This paper was selected as one among the best four papers of the conference out of 300 papers presented.
ABSTRACT:

This paper gives an assessment of the mapping potential of high-resolution Indian remote sensing satellites Cartosat-1 and Cartosat-2. The satellites are equipped with in-track stereo mapping capability; Cartosat-1 has two fixed panchromatic cameras and Cartosat-2 has a single panchromatic camera and body steering capability for along-track stereo acquisition. At ADRIN, we have developed a methodology for correction of images with a rigorous sensor model and minimum GCPs which is used for georeferencing of a wide class of linear CCD array sensors. The model is based on the photogrammetric collinearity equations. Variations in the sensor model with respect to the viewing geometries of Cartosat-1 and Cartosat-2 are explained in the paper. Aspects of photogrammetric processing of the imagery are discussed. The geometric accuracy achieved from Cartosat-1 and Cartosat-2 images over the same set of check points are analysed. Cartosat-1 DEM, geometric accuracy and capability for topographic feature capture are good enough for making 1:10000 scale maps. Geometric accuracy and feature detectability of Cartosat-2 indicate that it is capable of making 1:7000 scale maps. Cartosat-1 satellite is more stable because it is not continuously changing the view while imaging. Based on the error estimation and analysis, it is concluded that if the strict photogrammetric processing model and ground control points are employed, high-resolution satellite imagery can be used for the generation and update of topographic maps of scale 1:10,000 and larger.

1. INTRODUCTION

The new very high space resolution satellite images, with a ground pixel size of better than 1m, open new possibilities for cartographic applications. For the full exploitation of the potential of this data, the “classical” satellite image processing methods must be extended in order to describe the imaging geometry. In general, the processing of these kinds of images provides a challenge for algorithmic redesign and this opens the possibility to reconsider and improve many photogrammetric processing components, such as image enhancement, image orientation (georeferencing), orthophoto and DTM/DSM generation and object extraction. Many different geometric models of varying complexity, rigour and accuracy have been developed for rectification of satellite images. In recent years, a large amount of research has been devoted to efficiently utilize these high spatial resolution imagery data. Examples can be found in sensor modeling and image orientation (Baltsavias et al., 2001; Jacobsen, 2003; Grodecki and Dial, 2003; Fraser et al., 2002; Radhadevi et.al, 2008a, b), automatic DTM/DSM generation (Jacobsen, 2004; Toutin, 2004; Poli et al., 2004). Indian space programme witnessed several major accomplishments and scaled newer heights in mastering space technology during the last few years. Cartosat series of satellites with stereo mapping capabilities have become main stay towards large scale mapping for urban and rural applications. A method for processing the Cartosat-1 data is explained in Srivastava et.al, 2007.

In our work, the used geometric model is based on the viewing geometry of the satellite, combining the principles of photogrammetric collinearity equations, originally developed for SPOT-1 [Radhadevi et al., 1994], and further adapted and tested for different sensor geometries. The sensor position is derived from the given supplementary data, while the attitude variations are modeled by a simple polynomial model. For self-calibration, two additional parameters are added to the model: the focal length (camera constant) and the principle point correction. The exterior orientation and the additional parameters of the sensor model are determined in a general formulation of the least-squares adjustment.

1.1 Features of Cartosat-1 and Cartosat-2

Cartosat-1 (IRS-P5) is the first satellite of ISRO designed to provide high resolution along-track stereo imagery for mapping applications. The platform contains two panchromatic camera payloads with +26° and -5° tilted with respect to nadir. The base to height ratio is about 0.62. Data is quantized with 10 bits. Integration time is 0.336ms. Nominal GSD is 2.5 m. Each CCD has 12000 pixels, separated in to 6000 each of odd and even pixels. These odd and even pixel rows are separated by 35μm (equal to 5 pixels). India’s highest resolution imaging satellite Cartosat-2 was launched form Satish Dhawan Space Centre (SDSC) on January10, 2007. Cartosat-2 is an advanced
2. MAPPING FROM SATELLITE IMAGERY

The major thrust of the current and future technologies are on generation of spatial information on large scale. With the higher spatial resolution satellite images available on these days, it is possible to prepare accurate base maps larger than 1:10,000 scale. Cartosat series of satellites with stereo mapping capabilities have become main stay towards large scale mapping for urban and rural applications.

Important criteria or considerations while going for large scale mapping from satellite images are

1. Information content
2. Geometric fidelity

Information contents or the feature delineability will be increased as and when the spatial and spectral resolution of the satellite improves. But achievable geometric accuracy depends upon many factors including the stability of the satellite, method of imaging (synchronized, asynchronous, TDI, Step and Stare, look angle etc.), used control points and the model used to rectify the imagery. Capability for mapping from satellite imagery depends upon the following factors.

2.1 Resolution of the image

Spatial as well as spectral resolution of the image is important. The ground sampling distance (GSD) – the distance of the pixel centres on the ground – may not be the same as the size of the physical pixels projected to the ground. We do have the influence of the optics, the actual situation of the atmosphere and a numerical over or under sampling. In addition, the image quality, especially the contrast, is depending upon the grey value range which goes from 6 bit or 64 different grey values to 12 bit or 4096 different grey values. Object identification is easier in multi-spectral images compared to panchromatic images.

2.2 Viewing geometry/agility of the satellite

High resolution images can be acquired by different methods like step and stare technology, TDI, asynchronous imaging, synchronous imaging etc. Stability of the platform is very important in deciding the final achievable accuracy. Along-track stereo images taken by fixed camera system with a good base-to-height ratio is preferred for mapping compared to images taken by agile satellites using a single camera. To acquire stereo along the pass with a single camera system, the satellite body has to be tilted with high oblique angles. There is a strong influence of the sun elevation and azimuth to the object identification.

2.3 On-orbit Calibration of the sensor

Precise on-orbit calibration of sensors during the commissioning phase of the satellite becomes very important with high resolution agile satellites especially when we talk about direct georeferencing. The primary challenge in alignment calibration is the need to estimate the underlying alignment trend for each sensor from a series of precision correction solutions, which measure a combination of orbit, attitude and alignment errors. Correlation between the physical parameters of the camera and the bore sight misalignment parameters between the payload and body is very significant.

2.4 Sensor model used for ground to image and image to ground transformation

The sensor model used is very crucial in deciding the final geometric accuracy of the product. Each image acquisition system produces unique geometric distortions in its raw images, which vary considerably with different factors, mainly the platform, its orbit, and the sensor. The geometric correction methodology has to take care of all these aspects. Different mathematical models used for establishing the relation between ground coordinates and image coordinates are polynomial model, rational function model and rigorous sensor model. Rational function model can be used as a replacement model if ephemeris and sensor parameters are not provided to the user. Rigorous sensor model based on the collinearity equation will reconstruct the imaging process. We have developed a methodology to rectify the satellite imagery with a rigorous sensor model and minimum GCPs. This model is used for mapping from Cartosat-1 and Cartosat-2/2A.

2.5 Ground control points

When the spatial resolution of the camera increases, the capability of topographic data capture also increases. But geometric fidelity may not increase in the same proportion especially due to the difficulty in transferring GCPs into high resolution images. For making ortho-adjustment of high resolution data, it is most important to assure a high precision
GCPs identification, interpretation and measurement in terrain and on the image. Variability of viewing angles within an image, if not respected properly, affect the accuracy potential and become very sensitive to the number and distribution of control points.

3. RIGOROUS SENSOR MODEL (RSM)

A sensor model reconstructs the imaging geometry. Reconstruction of the viewing geometry includes the exterior and interior orientations of the sensor. The model relates 3-D object point position to their corresponding 2-D image positions by describing the geometric relationship between the image space and object space. The algorithm for orbit attitude model, which combines the principles of viewing geometry of the satellite with photogrammetric collinearity equations, was originally developed for SPOT-1 and IRS-1C/D. This model has been adapted to suit the camera characteristics of Cartosat-1 and Cartosat-2. The information about of the satellite ephemeris, attitude, sidereal time, etc., are extracted from the ADIF. The orbit parameters in the collinearity equations are position \( (X_p, Y_p, Z_p) \), velocity \( (V_x, V_y, V_z) \) and attitude parameters are roll \( (\phi) \), pitch \( (\theta) \), and yaw \( (\kappa) \). Satellite position and orientation are given at every 125 msec. Attitude data in terms of quaternion are converted into Euler angles. Fitting of the given telemetry values are done for predicting at required time interval i.e. to make it continuous from discrete values given. The initial values of all the parameters are derived by least squares adjustment to the ephemeris data using a generalized polynomial model.

Collinearity equations express the fundamental relationship that the perspective centre, image point and object point lies on a straight line i.e.

\[
\begin{bmatrix}
  f \\
  -x_s \\
  -y_s
\end{bmatrix}
= d. M
\begin{bmatrix}
  X - X_p \\
  Y - Y_p \\
  Z - Z_p
\end{bmatrix}
\]  

(1)

where \((f, -x_s, -y_s)\) are the image coordinates, \((X, Y, Z)\) are the coordinates of the object point and \((X_p, Y_p, Z_p)\) are the co-ordinates of the perspective centre, \(d\) is the scale factor and \(M\) is the orthogonal rotation matrix to transform the geocentric to sensor co-ordinate system. The rotation matrix \( M = Q_{GI} * Q_{BP} * Q_{OB} * Q_{BP} * Q_{PC} \), where

\[
Q_{PC} = \text{CCD to payload transformation matrix}
\]

\[
Q_{BP} = \text{Payload to body transformation matrix}
\]

\[
Q_{OB} = \text{Body to Orbit matrix}
\]

\[
Q_{GI} = \text{ECI to ECEF matrix}
\]

CCD to payload transformation matrix is included into the rotation matrix. Thus, a pixel in any band of a camera can be projected onto ground co-ordinates through a series of transformations.

3.1 Combined camera adjustment for Cartosat-1

We have refined our physical sensor model to simultaneously correct the images from both the cameras through a tied-camera approach. In such an approach, in-flight calibration of the cameras is a very important pre-requisite. The objective of in-flight calibration is to compute the individual and relative alignment offsets of the cameras and include them in the sensor model. Remaining errors at the system level are due to small uncertainties in the body attitude, which are shared by both the cameras. This can be corrected with few conjugate points. Each conjugate point serves as two GCPs separated in the time line by 52 sec. A generic polynomial model is developed so that by selecting the order of polynomial, it can be adapted for different types of sensors. This option allows the modelling of the sensor position and attitude with 3rd, 2nd or 1st order polynomials. Corrections up to constant and 1st order coefficients are done for Cartosat-1. Over a long pass, the variation in the attitude angles will not be a bias and therefore, time-dependent coefficients are also updated with GCPs. If fore and aft images are independently corrected with GCPs, correction of the constant terms (3 parameters) is enough because the length of the orbital arc will be small (for each camera image) and can be piecewise corrected.

3.2 Sensor model updation for Cartosat-2

Cartosat-2 is an agile satellite. Figure1 shows the attitude variations over the entire strip. Self-calibration approach with correction to the constant term as well as first order and second order time-dependent terms is used for Cartosat-2.

![Figure 1 Attitude variations over the strip length](image)

4. MAPPING FROM CARTOSAT-1 AND CARTOSAT-2 DATA

Cartosat-1 is a very stable satellite meant for mapping applications. ADRIN is routinely generating DEM and Orthoimage from Cartosat-1 data using in-house developed sensor model and DEM generation methodology. To check the achievable accuracies from Cartosat-1, we have used the base maps, which are of 70 cm accurate, as reference data. Accuracy evaluation is done over 6 data sets. Only a single GCP is used in all the cases. Area covered in each data is 30 km X 30 km. Distributed Check points are identified. Errors obtained for different datasets are shown below. GCP requirement is minimized by using the ephemeris and attitude data and precise payload geometry in to the rigorous sensor model.
It is clear from this figure that Cartosat-1 data is capable of giving 3-4m accuracy just with 1 GCP. DEM and ortho images are generated from these datasets.

Mapping potential of Cartosat-2 imagery was evaluated with multi view images and strip images over the areas where Cartosat-1 accuracy evaluation was done. Following Figure shows RMS errors achieved.

Figure 4 shows vector layer from the reference data overlaid on to the orthoimage. All road networks and other features are exactly sitting over the image.

Figure 5 shows achievable accuracies from Cartosat-2 (2GCPs used).

Figure 6 shows vector layer from reference data overlaid on spatially accurate Cartosat-2 imagery (same area of fig. 4).
Figure 7 Comparison of along-track error over same check points with same GCPs used for both Cartosat-1 and Cartosat-2 (RMS error: Cartosat-1=1.7m; Cartosat-2= 1.3m)

Figure 8 Comparison of across-track error over same check points with same GCPs used for both Cartosat-1 and Cartosat-2 (RMS error: Cartosat-1=2.4 m; Cartosat-2= 1.7m)

The above figures (figures 7 & 8) give a comparison of geometric accuracy achieved from Cartosat-1 and Cartosat-2 images over the same set of check points. Two GCPs are used for Cartosat-1 and Cartosat-2 images for correction. It is obvious from Figures 7 and 8 that achievable accuracy will not linearly improve in the same proportion as resolution increases. Both satellites, Cartosat-1 and Cartosat-2 shows almost same range of accuracies with same set of check points.

4. CAPTURING TOPOGRAPHIC VECTOR DATA FROM THE IMAGERY

The orthorectified imagery was analysed with the capture of spatial information. Sub-areas of the image were analysed to ensure that different types of topography were investigated, viz. urban, semi-urban and rural. In each of these areas we attempted to capture all the features present in the specifications of the various mapping scales. The features collected in this study included roads, railways, tracks and paths, buildings, vegetation limits, water features and field boundaries. Many of the feature types that are required for 1:10,000 scale mapping could be satisfactorily identified and captured in Cartosat-1 and Cartosat-2 satellite images. In some cases, features required for larger than 1:10,000 scale mapping (e.g. roads and woodland boundaries at 1:2500 scale) could also be captured in the images. Major exceptions to this are transmission lines, walls, fences and hedges, which are generally impossible to distinguish even in imagery with 0.4m resolution. Figures 9 and 10 show the feature delineability from Cartosat-1 and 2 at different scales. The national mapping accuracy standards in Great Britain indicate RMSE of 1.1m for 1:2500 scale data and 3.4m for 1:10,000 scale data.

Figure 9 Feature delineability at 1:5000 scale (a) Cartosat-2 (b) Cartosat-1

Figure 10 Feature delineability at 1:10,000 scale (a) Cartosat-2 (b) Cartosat-1

Over a built-up area of 2*3 km, base map was generated at 10,000 scale from Carto-1 and Carto-2, and are shown in figure 11.
Major road networks and buildings could be captured from both satellite images. The level of features in Carto-1 and Carto-2 are comparable at 10,000 scale. Thus, generated base map clearly demonstrate the mapping potential of Cartosat imageries

5. CONCLUSIONS

In this study, we have evaluated the potential of Cartosat-1 and Cartosat-2 satellites for large scale mapping. Following are the major conclusions.

- Cartosat-1 DEM, geometric accuracy and capability for topographic feature capture are good enough for making 1:10000 scale maps.
- Geometric accuracy and feature detectability of Cartosat-2 indicate that it is capable of making 1:7000 scale maps.
- Cartosat-1 satellite is more stable compared to Cartosat-2 because it is not continuously changing the view while imaging. This ensures that no scale variation will be there at different parts of the imagery and will give uniform accuracy over a single image as well as images taken from different orbits. It is better to use stable satellites than agile for mapping applications.
- Number of GCP requirement is less for Cartosat-1. One conjugate point from Fore and Aft images over a scene gives an accuracy of about 3-4m. Minimum two GCPs are required for correction of Cartosat-2 to take care of the agility of the satellite.
- The majority of features seen in Cartosat-2 images are delineable in rural and mixed areas in Cartosat-1 images with the desired accuracy.

REFERENCES


ABSTRACT:

SPOT-5 and Cartosat-1 are mapping satellites with high resolution and along-track stereo capability. This paper describes the work carried out towards the qualitative and quantitative comparison of the Digital Elevation Models (DEM) derived from stereo pairs of SPOT-5 (HRS1 and HRS-2) and Cartosat-1 (Fore and Aft) over the test site located in Bavaria, Germany. This is one of the test areas selected towards SPOT-5 Assessment Programme. DEMs are generated with two different kind of modelisation: one with geometric correction of images using physical sensor model and other one with Rational Polynomial Coefficients (RPC). In the first approach, Ground control points (GCP) are used for bundle adjustment with a self calibration to improve the interior and exterior orientation parameters. In the second approach, RPC’s are derived initially from the grid generated through direct georeferencing using the physical sensor model and then compensated with GCPs. Out of the 47 points provided, 5 are used as GCPs for rectification of SPOT images and 3-D modeling was checked on remaining 42 independent points. Both orientation methods gave RMS errors less than a pixel for both mono and stereo orientation. We tried to transfer these points to Carto-1 fore and aft images through sub-pixel matching. But most of the points could not be precisely transferred to Cartosat-1 as the GCP locations are not clear cut features on the SPOT image. Secondary controls are derived by identifying few well defined road junctions in SPOT scenes and deriving the corresponding ground co-ordinates through SPOT stereo intersection which gave an accuracy of 2-3m. They are manually identified in Cartosat-1 images. Two stereo GCPs are used for modeling Cartosat-1 fore and aft images. Accuracy is evaluated at the remaining points for different subscens. RMS errors of the order 6 to 7m in X, Y, Z are obtained. Increasing the number of GCPs does not improve the accuracy. The DEMs are generated using a combined approach of feature based and area-based multi-scale image matching method and semi automatic editing tools. The quality of the matching is controlled by forward and backward matching of the two stereo partners using the least squares matching method. The “no match” areas are filled with interpolation during the DEM production process and final DEM is generated at regular interval. DEM accuracy is determined by using the available DEM data of superior accuracy. Detailed visual and quantitative comparison results of the DEMs from SPOT-5 and Carto-1 are presented in the paper. Even tough absolute accuracy is poor for Cartosat-1 due to the inaccuracy of secondary controls, quality of the DEM is much superior to SPOT-5 DEM. Statistics of the errors are analyzed and tabulated for the DEMs generated with different global spacing.

1. INTRODUCTION

As part of Assessment Programme of SPOT-5 (CNES-ISPERS-HRS Study Team) and Cartosat-1 (ISPRS-ISRO-Cartosat-1 SAP), various international specialists have evaluated and reported the accuracy of the DEMs generated from these satellites (Jacobsen,K,2004;Poly,D,2004;Reinartz,P,2004;Srivastava,PK,et.al,2007;Lehner,M,et.al,2006,Crespi,etal,2008;NandaKumar,et.al,2008). Both satellites provide along-track stereo pairs. HRG produces image stereo pairs with two optics looking forward and backward (+20 degrees) with respect to the nadir direction. The camera has a spatial resolution of 10 meter across track and along track, but a ground sampling distance of about 5 meter along track. Cartosat-1 has two fixed panchromatic cameras for along-track stereo acquisition; Forward camera (F) and an Aft camera (A) with tilts in flight direction of +26 and -5 respectively. There is 52sec gap in imaging the same area by the other camera. The focal plane is composed of a staggered CCD array configuration of 12,000 pixels with 7 microns pixel spacing, separated into 6000 each of odd and even pixels. These odd and even pixel rows are separated by 34µm (equal to 5 pixels) in the focal plane. Resolution of Cartosat-1 is about 2.5m. B/H ratio of SPOT-5 is about 0.85 and that of Cartosat-1 is 0.62.

In this paper, generation, evaluation and comparison of DEMs from SPOT-5 and Cartosat-1 stereo pairs is reported. For orienting the imagery, two alternative approaches have been used: one with a rigorous sensor model and the other one with Rational Polynomial Coefficients (RPC). A generic sensor model for georeferencing of linear CCD array images has been developed. This model is very flexible and has been successfully used for the orientation of SPOT-1, IRS-1C/1D, TES, IRS-P6 (Radhadevi et al., 1994, Radhadevi, 1999, Radhadevi et al, 2008) The algorithm is purely based on the viewing geometry of the satellite, combining the principles of photogrammetric collinearity equations, originally developed for SPOT-1 and further adapted and tested for different sensor geometries. For SPOT-5, as the precise interior orientation parameters are not known, a modified sensor model is used.
with a self-calibration approach in which interior orientation parameters (effective focal length and modified centre pixel) are also updated along with the exterior orientation parameters. For Cartosat-1, generic sensor model itself is used along with in-flight calibrated camera parameters fixed. The alternative method, independent from the camera model, does not describe the physical imaging process, but uses rational polynomials to relate image and ground coordinates to each other. This algorithm consists of two steps: 1) calculation of Rational Polynomial Coefficients (RPC) for each image with least-squares using the geometric information contained in the metadata files; 2) RPC compensation using GCPs. The derived DEMs are then compared with the high precision reference DEM by several methods regarding: height accuracy, location accuracy, blunders, error budget depending on surface properties etc. After the description of the available data, the processing algorithms applied for images orientation, matching and DEM generation are presented. The results obtained after the comparison between the generated DEMs with the reference ones are reported and analysed. Details of the RSM and RFM are available in Radhadevi & Solanki, 2008 and Nagasuubramanian et al. 2007.

