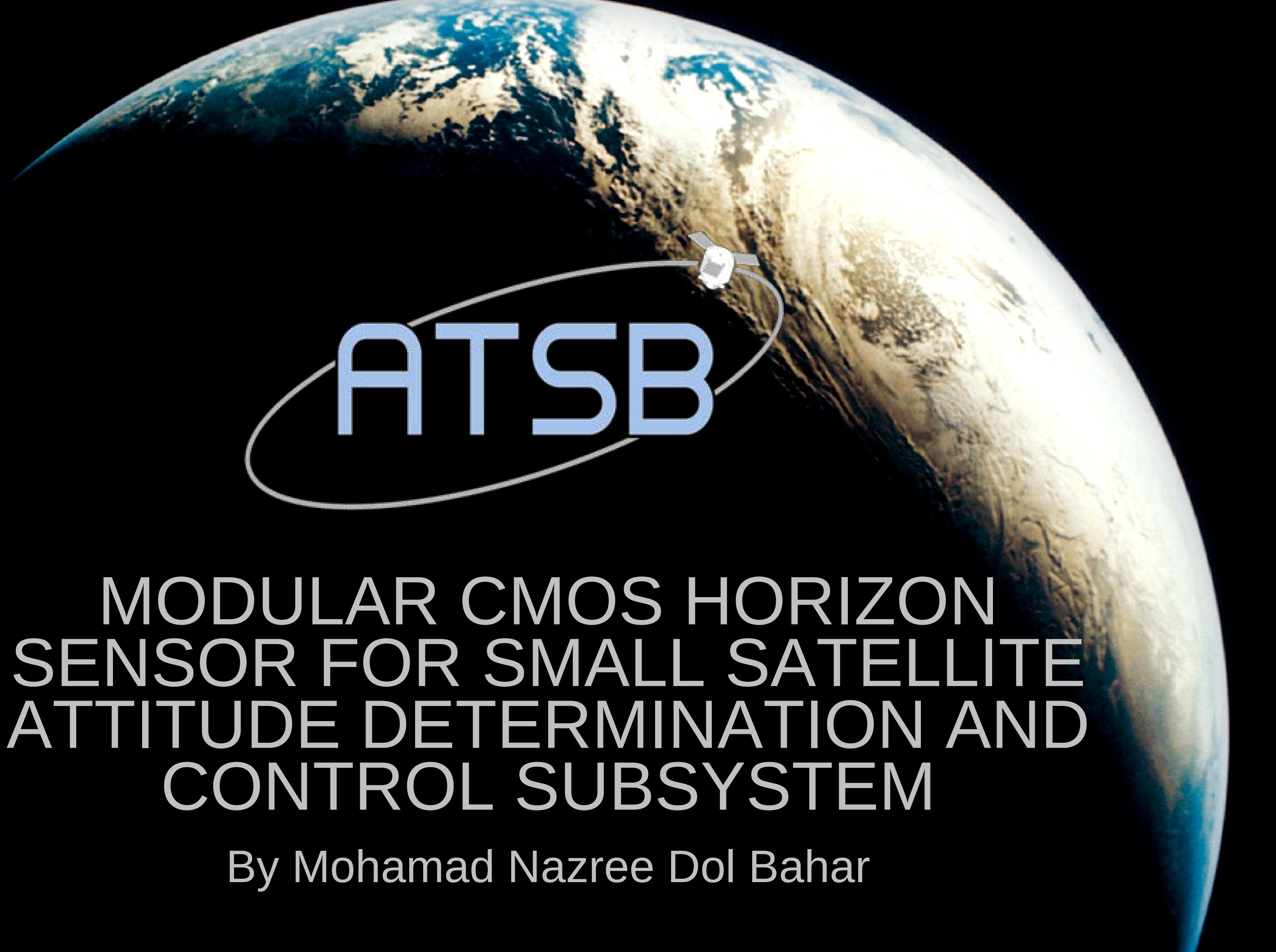

ATSB

MODULAR CMOS HORIZON SENSOR FOR SMALL SATELLITE ATTITUDE DETERMINATION AND CONTROL SUBSYSTEM

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CONTENTS

INTRODUCTION

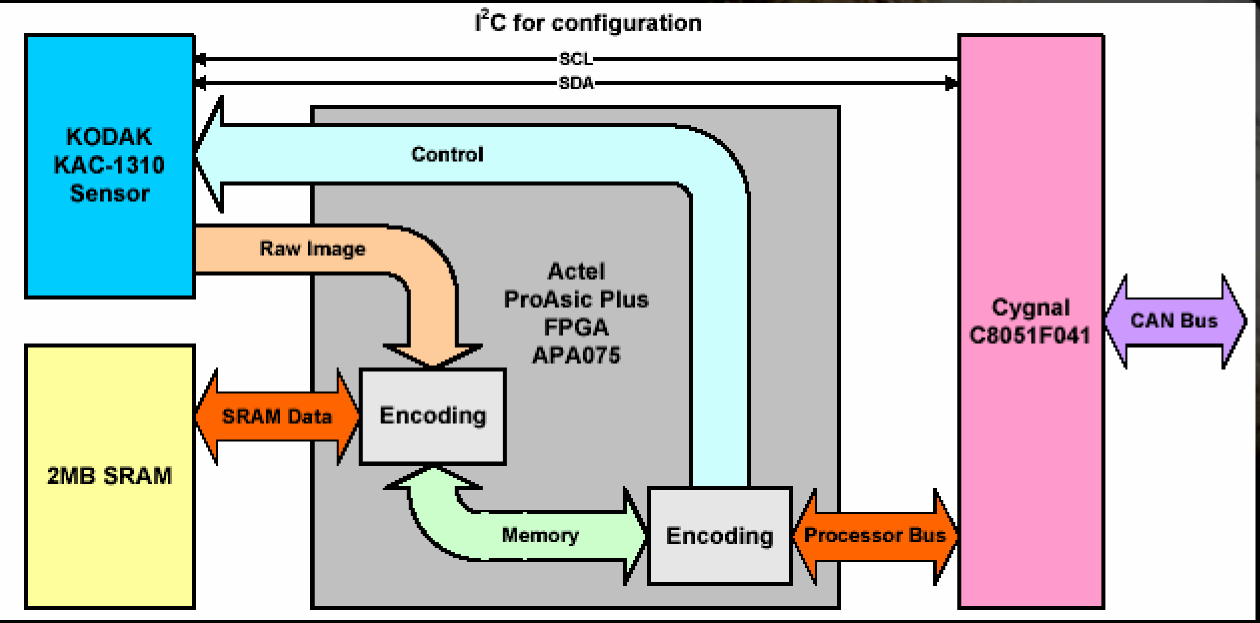
INTRODUCTION

- Horizon sensors are typically IR devices that sense and detect the contrast between the heat of Earth's atmosphere and the cold of the deep space.
- The ATSB™ CMOS Horizon Sensor performs imaging in the visible light spectrum, detecting the horizon as the contrast between the sunlit lower atmosphere and the dark deep space background.
- This Horizon Sensor provides Earth-relative information directly for Earth-pointing satellite, thus simplify on-board processing.

SYSTEMS DESCRIPTION

Introduction

- Horizon sensor is used for satellite's orientation control.
- The CMOS Imager will capture an image of the earth, followed by centroid calculation algorithm by the 8051 microprocessor.
- The point vector determined will be sent to ADCS OBC for orientation control.



	Bus	Function
1.	I^2C	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.

