

Digital CMOS Cameras for Attitude Determination

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Abstract:

The Ionospheric Observation Nanosatellite Formation (ION-F) satellite cluster consists of three individual spacecraft, which are being developed by the University of Washington (UW), Utah State University (USU), and Virginia Polytechnic Institute and State University (VT). The satellites will demonstrate formation flying and distributed satellite capabilities. A novel component of the Attitude Determination System (ADS) for each satellite is use of low-power, low-mass, inexpensive CMOS cameras for Sun and Earth horizon sensing. This paper describes a candidate camera set of specifications, the configuration of cameras on each ION-F satellite and a sensor fusion scheme for the ADS. Several algorithms for nadir vector determination are described.

1. Introduction

The Department of Defense, NASA, and industry are jointly sponsoring the development and launch of ten university nanosatellites to demonstrate miniature bus technologies, formation flying, and distributed satellite capabilities. The University of Washington (UW), Utah State University (USU), and Virginia Polytechnic Institute (VT) are designing and developing a system of three 15 kg spacecraft to investigate satellite coordination and management technologies and distributed ionospheric measurements. The three universities are coordinating on satellite design, formation flying and mission development, and science instruments and mission. Advanced hardware for distributed space systems that is to be demonstrated includes micro pulsed-plasma thrusters, and a gimballed magnetic attitude control actuator. In addition, an Internet based operations center will be designed to enable each university to control its satellite from its own remote location. The ION-F will focus on mission objectives to benefit TechSat 21 and future Air Force and NASA missions.

The program objectives for the ION-F follow:

1. Formation flying and inter-satellite communication.
2. Basic research mission of investigating global ionospheric effects which affect the performance of space-based radar, and other distributed satellite measurements.
3. Baseline new technologies including micro-thrusters, magnetic gimballed attitude control, and an Internet based operations center.
4. Bring a unique, hands-on, space design experience for students.

The basic satellite design will accommodate AFRL's proposed deployment from the Shuttle Hitchhiker Experiment Launch System (SHELS). All satellite structures are hexagonal with an approximate 18-in. width and maximum 13-in. height.

A common component of each satellite's Attitude Determination System (ADS) is the use of digital, Complementary Metal-Oxide-Semiconductor (CMOS) cameras for attitude determination and control. VT will use the cameras for Earth sensing alone, while the UW and USU will use cameras for both Earth and Sun sensing. On-board Global Positioning System (GPS) receivers will determine inertial position and velocity at all times during the mission. The information will then be used to determine the location of the satellites with respect to the Sun and magnetic field of Earth. The Earth and Sun sensors, in addition to a Honeywell 3-axis magnetometer, provide absolute measurements from the spacecraft body frame that will be used to update relative angular rate measurements from three Systron Donner QRS-11 Gyroscopes.

The use of digital, optical, CMOS cameras offers many advantages over traditional Sun and Earth sensing technologies, such as Infrared (IR) sensors and analog cameras. The Fuga 15d, from the IMEC Company, is a 512×512 pixel, addressable imaging chip that behaves similar to a 256 Kbyte ROM. After reading an X-Y address, the pixel intensity is directly read out and returned in a digital word of 8 bits, allowing true random access. Direct readout means that the output signal is an instantaneous measure of the photocurrent. Camera response is logarithmic, which allows the chip to capture six or more orders of magnitude of intensities in the same image. As a result, the sensor is virtually immune to blooming. The camera can take a picture of a welding arc without saturating. The Fuga 15d camera is shown in Fig. 1.

Direct readout and random access are a substantial advantage over analog imagers. Classic Charged Coupled Device (CCD) and even addressable Metal-Oxide-Semiconductor (MOS) imagers of the "integrating" type must be read out after a defined integration time, and thus cannot be used as true random access devices. Analog cameras also require frame grabber hardware, whereas the full matrix of pixels on the Fuga 15d can be simply scanned and read directly into a buffer.

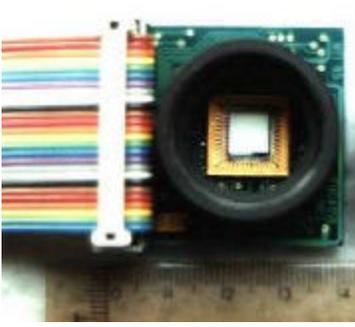


Figure 1: The Fuga 15d Digital CMOS Camera

A wide field of view (FOV) is another substantial improvement over traditional IR scanning sensors that require either a spinning spacecraft or a scanning sensor mount. All three ION-F satellites are 3-axis stabilized, requiring a sensor with a large FOV. The Fuga 15d sensor can operate over the full dynamic range with a simple fixed iris lens, which is currently baselined with a 67° FOV. Proper placement of a small number of cameras can provide adequate coverage to locate a desired target for almost any orientation of the spacecraft.

2. Sensor Measurements

The determination of a spacecraft's attitude is equivalent to determining the rotation between the Satellite Body-Fixed Frame (SBFF) and some known reference frame, such as the Earth Centered Inertial (ECI) frame¹. The sun and Earth sensors are responsible for delivering two measurements to the ADS; the Sun (s_b) and nadir (n_b) pointing vectors expressed in the SBFF frame. The measured components of the sun and nadir vectors, with respect to the ECI frame, are denoted s_i , and n_i , respectively.

