GEOMETRIC CORRECTION OF PUSHBROOM-TYPE HIGH RESOLUTION SATELLITE IMAGES

Dongseok Shin and Young-Ran Lee
Remote Sensing Section, Satellite Technology Research Center
Korea Advanced Institute of Science and Technology
373-1 Kusung-dong, Yusung-gu, Taejon, 305-701 Republic of Korea
dshin@krsc.kaist.ac.kr, yllee@krsc.kaist.ac.kr

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ABSTRACT

This paper describes a geometric correction algorithm for high-resolution pushbroom type sensor images. In the systematic correction module, a sensor-orbit-Earth model was designed by using a vector projection technique which resulted in a forward transformation from raw image coordinates to geocentric coordinates. In order to avoid a large amount of computational load of the forward transformation algorithm, an inverse transformation algorithm was derived. The inverse transformation algorithm reduces the processing time significantly in resampling process.

A precision geometric correction algorithm was also developed. Ground Control Points (GCPs) were extracted from scanned map images instead of paper maps attached on a digitizing table. The use of scanned raster map images for the GCP extraction gave many advantages for an operator as well as good accuracy. The GCPs extracted from a raw image and a scanned map image were used to estimate the values of geometric error sources such as the position, velocity and attitude of the satellite. An extended Kalman filter was used for the optimal estimation.

The geometric correction algorithm described in this paper was included in a pre-processing software for the KITSAT-3 high-resolution multi-spectral sensor images. The pre-processing software was developed by using Visual C++ programming language and it will run on PC-Windows^{TM} environment.

1. INTRODUCTION

An accurate geometric correction algorithm is one of the most important module in satellite image pre-processing systems. This is especially true for high-resolution images which are used largely for high precision mapping.

As the satellite technology was developed rapidly in the last decade, several land observing satellites with high spatial resolution such as Landsat, SPOT, JERS and IRS have been launched. In the very near future satellites will provide land image data with 1 - 5m spatial resolution. In this sense, satellite images begin to take the role of air-photos which have long been used for mapping, GIS and so on.

Most of the high-resolution Earth observing sensors currently in operation and in development are based on pushbroom-type scanning systems using linear CCD array. The pushbroom-type sensor provides a continuous image strip along the satellite track with a longer dwell period on ground targets compared with the across-track scanning sensors at the expense of large number of detector cells.

This paper describes mainly the algorithm developed for the geometric correction of high resolution pushbroom-type sensor images. Since the geometric distortions in the images obtained from all this type of satellite sensors have almost similar nature so that a common sensor-orbit-Earth geometry can be used.

The geometric correction algorithm described in this paper was developed originally for the pre-processing of KITSAT-3 images. KITSAT-3 is a mini-satellite currently in development and it will be launched in mid-1998. Section 2 describes the characteristics of KITSAT-3 and the ground station systems for the reception, storage, pre-processing and distribution of KITSAT-3 image data.

The two steps of the geometric correction algorithm : systematic correction and precision correction are described in Section 3 and Section 4 respectively. A sensor-orbit-Earth geometric model was designed in the systematic correction algorithm. The raw image is transformed to the corrected image domain using the sensor-orbit-Earth model and *a priori* information such as the position, velocity and attitude of the satellite. Since the forward coordinate transformation from a raw image to a corrected image has disadvantages in resampling process, an inverse transformation model from the corrected image to the raw image was developed.

The geometric model and *a priori* ephemeris data have uncertainties in nature. In order for the high-accuracy geometric correction, a precision correction algorithm must be developed. In the precision correction algorithm described in Section 4, ground control points (GCPs) are extracted from a raw image and a scanned raster map image rather than from a paper map attached on a digitizing table. The use of scanned map images for the GCP extraction reduces time and efforts of an operator significantly. The major sources of image geometry distortion: the position, velocity and attitude of the satellite are estimated from the GCP measurements. An extended Kalman filter is used for optimal estimation. The error source estimation technique correct the image geometry very accurately with very small number of GCPs.

2. KITSAT-3 AND GROUND STATION

2.1. KITSAT-3

The Satellite Technology Research Center (SaTReC) of the Korea Advanced Institute of Science and Technology (KAIST) is currently developing KITSAT-3 (Park et al., 1995), a mini-satellite (~100kg) which will be launched in mid-1998 by the Indian PSLV launcher. KITSAT-3 carries an high-resolution (13.8m) multispectral (R, G, Near-IR) camera. It has a linear pushbroom-type CCD sensor with 3456 cells which gives approximately 48km image swath. By tilting the satellite body by up to 26°, the image acquisition form KITSAT-3 will give higher image revisit frequency. The main purpose of the KITSAT-3 development is to provide high-resolution multi-spectral Earth images with very low development and launch cost.

