Earth Reference Imager Experiment for Satellite Attitude Determination

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Abstract

The Earth Reference Imager (ERI) experiment on board the ASUSat 1 student satellite will provide valuable attitude information to validate the new attitude sensors along with the GPS data. Using the concept of triangulation, the satellite's tilt, swing, height, azimuth, and coordinates will be attained from an image of the Earth. This information will then be compared with the attitude sensors to confirm the data received from the satellite.

Nomenclature

A, B, C	ground control points
a, b, c	image ground control points
f	focal length
H	altitude of satellite
h_A, h_B, h_C	elevation at point
L_o	distance from nodal point of lens to place of photograph
L	space position of front nodal point
N	ground nadir point
n	nadir point
o	principal point
R_G	ratio between AB and AC on the ground
R_V	ratio between AB and AC on a vertical photograph
S_G	ratio between AB and BC on the ground
S_V	ratio between AB and AC on a vertical photograph
s	swing of photograph
t^*	introduced tilt of arbitrary amount
X_L, Y_L, Z_L	space coordinates of exposure station
(x, y)	photographic coordinates of image
x', y'	ground coordinates with arbitrary tilt calculated about the y axis
x", y"	ground coordinates with arbitrary tilt calculate about the x axis
α_G	ground survey azimuth
α_{no}	azimuth of principal plane
α_p	azimuth of control line
θ	amount of rotation

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1. Introduction

1.1 ASUSat 1

Since its inception, Arizona State University's first small satellite, ASUSat 1, has been a student-designed project. Many members of local industry and the faculty of ASU have been very supportive of the project, and have sponsored and advised several aspects of the program.

Weighing ten pounds (4.5 kg), the satellite will be the lightest ever put into orbit with meaningful science experiments[1]. The payload will be launched by Orbital Sciences Corporation on a Pegasus launch vehicle and will be placed at a 325-km sun-synchronous orbit. It is expected to remain in orbit for approximately 22 days.

ASUSat 1 will allow researchers to measure the properties of the ionosphere at a low cost. Furthermore, it will provide an audio transponder for amateur radio operators.

There have been an average of forty students ranging from high-school through Ph.D level working in ten different sub-systems. These are science, structures & materials, dynamics & controls, communica-tions, power, thermal, commands, ground support equipment (GSE), software & data analysis, and systems integration.

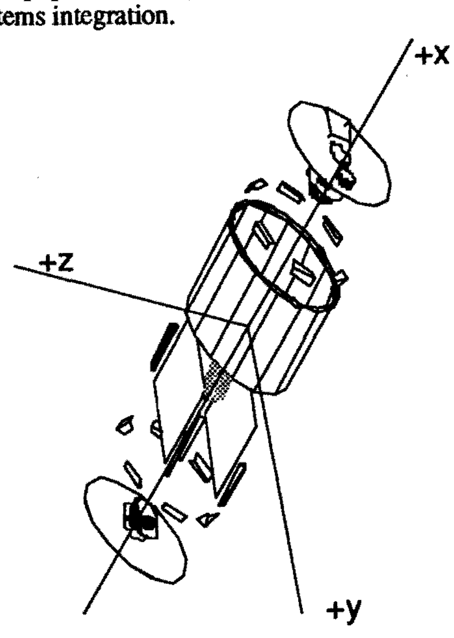

Figure 1 Pullaway view of ASUSat 1. Drawing by Shea Ferring and Chris Michaelis, Structures Team.

The science team is developing a Hall-Current Ion Accelerator, a Magnetohydrodynamic Generator, Ion Thrusters, and the Earth Reference Imager.

The structures team designed a fourteen-sided graphite / epoxy bus and overlooks cabling and mounting on the satellite.

Dynamics is providing stabilization with an aerodynamic boom and a fluid damper. Moreover, they are providing positioning information through a GPS receiver and an array of photodiodes.

Communications has student-built the modem and designed a deployable antenna.

The power sub-system will be providing power to the satellite through two six-packs of Sanyo NiCd batteries, re-charged with GaAs solar cells around the fourteen sides of the bus. The satellite will be powered up with a mechanical switch when the satellite is deployed.

The thermal team keeps track of the temperatures inside the bus, and stabilizes them with paints and highly emissive coatings. The temperatures expected outside the satellite are in the range of -24° C to 90° C.

Commands is designing the processor around the INTEL 80C188EC chip, running it at 10 MHz. Two I/O ports provide interfaces with the science/dynamics board and with the camera interface board. There is also an Error Detection and Correction (EDAC) facility built in for the 1 Mbyte of RAM available for the satellite's data. One EPROM will be used for the default operating system, while another will contain the bootloader for the satellite's system.

