

Modular CMOS Horizon Sensor for Small Satellite Attitude Determination and Control Subsystem

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ABSTRACT: A typical horizon sensor has an average RMS accuracy of 0.2° for satellite attitude determination, with a mass of between 1 to 4kg and consumes 3 to 10W total power, while the ATSB™ CMOS horizon sensor has an RMS accuracy of better than 0.1° , a mass of 560g and consumes only 550mW when imaging. The CMOS horizon sensor which has a total Field of View (FOV) of approximately 90° can process the image data, calculate and transmit the nadir vector to the Attitude Determination and Control Subsystem (ADCS) On Board Computer (OBC) via a dual redundant CAN communication bus. Apart from attitude sensing, the CMOS horizon sensor has the capability of taking panchromatic images of up to 1M pixels in size. In this paper, the design, calibration, performance and test results of the horizon sensor will be discussed.

Keywords: Sun Sensor, Horizon Sensor, Centroid Algorithm, ADCS, Nano-satellite

INTRODUCTION

Sensor or attitude determination is one of the most important subsystems in a satellite. This component determines the satellite's attitude and orientation relative to the Earth, Sun or other objects. Among the sensors that are used in a satellite are Sun Sensors, Magnetometers, Star Trackers and Horizon Sensors.

The selection of sensor is influenced by its accuracy and the required orientation of the spacecraft such as Earth or inertial-pointing. Other factors include field of view requirements, redundancy, fault tolerance, and available data rates. Typically, we identify candidate sensor suites and conduct a trade study to determine the best, most cost-effective approach. In such studies, the existence of off-the-shelf components and software can strongly influence the outcome. However in this article we will focus on Horizon Sensors.

Horizon sensors are typically IR devices that sense and detect the contrast between the heat of

the Earth's atmosphere and the cold of deep space. Other horizon sensors perform imaging in the visible light spectrum, detecting the horizon as the contrast between the sunlit lower atmosphere and the dark deep space background. The sensor presented in this paper is of the latter type. Scanning horizon sensors use a rotating lens or mirror to replace or augment the spinning spacecraft body. Simple narrow field-of view fixed-head types called pippers are used on spinning spacecraft to measure Earth phase and chord angles which define two angles to the nadir vector, together with orbit and mounting geometry. Some nadir-pointing spacecraft use staring sensors which view a portion of the limb from LEO or the entire Earth disk from GEO. The sensor presented in this paper is of the fixed-head type. The sensor fields of view stay fixed with respect to the spacecraft.

Horizon sensors provide Earth-relative information directly for Earth-pointing spacecraft, which will simplify onboard processing. Typical accuracies for systems using horizon sensors are 0.1 to 0.25 degrees. For the

highest accuracy in low-Earth orbit, it is necessary to correct the data for seasonal horizon variations and Earth oblateness.

SYSTEMS DESCRIPTION

The foundation of this Horizon Sensor design is based on a CMOS image sensing device, which will capture an image of a round object (Earth) and the centroid of the object (Earth) is calculated by imaging algorithms. The nadir vector can then be used for attitude determination and orientation control.

The image sensor is triggered every second to take an image by a microprocessor which is part of the CAN node on the horizon sensor (HS). After the image is captured the sensor notifies the FPGA that the image is ready to be transferred to the SRAM. Once in the SRAM the microprocessor can do the centroid calculation from the captured image. The centroid value is transmitted to the ADCS-OBC via the dual redundant CAN communication bus. The HS can communicate with ADCS-OBC of the satellite to receive telecommands and pass on telemetry.

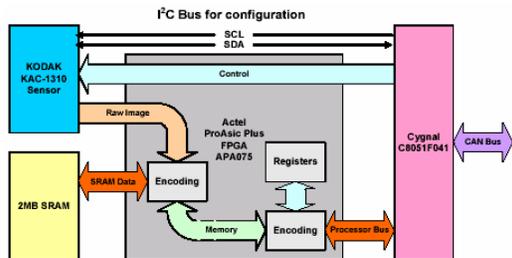


Figure 1. High level block diagram of the HS.

