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ESTIMATION OF IMAGE GEOLOCATION USING PARAMETRIC MODEL FOR EARTH OBSERVATION SATELLITES

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ABSTRACT

The aim of this study is to calculate the geolocation of an image acquired from an electro-optic earth observation satellite using the satellite external and internal orientation parameters. The main purpose of this study is to determine the intersecting coordinates of an ellipsoid model defined according to WGS84 and a looking vector. In the first phase, these calculations will be conducted without any Digital Terrain Model (DTM). In order to compare the results, in a second phase, the same calculations will be conducted with DTM. For demonstration purposes, a geolocation software will be developed using open-source libraries. This software will be tested with sample data from the SPOT-5 satellite. There are several plug-ins for certain open source and commercial Geographical Information Systems (GIS) software. One of the objectives of this study is to later develop an independent program which will be used to assist in the development of a satellite and a ground station image processing unit. This program is also intended to be used in the training of individuals with various areas of expertise.

INTRODUCTION

The latest satellite technologies allow us to capture images with a 30 cm ground sampling distance. This leap in technology brings forth expectations of considerable increase in the accuracy of geolocation of images. Therefore, geometric correction and geolocation processes have become more important. There have been academic and industrial studies conducted for this matter yet it is still necessary to develop independent studies towards revealing needs.

In geolocation estimations that are calculated by using parametric models, acquiring a particular performance value is very important. It is very clear that this performance value depends on working with several disciplines from satellite design to sensor test and measurement methods, from ground station image processing to improving the satellite external position parameters with related algorithms. Another purpose of this study is to acquire all the necessary know-hows of rough geolocation, and the software planned to be published as open source.

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METHOD

As a starting point, literature review has been done, conventional solutions has been investigated and a roadmap has been identified. Accordingly, Geometry Handbook of the SPOT-5 satellite has been taken as a reference [Riazanoff, 2004].

In this study, the sensor geometry, satellite orbit and attitude parameters were used as is, however for the usage of more detailed models, it was decided to create certain necessary modular structures [Riazanoff, 2004]. Primarily, the software to be developed was aimed to be as clear and simple as possible and to only contain basic approaches to solutions rather than complex ones.

The SPOT-5 satellite pursues a nadir-looking direction in orbit. Mirrors are used on the HRG-A (High Resolution Geometry) and HRG-B telescopes to acquire images outside of the nadir-looking angle. These telescopes have a single 12k-pixel sensor in the focal plane and provide a ground sampling distance of 5 meters at an average altitude. The HRG-A and HRG-B telescopes point towards earth with a difference of 17.5 meters in the along-track and 2.5 meters in the across-track direction. The difference in these angles and the adjustable line sampling clock on the satellite gives the satellite an advantage, the PAN image from both sensors can be resampled as if it were being taken from a single 2.5 meters 24k-pixel viewer [Raizanoff, 2004]. In addition, the SPOT-5 Satellite provides a test image for uncommercial users. This image is also provided with the satellite external orbit and attitude parameters. This test image was taken in the nadir-looking state of the off-nadir imaging mirrors and therefore was evaluated to be suitable for geolocation software development using a parametric model. The look angles which are defined on the satellite reference coordinate system, for the HRG-A and HRG-B telescopes are provided by the manufacturer. Using these angles, the intersection of each pixel with the WGS84 ellipsoid at the line sampling time (line dating) can be calculated.

Finally, Digital Terrain Model was introduced to the program to acquire more accurate longitude and latitude values.

To achieve the steps determined above, the algorithms in the geometry handbook of SPOT-5 satellite were applied using the Java programming language.

Frame Definitions

Navigation Reference Coordinate System:

The Navigation Reference Coordinate System (NRCS) is a body fixed coordinate system that is used to maintain the nadir looking attitude by coinciding the auxiliary frames with itself. The NRCS is centered at the satellite's center of mass. The CCD geometry is defined with respect to NRCS, therefore it is one of the most important frames of the SPOT-5 satellite. Furthermore, the looking angles ψ_x and ψ_y are measured from the camera field of view and they are used to represent the pixel orientation or so called the look direction.

