University of Colorado
Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

Earth Horizon Sensor (ETHOS)
Conceptual Design Document

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1 Information

Project Customers

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2 Project Description

2.1 Purpose

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 **[1]**, 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 arcseconds. Earth horizon sensors are another source of attitude determination when the sun may not be visible or provide the right amount of accuracy or also when a star tracker will not track correctly or fit within budgetary constraints. These sensors have accuracies between star trackers and sun sensors **[1]** with 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.

This project will create and test an engineering model, which is defined as a prototype Earth horizon sensor, that will be tested in a laboratory environment while simulating a specific spectrum of the Earth as seen from simulated altitudes of 250-750 km. This project does not have the means (testing environments or funds) to create a flight-ready Earth horizon sensor that can be tested in a space-like environment, hence the scope of this project will be to design a prototype. The engineering model will have a mass of less than 600 grams, be no larger than 95x107x63 mm in size, and be contained in its own structure so that integration with a satellite would require only attachment of the structure to the satellite. The model is required to store 200 minutes of data (nadir vector, voltages, currents, and temperatures). In addition, the engineering model must be able to transmit said data to the bus as commanded by the bus. Surrey requires that the whole system must not use more than 5 Watts and must use the *controller area network* (CAN) protocol for data communication.

2.2 Objectives

The specific objectives for the project are divided into the four levels of success as listed below. The ultimate goal of the project is to create an engineering model capable of observing a simulated Earth horizon and providing a two-dimensional nadir vector in the model's coordinate frame. The engineering model should also satisfy the specified accuracy requirements inside and outside of a simulated eclipse region, be physically compatible with the satellite, and be compatible with the satellite's power supply and communication subsystem. The deliverable prototype Earth horizon sensor will be tested in and designed to work only in an Earth based laboratory environment.

Level 1: 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.

Level 2: The sensor will be able to meet the 0.5 degree accuracy requirement while inside a simulated eclipse region. The sensor is capable of maintaining performance while it is pointing as far as 40º off of sensor desired attitude. 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 of a simulated eclipse as well as outside of a simulated eclipse.

Level 3: The sensor has been integrated with a housing that meets the customer's specifications of weighing less than 600 g and has the dimensions of less than 95x107x63 mm. The sensor is capable of recording and saving 200 minutes worth of health data (currents, voltages, temperatures, and stale data health flag) recorded at a rate of 0.5 Hz (negotiable) and 200 minutes of attitude information recorded at a rate of 5 Hz.

Level 4: The engineering model meets the customer's power requirements of accepting an input voltage of 22-34V and does not exceed a maximum of 5 W of power consumption during any mode of operation. The sensor is capable of transmitting and receiving data via a CAN bus protocol at no more than 388 kbps, as required by the customer for their current line of satellites.

2.3 Concept of Operations

The concept of operations for an Earth horizon sensor is shown below. This would be an example of how the sensor is applied in a real-world application and does not reflect the use of the final product of this project. Multiple types of sensors are capable of being used to observe the Earth and determine the nadir vector. These include cameras that detect in the visible and infrared spectrum, thermopiles that detect thermal energy, and magnetometers that detect magnetic field.

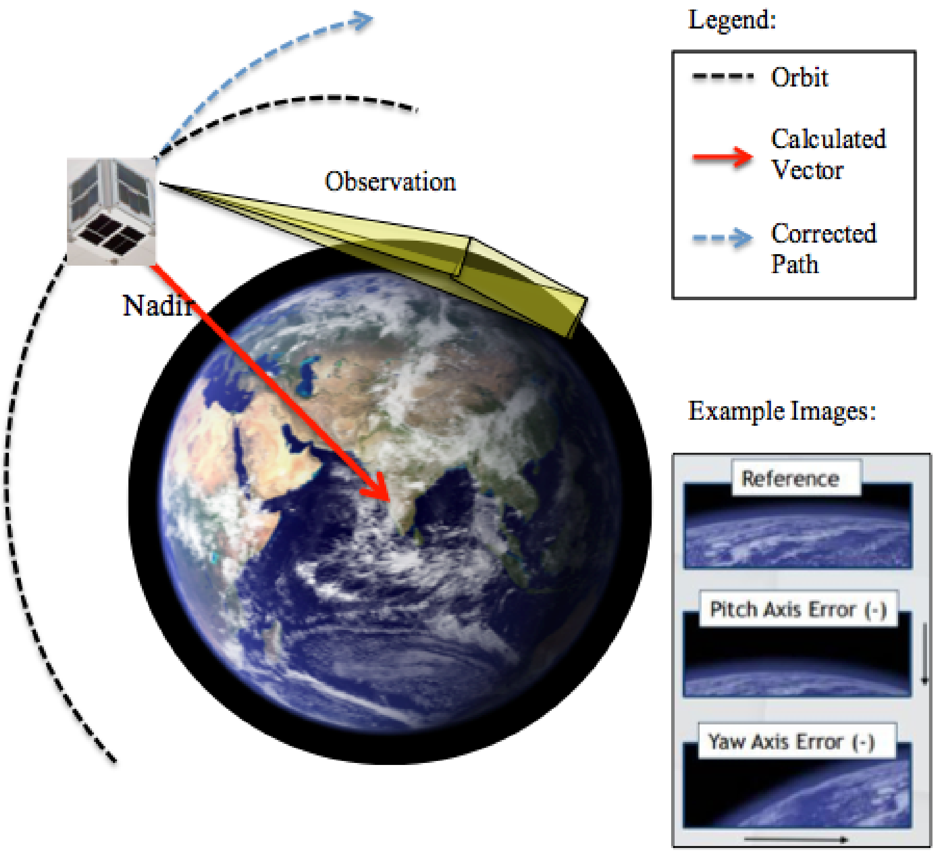

Figure 1: Theoretical Real-World CONOPS [2]

In Figure 1, the Earth horizon sensor makes an observation of the Earth. With this collected data, a nadir vector relative to the sensor is calculated and passed to the spacecraft. The satellite uses this information to determine its own orientation and make any necessary attitude adjustments. However, designing an Earth sensor that is flight ready is not within the scope of this project and thus a laboratory based prototype must be designed. Concept of operations for testing in a laboratory environment is shown below for a few methods.