Ground support is providing the testing equipment and facilities. Orbital Sciences has allowed the ASUSat 1 team to use several of its facilities.

The software for ASUSat 1 is being written in C and compiled to run in the BekTek Real-time Spacecraft Operating System designed for micro-satellites.

Finally, the systems and integration team is coordinating all the designing, integration, testing and documentation of all the sub-systems of the satellite.

The pointing requirements have been defined to be ± 10°, with orbital positioning being within ± 1 km[1] to attain full coverage of the Earth. It is hoped that the drag coefficient can be calculated. To achieve these goals, a new attitude-sensors array has been designed and developed to give the satellite's orientation.

The coordinate axis is defined as shown in figure 1. The x axis lies along the axis of symmetry, y axis runs parallel to the inside panels and perpendicular to the x axis, and the z axis runs perpendicular to the panels, through the center.

1.2 Earth and Sun Sensors

To keep control of the satellite, its orientation information will be recorded through a complex network of photo sensors. With a total of sixty of these photodiodes positioned around the satellite, there will be almost complete coverage of the sky. Of the sixty sensors, forty-six will be sun sensors which will be keyed in to visible light, and the remaining fourteen will be Earth sensors, filtered to receive in the infra-red.[2]

There will be blocks of three sun sensors on each of the fourteen sides of the satellite, one being normal to the surface of the side, and the other two at ± 45° from the normal. Earth sensors will be positioned on every other side of the satellite, and the remaining sensors will be placed on the front and back plates of the satellite.[2]

The sensors themselves are Motorola Photo Detectors, MRD510, with filters being placed on the Earth sensors. These diodes will produce voltages ranging from 0-5 V, proportional to the amount of light received. The readings from each sensor will be recorded every five minutes, and the data will later be processed on the ground.[2]

However, this dynamics sensor array has never been flown, and other data is necessary to confirm the accuracy of the data from the satellite's sensors. To confirm the information received from the sensors, a camera will be flown to image the Earth vertically. Then, by performing the methods of triangulation on the ground images from the satellite, it is hoped to confirm the positioning data given by the sensors array. To ensure that the camera is perpendicular to the Earth, the sensors will be used to approximate where the Earth is relative to the satellite.

1.3 GPS

The Global Positioning System (GPS) was developed primarily for military purposes by the Department of Defense. However, the technology has become available to the public.

Consisting of a global network of twenty-four satellites at high altitudes, GPS provides its users with accurate position and velocity data. GPS receivers have been used on Lower Earth Orbit satellites in the past for determining the satellite's orbital parameters.[3] By a method of triangulation, the satellites are able to practically pinpoint the receiver's position.

Several factors have introduced errors in the GPS measurements such as the ionosphere which causes some interference. On the average, GPS may be off by about sixty feet, and in the worst case, GPS data may be off by as much as 350 ft. [3]

ASUSat 1 will carry a Trimble GPS receiver on board. The SVee Six-CM2 is a terrestrial board with 6 channels and has never been flown in space before, but it has been rigorously tested by ASU students to ensure that it will survive in space.[4,5] The accuracy of this particular unit is 25m. Readings will periodically be measured and recorded from the GPS to determine the satellite's position and velocity.[4]

From the GPS data included in the telemetry, it will be known from where the images were taken. This will prove useful in identifying the precise location of the image, and in verifying the position calculations from the images.

1.4 Earth Reference Imager

Once the images have been received and processed on the ground, it will be possible to perform several measurements on the images, and do calculations on them with a certain degree of error. The error will depend on the resolution of the image and on the scale of the photograph.

From the image, three points will have to be identified, the distances between each of them calculated, and the elevations from sea level of each point attained to perform the desired calculations[6].

2 Earth Reference Imager

2.1 Imager

The cameras being used for the experiments on ASUSat 1 are single-chip CMOS digital cameras. The cameras, VVL-1070, have a pixel resolution of 160 x 160 pixels, and put out 8-bit digital parallel output. The pixel size is 10.5 µm x 10.5 µm, giving a total effective array size of 1.68 mm x 1.68 mm. The camera also provides analog output, and an exposure control (2,000:1), gain control, and variable frame rate (0.5 - 24 frames/sec). At 5V, the chip consumes less than 100 mW.