KITSAT-3 has two main drawbacks in the remote sensing point of view. Firstly, KITSAT-3 does not have on-board propulsion system for orbit maneuvering. Although the KITSAT-3 orbit will be sun-synchronous, its long-term periodical ground tracks cannot be made due to the absence of the orbit maneuvering system. Secondly, the X-band image data transmission rate is low (3.2Mbps). It is not possible, therefore, to transmit full image data in real time while the satellite takes Earth images. The 1/4 sub-sampled one-channel image data are transmitted in real time and the full image data are recorded on solid-state memory on-board. The recorded data are transmitted during the next passes over ground station. The low transmission data rate was chosen in KITSAT-3 design phase in order that any ground station with a small-size antenna dish (<5m) can receive the KITSAT-3 image data.

2.2. Image data handling ground station

Figure 1 shows the KITSAT-3 image data reception, storage, pre-processing and distribution system. The system is basically PC-based in order to meet the requirement of low-cost and modular strategy (Lee et al, 1996). The antenna system with a 13m dish has already been installed and SaTReC is currently receiving high resolution image data from SPOT and JERS-1 by using this antenna system. This antenna system will be used for KITSAT-3 image data with a minor modification.

A data receiving printed circuit board card was developed for descrambling and converting input serial data to parallel data (Kim, 1996). The card can be plugged in a PC slot like a commercial video card. The input image data are transferred into PC memory by using a direct memory access technique and then stored in PC hard disk. This type of direct ingest technique instead of using serial data recording tapes is currently very popular in many satellite data ingest systems.

The catalogue and browse images of received image data are generated and stored in distribution system database so that users can browse the available scenes through WWW. The pre-processing system corrects the radiometric and geometric distortion in the raw images and produces suitable image data products for users.

In the following sections, the geometric correction algorithms in the pre-processing software are described in detail.

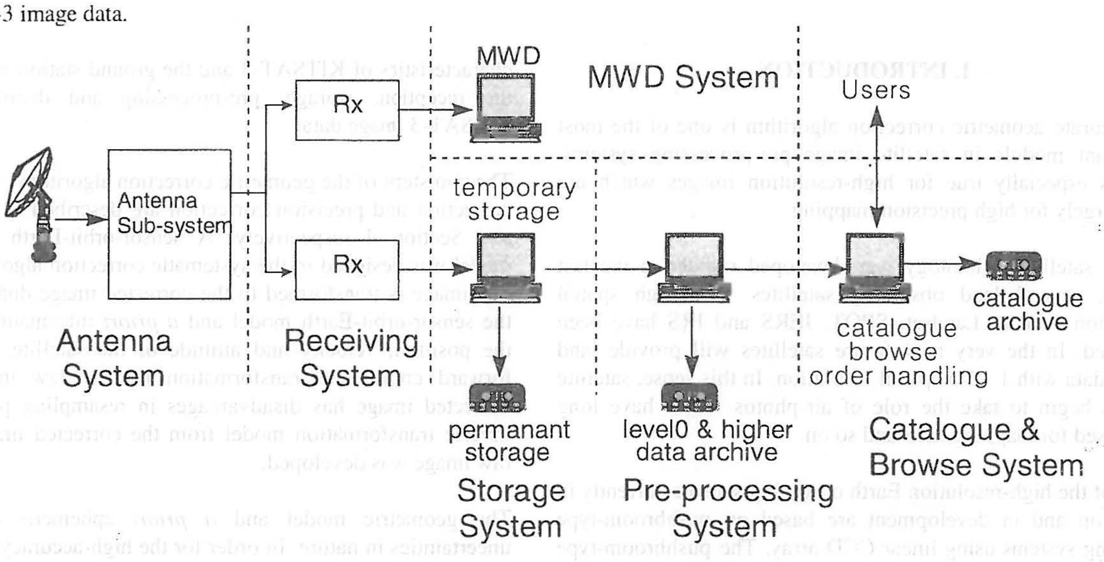

Figure 1. KITSAT-3 image data handling systems

3. SYSTEMATIC CORRECTION

3.1. Forward transformation

The systematic geometric correction algorithm eliminates geometric distortions in raw images by modelling the sensor's scanning mechanism, the orbit and attitude of the satellite and Earth's shape and rotation with the use of *a priori* information. Since the geometric correction of high-resolution images requires as good accuracy as possible, minimum approximation on the sensor-orbit-Earth model should be made. In this sense, the model derived by the *vector projection method* was found to be the most analytic method which contains minimum approximation (Shin *et al.*, 1997).

