IKONOS STEREO FEATURE EXTRACTION - RPC APPROACH

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ABSTRACT

IKONOS stereo imagery is particularly well suited for 3-D feature extraction. The sophisticated geometric and radiometric characteristics of the IKONOS sensor provide the end user with excellent metric accuracy and wealth of information which can be used for interpretive analysis. In order to be able to perform stereo feature extraction with sufficient accuracy the very complex IKONOS sensor model needs to be effectively communicated to softcopy photogrammetric software. The Rational Polynomial Camera (RPC) model accomplishes such task with great efficiency and no discernable loss of accuracy. Since the RPC IKONOS model is expressed simply as a ratio of two cubic polynomials it is generic enough to be easily interfaced with most COTS photogrammetric packages. Furthermore, it contains enough degrees of freedom to maintain full accuracy of the physical IKONOS sensor model. The paper demonstrates that the RPC IKONOS model differs by no more than 0.04 pixel from the physical model, with the RMS error below 0.01 pixel.

IKONOS GEOMETRIC AND RADIOMETRIC CHARACTERISTICS

The IKONOS sensor radiometric properties such as 11-bit radiometric resolution and 4-band multispectral capability provide the end user with wealth of information. The pan-sharpened 1-meter GSD (Ground Sample Distance) color images are particularly well suited for stereo feature extraction. These are produced using a pan-sharpening process that optimally combines the lower resolution multispectral data with 1-meter GSD panchromatic image resulting in high resolution 1-meter GSD color images.

Geometric accuracy of IKONOS stereo products depends on the availability and usage of ground control points. Without ground control the accuracy is determined by the knowledge of the satellite ephemeris and attitude. The satellite ephemeris is determined using the on-board GPS receivers and sophisticated ground processing of the GPS data. The satellite attitude is determined by optimally combining the star tracker data with the measurements taken by the on-board gyros which measure the relative attitude changes during image acquisition [Dial, 2000]. As seen in Table 1, use of ground control points significantly improves stereo metric accuracy. It should be noted that IKONOS stereo accuracy has been rigorously tested and thoroughly verified during the On-Orbit Acceptance Test program.

Table 1. IKONOS Stereo Metric Accuracy [Dial, 2000]

Stereo Product Type	Horizontal Accuracy, CE90	Vertical Accuracy, LE90
Single stereo pair, without Ground Control	25.0m	22.0m
Single stereo pair, with Ground Control	2.0m	3.0 m

IKONOS SENSOR MODEL

The sensor model relates the image coordinate space to the object coordinate space. It allows one to determine object coordinates of an object being imaged from the image coordinates. For an image taken by a pushbroom sensor each image line is taken at a different instance of time (see Figure 1), i.e. each scan line has its own perspective projection model. The exterior orientation parameters, i.e. the attitude angles (roll(t), pitch(t) and yaw(t)) and position of the perspective center (PC(t)) change from scan line to scan line. The interior orientation parameters, which comprise focal length, principal point location, lens distortion coefficients, and other parameters directly related to the physical design of the sensor, are the same for the entire image.