Imaging CONOPS

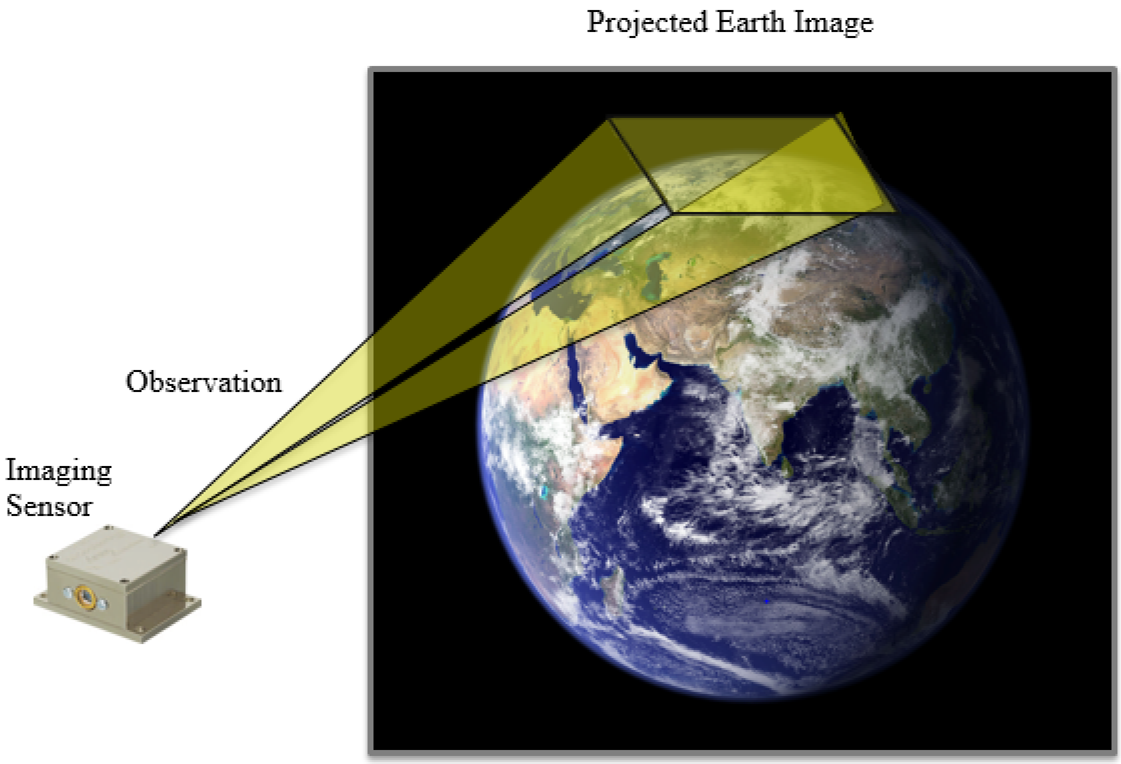

Figure 2: 'Imaging' Sensor Testing CONOPS

1) A simulation of Earth (a visual projection or heated disk) is displayed in a laboratory environment. 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 in the sensor's body coordinates is calculated. Knowing the experimental setup, the calculated nadir vector can be verified. 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.

Radiance Balancing CONOPS

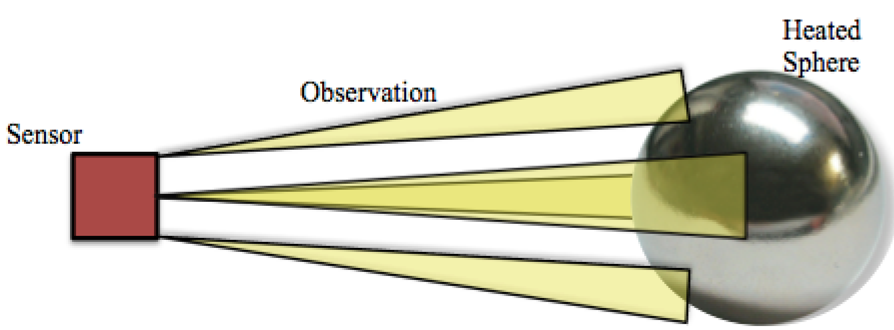

Figure 3: Radiance Balancing Sensor Testing CONOPS

1) A sphere or disk is uniformly 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 sensor. The sphere will be large enough to ensure it can be properly heated.

2) The sensor is placed in a similar manner as the visible test. What the sensor 'sees' of the sphere will be the same as what would be 'seen' at their proposed altitude. The orientation of the sensor can be manipulated to review different temperature gradients at various possible satellite orientations. 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.

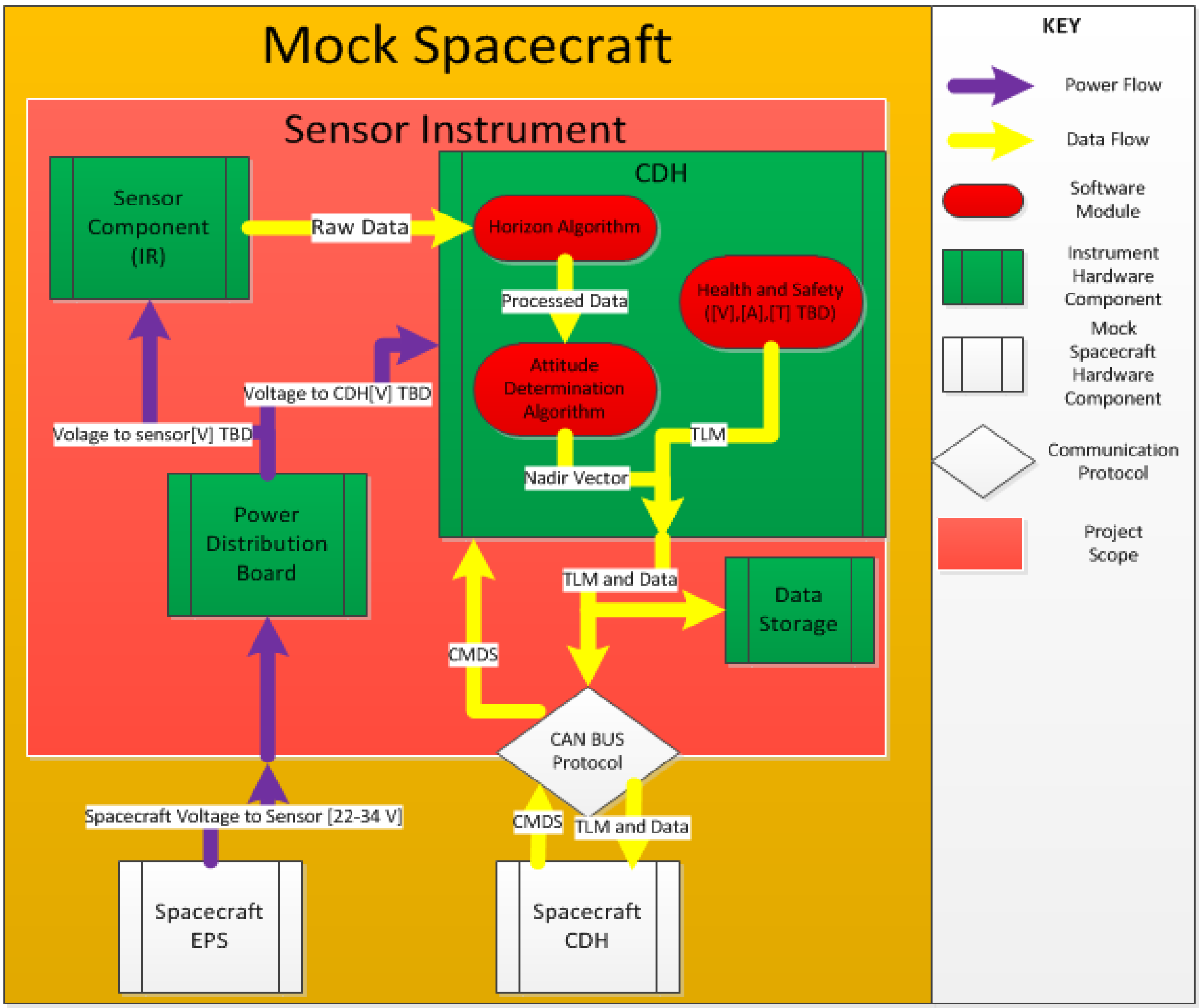

Figure 4: Functional Block Diagram

2.4 Functional Requirements

The functional requirements for the sensor are listed below, preceded by a functional block diagram outlining the processes of the sensor model and detailing how it should interact with the subsystems on board the simulated spacecraft.

FR.1 A statics sensor, at a simulated altitude of 250-750 km, makes an observation of the simulated Earth horizon.

FR.2 The engineering model must be able to receive raw data from the sensor then calculate and store the nadir vector. The engineering model must also store health and safety telemetry (voltages, currents, and temperatures).

FR.3 The engineering model must integrate with a simulated spacecraft bus and be designed for a small spacecraft.
The engineering model must be able to output both the nadir vector and health and safety telemetry when commanded by the simulated spacecraft.

3 Design Requirements

The functional requirements (FR.X) are listed below with the corresponding design requirements (DR.X) to show the design requirements flowdown.