Fig. 2 illustrates the various coordinate frames defined for ION-F ADS measurements. The ECI frame is denoted by the axes X_i , Y_i , Z_i . The Satellite Reference Frame (SRF), denoted X_r , Y_r , Z_r , is based on a coordinate transformation from the ECI frame, and is updated continuously throughout each orbit. The SBFF shown as X_b , Y_b , Z_b , represents the true attitude of the satellite.

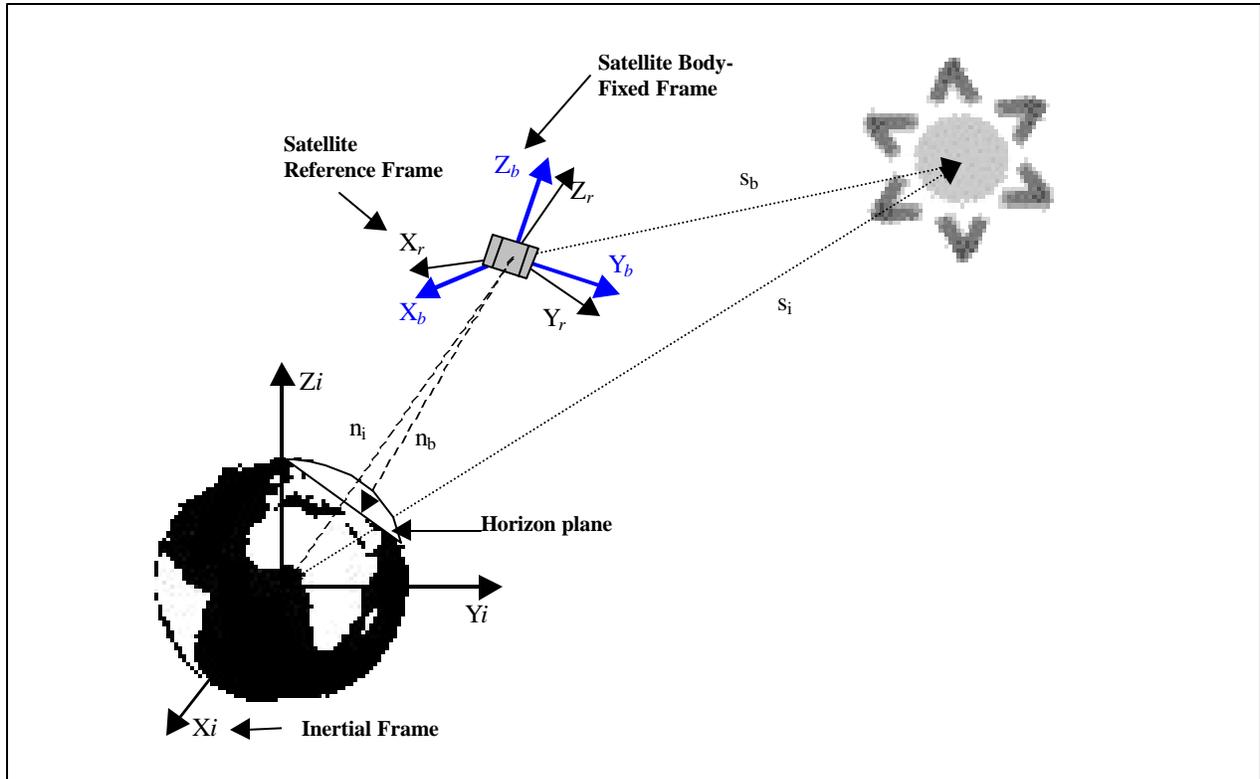


Figure 2: Inertial, satellite reference and satellite body-fixed coordinate frames for ION-F sensor measurements

A rotation matrix from the SBFF to ECI frame, denoted as R^{ib} , is a direction cosine matrix containing nine elements. However, this matrix can be determined with only three pieces of information. Therefore, individual measurements of the sun or nadir vectors cannot determine the full 3-dimensional attitude, since each measured unit vector provides only two pieces of information. Therefore at least two different measurements are required to determine the attitude, s_b and n_b . In fact, this results in an over-determined problem with three unknowns and four known quantities. The attitude determination problem then consists of determining an optimal estimate of R^{ib} from the available information. Several well-known algorithms exist to determine the optimal estimate of R^{ib} , such as the *Triad*² and *QUEST*¹ algorithms.

The Sun and Earth sensors form only one component of the overall sensor system. A simplified schematic showing each sensor and its contribution in the overall attitude

determination and sensor fusion scheme is shown in Fig. 3. Cameras give Earth and sun images that are sent to the Image direction. Processing Algorithm (IPA). The IPA calculates s_b and n_b from the images and sends the measured vectors to the Orientation Estimation Algorithm (OEA). Given s_i and n_i , the OEA determines the desired rotation matrix, R^{ib} .

The primary use of the solar arrays in the ADS is to provide a rough estimate of the sun direction. This can indicate which camera is most likely to acquire the Sun in its FOV and improve the operating efficiency of the camera system. The solar strings can also be used to provide a coarse estimation of the actual Sun vector in the event of an algorithm fault, or for use in the nadir vector determination algorithm to eliminate false horizon results. This adds a layer of fault tolerance to the overall sensor system.