Figure 1 shows a high level block diagram of the Horizon Sensor. There are five communication routes (Table 1) required to calculate a centroid which can be seen on the Figure 1. The SRAM Data bus is a multiplexed bus consisting of the Raw Image and Memory buses and the Processor Bus is a multiplexed bus consisting of the Memory and Registers buses. The I²C (Inter-Integrated Circuit) bus is used to configure the Imager Sensor.

Table 1. Major HS communication routes.

Bus	Function
1. I²C	Imager configuration.
2. Control	Triggering of image capturing.
3. Raw Image	Storage of image from Sensor to SRAM.
4. Memory	Calculation of centroid and image download.
5. CAN	Communicating the results with ADCS-OBC.

To be able to capture images of the Earth’s horizon, the image sensor is tilted at an angle of 24° degrees with respect to the spacecraft body. This angle is based on Low Earth Orbit (LEO) with approximately 600km altitude. The image taken, apart from being used for centroid calculation, can also be downloaded to OBC via CAN or serial RS232 or RS485.

Figure 2 below shows the tilt angle calculation:

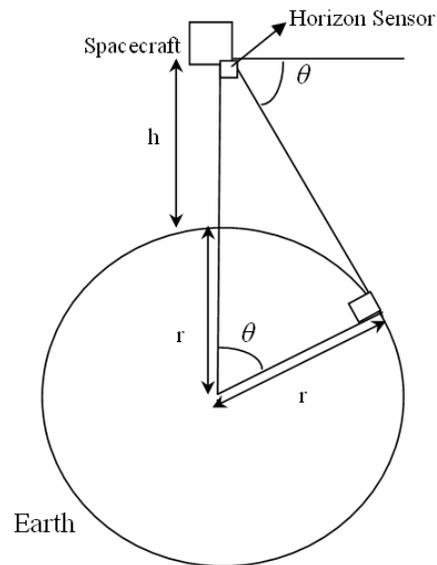


Figure 2. Tilt angle calculation based on the altitude.

The tilt angle depends on the altitude of the spacecraft. The higher the altitude, the bigger the tilt angle will be.

$$\theta = \cos^{-1} \left[\frac{r}{r + h} \right] = 24^\circ \tag{1}$$

where θ = tilt angle
 h = spacecraft altitude = 600 km
 r = Earth radius = 6378 km

This device is a 90 degrees full cone Field of View (FOV) Horizon Sensor capable of nadir vector determination, in the temperature range of -10 to +50°C. This sensor is conceived as a single unit of about 560g mass and 550mW

power consumption, cubic shaped with size 63 x 95 x 121mm, supporting also the optics with 4.2mm focal length, mounted with tilt angle of 24°. With a pixel size of 6µm x 6µm, the imager resolution is 1024 x 1024 pixels. This CMOS Horizon Sensor features an attitude measurement accuracy of better than 0.1°.

Figure 3 shows the Horizon Sensor after being mechanically integrated.



Figure 3. Horizon Sensor

The Power Distribution Unit (PDU) will supply an unregulated, but filtered bus voltage in the range of 12V_{DC} to 32V_{DC}. A switch mode regulator is used to generate +3.3V from the power supply input and a +2.5V will be generated from the regulated +3.3V using a Linear Low Dropout (LDO) regulator.

Table 2. The measured power consumption for the HS.

Description	Typ.	Units
Totals (max)		
Dynamic	549.4	mW
Standby	211	mW

In order to employ a centroid algorithm, high speed calculations are required on the image. In view of this fact and the possibility of communication and timer interrupts, the image was required to be buffered in temporary SRAM memory. For maximum resolution (1288 x 1032) and maximum image size (10-bit colour depth) the memory required equates to 1.6 MB. It was decided to work with an image size of 1024 x 1024 pixels and an image resolution of 8-bits, the memory required then equates to only 1MB. Discarding the 264 rows and 8 columns causes a 21.1% lose of the image.

Interfacing of the three major components (generic node, CMOS sensor and SRAM) was placed on the FPGA and routed accordingly. This significantly helped in keeping the design of the PCB uncomplicated.

