SIMULATION OF DIRECT GEOREFERENCING FOR GEOMETRIC SYSTEMATIC CORRECTION ON LSA PUSHBROOM IMAGER

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Abstract. LAPAN has developed remote sensing data collection by using a pushbroom linescan imager camera sensor mounted on LSA (Lapan Surveillance Aircraft). The position accuracy and orientation system for LSA applications are required for Direct Georeferencing and depend on the accuracy of off-the-shelf integrated GPS/inertial system, which used on the camera sensor. This research aims to give the accuracy requirement of Inertial Measurement Unit (IMU) sensor and GPS to improve the accuracy of the measurement results using direct georeferencing technique. Simulations were performed to produce geodetic coordinates of longitude, latitude and altitude for each image pixel in the imager pushbroom one array detector, which has been geometrically corrected. The simulation results achieved measurement accuracies for mapping applications with Ground Sample Distance (GSD) or spatial resolution of 0,6 m of the IMU parameter (pitch, roll and yaw) errors about 0.1; 0.1; and 0.1 degree respectively, and the error of GPS parameters (longitude and latitude) about 0.00002 and 0.2 degree. The results are expected to be a reference for a systematic geometric correction to image data pushbroom linescan imager that would be obtained by using LSA spacecraft.

Keywords: *direct georeferencing, pushbroom imager, systematic geometric correction, LSA*

1 INTRODUCTION

Direct georeferencing is one of the very important topics in photogrammetry industry today. In its mapping process, *aero-triangulation* phases could be ignored when direct measurements to external orientation parameters of each single image was used when the camera was recording an object. Therefore, direct georeferencing enables a wide range of mapping products to be produced from aircraft navigation and image data with minimal ground control points (GCP) for Quality Assurance (Q/A) (Mostafa 2001).

Directly georeferenced image sensing is essentially a process of labeling the coordinate (calibration position) of remote sensing imagery with exact coordinates on the Earth system. Simply, this process can be done with the help of a geometric formula that connects point system and the spacecraft orbiting the Earth system. Georeferencing process was an early necessary stage in remote sensing image geometric correction process to generate encoded data or image to a map (geocoded image). To get onto this stage, resampling process has to be done, which was not discussed in this paper (Maryanto 2016).

As illustrated in Figure 1-1, direct georeferencing vector is calculating vector $\hat{\imath}$ by exploring geometric relationship, which is built by the physical relation of image acquisition devices involved. Each device geometrical acquisition can be seen as a single entity reference system with its own terms of reference (GAEL Consultant 2004). Therefore, the exploration of geometric relationships in the direct georeferencing generally starts from extracting image orientation (direction of viewing each image pixel to object partner) according to the physical devices that make it up, namely the camera. Since this process only reviews internally within the camera itself, the viewing direction identified with an orientation is also called internal or intrinsic orientation.

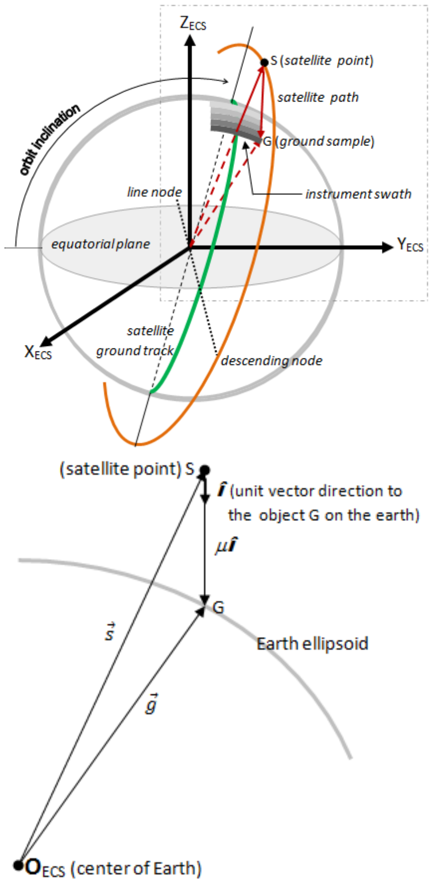

Figure 1-1. Geometric point formation of center of Earth, satellite point on a current time, and object point or target point forming a vector relation

Methodologically, formulation of internal orientation to all cameras were similar. In order to identify the location of the image (pixels in the image file) on the detector cell (pixel detector), which produced itself, center point of view or the central perspective identification inside the lens system was taken as a point of coordinate system origin. The coordinate axes defined the right for a 3-D space centered at the origin point, then calculated the position vector of each pixel's detector that represents the image pixel on the defined camera coordinate system.

The formulation of internal orientation (intrinsic vector perspective) was fixed because of the structure of the camera was usually a fixed physical construction. Differences in the formulation of vector viewing occurs at the technical level, on how the cameras captured images or adopted scanning technology being used, as well as the magnitudes of physical camera components used. By defining vector of view internally on physical devices that produce them, the next step in the process of exploring the relation of geometric the direct georeferencing was to identify the physical relationships camera with the next physical device (system). For example, cameras in non-active mode mounted on the satellites, and formulate an appropriate geometric transformation of the camera reference system to the system, so that it can be defined as the vector viewpoint according to the system (satellite). Furthermore, it was done over and over in the same steps to connect satellite systems with Earth, so that the end out of orientation system was obtained in the Earth reference system (Maryanto, 2016).