The vector projection model relates the column and row of each pixel in the raw image to the latitude and longitude or specific map projection coordinates on Earth surface.

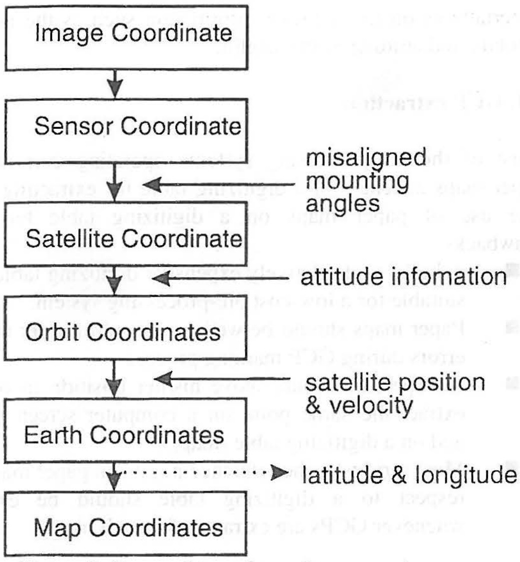

Figure 2. Forward transformation procedure

Figure 2 describes the coordinate transformation procedure from the raw image to Earth surface. Firstly, the column/row of a raw image pixel is transformed to 3D pointing vector (sensor coordinates) according to the sensor's scanning mechanism. The sensor coordinates to satellite coordinates transformation takes into account the misaligned angle between the sensor and the spacecraft body. Using the information on the attitude determination sensors on board the satellite, the pointing vector is then transformed to the coordinate system defined by the orbit of the satellite. The position and velocity vectors of the satellite are calculated by a orbit determination programme using the scene acquisition time and the regular update of orbit elements. The pointing vector is then transformed to Earth-centered coordinates. Finally, the cross point between the pointing vector line and ellipsoidal Earth surface is calculated in the Earth-centered coordinates. This point provides the latitude and longitude of the point which was viewed from the specified pixel in the raw image. The map coordinate transformation depends on the specific map projection method required by data users.

The way of the transformation from the raw image coordinates to the Earth surface coordinates described above is called forward transformation. Although this forward transformation technique derives the target position on Earth surface very accurately, it has a serious drawback in a resampling process. This is shown in Figure 3.

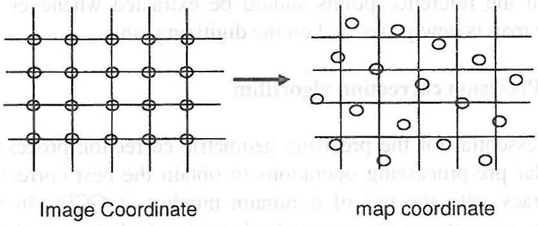

Figure 3. Forward coordinate transformation

Figure 3 shows the result of the forward transformation from the raw image to the map domain. The purpose of the resampling is to find a suitable grey level on each pixel grid in the map coordinate (corrected image grid) according to the raw image grey levels and the forward transformation result.

In the case of the forward transformation, lots of calculations are required for resampling because the resulting positions are irregular with respect to the corrected image grids. Due to this irregularity the resampling should be performed after the forward transformation of all raw image pixels is performed. Therefore, a large amount of memory or data storage is required in order to store the resulting positions of all raw image pixels.

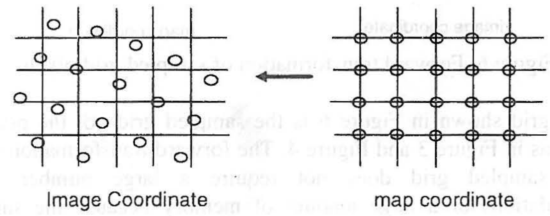

Figure 4. Inverse coordinate transformation

If an inverse transformation from the corrected image coordinates to the raw image coordinates is made as shown in Figure 4, the resampling would be very simple and fast. Since the grey levels in the raw image is regularly spaced, the number of the calculations for the resampling are reduced siginificantly. In addition, each pixel grey level in the corrected image can be assigned as soon as the inverse transformation is performed for each pixel, so that no additional memory is required.

