such a misalignment. The operation principle of a typical conical scanner in a low Earth sun-synchronous orbit is described as much as the mathematical modelling of the misalignment and the simulation procedure. Numerical simulations are presented and they show that the magnitude of the errors vary with orbital parameters and the sensor position with respect to the spacecraft. These simulations also show that the attitude errors are small for ordinary misalignments. Results for two sensor heads are also shown.

Key words: Horizon sensor, attitude errors, errors simulation

INTRODUCTION

By detecting the thermal horizon of the Earth, a horizon sensor system provides the spacecraft the ability to determine the local vertical at any time. The local vertical becomes a reference for attitude measurements and spacecraft stabilization. A conical scanning horizon sensor consists of an infrared optics, spectral band-pass filter at 14-16 μm of wave length, thermistor bolometer and processing electronics. The field of view (FOV) of the sensor is tilted 40° to 60° by a rotating germanium prism and the rotation of the optical system results in a conical scanning of the space. During scanning, the sensor detects the intersection of the FOV with the Earth's horizon. The period between space-to-Earth and Earth-to-space crossing produces an electronic pulse, whose width corresponds to the chord of the Earth sphere. The scan mechanism also generates a reference pulse whenever the sensor crosses the direction of the expected local vertical.

Figure 1(a) shows the spacecraft reference frame, in which a conical sensor is positioned. In this figure, **RPY** represents the pitch, roll and yaw axes, fixed on the satellite body and supposed to be aligned to the orbital frame, that means that there are no attitude errors. The α and β angles stands for the nominal mounting angles of the sensor's optical axis. When the spacecraft rotates around the sensor spin axis ($\Delta\Phi$), an asymmetry of the reference pulse with respect to the chord length will indicate this motion. On the other hand, if the rotation occurs around an axis perpendicular to the sensor axis, lying on the roll-pitch plane ($\Delta\eta$), then the motion is inferable by the variation in the chord length. The roll and pitch errors (ζ_r and ζ_p) are obtained by coordinate transformations.

Remote sensing, weather and other satellite types demand increasingly better accuracy in their Earth referred positioning. For an Earth horizon sensor, the accuracy is limited by systematic and random errors which amount to about 0.5°. Some of these errors arise from Earth oblateness, seasonal and latitudinal variations of Earth infrared radiation and have already been properly quantified in early works [1-3]. One of these sources is the misalignment between the spin axis and the optical axis in a conical scanning horizon sensor, whose mathematical modelling and results are explained in the next sections.

MATHEMATICAL MODELLING AND SIMULATION PROCEDURE

Consider now, as indicated in Figure 1(b), the angles σ and Φ_B, which represent the offset angle between the sensor spin axis and the optical axis and the phase of the FOV respectively. In this figure, $\hat{\mathbf{S}}$ is the sensor spin vector and $\hat{\mathbf{H}}$ is the unit horizon vector ($\mathbf{H}_I$ in Fig. 1(b)). The misalignment has mechanical and thermal causes that appear during the sensor assembling and operation and can only be avoided up to a limited extent. The angle ψ between the spin axis and the Earth horizon (Ψ_I in Fig. 1(b)) can be quickly calculated from the spherical triangle **SAH** resulting in:

$$\cos\psi = \frac{\cos\sigma\cos\gamma - h(\cos^2\sigma + h^2 - \cos^2\gamma)}{\cos^2\sigma + h^2}, \tag{1}$$

where γ is the half apex conical angle and

$$h = \sin\sigma\cos\Phi_B. \tag{2}$$

The semi-chord Φ (Fig. 1(b)), is thus determined using the law of cosines for sides applied to spherical triangles:

$$\Phi = \arccos\left(\frac{\cos\rho - \cos\psi\cos\eta}{\sin\psi\sin\eta}\right), \tag{3}$$

where ρ is the Earth disk angular radius and $\eta = 90° - \alpha$ is the angle between the sensor spin axis and the local nadir.

The error caused by the misalignment of the optical axis in the reference pulse is given by the expression:

$$\Delta\Phi = (\Phi_I - \Phi_O)/2. \tag{4}$$

Note that the angles Φ_I and Φ_O, for space-to-Earth and the Earth-to-space transitions are identical, resulting $\Delta\Phi = 0$. In other words, the optical axis misalignment causes no error in the reference pulse angle.

The sensor measuring error about the axis perpendicular to the spin axis ($\Delta\eta$) can be obtained from the scanned chord using the law of cosines, that leads to:

$$\cos\rho = \cos\gamma\cos\eta_s + \sin\gamma\sin\eta_s\cos\Phi, \tag{5}$$

where η_s stands for the nadir angle of the sensor spin axis considering null misalignment. The Equation 5 leads to a quadratic equation in $\cos\eta_s$ [1] whose meaningful solution is:

$$\cos\eta_s = \frac{\cos\gamma\cos\rho - k(\cos^2\gamma + k^2 - \cos^2\rho)}{\cos^2\gamma + k^2}, \tag{6}$$

with k given by:

$$k = \sin\gamma \cos\Phi. \quad (7)$$

Once η_s has been resolved the measuring error $\Delta\eta$ is calculated from

$$\Delta\eta = \eta - \eta_s. \quad (8)$$

RESULTS

A simulation was carried out using the above equations for a conical horizon sensor installed in a 3-axis stabilized satellite. It was supposed an orbital semimajor axis of 7280 km, sun-synchronous, starting from a circular orbit up to a eccentric orbit with eccentricity equal 0.1 in steps of 0.025, as indicated in Figure 2(a).

