Low Cost Earth Sensor based on Oxygen Airglow

Executive Summary

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oerlikon space

1 ABSTRACT

This project has demonstrated the feasibility of a low-cost Earth sensor based on imaging oxygen airglow, allowing 0.4° accuracy from GEO under any Earth illumination condition.

Available Earth Sensors (ES) are based on the measurement of the earth's infrared radiation to determine the vector to the Earth's centre. This design provides excellent accuracies over a large field of view, but such sensors are often heavy, large, require cooling or temperature stabilization and are power hungry. In addition, the sensor concept for a LEO or GEO application ES differs significantly.

The EPFL (the Microsystems for Space Technologies Laboratory and the Quantum Architecture Group) and Oerlikon Space carried out a study to develop a novel ES concept for applications where milli-degree accuracy is not required, but where low-cost is essential and lower accuracy is acceptable. Such a sensor could be used in new scenarios and to improve spacecraft reliability by providing a low-cost back-up sensor.

The earth sensor concept developed and herein summarized is based on imaging atmospheric oxygen emission at 762 nm using highly sensitive detectors. In both night-time and daytime there is continuous emission at 762 nm due to oxygen recombination. Low-noise active pixel sensors (APS) or low-light detector based on arrays of single photon avalanche diodes (SPAD) enables the ES to operate at night and day, over a wide temperature range, with a very compact optical system (aperture of 8 mm, focal length of 11 mm) and no scanning elements, yet a resolution of better than 0.4° from GEO. A modular design allows designing similar instruments using the same wavelength band, the same detector technology, the same optics, the same power and data interfaces and similar algorithms for GEO and LEO applications, thus reducing the development and non-recurring costs.

We have developed an Earth appearance model at 762 nm, which was used as input for the mechanical, optical and electric design of the Earth Sensor (conceptual design). In order to achieve a low-cost solution, simplicity and reduction of part count was a driving factor in the design trade-offs. Total mass for the GEO design is 845 g with a mean power consumption of 4 W. Algorithms were developed to determine the vector to the Earth from the images. A breadboard was built to display a simulated picture of the Earth under varying conditions, image those pictures at different temperatures with a radiation tolerant APS (LCMS), and verify the correct operation of the algorithms.

In addition to the conceptual design and breadboard level demonstration of key technologies, a novel detector chip was designed and fabricated: a radiation-tolerant array of single photon avalanche photodiodes (SPADs) build using conventional 0.35 µm CMOS technology. The chip was tested under proton and gamma irradiation, and operated with only minor changes in dark current after 30 krad TID.

Having shown the feasibility of such an Earth Sensor, this work concluded with a development plan to lead to a flight model within 2 years.

2 AIRGLOW AND EARTH APPEARANCE AT 762 nm

Airglow is a continuous luminosity due to photodissociation, photo-excitation and atomic recombination which occurs at an altitude of 50 to 120 km in the mesosphere and lower thermosphere. Figure 1 shows the airglow at the earth's limb (photo taken form the Space Shuttle).

The O2 (0-0) A-band at 762 nm, only visible from space, emits the strongest airglow and has therefore been selected for the ES.

A number of studies exist on the temporal and latitudinal variability in the oxygen emissions and data, provide a wide database on the airglow emission rates in the 762 nm band for different altitudes, local times and latitudes. Using this data on airglow over 9 years, we have developed an Earth Appearance model at 762 nm, which allows the earth appearance to be simulated for any altitude, local solar time, and season (sample output in Figure 2).

Using the visible band rather than the LWIR band offers several advantages including much lower cost detectors, no need for cooling, a more relaxed thermal design, simpler optics, no need for any scanning mirrors or choppers, higher sensitivity and hence low cost.

Figure 1: Airglow layer (green), aurora borealis and city lights (picture taken by STS-108).