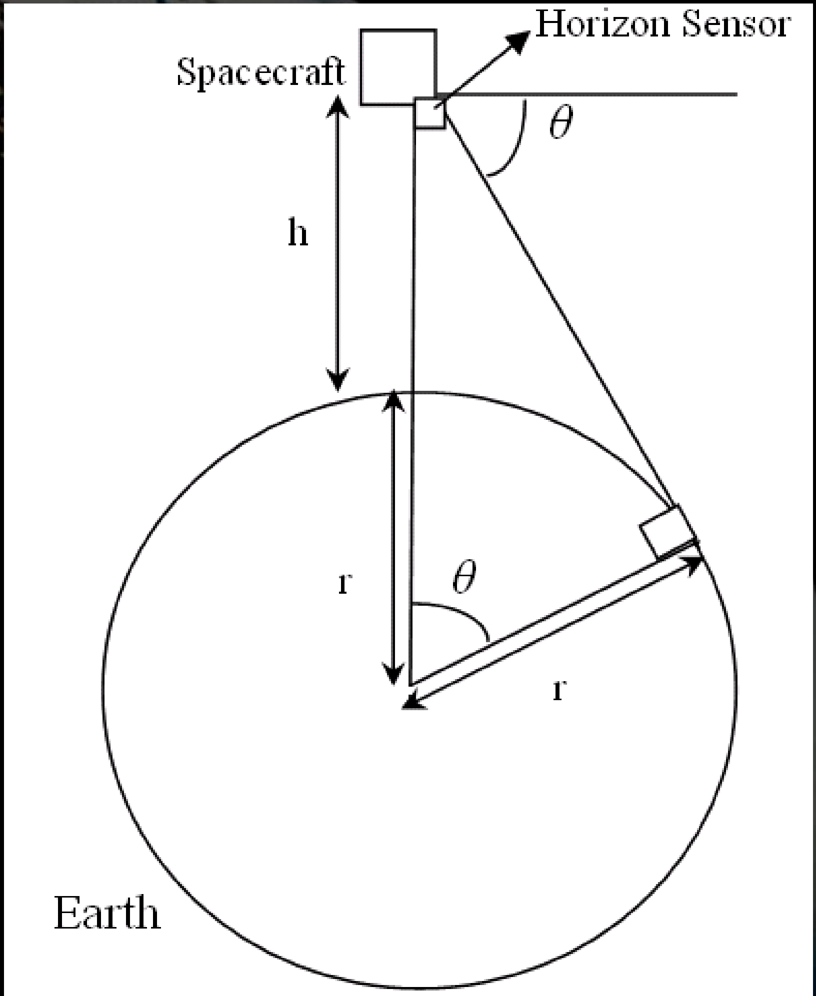
- **Tilt angle of the CMOS Horizon Sensor**
  - **The higher the altitude, the bigger the tilt angle**

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

where θ = tilt angle

h = spacecraft altitude = 600 km

r = Earth radius = 6378 km



CMOS Horizon Sensor with mechanical:

Dimension = 82.9mm (height) x 95mm (width) x 126mm (length)

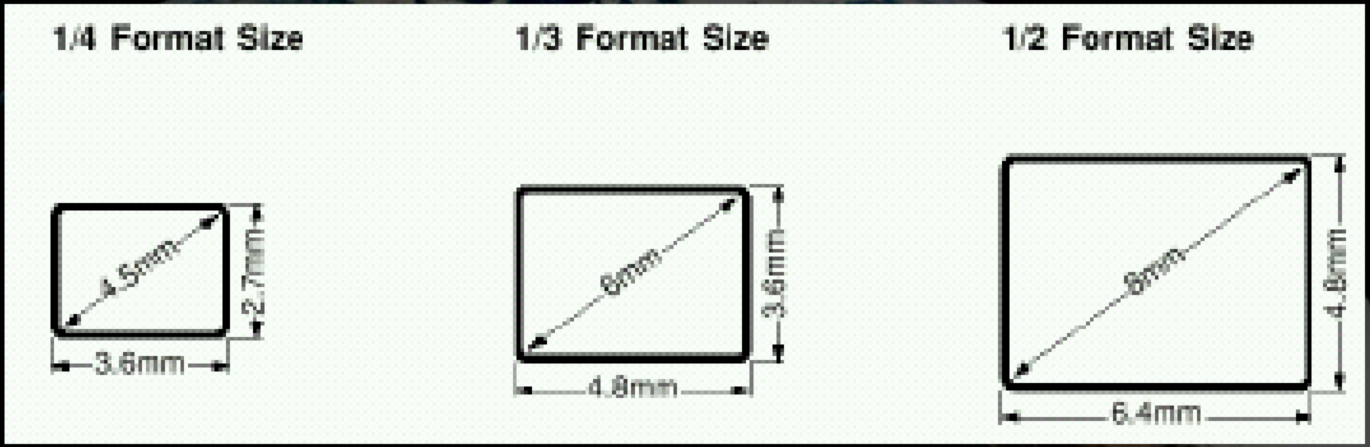
Characteristics:

- Field of View (FOV): 90° cone
- Operating temperature: -10° to 50°C
- Mass: 560g
- Power consumption: 550mW
- Dimension: 63 x 95 x 121mm
- Tilt angle: 24°
- Imager Resolution: 1024 x 1024 pixels
- Accuracy: < 0.1°

