University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018
Project Definition Document (PDD)

Earth Horizon Sensor (ETHOS)

Approvals

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1.0 Problem or Need

With the increasing number of satellites in orbit, there is a high demand for attitude determination sensors. These sensors use the earth limb to determine the nadir vector for the spacecraft. Many satellite customers require attitude determination that is more accurate than a sun sensor[4], which have about one degree of accuracy, but cannot afford the cost or require the high level of accuracy of a star tracker, which have accuracies on the order of arc seconds. Earth horizon sensors are another source for attitude determination when the sun may not be visible or when a star tracker will not track correctly. These sensors have accuracies between star trackers and sun sensors[4] with an accuracy within 0.5 degrees and 2 degrees of freedom. Currently, Surrey Satellite Technology only offers star trackers and sun sensors. An earth horizon sensor will allow Surrey to compete for a wider range of business and increase their customer base. This project will design a solution for Surrey that will meet these needs.

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The project has a budget of 5000 USD to create and test an engineering model that will have a mass less than 600 grams, be no larger than 95 x 107 x 63 mm in size, and will be contained in its own structure so that integration would require attachment of the structure to the satellite. For further simplicity for integration, the Sensor will require data to be stored by the horizon sensor and commandable for data and telemetry including voltages, currents, and temperatures. The data communication between the spacecraft and the sensor will use the Controller Area Network (CAN) protocol and will require less than 1 Watt power from the spacecraft. This project will focus on testing in a laboratory environment using pictures or heated elements to simulate the visual or IR spectrum of the earth, using a scaling factor to compensate for the difference in size and distance. A successful delivery to Surrey Satellite Technologies will consist of an engineering model that will operate with a simulated altitude of 250-750 km and have tracking capabilities in a simulated eclipse of at least 35 minutes.

2.0 Previous Work

An Earth horizon sensor is an instrument that takes a measurement from the Earth's limb, and derives 2DOF attitude information. The development of Earth horizon sensors first began in 1958 for use on Jupiter rockets and have since then been used for attitude determination on the Mercury, Gemini, and OGO spacecraft, as well as more recently on spacecraft such as Envisat, ADEOS 1 and 2, and the MetOp family of satellites[1,2]. Earth horizon sensors are generally grouped into one of two categories: scanning and static. This project will focus on developing a static sensor, as per the customers design criteria, which is driven by the need for a small, simple, and robust attitude sensor, and the customer's spacecraft are not usually spinning. Previous designs of static Earth sensors can be broken down into two categories by function: radiance balancing sensors, and horizon imaging sensors. Both types of sensors generally operate in the 14μm-16μm infrared (IR) spectrum. Reason for sensitivity to this region of the IR spectrum is to utilize the Earth's CO_2 emission band, which is at 15μm. Viewing in the CO_2 emission band has been found to have the greatest effect on minimizing the angular instability of the horizon, thus allowing for a more accurate attitude measurement to be made under varying solar illumination conditions[1]. Furthermore, it has been found that the Earth radiates significantly at wavelengths greater than 6μm, and that at wavelengths below 5μm, solar radiation is much greater than the Earth's emission in the CO_2 band . Utilizing a sensor that uses the IR band above 5μm will allow for use in the Earth's umbra because Earth's radiation is greater than solar radiation above 5μm. Although both radiance balancing sensors and imaging sensors generally operate in the same portion of the IR spectrum, the two have significantly different means of utilizing the Earth's horizon to determine attitude information.

The radiance balancing sensors generally have several IR sensitive thermopiles[5] mounted at an angle such that each one sees an equal part of the horizon in a different direction while the sensor is nadir pointing. If the sensor is allowed to pitch or roll, the thermopiles will register a difference in radiative flux[5], thus allowing the sensor to determine its attitude. Figure 1 shows an example of a radiance balancing sensor in orbit.