FR.1 ETHOS shall be able to make observations of a simulated Earth.
- **DR.1.1** ETHOS shall make observations from simulated orbital altitudes of 250-750 km.
  - **DR.1.1.1** ETHOS shall be able to make observations outside of a simulated eclipse region.
  - **DR.1.1.2** ETHOS shall be able to make observations during a simulated eclipse period lasting at least 35 minutes.
- **DR.1.2** ETHOS shall be a static system, it shall not be a scanning system.

FR.2 ETHOS shall receive raw data from the sensor and return the nadir vector.
- **DR.2.1** ETHOS should post process raw data from sensor.
- **DR.2.2** ETHOS shall determine the Nadir vector from observations of a simulated Earth.
  - **DR.2.2.1** ETHOS software shall determine the nadir vector to within 0.5 degree accuracy.
  - **DR.2.2.2** ETHOS software shall determine the nadir vector for 2 *degrees of freedom* (DOF).
  - **DR.2.2.3** ETHOS should determine nadir vector after a 40 degree disturbance from center.
- **DR.2.3** ETHOS sensor management system (SMS) shall monitor the health and status of itself.
  - **DR.2.3.1** The SMS shall monitor the input current and voltage.
  - **DR.2.3.2** The SMS flag 'stale' telemetry data (data that did not update and should not be used in attitude solution).
- **DR.2.4** The software must store health data and the nadir vector.
  - **DR.2.4.1** The software must store nadir vector data at 5 Hz.
  - **DR.2.4.2** The software must store health and status data at 0.5 Hz.
  - **DR.2.4.3** The SMS will be able to store 200 minutes of telemetry data.
  - **DR.2.4.4** The stored data may be overwritten oldest to most recent.

FR.3 ETHOS shall integrate with a simulated spacecraft bus.
- **DR.3.1** ETHOS shall have a data output compatible with CAN specification, ver. 2 Bosch GmbH (RD-1)-CAN extended B, 29 bit identifier.
  - **DR.3.1.1** Nadir vector output shall be between 1 & 5 Hz.
  - **DR.3.1.2** Health and status output shall be 0.5 Hz.
  - **DR.3.1.3** Total data output shall not exceed 388 kbps.
- **DR.3.2** ETHOS shall be designed to integrate with small satellite buses.
  - **DR.3.2.1** ETHOS shall have no dimension exceeding 95 X 107 X 63 mm.
  - **DR.3.2.2** ETHOS shall have a mass no greater than 600 grams.
  - **DR.3.2.3** ETHOS shall consume no more than 5 Watt (peak) for any mode of operation.
  - **DR.3.2.4** ETHOS shall accept an input voltage between 22 V and 34 V.

4 Key Design Options Considered

4.1 Observation Medium

The ETHOS team approached the design of an Earth sensor by first examining the observation medium. This section addresses the three options considered: the infrared and visible spectra, and the magnetic field as they are observed from orbit.

4.1.1 Infrared

The *infrared* (IR) spectrum is generally characterized as the electromagnetic radiation with a wavelength spanning from 0.7 µm in the near IR, to 1000 µm in the far IR. It has been found that at wavelengths below 5 µm, the reflected solar radiation is significantly greater than the Earth's emitted radiation. As viewed from space, the Earth emits significantly at wavelengths greater than 6 µm. Because the Earth radiates significantly more than the reflected radiation of the Sun above 6 µm, it will be possible for a sensor using the far IR band above 6 µm to view the Earth in both an eclipse and in sunlight. The drawbacks to viewing the Earth in the far IR band are primarily due to instability in atmospheric temperature, which is caused by local weather patterns, as well as seasonal variations. The emission band with the most stability is the CO_2 emission band, which encompasses wavelengths from 14 to 16 µm. The CO_2 emission band has been used by previous Earth sensors to achieve a pointing accuracy of 0.5° or less, and were included on spacecrafts such as Mercury, Gemini, OGO, ADEOS, and MetOp. **[3][4]**

Table 1 : Infrared Pros and Cons

Pros	Cons
Far IR can be seen in eclipse **DR.1.1.1**	Seasonal variations in atmospheric temperature
Radiation of Earth is greater than reflection of solar radiation at wavelengths greater than 6µm	Difficulty of testing by recreating emission at specific spectral band, and simulating space
CO_2 emission band is stable	
Has been used by previous sensors to achieve 0.5° accuracy **DR.2.2.1**	

Table 2: Infrared Facets

Facet	Value
Testing Complexity	High: would need to simulate Earth-sensor system with heated sphere/disk and cooled background in lab
Interference Sources	Seasonal atmospheric variations
Eclipse Functionality	Functions in eclipse in far IR band above 6 µm
Uniformity	Uniform in 14 to 16 µm CO_2 emission band

4.1.2 Visible Light

The visual spectrum of light is defined as the electromagnetic radiation with wavelengths ranging from 0.4 to 0.7 μm. For a sensor in Earth orbit, outside of eclipse, there is visible radiation coming from the Sun, as well as reflected solar radiation from the Earth. For a sensor in eclipse, the only visible radiation is reflected solar radiation at the terminator, which is defined as the boundary between day and night on the Earth. Due to the wide variations in the albedo (fraction of reflected solar energy) of different materials on Earth's surface (0.06 for vegetation vs. 0.8 for snow), the terminator is not well defined enough for an accurate horizon measurement **[5]**. Although a measurement in the visible spectrum would be impractical for a sensor in eclipse, a sensor operating outside of eclipse in the visual spectrum would have the benefit of simple testability.

Table 3: Visible Pros and Cons

Pros	Cons
Ease of testing: Projected visible image	Inconsistent spectrum
	Does not allow data taking at night **DR.1.1.1**

Table 4: Visible Facets

Facet	Value
Testing Complexity	Simple: visual sensor can be tested with projected image
Interference Sources	Non-Earth light sources, man-made light
Eclipse Functionality	No; data cannot be taken since the emission of light is not intense enough
Uniformity	Non-uniform: Large variations of albedo between materials

4.1.3 Magnetic Field

Differing from the previous spectra considered, the field is measured by magnetic flux density as opposed to a light spectrum. Earth's magnetic field ranges from 25,000 to 65,000 nanoteslas **[6]** and variations in the intensity of the field occur with the approach to the poles of the Earth. While there is the general trend of intensity towards and away from the poles, there are also variations in regions. To compensate, local estimation methods were created by various groups (e.g. The International Union of Geodesy and Geophysics **[7]**) to analyze and diminish the effect of these variations. There is also a database **[8]** of the global magnetic field estimations using this method that is updated every five years. Magnetic field variation over time can occur on the order of milliseconds or years, though the changes are minute, they add a level of uncertainty to the measurements that would be taken. While these uncertainties exist, they are not dependent on night and day cycles of the Earth. The database can be used regardless of the time of day with the same amount of associated error. Due to the variations alone, the geomagnetic field does not seem to be a feasible option for observations.

Table 5: Pros and Cons of Magnetic Field

Pros	Cons
Expansive database of estimated magnetic field intensity values	Frequent deviations from models
Functions in both day and night **DR.1.1.1**	Variations in the Earth's magnetic field would be hard to model

Table 6: Magnetic Field Facets

Facet	Value
Testing Complexity	Medium-High; Depending on the testing environment, it may be difficult to isolate relevant magnetic waves and accurately model the Earth's magnetic field
Interference Sources	Solar wind, solar flares, currents in ionosphere, daily variation
Eclipse Functionality	Yes, Magnetic field in unaffected by eclipse cycles
Uniformity	Non-uniform across the magnetic range

4.2 Sensor Categories

The ETHOS team then approached the next part of the design of an Earth sensor by examining the observation method, or sensor. This section addresses the three options considered: an imaging sensor, radiance balance sensor, and a magnetometer.