2. TEST AREAS AND GROUND REFERENCE DATA

Data provided by Dr. Jacobsen contains stereo images from SPOT5-HRS sensor with corresponding metadata files, the description of the exact position of 47 object points measured with surveying methods and the reference DEMs produced by Laser data and conventional photogrammetric and geodetic methods. The image co-ordinates of the GCP locations are also provided for HRS-1 and HRS-2 images. The points are in Graus-Kruger projection and Bessel datum. SPOT images were acquired on 1st October 2002 with a sun elevation of 38º and nearly no clouds.

Test regions are chosen for DEM generation over Bavaria area. The elevations range from 400 to 1700 meters. This area contains different types of terrain which allows the comparison of DEM for different land surface shapes, including forest and steep terrain. 4 regions over this area are analyzed. Reference DEM 1 has an overall size of about 5km X 5km over Gars area with a spacing of 5m derived from airborne laser scanning. Reference DEM 2 has also the same size over Prien area. Reference DEM 3 also covers an area of about 5km X 5km over Peterskirchen. The height accuracy of all these DEMs is better than 0.5 meter. Reference DEM 4 is of 50km X30km. But only a part of this is covered by SPOT-5 as well as Cartosat-1 images. Accuracy of this DEM is about 2-3m.

The corresponding area is covered by 5 sub scenes of Cartosat-1. Coverage of SPOT-5 and Cartosat-1 data along with GCP locations and reference DEM locations are shown in Fig.1. Cartosat-1 data have been acquired on 30th January 2006, 26th July 2007 and 1st August 2007.

3. DEM EVALUATION AND RESULTS

Evaluation is done at independent checkpoints using sensor model, and also by comparison of generated raster DEM with reference data.

3.1 Results on Stereo-model computations

3D modeling accuracy was tested on independent checkpoints. Table 1 gives the RMS errors of the least square adjustment computations for SPOT-5 and Table 2 gives the computation accuracy of Cartosat-1. Errors are estimated at the checkpoints. RMS errors at the checkpoints reflect the restitution accuracy. For SPOT-5, accuracies of the order 2-3m is achieved with 5GCPs. As we see in Table 2, for Cartosat-1, by choosing one
conjugate GCP, geometric accuracy increases significantly. Here, input GCPs as well as check points are secondary controls derived from stereo intersection of SPOT-5 images. Accuracy of them is of the order of 3-4m. Just with 1 conjugate GCP, Cartosat-1 stereo restitution accuracy is about 6-7m which are of the same order of input GCP/data errors, being a combination of image pointing error and planimetric error in addition to the propagation of Z-error depending on the viewing angles. This accuracy is dominated by the limited control point quality. Increasing the number of GCPs does not increase the accuracy considerably.

Table 1 Errors at check points using rigorous orientation model for stereo intersection (HRS1 & HRS2)

<table>
<thead>
<tr>
<th>Path/Row</th>
<th>Number of GCPs + CPs</th>
<th>RMS Lat(m)</th>
<th>RMS Lon(m)</th>
<th>RMS Ht.(m)</th>
<th>Min.Ht.err (m)</th>
<th>Max.Ht.err (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>159/179 (scene 5)</td>
<td>5+42</td>
<td>1.53</td>
<td>3.22</td>
<td>2.87</td>
<td>-5.27</td>
<td>7.92</td>
</tr>
<tr>
<td></td>
<td>6+41</td>
<td>1.36</td>
<td>2.73</td>
<td>2.66</td>
<td>-4.13</td>
<td>6.81</td>
</tr>
<tr>
<td></td>
<td>7+40</td>
<td>1.40</td>
<td>2.73</td>
<td>2.69</td>
<td>-3.74</td>
<td>7.41</td>
</tr>
<tr>
<td></td>
<td>8+39</td>
<td>1.69</td>
<td>2.83</td>
<td>3.13</td>
<td>-2.43</td>
<td>9.01</td>
</tr>
</tbody>
</table>

Table 2 Errors at check points using rigorous orientation model for stereo intersection of Cartosat-1 (Aft+Fore)

3.2 Results on DEM evaluation

The accuracy numbers are only one indicator for the quality of a height model. The SPOT-5 HRS sensors have a spectral range from 0.48 up to 0.70µm wavelength, that means only the very first part of infrared is included, while Cartosat-1 has a spectral range from 0.50 up to 0.85µm, including the near infrared. In the near infrared the vegetation has a strong reflectance. By this reason the automatic image matching with Cartosat-1 images over forest areas is very successful. In SPOT-5 HRS images the forest is always dark, causing severe matching problems.

We analyze the qualitative and visual evaluation of the DEM and quantitative and statistical evaluation of the DEM with the reference DEM. Matching is done at different intervals, viz; 5m, 15m, 30m and 50m. The tonal variation of vegetation constrains the matching to a low correlation factor. The areas where correlation is poor, the match point may not be the correct terrain point. Thus, a low pass filter is used to free it from blunders. Analysis with reference and stereo DEM points are done with the help of Arc/Info. The contours replicate the pattern as the reference DEM. The planimetric accuracies are estimated from contour nearness of corresponding lines. Vertical accuracy of this stereo data DEM is concluded from statistical analysis of difference DEM that is derived from the deviations in heights of data derived points from that of the reference points.

Figure 2 shows the DEM generated with 5m spacing over Gars area from SPOT-5, Cartosat-1, corresponding map and the reference DEM. The generated height model is describing the visible surface from the camera and not the bare ground required for a DEM. It is obvious from this figure that the generated DEM well reproduces the terrain relief and topographic features. Horizontal height profile over Gars is compared for Cartosat-1 DEM and reference DEM in figure 3. DEMs generated over Prien area and Vilshiburg area are shown in figures 4 and 5 respectively. Figure 6 shows the horizontal height profiles over the DEM s of Prien area.
The DEM generated is compared to the reference DEM and statistics are derived using Arc/Info. As output, the s/w gives the number of points compared, minimum difference, maximum difference, and mean difference, standard deviation and RMS errors. DEM is assessed according to the land cover and slope categories. Table 4 gives the accuracies of the generated height models of SPOT-5 and cartosat-1. The frequency plots over sloped and flat areas of a small window over Prien were analysed. For both cases, it was seen that mean difference is more for Cartosat-1 DEM but standard deviation is less for Cartosat-1 DEM compared to SPOT. DEM accuracy depends on terrain slope and type of terrain. Standard deviations of filtered height models in open areas give very good accuracy. The DEMs comparison shows that the derived DEM from Cartosat-1 is very much close to the reference one. With respect to the thematic content, the image quality is good. The 10-bit dynamic range enables the detection and identification of features and terrain patterns as they are visible. Cartosat-1 reproduced quite well not only the general features of the terrain relief but also small geomorphological and other features visible in the terrain.

Table 4: Comparison of height for high quality points between reference DEM, SPOT-5 DEM and Cartosat-1 DEM

<table>
<thead>
<tr>
<th>Reference DEM</th>
<th>Reference area</th>
<th>Size and Accuracy of Ref. DEM</th>
<th>Cartosat-1</th>
<th>SPOT-5</th>
<th>Points [#]</th>
<th>Points [#]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM-01</td>
<td>Gars</td>
<td>5 x 5 km, 0.5 m</td>
<td>-2.2</td>
<td>48000</td>
<td>2.3</td>
<td>37000</td>
</tr>
<tr>
<td>DEM-02</td>
<td>Prien</td>
<td>5 x 5 km, 0.5 m</td>
<td>-7.8</td>
<td>18624</td>
<td>4.9</td>
<td>14567</td>
</tr>
<tr>
<td>DEM-03</td>
<td>Peterskirchen</td>
<td>5 x 5 km, 0.5 m</td>
<td>-5.6</td>
<td>45396</td>
<td>4.9</td>
<td>97000</td>
</tr>
<tr>
<td>DEM-04</td>
<td>Vilsbiburg</td>
<td>50 x 30 km, 2-3m</td>
<td>-0.9</td>
<td>25000</td>
<td>-4.2</td>
<td>23100</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

In this paper we have compared Digital elevation models generated from stereo pairs of SPOT-5 (HRS1+HRS2) and Cartosat-1(Fore+ Aft) over Bavaria site. The DEM generation is done using a physical sensor model based on collinearity equations and also using RPC coefficients. The hierarchical matching is done after epipolar registration. A quantitative and qualitative evaluation of the DEM generated was conducted by comparison with a reference DEM. RSM and RFM give almost comparable results. The absolute accuracy of the generated DEM is about 3-4 m for SPOT-5 and 6-7 m for Cartosat-1 where GCPs as well as check points of Cartosat-1 are of accuracy of 3-4 m. All height models based on space information are digital surface models, showing the visible surface of the vegetation and artificial objects. A filtering of the DSMs in the closed forest area has limited effect because only few object points are really located on the bare earth. Nevertheless the morphologic details in the Cartosat-1 height model are at least on the level of the existing DEM of the topographic map 1 : 25 000. The SRTM C-band height model or SPOT-5 height model of course cannot show the same level of detail. Quality evaluation of generated DEMs reveals that information content in Cartosat-1 is much superior to SPOT-5 DEM. But geometric fidelity of SPOT-5 HRS images is really surprising. It is proven with this research that it is possible to extract good quality DEM using along-track stereo pairs of Cartosat-1 and SPOT-5.

REFERENCES


Lehner, M., Müller, Rupert, Reinartz, P., 2006: Stereo Evaluation of CARTOSAT-1 Data on Test Site 5 – First DLR Results, Proceedings of ISPRS-TC IV Symposium, Sept. 27-30, Goa, India


ACKNOWLEDGEMENTS

The authors gratefully acknowledge Dr. J. Sai Baba, Group Director, SDA & A, ADRIN and Smt Geeta Varadan, Director ADRIN for their encouragement and support for this work.
Automated co-registration of images from multiple bands of Liss–4 camera

P.V. Radhadevi*, S.S. Solanki, M.V. Jyothis, V. Nagasubramanian, Geeta Varadan
Advanced data Processing Research Institute, Department of Space, Manovikasnagar P.O., Secunderabad 500 009, India

1. Introduction

1.1. Co-registration schemes

A continuous and automated co-registration and geo-location of image data from multiple bands of Liss–4 camera is one of the basic requirements of IRS-P6 data processing. Slight difference in viewing geometries and other inconsistencies at the time of imaging presents an interesting challenge to this requirement. Binding of these bands with spatial correspondence in image locations should be done at the sub-pixel level. Co-registration between the bands can be achieved through image-based or geometry-based methods. Co-registration using the imaging geometry and auxiliary data is achieved indirectly by registering each band to a common coordinate system on the ground. Theiler et al. (2002), explain automated co-registration of Multi-spectral Thermal Imager (MTI) bands using photogrammetric methods. They have also reported the automated image registration of MTI imagery through entirely image-based methods. Initially these two approaches were developed as parallel methods for co-registration and later they were combined into a more hybrid approach (Pope et al., 2003). Co-registration and in-flight calibration updates of MISR (Multi-angle Imaging Spectro Radiometer) imagery are explained by Jovanovic (2002).

The image-based method does not require the knowledge of satellite position and orientation. As the motion of the spacecraft is relatively uniform, the image-based approach generally produces reasonable co-registration in images over plain terrain. In this method, registration of two images is achieved by identification of conjugate points through matching with which a transformation is fitted to rotate one with respect to the other. Image-based approaches involve heuristics about the widow size, similarity measure etc. They work better over images of small sizes like sub-scenes (23 × 23 km) where terrain undulations are not rapid. The process will become very slow when the window sizes are made wide. They are likely to fail when larger areas with undulations over terrain are considered, where matching widow ranges are not good enough to accommodate the offsets. Also, the change in reflectance between the extreme bands gives only few conjugate points after matching, so that warping becomes impossible in many cases. Thus, image-based registration techniques using cross-correlation are likely to fail with images over hilly terrain, containing snow, cloud and areas without many man-made and natural features. These methods either interactive or automated image matching, though do not require any knowledge about satellite orientation or internal geometry of optics, cannot become a better choice for this purpose.
Therefore, the development of an automatic registration method for different bands, benefiting from the same orbit acquisition and imaging geometry is essential. Taking advantage of the information of the camera and the satellite, a ground processing makes the estimation and correction process much simpler to achieve even to sub-pixel level co-registration. The software collates the output of all the bands into a spatially consistent multi-spectral image cube where a given location on the ground corresponds to the same position in the image for each of the spectral bands. This is done by aligning the spectral bands to a common grid that is defined in terms of coordinates on the ground. A digital elevation model is used to correct the perspective shifts due to the combined effect of terrain height and view angle of the imaging platform. Direct georeferencing approach is done initially for performing the co-registration task. The major advantage in this approach is its autonomous nature and ability to remove the bulk distortions, which result in mis-registration within the raw data. A validation and fine-tuning of the unaccounted residual offsets are done at the final stage with the help of image-based matching at one or two points to accommodate the bias left if any.

This paper analyzes the effect of various factors on band-to-band mis-registration and explains the development and implementation of an approach for co-registration of multi-spectral bands of Liss-4 within a production environment. We present a geometry-based co-registration approach that accounts for the offsets arising from the imaging geometry and terrain undulations. This method requires extensive information about the satellite position and pointing as a function of time and the precise configuration of the focal plane. These must be combined with the knowledge of the position and altitude of the target on the rotating ellipsoidal earth. Accurate calculation of the exterior orientation parameters with Ground Control Points (GCPs) is not required for this purpose. Instead, the relative line of sight vector of each detector in different bands in relation to the payload is addressed.

1.2. Camera system of Liss-4

From its near polar sun synchronous 817 km altitude orbit, IRS-P6 satellite images with three sensors Liss-4 (L4) Liss-3 (L3) and AWiFs (AWF). Ground Sampling Distance of L4 is 5.8 m (at nadir), L3 is 23.5 m and AWF is 56 m (at nadir). The steerability of the L4 camera, of about ±26° relative to the vertical, enables the generation of across-track multi-date stereoscopy from two different orbits. L4 camera uses a staggered array of 12,000 detectors for each one of the three bands. This camera operates in two modes, wide mono and multi-spectral. In the wide mono mode, all the 12,000 detectors (of only one band) will be active and will have a swath of 70 km. In the multi-spectral (MX) mode, only 4200 detectors (out of 12,000) will be active to image a swath of 23 km. Placement of different bands is shown in Fig. 1. The three arrays corresponding to the three bands are physically separated in the focal plane but share the common optics. In view of the geometry, the same line on the ground will be imaged by extreme bands with a time interval of as much as 2.1 s, during which the satellite would have moved through a distance of about 14 km on the ground and the earth also would have rotated through an angle of 30 arc s. The multi-spectral bands are separated as shown in Fig. 2 with an angular separation of 0.963° between leading and following bands. A yaw steering is being employed to compensate the earth rotation effects to ensure a first level registration between the bands. This will not account for the factors like orbit and attitude fluctuations, terrain topography, variable offsets between the bands due to the location of the start pixels in the array, Payload Steering Mechanism (PSM) and small variations in the angular placement of the CCD lines.

2. Effect of various factors on BBR

BBR is of critical importance to the successful generation of data products. Perfect alignment of the bands requires information about the focal plane geometry, satellite orbit and attitude and about the target location. For a push-broom sensor like IRS-P6, the largest source of mis-registration is due to uncertainties in the information about the platform during image acquisition. As the ephemeris and attitude are given at an interval of 125 ms, changes in the orbit and attitude behavior within this interval will not get reflected in the navigation data and therefore, cannot be corrected with GCPs. Other factors, which affect BBR, are errors due to inaccuracies in modeling the sensor optics and focal plane and earth’s terrain. Finally, the smallest errors are due to modeling the earth’s shape, platform jitter and atmospheric refraction.

Orbit determination accuracy of IRS-P6 in the GPS mode is about 10 m and attitude determination accuracy with star sensor in loop is about 202 m. Analysis of the attitude behavior of many datasets reveals that high frequency jitters or disturbances are not present even with high look angles (PSM steering) of the L4 camera. Systematic errors due to unknown modeling errors are much smaller compared with random errors. Simple systematics errors are due to uncertainties in the precise knowledge of position, velocity and attitude. The smallest errors are due to modeling the earth’s shape, platform jitter and atmospheric refraction.

Orbit determination accuracy of IRS-P6 in the GPS mode is about 10 m and attitude determination accuracy with star sensor in loop is about 202 m. Analysis of the attitude behavior of many datasets reveals that high frequency jitters or disturbances are not present even with high look angles (PSM steering) of the L4 camera. Systematic errors due to unknown modeling errors are much smaller compared with random errors. Simple systematics errors are due to uncertainties in the precise knowledge of position, velocity and attitude. The smallest errors are due to modeling the earth’s shape, platform jitter and atmospheric refraction.
different bands will reflect as a mis-registration artifact and will be corrected while fine-tuning the product. The main factors affecting band-to-band registration are the angles of deflection, combined effect of velocity and attitude fluctuations, terrain undulation and the start pixel location. Some errors like velocity and attitude have larger effects than others, and it is important to quantify these effects. Following the method of estimating the effect of various errors in registration of MTI bands proposed by Theiler et al. (2002), we compute the magnitude of these effects for the L4 sensor.

2.1. Placement of detector arrays in the focal plane

Detector arrays corresponding to the three bands are placed with a look angle difference of 0.963° between the extreme bands (in the along-track direction) with respect to the payload cube normal. In the multi-spectral mode, only 4200 detectors (out of 12,000) are switched on for imaging. If this active array is near the center, the offsets in images are minimal and they increase if the array is away from center to extremes. Depending upon the start pixel location, the pixel offsets in the raw image will vary. The difference in pixels between the bands is not uniform throughout the entire length of the array. This is shown in Fig. 3. In-flight calibrated camera geometry model integrated within the rigorous sensor model is used to correct this.

2.2. Angle of deflection

Angle of view of the camera optical system of L4 is adjustable within ±26° to ±26°. During imaging, the view is fixed. Also, the angles of view of individual pixels of CCD lines are fixed. Deflection of the optical system from the nadir position results in a change of trace of these angles on the ground area, so they change the dimensions of the ground pixels as well as the width of the imaging area. This has been shown in Fig. 4. If \( P_x \) and \( P_y \) are pixel sizes at nadir angle, pixel sizes at deflection angles \( \psi_x \) and \( \psi_y \) are

\[
P_{x1} = P_x / (\cos \psi_x \cos \psi_y) \quad \text{and} \quad P_{y1} = P_y / (\cos \psi_x \cos^2 \psi_y).
\]

Here, \( \psi_x \) is the tilt of the camera (PSM steering) and \( \psi_y \) is the placement angle of the array in the along-track direction with respect to the payload cube normal. With high-oblique angle \( \psi_x \), \( P_{x1} \) and \( P_{y1} \) can be 7.3 m and 6.5 m respectively. The combined effect of view angle and altitude of the terrain will introduce considerable offsets in image locations between bands, which can be prominent when payload is steered to the extreme limits. The rigorous sensor model (along with a DEM) in general accounts for these offsets.

2.3. Velocity effects

In Fig. 5, \( \Delta \psi \) is the angle between a pair of bands in the focal plane (\( I \) is the leading band and \( f \) is the following band). If the spacecraft altitude above the ground is \( h \), then it will travel a distance \( h \Delta \psi \) before the \( I \) and \( f \) bands line up on the ground. If the effective velocity of the spacecraft is \( v \), the time for the spacecraft to do this is \( \Delta t = h \Delta \psi / v \). The co-registration will then line up \( I \) and \( f \) bands with a time delay of \( \Delta t \). However, if due to a miscalculation, the velocity is assumed to be \( v \) but is actually \( v + \Delta v \), then lining up the bands using the \( \Delta t \) delay will lead to a mis-registration error (in meters on ground) of \( \Delta v \Delta t = h \Delta \psi \Delta v / v \).

For the L4 sensor, \( h \sim 820 \text{ km}, \Delta \psi \sim 0.963^\circ (0.0168 \text{ rad}) \) and \( v \sim 7 \text{ km/s} \), so for instance, if \( \Delta v \sim 10 \text{ m/s} \), then the band-to-band offset on the ground would be 19.68 m or as big as 3.3 pixels. Attitude errors also manifest as velocity effects.