To do direct georeferencing, all of these parameters (internal and external orientation of the camera system, GPS navigation vector viewpoint of the camera system, and the topography of the Earth surface) must first be known accurately enough. It was the primary key to successfully using direct georeferencing. If these parameters were highly accurate, the ground control points would not be not used (GCP) in rectification process (Müller et al. 2012).

This research aims to develop a simulation algorithm on direct georeferencing and performs simulations using a pseudo-data. It was done by building relationships on geometric image-object, assuming the image data obtained from pushbroom sensors, which is mounted on LSA spacecraft—carrier for pushbroom linescan type. The simulation described the spatial error value from simulation by adjusting the IMU parameters value (pitch, roll and yaw), GPS parameters (longitude and latitude) and camera parameters (length focus). The results were expected to be a reference for selecting the specification of IMU and

GPS requirement considering their accuracies.

2 SENSOR ORIENTATION OF THE PUSHBROOM LINESCAN IMAGER

2.1 Pushbroom Sensor in a Spacecraft

In the acquisition geometry context, pushbroom sensor can be described simply as a system in the field of focus lens array detector mounted straight (linear detector arrays, for example CCD) as recording image formed by the lens system. Since the detector is only a cell array or detector pixels that form a straight line, then the image is only in the form of a picture line elements which has very small width, so that it can be regarded as one-dimensional image. 2 dimensional (2D) in pushbroom imager is only formed if the camera is shifted regularly when the camera takes images in accordance to the width of each line of the image as shown in Figure 2-1.

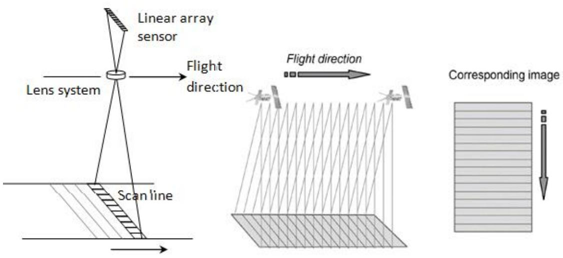

Figure 2-1. Imaging principle with line scanning technique (pushbroom). 2D image is obtained through hundreds to thousands of times shooting with camera panning is the right of the places in each and every shot.

In remote sensing satellites system, satellites with pushbroom sensors shoot hundreds to thousands with set range times and adapted to flying speed of the satellite relative to the Earth and with specified line width size of the image (spatial resolution) (Maryanto 2016).

2.2 Internal Pushbroom Sensor Orientation

Internal orientation on pushbroom imager can be formulated through mapping (transformation) the location of the image pixel array detector and the identification of the physical structure of the camera as a whole, which is located inside the detector array. In this case, we involved the image coordinate system (ICS), which became input parameters of the detector coordinate system (DCS). DCS was also the input parameters to the camera coordinate system (CCS). CCS in this case was the data position (latitude, longitude) and the attitude/attitude of the camera (roll, pitch, yaw) or abbreviated LLA (latitude, longitude, attitude). LLA at CCS parameters were obtained from the geo-location using GPS (Global Positioning System) receiver sensor devices and IMU (Inertial Measurement Unit) attitude sensors, which was mounted on the camera system (Poli 2005). Detail explanations are discussed in the methods section.

2.3 External Pushbroom Sensor Orientation

The external orientation of pushbroom imager can be formulated as relations established between the camera sensor and the Earth as a reference, called: relation between the camera sensor and the carrier sensor (Spacecraft/Aircraft), relation between the camera sensor and the reference system of local orbital. The local orbital relationships towards the Earth and the intersection of the viewing direction of the sensor carrier on the Earth surface produced the coordinates of the objects. All parameters of the relationship mentioned above, will be taken into account to obtain the coordinates of the image on Aircraft (LSA) or Aircraft Coordinate System (ACS). Moreover, the relationship between ACS toward the movement of the Earth (rotation), and then the factor of Earth's rotation will change ACS into Rotated Aircraft Coordinate System (RACS) need to be considered. The last part was RACS orientation towards the Earth's surface. To change the RACS orientation into Earth Coordinate System (ECS) at each pixel of image data, the intersection of image coordinates and coordinates on the Earth's surface need to be calculated (Poli 2005). Detail explanations are discussed in method section.

2.4 Coordinate Transformation from Geocentric to Geodetic Coordinate

To obtain the geocentric coordinates, we calculated the internal and external orientation sensor to the Earth. After getting geocentric coordinates, the final stage was to transform geocentric coordinates into geodetic coordinates by calculating the point of intersection image pixel's vector direction with the Earth's ellipsoid as a reference for determining the position vector image point on the Earth surface. This transformation process will changed the position vector to the geographical coordinates of latitude and longitude geocentric and subsequently changed the geocentric geographic coordinates of latitude and longitude geographic coordinates to geodetic (Rizaldy and Firdaus 2012).