4.2.1 Radiance Balance

The radiance-balancing type sensor is a static sensor which uses a differential in the Earth's radiative flux to determine a 2 DOF nadir vector to the Earth. Radiance balancing sensors generally use multiple thermopiles, which consist of an array of small thermocouples connected in series. These convert temperature differences into voltage using the Seebeck effect. This means that thermopiles are passive sensors, and do not require any input voltage. To achieve an accurate temperature measurement, the temperature of the cold junction and sensor housing must be known. Several types of thermopiles have options to include this measurement via an integrated thermistor **[9]**.

These thermopiles are pointed at different locations on the Earth's horizon, such that when the sensor is nadir pointing, the radiative flux received by each thermopile is equal. If the sensor is perturbed from nadir pointing, the resulting change in horizon position within each thermopile's field of view will cause a change in radiative flux received by each thermopile. This difference is analyzed and the nadir vector is determined.

One method is to use a set of four orthogonal thermopiles pointed at the Earth horizon, such that the sensor's z-axis is nadir pointing. In this configuration, the sensors' outputs will be equal when the z axis is aligned with the nadir vector; any imbalance between the outputs can be converted into a vector. Figure 5 below depicts a sensor that has been perturbed from nadir. As a result, the left facing thermopile is experiencing an increase in radiative flux, while the right facing thermopile experiences a reduction in radiative flux.

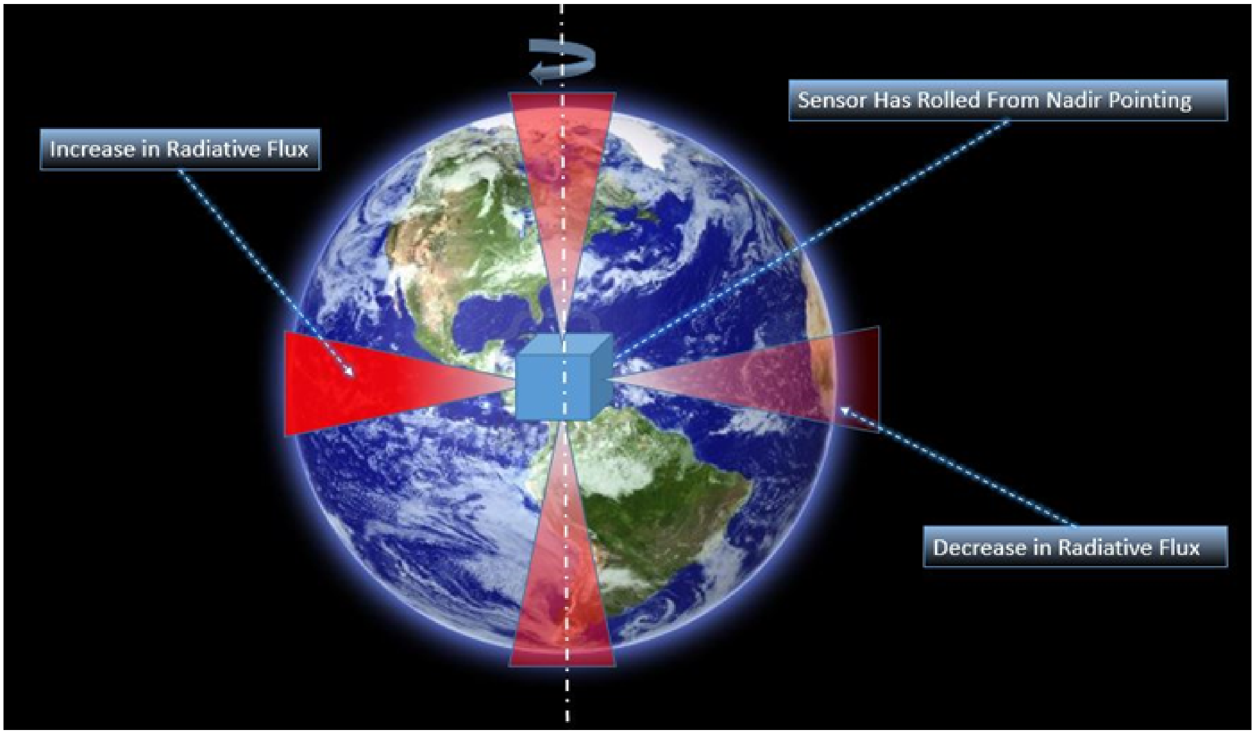

Figure 5: Perturbed radiance balancing sensor

To ensure the feasibility of radiance balancing sensors, it must be shown that thermopiles with specifications representative of commercially available sensors will perform within their limitations at the simulated altitudes (250-750 km). The details of the following calculations are included in Appendix A. For this analysis, the Earth's horizon is simplified to a flat disk (which will be called "source") emitting at a 15 μm wavelength, and a detector with a radius of 0.6 mm at a distance of 750 km. The total voltage output should be within the resolution ranges given by the manufacturer for the thermopile to be considered feasible. Table 7 shows the analytical results of two thermopiles, an analog type thermopile, which is housed in transistor-type packaging **[10]**, and a MEMS thermopile, which is housed in a wafer chip–scale package **[11]**. The Dexter ST120, and the Texas Instruments TMP007B, represent the analog thermopile and a MEMS thermopile, respectively.

Table 7: Thermopile Feasibility Analysis [10][11]

15μm Emission at 750 km	Desired Voltage Output (mV)	Modeled Voltage Output (mV)
Dexter ST120	0.1800	0.1769
TI TMP007B	> 3×10^{-4}	0.0189

For a feasible solution, it is necessary to view specific portions of the Earth's limb and limit the radiative flux of the thermopiles to within operating limits, by restricting the FOV. This can be calculated with simple trigonometry as detailed in Appendix A. When using multiple sensors, it would be unnecessary to have a FOV with a diameter larger than half of the Earth disk or 6500 km, which corresponds to a half angle of 25 degrees. To obtain this field of view, a small box with a pinhole can be constructed. For a 25 degree FOV, a 0.4 mm pinhole is necessary which is within the capabilities of the Aerospace machine shop.

Table 8: Pros and Cons of Radiance Balancing

Pros	Cons
Low power consumption. Traditional thermopiles are completely passive, and MEMS uses 0.528 mW. **DR.3.2.3**	Testing is difficult in laboratory setting due to problem of emitting in CO2 band.
Works during eclipse. **DR.1.1.1**	Integration requires precise installation.
Small volume on the order of 1.5x0.3x0.5 mm. **DR.3.2.1**	
Any required pinholes are able to be manufactured at the aerospace machine shop.	

Table 9: Table of Typical Facet Values for Radiance Balancing Sensor

Facets	Value
Cost	~ $6
Volume	~0.225 mm^3
Mass	~10 g
Integration/Manufacturing Complexity	High
Required Processing Power	Low
Power Dissipation	<= 1 Watt
Testing Complexity	Moderate

4.2.2 Imaging

Imaging sensors work by capturing intensity data from within the sensor's FOV with a dense pixel array. This intensity data can be interpreted by a processor to determine the simulated Earth horizon line and calculate a nadir pointing vector in the sensor's reference frame. Imaging sensors typically have a large number of pixels (much greater than 1000 pixels), allowing them to have a high spatial resolution. Imaging sensors are available in a wide range of prices inside and outside of our budget (total of $5000), with FOV options between 10º and 120º, which provide enough options to easily satisfy **DR.2.2.3**. Inexpensive imaging sensors (less than $250) typically function only in the visible spectrum and their optics are of lesser quality. Imaging sensors between $250 and $2500 are available in many different spectrums and have higher quality optics and construction. Imaging sensors typically have a data rate of greater than or equal to 10 Hz, which exceeds **DR.3.1.1**. Finally, an imaging sensor typically dissipates less than or equal to 1 W of power, meeting **DR.3.2.3**. Imaging sensors are usually pre-installed on circuit boards for easy integration into existing systems with dimensions of less than 20x20x10 mm (**DR.3.2.1**).