2.4. Elevation effects

Mis-specified elevation introduces an error in co-registration. Fig. 6 illustrates this effect. If the elevation above sea level is in error by an amount \( \epsilon \), then the mis-registration error will be \( \Delta t (\epsilon \tan \theta) = \Delta t \epsilon \sec^2 \theta \Delta \psi \), where \( \theta \) is the angle off-nadir. For IRS-P6 L4 image, nadir look with an altitude error of 1 km, would lead to a band-to-band offset on ground to 16.8 m or 2.9 pixels. On a highly undulating terrain like the Himalayas, error would be more.
will reflect as mis-registration in the along-track direction. These elevation differences as they are not uniform, will reflect as non-uniform offsets along the satellite track as shown in Fig. 6. (Points A and B have different offsets as they are at different heights over the reference plane.) Incorporating the knowledge about terrain height in the geometric model is used to overcome this. While projecting a particular pixel in the array onto the ground, the height of the ground point is extracted from a public domain DEM so that shift due to terrain undulation is minimized. The accuracy of the DEM is not very critical because we are determining the relative shift between the bands and not the absolute accuracy of the line of sight vector.

3. Geometry-based co-registration

Fig. 1 illustrates the displacement of different bands of L4 relative to the detector coordinate system. The bore sight is located near band3. Separation between the extreme bands is about 2359 lines. There is a time delay of 2.1 s in imaging the same ground point in extreme bands. Although viewing geometries encountered under operational conditions vary substantially from one image to another, especially for off-nadir images, the same timing sequence is used for each image acquisition. This leads to varying band-to-band alignments. As explained in the previous section, the largest source of mis-registration is due to uncertainties in the information about the platform during image acquisition.

Co-registration of images, acquired by different bands of the same sensor which are not aligned in the payload is a process through which the pixels in the images corresponding to same ground point are made the same. That means a feature imaged in one band is located in the same row and column in the other bands after co-registration. This is the basic requirement in the case of multi-spectral data for better image analysis and classification. L3 and AWF data of IRS-P6 do not have serious band-to-band offsets as different bands are aligned in the focal plane unlike in the case of L4. Geometry-based approach is adopted for co-registration of L4 bands that accounts for the offsets arising from the imaging geometry and terrain undulations.

Different levels of applications are envisaged with the co-registered data. Data selection through browsing, data for texture draping application, data input to interpretation and classification, input to flythrough, cartographic applications etc. are some of them. The volume of data in the case of full pass processing is very high. These huge data volumes are to be handled with intelligence in processing and storage. From this point of view, we suggest and explain the procedure of two types of co-registered products, viz., geo-aligned and orbit-aligned. Schema for automated band-to-band registered product generation is shown in Fig. 7.

3.1. Geo-aligned product generation

Co-registered product can provide the imagery that is “geo-aligned”. This means that the grid to which the points are resampled is nominally a standard polyconic projection in which the north is “up”. The final product in this case is the co-registered bands that are oriented with respect to true north, rescaled to the required resolution, and written to the projection optioned for. In this product, x-axis of the ground coordinate system points East (Longitude) and y-axis towards North (Latitude). The geo-aligned product is ready to be used with any spatial modeling package and is preferred in applications like large area mapping and database generation. The products will have system level accuracy. If ground control points are identified and supplied, the software package can generate products that are more precise in absolute accuracy. But, accurate calculation of the exterior orientation parameters with ground control points is not essential for the generation of band-to-band registered products.

The steps involved in generating geo-aligned co-registered products are
1. In-flight camera calibration (carried out during the commissioning phase of the satellite).

Initial interior orientation parameters of different cameras of IRS-P6 were determined by pre-launch lab measurements. Some of these parameters are again calibrated during the first few months of the mission and later on updated based on the quality assessments. The output of the in-flight camera calibration, which is performed during the initial phase of the mission, is a camera model that describes the interior (instrument-related) orientation of the instrument. In-flight calibration will ensure the individual sensor alignment, inter-camera alignment, effective focal length, first level BBR and alignment of staggered arrays. This is to correct for any alignment changes that may have occurred during launch and to account for thermally induced pointing variations affecting the instrument. The in-flight calibrated camera model is an input for standard processing and co-registration, which will reduce the processing load and help in producing the best possible geo-located and co-registered products. Taking advantage of the same orbit acquisition, calibration of different cameras is done with rigorous geometric reconstruction of the sensor orientations. Relative orientation of cameras with respect to a nadir looking camera (with high resolution) is performed. For the L4 camera, relative orientation of band2 and band4 with respect to band3 is done to take care of the alignment of the detector arrays in the focal plane. Detailed in-flight calibration methodology of different cameras of IRS-P6 is explained in Radhadevi and Solanki (2008).

2. Orbit attitude modeling. (Sensor Model)

For attaining co-registration through geometry-based methods, development of a sensor model is essential. The algorithm for orbit attitude model, which combines the principles of viewing geometry of the satellite with photogrammetric collinearity equations, was initially developed for SPOT-1 and IRS-1C/D (Radhadevi and Ramachandran, 1994; Radhadevi et al., 1998). This model has been adapted to suit the L4 camera characteristics of IRS-P6. In order to do direct georeferencing, the spacecraft navigation and attitude data must be known. The information about the satellite ephemeris, attitude, look angle, start pixel, time etc. is extracted from the ancillary data file during the pre-processing and stored. With these values, initial fitting of the trajectory is done with a generic polynomial model.

These parameters at a particular time are connected to the corresponding ground coordinate and image coordinate through collinearity equations. Collinearity equations express the fundamental relationship that the perspective center, image point and object point lie on the straight line. Thus, for IRS-P6, a pixel in any array (odd or even) of any band of L4 can be projected onto earth through a series of transformations and re-projected back to any other band/array through a reverse series of transformations using the parameters of the corresponding cameras in the rotation matrix and thereby fixing the relative positions of individual arrays in the focal plane. Payload to body biases of each camera is computed during the in-flight calibration and correct residuals are included in the rotation matrix. The series of rotations a pixel undergoes before it is projected on to the ground is shown in Fig. 8. Details about the rigorous sensor model are available in Nagasubramanian et al. (2007).

3. Regular grid generation in the object space coordinates corresponding to the required product extent.

The area for product generation can be selected either by map-based or by ROI. Map-based products with areas equivalent to three different scales of maps (1:25,000, 1:50,000 and 1:250,000) according to the Survey of India referencing scheme are supported. ROI can be selected from the image or from the coverage map. A regular grid is generated in the object space for the required extent with a grid spacing that can be set by the user. The user can also set other parameters like output resolution, datum and projection.

4. Extraction of height from a global DEM.

Height at each grid point is extracted from a coarse resolution Digital Elevation Model. A study of SRTM versus GTOPO as backdrop DEM for product generation of IRS-P6 L4 images has been explained by Jyothi et al. (2008) that recommends inclusion of GTOPO30 in L4 product generation from the data-handling viewpoint. Therefore, from the available public domain DEMs like DCW, GTOPO30, SRTM etc, GTOPO30 is used for BBR for its wider coverage and simple format of each tile.
5. Ground to image transformation for all bands.

Image point intersection is done for all the grid points through a backward projection transformation derived from the collinearity equations.

6. Template image location identification.

The goal of this operation is to recognize the area in the image where image matching can be done favorably. A subsection of size 100 rows and 100 columns from band3 is selected where maximum gray value difference occurs. This subsection is called a "template image". For deciding the template, a difference image with a mask of $3 \times 3$ is created over band3 and is then tiled to $100 \times 100$. The tile that gives maximum average difference will be considered as the template for matching. Search window locations from bands 2 and 4 are taken around the center of tile identified in band3. The algorithm will eliminate homogeneous regions that are not suitable for image matching, like ocean regions, snow covered areas etc.

7. Resample and generate geocoded products (in the specified resolution, datum and projection) of this small area from all the bands. These template products are generated first to compute the residual offsets between the bands.

8. Sub-pixel matching between these products for computing the finer offsets between band2 and band3 and also between band4 and band3. The matching algorithm makes use of the maximum cross-correlation method, which is applied locally at the template products. The image-based matching is used to determine the row and column translations required to register the bands. With the match points identified, a parabolic surface is fitted over correlation values centered around the matched point to calculate sub-pixel coordinates. This accommodates the unaccounted errors in terrain height, in the imaging geometry model and camera geometry model. While handling full pass data, template image creation and refinement with image matching are done at every 1000 km to account for the across-track parallax due to earth rotation.

9. Offsets (converted into raw space) are added to image coordinates of band2 and band4 computed using the inverse of the rotation matrix.

10. Resample the raw images with new image coordinates to generate products corresponding to the object space grid generated for the region of interest.

Once the geo-aligned product is generated, referring back to its original geometry and sampling is difficult. Firstly, application has to accept many inputs (like projection, resolution, and GCP (optional)) to process and present the data. Apart from the computational load, storage requirements are high when full pass data is handled as a 23 km swath image may diagonally extend to hundreds of kilometers where no data regions are to be left void due to rotation with respect to true north. Secondly the geo-aligned product makes mapping sensitive to the sample scale in which it is written. Thirdly, the adoptability of the geo-aligned product into many applications is not straightforward like comparing the fresh temporal data in the first look after acquisition. Due to these reasons, geo-aligned co-registration is done on an "as needed" basis. Another product with orbit alignment is planned as default mode as it overcomes the above-mentioned limitations.

3.2. Orbit-aligned product generation

In the orbit-aligned frame, the y-axis is aligned to the direction of the satellite. It is always approximately northward with a small alignment angle. This is the default mode of co-registered product generation. In orbit-aligned products, the middle band is untouched and extreme bands are aligned with respect to the middle band, minimizing the resampling artifacts. Thus, the original raw geometry of band3 is preserved. Data-handling aspects are also taken care of. It requires less memory as less padding is there around the edges. The orbit-aligned product is sufficient for most of the upcoming applications in computer-based visualization, data browsing, temporal data analysis etc.

The steps involved in generating orbit-aligned co-registered products are:

1. In-flight camera calibration.
   - The details of in-flight calibration are given in the previous section.
2. Orbit attitude modeling.
   - Description of the sensor model is also given in the previous section.
3. Image to ground transformation corresponding to a regular image grid in band3 with an average height.
4. Extraction of height from a global DEM at the ground coordinates derived through step 3.
5. Repeat step 3 with correct height.
6. Computing the image coordinates corresponding to these ground points on the extreme bands (band2 and band4).
7. Fitting of affine transformation between the images coordinates of band3 and band4 and also between band3 and band2.
8. Automatic identification of area where there exists maximum gray value variation.
9. Resample and generate template products (with identified point as center) ($100 \times 100$ pixels) of band2 and band4 with respect to band3.
10. Compute the offsets between the bands using image matching to sub-pixel level.
11. Refine the image coordinates of band2 and band4 by adding the biases. This will do the fine-tuning of the final product.
12. Resample band2 and band4 images with respect to band3 while band3 will be geometrically raw.

4. Test and evaluation

4.1. Test data

Nine datasets are chosen for the analysis such that different terrain types—plain, moderate, hilly and highly undulating are covered. Images with different look angles are considered to study the combined effect of look angle and terrain undulation on BBR. Also, images with different start pixel location (over the entire length of the detector array) are selected to analyze the precision of the interior orientation parameters. Details like orbit number, look angle, start pixel in full array and the terrain undulation over which the imaging is done are shown in Table 1. The high Himalayan mountain region covered with snow is processed. Clouded regions, that are difficult for BBR using purely image-based methods, are also taken up for the analysis. Data is arranged in the order of the look angle. Data1 and data9 are with extreme oblique viewing geometry. Data2 and data9 are high mountainous regions where heights are around 5000 m viewed with nadir and high-oblique look angles. Data3, data4, data5 and data8 are of plain terrains. Data6 and data7 are moderate terrains. Data7 is 75% clouded region. Data2 is the Himalayan region covered with 75% snow.

4.2. Evaluation procedure

Co-registration procedures explained in Section 3 are implemented in the product generation scheme. Quality assessment of the products is a routine and automatic process. The evaluation module is also a part of the product generation software. Image-based automated matching does evaluation of BBR accuracy of the products. Band3 is taken as reference and the other two bands are evaluated with respect to this. Feature-based image matching where interest points are identified by the Förstner operator is adopted for this purpose. Cloudy and homogeneous areas are avoided from matching by entropy-based area selection. Normalized cross-correlation being the measure of similarity between the bands, points with high confidence (correlation coefficient greater than 0.8) are considered for parabolic surface fitting.
which yields sub-pixel level accuracies. The offsets are computed from the statistics of the match-point data. The numbers of points are very high which raises the confidence in the arrived values.

5. Results and discussion

The band-to-band mis-registration can be characterized by two values called along-track parallax (scan) and across-track parallax (pixel). Along-track parallax is a direct result of the time delay in imaging the same ground point by extreme bands. Across-track parallax is a result of small scale variations between different bands, shift due to look angle, start pixel location within the detector array for multi-spectral imaging, and shift due to earth rotation. A major portion of the across-track parallax between the bands arising due to the start pixel location and focal plane geometry can be pre-estimated during the in-flight calibration. Alignment offset due to view angle, body roll angle etc. corresponding to each imaging event is corrected during product generation. The magnitude of error due to earth rotation is insignificant. But, earth rotation varies with latitude and that variability is important in defining the optimum length of the image for which one set of parameters for image coordinate refinement work will form. When we are handling full pass data of about 3000 km, the refinement with image matching is done at every 1000 km. Correction of along-track parallax is more complex. It is coupled with the view angle of the sensor, terrain undulation and the spacecraft pitch error (total) and spacecraft pitch error during the time difference between the bands. Only a minor portion of the along-track parallax due to the placement of the detectors will get corrected using the in-flight calibrated parameters. A major portion of the along-track offsets will be addressed at the time of product generation using the rigorous sensor model and an external DEM.

All the datasets tabulated in Table 1 are processed for the BBR. The co-registered output products are submitted for evaluation. The accuracies achieved are given in Table 2. The scan shows the errors in the along-track direction and the pixel shows the errors in the across-track direction. Different measures like standard deviation, maximum difference, minimum difference, total number of match points, peak values of the frequency curves etc. are shown in Table 2. Results show that co-registration between the bands to the sub-pixel level is achievable. It is clear from Table 2 that maximum frequency occurs at 0.0 except for data2 and data9 that have highly undulating terrain for which the underlying DEM may not be appropriate, though DEM inclusion has improved BBR accuracy to half a pixel. Thus, achievable accuracy is uniform, irrespective of the look angle and terrain type or even land cover type like snow as shown in Fig. 9. The ge-aligned product undergoes a rotation to point North and analysis as explained in Section 4.2. Both types of products, orbit-aligned and geo-aligned, are generated and tested. As shown in Fig. 11, the orbit-aligned product shows no void pixels and the storage requirement is minimum. This product acts as a reference for any new data for a temporal analysis with minimal processing. The resolution is untouched and thus at any time of requirement the multi-spectral bands can be pulled for its basic spectral-based understanding. Full pass data, which is co-registered and orbit-aligned, is much easier and faster to generate and store. The geo-aligned product undergoes a rotation to point North along with specified projection/datum. This rotation creates a void which occupies a significant portion in the output image data. The resampling slightly alters the original spectral signatures. The terrain induced effect is reduced by the inclusion of the public domain digital elevation model. This is shown in Fig. 12.

In the Himalayan region, inaccuracies in the external DEM girded at coarser interval that may not include the rapid undulation within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel. The geometry-based model can handle the snow bound areas within its grid resolution, can dilute BBR up to half a pixel.
and under continuous cloud coverage. The alignment of spectral bands is perfect as shown in Fig. 13. For this reason, the confidence in the automated co-registration model is raised and it also scores better compared to purely image-based methods in addressing the correspondence precisely. This hybrid model, where rigorous sensor model takes a lead in addressing the band-to-band correspondence is more generic with promising co-registered output.

To confirm the procedural accuracy in the L4 co-registration method, a corresponding L3 multi-spectral data that senses in the same spectral frequencies like L4, of the same day and area is taken up. L3 multi-spectral data acquisition is synchronized and there are no alignment offsets between the bands in the focal plane. This image is submitted for the feature-based image matching.

Finally L4 band-to-band registration accuracies are compared with the values obtained from L3. The order and magnitude are the same. This indicates that the residuals are due to the limitations beyond which two different bands cannot be co-registered to ideal zero offsets. These may vary little from data to data depending on the image content and their corresponding spectral signatures recorded in different bands. The number of points and the statistics of data like minimum, maximum, mean and the spread in the offsets also show a variation due to the same reason.

6. Conclusions

We have developed and implemented a method for automatic co-registration of multiple bands of the L4 camera using...
photogrammetric means and complemented it with an image-based matching technique to remove unaccounted mis-registration residuals. An in-flight geometric calibration of the detector elements in the focal plane is the first pre-requisite for defining the direction and orientation of the imaging ray originating from a pixel and projected onto the correct ground location. Forward or inverse transformation between the coordinate systems connecting the orbit, attitude, focal plane and terrain with accurate time tagging is the second requirement. Thirdly, an image-based matching at a template image gives the remaining mis-registration residuals. This has been tested for many images with high-oblique angles (PSM steering) covering highly undulating terrains. BBR accuracies of the order of less than 0.5 pixels could be achieved in all cases. Implementing a capability of creating both orbit-aligned and geo-aligned products is a fruitful endeavor because the geo-aligned product is expected as the output of value added products generation system like VAPS for large geo-database generation whereas orbit-aligned products are required in applications demanding high speed browsing of full pass data and quick target reporting. The decision to resample by going back to the original raw data when creating the product was a good one, since it avoided the loss in contrast which would have occurred by resampling twice. In closing, we propose that if the focal plane geometry of L4 is to be re-used in any future mission, the staggered timing between the bands is not recommended, especially for agile satellites.

Fig. 10. Frequency curves showing the co-registration accuracy between extreme bands of Liss-4 for data5 (orbit-1933).

Fig. 11. Co-registered products of data2 (orbit-6409). (a) Orbit-aligned (b) Geo-aligned. The small rectangle shows the overview and the highlighted portion is shown in the original scale.

Fig. 12. Effect of altitude error on band-to-band registration (data2). Without GTOPO, reference height for all the points is taken as zero.
Fig. 13. Orbit-aligned product of data7 (orbit-2488) with 75% cloud cover.

Acknowledgements

The authors gratefully acknowledge Dr. R Krishnan, Director, IIST and R Ramachandran, Director, CRSA for their encouragement and support for this work.

References


This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier’s archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright
Pre-processing considerations of IRS-P6 LISS-4 imagery

P.V. Radhadevi*, S.S. Solanki, R. Ramchandran, R. Krishnan
Advanced Data Processing Research Institute, Department of Space, Manovikasnagar P.O., Secunderabad 500009, India
Received 1 June 2007; accepted 23 November 2007

Abstract

Wide image swath with a high geometric resolution is required for photogrammetric applications. Both demands can be satisfied using staggered line arrays. Different bands of IRS-P6 LISS-4 sensor use staggered arrays for imaging. This paper describes a method for computing the offset for geometric alignment of odd and even lines of the staggered array of IRS-P6 LISS-4 imagery. The odd and even pixel rows are separated by 35 \( \mu \text{m} \) (equal to 5 pixels) in the focal plane in the along-track direction. Slightly different viewing angles of both lines of a staggered array can result in a variable sampling pattern on the ground because of the attitude fluctuations, satellite movement, terrain topography, PSM steering and small variations in the angular placement of the CCD lines (from the pre-launch values) in the focal plane. Non-accounting of this variable sampling value during the video data alignment will introduce deterioration of image quality and geometric discontinuity of features. The stagger parameters can be computed by the reconstruction of the viewing geometry with a calibrated camera geometry model and a public domain DEM. The impact of the line separation in the focal plane during imaging for different viewing configurations and terrain heights are studied and reported in this paper. Computed values from the model are in good agreement with what is observed in the raw image for different view angles. The results verify the model and are representative of the stability of the platform.

© 2008 Elsevier B.V. All rights reserved.

Keywords: Collinearity equation; Payload steering mechanism (PSM); Geo-referencing; Staggered array

1. Introduction

Technology developments provide new solutions for high resolution image acquisition with wide swath. IRS-P6 is envisaged as a continuation of IRS-1C/1D with enhanced capabilities. It has three sensors on-board namely linear imaging and self-scanning sensor (LISS-3), advanced wide field sensor (AWiFS) and high resolution multi-spectral camera LISS-4 along with an on-board solid state recorder (OBSSR). PAN camera of IRS-1C/1D consisted of three CCD arrays each (each having 4096 sensor elements) with 23.5 km swath and an overlap between them. There is a small rotation and translation between the CCD arrays, which are having slightly different focal lengths. Therefore, the combined adjustment of all CCDs of IRS-1C/1D (to have wide swath) is complex (Radhadevi, 1999; Jacobsen, 1998). The payload design of LISS-4 camera of IRS-P6 is such that the odd and even detectors are staggered by five scan lines (35 \( \mu \text{m} \)) in the focal plane. However, this separation in the focal plane does not translate into a constant stagger in the image data.