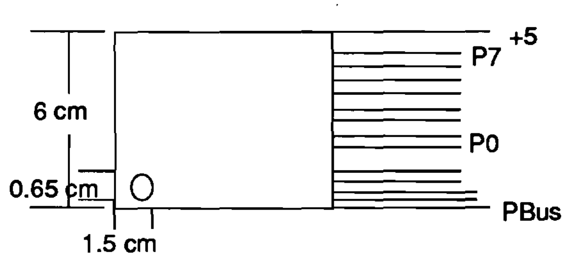

Figure 2 Dimensions and basic layout of camera board. There are five control lines and eight data lines on each board. The lens is mounted in the corner.

2.2 Optics

The lenses being used for the cameras are V-4308 multi-element lens with a diameter of 15 mm across the top and focal length of 8mm with an f-stop of 2.0. The lens weighs about 7 grams. The field of view given in the specifications is 31° x 23° (H x V). [7] Assuming the satellite is at a 325 km orbit and that the camera is facing vertically down to Earth, the range of the image would be 195.3km x 138km. [8] giving a resolution of about 1 km per pixel (Fig. 3). Furthermore, the scale is calculated as the focal length over the altitude of the camera, which is approximately 1: 40,625,000 in this case. [7] By keeping the field of view and ground coverage limited, the resolution should be optimized for the digital camera chips.

2.3 Placement

The lens will be fixed over the camera on the camera board using a lens holder, with the appropriate focal length to focus the image. The board will measure approximately 4 cm x 6 cm (Fig. 2), allowing the camera to be placed along the side of one of the satellite's side panels. A hole of 0.65 cm in diameter will be drilled to allow the lens to be mounted up to it to view the Earth at a right angle to the satellite's axis of symmetry (Fig. 4) close to the z axis (Fig. 1).

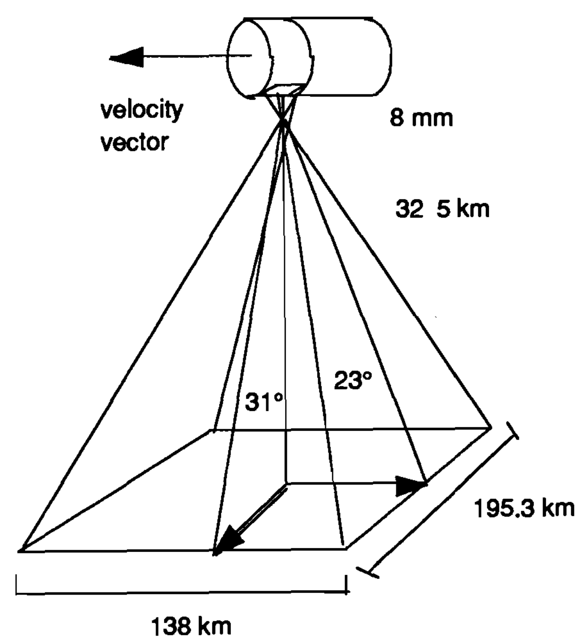

Figure 3 With a field of view of 31°-23°, altitude of 325 km, and focal length of 8 mm, the ground coverage should be about 138 km x 195.3 km.

2.4 Protection

The circuitry for the camera board will be surface mounted and conformal coated to protect from vibration and shock. Dampers will be placed around the board and lens as well. A gold foil will be put around the outside camera board to reflect the sun's radiation, to keep it cool, and to protect the circuitry from cosmic particle hits.

3 Camera Boards

The VVL-1070 chip has a built-in analog-to-digital converter (A/D) circuit, so the output is already digital.[9] The supporting electronics, then, drive the camera at real-time clock speeds, and transfer the images to the main CPU bus through a 25-pin interface.

ASUSat 1 will carry two CMOS cameras, one for determining the satellite's roll rate, and the other for the ERI experiment. Both will have the supporting circuit board (Fig. 2). The boards consist of their own microprocessors and memory with built-in commands to run the camera. Running at real time rates, the image will be dumped into the local memory, where the main CPU can then read the memory at its own rate and store it to be downloaded at a later time.[10] There will also be an interface board between the two camera boards and the main CPU which handles the control of the two cameras from a chip select in the interface. The interface consists of five control lines for each camera, and eight data lines which will be shared by both cameras (Fig. 5). The camera boards will be designed by Gordon Minns & Associates in Wyoming.