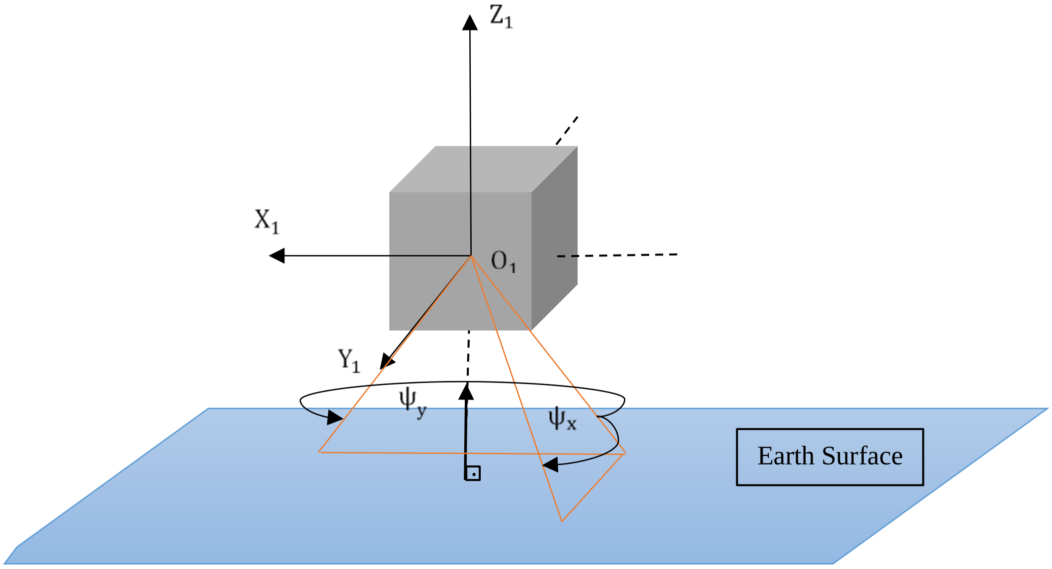

Figure 2: Navigation Reference Frame

Orbital Coordinate System:

The Orbital Coordinate System (OCS) is an orientation depended system that is centered on the satellite's center of mass. Even though it coincides with the center of the NRCS, the OCS depends on the satellite position and velocity. Therefore, one needs to map the look vectors that are initially defined in the NRCS to the OCS. This can be done by using the attitude information that is provided by the Star-Trackers. The attitude measurements are done with respect to the NRCS frame. Therefore, it provides the transformation matrix between the NRCS and the OCS from the measured Euler angles. The definition of the OCS is given as follows;

$$\overrightarrow{Z_2} = \frac{\vec{P}(t)}{\left|\left|\vec{P}(t)\right|\right|} \quad \text{Eq 1}$$

$$\overrightarrow{X_2} = \frac{\vec{V}(t) \times \vec{Z}_2}{\left|\left|\vec{V}(t) \times \vec{Z}_2\right|\right|} \quad \text{Eq 2}$$

$$\overrightarrow{Y_2} = \overrightarrow{Z_2} \times \overrightarrow{X_2} \quad \text{Eq 3}$$

International Terrestrial Coordinate System:

The International Terrestrial Coordinate System (ITRF) is a non-inertial reference frame, which is crucial for the geolocation algorithm [Wolf Et all, 2014]. The ITRF is defined with respect to the International Earth Orientation Service (IERS). Normally, an inertial frame to ITRF conversion requires complex set of rotations by using the earth orientation parameters. The satellite orbit is already provided with respect to the ITRF, which results to no necessary conversion.

Attitude Measurements Definition

The attitude data of the SPOT-5 is provided by the Star-Trackers and the gyroscopes with 8 Hz of frequency [Riazanoff, 2004]. The raw data from the sensors are downloaded and stored in the form of Satellite Auxiliary Data. The acquired satellite attitude values are going to be used without applying any filters. The attitude values are not directly represented in NRCS but its inverted system, which are labeled as $(\mathbf{0'_1}, \mathbf{X'_1}, \mathbf{Y'_1}, \mathbf{Z'_1})$. The definition of the inverted system is given as follows;

$$\overrightarrow{X'_1} = -\overrightarrow{X_1} \qquad Eq\ 4$$

$$\overrightarrow{Y'_1} = -\overrightarrow{Y_1} \qquad Eq\ 5$$

$$\overrightarrow{Z'_1} = \overrightarrow{Z_1} \qquad Eq\ 6$$

Roll and pitch components of the rotation matrix from NRCS to OCS is need to be multiplied by -1, yet the yaw component needs to be kept untouched.

Orbit Measurements Definition

The orbit data of the SPOT-5 satellite is provided by a DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) sensor, which has a measuring rate of 30 seconds [Riazanoff, 2004]. In order to calculate the geolocation, at least four ephemeris points before and after the acquisition must be provided by DORIS. The DORIS sensor has a high accuracy thus the provided ephemeris can be used directly without applying any filters. In the process of geolocation calculation, one must interpolate the state vectors to the required time of each line with the use of provided ephemeris. The state vectors are calculated directly with respect to the ITRF. Therefore, one can transform the looking vector that is defined in OCS by using the position and velocity components

Definition of Look Direction

The look direction is a vector, which defines the sensor's pixel orientation with respect to NRCS. As seen in Figure 2, the looking vector can be defined by Ψ_x and Ψ_y angles. These angles are called look angles. They are defined for every individual pixel of the sensor with respect to the NRCS. Even though these angles do not depend on the satellite position or the orientation, they are provided within the metadata since it is mandatory to use these angles to perform a geolocation.