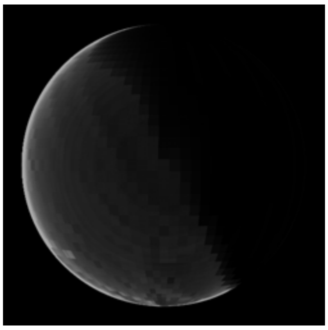


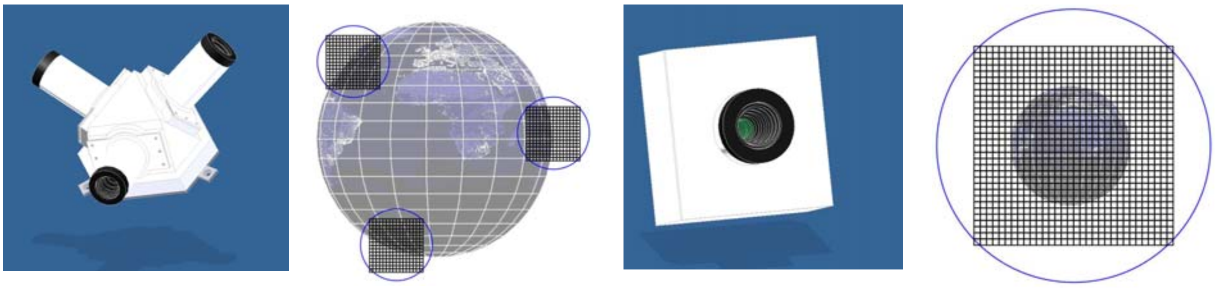
Figure 2: Maximum airglow emission at 06:00 LST.

3 EARTH SENSOR CONCEPTUAL DESIGN

The earth sensor concept developed in this study is based on imaging atmospheric oxygen emission at 762 nm using highly sensitive detectors. In both nighttime and daytime there is continuous emission at 762 nm due to oxygen recombination. A low-light detector enables the ES to operate at night and day, over a wide temperature range, with a very compact optical system (aperture of 8 mm, focal length of 11 mm) and no scanning elements.

A modular design allows designing similar instruments using the same wavelength band, the same detector technology, the same optics, the same power and data interfaces and similar algorithms for GEO and LEO applications, thus reducing the development cost. The main difference between the instrument used in a GEO or a LEO is the optical geometry: whereas a single tube design will be used in GEO, a triple-tube concept will be used for LEO to provide a larger FOV (Figure 3). Mass is 845 g for a GEO-instrument, and power consumption is less than 4 W. For GEO, accuracy is 0.4° with a 1 Hz update rate, and an Earth Presence flag.

The detector for the ES is a key element. Initially a 128x128 array of single photon avalanche diodes (SPAD) was planned at the baseline detector and was developed in the framework of this project. However, in parallel with the development of such a detector array, a careful system study showed that a low noise APS detector such as the LCMS can provide better overall performance with simpler optics, and since it is already space qualified and radiation tolerant, was used in the breadboard and in the final design.



A. LEO B. GEO

Figure 3: Earth Sensor configurations and geometries. The dark blue circles mark the telescopes FOV (20°), whereas the black arrays indicate the view of the active sensor elements. A. LEO case at 2'000 km altitude: Three telescopes each with a sensor array and a 20° FOV are used. B. GEO case at 36'000 km altitude: only one telescope and one detector array.

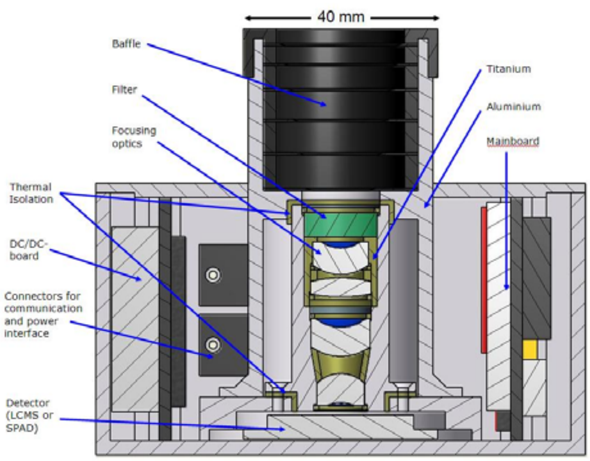


Figure 4: Cross-section of the preliminary design of the AIRES instrument for GEO applications.