Theoretically, for a staggered array, resolution is as good as a non-staggered array, but the radiometric quality should be higher because the cross talk between the pixels will be reduced, as the neighboring pixel is not imaging at the same instance. Improvement of spatial resolution with staggered arrays as used in the airborne optical sensor ADS40 is explained by Reulke...
et al. (2004). In practice, slightly different viewing angles of both lines of a staggered array can result in deterioration of image quality due to attitude fluctuations between the CCD lines, terrain undulation, off-nadir viewing, and the placement of the CCD lines in the focal plane. The result is a variable sampling pattern on ground. The image data of both staggered lines can be combined, using a one-dimensional resampling, accounting for all these effects. The staggering parameters can be computed using a calibrated camera geometry model, an orbit attitude model and a public domain DEM. The model is designed to provide an accurate method of transforming points from image space to object space and vice versa.

This paper describes the method for computing the offset for geometric alignment of odd and even lines of the staggered array of IRS-P6 LISS-4 imagery. The algorithm is purely based on the viewing geometry of the satellite, combining the principles of photogrammetric collinearity equations. The impact of the line separation between the odd and even arrays in the focal plane during imaging for different viewing configurations and terrain heights are studied and reported in this paper.

2. Camera system of LISS-4

Multi-spectral imaging and high resolution are the key features of LISS-4 camera. This camera can be operated in two modes: wide mono and multi-spectral. In the multi-spectral mode, data is collected in three spectral bands. The sensor provides data corresponding to pre-selected 4200 contiguous pixels covering 23.9 km swath. The 4200 detectors can be selected anywhere within the 12,000 pixels by commanding the start pixel number using an electronic scanning scheme. In mono mode, the data of all 12,000 pixels of any one selected band, corresponding to a swath of 70 km, can be achieved. The LISS-4 camera has the additional feature of off-nadir viewing capability by tilting the camera by ±26°. This way it can provide a revisit of 5 days. LISS-4 camera is realized using the three mirror reflective telescope optics and 12,000 pixels linear array CCDs with each pixel of size 7 μm. The three bands are separated in the along-track direction and the projection of this separation on ground translates into a distance of 14.2 km between band 2 and band 4 image lines. While band 3 is looking nadir, band 2 will be looking ahead and band 4 will be looking behind in the direction of velocity vector. Significant processing is required for band registration. The CCDs employed in LISS-4 camera are of Thomson make THX31543A. Each CCD has 12,000 pixels, separated in to 6000 each of odd and even pixels. These odd and even pixel rows are separated by 35 μm (equal to 5 pixels). To avoid any gap in the image due to this separation, coupled with the earth rotation, the spacecraft is given a rate about Yaw axis. The focal plane geometry of LISS-4 camera is shown in Figs. 1 and 2. More details about the satellite are available in IRS-P6 Data User’s Handbook (see reference).

![Fig. 1. Ground projection of different bands of Liss-4.](image-url)
3. Stagger computation methodology

As illustrated in Fig. 1, the optical detectors on the odd and even arrays are not arranged in a simple matrix of rows and columns. Slightly different viewing angles of both lines of a staggered array can result in a variable sampling pattern on the ground. Therefore, video alignment by sliding the images from the two arrays (by five lines) is not feasible. The stagger parameters are computed by the reconstruction of the viewing geometry with a calibrated camera geometry model. Reconstruction of the viewing geometry includes the exterior and interior orientations of the sensor. The model relates 3D object point position to their corresponding 2D image positions by describing the geometric relationship between the image space and object space. The algorithm for orbit attitude model, which combines the principles of viewing geometry of the satellite with photogrammetric collinearity equations, was originally developed for SPOT-1 and IRS-1C/D (Radhadevi and Ramachandran, 1994; Radhadevi et al., 1998; Radhadevi, 1999). This model has been adapted to suit the LISS-4 camera characteristics of IRS-P6.

The first step in computing stagger through a viewing geometry model is to fit the initial trajectory. LISS-4 data in Level-0 consists of signal in framed raw expanded data (FRED) format and metadata in ancillary data information file (ADIF). Level-0 data is radiometrically and geometrically raw as it is received from the satellite. The data from odd and even arrays are transmitted in two channels ‘I’ and ‘Q’. Channel separation is to be done first. Interleaved pixels are then filled with corresponding pixel from the other channel to form the image involving a vertical resampling. This is called stagger correction. Stagger correction and radiometric correction are part of the pre-processing, which will generate image in Level-1A. The information about of the satellite ephemeris, attitude, look angle, sidereal angle, start pixel, time etc. are extracted from the ADIF. The orbit parameters in the collinearity equations are position \((X_p, Y_p, Z_p)\), velocity \((V_x, V_y, V_z)\) and attitude parameters are roll \((\omega)\), pitch \((\phi)\), and yaw \((\kappa)\). Satellite position and orientation are given at every 125 ms. That means only one set of values will be given for approximately 142 lines. Therefore, attitude fluctuations within the interval of 125 ms will not be reflected in the navigation data but will be visible in the image. Attitude data in terms of quaternion are converted into Euler angles. Fitting of the given telemetry values are done for predicting at required time interval, i.e. to make it continuous from discrete values given. The initial values of all the parameters are derived by least squares adjustment to the ephemeris data using a generalized polynomial model.

Second step in stagger computation is the projection of detectors in the odd array on to ground. A direct geo-referencing from the fitted trajectory is done using the rigorous sensor model. Accurate calculation of the exterior orientation parameters with GCPs is not required for stagger computation. Instead, the line of sight vector of each detector in the two arrays in relation to the payload is addressed to compute the relative shift between them. The refined detector placements and camera parameters after in-flight calibration are incorporated in to the model to define the line of sight vector. Now, the first pixel in the odd array is projected on to the ground through image to ground transformation. Height of the point should be an input to compute the ground co-ordinates. The accuracy of the DEM is not very critical in the computation of stagger because we are determining the relative shift between the odd and even pixels and not the absolute accuracy of the line of sight vector. The point where this ray intersects on the ground is re-projected in to the even array (in image space) through ground to image transformation. The offset is computed. Using this offset, a one-dimensional resampling and joining of odd and even arrays are done. To construct a scan line from staggered pixels, we have adopted cubic convolution with four points span for vertical resampling, whose kernel is...
given by
\[
K(x) = (a + 2)|x|^3 - (a + 3)|x|^2 + 1, \quad |x| < 1
= a|x|^3 - 5a|x|^2 + 8a|x| - 4a, \quad 1 < |x| < 2
\]
where parameter \(a' = -1\)

3.1. Mathematical model

Collinearity equations express the fundamental relationship that the perspective centre, image point and object point lies on the straight line, i.e.

\[
\begin{pmatrix}
-X_s \\
-Y_s \\
end{pmatrix} = dM \begin{pmatrix}
X - X_p \\
Y - Y_p \\
Z - Z_p
end{pmatrix}
\]

where \((f, -x_s, -y_s)\) are the image coordinates, \((X, Y, Z)\) are the coordinates of the object point and \((X_p, Y_p, Z_p)\) is the perspective centre \(d\) is the scale factor and \(M\) is the rotation matrix, i.e.

\[
\begin{pmatrix}
-X_s \\
-Y_s \\
end{pmatrix} = d \begin{pmatrix}
m_{00} & m_{01} & m_{02} \\
m_{10} & m_{11} & m_{12} \\
m_{20} & m_{21} & m_{22}
end{pmatrix} \begin{pmatrix}
X - X_p \\
Y - Y_p \\
Z - Z_p
end{pmatrix}.
\]

After rearrangement, Eq. (2) can be written as two equations.

\[
f_1 = (fm_10 + x_m00)(X - X_p) = 0
\]

\[
f_2 = (fm_20 + y_m00)(X - X_p) = 0
\]

where \(m_{00}, m_{11}, m_{22}\), etc. The rotation matrix \(M = Q_{OB}, Q_{OB}, Q_{IN}, Q_{PC}\), where \(Q_{PC}\) is the CCD to payload transformation matrix, \(Q_{BP}\) the payload to body transformation matrix, \(Q_{OB}\) the body to orbit matrix, \(Q_{OBO}\) the orbit to inertial matrix and \(Q_{OB1}\) is the inertial ECI to ECEF matrix.

CCD to payload transformation matrix is included into the rotation matrix. Thus, a pixel in any array (odd or even) of any band of any camera can be projected onto earth through a series of transformations and re-projected back to any other camera (band/array) through a reverse series of transformations using the parameters of the corresponding camera (band/array) in \(Q_{PC}\) matrix.

4. Factors affecting stagger

Various factors affecting the stagger parameter are analyzed. Pope et al. (2004) has explained the LANL (Los Angles National Laboratory) experiences with Coregistration of MT1 images. Theiler et al. (2002) has also done a study for estimating the effect of various errors for MTI spectral bands. The perfect alignment of odd and even arrays requires accurate sensor model connecting the satellite orbit, attitude and the target location. Approximations of this information will reflect as image quality deterioration.

 Orbit determination accuracy of IRS-P6 in GPS mode is about 10 m and attitude determination accuracy with star sensor in loop is about 202 m. Due to these uncertainties, the location accuracy of system level product is expected to be 286 m. Analysis of the attitude behaviour of many datasets reveals that high frequency jitters or disturbances are not present even with high look angles (PSM steering) of LISS-4 camera and thus giving a smooth trajectory. As the satellite is not agile and is not changing its view direction while imaging, the error due to the uncertainties in the precise knowledge of position, velocity and attitude will not affect the stagger value and will manifest itself only as a bias within the small duration of imaging of odd and even arrays. The relative difference between the arrays is computed through the model. Accurate exterior orientation parameters are not required for this purpose. Therefore, the main factors affecting the stagger are the angles of deflection and combined effect of velocity and attitude fluctuations. Terrain effects are negligible.

4.1. Angles of deflection

Angle of view of the camera optical system of LISS-4 is adjustable within ±26°. During imaging, the view is fixed. Also, the angles of view of individual pixels of odd and even CCD lines are obtained from the calibrated camera geometry. Deflection of the optical system from nadir position results in a change of trace of these angles on the ground area, so they change the dimensions of the ground pixels. It has been shown in \(\text{Fig. 3.}\) If \(P_x\) and \(P_y\) are pixel sizes at nadir angle, pixel sizes at

![Diagram showing pixel size on ground as function of deflection angles.](image-url)
deflection angles $\psi_x$ and $\psi_y$ are

$P_{x1} = \frac{P_x}{(\cos^2\psi_x \times \cos\psi_y)}$ and $P_{y1} = \frac{P_y}{(\cos\psi_x \times \cos^2\psi_y)}$.

Here $\psi_x$ is the tilt of the camera in PSM steering and $\psi_y$ is the placement angle of the odd and even array in the along-track direction with respect to the payload cube normal, which is constant. With high oblique angles ($\pm26^\circ$), $P_{x1}$ and $P_{y1}$ can be 7.3 and 6.5 m, respectively. Increase in $P_{x1}$ will increase the ground swath. Along-track resolution of 6.5 m will have a direct impact on stagger correction (Table 1).

### Table 1

<table>
<thead>
<tr>
<th>Orbit (ss/fp)</th>
<th>Date</th>
<th>Look angle</th>
<th>Start pixel</th>
<th>Height range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8,128 (ss)</td>
<td>11-05-2005</td>
<td>-17.4877</td>
<td>3797</td>
<td>200–250</td>
</tr>
<tr>
<td>5,230 (ss)</td>
<td>19-10-2004</td>
<td>25.5487</td>
<td>3765</td>
<td>1400–2100</td>
</tr>
<tr>
<td>3,127 (ss)</td>
<td>24-05-2004</td>
<td>2.3699</td>
<td>6797</td>
<td>1200–2000</td>
</tr>
<tr>
<td>4,704 (ss)</td>
<td>12-09-2004</td>
<td>-15.4719</td>
<td>93</td>
<td>4300–5600</td>
</tr>
<tr>
<td>1,933 (ss)</td>
<td>01-03-2004</td>
<td>2.1839</td>
<td>93</td>
<td>50–150</td>
</tr>
<tr>
<td>7,048 (ss)</td>
<td>24-02-2005</td>
<td>5.3736</td>
<td>3925</td>
<td>50–150</td>
</tr>
<tr>
<td>6,409 (ss)</td>
<td>10-01-2005</td>
<td>-3.3866</td>
<td>4309</td>
<td>1900–2500</td>
</tr>
<tr>
<td>5,912 (ss)</td>
<td>06-12-2004</td>
<td>18.8063</td>
<td>3765</td>
<td>3400–5600</td>
</tr>
<tr>
<td>5,613 (ss)</td>
<td>15-11-2004</td>
<td>-23.2274</td>
<td>4021</td>
<td>290–330</td>
</tr>
<tr>
<td>2,118 (ss)</td>
<td>14-03-2004</td>
<td>2.1664</td>
<td>93</td>
<td>50–150</td>
</tr>
<tr>
<td>10,785 (fp)</td>
<td>14-11-2005</td>
<td>0.7729</td>
<td>2877</td>
<td>50–2000</td>
</tr>
<tr>
<td>12,859 (fp)</td>
<td>09-04-2006</td>
<td>2.418</td>
<td>61</td>
<td>400–4600</td>
</tr>
<tr>
<td>12,448 (fp)</td>
<td>11-03-2006</td>
<td>7.11</td>
<td>573</td>
<td>50–4500</td>
</tr>
<tr>
<td>10,785 (fp)</td>
<td>14-11-2005</td>
<td>0.7729</td>
<td>2877</td>
<td>50–2000</td>
</tr>
<tr>
<td>12,859 (fp)</td>
<td>09-04-2006</td>
<td>2.418</td>
<td>61</td>
<td>400–4600</td>
</tr>
<tr>
<td>12,448 (fp)</td>
<td>11-03-2006</td>
<td>7.11</td>
<td>573</td>
<td>50–4500</td>
</tr>
</tbody>
</table>

ss: sub-scene; fp: fullpass.

Fig. 4. Along-track offsets computed between odd and even arrays as a function of tilt angle (at 6000th pixel).

Fig. 5. Offset between odd and even arrays along the length of the array with various tilt angles.

Fig. 6. Offset between the odd and even array for the entire pass (tilt angle 0.77).

### 4.2. Velocity/attitude effects

Let $\Delta \theta$ is the angle between odd and even arrays in the focal plane (o is the odd array and e is the even array). If the spacecraft altitude above the ground is $h$, then it will travel a distance $h\Delta \theta$ before the o and e line up on the ground. If the effective velocity of the spacecraft is $v$, the time for the spacecraft to do this is $\Delta t = h\Delta \theta / v$ which will be equal to five times the integration time. However, if due to a miscalculation, the velocity is assumed to be $v$ but is actually $v + \Delta v$, then lining up the arrays using the $\Delta t$ delay will lead to an error (in meters on ground) of $\Delta v \Delta t = h\Delta \theta / v$. For IRS-P6, $h \sim 820$ km, angle between odd and even arrays $\Delta \theta \sim 0.002^\circ$ ($3.4906e-5$ radian) and $v \sim 7$ km/s. For instance if $\Delta v \sim 20$ m/s, then the along-track shift would be 0.07 pixels. Attitude fluctuations will also manifest as velocity error.
5. Results and discussion

Fourteen datasets with different view angles and start pixels are selected for the analysis. Three of them are full pass data with each one covering approximately 2000 km. A set of well distributed points in the entire length of the odd array image are projected using the line of sight vector computed from the viewing geometry model and a global DEM. The intersected points on the earth ellipsoid are re-projected onto the even array image. As seen in Fig. 1, odd and even array configuration is similar for bands 2 and 4, but reverse for band 3. The difference in the image coordinates between the odd array and even array are plotted. Fig. 4 shows stagger values at the centre pixel for different view angles. It is obvious that five lines separation in the focal plane between the arrays are reflected as variable sampling values for different view angles. It ranges from 5.6 lines for oblique viewing images (±26°) to 5 lines for nadir looking images. Offset values for the entire length of the detector array are plotted in Fig. 5 for different view angles. Stagger values for oblique tilts of PSM with negative and positive angles show exactly opposite behaviour. It increases from 5.5 to 5.7 lines along the length of the array for 25.55° and decreases from 5.7 to 5.5 lines for −24.27°. For vertical images (<7°), stagger reflects as five lines over the entire length of the array.

All bands show same behaviour in terms of magnitude and orientation. Across-track pixel offset between odd and even arrays is of the order 0.01–0.02 pixels and therefore negligible. Stagger pattern along the full length

Fig. 7. Feature from band 3 with stagger correction (a) aligned by shifting of constant integer value (5 lines), (b) aligned by resampling with variable subpixel value (computed), (image tilt angle: 22.52°).

Fig. 8. Feature from band 3 with stagger correction (a) aligned by shifting with constant integer value (5 lines), (b) aligned by resampling with variable subpixel value (computed), (image tilt angle: 1.75°).
of about 2000 km long image is studied. The value is not changing beyond 0.01 pixels over 500,000 lines. This is shown in Fig. 6. Figs. 7 and 8 show the computed stagger parameters applied on to a highly tilted image and a nadir image respectively. From Fig. 7, it is explicit that for high look angles we should do a one-dimensional resampling rather than a sliding of images with a constant integer stagger value. The stagger values observed in the images are exactly in agreement with the computed offsets.

6. Conclusions

Important conclusions drawn from the results are the following:

1. Stagger is neither a constant nor an integer for high oblique viewing images. Therefore, a one-dimensional resampling, taking into account of the variable sampling pattern at different pixels of the array is required to get the full length of the 12,000 detectors without any geometric discontinuity and quality deterioration. Otherwise, it will have impact on the radiometric quality. If left uncorrected, these artefacts will be mixed up with misregistration errors between the bands for which co-registration is another challenge.

2. For nadir looking images, the stagger is a constant. We can avoid the resampling in pre-processing of images with look angles less than 7°. Image from one detector array can be slide by 5 lines to align with the image from the other array.

3. Analysis over 2000 km long strip reveals that stagger is not changing for the entire length of the full pass image and is more or less a constant. This shows the stability of the platform.

The computed offsets are in exact agreement with what is seen in the image data. This shows the accuracy and stability of the used viewing geometry model connecting the orbit, attitude, camera and the terrain. The results are representative of the stability of the platform and show the potential of IRS-P6 for accurate geo-tagging of images.

Acknowledgements

The authors gratefully acknowledge Dr. A.S. Kiran Kumar, Group Director, EOSG/SEDA, SAC, for providing the payload geometric parameters of IRS-P6. Additional thanks are due to all colleagues of Advanced Techniques Group, ADRIN for their support for this work.

References

IN-FLIGHT GEOMETRIC CALIBRATION OF DIFFERENT CAMERAS OF IRS-P6 USING A PHYSICAL SENSOR MODEL

P. V. RADHADEVI (adrin_radhadevi@yahoo.co.in)
S. S. SOLANKI (solanki@adrin.res.in)
Advanced Data Processing Research Institute, Department of Space, Hyderabad, India

Abstract

The IRS-P6 satellite has multi-resolution and multispectral capabilities on a single platform. A continuous and autonomous co-registration and geolocation of image data from different sensors with widely varying view angles and resolution is one of the unique challenges of IRS-P6 data processing. This requires in-flight geometric calibration of the cameras. In-flight calibration includes alignment calibration of individual sensors and calibration between the sensors. A method for in-flight geometric calibration and quality assessment of IRS-P6 images is presented in this paper. The objectives of this study are to ensure the best absolute and relative location accuracy of different cameras, and the same location performance with payload steering and co-registration of multiple bands. This is done using a viewing geometry model, given ephemeris and attitude data, precise camera geometry and datum transformation. In the model, the forward and reverse transformations between the coordinate systems associated with the focal plane, payload, body, orbit and ground are rigorously and explicitly defined. System-level tests using comparisons to ground check points have validated the operational geolocation accuracy performance and the stability of the calibration parameters.

KEYWORDS: band-to-band registration, in-flight calibration, inter-camera alignment, payload steering alignment, sensor model, staggered array

INTRODUCTION

IN-FLIGHT CALIBRATION is important for satellite sensors because, during the launch, the environmental conditions change rapidly and drastically and this usually causes changes in the internal sensor geometry that is determined in a pre-launch calibration. The mathematical model used for georeferencing should respect the current geometry. In recent years, a large amount of research has been devoted to the in-flight calibration, geometric rectification and quality assessment methods that are necessary for both efficient utilisation of high-resolution image data and full exploitation of the highly accurate ephemeris and attitude data from the on-board GPS and star sensors. In-flight calibration of the sensor is a prerequisite for direct georeferencing. The accuracy of the parameters computed by in-flight calibration is crucial for
overlaying the data from multiple sensors with existing data-sets or maps and using them for evaluations such as change detection and map updating.