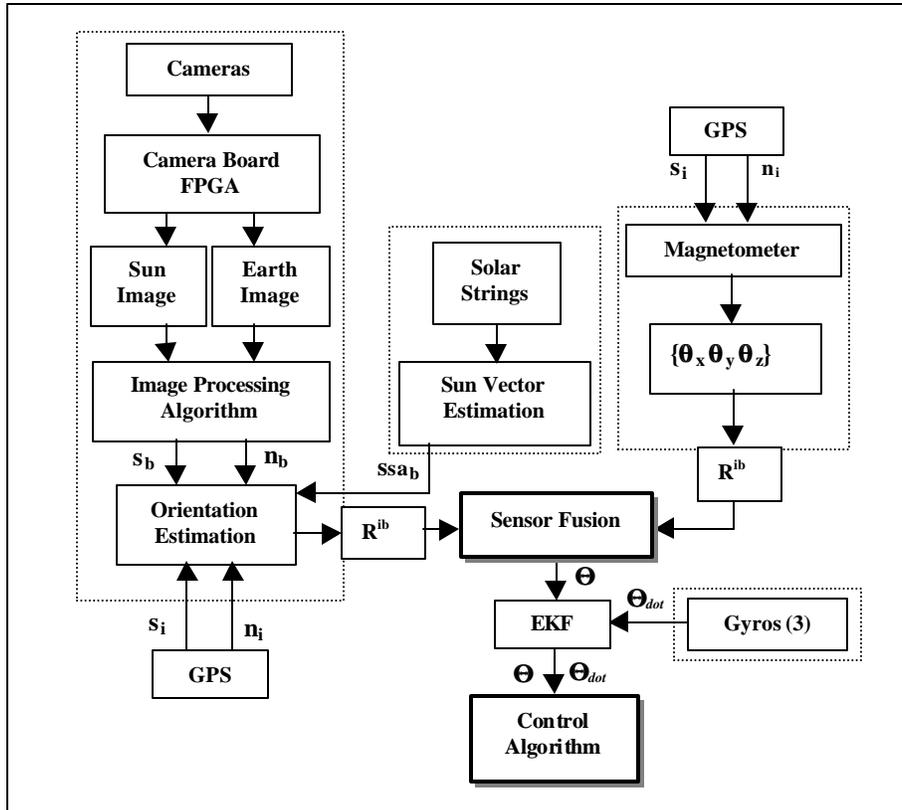


Figure 3: ION-F Sensor Fusion Schematic

The Honeywell 3-axis magnetometer will be used to determine another estimate of the rotation matrix, R^{ib} . This sensor measures the X, Y and Z components of the Earth's magnetic field. When these measurements are compared with theoretical magnetic field models, a three-dimensional satellite attitude can be determined.

In the end, two distinct estimates of R^{ib} will be generated from the cameras and magnetometer. It is the task of the sensor fusion logic to determine how to combine both of these independent measurements into the optimal estimate of the satellite attitude.

The optimal R^{ib} is then fed to an Extended Kalman Filter (EKF), which will take angular position estimates from R^{ib} and angular rate measurements from the gyroscopes to continuously estimate the full state of the satellite. The Systron Donner gyroscopes are the primary ADS sensors. The gyroscopes accumulate an error bias over time, corrupting the accuracy of the rate measurements. The primary task of all other sensors will be to periodically update the gyroscope measurements and zero out the accumulated bias. This is accomplished through the EKF. A gyroscope bias state will be added to the filter dynamics. With periodic inputs of the optimal attitude estimate, the EKF can continuously estimate the bias state and eliminate the problem of error accumulation.

3. Nadir Vector Determination

3.1 Edge detection

The ADS must be able to determine the actual horizon line from a camera image. A method of edge detection has been developed to meet the constraints of limited CPU and memory available on board the satellite. This method is briefly outlined in this section.

Edge detection is a method of extracting image curves or contours by searching for the position of intensity discontinuities. Typical of edge detection are one-dimensional and two-dimensional edges. The 1-D edge is a step

change of intensity from low to high. In practice, noise disturbs the signal as shown in Fig. 4. The edge is then defined as the transition from an average low to an average high intensity. Such edges are characterized by their contrast (difference between high and low intensity).

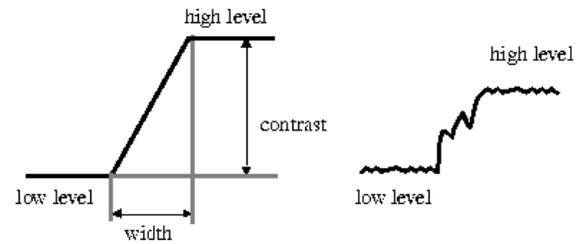


Figure 4: 1-D edge model³

A 2-D edge detection algorithm⁴ uses convolution with a smoothing filter and detects the edge by localizing the maxima of intensity gradients. This technique is unsuitable for the nanosatellite due to large CPU time and memory required to analyze a full image. An ADS requirement has been developed that states that the sensor processing must deliver an estimate of the spacecraft 3-D rotational state at a minimum rate of 2 Hz..

The ION-F design will use 1-D edge detection to minimize CPU time and memory costs. The following process is applied to the image scan data:

1. Calculate an average high intensity. Normalize all data using this average and round to the nearest binary value (0 or 1).
2. Apply logic condition to filter noise. For example, if a local measurement has a high average intensity, the output is set to 1 in binary mode. This logic filters high intensity noise.