There are three different software implementations required to run the CMOS Horizon Sensor. The first part is the microprocessor C-firmware which is used to interface to the SRAM via the FPGA and control the imager. It will also be responsible for communication with the ADCS-OBC and general housekeeping. The second part of the code is the FPGA VHDL firmware which will function as interfaces between the micro-processor, SRAM and imager. The third part is the external software for the Ground Support Equipment (GSE) which is required when the Horizon Sensor interfaces to the GSE emulating the ADCS-OBC or just performing a debugging and display function.

The Window of Interest (WOI) is only 1024 (Horizontal) x 1024 (Vertical) pixels in size. In order to calculate the Field of View (FOV) the diagonal length of the exposed field in this WOI must be determined. Figure 4 illustrates the definition of the diameter of the exposed image. For this implementation the WOI is:

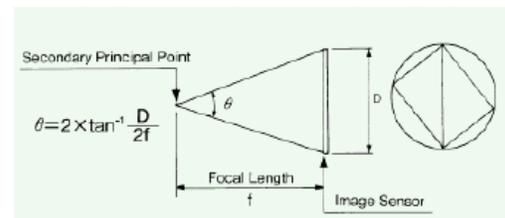


Figure 4. The relationship between the FOV, the image diameter and the focal length.

Therefore, from Figure 4 the FOV can be expressed as follows. Note that the FOV is inversely proportional to the focal length (f) which is in its turn a characteristic of the chosen lens.

$$\theta = 2 \times \arctan\left(\frac{D}{2 \times f}\right) \quad (2)$$

where θ = field of view (FOV)

D = diameter or diagonal of the exposed image

f = focal length

The size of the image sensor is called the image format. Different sensor formats require corresponding lens formats. The lens needs to cover an area equal to or larger than the sensor size. However, larger lens formats reduce distortion on the lens perimeter area. Hence, the lens format should be at least equivalent to the

camera format. Most imager sensors come in sizes of 1", 2/3", 1/2", 1/3" and 1/4".

Figure 5 below illustrate some of these lens formats.

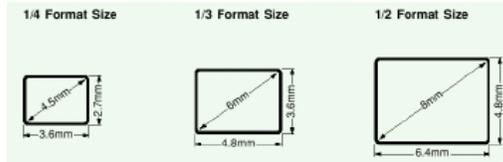


Figure 5. An illustration of 1/4", 1/3" and 1/2" format lenses.

The following table is a summary of the Horizon Sensor FOV for this lens.

Table 3. Calculated vs. specified Horizon Sensor FOV for the selected lens with the given exposed image diameter.

Focal Length	Diameter	Calculated FOV	Specified FOV (Lens)
4.2mm	8.69mm	91.94°	86.77°

CENTROID ALGORITHM

The Earth’s size is too large to fit into the Field of View (FOV) of the Horizon Sensor. The detection algorithm detects points that lie on the edge of the Earth and the dark space. From these points the centroid of the Earth can be computed.

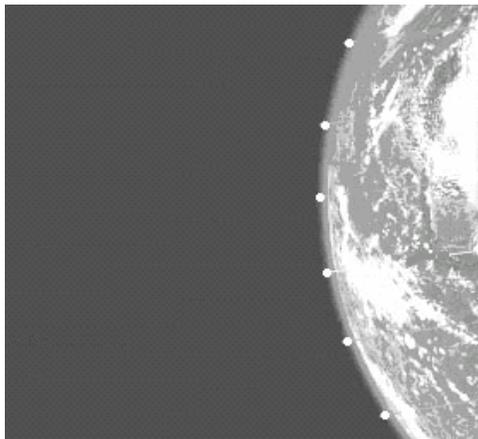


Figure 6. Edge of the Earth is scanned and used for centroid calculation

Basically the algorithm can be divided into a scanning part and a circle part fit. The scanning loop detects the transitions from dark to light by making use of image gradients.