The inverse transformation is basically the inverse procedure of the forward transformation shown in Figure 2. The derivation of the inverse transformation has, however, a major technical difficulty due to the moving focus of the linear pushbroom-type camera. In other words, although we can determine the position of the focus (the position of the satellite macroscopically) directly for a certain pixel in the raw image, we cannot determine the position of the focus directly when a certain position on Earth surface was viewed. The derivation of the focus position for a grid pixel on the corrected map is therefore derived by an iterative algorithm which is described in the next section.

3.2. Inverse transformation

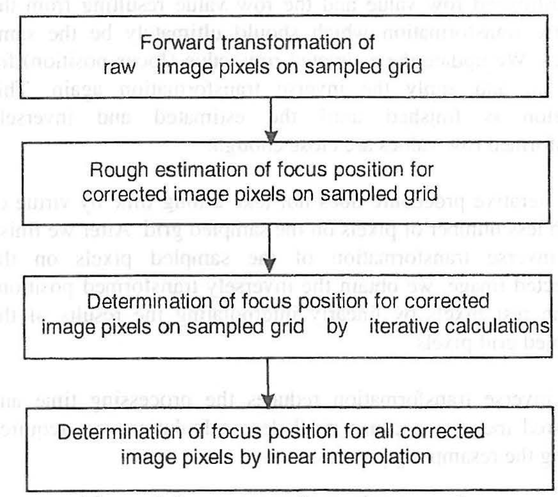

Figure 5. Inverse transformation procedure

Figure 5 shows the procedure of the determination of the focus position for each corrected image pixel. Firstly, a sampled grid is defined in the raw image. This is the sub-sampled grid of the raw image by 50 - 100 pixels. The columns and rows on the raw image sampled grid are transformed forward as shown in Figure

6.

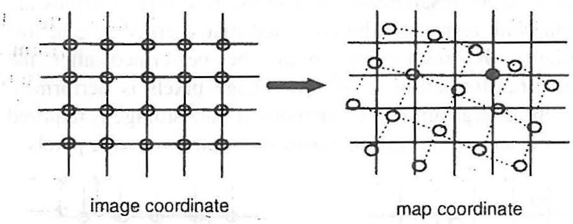

Figure 6. Forward transformation of sampled grid pixels

The grid shown in Figure 6 is the sampled grid not the pixel grid as in Figure 3 and Figure 4. The forward transformation of the sampled grid does not require a large number of calculations or a large amount of memory because the sub-sampling rate is very high. If we enlarge one imaginary quadrangle in the Figure 6, especially around the one cross point on the corrected image sampled grid shown by a filled circle, we can obtain Figure 7.

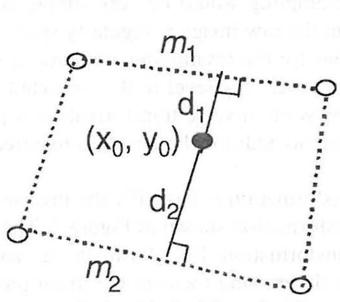

Figure 7. A sub-sampled grid pixel location in map coordinate

We know the focus position for each row of the raw image such as m_1 and m_2. The issue in this section is to determine the focus position for the (x_0, y_0) in Figure 7. First of all, we estimate the focus position of (x_0, y_0) by using the linear distance ratio of d_1 and d_2 and the focus positions for m_1 and m_2. Using the estimated values for the focus position, we apply the inverse transformation procedure to (x_0, y_0) in order to obtain the resulting column and row in the raw image. We can compare the estimated row value and the row value resulting from the inverse transformation which should ultimately be the same values. We update the estimated row value (focus position) for (x_0, y_0) and apply the inverse transformation again. This iteration is finished until the estimated and inversely transformed row values are close enough.

This iterative procedure does not take a long time by virtue of much less number of pixels on the sampled grid. After we finish the inverse transformation of the sampled pixels on the corrected image, we obtain the inversely transformed positions of the rest pixels by linearly interpolating the results of the sampled grid pixels.

The inverse transformation reduces the processing time and required memory because much less calculations are required during the resampling process.

4. PRECISION CORRECTION

Many high-resolution satellite image pre-processing systems provide a precision geocoding capability in which the image is compared with a map using Ground Control Points (GCP). This is required for high-accuracy geometric correction due to uncertainties on the *a priori* information such as the position, velocity and attitude of the satellite.