There were many ways to perform the transformation from geocentric to geodetic coordinates, or vice versa. One of the popular ways was to involve the tangential component of the geocentric latitude of the ellipsoidal Earth (Jacobsen 2002). In this case, the process enforced the intersection of image pixel direction vector with ellipsoid Earth as a reference for determining the position vector of each image point on the Earth's surface. The vector of the Earth's surface was determined by ellipsoidal formula corresponding with standard Earth Flattening parameter WGS-84. This stage produced ECS in ECEF coordinates (Jacobsen and Helge 2004).

Finally, after obtaining a vector pointing intersections of each pixel with the Earth's surface, it was time to change back to the vectors ECEF coordinate system into LLA coordinates (longitude, latitude, altitude) (Schroth 2004). However, in this simulations, we assume that the height (altitude) of each pixel in the image data was 0 (zero) meter. Detail explanations are discussed in the methods section.

3 MATERIALS AND METHODOLOGY

General algorithm which was commonly used in the process of direct georeferencing were as follow: data input position (latitude, longitude) and the attitude of the camera (roll, pitch, yaw) or abbreviated as LLA (latitude, longitude, attitude) obtained from the geo-location by using pseudo-data derived from the GPS sensor receiver and IMU sensor which were mounted on the camera system. Input parameters of the pushbroom linescan imager used in this research were: the number of pixels at 2048, detector's length at 28.672 mm, and the camera's focal length at 35 mm.

This research has built an algorithm to directly calibrated the image geometric (direct georeferencing) as shown in Figure 3-1. In this case, the general process of direct georeferencing was done in following stages:

1) Assigning a formula or defining the internal orientation of the image pixels on the camera system;
2) Establishing formulas or relationships, which states the orientation of the image pixel in the satellite reference system;
3) Calculating the calendar at the time an image pixel was obtained;
4) Calculating the position and attitude of the satellite at the time of taking the image pixel was done
5) Calculating the direction vector image pixel on the orbital reference system;
6) Calculating the direction of vector image pixel on the earth's reference system;
7) Calculating the intersection vector point of the image pixels direction with referenced ellipsoid Earth to determine the position vector image point on the Earth's surface, namely:

- Changing the position vector into the geographical geodetic latitude and longitude geocentric coordinates;

- Changing the geocentric geographic coordinates into geodetic latitude and longitude geographic coordinates.

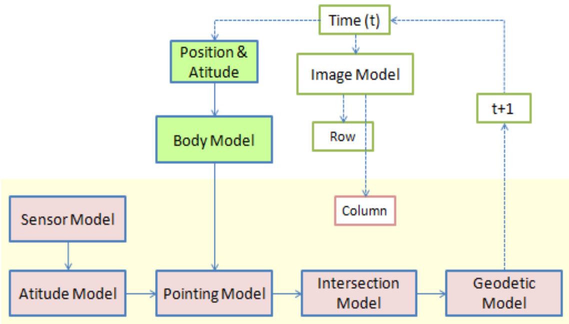

Figure 3-1. General algorithm of direct georeferencing for linescan pushbroom imager camera

Direct georeferencing program's processing flowchart is shown in Figure 3-1. In general, direct georeferencing process was a process of projecting each point sensor (pixel) on the Earth surface with intersection principle. However, to use the intersection, the sensor position and the Earth's surface must be on the same coordinate system. Then the sensor operation toward the attitude (roll, pitch, yaw) was running on ACS system, while the intersection was running on ECS system.

3.1 Input Parameters: GPS and IMU

The input parameters in this study were come from two sensors, i.e. position interpolation parameters derived from the GPS and attitude parameters derived from the IMU. Interpolation of these two sensors in this study was built with pseudo-data. The first parameter input was the LLA position (interpolation GPS sensor such as latitude, longitude, altitude) per line, which is known from GPS receiver. After that the LLA value was converted into ECEF coordinates (Earth Centered Earth Fixed). It was a reference terrestrial conventionally as a frame of reference with Earth as the center (geocentric). It went along with the Earth's rotation with the origin point at the center of mass of the Earth. The positive X direction was the point of intersection of the equator at longitude zero. The direction of the earth's rotation axis towards the north pole was the direction of the positive Z-axis, while multiplying the cross direction of the positive Z-axis with positive X-axis was as the Y-axis positive direction according to the rules of right hand. ECEF coordinate system has been defined by the Bureau International de l'Heure (BIH), and it was equal to the geocentric reference system U.S. Department of Defense World Geodetic System 1984 or known as WGS-84. The purpose of changing LLA into ECEF was to obtain the coordinates referring to ECS. The output will then be used as the origin of the sensor for each line on linescan.

The second input parameter comes from an attitude sensor (IMU sensor interpolation in the form of roll, pitch, yaw (relative to magnetic north)) derived from the IMU. Both of GPS and IMU in this simulation are assumed ideal and we can give some errors to test the accuration. Other input parameters was derived from pushbroom linescan imager camera sensor, which was used with the number of pixels in 2048, 28.672 mm length detector. The camera lens focal length was at 35 mm. The third parameter of this input will be processed by using the Python programming to generate output coordinates of longitude and latitude at each pixel on the detector linescan pushbroom.

3.2 Coordinate Transformation LLA into ECS (ECEF)

To transform the LLA coordinate values into ECEF coordinates, we should change the GPS input sensor coordinate system, from LLA into ECS (in ECEF). The Earth parameter used was WGS-84, as shown in Figure 3-2.