Scanning phase

In the scanning loop, the edge points were detected if the image gradient at that point is bigger than the gradient threshold. Due to the presence of noise, the image gradients are calculated using Sobel operators. The Sobel edge detecting kernels are:

$$G_x = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} \quad (3)$$

$$G_y = \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \quad (4)$$

The formulas for calculating the image gradient then become:

$$I_x(x, y) = -i(x-1, y-1) + i(x+1, y-1) \dots - 2i(x-1, y) + 2i(x+1, y) \dots - i(x-1, y+1) + i(x+1, y+1) \quad (5)$$

$$I_y(x, y) = -i(x-1, y-1) - 2i(x, y-1) \dots - i(x+1, y-1) + i(x-1, y+1) \dots + 2i(x, y+1) + i(x+1, y+1) \quad (6)$$

where $i(x,y) = image_brightness(x,y)$

Both horizontal and vertical scans are performed during the scanning phase. For horizontal scans, the image gradient with respect to x is calculated. For vertical scans, the image gradient with respect to y is computed. Both are called I_x and I_y , as above. An edge is registered if the image gradient is large for that image location.

Circle fit phase

In circle fit part, circle geometry method is used to compute the center coordinate of the circle. From the Circle Theorem, a chord is a straight line that connects any two points on the circle. The perpendicular bisector of a chord passes through the center of the circle. The center of the circle can be determined by having a minimum of two bisecting lines (chords), which in turn requires a minimum of three edge points that lie on the circle. The center of the circle is the point intersection of two perpendicular bisectors of the two chords.

By using this theory, the Earth centroid can be calculated. For better results, the final center coordinate of the circle by averaging the individually calculated intersection coordinates.

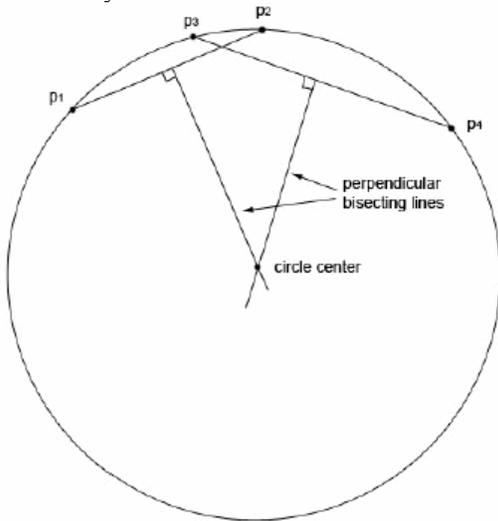


Figure 7. Centroid of the Earth determined from two perpendicular bisecting lines.

The horizon edge detection algorithm produces the centroid coordinate of the Earth. A pointing vector can be formed from the centroid coordinate:

$$s = \begin{bmatrix} -x \\ -y \\ f \end{bmatrix} \quad (7)$$

where f is the nominal focal length of the lens.

CALIBRATION

The detected coordinates of the Horizon Sensors have to be corrected for lens distortion. The calibration is performed in two steps. The first step is to make sure all coordinates are referenced to the optical axis intersection. The second step is to determine the focal length error and the coordinates are corrected for lens distortion.

Optical Axis Intersection

The optical axis intersection is the location on the CMOS sensor where the optical axis intersects it. The optical axis is the axis passing through the optical center of the lens system. Light rays traveling along the optical axis are not deflected or distorted. Coordinates of positions

of interest on the sensor are measured as a pixel row and column. These are referred to as the sensor coordinates. All measured coordinates are referenced to the optical axis intersection. If a point has a sensor coordinate of (x, y) then the optical axis intersection referenced coordinate (x', y') is:

$$x' = x - x_{\text{oi}} \quad (8)$$

$$y' = y - y_{\text{oi}} \quad (9)$$

Focal Length

Focal length is the effective distance from the optical center of the lens to the CMOS sensor surface.

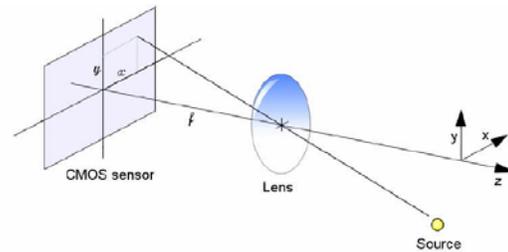


Figure 8. Focal length of the lens.