- **Functions:**
  - Calculate the centroid of the earth after taking an image of it
  - Communicate with ADCS-OBC of the satellite via the dual redundant CAN communication bus to receive telecommands and pass on telemetry
  - Download an image to OBC

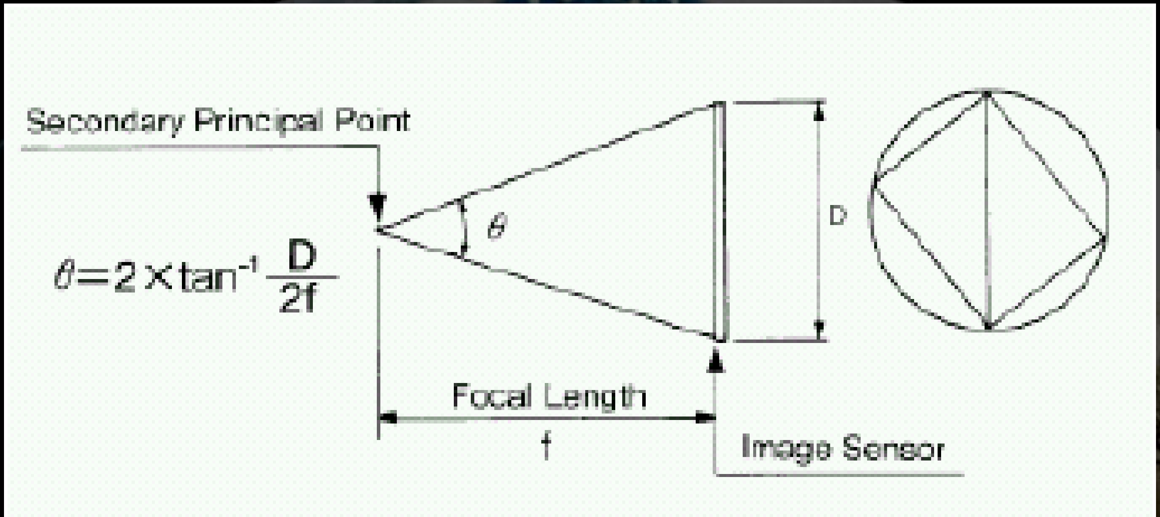
- **Software Implementations:**
  - Microprocessor C-firmware:
    - to interface to the SRAM via the FPGA and control the imager
    - for communication with ADCS-OBC
  - FPGA VHDL firmware:
    - interfaces between microprocessor, SRAM and imager
  - External software for the Ground Support Equipment (GSE):
    - required when Horizon Sensor interfaces to the GSE emulating the ADCS-OBC or performing debugging

▪ Image Format:



- Image format – size of the image sensor
- Lens needs to cover an area equal to or larger than the sensor size
- This CMOS Horizon Sensor uses ½ Format Size

- # FOV Calculation:



where θ = field of view (FOV)

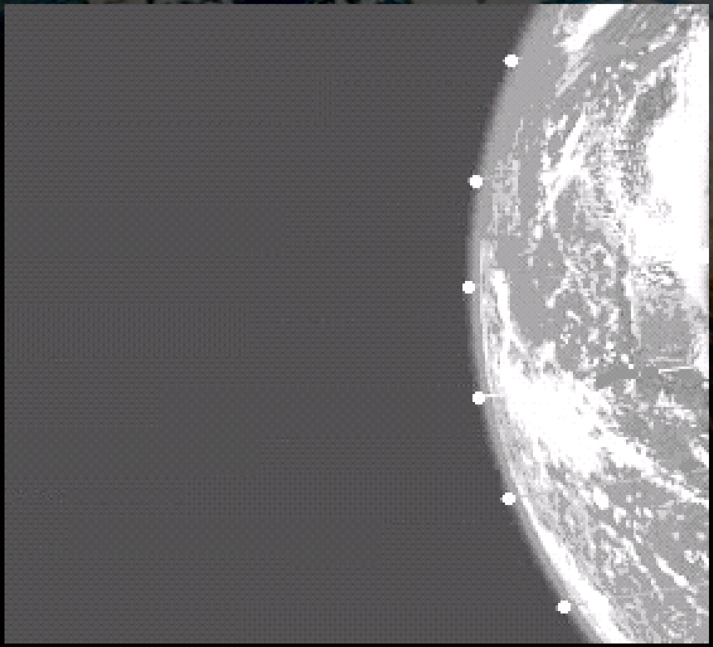
D = diameter or diagonal of the exposed image

f = focal length

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

CENTROID ALGORITHM

▪ Centroid Algorithm:



- The Earth's size is too large to fit into the 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.
- The algorithm can be divided into scanning part and circle part fit.