LLA coordinate transformation into the equation ECEF was done using this following formula:

$$x = (R_N + h)\cos\phi\cos\lambda \qquad (1)$$

$$y = (R_N + h)\cos\phi\sin\lambda \qquad (2)$$

$$x = ([1 - e^2]R_N + h)\sin\phi \qquad (3)$$

Where: ϕ = Latitude, λ = Longitude and h = Altitude,
with:

$$R_N = \frac{a}{\sqrt{1-e^2 sin^2 \emptyset}} \quad (4)$$

where: a = Earth Equator Radius, e = eccentricity (with WGS-84 parameter).

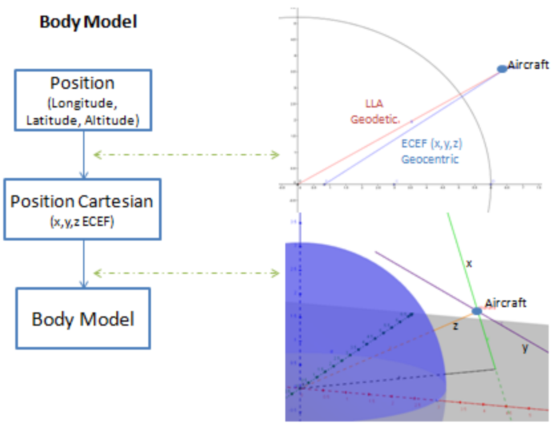

Figure 3-2. Convert parameter calculation for LLA into ECEF according to ECS

Coordinate output was in Cartesian (x, y, z) with the center of the Earth (geocentric) as the center coordinates, the z axis leads to the zenith geographical axes of the Earth, the x-axis lead to the longitude 0°, and the y-axis completes the z-axis and x according to the rules hand right as shown in Figure 3-2. The output will be used as the origin of the sensor for each line on linescan.

3.3. Coordinate Transformation from ECS (ECEF) into ACS

After obtaining the ECEF coordinates which refers to ECS, the ECS was then applied to calculate the position of the spacecraft toward the Earth. ECS was then converted into ACS. In this case, the Earth coordinates center becomes the spacecraft coordinates center (sensor). ACS was a representation to determine the position of the spacecraft that brings the sensor to the Earth where the X-axis leads to true north, the Y-axis east leads to the east and the Z-axis and leads to the Earth center geocentric as the right hand rule. The process of converting ECS into ACS was done by transforming matrix as illustrated in Figure 3-3.

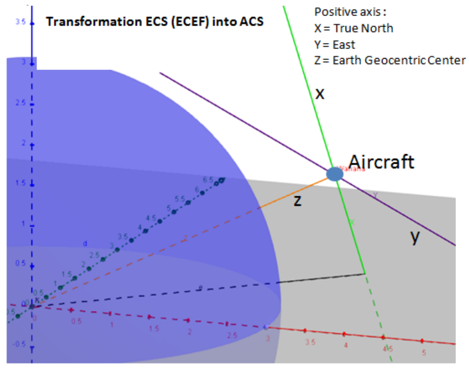

Figure 3-3. Calculation of transformation matrix to implement ECS coordinates into ACS

The coordinate matrix will be used as the inverse of RACS into ECS. The transformation of ECS coordinate (ECEF) into ACS was conducted by the equation:

$$\vec{r}_{ECS} = \begin{bmatrix} x_{ECS} \\ y_{ECS} \\ z_{ECS} \end{bmatrix} \quad (5)$$

$$\overrightarrow{ez}_{ACS} = -\frac{\vec{r}_{ECS}}{|\vec{r}_{ECS}|} \quad (6)$$

$$\overrightarrow{ey}_{ACS} = -\frac{\overrightarrow{ez}_{ACS} \times \overrightarrow{z_0}}{|\overrightarrow{ez}_{ACS} \times \overrightarrow{z_0}|} \text{ with } \overrightarrow{z_0} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (7)$$

$$\overrightarrow{ex}_{ACS} = -\frac{\overrightarrow{ey}_{ACS} \times \overrightarrow{ez}_{ACS}}{|\overrightarrow{ey}_{ACS} \times \overrightarrow{ez}_{ACS}|} \quad (8)$$

$$M_{ECS \to ACS\,(row)} = \begin{bmatrix} \overrightarrow{ex}_{ACS} \\ \overrightarrow{ey}_{ACS} \\ \overrightarrow{ez}_{ACS} \end{bmatrix} \quad (9)$$

3.4. Coordinate Transformation from ACS into RACS

Rotation operation on spacecraft coordinate system was based on the attitude sensor's input (IMU). The principle used was that the positive angle roll (θ) which means rotation angle on the X-axis opposite clockwise, the positive pitch angle (ρ) was the rotation angle on the Y-axis counterclockwise, and the positive yaw angle (γ) was the rotation angle on the Z-axis counterclockwise. With the initial position Pointing pixel in the Z axis (0,0,1) as shown in Figure 3-4.