The range in FOV, price, and resolution of imaging sensor provide significant flexibility in overall design options. Depending on the sensor models chosen for the final design, imaging sensors can be used as single units, or combined with other imaging sensors to increase FOV, resolution, accuracy, error checking, and redundancy. Figure 6 shows how two imaging sensors can be combined in order to increase the FOV.

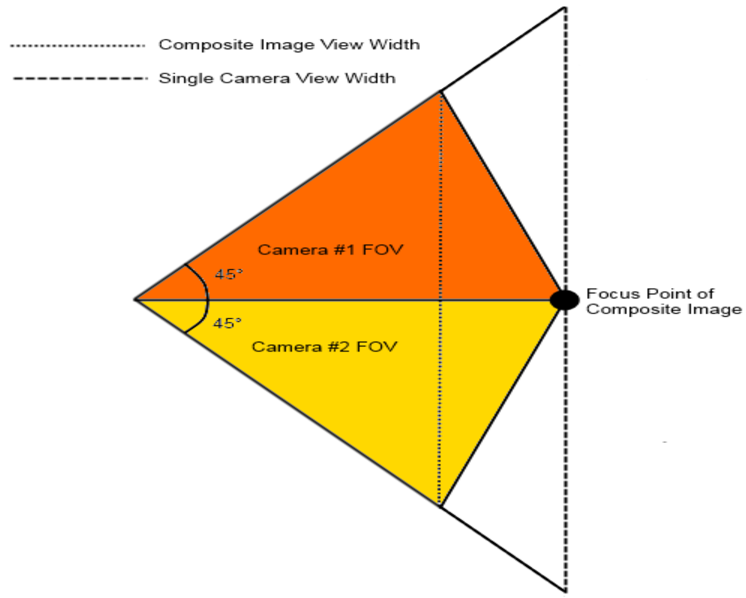

Figure 6: Combined Sensor FOV

Table 10: Pros and Cons of Imaging Sensor

Pros	Cons
Many FOV options to meet **DR.2.2.3**	Cheap lenses can cause optical distortion, decreasing overall accuracy. **DR2.2.1**
Data rates typically greater than 10 Hz. **DR.3.1.1**	Increased data due to high resolution requires increased data processing resources.
Typically <= 1W of power dissipation. **DR.3.2.3**	

Table 11: Table of Typical Facet Values for Imaging Sensors

Facets	Value
Cost	\$20 - \$3000 (many options exist between \$20 and \$300)
Volume	~5000 mm^3
Mass	~5 g
Integration/Manufacturing Complexity	Low
Required Processing Power	High
Power Dissipation	<= 1 W

Testing Complexity	Easy

4.2.3 Magnetometer

Magnetometers are devices that can be used to detect magnetic fields that are present. They work by sending an alternating current through one coil, which produces a magnetic field. This field is picked up by a second coil and then outputs the magnetic waveform. When a separate magnetic field is present, like the Earth's, the output waveform is changed. This change in waveform can be analyzed to find the magnitude of the detected magnetic field. Research shows that having three magnetometers in a three-axis configuration would be able to be combined into a vector of the Earth's magnetic field **[12]**, although knowledge of the Earth's magnetic field relative to the location in the orbit of the magnetometer would have to be known because the strength and direction of the field depends location around Earth. All electronics emit some amount of a magnetic field, which means that interference with the sensor's or spacecraft's electronics can be a problem. This interference sometimes requires the magnetometer to be attached to the satellite via a boom in order to minimize the interference.

The feasibility of the design can be brought back to the requirements of the sensor system. One of the requirements for this sensor is that it works in and out of eclipse. The Earth's magnetic field is constant with respect to eclipse which means that this sensor meets requirement **DR.1.1.1**. A typical three-axis magnetometer consumes around 0.6 Watts which also meets the power requirement **[13]**. The size of a typical magnetometer is 88x106x30mm for the electronics and 40x40x31mm for the sensor itself, which meets the size requirement by only taking up 51.4% of the total volume. The magnetometer was the largest option that was considered. Generally, as COTS magnetometers gets more accurate, the total volume increases as well. A typical COTS three-axis magnetometer costs is in excess of $9820, which is nearly twice the project budget.

Table 12: Pros and Cons of Magnetometer

Pros	Cons
Three-axis magnetometer is a proven method of attitude sensing.	Larger size than the other options considered. **DR.3.2.1**
Typical power consumption is around 0.57 Watts. **DR.3.2.3**	Typical cost for high accuracy is around $9,820.
Works during eclipse. **DR.1.1.1**	Not an Earth horizon sensor.
	Interference from other electronics.

Table 13: Table of Typical Facet Values for Magnetometers

Facets	Value
Cost	$9,000
Volume	300,000 mm^3
Mass	~450g
Integration/Manufacturing Complexity	High
Required Processing Power	Low
Power Dissipation	0.6 Watts

Testing Complexity	High

5 Trade Studies

5.1 Trade Study Process

This section contains the two trade studies that determine the optimal choice for the observation medium and sensor. In this process, facets that have already been described for each of the design options are assigned a weighted value to objectively compare the benefits and constraints associated with each design option. A higher score indicates a more favorable aspect.

5.2 Observation Medium Trade Study

5.2.1 Observation Medium Facet Descriptions

Testing Complexity: This facet represents the difficulty of testing a sensor operating within a given medium. Since the sensor will be tested in a laboratory environment, it must be possible to create a simulation of the Earth within the chosen medium. This facet was chosen because **FR.1** requires that the sensor observe a simulated Earth.

Interference Sources: This facet represents the amount of interference generated by external sources that can negatively affect within a given medium. Interference will reduce accuracy or in extreme cases prevent the nadir vector from being determined at all. This facet was chosen because of its importance to successfully fulfilling the general requirement of determining the nadir vector in **FR.1** and to satisfying the accuracy requirements in **DR.2.2.1** and **DR.2.2.2.**

Eclipse Functionality: This facet represents the ability to view the simulated Earth during a simulated eclipse period. In order for the sensor to provide the nadir vector for an entire orbital period the simulated Earth must be viewable in daylight and eclipse for the chosen observation medium. This facet is essential for satisfying **DR.1.1.2.**

Uniformity: This facet represents how uniform the Earth appears within a given observation medium. A more uniform Earth will be easier to distinguish from the space background and will allow for the nadir vector to be returned with greater accuracy. Inconsistencies in terrain, temperature, clouds, and other factors may reduce the accuracy at which the horizon can be distinguished, thus reducing nadir vector accuracy. This facet is also important for satisfying **FR.1**, **DR.2.2.1** and **DR.2.2.2.**

5.3.2 Observation Medium Facet Weights and Rationale

Table 14: Observation Medium Facet Weights

Facet	Weight	Rationale
Testing Complexity	30%	Testing complexity is a very important issue to consider since the sensor will be tested in a laboratory environment. This facet was considered to be important since it must be possible to simulate the Earth in the chosen medium with the available testing facilities.
Interference Sources	15%	Interference sources are important to consider when assessing possible error. However, interference can be reduced with the appropriate testing apparatus or with good noise characterization. This facet was considered to be the least important since measures can be taken to reduce interference.
Eclipse Functionality	35%	Eclipse functionality is essential for satisfying **DR.1.1.2.** This facet was considered to be more important than the others since observation during eclipse is critical for being able to provide the nadir vector in any lighting condition.
Uniformity	20%	Uniformity is important when considering the accuracy at which the horizon can be distinguished. However, the accuracy of the algorithm that is ultimately used to determine the location of the horizon will also have a large effect on the accuracy of the returned nadir vector. Because of this, the uniformity facet was not considered to be as important as the testing complexity or eclipse functionality.