▪ Scanning Phase:

- The scanning loop detects the transitions from dark to light by making use of image gradients.
- The edge points will be detected if the image gradient at that point is bigger than the gradient threshold.
- Due to presence of noise, the image gradients are calculated using Sobel operators.
- The Sobel edge detecting kernels are:

$$G_x = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} \qquad G_y = \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$$

- The formulas for calculating the image gradient then become:

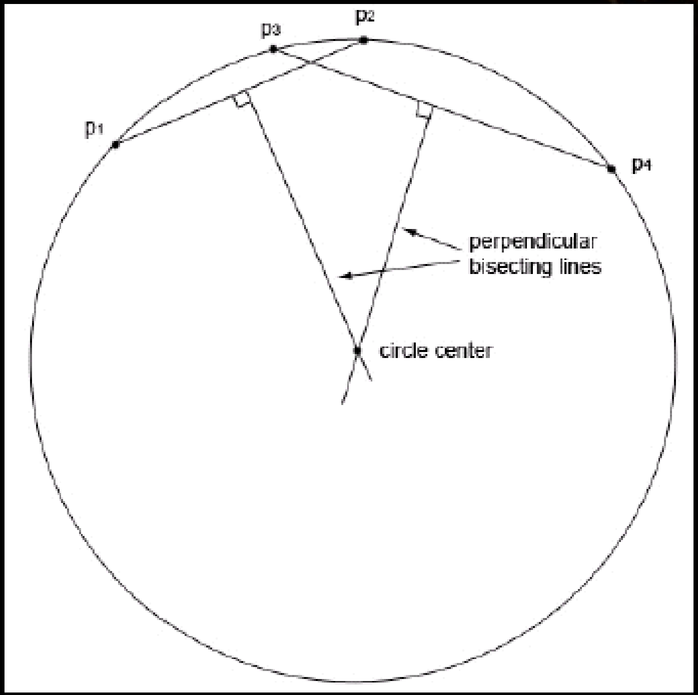
$$\begin{aligned} I_x(x,y) &= -i(x-1,y-1) + i(x+1,y-1)\ldots \\ &- 2i(x-1,y) + 2i(x+1,y)\ldots \\ &- i(x-1,y+1) + i(x+1,y+1) \end{aligned}$$

$$\begin{aligned} I_y(x,y) &= -i(x-1,y-1) - 2i(x,y-1)\ldots \\ &- i(x+1,y-1) + i(x-1,y+1)\ldots \\ &+ 2i(x,y+1) + i(x+1,y+1) \end{aligned}$$

where i(x,y) = image brightness(x,y)

▪ Circle Fit Phase:

- Circle geometry method is used to compute the center coordinate of the circle.
- Any perpendicular bisector passed through the center of the circle.
- The center of the circle can be determined by having a minimum of two bisecting lines, which in turn requires a minimum of three edge points that lie on the circle.
- For better results, the final center coordinate of the circle is calculated by averaging the individually calculated intersection coordinates.



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

$$s = \begin{bmatrix} -x \\ -y \\ f \end{bmatrix}$$

where f is the nominal focal length of the lens.

CALIBRATION

▪ Calibration:

- The detected coordinates of the Horizon Sensors have to be corrected for lens distortion.
- Two steps of calibration:
  - a) to make sure all coordinates are referenced to the optical axis intersection
  - b) to determine the focal length error and the coordinates are corrected for lens distortion

▪ Optical Axis Intersection (oai):