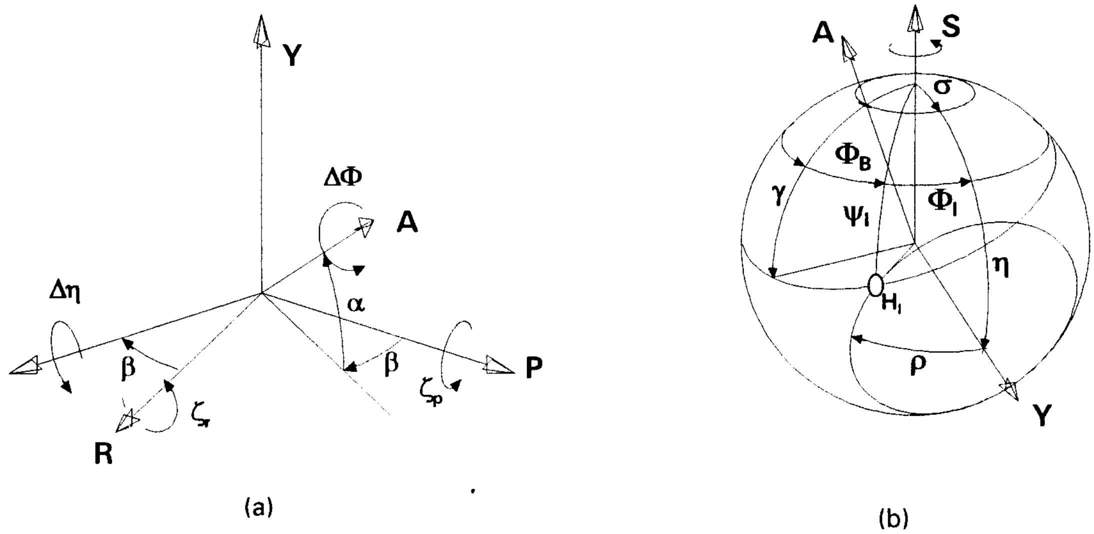

Fig. 1. a) Satellite reference frame and sensor positioning, b) Earth sensor scanning geometry.

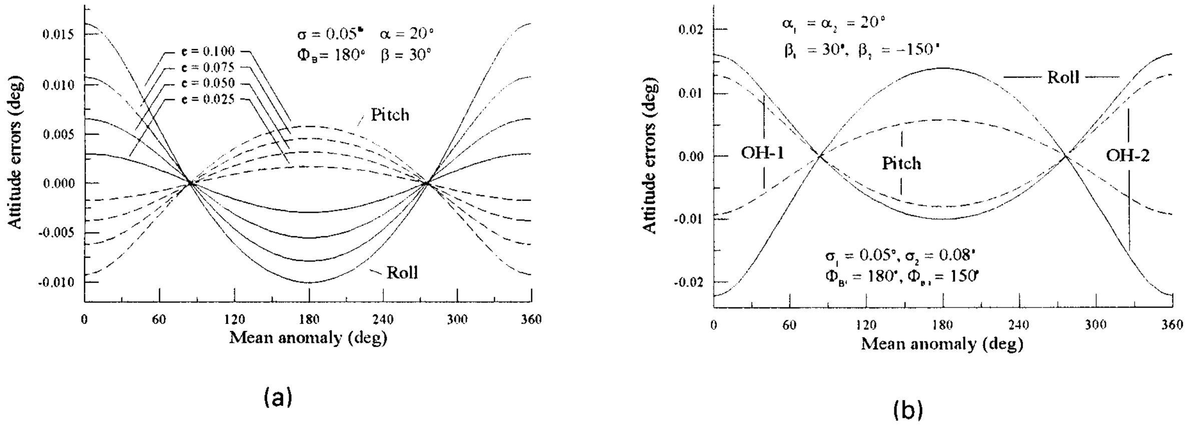

Fig. 2. Attitude errors (roll and pitch) for the 45° half apex conical scanner for: a) one optical head, b) two optical heads and e = 0.1.

Figure 2(b) shows the roll and pitch errors for a spacecraft with two conical scanning sensors (OH-1 and OH-2). The orbital parameters are: semimajor axis 7280 km, eccentricity 0.1, inclination 97.7°, and the half apex angle considered was 45°. During the simulation the errors vary with the satellite altitude but never exceed 0.02 degrees, a small value when compared to the other sources of errors. For the circular orbit the error is constant and increases from a magnitude of 10^{-4} degrees, for $\alpha = 20°$, up to a magnitude of 10^{-2} degrees, for $\alpha = 0°$.

CONCLUDING REMARKS

This work shows some results for induced errors by misalignments between the spin axis and the optical axis in conical horizon sensors. They show that the sign and magnitude of the sensor errors vary with orbital parameters and the sensor position in the spacecraft. For the expected misalignments during sensor operation, the errors are small when compared with others sources as the oblate shape of the Earth or radiance effects. Since the sensor spin axis misalignment results in a fixed bias in the half apex conical angle and once the bias can be detected by careful ground analysis, the errors can be eliminated by adequate changes in the standard chord length or by simple subtraction of the modeled errors.

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