5.3.3 Observation Medium Facet Value Range

Table 15: Observation Medium Facet Value Range

Facet	5	3	1	Heuristic
Testing Complexity	Low	Moderate	High	Less testing complexity is desirable so that the sensor can be successfully tested in a laboratory environment.
Interference Sources	Few	Moderate	Many	Fewer sources of interference will help reduce error when distinguishing the Earth horizon from space and allow for a greater accuracy when determining the nadir vector.
Eclipse Functionality	Yes	-	No	In order to satisfy **DR.1.1.2** the sensor must be able to function during eclipse. There isn't a middle ground for this facet as the medium will either allow for observation during eclipse or it won't. Therefore this facet can be evaluated on a pass/fail basis.
Uniformity	Very Uniform	Somewhat Uniform	Not Uniform	Greater uniformity in the Earth's appearance within a given observation medium will allow for greater accuracy in returning the nadir vector. This will help satisfy **DR.2.2.1** and **DR.2.2.2.**

5.3.4 Observation Medium Trade Study

The results of the observation medium trade study are shown in Table 16 below. The weighted score for each facet is listed underneath the medium with its raw score noted in parentheses. The maximum score for each facet is 5 so the maximum weighted total value is also 5 and because of the way facets are graded the higher score a medium receives the more desirable it is for the purpose of this project.

Table 16: Observation Medium Trade Study Results

Facet	Weight	Visible	Infrared	Magnetic Field	Max Weighted Value
Testing Complexity	30%	1.5 (5)	0.9 (3)	0.3 (1)	1.5
Interference Sources	15%	0.45 (3)	0.75 (5)	0.15 (1)	0.75
Eclipse Functionality	35%	0.35 (1)	1.75 (5)	1.75 (5)	1.75
Uniformity	20%	0.6 (3)	1.0 (5)	0.2 (1)	1.0
Total	100%	**2.9**	**4.4**	**2.4**	**5.00**

5.3 Sensor Trade Study

5.3.1 Sensor Facet Descriptions

Cost: The use of each sensor may be limited by the availability of an affordable option. As the total budget for the project is $5,000, the sensors must be available within this price range. It would be beneficial to minimize the cost where possible, in order to maintain a budget that allows the other necessary components to be purchased. Additionally, our customer expects an engineering model that could potentially be an affordable alternative to star trackers.

Volume: As strict requirements regarding the maximum dimensions for the entire sensor model has been given, it is essential that any sensor be under these dimensional requirements. In order to handle this specification, the typical volume for the sensor type will be taken as a representative value of its dimensions in order to minimize the impact of the constraint given by **DR.3.2.1**.

Mass: An overall mass limit on the model has been given by the customer, which requires that the chosen sensor must be under 600 grams as given by **DR.3.2.2**. Minimization of the mass is important to ensure that the other components within the model are not limited by this constraint.

Integration/Manufacturing Complexity: The integration of the sensors with the engineering model is an important aspect for meeting the mechanical integration requirement given by **DR.3.2**. It is also necessary that the constraints specific to a sensor type, such as the number of sensors or pointing requirements, be met with the most precision possible, in order to meet the accuracy requirement given by **DR.2.2.1**.

Required Processing Power: In addition to the need for the sensor to adequately sense the Earth, it must be able to output the data to an electronics control unit. The sensor must be able to interface with a control unit through a common bus, and the data output from the sensor must be passed through an algorithm to output the nadir vector to fulfill the requirement given by **DR.2.2**.

Power Consumption: The power requirement given by **DR.3.2.3** states that total power consumption shall not exceed 5 watts for the entire model. Although most sensor options will fulfill this requirement, it is still necessary to appropriately distribute the power in order to ensure the electronics control unit has a sufficient power allotment.

Testing Complexity: Testing the function and accuracy is an important aspect that determines how feasible it may be to verify and validate the use of the chosen sensor. The tests that must be conducted may require a significant time and cost investment. Because of the impact it will have on the timeline of the project, this facet must be considered for each design option.

5.3.2 Sensor Facet Weights and Rationale

Table 17: Sensor Facet Weights

Facet	Weight	Rationale
Cost	10%	Cost is an important factor to consider since the project has a total budget of $5,000.
Volume	15%	Volume is also an important factor to consider since it must meet the requirement specified by **DR.3.2.1**. This facet must be balanced with other requirements so it is equally as important.
Mass	15%	Mass is another important factor to consider since it must also meet a requirement specified by **DR.3.2.2**. Mass and volume are closely related so they are also equally important.
Integration/Manufacturing Complexity	10%	Each type of sensor is roughly the same size. While the way in which they are integrated differs the complexity of integration and manufacturing is not as important.
Required Processing Power	10%	Processing power is not as important as other facets since The power requirements defined in **DR.3.2.3** allow for a powerful processor to analyze the data.
Power Consumption	20%	Power dissipation holds a very high weight due to the fact that the total power dissipation of the sensor module must be less than 5 W and many sensors have power dissipations of greater than 1 W. The lower the power consumption of the sensor, the larger the amount of power than can be allocated to other components. With an already tight constraint of 5 W, close attention had to be paid to the power usage of the sensors and the quick elimination of those that were too high.
Testing Complexity	20%	The complexity of testing determines the amount of time that will be spent on designing a testing environment and verifying the chosen sensor. The easier the sensor is to test, the more time can be spent troubleshooting. The variation in testing complexity among the options being considered in this document is negligible, therefore there is not significant weight given to the testing complexity of the options in the trade study.

5.3.3 Sensor Facet Value Ranges

Table 18: Sensor Facet Value Ranges

Facet	5	4	3	2	1
Cost	< $20	$20 - $300	$300 - $1000	$1000 - $5000	> $5,000
Volume	< 1 mm^3	1 - 1000 mm^3	1000 - 3000 mm^3	3000 - 10,000 mm^3	> 10,000 mm^3
Mass	<10g	10 - 50g	50 - 100g	100 - 400g	400 - 600g
Integration/Manufacturing Complexity	Low	-	Moderate	-	High
Required Processing Power	Low	-	Moderate	-	High
Power Consumption	<1 mW	1 - 300 mW	300 - 500 mW	500 mW - 1 W	1 - 2 W
Testing Complexity	Low	-	Moderate	-	High

The ranges for facet values are on a 1-5 scale and were chosen based on the minimum and maximum values assigned to the sensor types. The intermediate values were decided to be approximate linear interpolations of the max values. The values for the more subjective facets that do not have associated numerical values are based on the complexity levels for that facet. Integration/Manufacturing Complexity considers possible multi-sensor configurations and the level of accuracy needed when mounting. The Required Processing Power considers what the output from the sensor will be, and how complex the required algorithm will be to determine the nadir vector from that data.

5.3.4 Sensor Trade Study

The results of the sensor trade study are shown in Table 19 below. The weighted score for each facet is listed underneath the sensor type with its raw score noted in parentheses. The maximum score for each facet in this study is also 5 so the highest score represents the most desirable sensor.

Table 19: Sensor Trade Study Results

Facets	Weight	Radiance Balancing	Imaging	Magnetometer	Max Weighted Value
Cost	10%	0.50 (5)	0.40 (4)	0.10 (1)	0.5
Volume	15%	0.75 (5)	0.30 (2)	0.15 (1)	0.75
Mass	15%	0.60 (4)	0.75 (5)	0.15 (1)	0.75
Integration/ Manufacturing Complexity	10%	0.10 (1)	0.50 (5)	0.10 (1)	0.50
Required Processing Power	10%	0.50 (5)	0.10 (1)	0.50 (5)	0.50
Power Consumption	20%	1.00 (5)	0.80 (4)	0.40 (2)	1.00
Testing Complexity	20%	0.20 (1)	1.00 (5)	0.20 (1)	1.00
Weighted Total	100%	**3.65**	**3.85**	**1.60**	**5.00**

6 Baseline Design

6.1 Summary of Trade Study Results

Due to the nature of this project, only two major trade studies were performed. The first trade study was to determine the observation medium which included the infrared and visual spectrum, and Earth's magnetic field. The second trade study was conducted to determine the appropriate sensor type from the options of radiance balancing, imaging, and magnetometers. The rest of the components of this project depended on the choice of sensor, so those components will be considered in more detailed studies for the PDR.