The following example uses a 512×512 pixel, 8-bit image taken from MAQSAT[†]. The scan lines

[†] Image, and all occurrences, are copyright of ESA and have been processed by the ESTEC/WSP Image Lab

are shown in Fig. 5, and the resulting scan data is shown in Fig. 6. The signal is divided by the average high intensity and normalized to (0,1) as shown in Fig 7. Next, the program scans for the first change from 0 to 1, which signals an edge in the image. The remaining high intensity fluctuations are filtered out, as shown in Fig 8. The result shows that horizon points have been found at pixel coordinates (258,128), (215,256) and (200,384).

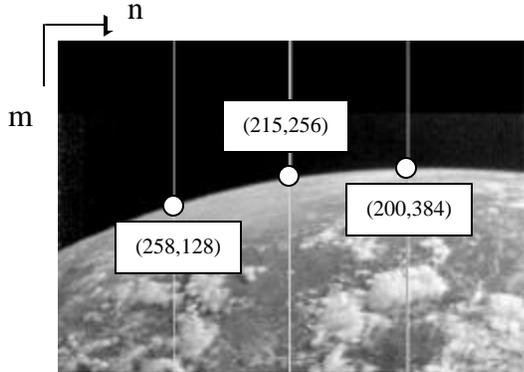
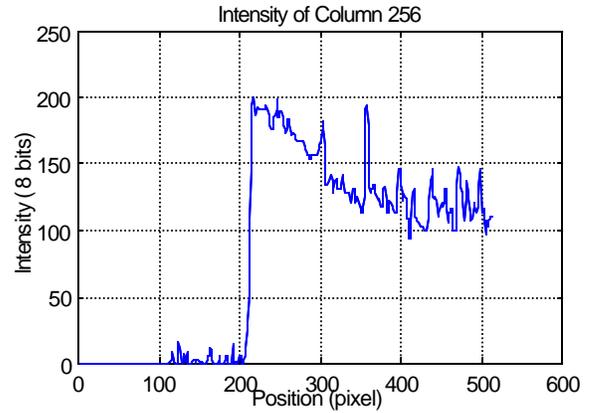
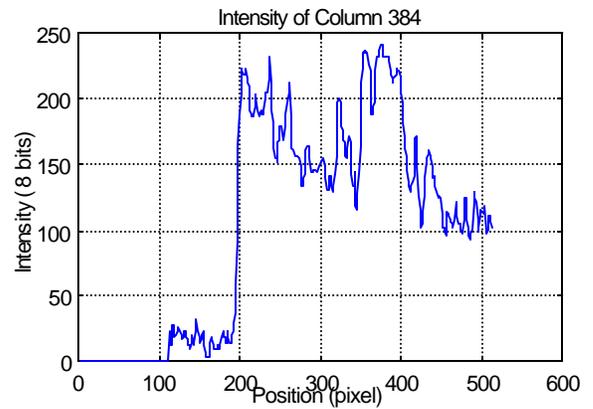


Figure 5: Image captured from MAQSAT using Fuga 15d. Scan lines at columns 128, 256 and 384.

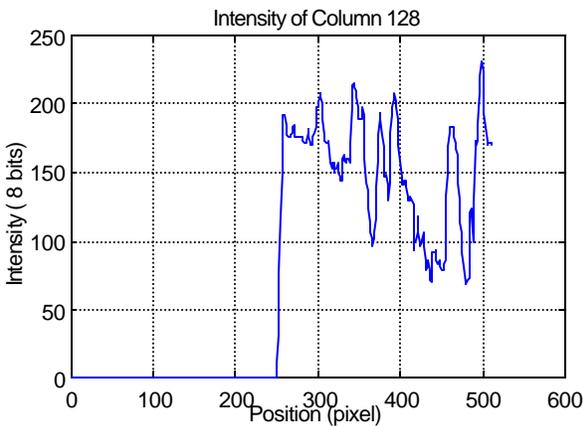


6.(b)

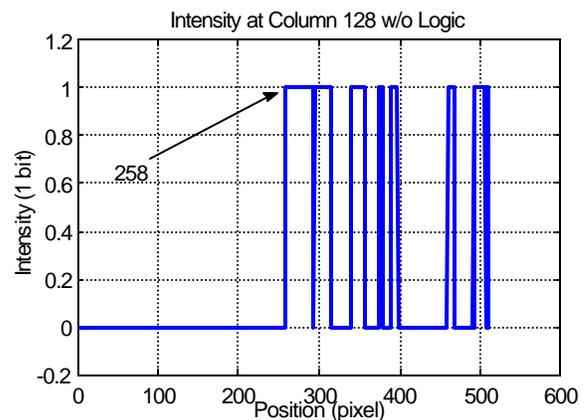


6.(c)

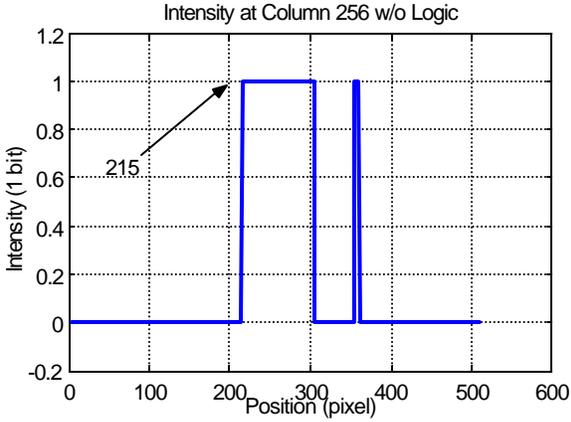
Figure 6: Intensity of scanning lines; (a) column 128, (b) column 256, (c) column 384