The software to control all three micro-processors will be written in ANSI C and will be compiled for a BekTek operating system.[11] The supporting software will be included with the camera-board product to be modified by the software team. The commands will be uploaded to the satellite, where the cameras will be allotted ten minutes per orbit to take images.[12] The camera boards will consume less than 100 mW as well, and the size of each image will be about 25 kB. At this size, it will be possible to take about ten consecutive images in one orbit.[10]

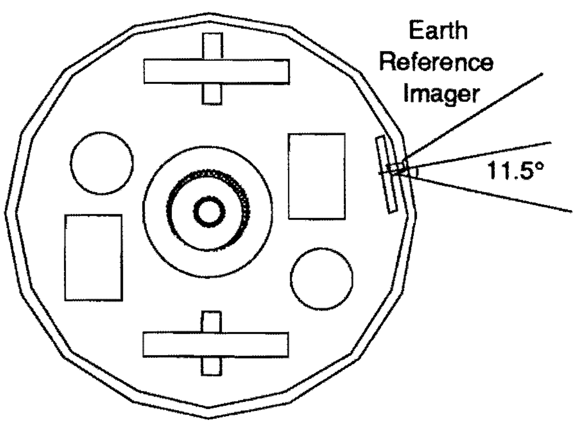

Figure 4 The ERI camera will be mounted to one of the 14 side panels of the satellite to view the Earth vertically with a range of 23°.

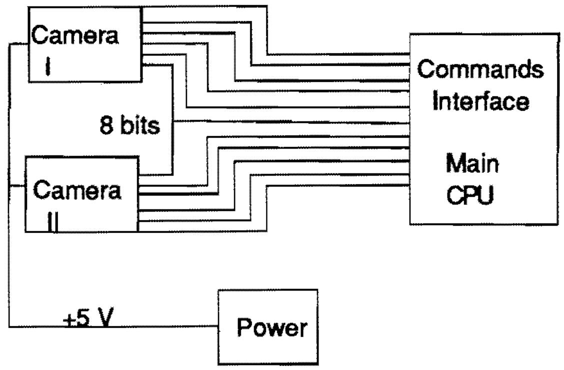

Figure 5 The two cameras on ASUSat 1 will go to a camera interface board which will connect to the main processor's control interface. The 8-bit data lines will be shared by both cameras.

4 Image Processing

Once the images have been taken, and transferred to the main CPU bus, the data will be downloaded to the ground station at Arizona State University several times a day. When the images have been successfully transferred, they will be moved over the internet to a Silicon Graphics machine for image processing. Using an image processing package such as XV, several analyses will be done on the images such as filterings, histograms, and averaging.[13] Software such as IDL is also available along with faculty experienced in professional image processing.

Once the images have been optimized, whether taking the average of consecutive frames or filtering high frequencies, the image will be ready for the data analysis.[8] From the image, it will be crucial to identify the objects and locations on Earth, or in the sky, for determining the satellite's attitude. This can be done by comparing daily weather maps, terrain maps, and GPS data along with the dynamics-sensors data to approximate the location at which the image was taken.[2] Weather maps will reveal cloud covers where an image may be completely white, in which case the image data will not be very helpful. Otherwise, the image can then be used to perform the triangulation.

5 Theory of Triangulation

5.1 Assumptions

The principle of triangulation is based on the fact that the ratio of two ground lengths computed from the ground coordinates of the tilted photograph must be the same as the ratio of the corresponding known ground lengths. To obtain two ratios, three lines are needed, so at least three points must be identified. This is assuming, of course, that three distinct points can be distinguished on the image, the distances between the three points on the ground can be calculated, and their respective elevations from sea level can be found as well. From these three ground points, A, B and C (Fig 6), the length between two pairs of the points can be determined analytically. Furthermore, the location of the three points on the globe will be known, so the position of the satellite can be determined if the tilt of the image is known.

5.2 Determining Tilt

A tilt t occurs when the optical axis is unintentionally deviated from the vertical axis coinciding with the direction of gravity.[14] This is given by the angle oLn as shown in figures 6 and 7, where L is the position of the satellite moving in the +x direction, o is the center or principal point of the image, and n is the nadir point. The nadir point is the point on the photograph vertically beneath the satellite's imager, or exposure station.

From the three points on the image, two control lines can be formed to find two independent ratios such as those given in (8). From these ratios, the two components of the tilt on the photograph, t_x and t_y, can be determined, as well as the swing of the camera.[7] The x component relates to a change in pitch of the satellite, while the y component of the tilt is related to roll in the satellite. The swing is the direction of the tilt with respect to the photographic axes.