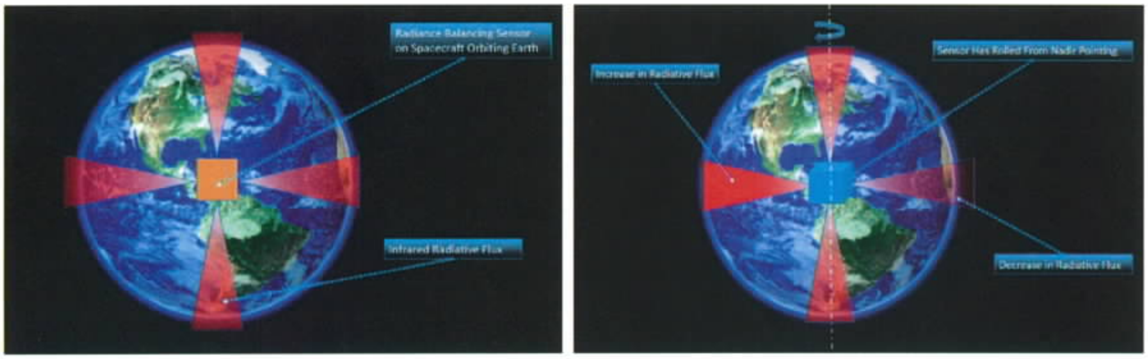

Figure 1: Radiance Balancing Sensor

The radiance balancing sensors, which utilize thermopiles, have been in use since the 1960s, and have displayed a high resistance to radiation damage by the space environment.[1] For this group's purposes, testing for this type of sensor would entail creating a thermally representative environment of the Earth as seen from space in a lab, and scaling distances to verify pointing accuracy requirements.

The horizon imager operates by taking a digital picture of the horizon, and derives an attitude reference based on the Earth's position in the camera's field of view (FOV). The horizon imaging scanners have the disadvantage of utilizing refracting optical lenses, which can create internal reflections.[1] Testing for this type of sensor may entail something as simple as having the sensor look at a printed picture of the Earth, and determining its attitude. Both the thermopile and the imaging approach will be considered as the final design.

3.0 Specific Objectives

In order to satisfy the design problem and customer requirements, project deliverables must include a sensor that is capable of observing a simulated Earth horizon at altitudes of 250-750 km and providing two-dimensional nadir vector to 0.5 degree accuracy. This is defined as the minimum level of success for the project. The second level of success concerns the sensor's ability to provide measurements of the Earth horizon or Earth center location while maintaining operation both inside and outside of a simulated eclipse. The third level of success focuses on making the sensor physically compatible with the satellite and assuring that it provides accurate measurements. The maximum level of success requires the sensor to be compatible with the satellite's EPS and CDH subsystems. The deliverable sensor model will be tested in and designed to work only in the Earth environment. The criteria to meet each level of success are described in greater detail below.

<u>Level 1:</u> Obtain or design a sensor that is capable of observing a simulated Earth horizon as would be seen from a satellite at 250-750 km in daylight. Develop software that is capable of processing the sensor's observations (e.g. pictures or intensities) to output the nadir vector within 0.5 degrees of accuracy. A laboratory based test shall be developed to verify that the sensor is capable of making observations in the chosen emission band while operating outside of a simulated eclipse region and that it is able to make measurements to the required degree of accuracy.

<u>Level 2:</u> The sensor will be able to meet the 0.5 degree accuracy requirement while inside the simulated eclipse region. The sensor has been integrated with a basic housing. The lab based test is improved in order to verify the accuracy of the sensor while operating inside the simulated eclipse as well as outside of the simulated eclipse.

<u>Level 3</u>: The sensor has been integrated with a housing that meets the customer's specifications of weighing less than 600g and has the dimensions of less than 95x107x63mm. The sensor is capable of recording and saving 200 minutes worth of health data (input current, voltage, temperature, and stale data health flag) and telemetry recorded at a rate of 0.5Hz (negotiable).

<u>Level 4:</u> The sensor meets the customer's power requirements of accepting an input voltage of 22-34V and does not exceed a maximum of 1W of power consumption during any mode of operation. The sensor is capable of transmitting and receiving data over CAN bus at no more than 388 Kbps.

4.0 Functional Requirements

1) The CubeSat, at an altitude of 250-750 km, makes a visual or infrared observation of Earth's horizon or records the temperature gradient given by the thermopiles. At a minimum, updates are sent to the bus at a rate of 0.5 Hz and will transmit and receive data at no more than 388 kbps, as requested by the customer.

2) In the case of both an image sensor and thermopiles, the sensor would need to be able to identify the nadir vector within 0.5 degrees. Once the sensor has made either one of these observations, the data would then be processed before being sent to the bus.

3) Once calculated, the processed data is output to the bus (the signal compatible with CAN specification, ver. 2 Bosch GmbH (RD-1)-CAN extended B, 29-bit identifier in order to properly communicate). Since our project sends data to the spacecraft, it does not perform attitude control on the spacecraft.

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How does the architecture differ (if at all) for the visible option?