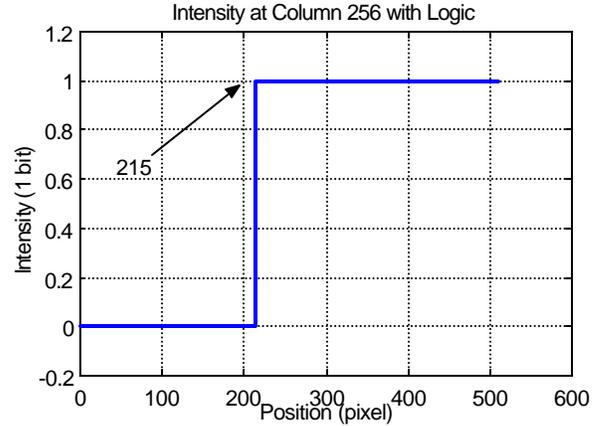
6.(a)



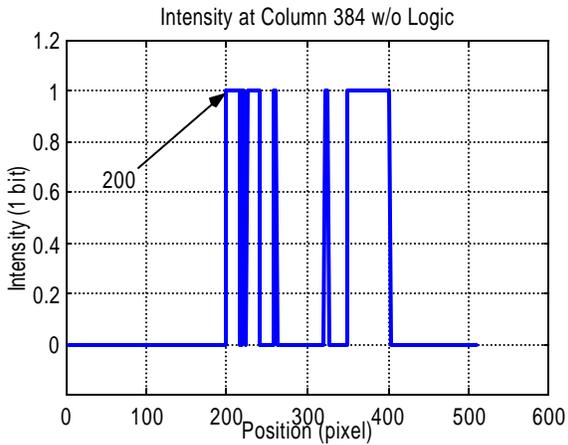
7.(a)



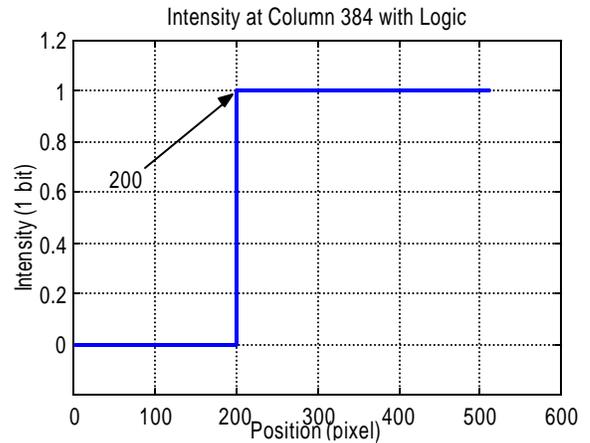
7.(b)



8.(b)



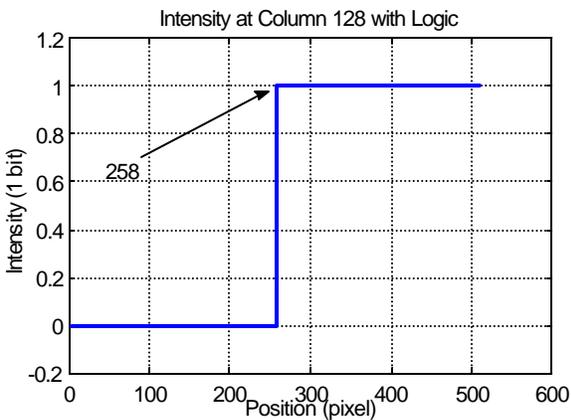
7.(c)



8.(c)

Figure 7: Intensity of scanning lines and position of edge in binary mode without filter logic; (a) column 128, (b) column 256, (c) column 384

Figure 8: Intensity of scanning lines and position of edge in binary mode with filter logic; (a) column 128, (b) column 256, (c) column 384



8.(a)

3.2 Vector Determination Algorithms

3.2.1 Determination of Horizon Plane Center and Radius

To simplify the following analysis, assume that the horizon image is homogenous. This means that each pixel represents the same spatial dimensions, in spite of lens curvature or distortion. Let three points determined from edge detection be (m_1, n_1) , (m_2, n_2) and (m_3, n_3) . The center point and radius of the circular horizon can be calculated from these points using a least squares method.

Substitute the points into three equations of a circle, assuming the center point (m_0, n_0) :

$$x^2 + y^2 = r^2 \quad (1)$$

$$(m_1 - m_0)^2 + (n_1 - n_0)^2 = r^2 \quad (2.a)$$

$$(m_2 - m_0)^2 + (n_2 - n_0)^2 = r^2 \quad (2.b)$$

$$(m_3 - m_0)^2 + (n_3 - n_0)^2 = r^2 \quad (2.c)$$

Expand each equation, rearrange to separate out the unknown terms (m_0, n_0) , and rewrite in matrix form:

$$\begin{bmatrix} (m_1 - m_2) & (n_1 - n_2) \\ (m_2 - m_3) & (n_2 - n_3) \\ (m_3 - m_1) & (n_3 - n_1) \end{bmatrix} \begin{Bmatrix} m_0 \\ n_0 \end{Bmatrix} = \frac{1}{2} \begin{bmatrix} (m_1^2 + n_1^2) - (m_2^2 + n_2^2) \\ (m_2^2 + n_2^2) - (m_3^2 + n_3^2) \\ (m_3^2 + n_3^2) - (m_1^2 + n_1^2) \end{bmatrix} \quad (3)$$

$$[A][X] = [B] \quad (4)$$

(m_0, n_0) can be calculated by a least squares method, using the pseudo-inverse:

$$\{X\} = [A]^{-1}[B] \quad (5)$$

With the center point known, the radius is found by substituting (m_0, n_0) into Eq.(2).