The observation medium trade study considered four major categories of importance to the project. These options included testing complexity, interference sources, eclipse functionality, and uniformity of the specturm. The most highly weighted facets considered were eclipse functionality, and testing complexity. These facets were found to have the largest impact on the project. Once the trade study was conducted, it was determined that the magnetic field and visual spectrum did not meet the necessary requirements, making the infrared spectrum the first choice.

The next trade had a different set of facets derived from the detailed requirements. These included cost, volume, mass, integration and manufacturing complexity, required processing power, power dissipation, and testing complexity. The radiance balancing option scored 3.65 and the imaging method scored 3.85. Even though these scores are very close the vast difference in testing complexity shows that the imaging method is a better choice. With the short timeline available; testing, verification, and validation are crucial aspects that will affect the success or failure of the project.

6.2 Selection of Baseline Design

Table 20: Selection of Baseline Design

Subsystem	Option	Requirements Met
Horizon Determination Sensor	IR Imager	● **DR.1.1** ○ **DR.1.1.1** ○ **DR.1.1.2** ● **DR.1.2** ○ **DR.2.2.1** ○ **DR.2.2.2** ○ **DR.2.2.3** ● **DR.3.2** ○ **DR.3.2.1** ○ **DR.3.2.2** ○ **DR.3.2.3** ○ **DR.3.2.4**
Electronics/Storage*	Microcomputer	● **DR.2.4.1 - DR.2.4.4** ● **DR.3.1.1** ● **DR.3.1.2** ● **DR.3.2.1 - DR.3.2.4**

* See Appendix B

Appendix A : Radiance Balancing Analysis

To ensure the feasibility of radiance balancing sensors, it must be shown that thermopiles with specifications representative of commercially available sensors will perform within their limitations at the simulated altitudes (250-750 km). For this analysis, the Earth's horizon is simplified to a flat disk (which will be called "source") emitting at a 15 μm wavelength, and a detector with a radius of 0.6 mm at a distance of 750 km. This scenario is shown in Figure A1.

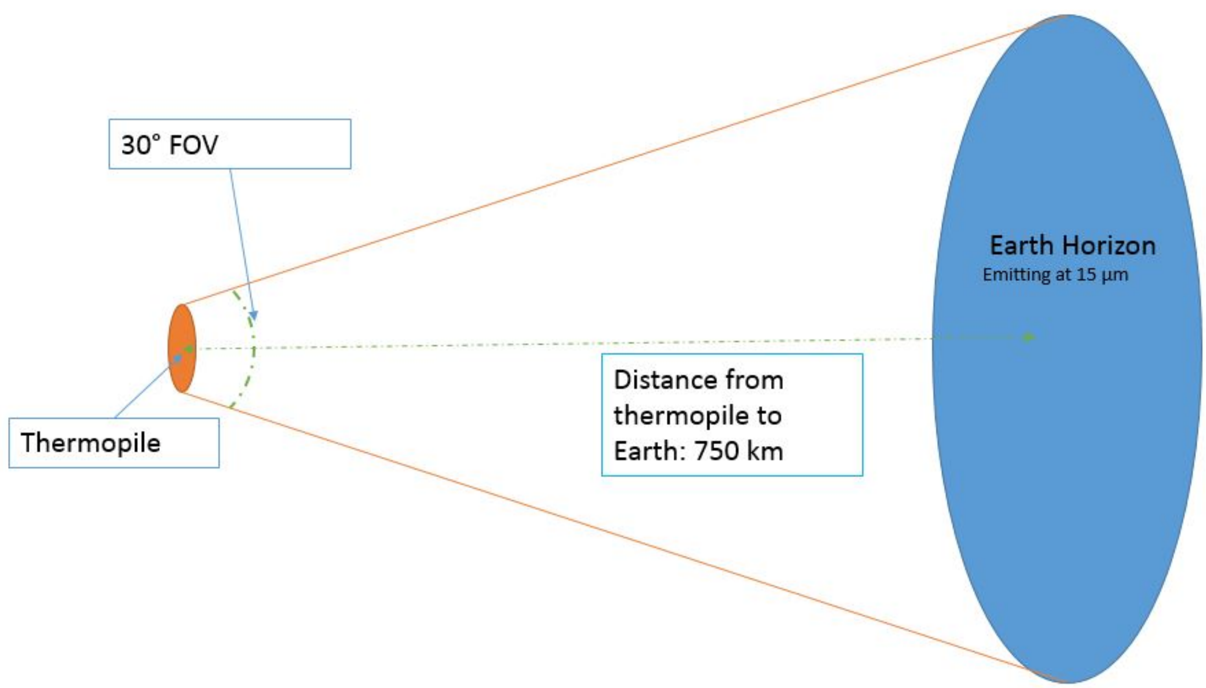

Figure A1: Simplified Sensor-Horizon System [14]

The total voltage output should be within the resolution ranges given by the manufacturer for the thermopile to be considered feasible. Table 7 shows the analytical results of two thermopiles, an analog type thermopile, which is housed in transistor-type packaging **[10]**, and a MEMS thermopile, which is housed in a wafer chip–scale package **[11]**. The Dexter ST120, and the Texas Instruments TMP007B, represent the analog thermopile and a MEMS thermopile, respectively.

Given a field of view for the thermopile and the altitude of the sensor, it is possible to calculate the radius of the source disk that the thermopile will be viewing. The temperature of the source can be determined by Wein's displacement law, given as Eq. 1.

$$T_{source} = \frac{C_3}{\lambda_{max}}, \text{ where } C_3 = 2987.8\ \mu m * K \quad (1)$$

For a 15 µm source, the temperature given by Wein's displacement law is 193.19 K. The detector's temperature is assumed to be the minimum operating temperatures for many thermopiles, which is -50 °C. Given this information, it is possible to calculate the transfer factor F, where r_s and r_d are the radius of the source and detector respectively, and alt is the altitude of the detector.

$$F = \frac{2\pi r_d^2}{r_s^2 + r_d^2 + alt^2 + \sqrt{\left(\left(r_s^2 + r_d^2 + alt^2\right)^2\right) - 4 * r_s^2 * r_d^2}} \quad (2)$$

This transfer factor F is used to calculate the net power (in Watts) exchanged through radiation from the source to the detector, which is shown by Eq.3.

$$\Theta = \frac{B * e_s * e_d * A_s * F}{\pi} * \left(T_s^4 - T_d^4\right) \quad (3)$$

Where A_s is the area of the source, e_s and e_d are the emissivities of the source and detector, respectively, and B is Boltzmann's constant. The emissivities in this calculation are assumed to be 1, reflecting an ideal blackbody. The total voltage output by the sensor due to the Seebeck effect is given by multiplying the responsivity of the thermopile, R (in V/W), with the net power exchanged, Θ **[14].**

$$V_{out} = R * \Theta \quad (4)$$

In order to view specific portions of the Earth's limb, as well as limit the radiative flux of the thermopiles to within operating limits, it will be necessary to restrict the FOV. When using multiple sensors, it would be unnecessary to have a FOV with a diameter larger than half of the Earth disk or 6500 km. The FOV can be calculated with simple trigonometry as shown below.