4.1. GCP extraction

Most of the pre-processing systems operating currently use paper maps attached on a digitizing table for extracting GCPs. The use of paper maps on a digitizing table has many drawbacks:

- A bulky and relatively expensive digitizing table is not suitable for a low-cost pre-processing system.
- Paper maps should be well preserved in order to avoid errors during GCP marking process
- An operator should move his/her position in order to extract the same point on a computer screen (image) and on a digitizing table (map).
- Most seriously, the reference points on paper maps with respect to a digitizing table should be extracted whenever GCPs are extracted for each image.

In order to overcome the disadvantages of using a digitizing table, we chose to use scanned maps for the GCP extraction. Firstly, we scanned 239 1:50,000 paper maps over Republic of Korea using 600dpi resolution. The scanned paper maps were produced by National Geography Institute of Korea. The scanned map images are stored in 7 CD-ROMS in BMP format which is a suitable format for PC-Windows^{TM}-based Visual C++ programming language. An operator can therefore extract GCPs on a satellite image and a scanned map image on the same screen.

The distortion which might be generated during the scanning process is modeled by a polynomial warping technique (Shin, 1996). We extract 4-6 reference points (their column/row in the scanned map image and latitude/longitude shown on the map) in order to generate 1st order polynomial models between the scanned map image coordinate and true latitude/longitude. It was found that the use of four corner points on the scanned map is enough to generate the polynomial models which result in less than 10m accuracy on the ground scale. This accuracy was tested by several test points which were different from the reference points.

Once the reference points are extracted and hence the map distortion modelling polynomials are generated, the coefficients of the polynomials are stored in database. This means that we don't need to extract the reference points anymore once they are extracted for each map. This reduced a great deal of efforts if compared with the conventional GCP extraction method in which the reference points should be extracted whenever the same map is newly attached on the digitizing table.

4.2. Precision correction algorithm

It is essential for the precision geometric correction process in regular pre-processing operations to obtain the best correction accuracy with the use of minimum number of GCPs. In this sense, geometric error source back-tracing technique with the camera-orbit model is the most suitable technique compared with other techniques such as the polynomial warping algorithm (Salamonowicz, 1986; Moreno, 1993; Friedmann *et al.*, 1983).

In this technique, geometric error sources are firstly defined. In general, the uncertainties on the position, direction and attitude of satellite are the main sources of the geometric distortion in images. The errors of the satellite position, velocity and attitude vectors are modelled as the time series as follows:

$$
\begin{aligned}
Xs_{error} &= xs_0 + xs_1 t + xs_2 t^2 + \ldots \\
Ys_{error} &= ys_0 + ys_1 t + ys_2 t^2 + \ldots \\
Zs_{error} &= zs_0 + zs_1 t + zs_2 t^2 + \ldots \\
Vx_{error} &= vx_0 + vx_1 t + vx_2 t^2 + \ldots \qquad (1) \\
Vy_{error} &= vy_0 + vy_1 t + vy_2 t^2 + \ldots \\
Vz_{error} &= vz_0 + vz_1 t + vz_2 t^2 + \ldots \\
Ap_{error} &= ap_0 + ap_1 t + ap_2 t^2 + \ldots \\
Ar_{error} &= ar_0 + ar_1 t + ar_2 t^2 + \ldots \\
Ay_{error} &= ay_0 + ay_1 t + ay_2 t^2 + \ldots
\end{aligned}
$$

The coefficients of the time series shown in Equation (1) are estimated from the GCP measurements. Although the maximum order of each time series is individually controllable in the algorithm, the position/velocity and attitude use the 0th order and the 1st order respectively. This is because the orbit error has nature of low-frequency variation while the attitude error has nature of mid-frequency variation compared with the scene acquisition time period (Friedmann *et al.*, 1983).

The error sources are estimated by the Kalman filter or a recursive least squares estimator for the optimal estimation in noisy environment. Since the transfer function of the model is non-linear in nature, the model should be linearized and the extended Kalman filter algorithm should be used.

The derivatives of the sensor-orbit-Earth model equations used in the systematic correction algorithm should be obtained in order to use the extended Kalman filter (Moreno, 1993). Due to the complexity of the sensor-orbit-Earth equations we determined to use numerical differentiation rather than using analytical derivatives (Shin *et al.*, 1997).

5. CONCLUSIONS AND DISCUSSION

The geometric correction algorithm described in this paper is currently in the final test and validation process. The algorithm is based on the most accurate and up-to-date geometric correction techniques which have been published so far. The inverse transformation algorithm for reducing processing load in the resampling process should be considered carefully. The use of scanned map images for GCP extraction can also give many advantages from the operator's point of view with satisfactory accuracy.

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