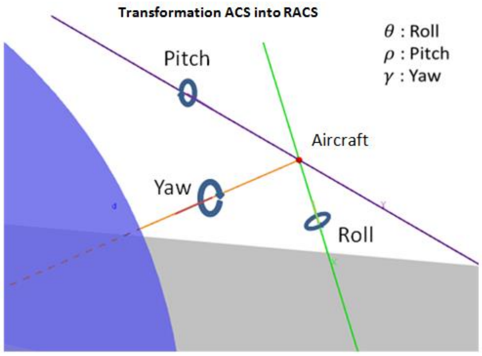

Figure 3-4. Operation rotate the camera sensor pushbroom linescan referring to RACS

ACS coordinates rotation operation RACS was done with the equation:

$$M_{rot\_roll} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\acute{\theta} & -\sin\acute{\theta} \\ 0 & \sin\acute{\theta} & \cos\theta \end{bmatrix} \quad (10)$$

$$M_{rot\_pitch} = \begin{bmatrix} \cos\rho & 0 & \sin\rho \\ 0 & 1 & 0 \\ -\sin\rho & 0 & \cos\rho \end{bmatrix} \quad (11)$$

$$M_{rot\_yaw} = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (12)$$

As shown in Figure 6 above, after acquiring RACS, we then performed rotation (pitch (ρ), roll (θ), yaw (γ)) at pushbroom linescan camera sensor. In this case, the scan pixels in one row occurs at the same time and placed on the X-axis rotation (roll) perpendicular to the direction of motion of the aircraft. If the roll angle was positive, the aircraft turned to the right and if pitch angle was positive, the pitch angle of the aircraft up to the top.

Operation rotation of aircraft coordinate system was based on the input from the attitude sensor (IMU). The principle used was the positive angle of roll (θ) which was rotation angle on the X-axis counterclockwise, the positive pitch angle (ρ) was the rotation angle on the Y-axis counter-clockwise, and the positive angle of yaw (γ) was the rotation angle on the Z-axis counterclockwise. In this case, the assumption that each pixel on one line applying roll rotational operation as shown in Figure 3-5.

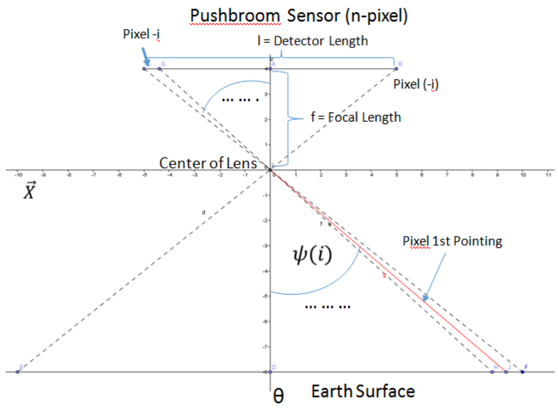

Figure 3-5. Pushbroom linescan camera sensor orientation toward the Earth referring to RACS

The roll angle per-pixel in one line was formulated as follow:

$$\acute{\theta} = \theta + \psi(i) \quad (13)$$

$$\psi(i) = \tan^{-1}\left(\frac{\left(\frac{i}{2} - 0.5\right)}{\left(\frac{n}{2}\right)} \cdot \frac{l}{f}\right) \quad (14)$$

Then, the transformation matrix in each pixel was:

$$M_{RACS} = M_{rot\_yaw} \cdot M_{rot\_pitch} \cdot M_{rot\_roll} \cdot \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (15)$$

3.5. RACS Inverse Coordinate Back into ECS (ECEF)

After the coordinate values of each pixel on the sensor was obtained, the next stage was to inverse RACS coordinate values into the ECS or ECEF coordinate. This was done to reverse the transformation value coordinates on the sensor to the Earth by vector pointing from each pixel on the sensor and finding the correlation of its value toward the coordinates on the Earth in ECEF reference frame as shown in Figure 3-6.

The operation was to change RACS into ECS for each pixel in one line using the following equations:

$$P_{ECS} = (M_{ECS \to ACS})^{-1} . M_{RACS} \quad (16)$$

$$\vec{V} = M_{RACS \to ECS} . M_{rot} \quad (17)$$

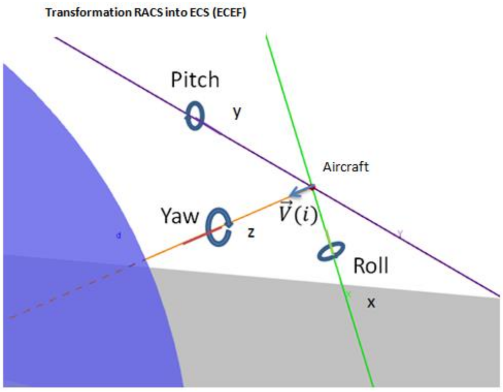

Figure 3-6. Sensor coordinate inverse value on RACS into ECS coordinate system (ECEF)

3.6 Pixel Pointing Intersection towards the Earth Surface

Referring to the shape of the Earth's surface, there should be a vector pointing intersection in each pixel on the sensor to the ellipsoid Earth surface shaped with referenced to the Earth's ellipsoidal equation to produce the intersection value that was closest to the Earth ellipsoidal field as shown in Figure 3-7.