From the sample image edge points were found at pixel coordinates (258,128), (215,256) and (200,384). Using these points, the center point and radius of the horizon are determined from Eq.(5) and Eq.(2) to be (837.17, 393.79) and 637.3, respectively. The horizon plane superimposed on the image is shown in Fig. 9.

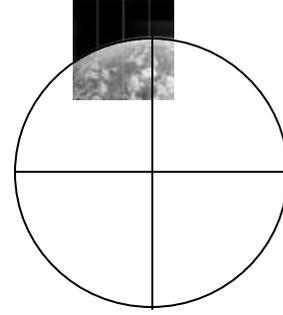


Figure 9: Horizon plane determined from edge detection

3.2.2 Nadir Vector Determination

Two approaches to nadir vector determination are now presented. The first is the *Graphic Method*, which deals with the two-dimensional horizon plane. The second is the *Vector Method*, which determines a rotation matrix from two measured vectors to update the nadir vector orientation.

Graphic method

The Graphic Method is based on the center pixel column (CPC) of the camera image and its projection onto the two-dimensional horizon plane. Camera installation requirements state that the optical axis must be aligned to pass through the origin of the SBFF frame; *i.e.*, the center of gravity. Under this constraint, the scanning line at the CPC, which projects downward as a plane, always passes through optical axis and the Z-axis of the SBFF. The intersection of this plane and the horizon plane is a line in the horizon plane. An intersection point of two such lines represents the intersection of the satellite nadir axis with the actual horizon plane. The nadir vector can be calculated from a known intersection point, horizon plane center point and the altitude of the satellite.

The following example uses two perpendicular cameras as shown in Fig. 10. Point Z is the intersection of the CPC planes in the horizon plane. Calculating spacecraft altitude and the ratio of pixels to kilometers, allows nadir vector determination.

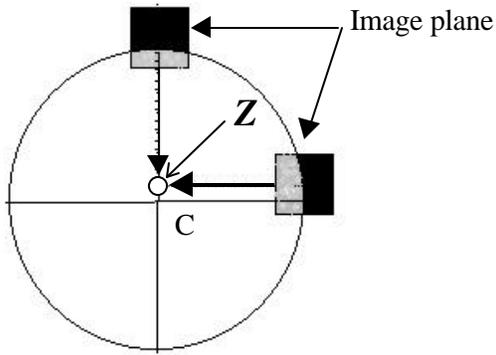


Figure 10: Graphic Method using 2 cameras

Vector Method

The Vector Method is a means of updating the nadir vector. Two successive vector measurements from a single, fixed camera gives information about the attitude change of the satellite. A rotation matrix can be determined from the two measurements and used to update the orientation of the nadir vector, as shown in Eq.(6).

$$N = [R] N_o \tag{6}$$

where

- N Updated nadir vector
- $[R]$ Nadir rotation matrix
- N_o Previous nadir vector

Fig. 11 illustrates the Vector Method and shows the Camera Reference Frame (CRF), Satellite Reference Frame (SRF) and Satellite Body-Fixed Frame (SBFF).

The vector Q is the optical axis, and represents the camera measurement before a change of attitude. This vector intersects the image plane and is aligned with Z_c . The vector P is the camera measurement after the satellite attitude has changed. This vector intersects the image plane and extends to the horizon.