The focal length can be obtained by measurement. A reference source such as a light source is required at a known angle, θ , from the optical axis. If the light rays coming from the source strike the CMOS sensor at coordinates (x', y') (where x' and y' are referenced to the optical axis intersection) then the focal length is obtained from

$$r = \sqrt{x'^2 + y'^2} \quad (10)$$

$$f = \frac{r}{\tan \theta} \quad (11)$$

Measurements such as these should be conducted at small angles to minimize the effect of lens distortion (see below). Focal length is used by the sensor to construct a pointing vector from a measured point, and to determine the azimuth and elevation angles of the point relative to the optical axis. For a point on the CMOS sensor with coordinates (x', y') (these coordinates are relative to the optical axis intersection), the vector that points to the source of the point, is given by

$$s = \begin{bmatrix} -x' \\ -y' \\ f \end{bmatrix} \quad (12)$$

The vector s is in the HS coordinate system – the positive z-axis points away from the CMOS sensor, and is aligned with the optical axis. The x-axis points in the direction of increasing x sensor coordinate values, and the y-axis point in the direction of increasing y sensor coordinate values. The azimuth and elevation angles between the HS coordinate system and the source of the point at (x', y') are given by

$$\alpha = \tan^{-1} \left(\frac{x'}{f} \right) \quad (13)$$

$$\varepsilon = \tan^{-1} \left(\frac{y' \cos \alpha}{f} \right) \quad (14)$$

with α = azimuth and ε = elevation angle

Lens Distortion

Light rays that do not coincide with the optical axis, are subject to distortion. This distortion is a property of the lens system. Light rays are either deflected away from the optical axis, or toward it depending on the nature of the distortion. The distortion is usually a function of the angle between the incident ray and the optical axis, and is radially symmetric.

To compensate for the distortion, a correction is applied to the measured x and y coordinates. The correction function can have many forms. For this implementation, a correction is applied that scales both x and y coordinates according to the deviation of the focal length from its nominal value, at that (x,y) location.

If the calculation in equations (16) and 17) is carried out for large angles between the incident ray and the optical axis, then because of the lens distortion, a different value for f will be obtained. The difference between the nominal focal length (measured at small incident angles) and the value of f for that point is the calibration value that is required.

A light source that causes a point on the CMOS sensor at (x', y') has an associated focal length of $f_{x,y}$. (The value of $f_{x,y}$ is determined during

calibration in a similar manner to obtaining the nominal focal length, f_{nom}). Then the correction that is applied is:

$$x'_{corrected} = x' \frac{f_{nom}}{f_{x,y}} \quad (15)$$

$$y'_{corrected} = y' \frac{f_{nom}}{f_{x,y}} \quad (16)$$

TEST RESULTS

Preliminary Test Results

The following two figures illustrate four images downloaded from the CMOS Horizon Sensor. The first two are test patterns generated by the processor, written to the SRAM, read back and then downloaded to a PC via RS232. The first image illustrates 32 shades of grey indicating 32 pages in the SRAM. The second image really just confirms that data was actually stored in the SRAM. The second set of images are generated by the CMOS imager, stored in the SRAM and then downloaded to the PC via the Micro processor.

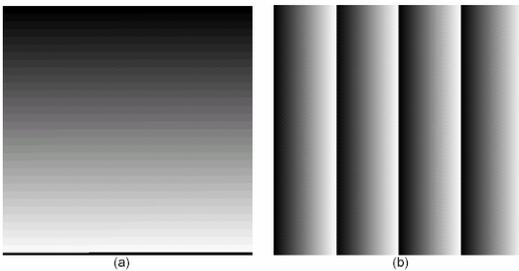


Figure 9. Two test patterns used to test the SRAM of the HS.



Figure 10. Two images taken with the HS imager. (Wide angle lens) (a) 512 x 512, (b) 1024 x 1024

From Figure 10 above, it can be seen that the sensor can also take images. Figure 10(b) is the clearest image the sensor can capture with maximum 1MB. For faster image transfer to ADCS-OBC, the image size needs to be smaller as can be seen on Figure 10(a) where the size is about 0.26 MB. The image is taken by readout of every second pixel row and column.