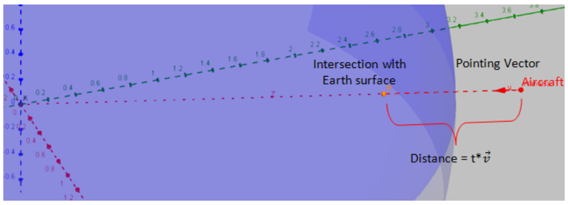

Figure 3-7. Vector pointing intersection per-pixel on sensor toward the ellipsoid Earth surface

The intersection process assumed that the extension of the pointing vector of each pixel (P_{ECS}) will intersect (intersection) with the Earth's surface, which was defined by the equation:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_{ECS} \\ y_{ECS} \\ z_{ECS} \end{bmatrix} + t.\begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} \quad (18)$$

or

$$\vec{O} = \overrightarrow{r_{ECS}} + t.\vec{V} \quad (19)$$

t is the sought extension of a vector pointing pixel scale (x_p, y_p, z_p). While the Earth's surface vector $(x_{ECS}, y_{ECS}, z_{ECS})$ is determined by the ellipsoidal formula according to the WGS84 Earth Flattening parameters as follows:

$$\frac{x^2+y^2}{a^2} + \frac{z^2}{b^2} = 1 \quad (20)$$

Where: a = 6378137 m, b = 6356752.3142 m (WGS-84 parameter)

Therefore, to get t value, the two formulas above became:

$$(b^2x_v^2 + b^2y_v^2 + a^2z_v^2)t^2 + (b^2x_{ECS}x_v + b^2y_{ECS}y_v + a^2z_{ECS}z_v)2t + b^2x_{ECS}^2 + b^2y_{ECS}^2 + a^2z_{ECS}^2 - a^2b^2 = 0 \quad (21)$$

3.7 Conversion of ECS (ECEF) Pixel Value into Latitude and Longitude

The final stage of direct georeferencing was to get the coordinates of geocoded Earth, which was in accordance with the rules of mapping. To obtain the coordinates of the geocoded Earth, the next stage was to change the result of the intersection vector in ECEF coordinates obtained into latitude and longitude coordinates for each pixel in the image. In this case, it was assumed that the height of the intersection is 0 (zero) meters above the surface of the ellipsoidal Earth. So with tangential mathematical equation, the latitude and longitude coordinates for each pixel in the image as shown in Figure 3-8 can be obtained.

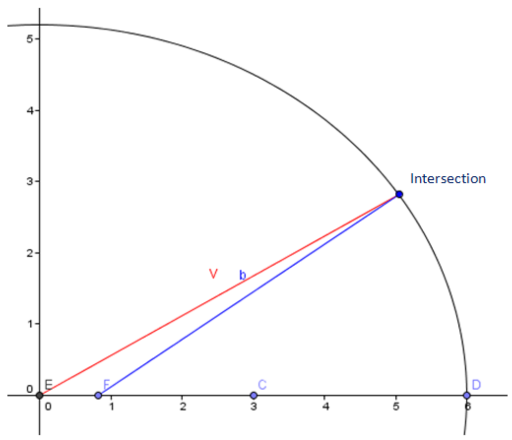

Figure 3-8. Changing the vector intersection (ECEF) into Latitude and Longitude coordinates for each pixel

To change back the ECEF coordinate systems into the Latitude and Longitude, the following formula was used:

Longitude:

$$\check{\lambda}(i) = \tan2^{-1}(y_i, x_i) \qquad (22)$$

and,

Latitude:

$$\check{\phi}(i) = \tan^{-1}\left(\frac{z_i}{(1-e^2)\sqrt{x_i^2+y_i^2}}\right) \qquad (23)$$

3.8 Horizontal Accuracy Standards for Geospatial Data

Based on ASPRS 1990's map accuracy class, we can compare the simulation's accuracy with the ASPRS legacy standard referred to Ground sample distance (GSD) that will be generated.

GSD explained the linear dimension of a sample pixel's footprint on the ground. GSD was used when referring to the collection GSD of the raw image, assuming near-vertical imagery. The actual GSD of each pixel was not uniform throughout the raw image and varies significantly with terrain height and other factors. GSD was assumed to be the value computed using the calibrated camera focal length and camera height above average horizontal terrain (ASPRS 2015).

To achieve the horizontal accuracy of imagery produced, we calculated the Root-Mean-Square Error (RMSE). Horizontal accuracy means the horizontal (radial) component of the positional accuracy of a data set with respect to a horizontal datum, at a specified confidence level. And RMSE was the square root of the average of the set of squared differences between data set coordinate values and coordinate values from an independent source of higher accuracy for identical points.

The accuracy test was referring to coordinate difference (x,y,z) between image coordinate and the true position coordinate on the Earth surface. This test was done to obtained 90% Circular Error (CE 90) trust level. RMSE calculated with the following formula:

$$RMSE_r = \sqrt{RMSE_x^2 + RMSE_y^2} \qquad (24)$$

Where,

$RMSE_x$ = Root-Mean-Square Error of point x

$RMSEy$ = Root-Mean-Square Error of point y

Then, the value of CE 90 calculate as follows:

$CE_{90} = 1{,}5175 \times RMSE_r$

4 RESULTS AND DISCUSSION

4.1 Simulation Results

Direct georeferencing simulation used Python programming language version 2.7 by inserting a sensor input parameters that will be simulated—the number of linescan pixels, the focal length of the lens (focal length), image length and sensor line length. In this case, the default value for the pixel linescan was 2048, the focal length of the lens (focal length) was 35 mm, the image length was 512, sensor line length was 28 672 mm. Based on WGS-84 parameters the value of the equatorial radius (a) was 6,378,137 km, the Earth's polar radius (b) was 6356752.3142 km and eccentricity (e^2) was 0.00669437999014.