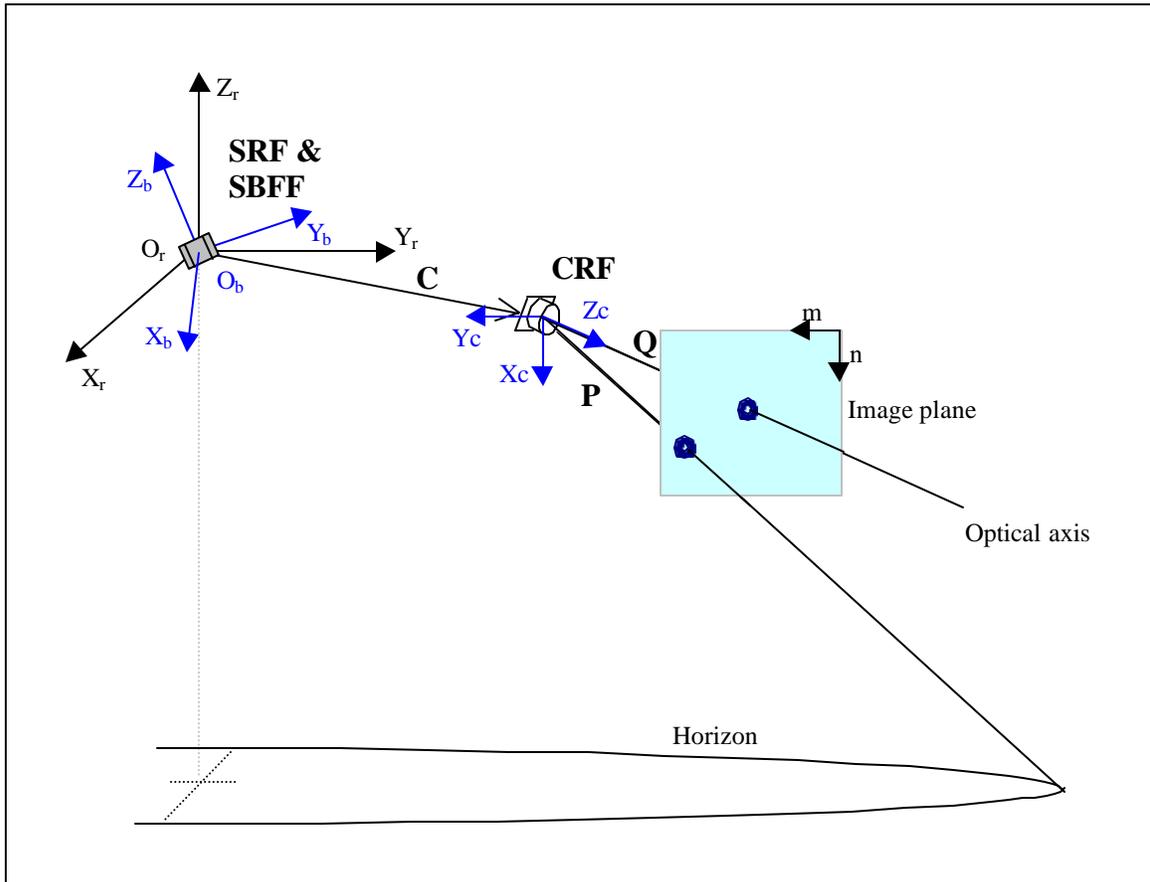


Figure 11: Vector Method illustration; camera, satellite, and reference coordinate frames

P and Q can be calculated directly from the camera image. A small time increment between these measurements allows the assumption that the change in the actual horizon is small. The two measurements can then be directly compared to determine a rotation matrix from Q to P . This rotation $[R]$ is used to update the nadir vector using Eq.(6)

3.3 Earth Shadowing Considerations

Earth sensing becomes more complex when shadowing effects are considered. At times the Earth will appear partially shadowed and the horizon sensing algorithm will locate points on the terminator as well as on the horizon. One cannot assume that all of the determined points lie on the true horizon, and further logic is necessary to determine the true horizon plane. This logic is based on known data, such as date, time, and orbital position. The view of the Earth from the satellite can be calculated with this information.

The optimal case occurs when the satellite sees no shadowing of the Earth. The camera system captures an image with each camera, and the vector determination algorithm finds the true horizon plane. Fig. 12 shows the optimal case for horizon plane determination.

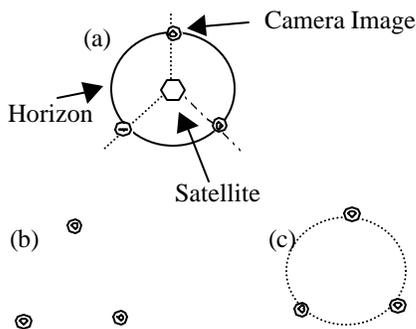


Figure 12: Detection of horizon points for optimal case and subsequent horizon plane

Fig. 13 shows a realistic case where part of the Earth lies in shadow. It is clear that the horizon determination algorithm will detect points that lie both on the true horizon and on the

terminator. A horizon plane extrapolated directly from these points would lead to a completely erroneous determination of the nadir vector.

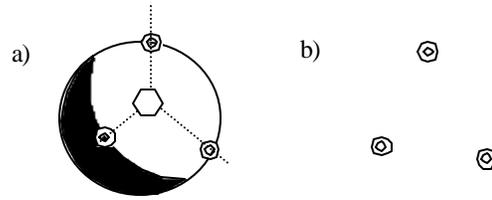


Figure 13: Realistic example of horizon detection

GPS gives the location of the satellite around the Earth and the current date and time are known. From this information, the rotation of the Earth around the Sun is also known and the shadowed portion of the Earth can be found. The result is a view of the Earth as seen by the satellite. A fitting technique can determine possible solutions to fit a plane to the detected horizon points. In many cases, however, the result is not unique. Fig. 14 shows an example of the uniqueness problem.

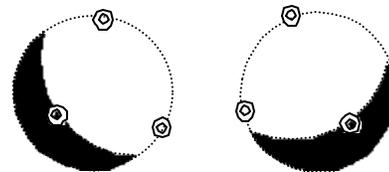


Figure 14: The uniqueness problem; Possible fits for horizon points with partial Earth shadow

Data from additional attitude sensors, such as the magnetometer and solar cell Sun sensor, can be used to eliminate incorrect results. With the correct fit, the true horizon plane can be found.

4. Camera System Configurations

4.1 VT Camera System Configuration

Three cameras are located on alternating side panels of the satellite. Each camera is mounted flush with the side, and separated by 120°. The FOV of each camera is approximately 67°, leaving 53° gaps in coverage around the

circumference of the satellite. Fig. 15 shows the VT satellite with camera FOV cones.