The first step is to calculate the ground coordinates based on the photographic coordinates. The photographic coordinates are measured with respect to the lines joining the opposite fiducial marks, giving the three photographic coordinates corresponding to the ground points,

$$\begin{aligned} &(x_a, y_a) \\ &(x_b, y_b) \\ &(x_c, y_c) \end{aligned} \tag{1}$$

The altitude of the satellite can be approximated from the equation[6]

$$\frac{f}{H_{app} - h_{AB}} = \frac{ab}{AB} \tag{2}$$

where h_{AB} is the average elevation of points A and B, H_{app} is the approximate altitude, f is the focal length of the lens, and the distances between the points are ab and AB. The scale of the photograph is calculated from[6]

$$scale = \frac{f}{H} \tag{3}$$

If the camera were truly vertical to the ground, then the ground coordinates would simply be[14]

$$\begin{aligned} X_A &= \frac{H - h_A}{f} - x_a, & Y_A &= \frac{H - h_A}{f} - y_a \\ X_B &= \frac{H - h_B}{f} - x_b, & Y_B &= \frac{H - h_B}{f} - y_b \\ X_C &= \frac{H - h_C}{f} - x_c, & Y_C &= \frac{H - h_C}{f} - y_c \end{aligned} \tag{4}$$

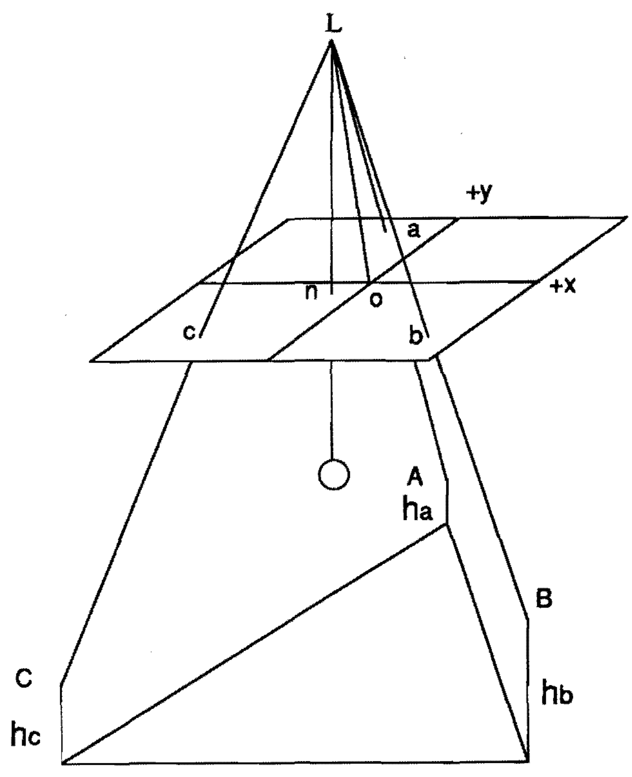

Figure 6 Three points on the ground represented by their corresponding points on a tilted image. The +x axis lies in the direction of the velocity vector.[14]

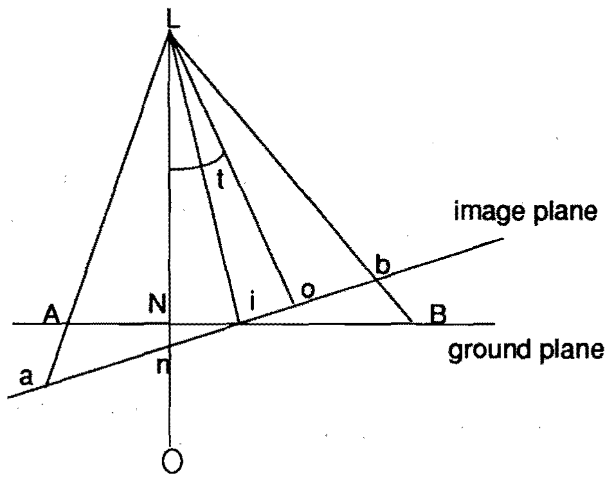

Figure 7 Tilt is the displacement of the pitch or roll on the image plane relative to the ground plane[14].