Direct georeferencing simulations performed on several control parameters or variables that can affect the results of the calculation of direct georeferencing in pushbroom linescan imager imaging system on a LSA spacecraft. Those parameters were derived from the GPS receiver (latitude and longitude), IMU (roll, pitch, yaw), linescan camera (focal length and the length detector) and LSA height/altitude. In this case the values were set as follows:

1. Camera parameters (the number of pixels in 2048, the length 28.672 mm detectors, the focal length of a 35 mm camera).
2. Position (Longitude 106, -6 latitude, altitude 1500 m)

From the simulation results with 6 (six) control parameters or variables mentioned earlier, we obtained the following results:

a) The attitude (pitch 0, yaw 0), parameter variables: roll
b) The attitude (roll 0, yaw 0), parameter variables: pitch
c) The attitude (pitch 0, roll 0), variable parameters: yaw
d) The attitude (pitch 0, yaw 0, roll 0), parameter variables: longitude
e) The attitude (pitch 0, yaw 0, roll 0), parameter variables: latitude
f) The attitude (pitch 0, yaw 0, roll 0), parameter variables: the focal length of the camera

The results of the simulation with six control parameters and variable (ranging from a to f) are shown in Table 4-1. We obtained the difference error values for each simulation.

Table 4-1 Deviation measurement results using the 6 control parameters and variables (error is expressed in degrees, while the values of min, max and mean are the distance deviation in meters)

a.

Pitch Error (degree)	Min (meter)	Max (meter)	Mean (meter)
0	0	0	0
0.1	1.745334	1.745357	1.745342
0.2	3.490683	3.49073	3.490699
0.3	5.236057	5.236131	5.236082
0.4	6.981468	6.98157	6.981502
0.5	8.726925	8.727058	8.72697
0.6	10.47244	10.47261	10.4725
0.7	12.21802	12.21823	12.21809
0.8	13.96368	13.96394	13.96377
0.9	15.70944	15.70974	15.70954
1	17.45529	17.45565	17.45541
1.1	19.20125	19.20167	19.20139
1.2	20.94733	20.94782	20.9475
1.3	22.69354	22.69412	22.69374
1.4	24.4399	24.44057	24.44012
1.5	26.18641	26.18717	26.18667
1.6	27.93309	27.93396	27.93338
1.7	29.67994	29.68093	29.68027
1.8	31.42697	31.42809	31.42735
1.9	33.1742	33.17547	33.17462

b.

Roll Error (degree)	Min (meter)	Max (meter)	Mean (meter)
0	0	0	0
0.1	1.745334	1.745357	1.745342
0.2	3.490683	3.49073	3.490699
0.3	5.236057	5.236131	5.236082
0.4	6.981468	6.98157	6.981502
0.5	8.726925	8.727058	8.72697
0.6	10.47244	10.47261	10.4725
0.7	12.21802	12.21823	12.21809
0.8	13.96368	13.96394	13.96377
0.9	15.70944	15.70974	15.70954
1	17.45529	17.45565	17.45541
1.1	19.20125	19.20167	19.20139
1.2	20.94733	20.94782	20.9475
1.3	22.69354	22.69412	22.69374
1.4	24.4399	24.44057	24.44012
1.5	26.18641	26.18717	26.18667
1.6	27.93309	27.93396	27.93338
1.7	29.67994	29.68093	29.68027
1.8	31.42697	31.42809	31.42735
1.9	33.1742	33.17547	33.17462

c.

Yaw Error (degree)	Min (meter)	Max (meter)	Mean (meter)
0	0	0	0
0.1	0.000349	0.714548	0.357446
0.2	0.000698	1.429095	0.714892
0.3	0.001047	2.143642	1.072337
0.4	0.001396	2.858187	1.429781
0.5	0.001745	3.572731	1.787224
0.6	0.002094	4.287272	2.144666
0.7	0.002443	5.001811	2.502106
0.8	0.002793	5.716345	2.859544
0.9	0.003142	6.430876	3.216981
1	0.003491	7.145403	3.574414
1.1	0.00384	7.859924	3.931845
1.2	0.004189	8.57444	4.289273
1.3	0.004538	9.288949	4.646698
1.4	0.004887	10.00345	5.004119
1.5	0.005236	10.71795	5.361536
1.6	0.005585	11.43243	5.71895
1.7	0.005934	12.14691	6.076358
1.8	0.006283	12.86138	6.433763
1.9	0.006632	13.57585	6.791162

d.