$$d_{FOV} = 2 * tan(\theta) * r_{orbit\ to\ earth\ plane}$$

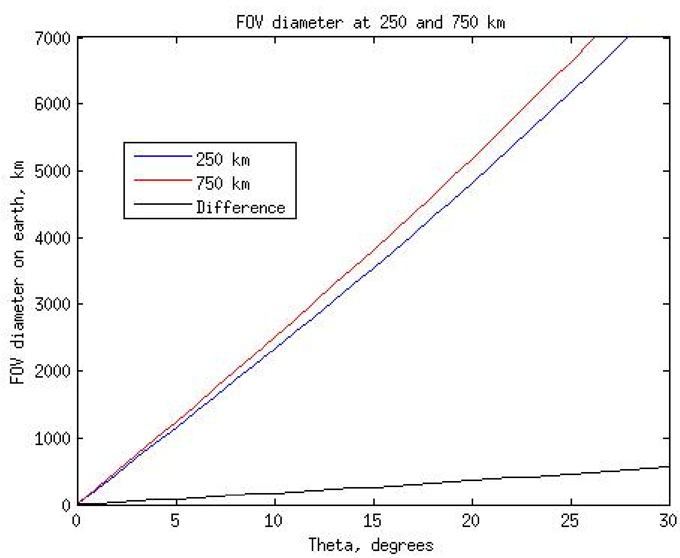

Figure A2: FOV diameter and angle

Looking at Figure A2 above, each sensor's half angle field of view would need to be limited to about 25 degrees. The same trigonometric relationship was used assuming a sensor height of 0.375 mm and a box height of 0.889 mm. Figure A3 below shows the required pin hole size for each half angle. This would require a 0.4 mm hole, which is possible to create in the Aerospace instrument shop.

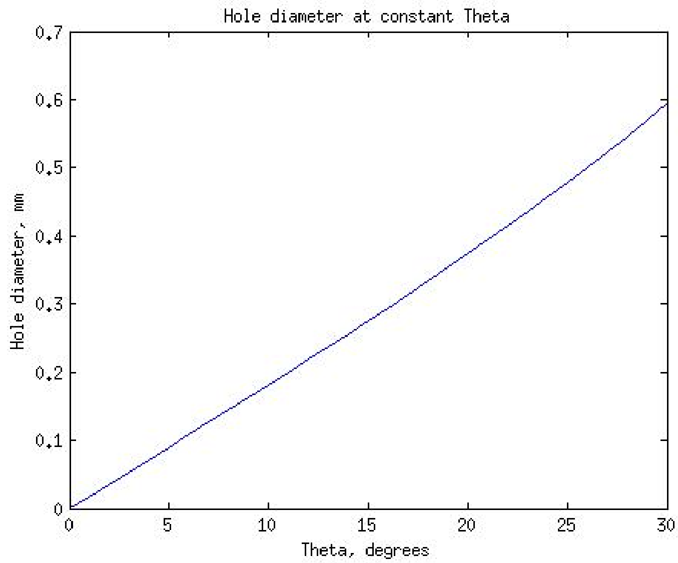

Figure A3: Pinhole diameter and angle

Appendix B : Electronics System Analysis

The choice of electronic control system will determine how the raw data from the sensor will be analyzed and converted into the required nadir vector. In addition to this, it must be capable of receiving commands and capturing the health telemetry, as well as interfacing with the simulated satellite via CAN bus in order to communicate the desired outputs. There are several viable options to use for this application, but our research has narrowed the most feasible options to microcomputers and microcontrollers. The benefits and constraints associated with each of these are discussed below, and what the potential application of each would be for a given sensor.

B.1 Microcomputer

Microcomputers are typically classified as single-board low-end computers that can perform a wide array of development tasks and include many common ports and accessories. This broad definition lends itself to the large selection of microcomputers that are available, however they are typically dominated by a few popular models. For this project, microcomputers are a design option that arise out of the need for the higher-processing power that some of the sensor options demand, as well as the ease of availability and support available for these common platforms.

Microcomputers typically operate on the order of 3-5 volts, and would therefore require an additional design solution, such as a dedicated *power distribution board* (PDB) to appropriately distribute and power the main processing unit and accessories. Microcomputers are able to run the widest range of software from the electronic system design options, capable of running a full operating system, and would be able to recover from power failures. However, the required power draw for microcomputers is excessive compared to microcontrollers, with a typical value of 2 watts which could significantly impact the viability of this design option.

The ability to interface with microcomputers would not be an issue, as they typically include a wide array of common ports communication protocols. The availability of these I/O ports would help the development process by making it easier to interface with a wider variety of sensors that use different communication protocols. The requirement of a CAN port might necessitate the addition of a CAN transceiver and driver for any microcomputer that does not integrate this specific port on the board, however, some popular models, such as the Beaglebone Black, come with this communication port and protocol integrated into the system, reducing the complexity in interfacing with the simulated satellite bus.

The most significant factor in choosing the microcomputer as a design solution would be the ability to perform computationally intensive operations such as image processing and floating-point calculations. The requirement of an efficient manner to perform image processing is an important aspect for some of our prospective sensor design options, e.g. IR imaging options. Microcomputers often come with a variable range of RAM options but are typically offered between 128 MB and 2 GB. The processing speed for common microcomputers is typically within the range of 700 MHz and 1 GHz. Both of these specifications allow for complex operations to be performed even on high-resolution photos without concern of running out of data memory, while maintaining sufficient calculation speed to maintain the data output frequency.

The mass and volume requirements imposed on the module may be restricting for a typical microcomputer. The addition of many common but unnecessary ports and accessories can have a more significant impact on these limits over a microcontroller. Structural housings could be fabricated quite easily, however, as many market solutions for a wide range of applications are available for the popular microcomputer options.

The microcomputer would be the most robust development solution for an IR imaging sensor, as they come with enough RAM and processing speed to effectively perform intensive operations such as image processing and floating-point calculations, and allow for a wider range of sensor options. They would also sufficiently be able to perform the calculations necessary for a radiance-balancing sensor, but would provide extraneous capabilities over the microcontrollers. The choice to use a microcomputer is highly dependent on which sensor is chosen.

Table A1. Pros and Cons of Microcomputers

PROS	CONS
RAM Typical: 128GB to 2GB	Power Draw Typical: 1W to 3W **DR.3.2.3**
Processor speeds Typical: 700 MHz to 1GHz	Mass Typical: 35g to 85g **DR.3.2.2**
Cost Typical: $50 to $150	Volume Maximum: 5mm x 50 mm x 90mm **DR.3.2.1**
Peripheral Support CAN and other common ports available **DR.3.1**	Need for PDB **DR.3.2.4**
Ease of Use Pre-assembled & availability of support materials	

B.2 Microcontroller

A microcontroller has the processor and memory integrated on the same chip as opposed to a computer that has these components located on separate chips connected via a motherboard. Since the microcontroller itself is integrated on to a single chip, they tend to be very power conservative which allows for more power to be used by sensor. Microcontrollers take an input voltage of 3-5 V, meaning a powerboard would have to be developed to distribute power throughout the sensor module.

Microcontrollers are highly customizable and have several peripherals that can be connected via a printed circuit board. This means a CAN bus interface can easily be added, and a wide range of sensors can be connected to the microcontroller. The processor speed on micro controllers typically range from 10 MHz to 200 MHz. These processing speeds restrict the amount of data capable of being processed. Thus, if a microcontroller were used, the best sensor options would be thermopiles as they output a single value each, and low resolution cameras. The data captured by the sensor must be processed and attitude information must be determined at a minimum of 5 Hz. Relative to microcomputers, microcontrollers use less power and are smaller in both size and mass.

Table A2. Pros and Cons of Microcontrollers

PROS	CONS
Power draw Typical: 0.2 W to 0.7 W **DR.3.2.3**	Low amounts of built in RAM which hinders image processing. Typical: 128 KB - 1 MB
Numerous peripheral options **DR.3.1**	Limited processing speeds Typical: 20 MHz - 200 MHz
Cost Typical: < 100$ pre-assembled	Need for PDB **DR.3.2.4**
Volume Typical 53 mm x 69 mm x 7 mm **D.R.3.2.1**	
Mass Typical: < 60 g **D.R.3.2.2**	

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