Pre-flight and in-flight geometric calibration of SPOT 5 high-resolution geometric and stereoscopic images (HRG and HRS, respectively) has been studied by Breton et al. (2002). Mulawa (2004) explains a method for the on-orbit geometric calibration of the OrbView-3 high-resolution sensors. In-flight calibration of the sensor is a prerequisite for direct georeferencing. This idea is explained by Honkavaara (2004). Baltcavias et al. (2001) report on a radiometric and geometric evaluation of IKONOS Geo images. Geometric aspects of the handling of space images based on the perspective imaging configuration have been given by Jacobsen (2002), who also explained the issues and method for in-flight and on-orbit calibration (Jacobsen, 2004). Jovanovic (2002) explains a method for automatic quality assessment and in-flight calibration of multi-angle imaging spectroradiometer (MISR) data. Pope et al. (2003) report the experience of Los Alamos National Laboratory (LANL) with co-registration of imagery from the multispectral thermal imager (MTI). They explain the direct georeferencing method to generate orbit-aligned or geo-aligned co-registered products from different bands. Theiler et al. (2002) explain the method of co-registration of MTI imagery using photogrammetric means. The staggered array configuration of the ADS40 airborne digital sensor and the improvement of spatial resolution due to the staggering have been studied by Reulke et al. (2004).

A method for in-flight geometric calibration and quality assessment of IRS-P6 images is presented in this paper. The objectives of this study are to ensure the best location performance for all sensors and to ensure the same relative location accuracy. This is in order to obtain the same location performance with different viewing angles of the “linear imaging and self-scanning” LISS-4 camera, as well as continuous and autonomous co-registration of the multiple bands, alignment of the staggered arrays and to ensure continuity between images from the two “advanced wide field sensors” (AWIFS-A and AWIFS-B).

In-flight geometric calibration operations are not part of the standard processing within the authors’ organisation. Instead, the outputs of in-flight calibration are used as inputs to georectification processing to reduce the processing load and to produce best possible geolocated and co-registered products from multiple cameras. Taking advantage of the same-orbit acquisition, calibration of different cameras can be achieved with rigorous geometric reconstruction of the sensor orientation. Relative orientation of cameras with respect to a nadir-looking camera (with high resolution) is performed. This is based on an extraction of tie points across the systematic products from different cameras and on evaluation of co-registration discrepancies relative to the nadir product. The accurate matching and tie point generation allows the detection and quantification of errors in the interior orientation as well as in the alignment of the cameras, caused by changes in the relative position of the CCDs. This way, a geometric in-flight calibration can be carried out without the need for testfields or signalised points. To start with, a brief review of the improvements of the IRS-P6 satellite compared to IRS-1C/1D will be presented.

IRS-P6 OVERVIEW

IRS-P6 is envisaged as a continuation of IRS-1C/1D with enhanced capabilities. Information given recently by Nagasubramanian et al. (2007) in connection with the rational function model used for sensor orientation will be repeated here in greater detail to ensure completeness of the present explanation of in-flight geometric calibration as a whole. This satellite provides remote sensing data services on an operational basis for integrated natural resource management in continuation with the services of IRS-1D. IRS-P6 has multi-resolution
and multispectral capabilities on the one platform. It has three sensors on board, namely, the linear imaging and self-scanning sensor 3 (LISS-3 (L3)), the advanced wide field sensor (AWF) and the high-resolution multispectral camera LISS-4 (L4), along with an on-board solid-state recorder (OBSSR). The average ground sample distances (GSDs) of L4, L3 and AWF at nadir are 5.8, 23.5 and 56 m, respectively. The scene coverage for the different cameras is shown in Fig. 1. L4 operates in three spectral bands of the visible region, and L3 and AWF record imagery in four spectral bands (three visible near infrared (VNIR) and one short-wave infrared (SWIR)). AWF has two fixed cameras tilted by ±12° with respect to the nadir in order to obtain a wide swath.

The L4 camera of IRS-P6 has the same resolution as the PAN camera of IRS-1C/1D. The orbit and attitude determination accuracy of IRS-P6 is improved from IRS-1C/1D, thanks to the precision of the on-board pointing devices. As a result, the location accuracy of system-level products is improved from about 2 km to 286 m. The PAN camera of IRS-1C/1D consists of three overlapping CCD arrays of 4096 sensor elements each, providing a 23.5 km swath. There is a small rotation and translation between the CCD arrays, which have slightly different focal lengths. Therefore, the combined adjustment of all CCDs of IRS-1C/1D (to achieve the wide swath) is complex (Jacobsen, 1998; Radhadevi, 1999).

Band 5 (SWIR) of L3 and AWF uses a staggered array with a two-line shift between the odd and even arrays in the focal plane. Each band of the L4 camera of IRS-P6 also uses staggered arrays of 12 000 detectors, separated into 6000 each of odd and even 7 μm pixels. These odd and even pixel rows are separated by 35 μm (equal to 5 lines) in the focal plane. Fig. 2 shows the ground projection of different bands and arrays of L4. Three bands are separated in the along-track direction (with a view angle difference of 0.9°) and the projection of this separation on the ground translates into a distance of 14.2 km between image lines of

---

**Fig. 1.** Scene coverage of different sensors of IRS-P6.
band 2 and band 4 (extreme bands). The L4 camera can be operated in two modes: wide mono and multispectral. In the multispectral mode (L4MX), data is collected in three spectral bands. The sensor provides data corresponding to 4200 pre-selected contiguous pixel segments covering a 23.9 km swath. These 4200 pixels can be set anywhere within the 12,000 pixels by commanding the start pixel number using an electronic scanning scheme. In mono mode, the data of the full 12,000 pixels of any one selected band, corresponding to a swath of 70 km, can be recorded. The L4 camera has the additional feature of off-nadir viewing, by tilting the camera by ±26°. In this way, it can provide a revisit time of 5 days. More details about the satellite are available in the Indian National Remote Sensing Agency’s IRS-P6 Data User’s Handbook (NRSA, 2003).

**SENSOR MODEL**

A sensor model reconstructs the viewing geometry. Reconstruction of the viewing geometry includes the exterior and interior orientations of the sensor. The exterior orientation describes the location of the projection centre and altitude of the bundle of rays, while the geometry of the bundle of rays will be reconstructed by the measured image position and interior orientation. CCD-array satellite images will have one set of exterior orientation parameters for each image line and the interior orientation is restricted to this line. Therefore, for satellite image sensors, the reconstruction of the imaging geometry involves a mixing of the interior and exterior orientations. The algorithm for the orbit–attitude model, which combines the principles of the viewing geometry of the satellite with photogrammetric collinearity equations, was originally developed for SPOT 1 and IRS-1C/1D (Radhadevi and Ramachandran, 1994; Radhadevi et al., 1998). This model has been adapted to suit the camera characteristics of IRS-P6, as already described by Nagasubramanian et al. (2007) in somewhat less detail in connection with the rational function model used for sensor orientation.
Level-0 data of IRS-P6 consists of a signal in “framed raw expanded data” (FRED) format with metadata in an ancillary data information file (ADIF). Stagger correction (between the odd and even detectors) and radiometric correction are part of the pre-processing, which will generate a Level-1A image. The following details are extracted from the ADIF for modelling the viewing geometry of the sensor.

1. Satellite ephemeris data containing the position and velocity at every 125 ms, in an earth-centred inertial (ECI) reference frame.
2. Data used for time synchronisation; for example, sweep start time of each band, ephemeris start time and attitude start time.
3. Attitude data in terms of quaternions (given at every 125 ms), measured by gyroscopes and star sensors.
4. Tilt angle of the camera for L4, due to the payload steering mechanism (PSM).
5. Sidereal angle given for the full pass at every 125 ms. This is required to convert from the ECI system to an “earth-centred earth-fixed” (ECEF) system. These coordinate systems are shown in Fig. 3.

The given quaternions are converted into Euler angles and a smoothing of these angles is required before the actual adjustment because discreteness in the angles caused by direct

---

**Fig. 3.** Series of transformations to convert a pixel to ground coordinates.
interpolation of the attitude data will result in a misregistration error between the bands. Therefore, a polynomial fitting is carried out for the given telemetry data. The initial values of all the parameters are derived by least squares adjustment from the ephemeris data using a generalised polynomial model. The position, velocity and attitude angles are expressed as functions of time \( t \):

\[
q = q_0 + q_1 t + \ldots + q_n t^n.
\]  

Here, \( t \) is the scan time and \( q \) corresponds to attitude \((\omega, \phi, \kappa)\), position \((X_p, Y_p, Z_p)\) and velocity \((V_x, V_y, V_z)\). The order \( n \) of the polynomial can be set. The coefficients of the polynomials for position, velocity, sidereal angle and attitude are computed. After fitting the least squares polynomial as a function of time for the different parameters of orbit and attitude, a file is generated containing the coefficients of position, velocity, sidereal angle and attitudes along with the scene and ephemeris start times. These parameters at a particular time are connected to the corresponding ground and image coordinates through the collinearity equations. Thus, if the initial trajectory is fitted, image-to-ground and ground-to-image transformation can be performed using the collinearity condition equations.

Collinearity equations express the fundamental relationship that the perspective centre, image point and object point lie on a straight line:

\[
\begin{pmatrix}
    f \\
    -x_i \\
    -y_i
\end{pmatrix}
= d M
\begin{pmatrix}
    X - X_p \\
    Y - Y_p \\
    Z - Z_p
\end{pmatrix}.
\]

Here, \((f, -x_i, -y_i)\) are the image coordinates with respect to the defined body and orbit coordinate systems, \((X, Y, Z)\) are the coordinates of the object point and \((X_p, Y_p, Z_p)\) are the coordinates of the perspective centre. Also, \(d\) is the scale factor and \(M\) is the orthogonal rotation matrix to transform from the geocentric to sensor coordinate system. Proper definition of reference systems is very important in a sensor model. Different coordinate systems that are to be considered are related to the sensor, payload, orbit, body and ground, hence the rotation matrix

\[
M = (Q_{GI} Q_{IO} Q_{OB} Q_{BP} Q_{PC}).
\]

Different components of the rotation matrix can be expanded as follows: \(Q_{PC}\) is the CCD-to-payload transformation matrix that is a function of the roll and pitch bias angles of the middle detector with respect to the payload cube normal. This transformation will relate the individual detectors to the payload. Roll and pitch angles of the middle detector of each CCD, available in the pre-launch camera calibration data, are modified after the in-flight calibration.

\(Q_{BP}\) is the payload-to-body transformation matrix. The basic scan model is a line-of-sight vector from the detector in the focal plane, through the payload, body and orbit to the ground point. This vector is orthogonal to the platform roll axis. A slight deviation from this orthogonality, which gives rise to residuals, is taken into account through the camera-to-body alignment matrix computed during in-flight calibration. \(Q_{BP}\) is a function of these offsets.

\(Q_{OB}\) is the body-to-orbit matrix, which is a function of the roll, pitch and yaw angles. The Euler angles with respect to the body frame are not given explicitly. They are computed from the given quaternion.
\( Q_{IO} \) is the orbit-to-inertial transformation matrix. This rotation will convert the position of the pixel in the orbit coordinate system to ground coordinates. This matrix is a function of the position and velocity of the satellite.

Finally, \( Q_{GI} \) is the ECI to ECEF transformation matrix, which is a function of the sidereal angle.

Through the rotation matrix \( M \), any pixel in any band of any camera can be projected onto the ground, and through the inverse rotation matrix this ground location can be reprojected to any other band or camera by using the corresponding parameters in \( Q_{PC} \). Each array of a multispectral band represents a separate image for calibration purposes. The series of transformations a pixel undergoes before it is projected onto the ground is shown in Fig. 3.

**In-Flight Geometric Calibration**

Pre-flight calibrated parameters can undergo some changes when the camera is mounted on the spacecraft and launched into orbit. The causes for this are launch shock, loss of moisture due to vacuum and gravity release. Generally, an initial geometric calibration during the satellite commissioning phase and periodic geometric calibrations thereafter are performed. Effects of certain parameters cannot be measured explicitly. Instead, a resulting total effect will be measured and assigned only to the selected parameters. This is called in-flight calibration. So, the in-flight calibrated parameters may not facilitate the best characterisation of the individual parameters of the camera, but they will provide the most accurate total pointing vector.

Jovanovic (2002) categorises the errors affecting the georectification and co-registration accuracy into the following three groups:

(i) static pointing errors;
(ii) dynamic pointing errors; and
(iii) errors associated with the topography of the projection surface.

The topography errors can be accounted for by including a digital elevation model (DEM) during the georectification. In-flight calibration is designed to take into account static pointing errors. The model consists of a set of parameters used in a mathematical expression that gives the pointing direction of an arbitrary pixel to the spacecraft attitude frame of reference. These parameters represent the geometry of the camera system and account for distortions from an ideal optical system. The errors due to slight variations in these parameters are static in nature. In order to deal with dynamic errors due to high oblique viewing and the satellite attitude variations during a pass, a differential correction of the orbit and attitude parameters with the help of ground control points (GCPs) needs to be incorporated into the adjustment model.

Initial interior orientation parameters of IRS-P6 were determined by pre-launch laboratory measurements. Refining the pre-launch sensor alignment knowledge is critical to ensuring that products meeting geodetic accuracy specifications are produced. The biases are included in the camera geometry to assess the absolute accuracy. An important aspect of this assessment is the help provided in deciding which parameters of the geometry of the camera most probably need adjustment. A selection of a subset of parameters is recommended in order to avoid cross-correlation effects and to increase redundancy and the overall robustness of the least squares estimation. In-flight calibration of multiple sensors of IRS-P6 is achieved by proceeding through a series of steps. They are (1) individual sensor alignment calibration, (2) inter-camera alignment calibration and (3) focal plane calibration. The focal plane calibration includes effective focal length computation, band-to-band registration and
alignment of staggered arrays. Each of these calibration methods is discussed further in the following sections.

**Test Details**

The in-flight calibration of different cameras of IRS-P6 is performed using conjugate points and control/check points from 15 data-sets, the details of which are given in Table I. The data selection criteria were the following:

1. The start pixel location of the L4 images should vary over the entire length of the detector array. If any scale error exists in the across-track direction, it can be analysed using different data-sets with varying start pixels.
2. L4 images with different look angles are needed to analyse focal plane distortion, scale variation and the effect of stagger during payload steering.
3. Nadir-looking images of flat terrain are required to establish the tie between the multiple cameras.
4. Images of highly undulating terrain are necessary to check the variation in line direction between the different bands of L4MX. This is to ensure that the different bands lining up on the ground do not leave any misregistration error if an underlying DEM is included.

The control and check points were collected from manual digitisation of 1:50 000 scale topographic maps from the Survey of India. A 1:50 000 scale map has a standard error of around 15 m in planimetry. In practice, it was found that when digitising a specific feature for control, the error could be as large as 25 m in planimetry. A few surveyed points were also used for precise focal plane calibration. The conjugate points (or tie points) between different bands of a camera (or between different cameras) were identified using automatic techniques based on mutual information and correlation matching.

**Individual Sensor Alignment Calibration**

Individual sensor alignment calibration deals with the orientation of each sensor with respect to the attitude frame. This includes the determination of the attitude relationship and
shifts between the coordinate systems of the star sensor, body and imaging sensor, along with the interior orientation of the sensor. Computation of boresight misalignment angles is a difficult task. Each CCD array of a sensor in the focal plane has an orientation with respect to the payload and each payload has an orientation with respect to the body. The body frame has an orientation with respect to the inertial frame. The primary challenge in alignment calibration is the need to estimate the underlying alignment trend for each sensor from a series of precision correction solutions that measure a combination of orbit, attitude and alignment errors. The following criteria are followed to decide the alignment trend for each sensor:

(i) If each of the three payloads shows errors of the same order of magnitude over the same ground area, then the bias is in the attitude determination.

(ii) If errors are consistent over different images (with different viewing configurations) from the same sensor, but vary from sensor to sensor, the error can be due to a combination of payload-to-body residuals of different sensors and attitude determinations.

(iii) If the errors of a particular ground area are not consistent over different images of the same payload (L4 on different viewing configurations), the errors can be due to payload steering.

An extensive analysis with different data-sets can reveal the behaviour of each sensor. The modelling error, that is, the inability of the model to reconstruct the viewing geometry, also reflects as an error at the check points after precision correction. Therefore, use of a correct mathematical model is very important for in-flight calibration. The boresight misalignment is computed by comparing the attitude parameters determined by the navigation system with the parameters after correction with GCPs.

Band 3 of the L4 camera, with its vertical viewing configuration, is taken as the primary sensor for which the focal length and angular placements of the first and last detectors are treated as fixed. The vertical viewing image is preferred to compute individual sensor alignment biases because the disturbances introduced over these biases due to payload steering for oblique viewing should be analysed separately. Relatively few but well distributed GCPs and check points need to be identified in the images, as distribution ensures final biases estimated are representative of complete image characteristics. Initially, a zero value was assigned to the payload alignment biases in the rotation matrix of the sensor model. Then, ground coordinates were computed for the check points using the sensor model and the given GPS/INS (inertial navigation system) orientation parameters. The differences between the derived ground coordinates and the actual coordinates were then analysed. The error vectors from many images showed the same trend.

The sensor orientation parameters are then updated with the rigorous sensor model and GCPs. The differences in exterior orientation parameters before and after correction were computed for all the data-sets and compared. The roll bias turned out to be about 0.09°, the pitch bias 0.04° and there was no measurable yaw bias. These biases will account for offsets between the body frame and payload, for small variations in the interior orientation of the sensor and focal plane geometry, for alignment offsets between the inertial and body frames, and for uncertainty in the given orbit and attitude parameters. Each cannot really be apportioned individually. But, the common bias trend from the images of a sensor should be taken out as the offset of the payload and this will account for the first two offsets mentioned above.

Fig. 4 shows the planimetric error vectors for a set of check points over a nadir-looking image of L4. Fig. 4(a) shows the errors before calibration and Fig. 4(b) shows their distribution after calibration. Products of the same ground extent are generated through direct georeferencing with and without inclusion of the biases in the rotation matrix. Fig. 5 shows
a superimposition (blend) of these products. Feature displacements are of almost the same magnitude as shown in Fig. 4. This exercise is carried out for band 3 of L3 and AWF also, in order to achieve the sensor alignment offsets. Individual sensor alignment calibration will ensure that the location performance of all the images is within the system-level accuracy specifications.

**PAYLOAD STEERING ALIGNMENT CALIBRATION OF L4**

The behaviour of the payload steering is analysed and measured by means of payload steering alignment calibration. The L4 camera is capable of imaging with view angles up to ±26° using the PSM. When the payload is tilted, the bias angles between the payload and attitude coordinate system can be disturbed. Also, small unintentional rotation angle perturbations can be introduced in other directions. To study this behaviour, many images with different look angles (from different orbits) are analysed. The error due to the combined effect of terrain topography and look angle will be mainly in the across-track direction. Inclusion of a global DEM during georectification can minimise this error. The process compares the terrain-corrected image to a high accuracy reference image to detect systematic deviations of the payload steering motion from its nominal pre-launch profiles for forward and reverse payload steering. The measured deviations are analysed as a function of look angle.

To verify the offsets, another method is also adopted. Attitude parameters from the telemetry are updated using GCPs. The differences in the parameters before and after update
are tabulated. Fig. 6 shows these residuals for L4 images with different look angles. Roll and yaw residuals do not show any trends, only small random fluctuations. This is due to the discrepancy in the attitude accuracy provided by the telemetry for different orbits. Roll and yaw biases are approximately 0-09° and 0°, respectively, for all look angles. But pitch shows a dependency on the look angle, which can be fitted with a polynomial function. The pitch offset, which is around 0-04° at nadir, increases up to 0-08° at a +26° look angle and it is slightly less than 0-04° for negative look angles. Fig. 7 shows the system-level accuracies of images before and after accounting for the residuals. The system-level accuracy is better than 250 m for all data-sets after including the residuals, whereas without including the offsets it is as high as 2000 m. The residuals computed for a particular look angle, for a particular step number in PSM, will remain unchanged throughout the life of the satellite.

**INTER-CAMERA ALIGNMENT CALIBRATION**

Inter-camera alignment is carried out to ensure that the same relative location accuracy is achieved from all sensors. Approximate alignment offsets of all sensors with respect to the body frame are achieved from individual sensor calibration using check points. Checking the relative location performance via identification of corresponding points in L4, L3 and in AWF is very difficult in practice as the images are of very different resolution. After fixing the residuals, band 3 of the L4 nadir-looking image is taken as the primary sensor and other sensors are oriented relative to this primary sensor. Any fixed ground extent covering long clear-cut features in L4, for example rail or road networks, is georeferenced without GCPs at the resolution of L3 (23.5 m) using a global DEM included in the rectification. For the same ground extent, georeferenced products are generated from L3 and AWF at the same resolution with a DEM. Inclusion of a DEM while generating the products is very important to ensure that the computation of the sensor alignments is not influenced by terrain topography. The various sensors have different look angles and resolutions. Therefore, the effect of terrain relief on different images will also be different. Superimposition of the products, along with their
Fig. 6. Look angle versus alignment offsets between payload and body of L4 camera: (a) roll residual; (b) pitch residual; (c) yaw residual.
Fig. 7. System-level rms errors for various data-sets of L4 before and after including the boresight alignment offsets: (a) latitude error; (b) longitude error.

comparison, will yield relative alignment offsets which can be corrected by fine-tuning the biases of L3 and AWF with respect to the body axes. Figs. 8, 9 and 10 show such superimposed images from different cameras before and after fine-tuning the biases between
them. These parameters will not change for different orbits as the L3 and AWF (AWF-A and AWF-B) cameras are not tiltable. It is clear from these figures that after correcting for inter-camera alignments, a co-registration between the images from different cameras is achieved. Once the relative calibration is considered reliable, the remaining location errors are shared by all cameras and are due to uncertainty in the recorded attitude data.