However, taking a swing θ about the y-axis with an induced tilt of t^*, the ground coordinates are adjusted by[14]

$$x' = x\cos\theta + y\sin\theta$$
$$y' = -x\sin\theta + y\cos\theta + f\tan t^* \qquad (5)$$

Repeating a similar rotational tilt about the x-axis yields x" and y". Then, substituting (5) into (4), the new equations for the ground coordinates become, in general,[15]

$$X' = \frac{H-h}{f\sec t^* - y'\sin t^*}x'$$
$$Y' = \frac{H-h}{f\sec t^* - y'\sin t^*}y'\cos t^*$$
$$X'' = \frac{H-h}{f\sec t^* - y'\sin t^*}x' \qquad (6)$$
$$Y'' = \frac{H-h}{f\sec t^* - y'\sin t^*}y'\cos t^*$$

These X and Y coordinates are calculated for each point, A, B & C. X' and Y' represent the ground coordinates when the tilt is induced about the +y axis, while X" and Y" represent the ground coordinates when an arbitrary tilt is induced about the +x axis in a similar fashion. The lower case x and y in (6) represent the photographic x and y coordinates. See figure 11 for an illustration of X' and Y'. These are the calculated ground coordinates that will be used.

Since the ground-control coordinates have now been determined, the ground-control lengths of the vertical photograph can be calculated by the distance formula to yield

$$AB = \sqrt{\left(\left(X_B - X_A\right)^2 + \left(Y_B - Y_A\right)^2\right)}$$
$$AC = \sqrt{\left(\left(X_C - X_A\right)^2 + \left(Y_C - Y_A\right)^2\right)} \qquad (7)$$
$$BC = \sqrt{\left(\left(X_C - X_B\right)^2 + \left(Y_C - Y_B\right)^2\right)}$$

Using the three lines above for the triangulation, the two ratios are then defined as[14]

$$R_G = \frac{A_G B_G}{A_G C_G}$$
$$S_G = \frac{A_G B_G}{B_G C_G} \qquad (8)$$

If the camera were vertical or perpendicular to the Earth's surface, then the following ground ratios for the vertical image could be defined as

$$R_V = \frac{AB}{AC}$$
$$S_V = \frac{AB}{BC} \qquad (9)$$

If equations (8) do not equal the respective ratios in (9), then the photograph has some tilt since the ratios of the two lines' lengths are not the same. That is, the ratios of the lengths from the calculated ground coordinates on the photograph do not equal the ratios of the same control lengths on the ground. Assuming the satellite image will have some tilt, either in the pitch or roll, then [14]

$$R' = \frac{A'B'}{A'C'}$$
$$S' = \frac{A'B'}{B'C'} \qquad (10)$$

$$R'' = \frac{A''B''}{A''C''}$$
$$S'' = \frac{A''B''}{B''C''} \qquad (11)$$

R' and S' are the ratios of the lines calculated when a tilt was introduced about the +y axis. Similarly, R" and S" are the ratios of the lines when an arbitrary tilt was introduced about the +x axis. These are found by substituting the equations in (6) into the lines defined by (7), and taking the ratios as in (8).

From the information given thus far, the change in the ratios can be calculated as the change due to the tilt. That is, the change in the ratios due to the tilt t_y of the camera for the y axis is

$$R' - R_V \tag{12}$$

The change in the ratios due to the tilt t_x can likewise be defined as $S'-S_V$. The rate of change per minute for the y axis is then[14]

$$\frac{R' - R_V}{t^*} t_y, \quad \frac{S' - S_V}{t^*} t_y \tag{13}$$

and

$$\frac{R'' - R_V}{t^*} t_x, \quad \frac{S'' - S_V}{t^*} t_x \tag{14}$$

for the tilt in the x axis.

Since the equations in (8) represent the true ground ratios, the changes due to the components of the tilt are added. Adding (13) and (14) to the equations in (8) yields[14]

$$\begin{aligned} R_G &= R_V + \frac{R' - R_V}{t^*} t_y + \frac{R'' - R_V}{t^*} t_x \\ S_G &= S_V + \frac{S' - S_V}{t^*} t_y + \frac{S'' - S_V}{t^*} t_x \end{aligned} \tag{15}$$

The equations in (15) can then be simultaneously solved using linear algebra to find t_x and t_y, the two components of the camera's tilt. From the solutions to (15), the pitch and roll of the image, and consequently of the satellite, can be determined. Furthermore, once the two components of the tilt have been found due to the pitch and roll of the satellite, the angle t can be found. To solve for t,[14]

$$t = \sqrt{\left(t_x{}^2 + t_y{}^2\right)} \tag{16}$$

is used. Consequently, the tilt of the camera can be determined from the tilt of the image and the position of the satellite relative to the Earth can also be determined.