The look angles can be written with respect to the pixel number as follows;

$$\varphi_X = (\varphi_X)_p \qquad Eq\ 7$$

$$\varphi_Y = (\varphi_Y)_p \qquad Eq\ 8$$

p; represents the pixel number (p = 1...12000),
$(\varphi_X)_p$; represents the along-track look angle for the pixel number p,

$(\varphi_Y)_p$; represents the across-track look angle for the pixel number p.

The Look direction can be written in NRCS as follows:

$$\vec{u}'_{1,p} = \begin{bmatrix} -\tan\left(\varphi_y\right)_p \\ \tan(\varphi_x)_p \\ -1 \end{bmatrix} \qquad Eq\ 9$$

Note that the NRCS is a body fixed frame and is only used for the definition of the look vector.

APPLICATIONS

A Java program was developed with the algorithms mentioned in the Methods section. This program performs geolocation estimation using the parametric model. The algorithms and their explanations are given below:

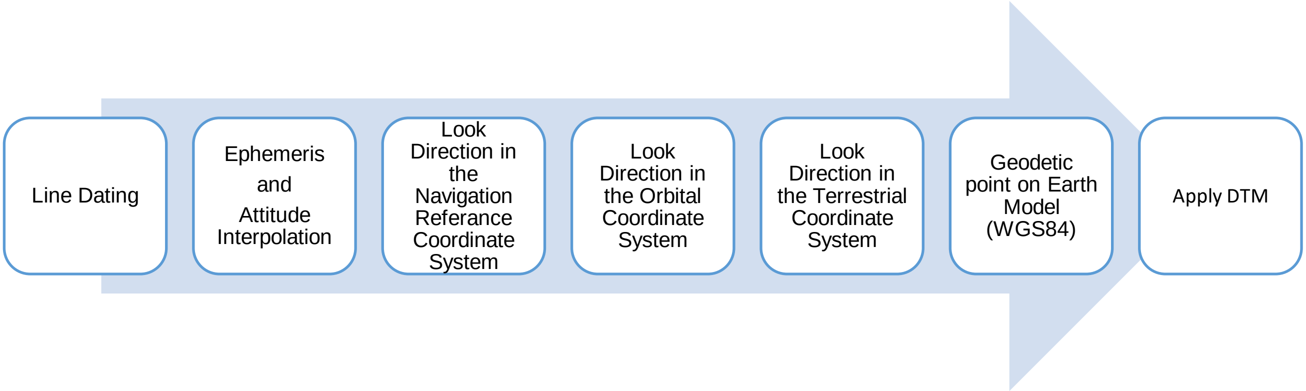

Figure 1: Scheme of Algorithm

Line Dating

This algorithm represents the relation between any pixel of the image (l,p) and acquisition time. One can calculate the corresponding acquisition time of a particular pixel by just knowing the line sampling period of the sensor.