**Focal Plane Calibration**

Focal plane calibration includes the alignment of different bands in multispectral imagery and computation of the effective focal length and alignment of odd and even detectors within each CCD array.

**Effective Focal Length Computation**

Effective focal length computation experiments are carried out for the L4 camera. Alignment offsets of band 3 of this camera, computed through individual sensor alignment
calibration and payload steering calibration, are fixed. Pre-launch focal length and angular placements of this band in the focal plane are kept unaltered. The effective focal lengths and alignment offsets of band 2 and band 4 are then computed relative to band 3. Effective focal lengths are computed by comparing the longitude error (rms) of a set of check points. The object coordinates of measured image points are intersected based on the system-level position and attitude data provided, which has been improved through boresight misalignment compensation. This is repeated with slightly different focal lengths. The process terminates at the focal length that results in the lowest longitude error. Band 4 did not show any change in the focal length from the pre-flight calibrated value whereas band 2 showed that an effective focal length change of about \( -0.3 \) mm from the pre-launch value was required to produce the optimum absolute location performance (also the same relative location performance as with band 3).

**Band-to-Band Registration**

Band-to-band registration or co-registration means that a feature imaged in one band can be mapped to a specific row and column in another band. This is relevant for L4, as

![Fig. 9. Superimposition of system-level products (band 3) generated from L3 and AWF-A: (a) before fine-tuning inter-camera alignment angles in the adjustment; (b) after including the inter-camera alignment angles.](image)
well as for band 5 of L3 and AWF. The payloads of L3 and AWF are not tiltable. The difference in view direction between band 5 and the other bands is very small, and terrain-induced effects are negligible. Therefore, in the case of L3 and AWF, a single set of alignment angles computed from the images should solve the problem. But, automated co-registration of image data from multiple bands of the L4 camera is more complicated and is one of the basic requirements of IRS-P6 data processing. Differences in the viewing geometry between the bands, as well as inconsistencies between the staggered timing and the viewing geometry at the time of image acquisition, present an interesting challenge to this requirement. Co-registration using the imaging geometry and auxiliary data is produced indirectly by registering each band to a common coordinate system on the ground.

Direct georeferencing of images from different bands is performed using the given navigation data. Band-to-band registration assessment requires scenes that contain significant spatial frequency content common to all the bands. Different bands are compared for co-registration discrepancies relative to the nadir band. Inclusion of a global DEM in the product generation minimises the distortion due to terrain. Precise conjugate points are identified from different bands of L4. Points in band 3 are then taken as reference points. By using the camera geometry and the projection model, an image point of band 3 is projected onto the ground and this intersected ground point is reprojected into the other bands. The differences between the actual points and projected points in band 2 and band 4 are computed.

Fig. 10. Superimposition of system-level partial products generated from band 3 of AWF-A and AWF-B after inter-camera alignment correction (overlap area is shown).
The resulting image residuals show the remaining optical and focal plane distortions. The distortion is divided into two separate directions, line and sample residuals. The distortion in the line direction is primarily due to unaccounted terrain relief and slight variations in the angular placement of the CCDs. The major contributors for the distortion in the sample direction are focal length and scale variations. The in-flight calibration residual errors of bands 2 and 4 with respect to band 3 in the sample direction are shown in Fig. 11 against the GCP layout. The points are from many data-sets with different starting pixels and look angles, so that they are distributed over the entire length of the detector array. The residuals show a small slope (within 2 pixels) over the 12 000 pixels. In a single image of L4MX, only 4200 detectors (out of 12 000) will be active and the offset between the bands within the width of the image is less than a pixel. This can be due to small variations in the focal lengths of different bands or changes in the alignment angles of the bands in the focal plane from the pre-launch values. A constant vertical line bias of ~1.5 lines was observed between band 3 and band 4. No shift was seen in the vertical direction between band 3 and band 2. The effect of terrain undulation will also manifest itself as a misregistration between the bands in the vertical direction. Therefore, the vertical biases are computed using nadir images of planar areas with a DEM included in the adjustment. The residual offsets of each detector of bands 2 and 4 are stored in a lookup table and used at the time of product generation. This will ensure a first level of registration between the bands, especially in the column alignment, and it minimises the computational load on the product generation system. The remaining misregistration errors specific to each acquisition depend upon the look angle and terrain topography. These effects will be manifested mainly as misregistration errors along the line (row) and they are addressed at the time of product generation. The value-added product generation system (VAPS) of IRS-P6 is designed in such a way that it performs an on-demand resampling of colour images of L4 in order to provide perfectly registered images after inclusion of the lookup table of residuals computed from in-flight calibration.

![Figure 11](image_url)

**Fig. 11.** In-flight calibration residuals of band 2 and band 4 with respect to band 3 of L4 camera (shift between actual pixel and computed pixel).
Alignment of Staggered Array

The payload design of L4 and the SWIR band (band 5) of L3, as well as AWF, are such that odd and even detectors are staggered by 5 lines and 2 lines, respectively, in the focal plane. Slightly different viewing angles of both lines of a staggered array can result in a variable sampling pattern on the ground because of attitude fluctuations, satellite movement, terrain topography, PSM and small variations in the angular placement of the CCD lines in the focal plane from their pre-launch values. Failure to account for this variable sampling value during the video data alignment will introduce a deterioration in image quality and a geometric discontinuity of features. The stagger parameters can be computed via a reconstruction of the viewing geometry with a calibrated camera geometry model and a public domain DEM.

The refined detector placements and other camera parameters must be incorporated into the model to define the line of sight vector. While projecting a particular pixel in the odd array onto the ground, the height of the ground point is extracted from a public domain DEM so that any planimetric shift due to terrain undulation is minimised. The point where this ray intersects is reprojected onto the even array in image space. Thus, the offset is computed. With this offset, a one-dimensional resampling and a joining of odd and even arrays are performed. As the L3 and AWF cameras are not tiltable, one set of computed values will solve the problem. Also, the effect of stagger of the two lines between the odd and even arrays on image resolution will be very small. In the case of L4, the stagger will change slightly with look angle. It is clear from Fig. 12 that with high look angles, the offset between the odd and even arrays in the along-track direction is 5·6 lines instead of 5 (integer) lines. The stagger offset shows a systematic behaviour as a function of look angle. A lookup table for stagger values for different look angles is included as part of the pre-processing for video alignment.

SUMMARY OF RESULTS

The alignment of individual sensors as well as their relative alignment to each other is ensured through in-flight calibration. In-flight calibration includes individual sensor calibration, inter-camera alignment calibration, payload steering alignment calibration, band-to-band

![Graph](image-url)

**Fig. 12.** Along-track offset between odd and even arrays of band 3 of L4 as a function of tilt angle (computed at 6000th pixel).
registration and alignment of each staggered array. The following constitute the major results for the IRS-P6 sensors:

(1) The effective focal length of band 2 of the L4 camera was adjusted from its pre-launch value estimated during ground calibration by –0.3 mm. No change was observed in the focal lengths of other bands.

(2) The angular positions of all bands of all cameras with respect to the payload were retained. The residuals between bands 2 and 4 of L4 were found to be about a pixel in the across-track direction, with respect to band 3, and about –1.5 pixels of bias in the along-track direction between bands 3 and 4. The offsets for each detector in band 2 and band 4 with respect to band 3 are now stored in a lookup table and are incorporated as image coordinate refinements during product generation.

(3) The inter-camera alignment residuals were computed, keeping the vertical image of L4 as a reference, and were corrected as modified residuals in roll and pitch between the payload and body.

(4) It was observed that with the payload steering, the focal plane geometry was slightly disturbed and a small magnitude of pitch angle error was being introduced. This perturbation is a function of look angle, which varies from 0.03° to 0.08° with look angles from –26° to +26°. The roll and yaw biases of the payload-to-body relationship of the L4 camera did not change with look angle and were computed as –0.09° and 0°, respectively.

(5) Along-track stagger between odd and even arrays of L4 changes from 5 lines with vertical images to 5.6 lines with high oblique images. The stagger values computed from geometry were in perfect agreement with what was observed in the image data. The computation of stagger values from geometry is now included as a pre-processing tool required for video alignment.

(6) After incorporating the sensor alignment residuals into the adjustment model, the system-level accuracy was better than 250 m in all viewing configurations for all cameras, which is within the specification.

**CONCLUSION**

The concept of in-flight calibration for the IRS-P6 satellite, which carries multiple cameras with widely varying look angles and resolutions, has been realised through adoption of a rigorous sensor model employing metadata information for satellite position and attitude, as well as precise camera geometry and datum transformations. The results of the present study satisfy all the objectives of in-flight calibration. System-level tests using comparisons to ground check points have validated the operational geolocation accuracy performance. The imagery was collected over a period of 2 years and this demonstrates the stability of the calibration parameters. The calibration results are included for operational use in the value-added product generation system (VAPS) of IRS-P6, affording a significantly simplified process for georectification during standard processing.

**ACKNOWLEDGEMENTS**

The authors gratefully acknowledge Dr A. S. Kiran Kumar, Deputy Director (SEDA), SAC, for providing the pre-launch geometric parameters of different payloads of IRS-P6. The authors are grateful to Dr R. Krishnan, Director, and R. Ramachandran, Deputy Director (ATG & PP), ADRIN, for their encouragement and support for this work.
RADHadevi and Solanki. In-flight geometric calibration of different cameras of IRS-P6

REFERENCES


Résumé

sur l’attitude et les éphémérides, de la géométrie exacte des caméras, et d’un modèle de transformation. Dans ce modèle, on formule explicitement et rigoureusement les transformations directes et inverses entre les systèmes de coordonnées basées sur le plan focal, le mode de prise de vues, la plate-forme, l’orbite et le terrain. Les essais effectués au niveau du système par des comparaisons sur des points de vérification au sol ont validé la qualité opérationnelle de la précision de localisation et la stabilité des paramètres d’étalonnage.

Zusammenfassung


Resumen

El satélite IRS-P6 tiene capacidad multispectral y multiresolución en una misma plataforma. Así, uno de los retos más importantes que plantea el procesamiento de los datos de este satélite es el registro y georreferenciación autónoma y continua de las imágenes de los diferentes sensores con distintos ángulos de campo y resolución, lo que requiere una calibración geométrica de las cámaras durante el vuelo. La calibración en vuelo incluye tanto la calibración de la alineación individual de los sensores como la calibración entre ellos. En este artículo se propone un método para realizar la calibración en vuelo y la evaluación de la calidad de las imágenes obtenidas por el satélite IRS-P6. El objetivo es obtener la mayor exactitud absoluta y relativa de las diferentes cámaras e iguales resultados de geolocalización mediante la orientación de la carga útil y el coregistro de bandas múltiples. Ello se consigue utilizando un modelo geométrico de las tomas, datos de las efemérides y la orientación angular, la geometría precisa de la cámara y la transformación del datum. En el modelo se definen rigurosamente y explícitamente las transformaciones directa e inversa entre los sistemas de coordenadas asociados al plano focal, a la carga útil, al cuerpo de la cámara, a la órbita y al terreno. La verificación del sistema utilizando puntos de control terrestre ha permitido validar la exactitud operativa de la georreferenciación y la estabilidad de los parámetros de calibración.
RATIONAL FUNCTION MODEL FOR SENSOR ORIENTATION OF IRS-P6 LISS-4 IMAGERY

V. NAGASUBRAMANIAN (nagasmn@yahoo.com)
P. V. RADHADEVI (adrin_radhadevi@yahoo.co.in)
R. RAMACHANDRAN (ramachandran@adrin.res.in)
R. KRISHNAN (krishnan@adrin.res.in)

Advanced Data Processing Research Institute, Department of Space, Hyderabad, India

Abstract

This paper explores the application of a rational function model (RFM) as a replacement sensor model for IRS-P6 LISS-4 imagery. The rational polynomial coefficients (RPCs), initially generated using a rigorous sensor model (RSM) through direct georeferencing, are bias-compensated with a minimum number of ground control points and are used for various photogrammetric applications such as digital elevation model and ortho-image generation. The performance of RFM and RSM is compared in the sensor modelling of LISS-4 imagery over long strips. Results show that accuracies achieved using RFM are within 1 pixel (worst case) of the accuracies derived using RSM. Error variation as a function of the number of quasi-control points (anchor points) used for RFM fitting as well as model errors with respect to the length of the image strip are analysed. System-level accuracy does not deteriorate when the RFM is fitted up to a length of 1200 km. Absolute positioning accuracy of 1.5 pixels (≈9 m) is achieved from bias-compensated RPCs. The results demonstrate the potential of RFM as a replacement sensor model. This allows standardisation of product generation packages to handle multiple sensors.

KEYWORDS: anchor points, IRS-P6, LISS-4, rational function model, rational polynomial coefficients, rigorous sensor model

INTRODUCTION

During the past few years, the photogrammetric community has become aware of the use of rational function models (RFMs) for image restitution. Dowman and Dolloff (2000) used “replacement sensor model” as the generic term, which uses ratios of polynomial functions to define the transformation from object space to image space. The RFM has been universally accepted and validated as an alternative sensor orientation model for high-resolution satellite imagery such as IKONOS and QuickBird. Recently it was tested with SPOT 5 HRS (Poli et al., 2004; Fraser et al., 2006). A number of authors (Tao and Hu, 2000, 2002; Fraser and Hanley, 2003; Grodecki et al., 2004; Lutes, 2004; Chen et al., 2006) have indicated that high accuracy can be achieved with RFM. Nowadays, commercial off-the-shelf (COTS) digital
photogrammetric workstations have incorporated RFM as a method for image exploitation. If rational polynomial coefficients (RPCs) are computed from a priori sensor orientation parameters, the geopositioning accuracy can be improved with a number of ground control points. Recently, the use of satellite images within the mapping sector has increased tremendously. With the frequent launch into orbit of high-resolution satellites, it has become mandatory that the processing and product generation system be sensor-independent. The satellite agencies may not like to release the complex camera model and metadata to users. RFM is a solution to this problem. Together with the image data, some satellite agencies provide a grid, containing a set of image coordinates and corresponding ground coordinates, from which RPCs can be generated. Some other vendors offer the RPCs themselves. If the camera model, ephemeris and attitude data are provided along with the image, a grid can be generated (using a rigorous sensor model (RSM) in the pre-processing) for fitting the RPCs. If the images along with corresponding RPCs are the input to the product generation system, no other information about the sensor is required.

An RPC model was developed and tested with Russian TK-350 frame camera images, asynchronous images of EROS-1A/1B and images with “step and stare” viewing geometry. In the present study, this model has been modified for the restitution of “linear imaging self-scanning sensor” (LISS-4) imagery. One of the main objectives of this paper is to compare the geometrical accuracy of RFM and RSM for long strips of LISS-4 imagery. Other objectives are to analyse the effects on accuracy of strip length, number of height layers and number of anchor points (for fitting RPCs). The aim of the present study is to establish this model as a universal sensor model that allows the user to deal with various sources of imagery in a unified approach without knowing all the details of the camera systems by which the images have been taken. The physical sensor model is used as a pre-processing tool for generating the RPCs. Using the RSM, the initial orbit trajectory is fitted with the given ephemeris and attitude data for the full pass. Corresponding to the multiple elevation grids, anchor points are generated with RSM. These points are used for generation of RPCs. Once the RPCs are generated, the photogrammetric chain of operations for product generation will be unaltered irrespective of the source of the imagery.

**LISS-4 Camera Geometry**

The IRS-P6 satellite offers multispectral and multi-resolution capabilities on the same platform. The satellite uses three sensors, LISS-4, LISS-3 (L3) and AWIFS (AWF), to capture images. The average ground sample distances (GSD) of these sensors are 5.8 (at nadir), 23.5 and 56 m (at nadir), respectively. LISS-4 (linear imaging self-scanning sensor-4) is a three-band pushbroom camera using three mirror reflective telescope optics and 12 000 pixels staggered array CCDs, separated into 6000 each of odd and even pixels. These odd and even pixel rows are separated by 35 μm (equal to 5 pixels) in the focal plane. The camera can be operated in two modes: wide mono and multispectral. In the multispectral mode, data is collected in three spectral bands. The sensor provides data corresponding to 4200 pre-selected contiguous pixels covering a 23.9 km swath. These 4200 pixels can be anywhere within the 12 000 pixel array by commanding the start pixel number using an electronic scanning scheme. In mono mode, the data of all 12 000 pixels of any one selected band, corresponding to a swath width of 70 km, can be obtained. The LISS-4 camera has the additional feature of off-nadir viewing capability by tilting the camera by ±26°, thus providing a 5-day revisit capability. More details about the satellite are available in the *IRS-P6 Data User’s Handbook* (NRSA, 2003).
RIGOROUS SENSOR MODEL (RSM)

A sensor model describes the imaging geometry. Reconstruction by means of the viewing geometry includes the exterior and interior orientations of the sensor. The model relates 3D object point positions to their corresponding 2D image positions by describing the geometric relationship between the image space and object space. The algorithm for the orbit–attitude model, which combines the principles of viewing geometry of the satellite with photogrammetric collinearity equations, was originally developed for SPOT 1 and IRS-1C/D (Radhadevi and Ramachandran, 1994; Radhadevi, 1999). This model has been adapted to suit the LISS-4 camera characteristics of IRS-P6.

LISS-4 data in Level-0 consists of the signal in framed raw expanded data (FRED) format and metadata in an ancillary data information file (ADIF). Stagger correction (between the odd and even detectors) and radiometric correction are part of the pre-processing, which will generate a Level-1A image. The information about the satellite ephemeris, attitude, look angle, sidereal angle, start pixel, time and so on is extracted from the ADIF. The orbit parameters in the collinearity equations are position \((X_p, Y_p, Z_p)\), velocity \((V_x, V_y, V_z)\) and attitude parameters are roll \((\omega)\), pitch \((\phi)\) and yaw \((\kappa)\). Satellite position and orientation are given every 125 ms. Attitude data is converted from quaternion to Euler angle form. Fitting of the given telemetry values enables computation at required time intervals, thus also converting the given discrete values to continuous form. The initial values of all the parameters are derived by least squares adjustment from the ephemeris data using a generalised polynomial model as follows:

\[ q = q_0 + q_1 t + \ldots + q_n t^n \]

where \(t\) is scan time and \(q\) corresponds to \(\omega, \phi, \kappa, X_p, Y_p, Z_p, V_x, V_y and V_z\). The order of the polynomial, \(n\), can be set. The coefficients of the polynomials for position, velocity, sidereal angle and attitude are computed. These parameters at a particular time are connected to the corresponding ground coordinate and image coordinate through collinearity equations. Thus, if the initial trajectory is fitted, image to ground and ground to image transformation can be done using the collinearity condition equations.

Collinearity equations express the fundamental relationship that the perspective centre, image point and object point lie on a straight line, that is

\[
\begin{pmatrix}
    f \\
    -x_s \\
    -y_s
\end{pmatrix} = dM \begin{pmatrix} X - X_p \\ Y - Y_p \\ Z - Z_p \end{pmatrix}
\]

(1)

where \((f, -x_s, -y_s)\) are the image coordinates, \((X, Y, Z)\) are the coordinates of the object point and \((X_p, Y_p, Z_p)\) are the coordinates of the perspective centre, \(d\) is the scale factor and \(M\) is the orthogonal rotation matrix to transform from the geocentric to the sensor coordinate system, that is

\[
\begin{pmatrix}
    f \\
    -x_s \\
    -y_s
\end{pmatrix} = d \begin{pmatrix}
    m_{00} & m_{01} & m_{02} \\
    m_{10} & m_{11} & m_{12} \\
    m_{20} & m_{21} & m_{22}
\end{pmatrix} \begin{pmatrix} X - X_p \\ Y - Y_p \\ Z - Z_p \end{pmatrix}.
\]

After rearrangement, equation (1) can be written as two equations:

\[
\begin{align*}
    f_1 &= (f m_{11} + x_s m_{01}) (X - X_p) = 0 \\
    f_2 &= (f m_{20} + y_s m_{00}) (X - X_p) = 0
\end{align*}
\]

(2)
where \( m_{i0} = (m_{i1}, m_{i2}, m_{i3}) \) etc. The rotation matrix \( \mathbf{M} = \mathbf{Q}_{\text{GI}} * \mathbf{Q}_{\text{IO}} * \mathbf{Q}_{\text{OB}} * \mathbf{Q}_{\text{BP}} * \mathbf{Q}_{\text{PC}} \), where

- \( \mathbf{Q}_{\text{PC}} = \) CCD to payload transformation matrix
- \( \mathbf{Q}_{\text{BP}} = \) payload to body transformation matrix
- \( \mathbf{Q}_{\text{OB}} = \) body to orbit matrix
- \( \mathbf{Q}_{\text{IO}} = \) orbit to inertial matrix
- \( \mathbf{Q}_{\text{GI}} = \) earth-centred inertial (ECI) to earth-fixed earth-fixed (ECEF) matrix.