Calibration Results

Data received from the calibration by using the Horizon Sensor Calibrator, was processed and analysed. The figures below illustrates preliminary calibration results:

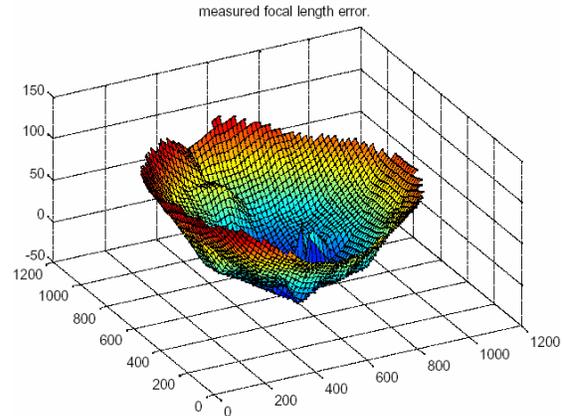


Figure 11. Graph of the measured focal length error

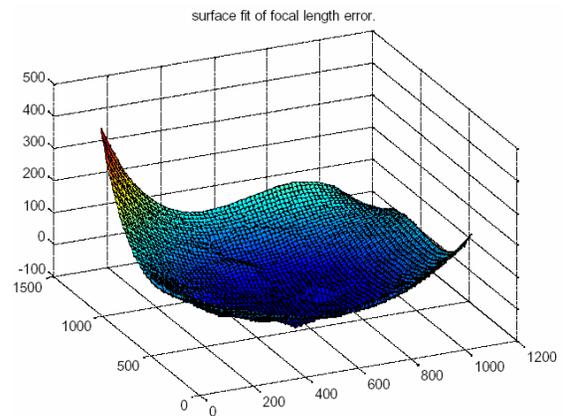


Figure 12. Graph of surface fit of focal length error

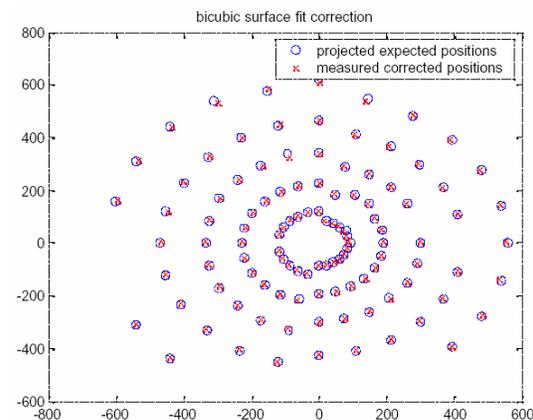


Figure 13. Bicubic Surface Fit Correction

Figure 11 shows the measured focal length error and Figure 12 shows the surface fit of focal length error whereby the polynomial functions are used to smoothen the focal length error in figure 11. The purpose of this surface fit of focal length error is to get corrected x and y coordinate

of the Earth centroid pointing vector that are distorted due to lens aberrations.

Figure 13 shows the projected expected positions and the corrected measured positions of the Earth centroid. The figure shows the significance of having surface fit of focal length error in order to achieve measured positions as close as possible to the true positions.

CONCLUSION

The Horizon Sensor was designed and built for a future ATSB™ Nano-satellite with altitude around 600km. The preliminary calibration done has not yet achieved the intended accuracy of below 0.1° over the full FOV. The accuracy is not yet as expected because of mounting and pointing errors of the Horizon Sensor on the current Horizon Sensor Calibrator.

The second calibration will be done by using a more accurate Horizon Sensor Calibrator with a new improved calibration procedure. It is expected to get the expected accuracy from this second calibration process which is currently being implemented.

From measurement and duty cycle calculations, the average orbit power consumption is 289mW. Mass is also low at only 560g. Hence, these minimal resources make this CMOS Horizon Sensor very attractive for any small satellite.

Standard and simple interfacing to a satellite bus by either using CAN or RS232/RS485 serial link simplifies the use of this sensor for any satellite or spacecraft application.

Apart from attitude determination, this CMOS Horizon Sensor can also be used to capture images of the Earth or other space objects with a maximum resolution of 1 Mega pixels.

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