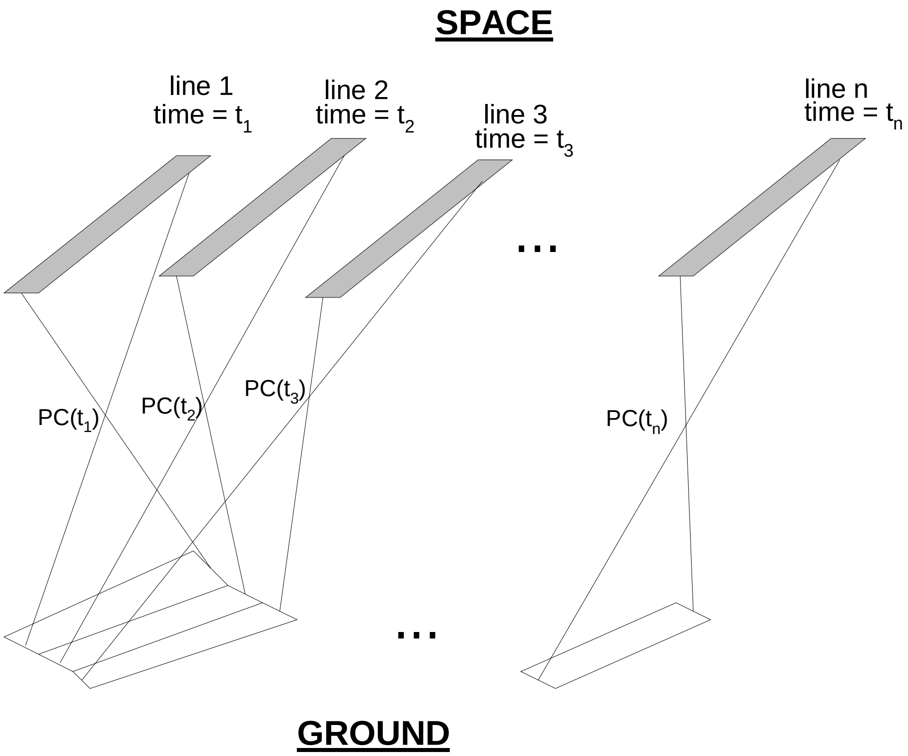

Figure 1. Pushbroom Sensor

Needless to say, owing to the dynamic nature of a pushbroom sensor, the physical IKONOS sensor model is extremely complex making it enormously difficult to implement in the COTS stereo exploitation environment. To facilitate transfer of IKONOS stereo data and to aid COTS software vendors in developing support for IKONOS imagery, Space Imaging uses the Rational Polynomial Camera (RPC) model in lieu of the physical IKONOS sensor model to communicate the stereo imaging geometry to the end user. As demonstrated below, the RPC model accomplishes these objectives with great efficiency and no discernable loss of accuracy

RATIONAL POLYNOMIALS

The Rational Polynomial Camera (RPC) model relates the object space (latitude, longitude, height) coordinates to image space (line, sample) coordinates. The RPC functional model is of the form of a ratio of two cubic functions of object space coordinates. Separate rational functions are used to express the object space to line, and the object space to sample coordinates relationship.

The line RPC model is given as

$$l = \frac{Num_L(U,V,W)}{Den_L(U,V,W)}$$

where

$$\begin{aligned} Num_L(U,V,W) &= a_1 + a_2 \cdot V + a_3 \cdot U + a_4 \cdot W + a_5 \cdot V \cdot U + a_6 \cdot V \cdot W + a_7 \cdot U \cdot W + a_8 \cdot V^2 + a_9 \cdot U^2 \\ &+ a_{10} \cdot W^2 + a_{11} U \cdot V \cdot W + a_{12} \cdot V^3 + a_{13} \cdot V \cdot U^2 + a_{14} \cdot V \cdot W^2 + a_{15} \cdot V^2 \cdot U + a_{16} \cdot U^3 + a_{17} \cdot U \cdot W^2 \\ &+ a_{18} \cdot V^2 \cdot W + a_{19} \cdot U^2 \cdot W + a_{20} \cdot W^3 \end{aligned}$$

$$
\begin{aligned}
Den_L(U,V,W) = {} & b_1 + b_2 \cdot V + b_3 \cdot U + b_4 \cdot W + b_5 \cdot V \cdot U + b_6 \cdot V \cdot W + b_7 \cdot U \cdot W + b_8 \cdot V^2 + b_9 \cdot U^2 \\
& + b_{10} \cdot W^2 + b_{11} U \cdot V \cdot W + b_{12} \cdot V^3 + b_{13} \cdot V \cdot U^2 + b_{14} \cdot V \cdot W^2 + b_{15} \cdot V^2 \cdot U + b_{16} \cdot U^3 + b_{17} \cdot U \cdot W^2 \\
& + b_{18} \cdot V^2 \cdot W + b_{19} \cdot U^2 \cdot W + b_{20} \cdot W^3
\end{aligned}
$$