The CCD to payload transformation matrix is included in the rotation matrix. Thus, a pixel in any band of the LISS-4 camera can be projected onto ground coordinates through a series of transformations.

**RATIONAL FUNCTION MODEL (RFM)**

A rational function model can be represented as the quotient of two polynomials, which describe the geometrical relationship between object and image coordinates:

\[
I = \frac{p_1(X, Y, Z)}{p_2(X, Y, Z)} \tag{3}
\]

\[
S = \frac{p_3(X, Y, Z)}{p_4(X, Y, Z)} \tag{4}
\]

The \( p_i \) are third-order polynomials:

\[
p_i(X, Y, Z) = \sum_{i=0}^{3} \sum_{j=0}^{3} \sum_{k=0}^{3} a_{ijk}X^iY^jZ^k
\]

\[
= a_0 + a_1X + a_2Y + a_3Z + a_4 XY + \ldots + a_9Z^3
\]

where the \( a_i \) are polynomial coefficients and \( X, Y, Z \) are normalised object coordinates. This may be in a spherical or Cartesian coordinate system. The \( I, S \) are normalised image coordinates. Original values of image and ground coordinates are offset and scaled to fit between \(-1\cdot0\) and \(1\cdot0\).

These equations can be solved by either of two methods. The first method, which is terrain-dependent, uses a large number of ground control points (GCPs). A minimum of 40 GCPs are required per image. This requirement of accurate control is a major problem in remote and inaccessible areas. Therefore, the first method may be unrealistic, as indicated by Hu and Tao (2002). The second method, which is terrain-independent, is to use the onboard ephemeris and attitude data. This method is used for the present study. An initial orbit trajectory is fitted by means of the RSM. Image coordinates of grid points at regular intervals with different layers of heights are established. Corresponding ground coordinates are computed using the RSM. These are called anchor points (Chen et al., 2006). These points are used to derive RPCs.

The anchor points will represent the characteristics of the sensor and platform. Even though the resolution of LISS-4 of IRS-P6 is similar to that of the PAN camera of IRS-1C/D, the specified system-level accuracy is 286 m whereas that of IRS-1C/1D was about 2 km. This is because of the availability of high-precision orbit and attitude determination using GPS in combination with gyros and star trackers. This allows direct georeferencing and generation of quasi-control points for the RPC computation. The coordinates derived through the initial
RPCs will have a system-level error of about 286 m. A threshold of 0.5 pixels (about 3 m) is decided as the acceptance criterion for anchor points. The flow of the RFM process is described in Fig. 1.

**IMPLEMENTATION**

**Determination of RPCs**

The RPCs represent a comprehensive reparameterisation of exterior orientation parameters, but are not readily interpretable in a physical sense. RPCs are determined from anchor points generated through an RSM. Over the strip, for every hundred kilometres, object space coordinates are determined through direct georeferencing (using the initial orientation parameters and an average height). Within each segment of 100 km x 23 km area, minimum height and maximum height are extracted from a public domain digital elevation model (DEM) such as GTOPO 30 or SRTM. This is to decide the planes of multi-level object point coordinates with different elevations. The approximate height range determination over local areas is very important as the full-pass data which is being handled can have significant height
variations. A regular image grid is generated over the full extent of the strip at 200-pixel intervals in both directions. The object space coordinates are computed corresponding to these points at three different height layers (one at the minimum, one at the maximum and one at the average with different min–max values over different parts of the strip). Thus, each image point will have three sets of horizontal ground coordinates corresponding to three different heights. Each height layer will have hundreds of such points. The grid file generated (using the RSM) will have all the points in multiple height layers. A minimum of two height layers are required to generate anchor points for computing RPCs even in relatively flat areas because small variations in terrain height can give variations in horizontal coordinates due to the look angle of the camera. A set of points from the grid file is used for fitting the RPCs using a least squares approach. The remaining points are used as check points to compare RSM and RFM performance. The forward RPCs as well as inverse RPCs can be generated (Tao and Hu, 2002).

**Bias Compensation**

To evaluate the potential of RFM for sensor orientation and geopositioning of long strips, bias compensation of RPCs with ground control points is done. Image coordinates are computed using RPCs corresponding to the object coordinates of a few distributed GCPs. The errors or differences between the actual image coordinates and computed coordinates are modelled. An affine correction model is used for bias compensation of RPCs. The equations are

\[
l - l_{\text{comp}} = A_0 + A_1 l_{\text{comp}} + A_2 s_{\text{comp}}
\]

\[
s - s_{\text{comp}} = B_0 + B_1 l_{\text{comp}} + B_2 s_{\text{comp}}
\]

where \(l\) and \(s\) are actual line and sample coordinates of GCPs, \(l_{\text{comp}}\) and \(s_{\text{comp}}\) are line and sample coordinates computed through RPCs and \(A_0, A_1, \ldots, B_2\) are affine coefficients. After computing the affine coefficients, the bias-compensated RPCs can be substituted for the subsequent photogrammetric operations. It has been proved that an effective bias compensation, to 1 pixel, can be achieved by using only the shift terms \((A_0, B_0)\) for IKONOS and QuickBird (Baltsavias et al., 2001; Dial and Grodecki, 2002, 2005; Fraser and Hanley, 2003, 2005). All these papers evaluate images of length less than 50 km and narrow view angles. In the present study, the time-dependent exterior orientation parameters are fitted for the entire length of about 1200 km and the correction model is also to be applied for long strips. Therefore, drift terms \((A_1, B_1)\) cannot be neglected. For narrow angle viewing optics like IKONOS and QuickBird (around 1° and 2°, respectively), the distortions towards the edges of the image will be minimum. The IRS-P6 LISS-4 camera has a field of view of 48°. Therefore, correction terms \((A_2, B_2)\) also should be included along with shift and drift terms.

**Test Results and Discussion**

Two full-pass strips are used as test data-sets for evaluating the accuracy. Details of test data-sets are shown in Fig. 2. One pass covers eastern parts of India and the other covers the western side. Relative accuracy of the RFM method with respect to RSM is analysed. Then absolute accuracy is evaluated with bias-compensated RPCs.

Control points and check points are identified from aerial ortho-images and the corresponding DEM. Initially, RPCs are computed for the full-pass image. Four distributed points are used for computing the shift and drift parameters and solve equations (5) and (6). The points have an accuracy of approximately 3 m in \(X\), \(Y\) and \(Z\). But due to manual
TABLE I. Absolute accuracy with bias-compensated RPCs.

<table>
<thead>
<tr>
<th>Data-set</th>
<th>X Direction (rmse) (pixels)</th>
<th>Y Direction (rmse) (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data-set1</td>
<td>1.537</td>
<td>0.513</td>
</tr>
<tr>
<td>Data-set2</td>
<td>0.752</td>
<td>0.992</td>
</tr>
</tbody>
</table>

Fig. 2. Coverage and details of the test data-sets.

Identification of points in the images, the overall error can be of the order of 5 to 10 m. Table I shows the absolute rms errors at a set of 40 check points in data-set 1 and 52 check points in data-set 2. The error is within 1.5 pixels (<9 m) in both directions for both data-sets.

Effect of Strip Length

As the number of polynomial terms in RPCs is the same irrespective of the image length, there is a need to evaluate the accuracy for longer image strips. Behaviour of RPCs over the test strips is studied. Three-dimensional grid points and associated RPCs are computed for a number of different strip lengths. For each segment, the residuals are computed with respect to the RSM and worst-case error is analysed. In all cases, the interval between the grid points used for fitting is kept the same and the points are distributed. Fig. 3 shows the rms errors in across-track and along-track directions with different strip lengths. Up to 1000 km, rms error in the across-track direction with respect to RSM is within 0.01 pixels. Rms error in the along-track direction increases after 250 km, but is less than 0.3 pixels even when RPCs are fitted for the 1200 km length. Incorporating local min–max height range in the multi-level elevation grid
minimises the terrain-induced errors. Orbit determination accuracy in GPS mode is about 10 m and attitude determination accuracy with the star sensor in the loop is about 202 m; the location accuracy of the system-level product is then expected to be 286 m. As the RPCs are fitted using anchor points generated through direct georeferencing (without GCPs), the system-level error of 286 m will be present in the products generated through RPCs without bias compensation. Slight deterioration of up to 1 pixel (286 ± 5.8 m) over and above this error is accepted because a single set of RPCs over a long strip makes it easier to create large area databases of products. If multiple sets of RPCs exist for different length segments over the same strip, joining of products generated across the image lengths over which RPCs are generated should be ensured. Analysis of the attitude behaviour of many data-sets reveals that high frequency jitters or disturbances are not present even with high look angles (acquired through the payload steering mechanism) of the LISS-4 camera. This ensures the removal of system-level errors with a few GCPs using bias compensation of RPCs. The tests reveal that RPCs can capture the full range of view geometry up to a length 1200 km.

**Effect of Height Layers**

To decide the optimum number of height layers, the effect of height range on accuracy was studied. Data-set 1 is used for this study as it covers undulating terrain. The full length of the image data is segmented into 100 km lengths. For each 100 km segment, minimum and maximum heights are extracted from a public domain DEM. Within each 100 km, two height planes are formed, that is, one at minimum and one at maximum. The RPC fitting accuracies at all grid points are compared with RSM errors with direct georeferencing at the same nodes. This experiment is repeated with different numbers of height planes. Table II demonstrates the

<table>
<thead>
<tr>
<th>Table II. Effect of number of height layers on accuracy.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of layers</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>X Direction (rmse) (pixels)</td>
</tr>
<tr>
<td>Y Direction (rmse) (pixels)</td>
</tr>
</tbody>
</table>

Fig. 3. Effect of image length on accuracy.
The relation between height layers and rms error. RPC fit accuracy improves with addition of more height layers. The results show that three height layers will give a good accuracy over terrain with moderate undulations. Two height layers give an rms error of about 7 pixels, which is higher than the acceptance criterion for anchor points. If the terrain undulation is less than 1000 m, three height layers are enough to give good accuracy. Most of the areas fall under this category because in normal terrain conditions height differences will not exceed 1000 m within 100 km; this is therefore taken as the default option. Images with high view angles may require more height layers. Similarly, areas covering the Himalayan region can have very large height variations. The combined effect of view angle and terrain undulation will give much error in planimetry. Therefore, in such cases, the user can decide the number of height layers depending upon terrain undulation.

**Effect of Number of Anchor Points Used for Fitting RPCs**

The grid points are at regular intervals of 200 pixels in both directions. Out of these points, a set of well-distributed points is used for fitting RPCs and the remaining points are used to compare the relative accuracy with RSM. The image length is kept fixed. The number of points used for fitting is gradually increased and the rms of the differences at the remaining points are computed and plotted in Fig. 4. The accuracy increases with number of points. But the magnitude of variation is very small when the number of points is increased from 200 to 1200. This shows that approximately 200 distributed anchor points over an area of 500 km × 23 km are good enough to capture the orbit and attitude behaviour of the satellite through RPCs.

**Conclusions**

The analysis of the results shows that the specifications for IRS-P6 LISS-4 system performance are met with a rational function model. The results are representative of the stability of the platform and the potential of IRS-P6 for accurate georeferencing. It is proved that for a non-agile satellite like IRS-P6, RPCs can be fitted for a length of up to 1200 km.

![Graph](image.png)

**Fig. 4.** Effect of number of anchor points on accuracy (for image length of 500 km).
NAGASUBRAMANIAN et al. Rational function model for sensor orientation of IRS-P6 LISS-4 imagery

within which the relative accuracy with respect to RSM will not vary beyond a pixel. Approximately 200 distributed anchor points are good enough over an area of 500 km × 23 km to achieve the same accuracy as RSM. At least three height layers are required to achieve good accuracy. Bias-compensated RPCs give an absolute accuracy better than 1-5 pixels. The results demonstrate the potential of RFM as a replacement sensor model. This allows standardisation of product generation packages to handle multiple sensors.

REFERENCES


Résumé

On examine dans cet article la possibilité d’utiliser un modèle à fonction rationnelle (MFR) comme substitut au modèle du capteur de l’imagerie-satellite IRS-P6 LISS-4. Les coefficients polynomiaux rationnels (CPR), générés au départ en utilisant un modèle rigoureux du capteur (MRC) géoréférencé directement, sont compensés de tout biais avec un nombre minimal de points d’appui au sol et servent dans diverses applications photogrammétriques telles que la confection de modèles numériques des altitudes ou d’ortho-images. On compare les performances des MFR et MRC dans la modélisation du capteur de l’imagerie LISS-4 sur de longues bandes. Les résultats montrent que les précisions atteintes à l’aide du MFR se tiennent (dans le pire des cas) à un pixel des précisions obtenues avec le MRC. On a analysé la variation des erreurs en fonction du nombre de points de quasi-appui au sol (points d’ancrage) utilisés dans l’ajustement du MFR ainsi que les erreurs des modèles en fonction de la longueur de la bande d’images. La précision en nivellation du système ne se dégrade pas lorsque le MFR est ajusté avec des bandes allant jusqu’à 1200 km de long. On obtient une précision de localisation absolue de 1,5 pixel (~ 9 m) avec des CPR à biais compensés. Les résultats illustrent les possibilités du MFR pour remplacer le modèle rigoureux de capteur. Ce qui débouche sur la normalisation d’ensembles permettant de réaliser des produits par traitement de données issues de nombreux capteurs.

Zusammenfassung


Resumen

Este artículo examina la aplicación de un modelo de funciones racionales (MFR) como substituto del modelo del sensor de las imágenes IRS-P6 LISS-4. Los
coeficientes polinómicos racionales (CPR), obtenidos inicialmente con el modelo riguroso del sensor (MRS) mediante georreferenciación directa, una vez compensado el sesgo mediante un número mínimo de puntos de apoyo terrestre, se usan en aplicaciones fotogramétricas tales como el cálculo de modelos digitales de elevación y la generación de ortoimágenes. En el artículo comparamos el comportamiento del MFR y del MRS en el modelado del sensor LISS-4 para pasadas largas. Los resultados muestran que las exactitudes obtenidas utilizando el MFR están a menos de un pixel (en el peor de los casos) de las exactitudes obtenidas utilizando el MRS. Se analiza la variación del error en función del número de puntos de casi-control (puntos de anclaje) utilizados para el ajuste del MFR así como los errores del modelo respecto de la longitud de la pasada. La exactitud del sistema no se deteriora cuando se ajusta el MFR hasta una longitud de 1200 km. La exactitud de posicionamiento absoluto de 1,5 píxeles (~9 m) se consigue con los CPR a una vez compensado el sesgo. Los resultados demuestran el potencial del MFR como alternativa al modelo del sensor. Ello permite estandarizar las aplicaciones de producción para poderlas utilizar con múltiples sensores.
This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier’s archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright
Topographic data bases in the product generation of IRS_P6 Liss-4 imagery

M.V. Jyothi⁎, P.V. Radhadevi, S.S. Solanki

Abstract

A continuous and autonomous co-registration and geo-location of image data from multiple sensors with widely varying view angles and resolution is one of the unique challenges of IRS-P6 data processing. The Liss-4 camera is capable of imaging in either multi-spectral or panchromatic modes with steerability up to ±27°. As the satellite sweeps longer strips with oblique viewing configuration, data product generation requires an elevation database to accommodate the errors due to terrain topography. SRTM, GTOPO30, DCW etc. are becoming hidden information to product generation schemes. In this paper, we analyze and justify the requirement of inclusion of a global DEM in the product generation system for Liss-4 data. In the first part of the study, after a brief introduction of sensor model, comparison of elevation from SRTM and GTOPO30 is made which leads towards a conclusion that GTOPO30 is adequate for improving the accuracy. The second part deals with the impact of GTOPO30 on geometric accuracy. Thirdly we analyze the terrain effects on band-to-band registration of Liss-4 multispectral data. A perfect band-to-band registration cannot be achieved without inclusion of digital elevation model. Many Liss_4 data sets with different tilts that cover terrain patches with flat, rolling and highly undulating nature are studied and the results reported.

© 2007 International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS). Published by Elsevier B.V. All rights reserved.

Keywords: Georeferencing; Orthoimage; Band-to-band registration; DEM, GTOPO30

1. Introduction

The tendency to space images with higher resolution is continuing and more satellites are announced. The technological advancements in the area of sensors and the navigational supports from GPS/INS along with star sensor enable the satellite acquired optical imagery to be used in terrain mapping. The lack of qualified and accessible worldwide DEMs has been improved with the Shuttle Radar Topography Mission launched (SRTM) in February 2000(Jacobsen, 2001). The availability of the DEMs like SRTM, GTOPO 30 etc. make it possible to generate near ortho image without any other external inputs. This concept of rough ortho images becomes the trend in product generation, as it is less expensive. Quick Bird Standard images are being generated on the same lines (Buyuksalih et al., 2004). Euroimage (Eurimage Products & Services) supplies these Quick Bird Standard and Landsat GTCE(Geometric Terrain Corrected Enhanced) products which are normalized for the topographic relief over the reference ellipsoid using the coarser GTOPO30 with 30arc sec interval or SRTM 3arc sec data. The accuracies of these products are also rated better. This evolution in the product generation...
accommodating available GTOPO30 arc or SRTM 3 arc has its impact on the accuracies of low (system) level and geocoded products.

Indian Remote Sensing satellite IRS_P6 (RESOURCESAT) had been launched in 2003 with enhanced multi-spectral and spatial resolution with steerable optics. The satellite carried three sensors onboard: AWIFS; Liss-3; and Liss-4, with different spatial resolutions. Liss-4 is capable of imaging (at resolution 5.8m) in either multi-spectral (23km swath) or panchromatic (70km swath) modes with steerability up to +/- 27°. The navigation data from onboard GPS with INS provides better pointing accuracy. The attitude behavior of the sensor is so stable that it can be predicted over full pass. Data acquired by IRS_P6 satellite, with 5.8m resolution, is suitable to do mapping of the scale 1:50,000. More details about the satellite are available in IRS-P6 User Data handbook (NRSA, 2003b). One of the unique challenges of IRS-P6 data processing system is the georectification and co-registration of imagery from multiple cameras with widely varying view angles and multiple bands, which are separated in the focal plane in the along-track direction. To define the pointing direction of an imaging vector corresponding to the correct location, the following distortions should be minimized to zero (Toutin et al., 2002)

- Errors embodied in navigation, and attitude data or exterior orientation
- Errors in some of the parameters, which define pointing directions internal to the instrument, called interior orientation
- Distortions introduced by surface topography while imaging with significantly different view angles.

The first two types of errors can be corrected with a camera geometry model with GCPs, and an in-flight calibration. While generating products, the effect of terrain undulations should be respected including public domain DEMs. Even though resolution of IRS-P6 is similar to IRS-1C/D, the specified system level accuracy is about 300m (nadir view) whereas that of IRS-1C/D was about 2km. At off-nadir viewing angles, the planimetric pointing accuracy (mainly in longitude direction) can be poorer. The three arrays corresponding to the three bands of L4 camera are separated (along-track direction) in the focal plane but having a common optics. In view of the geometry, extreme bands with a time interval of as much as 2.1s will image the same line on the ground. An onboard yaw steering compensates the earth rotation effects, thus ensuring a first level registration between the bands. The remaining misregistration can be corrected using a camera geometry model, an in-flight calibration, an orbit attitude model and a global DEM. A ground processing, exploiting the same orbit acquisition and the knowledge about the alignments of the detectors on the focal plane, is to be done to achieve sub-pixel level registration and good geometric accuracy of the product. From this viewpoint, even a coarser DEM can be included as input that minimizes the errors globally. The residual errors can be handled comfortably with any matching algorithm before the bands are packed up and proceed for further classification or analysis.

Conventional photogrammetry employs an ortho rectification procedure to rectify the tilt and relief displacements (Jacobsen, 1997), which demands for an accurate DEM with rigorous rectification methods. The computational load to generate an ortho image slows down the product generation on the other hand. Handling of full pass data with an option to generate products of variable size that cover hundreds of kilometers along the pass is another major issue for the ortho rectification process. The satellite photogrammetric community is now re-orienting towards the compromising methods for rough orthorectified products, which will have minimized distortions and can be generated online.