Parameter	Mass per Unit
Tube	180 g
Housing and Shielding	385 g
Mainboard	105 g
DC/DC-Board	85 g
Connectors and Cables	50 g
Margin (5%)	40 g
Total mass	845 g

Table 1: Mass budget for the AIRES instrument for GEO applications

4 Algorithm

The function of the algorithm is to determine the earth vector with images of the airglow. Furthermore, earth presence detection and sun blinding recognition have been included. The algorithm was optimized to minimize memory and computation power, and is based on fitting a circle to the measured image. The circle corresponds to the airglow emission, and the center of circle is the center of the Earth. To balance speed and flexibility, the algorithm has been split in two phases: the acquisition phase and the tracking phase.

In acquisition mode the ES determines the earth vector based on a single airglow image without taking into account previous observations. The image processing algorithm is able to successfully detect the earth center within twice the FOV of the ES with a resolution of 0.5 pixels (i.e. 0.07° for the detector used). However, the processing time required in this mode to determine the earth vector is expected to be too high to satisfy the targeted 1 Hz refresh rate.

In tracking mode the ES determines the earth vector based on the last captured image and previous X, Y outputs (i.e., the approximate position of the earth centre is known from previous measurements). Since the satellite movement is expected to be slow (max rotation of 3°/s, max speed 7.8 km/s for LEO application and 0.4°/s & 3.1 km/s for a GEO application), the new position of the earth centre will be close to its position during the previous measurement and the processing time is smaller. In this mode, the algorithm is able successfully detect the earth centre within 12.5% of the FOV of the ES with a resolution of 0.5 pixels.