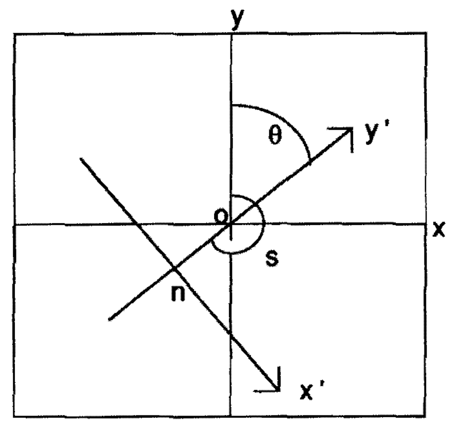

Figure 8 The swing is the displacement of the image's coordinate system to the ground's coordinate system, ie. a rotation of axes.[14]

5.3 Determining Swing

The swing of the photograph is the angle measured in the plane of the image from the positive y-axis clockwise to a line from the principal point o to the nadir point n.[14] This is illustrated in figure 8.

The swing of the camera, s, is easily calculated as a function of the components of the tilt of the camera, as found when the equations in (15) were solved. It is defined as, [14]

$$\tan s = \frac{t_y}{t_x} \tag{17}$$

where s can easily be solved if the components of t are known. The amount of rotation θ is defined to be

$$\theta = 180^\circ - s \tag{18}$$

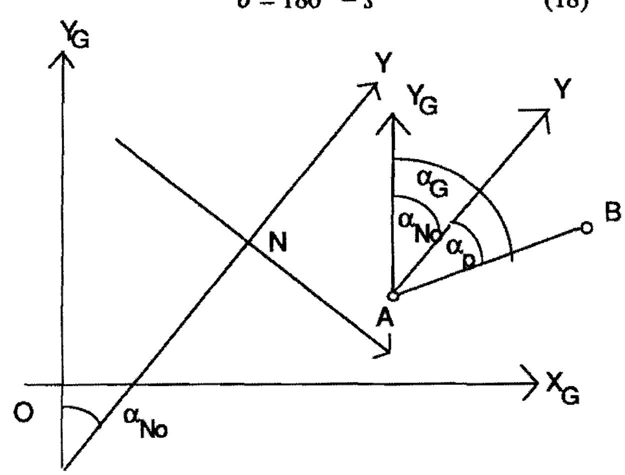

Figure 9 The ground survey azimuth is simply the sum of the azimuth of the principal plane to the azimuth of the given control line.[14]

5.4 Determining Azimuth

The ground-survey azimuth from the North is given by[14]

$$\tan\alpha_G = \frac{X_{G_2} - X_{G_1}}{Y_{G_2} - Y_{G_1}} \qquad (19)$$

where a_G is the ground-survey azimuth, and points 1 and 2 are the endpoints of the control lines that were used for the calculations of the tilt and swing. If

$$\tan\alpha_p = \frac{X_2 - X_1}{Y_2 - Y_1} \qquad (20)$$

where a_p is the azimuth of the control line based on the set of ground coordinates where

$$X_L = 0$$
$$Y_L = 0 \qquad (21)$$
$$\alpha_{No} = 0^\circ$$

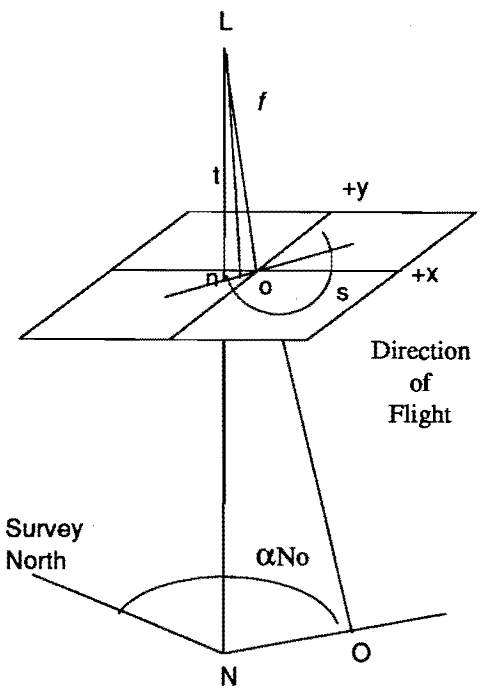

Figure 10 The azimuth of the principal plane is the clockwise horizontal angle measured about the ground nadir point from the ground survey north meridian to the principal plane of the photograph.[14]

then[14]

$$\alpha_{No} = \alpha_G - \alpha_p \qquad (22)$$

as illustrated in figures 9 and 10. The azimuth, as defined in figure 10, will give information on where the satellite was located when the image was taken.