Georeferencing of long strips of data has become easier with one or two ground control points in the pass. But the geometric distortions due to terrain undulations cannot be corrected without the height input for above reference level points (Wu and Lee, 2001). The direct georeferencing of IRS_P6 Liss-4 data to cater the needs of resource planning and disaster management is promoted for its platform stability and enhanced features. On these lines, data product generation models are designed to generate products with more precision and minimal interactive inputs. Progressing towards automation and to reduce the processing time, the current models are self-updated to accommodate the databases to retain their model accuracies while handling different types of terrains viewed with high oblique angles.

2. Mathematical model

Collinearity equations express the fundamental relationship that the perspective centre, image point and object point lies on a straight line i.e.

$$\begin{pmatrix}
f \\
x_p \\
y_p \\
z_p \\
\end{pmatrix} = d \cdot M \begin{pmatrix}
X - X_p \\
Y - Y_p \\
Z - Z_p \\
\end{pmatrix}$$

(1)

where \(f, x_p, y_p\) are the image coordinates, \((X, Y, Z)\) are the coordinates of the object point and \((X_p, Y_p, Z_p)\) are the co-ordinates of the perspective centre, \(d\) is the scale
factor and \( \mathbf{M} \) is the orthogonal rotation matrix to transform the geocentric to sensor co-ordinate system i.e.

\[
\begin{pmatrix}
  f \\
  -x_s \\
  -y_s
\end{pmatrix} = d \cdot \begin{pmatrix}
  m_{00} & m_{01} & m_{02} \\
  m_{10} & m_{11} & m_{12} \\
  m_{20} & m_{21} & m_{22}
\end{pmatrix} \begin{pmatrix}
  X - X_P \\
  Y - Y_P \\
  Z - Z_P
\end{pmatrix}.
\]

(2)

After rearrangement, Eq. (2) can be written as two equations.

\[
f_1 = (f m_0 + x_s m_1)(X - X_P) = 0
\]

(3)

\[
f_2 = (f m_2 + y_s m_1)(X - X_P) = 0
\]

(4)

where \( m_{ij} = (m_{00}, m_{01}, m_{02}) \) etc. The rotation matrix \( \mathbf{M} = \mathbf{Q}_{\text{GI}} \cdot \mathbf{Q}_{\text{TO}} \cdot \mathbf{Q}_{\text{OB}} \cdot \mathbf{Q}_{\text{BP}} \cdot \mathbf{Q}_{\text{PC}} \), where

- \( \mathbf{Q}_{\text{PC}} \) : CCD to payload transformation matrix
- \( \mathbf{Q}_{\text{BP}} \) : Payload to body transformation matrix
- \( \mathbf{Q}_{\text{OB}} \) : Body to Orbit matrix
- \( \mathbf{Q}_{\text{TO}} \) : Orbit to Inertial matrix
- \( \mathbf{Q}_{\text{GI}} \) : ECI to ECEF matrix.

The orbit attitude model developed for SPOT-1 and IRS-1C/D (Radhadevi and Ramachandran, 1994; Radhadevi, 1999) has been adapted to suit the camera characteristics of IRS-P6. The CCD to payload transformation matrix is included into the rotation matrix. Thus, a pixel in any band of any camera can be projected onto earth through a series of transformations and re-projected back to any other camera/band through a reverse series of transformations using the parameters of the corresponding cameras in \( \mathbf{Q}_{\text{PC}} \) matrix and thereby fix the relative positions of individual cameras and bands in the focal plane taking advantage of same acquisition. The given orbit and attitude data are fitted with polynomials. This initial trajectory is then updated with one or two GCPs.

Direct georeferencing (without GCPs) is not recommended for analyzing the effect of terrain undulation on accuracy because of two reasons.

1. System level error can be poorer in high oblique viewing images compared to nadir looking images. The deviations and fluctuations in the attitude information given also will manifest as positional errors. In undulating terrain, due to the combined effect of look angle, attitude fluctuations and height, we cannot apportion the errors and analyze the cause of each of them.

2. During the payload steering (PSM, for high looks), slight disturbances can be introduced in pitch and yaw direction (unwanted). These offsets are variable with step number. Even though these offsets, along with the constant biases between the payload and body axes, are computed through an in-flight calibration, unaccounted offsets, if any, will introduce variations in the location accuracy.

When we correct the orbit and attitude with ground control points, all the errors due to the viewing geometry will get corrected (to the GCP accuracy) and terrain effects alone will be left while transforming from image to ground.

3. Test details and results

The suitability of GTOPO30 for rough orthoimage generation is studied as the first part of the work. The second part emphasizes on the relief displacement of objects in oblique viewing geometries and the effect of GTOPO30 on error minimization with minimal control in product generation. The third and last part of the study focuses on the improvement of band-to-band registration of multiple bands of Liss-4 multi-spectral imagery. With the orbit attitude model described in the previous section, image to ground and ground to image transformation equations can be solved. Products are generated from 12 data sets having different look angles and covering undulating terrain. Details of the datasets are given in Table 1. The first 11 data sets are used for geometric accuracy evaluation and the data set 12, which is full pass data, is used for band-to-band registration evaluation.

3.1. Ground control and check points

The control and check points were collected from three different sources. Few points were identified from aerial orthoimages. Other points were from manual digitization of 1:50,000 and 1:250,000 scale topographic maps of Survey of India. The points from orthorectified aerial images with accuracy better than 1m provide the appropriate ground control for the high resolution data for its processing. But due to manual identification of these points in the Liss-4 images, they can have an error of 1 to 2 pixels. A 1:50,000 map has approximately an error of 12.5m in planimetry. In practice, while digitizing a specific feature for control, we have found that the error could be 25m-35m in planimetry for 1:50,000 map and about 100m for 1:250,000 map. The size of these errors was estimated.
by repeated digitization of a number of points. Height is approximated from the nearest contour or interpolated. Although it is clear that the control derived from map is worse than that derived from aerial ortho products or from ground survey, they were used as check points because the distribution over the entire length could not be ensured with surveyed GCPs.

3.2. GTOPO30 DEM data details

GTOP30 is global elevation data developed by U.S. Geological Survey at EROS Data center for regional scale topographic data at a coarser interval of 30arc sec (approximately 1km). GTOPO30 elevation data is compiled from eight different sources of elevation information.

![Fig. 1. (a). SRTM DEM of Western Ghats, (b). GTOPO30 DEM of Western Ghats, c). Histogram of heights along X profile, (d). Heights along X profile. Height values along the profile over Western Ghats taken from SRTM and GTOPO30 for analysis.](image-url)
Data is stored in 16-bit binary rectangular matrix form and is supported by every relevant meta data format in different auxiliary files. It also provides the information about the source data from which the elevations are drawn. This reveals the estimated accuracy of the points. The horizontal coordinate system is in latitude and longitude reference above WGS84 and the vertical unit in elevation above mean sea level. Half of global coverage is derived from DTED, one fourth of data from DCW and the rest from different high-resolution data. Accuracy and morphological analysis of GTOPO30 and SRTM DEMs done by N. Yastikli et al. (2006), over Istanbul areas where major source for GTOPO30 is DTED, shows the accuracy lies between 15.6m to 16.8m. Thus in areas where DTED is the basic input to GTOPO30, the process may produce better product compared to the locations where GTOPO30 is filled with DCW heights for the reason of non availability of better sources. The requirements of the DEM interval for the geometric process are dependent on the terrain slopes. Flat areas may require elevation point at coarser grid intervals. Steep slope terrain insists on a finer grid size for the corrections. The data organization of GTOPO30 is

Fig. 2. Height histogram and amplitude comparison of SRTM and GTOPO30 DATA over Himalayan region.

Fig. 3. RMS of differences in height (SRTM–GTOPO30) in meters analyzed over different types of terrains over Indian sub continent.
compact, and the Indian subcontinent is fully covered in a single tile. Thus, the data handling issues are put to minimum compared to the SRTM data. This encourages the data product generation to incorporate GTOPO30 as database. A comparative analysis of GTOPO30 with SRTM over Indian region is being carried out before its adoption to the scheme.

### 3.3. Study of SRTM with GTOPO as back drop DEM for product generation

First we analyze the feasibility of including SRTM DEM or GTOPO DEM in the product generation scheme. Comparison of SRTM and GTOPO data profiles on highly undulating Himalayan terrain as well as moderate Western Ghats was carried out. The data sets were compared at sampling interval of 1000m. The frequency curves and the amplitude curves show a great match (Figs. 1 and 2). In mountainous areas, accuracies of both GTOPO and SRTM data are poor. Unprocessed SRTM is not complete and has many holes. In high slope areas SRTM suffers from overlays and shadows thus provides data of poorer accuracy. GTOPO also equally suffers from data inaccuracies in these regions as it might have compiled from DCW charts because of non-availability of better data source.

![Diagram](image)

**Fig. 4.** Planimetric error in mono configuration of image due to the error in the input height ($dl = dh \cdot \tan \theta$).

![Image](image)

**Fig. 5.** GTOPO30 is used as external DEM. Vectors are digitized on map and the products generated with and without GTOPO30 DEM on. The vectors are analyzed for their closeness to the map based locations. (a) shows the vectors that are taken on ridgelines on mountains, which are better points. The offsets are shown in (b).

<table>
<thead>
<tr>
<th>Data_Id</th>
<th>Look angle</th>
<th>Absolute RMS error in product without GTOPO</th>
<th>Absolute RMS error in product with GTOPO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data_1</td>
<td>-24.23</td>
<td>206 m</td>
<td>56 m</td>
</tr>
<tr>
<td>Data_2</td>
<td>-10.05</td>
<td>160 m</td>
<td>20 m</td>
</tr>
<tr>
<td>Data_3</td>
<td>-9.83</td>
<td>25 m</td>
<td>6 m</td>
</tr>
<tr>
<td>Data_4</td>
<td>-4.32</td>
<td>16 m</td>
<td>15 m</td>
</tr>
<tr>
<td>Data_5</td>
<td>2.26</td>
<td>19.8 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Data_6</td>
<td>2.41</td>
<td>5 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Data_7</td>
<td>18.04</td>
<td>40 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Data_8</td>
<td>18.85</td>
<td>700 m</td>
<td>350 m</td>
</tr>
<tr>
<td>Data_9</td>
<td>23.76</td>
<td>55 m</td>
<td>11 m</td>
</tr>
<tr>
<td>Data_10</td>
<td>25.51</td>
<td>115 m</td>
<td>15 m</td>
</tr>
<tr>
<td>Data_11</td>
<td>25.51</td>
<td>910 m</td>
<td>310 m</td>
</tr>
</tbody>
</table>

![Table](image)
Seven geographic locations over Indian region are considered for the estimation of the elevation differences of SRTM and GTOPO. Only the terrains with sudden slope variations show discrepancies between the two data sets. In moderate terrain (height ranges from 0m to 1200m), GTOPO and SRTM-derived height variations are less than 50m at most of the points. Maximum height variation observed was 200m in Himalayan region. Fig. 3 shows the RMS error of computed differences in SRTM and GTOPO height values at different locations. The slope variations are similar along the profiles. The DEM from GTOPO is rasterized to show the different ranges of height and the RMS values are encircled on the locations. This encourages the product generation system to use GTOPO with the coarser grid as it is in much simpler form to handle and will account for gross errors. The availability of a better global DEM of uniform accuracy with higher resolution can reduce these residuals.

3.4. Geometric accuracy evaluation of products

Fig. 4 shows the planimetric error that can be introduced in mono configurations due to the error in the input height. A height error of 1000m will introduce a maximum of 500m planimetric inaccuracy on an image with extreme look angles of Liss-4 camera. This can be brought down considerably by using GTOPO heights. The multi-spectral Liss-4 data products are generated using a rigorous sensor model, with a single control point in each strip. By toggling the GTOPO option on/off, products of same extents are generated. Points, which are above or below the reference height, are taken for error computation. The well distributed points, more than 20 in numbers, on the products with and without GTOPO are compared with respect to maps/orthophotos from which control is derived. In snow bound regions of Himalayas where maps of only 1:250,000 are available, the control and check list is compiled from the clear-cut ridge junctions. The same features are digitized to compare the offsets from that of map. Vector overlays of the map products with and without GTOPO are

![Fig. 6. Errors at precise check points in products (of Liss-4 data with viewing angle 20°) generated with GTOPO30 and without GTOPO30 (average height=200 m).](image)

![Fig. 7. Terrain effect on offsets without and with GTOPO30 in product generation.](image)

![Fig. 8. Effect of GTOPO30 inclusion on BBR offsets along the pass where the points are equidistant at 35 km.](image)

### Table 3

<table>
<thead>
<tr>
<th>Data_ID</th>
<th>Look angle (θ)</th>
<th>Theoretical error in planimetry dh = dh · tanθ</th>
<th>Absolute RMS error in product without GTOPO</th>
<th>Absolute RMS error in product with GTOPO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data_3</td>
<td>−9.83</td>
<td>17 m</td>
<td>25 m</td>
<td>6 m</td>
</tr>
<tr>
<td>Data_6</td>
<td>2.41</td>
<td>4 m</td>
<td>5 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Data_7</td>
<td>18.04</td>
<td>32 m</td>
<td>40 m</td>
<td>10 m</td>
</tr>
<tr>
<td>Data_9</td>
<td>23.76</td>
<td>44 m</td>
<td>55 m</td>
<td>11 m</td>
</tr>
</tbody>
</table>

Theoretical error in the planimetry at the check points which are 100 m (dh) above the reference plane.
shown in Fig. 5(a) and (b). Vectors from map and products generated using GTOPO are very close. Other areas (Western Ghats) with better control from the 1:50,000 maps are processed and errors are summarized with respect to the same source. Some areas with better source of control (ortho image of accuracies better than 1m) are also studied. The shift in the longitude direction due to relief displacement is obvious in Fig. 5(b).

Table 2 shows the RMS error in products of data sets 1 to 11 with different view angles and different types of terrain. The model error and product error are matching and also they are in agreement with the theoretical computation of effect of look angle and terrain height on accuracy. Using one single GCP and check points from aerial ortho images, accuracies of the order of 5m to 10m over the terrain with height range 200m to 650m could be achieved with GTOPO heights used while generating the product. Products of highly undulating terrain over Himalayan region in data set 8, where height ranges from 4000m to 6700m were generated. The

Fig. 9. (a). Ground projection of different bands of Liss4. (b). Altitude effects on band-to-band registration of Liss4.
The planimetric shift along viewing direction was analyzed. The errors on North Western Himalayan region (look angle + 20.0°) with height range from 900m to 2500m at precise checkpoints are plotted as shown in Fig. 6. In high Himalayan regions the used DEM accuracy is also poorer where terrain induced distortions can be reduced but not completely minimized.

The data sets 3, 6, 7, and 8 are of the same ground area acquired with different look angles. This area has moderate undulations ranging from 200m to 650m height above mean sea level. The ground control point is derived from an aerial orthophoto. The reference plane is fixed at a height around 400m, i.e., approximately 100m above the reference plane. Table 3 shows the theoretical planimetric error products generated with and without use of GTOPO.

### 3.5. Band to band registration (BBR)

Continuous and autonomous co-registration and geo-location of image data from multiple bands of Liss4 camera is one of the basic requirements of IRS-P6 data processing. Differences in the viewing geometry between the bands as well as inconsistencies between the staggered timing and the viewing geometry at the time of image acquisition present an interesting challenge to this requirement. The three arrays corresponding to the three bands are physically separated in the focal plane but having a common optics. In view of the geometry, extreme bands with a time interval of as much as 2.1s will image the same line on the ground. During this time, the satellite would have covered a distance of about 14km on the ground and the earth would have rotated through an angle of 30°. A yaw steering is used to compensate the earth rotation effects, thus ensuring a first level registration between the bands. But this will leave misregistration error of few pixels due to many effects that are unaccounted. Therefore, a simple interactive registration and adjusting the raw images from different bands with respect to each other is not possible. A ground processing, exploiting the same orbit acquisition and the knowledge about the alignments of the detectors (here the angle between band2 and band4 is 0.9°) on the focal plane, is to be done to achieve sub-pixel level registration.

Co-registration using the imaging geometry and auxiliary data is produced indirectly by registering each band to a common co-ordinate system on the ground. An in-flight calibration is to be done to fix the absolute and
relative interior orientation parameters of the camera. Sensor alignment calibration is to provide improved knowledge of the geometric relationship between focal plane and attitude control reference system. Initial interior orientation parameters of IRS-P6 were determined by pre-launch lab measurements. Some of these parameters are again calibrated during the first few months of the mission and later on updated based on the quality assessments. Refining the pre-launch sensor alignment knowledge is critical to ensure that systematic product accuracy specifications are met. Direct georeferencing of different bands is done using the given navigation data. The georeferenced products are compared and evaluated for co-registration discrepancies relative to the nadir band. Band 3 of L4 is taken as the primary sensor. The offsets between different bands are included in the adjustment model. This will ensure the alignment across the track for different bands by accounting the errors due to focal length variation etc. The alignment offsets between the bands in the line direction are mainly due to the terrain undulation. This is because of the pitch viewing angles of the Liss-4 bands in the same focal plane. Including a global DEM in the product generation minimizes the effect of terrain undulation on BBR accuracy as shown in Figs. 7 and 8.

The three CCD array alignments with respect to normal are shown in Fig. 9(a) and the distortion due to terrain elevation error with view angle is shown in Fig. 9(b). Full pass data that cover a terrain patch that has plain, undulating and varying heights along the pass (data set 12 with orbit number 12859 full pass over Eastern Himalayan to Bay of Bengal) are considered for this study. The look angle is 2.50°. Conjugate points were taken with good distribution along the pass as shown in Fig. 10 with its length being 1500km. The band-to-band offset is a function of the terrain height on the ground and it is shown in Fig. 7. The offsets are seen to confine to a single pixel, as shown in Fig. 7 in products generated with the inclusion of GTOPO. The remaining misregistration error will be a bias (over the entire image) and can be removed by an automated matching process at a single point. This study covering a longer strip shows that the control height may not suffice when the height is set to the reference plane level. As the control points are taken on clear cut ground

---

![Image](image.png)

Fig. 11. (a). GTOPO30 DEM in original 1 km resolution for a portion of full pass data (data set 12). (b). The north–south profile heights from GTOPO30 corresponding to (a) of the strip approximately of length 800 Km (X axis shows the samples with 1 km resolution in line direction, Y axis shows the heights in meters).
but not on convex terrain surface which are either poorly textured or rarely have an identifiable feature, the image locations suffer severely from the height residuals from the level plane at high points. Providing a coarse 1000m posting DEM dramatically brings down the residuals to pixel level, which is the prime requirement of the multi-spectral image data products.

The data (data set 12) coverage of a full pass over the Eastern part of India is shown with the corresponding GTOPO30 DEM raster layer in Fig.10. Some of the conjugate points, which are used for BBR analysis, are shown along the pass over the terrain with the corresponding heights. This gives a complete idea about the strip data details and the conjugate point distribution along the pass. Half of the strip length covers Eastern Himalayas where mountain peaks, which rise above 6000m, are covered with snow. This range of heights is large enough as shown in the along track height profile plotted using ENVI soft ware, to assess the impact of terrain in band-to-band offsets. Though the distribution is not maintained at regular interval, the points show a good spread along the pass. The height range is 0m to 6000m for these points as shown in Fig.11.

4. Conclusions

GTOPO30 DEM for its data adequacy at coarser resolution enabled a product with better accuracies. The data handling issues are minimal and projection and datum related issues are negligible at 1km posting. GTOPO30 provides heights even for no map zones to go ahead for product generation. The system level product accuracies are also seen to be improved over hilly regions. For images over varying slopes, the inaccuracy is brought down considerably from hundreds of meters to tens of meters with OA model with single control and GTOPO30. In the test bed area with 200m to 650m height variation, where the control is taken from orthorectified aerial data with sub meter accuracy, this model proves that accuracy in the order of one pixel in the product is achievable. The analysis of products from multiple data sets with varying look angles shows that the theoretical offset and the observations are in agreement. The band to band offsets are efficiently handled by the model and are brought down to less than one pixel even in undulating terrain. The improvement in planimetry and band-to-band alignment shows that the inclusion of ready to plug in DEM databases is of great help in automated product generation. It also reduces the burden of height control at grid computation when full pass data is to be processed. Thus, data bases of DEM with less complication in its storage and handling can be adequately used in production of coarser ortho images from P6 Liss-4 data. This gives a re-orientation towards the compromising methods for rough orthorectified products, which can be generated online.

Acknowledgments

The authors gratefully acknowledge Dr R Krishnan, the Director and R Ramachandran, Deputy Director, ADRIN, for their encouragement and support for this work.

References