- Optical axis intersection (oai) is the location on the CMOS sensor where the optical axis intersects it.
- 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.
- All measured sensor coordinates are referenced to the optical axis intersection
- If a point has a sensor coordinate of (x,y) then the oai referenced coordinate:

$$x' = x - x_{oai}$$

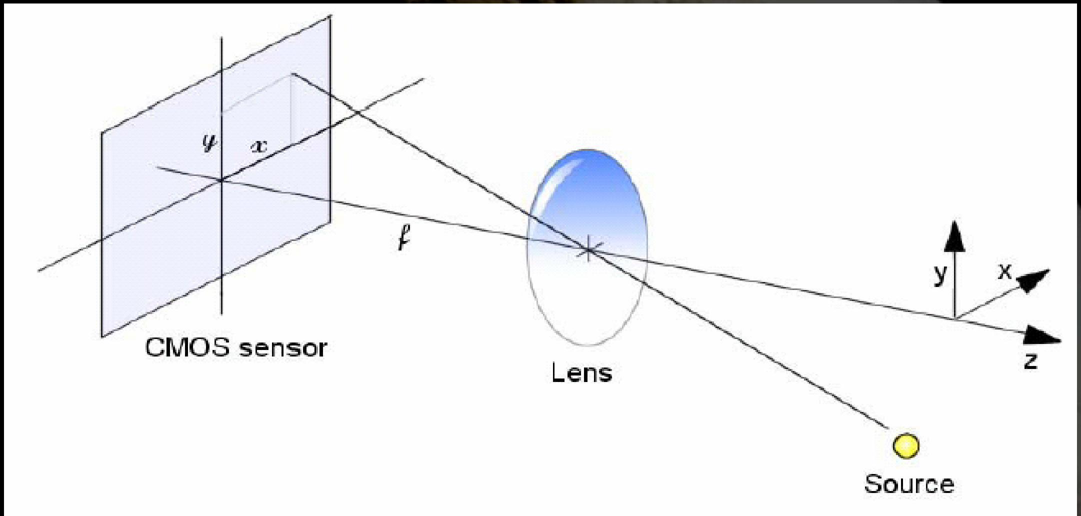
$$y' = y - y_{oai}$$

Focal length

- Focal length (obtained by measurement) is the effective distance from the optical center of the lens to the CMOS sensor surface.
- A reference source such as light source is required at a known angle, ***θ*** from the the optical axis.
- If the light rays coming from the source strike the CMOS sensor at coordinates (x’,y’):

$$r = \sqrt{x'^2 + y'^2}$$

$$f = \frac{r}{\tan\theta}$$



- Focal length is used to construct a pointing vector, *s* and to determine the azimuth, *α* and elevation, *ε*:

$$s = \begin{bmatrix} -x' \\ -y' \\ f \end{bmatrix}$$

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

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

Lens Distortion

- Light rays that do not coincide with the optical axis, are subject to distortion.
- Light rays are either deflected away from the optical axis or towards 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.
- 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.
- Nominal focal length, f_{nom} can be obtained by measuring at small incident angles.
- The difference between the nominal focal length 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 $f_{x,y}$

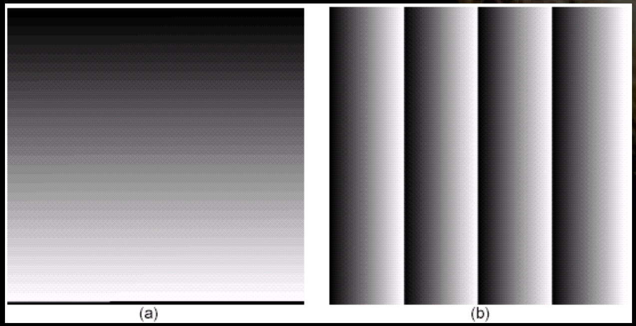
$$x'_{corrected} = x'\frac{f_{nom}}{f_{x,y}}$$

$$y'_{corrected} = y'\frac{f_{nom}}{f_{x,y}}$$

TEST RESULTS

▪ Preliminary Test Results:

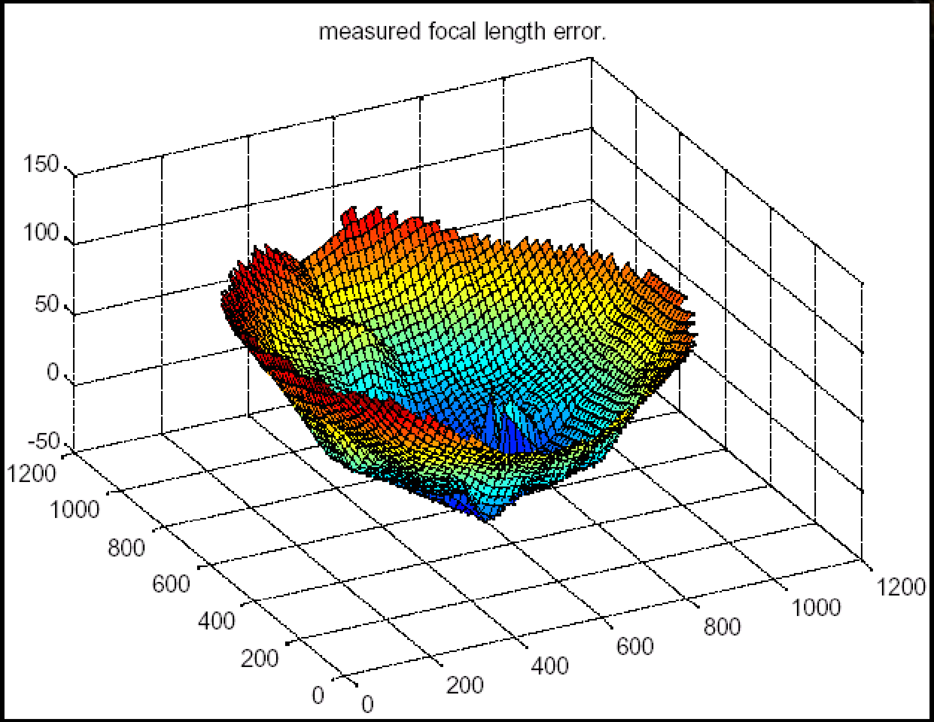
- Below are the test patterns generated by the processor, written to SRAM, read back and then downloaded to a PC via RS232.
- The image illustrates 32 shades of grey indicating 32 pages in the SRAM.

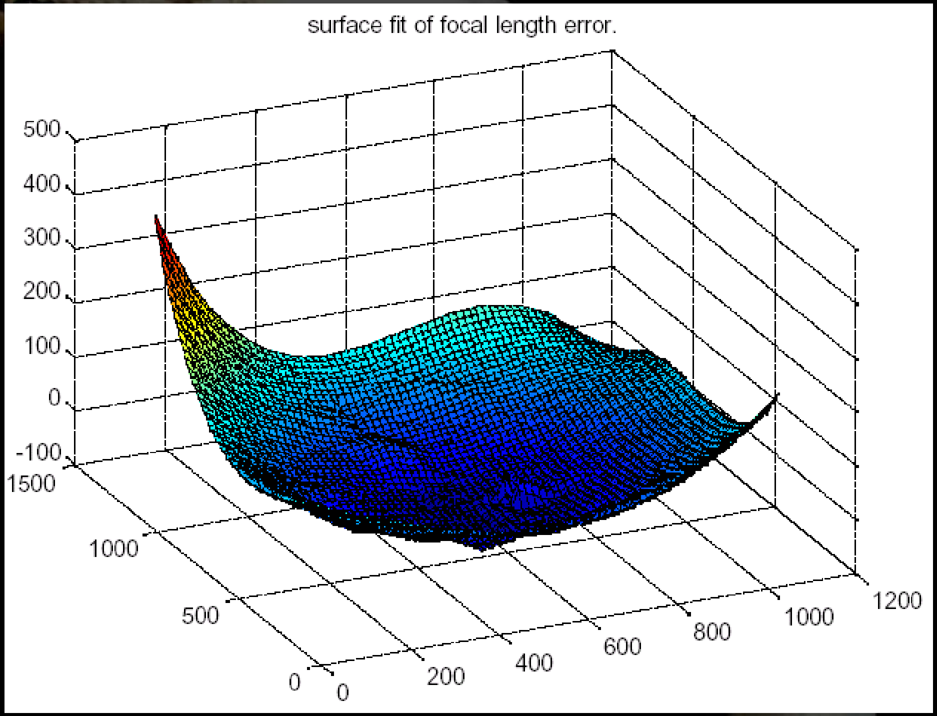


- The images below confirm that the data generated by the CMOS imager was actually stored in the SRAM and downloaded to PC via microprocessor.
- The total size for Figure (a) is 0.26MB (512x512) and for Figure (b) is 1MB (1024x1024)