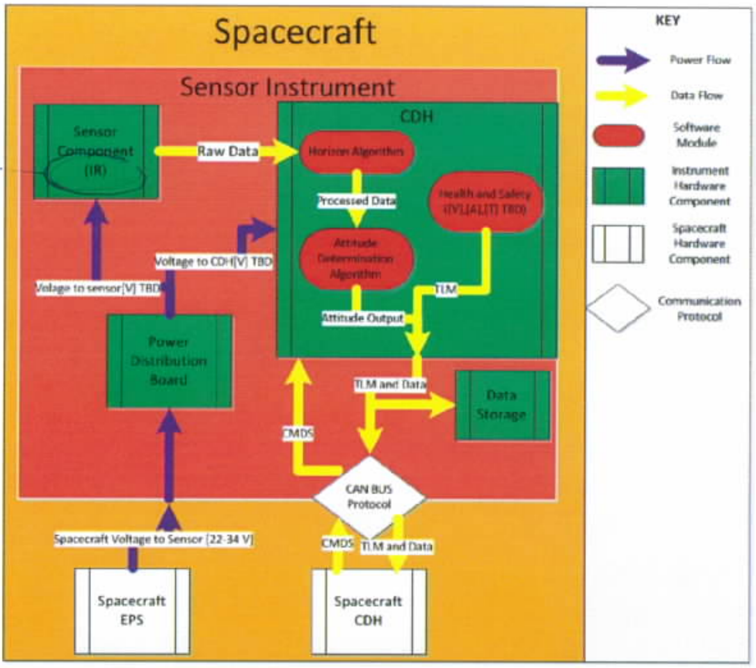

Figure 2: Functional Block Diagram

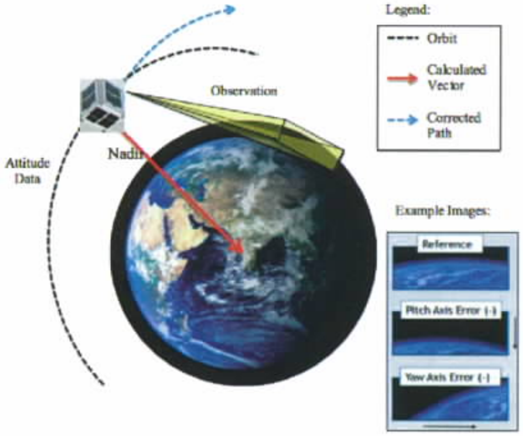

Figure 3: Imaging CONOPS[3]

Due to the multiple options of sensors, a method of testing was decided for each, listed below.

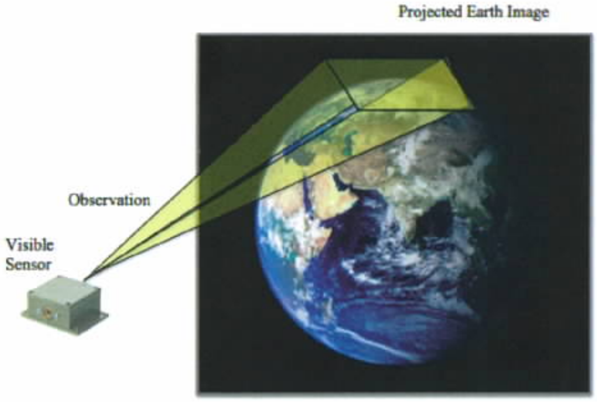

Figure 4: 'Visible' Testing CONOPS

1) An image of Earth is projected in a laboratory environment. Since the testing is being done with a visible light sensor, the image will be interpreted the same as an actual horizon. The sensor will be placed in such a way that the amount of the image it sees will be the same it would of Earth at the spacecraft's altitude.

2) The image data is processed and the nadir vector calculated. Knowing the experimental setup, the calculated nadir vector can be verified. Testing a visible light sensor is cheaper and more practical. The data received from this sensor could be used to verify the nadir-finding code and afterwards applied to the use of an infrared sensor.

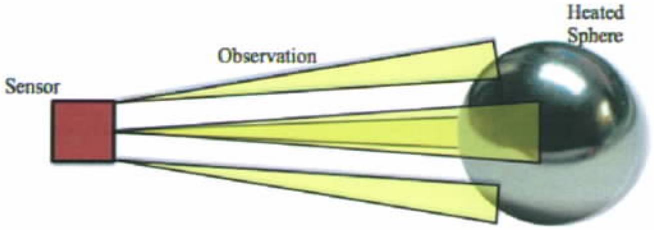

Figure 5:Thermopile Testing CONOPS

1) A sphere is heated in a laboratory environment, placed away from walls to better ensure a distinct temperature difference between the surface of the sphere and the surroundings detected by the thermopiles.

2) The sensor is placed in a similar manner as the Visible test. The orientation of the sensor can be manipulated to review different temperature gradients. Data is taken.

3) The data is processed and the nadir vector is calculated. The vector can then be verified from the use of the known pointing vector of the offset sensor. Both the pointing vector of the sensor and vector towards the center of the sphere are known before any calculation.

5.0 Critical Project Elements

Data Collection System - The sensor must collect data about position of the simulated Earth's horizon relative to the sensor. Choosing a sensor will require a large time commitment to conduct a trade study, determine a method of horizon detection (radiance balancing or image analysis), and the optical portions of the sensor will likely consume a substantial portion of the budget based on preliminary research.