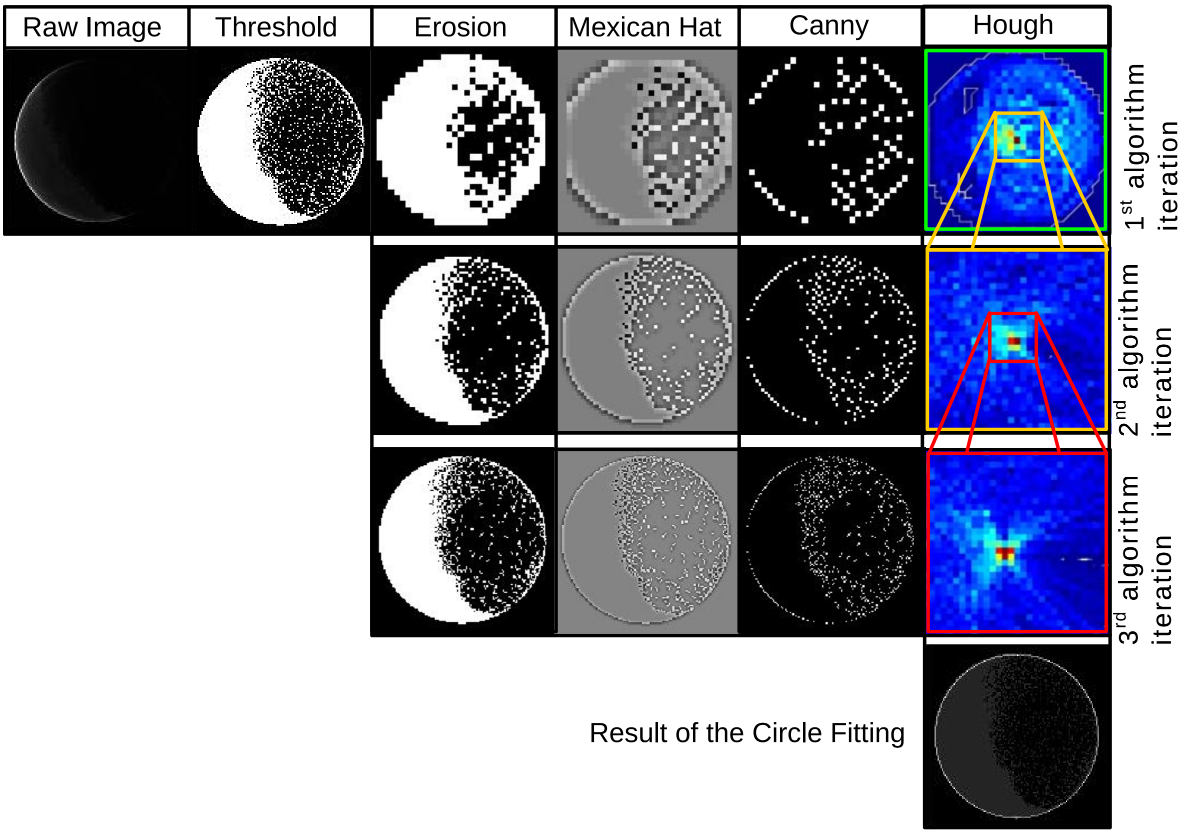


Figure 5: Iteration steps of the Hough algorithm for the acquisition phase (in tracking phase, only the last iteration is used)

5 SPAD: DESIGN & TEST

SPADs (Single-Photon Avalanche Diode) are single photon detectors that allow very high timing resolution. The integration of SPADs in a low-cost CMOS process became possible in 2003 and SPADS can now be built in arrays with complex readout schemes and integrated in ASICS. In this project, a radiation-tolerant SPAD array was developed of size 128x128 and 32x32 pixels, with a pixel pitch of 30 µm.

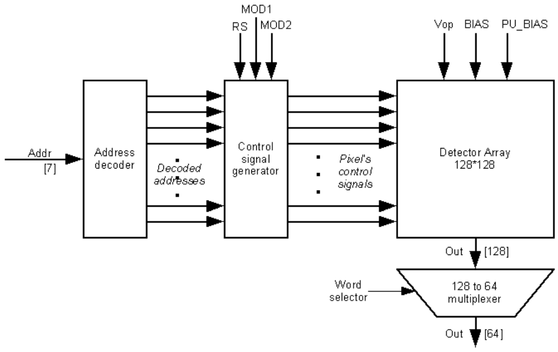


Figure 6: 128x128 Chip block diagram

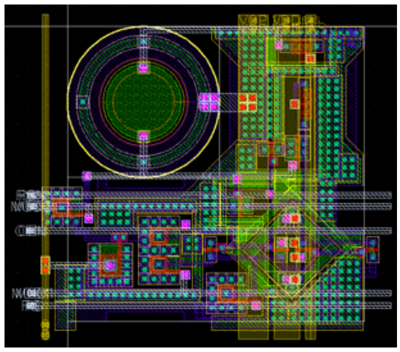


Figure 7: The layout of a single pixel

Figure 6 is a block diagram of the SPAD chip (128x128) that was developed and Figure 7 is the layout of one pixel. Figure 8 is a photograph of a 32x32 array on a daughterboard mated to an objective for testing. The 32x32 array operated as designed, running at nearly 1 MHz/pixel, and was tested up to 42 krad of gamma radiation (Co60) and with 11 MeV and 60 MeV protons. After gamma irradiation, the detector array continued to operate normally with only a 10% increase in dark count rate (Figure 9). After $6.0x10^8$ protons at 11 MeV the dark count rate increased from 140 Hz to 7 kHz.