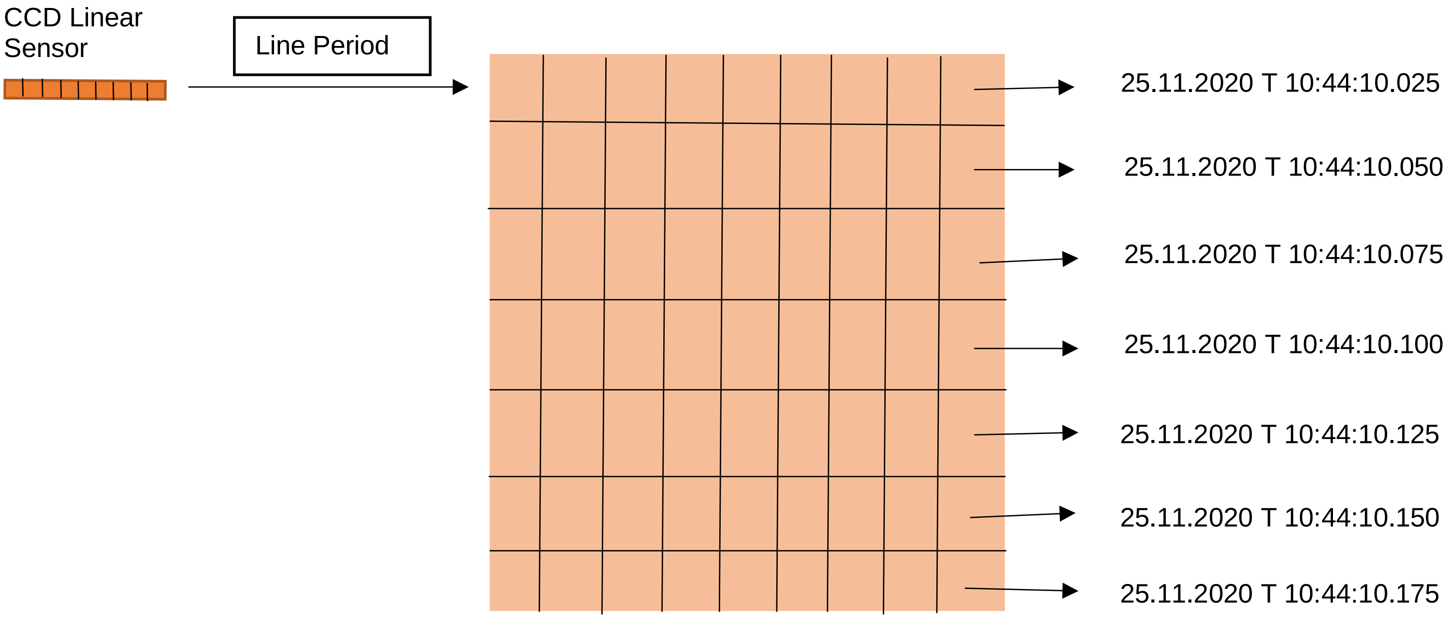

Figure 2: Line Dating

$$t = t_c + I_{sp} \times (l - l_c) \qquad \text{Eq. 10}$$

t_c scene center time,
l_c scene center line,
I_{sp} line sampling period.

Ephemeris Interpolation

This algorithm determines the position P(t) and velocity V(t) vectors at the time t. The Lagrange interpolation technique is used for the interpolation of ephemeris points, since the variation is nonlinear.

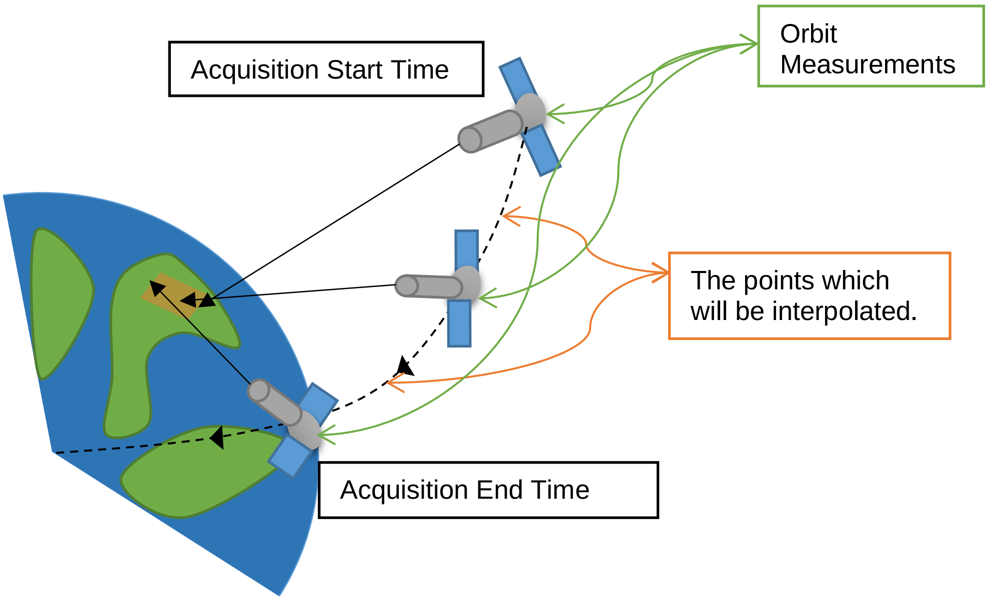

Figure 3: Ephemeris Interpolation

$$\vec{P}(t) = \sum_{j=1}^{8} \frac{\vec{P}(t_j) \times \prod_{\substack{i=8 \\ j \neq i}}^{8} (t - t_i)}{\prod_{\substack{i=1 \\ i \neq j}}^{8} (t_j - t_i)} \qquad \text{Eq. 11}$$

$$\vec{V}(t) = \sum_{j=1}^{8} \frac{\vec{V}(t_j) \times \prod_{\substack{i=8 \\ j \neq i}}^{8} (t - t_i)}{\prod_{\substack{i=1 \\ i \neq j}}^{8} (t_j - t_i)} \qquad \text{Eq. 12}$$

$P(t_i)$ Satellite position components,
$V(t_i)$ Satellite velocity components.

To achieve this algorithm, four points before and four points after the target time t are acquired. The acquisition time (9 seconds) is not included to these points. Here, it is not needed to apply any attitude interpolation.