5.5 Determining Ground Coordinates

The ground-survey coordinates of the exposure station, or the camera, can also be calculated, provided that the azimuth of the photograph is known from equation (22). Let the ground-survey coordinates of the exposure station be X_L and Y_L (Fig. 11). The ground-survey axes are defined as being X_G and Y_G, and the ground axes based on the nadir point N and the principal plane are X and Y. The ground-survey coordinates of point A are then (X_{GA}, Y_{GA}) and the ground coordinates are (X_A, Y_A). If the X and Y coordinate axes are rotated through the positive angle α_{No}, then the transformed coordinates of A become (X'_A, Y'_A). This transformation is achieved by[14]

$$X' = X\cos\alpha_{No} + Y\sin\alpha_{No}$$
$$Y' = -X\sin\alpha_{No} + Y\cos\alpha_{No} \qquad (23)$$

Then the ground coordinates are determined by[14]

$$X_L = X_{GA} - X'_A$$
$$Y_L = Y_{GA} - Y'_A \qquad (24)$$

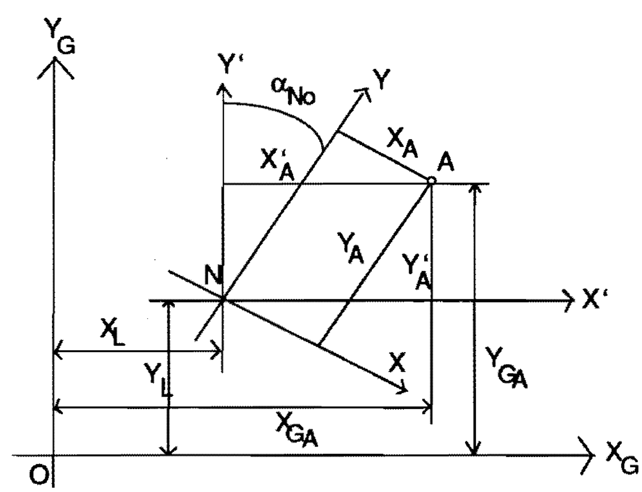

Figure 11 Ground-survey coordinates of exposure station for a point A using determined azimuth.[14]

6 Conclusions

Using images from the Earth Reference Imager experiment, the attitude of the satellite can be determined, and the data from the attitude-sensors array confirmed. The GPS receiver will help confirm the satellite's relative position as well. But using the principles of triangulation, it is possible to determine the tilt of the camera, the swing, azimuth, and ground survey location at a given time, and consequently, the satellite's orbital parameters. With this method and with extremely small, lightweight and low-power cameras, the attitude of any Earth satellite at a given time can easily be determined from an image of the Earth.

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8 References

[1] Rademacher, Joel. "Systems Specifications Document: 1.0 Overview." Arizona State University, (1995).

[2] Potterveld, Curtis. "Systems Specifications Document: 3.7 Dynamics/Control." Arizona State University (1995).

[3] Hurn, Jeff. GPS: A Guide to the Next Utility. Sunnyvale: Trimble Navigation, 1989.

[4] Stillman, Catherine. "Systems Specifications Document: 3.7.3.4.1 GPS." Arizona State University (1995).

[5] Gish, David. "Testing Procedures of the GPS Receiver." Testing documentation, Arizona State University (1995).

[6] Baker, Wilfred H. Elements of Photogrammetry. New York: The Ronald Press Company, 1960.

[7] Slama, Chester C., ed. Manual of Photogrammetry: Fourth Edition. Falls Church: American Society of Photogrammetry, 1980.

[8] Kiefer, Ralph W. and Thomas Lillesand. Remote Sensing and Image Interpretation, 2nd edition. New York: John Wiley & Sons, 1987.

[9] VVL Vision Ltd. "VVL-1070 Monochrome Monolitic Image Sensor with Analogue and Digital Outputs: Preliminary Data Sheet."

[10] Wightman, Mark. "Systems Specifications Document: 3.3.3 Commands." Arizona State University (1995).

[11] Vo, Perry. "Systems Specifications Document: 3.3.2 Software." Arizona State University (1995).

[12] Bowman, Roberta. "Systems Specifications Document: 3.4 Power." Arizona State University (1995).

[13] Cracknell, Arthur and Ladson Hayes. Introduction to Remote Sensing. New York: Taylor & Francis, 1991.

[14] Moffitt, Francis H. Photogrammetry. Pennsylvania: International Textbooks Company, 1967.

[15] Crone, D. R. Elementary Photogrammetry. New York: Frederick Ungar Publishing Co., 1963.