Figure 8: the 32x32 SPAD array mounted under a compact objective

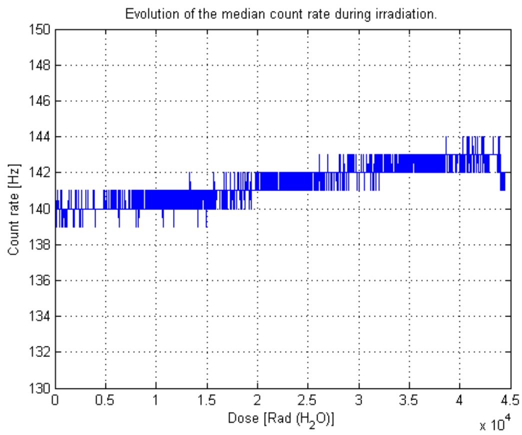


Figure 9: Median DCR during gamma irradiation.

6 BREADBOARD AND TESTING

An evaluation of the most promising algorithm was done in order to test the robustness of the earth sensor and to verify the following specifications. The performance metrics of the algorithms which have been tested are:

- Acquisition of earth by identification of its presence in the FOV
- Recognition of blinding by sun
- Angular accuracy of the X, Y output
- Stability in X, Y over temperature (5°C to 60°C)

The breadboard is schematically shown in Figure 10, and an example image acquired with the LCMS detector is shown in Figure 11.

The algorithm performed very well on images of the airglow taken from a satellite altitude of 45000 km. With exception of the image with minimum airglow signal at night for a sensor temperature of 60°C and an earth that is partially outside of the FOV, the algorithm can successfully determine the earth vector if the image threshold is chosen correctly.

We find good agreement between the simulated performance and measured performance on the breadboard.

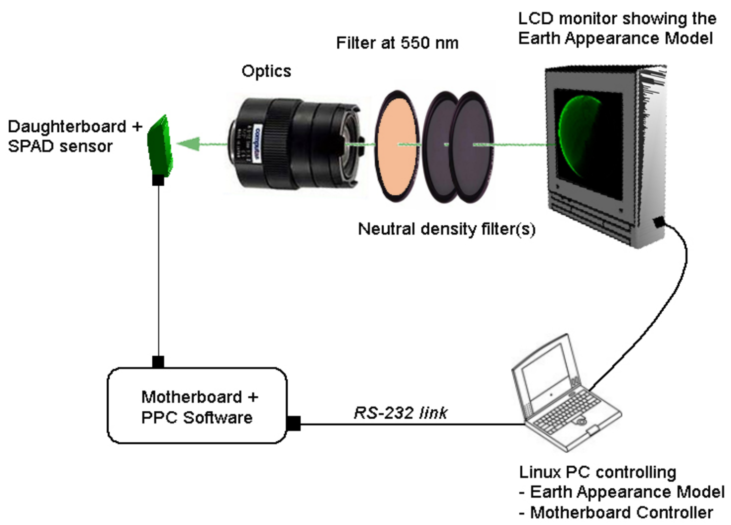


Figure 10: Breadboard to verify algorithm performance on simulated Earth airglow. The detector used was an LCMS

Figure 11: Example of image acquired with the breadboard

7 DEVELOPMENT PLAN

A development plan was written describing the strategy for the design, selection of components, manufacturing and verification, which shall lead to a Flight Model (FM) of the earth sensor. This development plan presented the model philosophy, the engineering logic and verification plan which have to be carried out in the different development phases in order to reach the scope. It is foreseen to reach the flight model level within 2 years.

8 CONCLUSIONS

This project carried out by EPFL and supported by Oerlikon Space provided a demonstration of the feasibility of using atmospheric oxygen airglow as the basis for a low cost Earth Sensor. A breadboard was built that validated the concept and verified operation of the algorithms. A conceptual design of the mechanical, electrical and optical design was performed, and the optimum detector was identified.

In parallel a prototype using the ES concept is designed and will be flown in 2009 on the SwissCube 1 kg satellite. In addition a novel radiation tolerant single photon detector array with nanosecond timing resolution was developed and tested.