Attitude Interpolation

Attitude variations are too small and several samples are taken during the acquisition. The samples that are given in the metadata are in the form of Euler angles. Linear interpolation is the best choice for the nadir looking instance. Thus, three linear interpolation functions are defined as follows;

$$a_p(t) = a_p(t_i) + \left(a_p(t_{i+1}) - a_p(t_i)\right) \times \frac{t - t_i}{t_{i+1} - t_i} \qquad \text{Eq 13}$$

$$a_r(t) = a_r(t_i) + \left(a_r(t_{i+1}) - a_r(t_i)\right) \times \frac{t - t_i}{t_{i+1} - t_i} \qquad \text{Eq 14}$$

$$a_y(t) = a_y(t_i) + \left(a_y(t_{i+1}) - a_y(t_i)\right) \times \frac{t - t_i}{t_{i+1} - t_i} \qquad \text{Eq 15}$$

i; is the index of valid attitude measurement whose time is just before t ($t_i < t < t_{i+1}$),
$a_p(t)$; is the rotation angle around the pitch axis at time t,
$a_r(t)$; is the rotation angle around the roll axis at time t,
$a_y(t)$; is the rotation angle around the yaw axis at time t,
$a_p(t_i)$; is the rotation angle around the pitch axis at time t_i found in auxiliary data,
$a_r(t_i)$; is the rotation angle around the roll axis at time t_i found in auxiliary data,
$a_y(t_i)$; is the rotation angle around the yaw axis at time t_i found in auxiliary data.

Look Direction Transformation to Orbital Coordinate System

The origin of the OCS is placed in the center of mass of the satellite. The Z-direction always represents the vector from the Earth center of mass to the satellite's center of mass. The X-direction is the dot product of the Z and Y-directions. In order to define the transformation between OCS and NRCS, one needs to interpolate the satellite attitude to the corresponding line date. The OCS frame is unique since the Euler angles are defined in this frame, and hence it differs from NRCS.

The OCS is used to map the NRCS using the Euler angles. The Spot-5 Satellite tries to maintain its nadir looking attitude during the imaging phase. Therefore, one needs to use the Euler angles to map NRCS to OCS.

The transformation matrix between NCRS and OCS frames can be written as follows;

$$DCM_{OCS}^{NCRS} = M_p \cdot M_r \cdot M_y \qquad \text{Eq 16}$$

$$M_p = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\left(a_p(t)\right) & \sin\left(a_p(t)\right) \\ 0 & -\sin\left(a_p(t)\right) & \cos\left(a_p(t)\right) \end{bmatrix} \qquad \text{Eq 17}$$

$$M_r = \begin{bmatrix} \cos(a_r(t)) & 0 & -\sin(a_r(t)) \\ 0 & 1 & 0 \\ -\sin(a_r(t)) & 0 & \cos(a_r(t)) \end{bmatrix} \qquad \text{Eq 18}$$

$$M_y = \begin{bmatrix} \cos\left(a_y(t)\right) & -\sin\left(a_y(t)\right) & 0 \\ \sin\left(a_y(t)\right) & \cos\left(a_y(t)\right) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \text{Eq 19}$$

Note that because of the attitude measurement definition, the rotation around X_1 and Y_1 axes are needed to be inverse signed.

Look Direction Transformation to Terrestrial Coordinate System

This algorithm represents the rotation between the OCS and ITRF. Since the position vector, P(t) and the velocity vector, V(t) are already on the ITRF and the definition of OCS depends on P(t) and V(t), one can use these basis vectors for the rotation.

$$DCM_{ITRF}^{OCS} = \begin{bmatrix} (X_2)_X & (Y_2)_X & (Z_2)_X \\ (X_2)_Y & (Y_2)_Y & (Z_2)_Y \\ (X_2)_Z & (Y_2)_Z & (Z_2)_Z \end{bmatrix} \qquad \text{Eq 20}$$

$$\overrightarrow{Z_2} = \frac{\vec{P}(t)}{\left\|\vec{P}(t)\right\|} \qquad \text{Eq 21}$$

$$\overrightarrow{X_2} = \frac{\vec{V}(t) \times \vec{Z}_2}{\left\|\vec{V}(t) \times \vec{Z}_2\right\|} \qquad \text{Eq 22}$$

$$\overrightarrow{Y_2} = \overrightarrow{Z_2} \times \overrightarrow{X_2} \qquad \text{Eq 23}$$