Longitude Error (degree)	Min (meter)	Max (meter)	Mean (meter)
0	0	0	0
0.00001	1.107137	1.107137	1.107137
0.00002	2.214274	2.214274	2.214274
0.00003	3.321412	3.321412	3.321412
0.00004	4.428549	4.428549	4.428549
0.00005	5.535686	5.535686	5.535686
0.00006	6.642823	6.642823	6.642823
0.00007	7.74996	7.74996	7.74996
0.00008	8.857098	8.857098	8.857098
0.00009	9.964235	9.964235	9.964235
0.0001	11.07137	11.07137	11.07137
0.00011	12.17851	12.17851	12.17851
0.00012	13.28565	13.28565	13.28565
0.00013	14.39278	14.39278	14.39278
0.00014	15.49992	15.49992	15.49992
0.00015	16.60706	16.60706	16.60706
0.00016	17.7142	17.7142	17.7142
0.00017	18.82133	18.82133	18.82133
0.00018	19.92847	19.92847	19.92847
0.00019	21.03561	21.03561	21.03561

e.

Latitude Error (degree)	Min (meter)	Max (meter)	Mean (meter)
0	0	0	0
0.01	6.98E-05	0.142793	0.07143
0.02	0.00014	0.285586	0.14286
0.03	0.000209	0.428379	0.21429
0.04	0.000279	0.571172	0.28572
0.05	0.000349	0.713965	0.35715
0.06	0.000419	0.856758	0.42858
0.07	0.000488	0.999551	0.50001
0.08	0.000558	1.142345	0.57144
0.09	0.000628	1.285138	0.64287
0.1	0.000698	1.427931	0.7143
0.11	0.000767	1.570724	0.78573
0.12	0.000837	1.713517	0.85716
0.13	0.000907	1.85631	0.92859
0.14	0.000977	1.999103	1.00002
0.15	0.001046	2.141896	1.07145
0.16	0.001116	2.284689	1.14288
0.17	0.001186	2.427482	1.21431
0.18	0.001256	2.570276	1.28574
0.19	0.001325	2.713069	1.35717

f.

Focus Length (degree)	Min (meter)	Max (meter)	Mean (meter)
0	0	0	0
0.01	5.71E-05	0.116943	0.058499
0.02	0.000114	0.233819	0.116964
0.03	0.000171	0.350628	0.175396
0.04	0.000228	0.46737	0.233795
0.05	0.000285	0.584046	0.29216
0.06	0.000342	0.700655	0.350492
0.07	0.000399	0.817198	0.408791
0.08	0.000456	0.933674	0.467056
0.09	0.000513	1.050084	0.525288
0.1	0.00057	1.166428	0.583487
0.11	0.000627	1.282705	0.641653
0.12	0.000683	1.398916	0.699786
0.13	0.00074	1.515061	0.757886
0.14	0.000797	1.63114	0.815952
0.15	0.000853	1.747153	0.873986
0.16	0.00091	1.8631	0.931987
0.17	0.000967	1.978981	0.989954
0.18	0.001023	2.094796	1.047889
0.19	0.00108	2.210545	1.105791

4.2 Evaluation Results

From the Table 4-1 (a-f), six parameters were used i.e. pitch, yaw, roll, longitude, altitude and focal length to simulate the all of parameter accuracy errors. From the camera parameter simulation, if LSA flight on 1500 meters (when number pixel line scan (2048), focal length (35 mm), image length (512) and sensor line length (28.672 mm)), we were able to produce GSD (Ground Sample Distance) or spatial resolution about 0,6 m.

Based on ASPRS 1990 map accuracy class, we can compare the accuracy of the result of this simulation with ASPRS legacy standard (CE 90) refer to Ground sample distance (GSD) has generated (ASPRS 2015). If the accuracy level needed to produce 1:2500 map is about 2 pixels, then the spatial error value from simulation needed to be at maximum 1.2 meters. To achieve this value, the IMU parameter (pitch, roll and yaw) errors i.e maximum 0.1; 0.1; and 0.1 degree, respectively. And the maximum error of GPS parameters (longitude and latitude) are about 0.00002 and 0.2 degree, respectively. And then the maximum error of camera focus is about 0.2 degree.

Based on these 6 simulations with variable parameters, we can say that in order to design a pushbroom linescan imager system in LSA spacecraft, it is very important to note the selection of IMU sensor and GPS to improve the accuracy of the measurement results using direct georeferencing technique. Error value of roll, pitch, yaw sensor from IMU attitude and longitude position, as well as latitude from GPS, need to be carefully selected in order to improve the accuracy of the measurement results with the direct georeferencing technique.

5 CONCLUSION

The accuracy requirement of camera sensor, GPS and IMU parameters are very important parameters to design a pushbroom linescan imager system in LSA spacecraft to improve the accuracy of the measurement results by using the direct georeferencing technique. The simulation results showed that the accuracy requirements of the camera sensors on the LSA which are derived using direct georeferencing method can be determined for mapping applications by selecting the required Inertial or GPS equipments. For example, if GSD is 0.6 m, the specification of Inertial or GPS equipments must have the maximum error of the IMU parameter (pitch, roll and yaw) is 0.1; 0.1; and 0.1 degrees and the maximum error of the GPS parameter (longitude and latitude) is 0.00002 and 0.2 degree. This process needs to be conducted in the early stage in order to produce corrected and coded systematic geometrically images to a map or geocoded image.

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