Attitude Determination Algorithm - The system must interpret the simulated horizon data received from the sensor and derive the simulated Earth nadir vector to within the desired 0.5 degree of accuracy. Development of the algorithm is most likely going to require a very large allocation of time due to the complexities inherent in the problem. This is the main objective of the project and must be accomplished for any level of success.

Software/Microcontroller - The system must output the simulated Earth nadir vector and telemetry to the simulated satellite bus using the CAN protocol so that it can be used by the control system, as well as manage on-board memory, data storage, and system health. No member of the team has experience with this protocol and a large amount of time and effort will expended to ensure that our sensor can transmit and receive data.

Testing/Verification - Methods for simulating the horizon in a laboratory environment must be determined to verify the 0.5 degree pointing accuracy requirement. Viable options for testing include projecting images of the Earth's limb to validate an optical sensor, or to simulate the thermal characteristics of the Earth from orbit to validate a radiance balancing sensor.

6.0 Team Skills and Interests

Critical Project Elements	**Team members and associated skills/interests**
Data Collection System	Experience: Interest: Neal Stolz, Jesse Keefer, Noah Buchanan, Taylor Dean
Algorithm	Experience: Taylor Dean - Performs algorithm development for missile tracking Patrick Klein - Experience with image processing, vectorization, and combinatorial optimization

	Interest: Jesse Keefer, Noah Buchanan, Matthew Cirbo
Software/Microcontroller	Experience: Jesse Keefer - Enrolled in ASEN 4519 & experience with Arduinos. Patrick Klein - Enrolled in ASEN 5519 & experience with the Raspberry Pi microcomputer Matthew Cirbo - Works at LASP. Neal Stolz - Experience with real time data logging with Beagle Board onboard UAV Interest: Matthew Busby, Taylor Dean, Cole Oppliger, Neal Stolz
Testing/Verification	Experience: Matthew Busby- Worked on the T&I team for the AREND project over the summer. Neal Stolz - Test engineer for Sierra Nevada; creating and implementing test procedures for RECUV Noah Buchanan - Matthew Cirbo - Works at LASP. Interest: Taylor Dean, Neal Stolz, Cole Oppliger

7.0 Resources

Critical Project Elements	**Resource/Source**
Data Collection System	• Dr. Palo has contributed and offered feedback on our decision for sensor design. • Availability and pricing of both infrared imaging sensors and thermopiles are being actively researched by contacting manufacturers. • Data sheets for the sensors are being used to determine their viability in the system (based on spectrum, power, interface, etc.).
Algorithm	• Taylor has industry contacts with expertise in space-based infrared systems and tracking algorithms. • MATLAB is widely available for use in modelling and designing a proof-of-concept for our algorithm. • IDEs for specific microcontroller families are also available on the computers in the aerospace department and the ITLL, which will be used in developing and writing the algorithm.
Software/Microcontroller	• Professor LaDolce has offered general help on the topics of micro-controllers and bus integration. • James Mack in the RECUV fabrication lab is willing to share his knowledge concerning micro-controllers and system integration. • Both the ITLL laboratory and aerospace instrumentation shops will provide an environment conducive to prototyping the power distribution board, microcontroller, and software. • Surrey has offered assistance with integration of the CAN bus protocol, in order to ensure it conforms to their industry standards.
Testing/Verification	• The Fiske planetarium may be able to provide visual images that may be used for preliminary algorithm development. • Testing of the sensors may require specialized equipment, such as a method of uniformly heating a sphere, an infrared light, or liquid nitrogen. These options are actively being researched to determine the best method for the chosen sensor.

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8.0 References

[1]Thomas, J., and Wolfe, W., "*Spacecraft Earth Horizon Sensors,*" NASA, SP-8033, Langley, Virginia, December 1969.

[2] "STD 16 Earth Sensor," EADS Sodern, Limeil-Brevannes Cedex, France, PDF.

[3]Courtesy of Surrey Satellite Technology US LLC.

[4]Winetraub, Yonatan, and Anna B. Heller. *Attitude Determination - Advanced Sun Sensors for Pico-satellites. AGI.com*. Handasaim School, Tel-Aviv University, n.d. Web. 15 Sept. 2014. <https://www.agi.com/downloads/corporate/partners/edu/advancedSunSensorProject.pdf>.

[5]Albukerque, J., F. Mathet, et al. "Development of Static Earth Horizon Sensors." *AIAA* (2003): n. pag. *AIAA.org*. Web. 15 Sept. 2014. <http://arc.aiaa.org/doi/pdf/10.2514/6.2003-5564>.