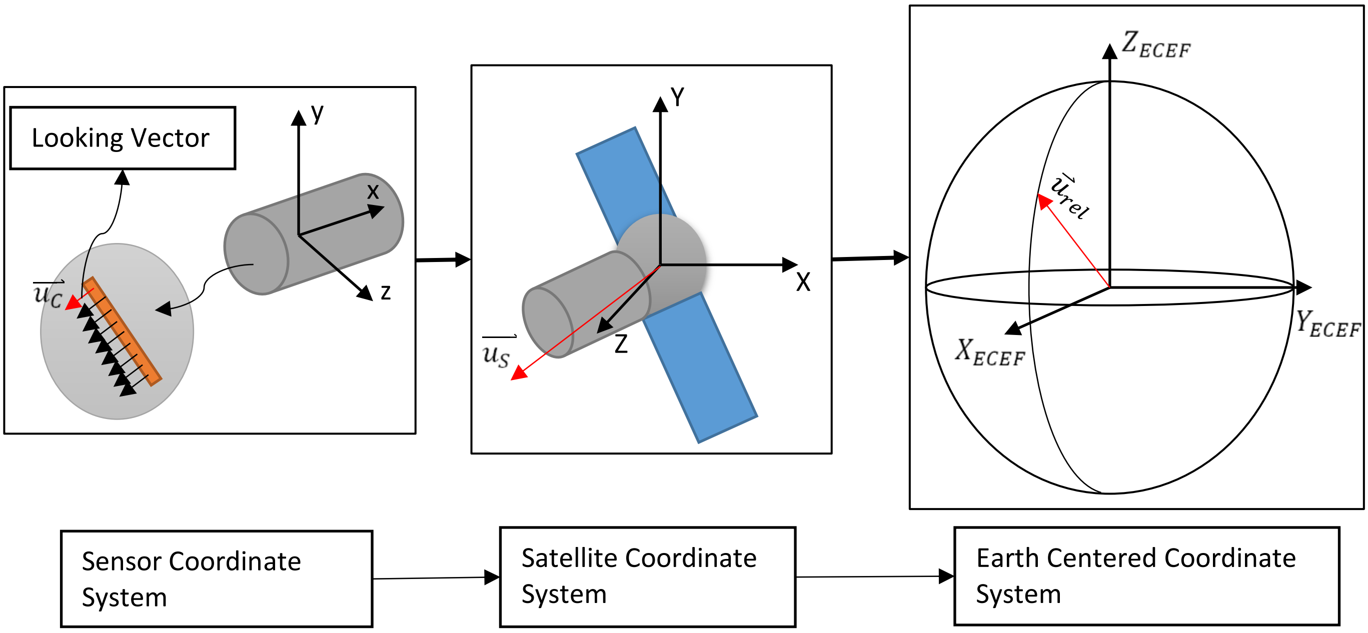

Figure 4: Abstraction of Coordinate Transformation

Intersecting to an Ellipsoid

After mapping the look direction into the ITRF frame, the intersection must be evaluated with the WGS84 Earth ellipsoid. Firstly, the look direction must be written with respect to the ellipsoid center. Afterwards, one needs to find the scale factor of the look direction which can cut through the WGS84 model. The elevation h is important for the intersection algorithm. Initially it is assumed to be 0. For the first case, geolocation is performed without Digital Terrain Model (DTM). For the second case, DTM is taken into account.

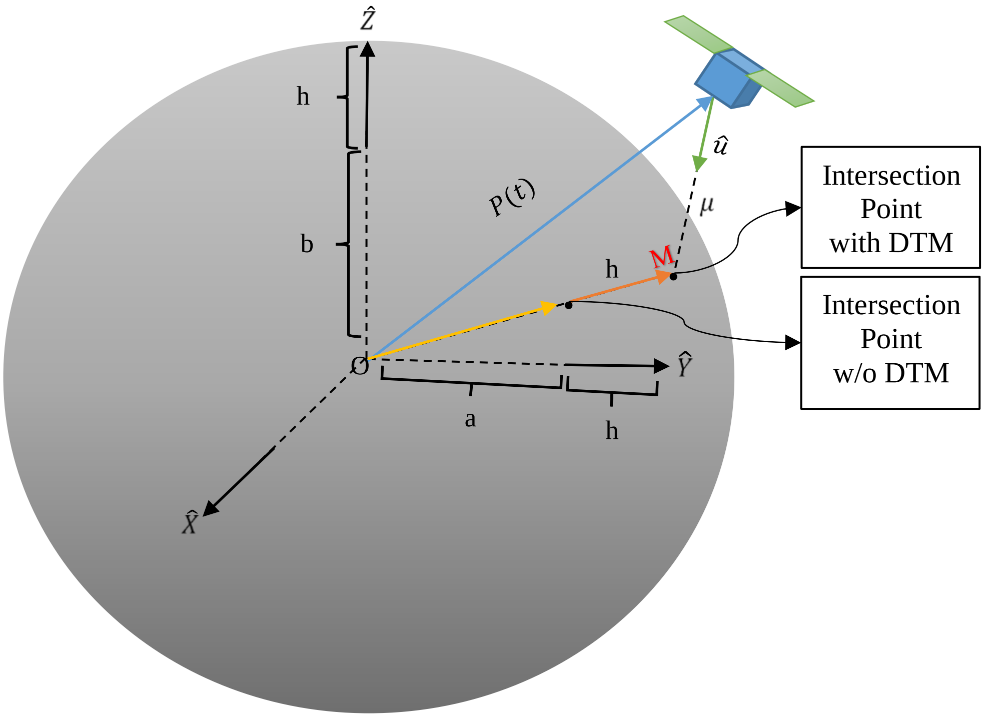

Figure 5: Intersection Geometry

From the relative vector analysis, and the equation of the ellipsoid one can write the following equations:

$$\overrightarrow{OM} = \vec{P}(t) + \mu \times \vec{u} \rightarrow \begin{cases} X = P(t)_X + \mu \times (u)_X \\ Y = P(t)_Y + \mu \times (u)_Y \\ Z = P(t)_Z + \mu \times (u)_Z \end{cases} \qquad \text{Eq 24}$$

$$\frac{X^2 + Y^2}{A^2} + \frac{Z^2}{B^2} = 1 \; with \begin{cases} A = a + h, \\ B = b + h, \end{cases} \qquad \text{Eq 25}$$