▪ Calibration Results

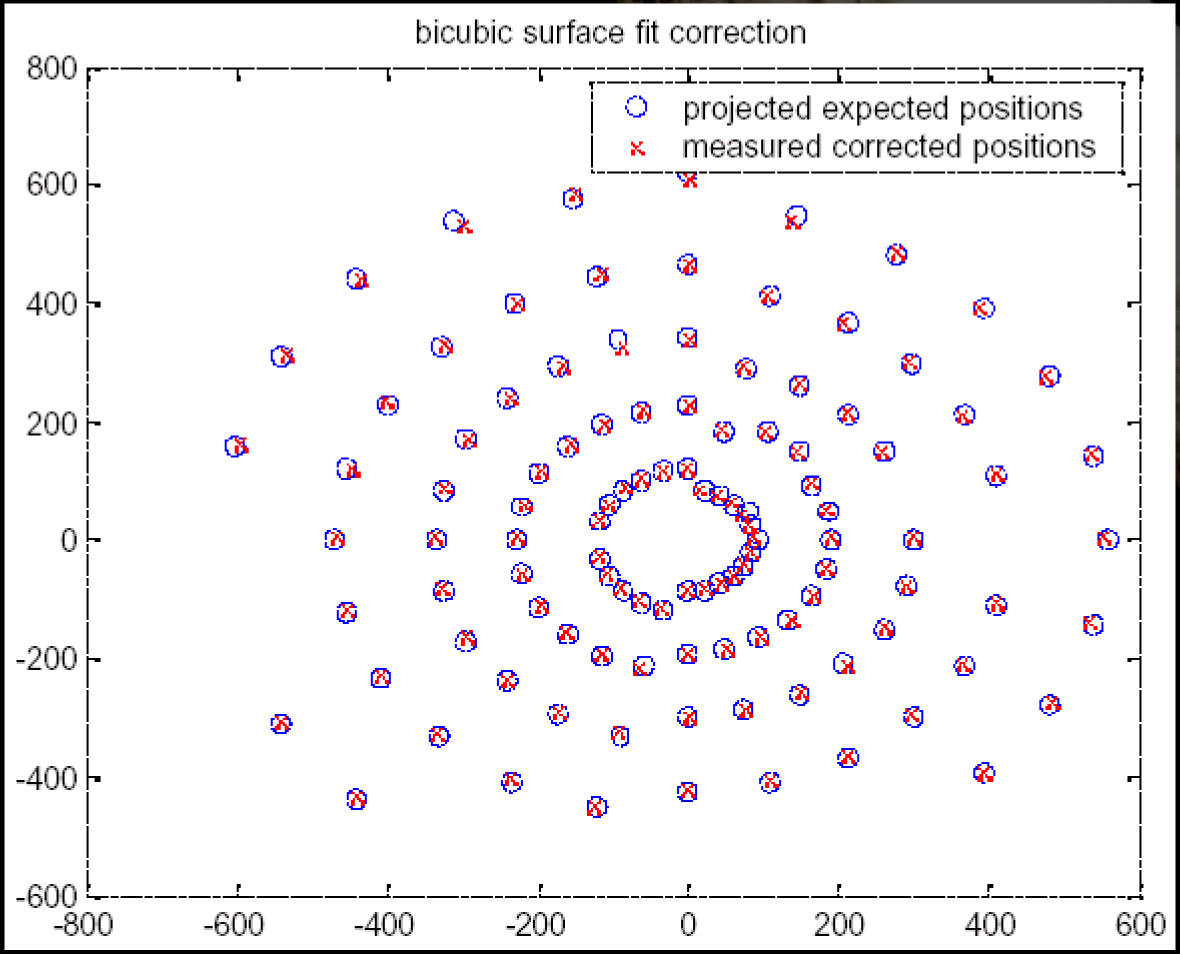
- The first figure below is the graph of the measured focal length error.
- The second figure below is the graph of surface fit of focal length error.





▪ Calibration Results:

- The figure below is the bicubic surface fit correction.
- 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.



Calibration Values:

Optical Axis Intersection X	495.4
Optical Axis Intersection Y	402.7
Focal Length	768.2832

The average error (distance) between the projected expected positions and measured corrected positions is 4.6 pixels.

CONCLUSION

▪ Conclusion:

- The CMOS Horizon Sensor was designed and built for ATSB^{TM} future Nano-satellite with altitude around 600km.
- Average power consumption = 289mW
- Mass = 560g
- Standard interfacing = CAN or RS232/RS485
- Accuracy = 0.3°, not as expected because of mounting and pointing errors of 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.
- This CMOS Horizon Sensor can also capture images of the Earth or other space objects with a maximum resolution of 1 Mega Pixels.