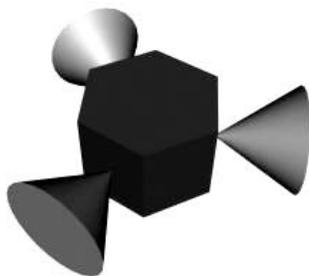


Figure 15: VT satellite with camera FOV cones

VT uses cameras for nadir vector determination, but not for Sun vector determination. Weight and complexity considerations limited the satellite to a maximum of three cameras. In addition, the top surface of the VT satellite is arranged such that it does not permit placement of a camera. With this configuration, the Earth horizon will be in view at almost all times, but the Sun may not be.

At the initial orbit altitude of 380 km, the horizon appears 20° down from the centerline field of view. This suggests that even if the satellite is rotated up to 15° from the desired nadir pointing orientation, the horizon will remain in the field of view of all three cameras. As the orbit decays, the horizon point appears higher in the field of view of the camera. This suggests that a greater rotation from the desired attitude will still permit the horizon to be seen in three cameras.

For nearly all possible orientations of the satellite, the horizon will be visible to the cameras. An exception might occur if the satellite were rotated such that one camera was pointing in the nadir direction. The remaining two cameras would then point away from Earth. No horizon points could be detected since the Earth would completely fill the FOV of the nadir-facing camera. A coarse attitude could be determined, however, since one camera would detect brightness, while the others would detect darkness.

4.2 UW Camera System Configuration

The UW ADS uses four cameras, each acting jointly as a Sun and Earth sensor. Three cameras are mounted near the center of every second side panel, while the fourth camera looks out of the top panel of the satellite. Fig. 16 shows the UW satellite with camera FOV cones.

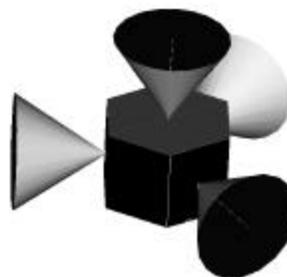


Figure 16: UW satellite with camera FOV cones

This configuration was chosen after a series of trade studies comparing different numbers and locations of cameras. Symmetry is a major advantage of the chosen configuration. A consideration for each study was the ability to locate the Earth horizon in one or more camera images. Since the formation will fly in a low Earth orbit, the horizon will dominate the images of all side panel cameras. An exception to this might occur for certain satellite orientations resulting from a loss of attitude control. This situation might find one of the cameras pointed into deep space, yet the symmetry of the design allows the remaining cameras to effectively assume the nominal nadir-pointing configuration.

Sun acquisition presents more difficulty due to its small apparent size, the limited number of cameras, and FOV limitations. The ability to view the Sun was, therefore, a driving requirement for any camera configuration. An analysis for each case determined an estimate of the percentage of time when any of the four cameras could locate an image of the Sun. The inertial position of the Sun and the satellite were propagated using *Free Flyer*^{®5} software. Given a 67° FOV and the camera configuration shown, Sun acquisition can be accomplished during

approximately 74% of the non-shadowed portion of a typical orbit.

4.3 USU Camera System Configuration

The USU satellite uses differential drag to alter its orbital velocity by exposing more or less surface area in the velocity direction. Because the satellite is expected to tip back and forth $\pm 90^\circ$, the camera arrangement helps ensure that the images captured over this range of motion will be useful in identifying the horizon. At all times at least 2 cameras have a view of the horizon, and at least one of them is ideal for scanning vertical lines of the image to determine the nadir vector from the horizon image.

One camera is pointed at a 55° angle from the nadir vector. The remaining two cameras are rotated plus and minus 45° in the vertical plane perpendicular to the previous rotation of the camera. Fig. 17 shows the USU camera configuration

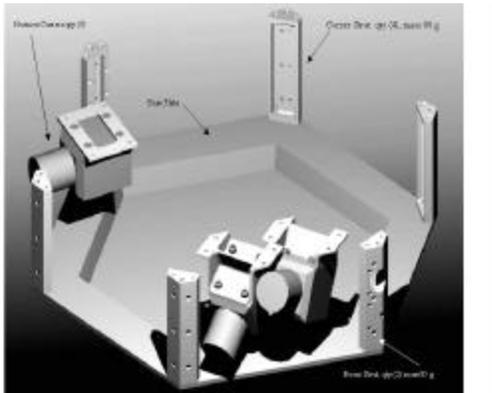


Figure 17: USU camera configuration

5. Conclusion

The ION-F satellite formation will incorporate digital, optical CMOS cameras into the ADS for Earth horizon sensing and nadir vector determination. The cameras offer several advantages over traditional analog or scanning sensors, and are ideal as sensors for 3-axis stabilized spacecraft. These include instant,

random access, low cost, low power, low mass and large FOV.

The ION-F ADS teams have proposed several algorithms for nadir vector determination. These methods must be further developed in order to evaluate the suitability of each towards fulfilling the role of the ADS, and meeting system requirements.

¹ Hall, Christopher D., "Chapter 4 - Attitude Determination," Class Notes. <http://www.aoe.vt.edu/~chall/courses/aoe4984/page4.html>

² Shuster, M.D. and S.D. Oh, "Three-Axis Attitude Determination from Vector Observations," *Journal of Guidance Navigation and Control*, Vol. 4, No. 1, January-February 1981, pp. 70-77.

³ "Edge Detection" <http://www.gre.ac.uk/~mi02/docu/html/refguide/chap8.html>

⁴ Canny, John. "A Computational Approach to Edge Detection," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 1986. Vol. PAMI-8, No. 6, pp. 679-698.

⁵ *Free Flyer*[®] Tutorial, Version 4.0, March 1999