To solve second degree equation:

Calling:

$$\alpha = \left[\frac{{(u)_X}^2 + {(u)_Y}^2}{A^2} + \frac{{(u)_Z}^2}{B^2}\right]$$

$$\beta = \left[\frac{P(t)_X(u)_X + P(t)_Y(u)_Y}{A^2} + \frac{P(t)_Z(u)_Z}{B^2}\right]$$

$$\theta = \left[\frac{{P(t)_X}^2 + {P(t)_Y}^2}{A^2} + \frac{{P(t)_Z}^2}{B^2}\right]$$

$$\alpha\mu^2 + \beta\mu + \theta = 1 \qquad \text{Eq26}$$

This equation has two different solutions (μ_1, μ_2). The greater root value is omitted and the smaller one is taken into account. When the results are re-introduced into Eq. 17, it gives the point M. Note that this M point is written with respect to Cartesian Coordinates. For proper analysis, one must convert Cartesian Coordinates into Geodetic Coordinates. This can be done using the algorithm provided by [Boucher, 1995].

DTM Iteration Algorithm

In this algorithm, an iterative approach was used. The intersection between the looking vector and the ellipsoid highly depends on the terrain of the intersection point. In order to determine the true height of the intersection point, it is mandatory to find it with an iterative method. The iteration scheme given in Figure 8 is used for the determination of the accurate elevation of the terrain.

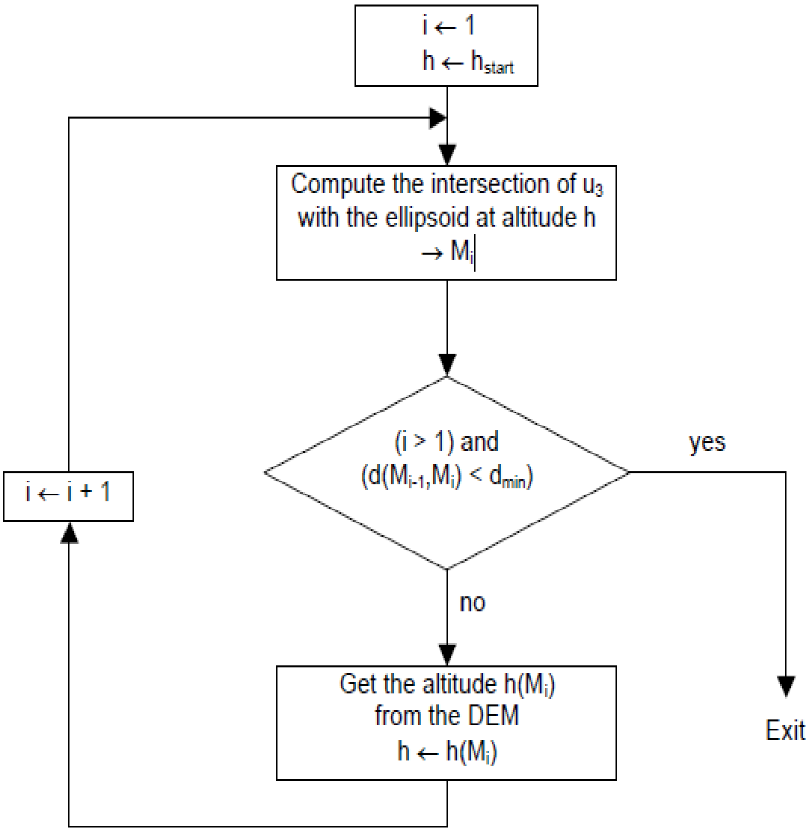

Figure 6: DEM Iteration Algorithm [Riazanoff, 2004]

Polynomial Function Model

A polynomial function is created as an improvement over the brute force method of storing all 576000000 pixels. This polynomial function takes the line number (l) and the pixel number (p) as parameters, and returns the geodetic latitude and longitude. The polynomial degree of this function is suggested to be three.

One can define a polynomial function as follows;

$$f_\lambda(l,p) = \lambda = \sum_{n}^{N}\sum_{m}^{M} a_{n,m} \times l^k \times p^l \qquad \text{Eq 27}$$

$$f_\varphi(l,p) = \varphi = \sum_{n}^{N}\sum_{m}^{M} b_{n,m} \times l^k \times p^l \qquad \text{Eq 28}$$

$a_{n,m}$ and $b_{n,m}$ coefficients can be found by using the linear least square method. These polynomials are the most efficient way to represent every pixel coordinate that is mapped on Earth.

Results

The program was integrated with the above algorithms and the OREKIT library [Maisonobe, 2010] was used for the time and frame handlings. Furthermore, the results are compared with the metadata of the provided image. Also note that, the first calculation is done omitting any DTM data, while the second one includes this data. In addition, a polynomial function is created as an improvement over the brute force method of storing all 576000000 pixels.

The acquired results after performing the above algorithm are compared with the values provided by the SPOT-5 satellite in the metadata file. The values have been rounded to the sixth decimal place.

Table 1: Computed Latitude Values without DEM

Line x Pixel	Latitude (Output)	Latitude (Metadata File)	Difference
(1 x 1)	41.765629	41.765629	4e-07
(1 x 24000)	41.600993	41.600993	4e-08
(24000 x 1)	41.244229	41.244229	4e-07
(24000 x 24000)	41.080596	41.080596	5e-07
(12001 x 12001)	41.424417	41.424417	2e-07

Table 2: Computed Longitude Values without DEM

Line x Pixel	Longitude (Output)	Longitude (Metadata File)	Difference
(1 x 1)	1.833191	1.833191	3e-07
(1 x 24000)	2.579140	2.579140	1e-07
(24000 x 1)	1.633764	1.633764	8e-08
(24000 x 24000)	2.374067	2.374067	1e-07
(12001 x 12001)	2.100964	2.100964	1e-07

Table 3: Computed Longitude Values with DEM

Line x Pixel	Longitude (Output)	Longitude (Metadata File)	Difference
(1 x 1)	1.832370	1.833191	8e-4
(1 x 24000)	2.578760	2.579140	4e-4
(24000 x 1)	1.633202	1.633764	6e-4
(24000 x 24000)	2.374067	2.374067	1e-8
(12001 x 12001)	2.099823	2.100964	1e-3

Table 4: Computed Latitude Values with DEM

Line x Pixel	**Latitude (Output)**	**Latitude (Metadata File)**	**Difference**
(1 x 1)	41.765826	41.765629	2e-4
(1 x 24000)	41.601085	41.600993	9e-5
(24000 x 1)	41.244365	41.244229	1e-4
(24000 x 24000)	41.080595	41.080596	9e-7
(12001 x 12001)	41.424692	41.424417	2e-4

Table 5: Polynomail Coefficinets for Rough Geolocation without DTM

	Coefficient Name	**Compute Value**	**Meta Data Value**
Latitude	***A0***	41.765672	41.765706
	A1	-2.172283E-5	-2.172031E-5
	A2	-6.604886E-6	-6.603697E-6
	A3	-1.800358E-13	1.738931E-12
	A4	1.789684E-12	-2.444078E-13
	A5	-1.061819E-11	-1.066590E-11
Longitude	***B0***	1.833202	1.833216
	B1	-8.368662E-6	-8.368747E-6
	B2	3.045743E-5	3.045914E-5
	B3	2.466332E-12	-9.803291E-12
	B4	-9.800935E-12	2.467793E-12
	B5	2.590250E-11	2.592081E-11

As illustrated in the tables above, the results were recorded for the corner pixels and the center pixel of the image. In total, 576000000 results were acquired which contains 24000 lines and 24000 columns for a scene. The output that is calculated with direct model without DTM, and the metadata values are nearly equal which means that the metadata contains geolocation values calculated without DTM. Hence, one can say that the metadata values need to be improved in order to find the precise geolocation values. In addition to this, one can say that the polynomial coefficients for the rough geolocation without DTM is close enough to the metadata values. Accordingly, the results of polynomial coefficients with DTM are not recorded, since the case without DTM is more precise with respect to the metadata. Yet, in reality, one needs to consider the DTM for rough geolocation.

CONCLUSION

According to the calculations without considering DTM, the latitude and longitude at the corner and center points of the test image from the SPOT-5 satellite were found with an error margin of less than 1e-8. In contrast, the results that are calculated with inclusion of DTM differs from the metadata values in the order of 1e-3. Hence, the results that are provided in the metadata is clearly considered to be calculated without any DTM. Even though the results with DTM is not close to the metadata, it is required to add DTM to the geolocation analysis in order to increase the precision.

The software was developed according to a generic geolocation model that is provided by the SPOT-5 Handbook. In further studies, the software is planned to be improved to allow users to define their own frames, sensor geometry and satellite dependent values.

At this point, the algorithm can handle the rough geolocation, which is mentioned in STANAG 7194 NATO Imagery Interpretability Rating Scale as a Level-0. For future studies, the algorithm is planned to be improved to handle precise geolocation analysis. That kind of analysis requires precise orbit and attitude determination rather than just a simple interpolation.

As a conclusion, a rough geolocation calculation software is developed with the help of the SPOT-5 Handbook. Thus, it can provide the know-how of geolocation to beginners as well as photogrammetry enthusiasts.

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