Likewise the sample RPC model is expressed as

$$s = \frac{Num_S(U,V,W)}{Den_S(U,V,W)}$$

where

$$
\begin{aligned}
Num_S(U,V,W) = {} & c_1 + c_2 \cdot V + c_3 \cdot U + c_4 \cdot W + c_5 \cdot V \cdot U + c_6 \cdot V \cdot W + c_7 \cdot U \cdot W + c_8 \cdot V^2 + c_9 \cdot U^2 \\
& + c_{10} \cdot W^2 + c_{11} U \cdot V \cdot W + c_{12} \cdot V^3 + c_{13} \cdot V \cdot U^2 + c_{14} \cdot V \cdot W^2 + c_{15} \cdot V^2 \cdot U + c_{16} \cdot U^3 + c_{17} \cdot U \cdot W^2 \\
& + c_{18} \cdot V^2 \cdot W + c_{19} \cdot U^2 \cdot W + c_{20} \cdot W^3
\end{aligned}
$$

$$
\begin{aligned}
Den_S(U,V,W) = {} & d_1 + d_2 \cdot V + d_3 \cdot U + d_4 \cdot W + d_5 \cdot V \cdot U + d_6 \cdot V \cdot W + d_7 \cdot U \cdot W + d_8 \cdot V^2 + d_9 \cdot U^2 \\
& + d_{10} \cdot W^2 + d_{11} U \cdot V \cdot W + d_{12} \cdot V^3 + d_{13} \cdot V \cdot U^2 + d_{14} \cdot V \cdot W^2 + d_{15} \cdot V^2 \cdot U + d_{16} \cdot U^3 + d_{17} \cdot U \cdot W^2 \\
& + d_{18} \cdot V^2 \cdot W + d_{19} \cdot U^2 \cdot W + d_{20} \cdot W^3
\end{aligned}
$$

U, *V*, and *W* are the normalized object space (••••, *h*) coordinates where •••••and *h* are latitude, longitude and height, respectively

$$U = (\varphi - O_\varphi) / SF_\varphi$$
$$V = (\lambda - O_\lambda) / SF_\lambda$$
$$W = (h - O_h) / SF_h$$

l and *s* are normalized image space (*L*, *S*) coordinates where *L*, and *S* are line and sample coordinates, respectively

$$l = (L - O_L) / SF_L$$
$$s = (S - O_S) / SF_L$$

$O_\lambda, O_\varphi, O_h, O_L, and\ O_S$ are the mean values

$$O_\lambda = \frac{1}{n} \sum \lambda$$
$$O_\varphi = \frac{1}{n} \sum \varphi$$
$$O_h = \frac{1}{n} \sum h$$
$$O_L = \frac{1}{n} \sum L$$
$$O_S = \frac{1}{n} \sum S$$

$SF_\lambda, SF_\varphi, SF_h, SF_L, and\ SF_S$ are the scale factors

$$SF_\lambda = \max(|\lambda_{\max} - O_\lambda|, |\lambda_{\min} - O_\lambda|)$$
$$SF_\varphi = \max(|\varphi_{\max} - O_\varphi|, |\varphi_{\min} - O_\varphi|)$$
$$SF_h = \max(|h_{\max} - O_h|, |h_{\min} - O_h|)$$
$$SF_L = \max(|L_{\max} - O_L|, |L_{\min} - O_L|)$$
$$SF_S = \max(|S_{\max} - O_S|, |S_{\min} - O_S|)$$

RPC ACCURACY ANALYSIS

The loss of accuracy due to using the RPC model in lieu of the physical IKONOS camera model was analyzed using the physical IKONOS camera model as a reference. Rational Polynomial Camera model was fitted to a data grid generated using the physical camera model, utilizing a least squares estimation approach described below. The accuracy of RPC models was subsequently computed from a grid of independent check points.

RPC Estimation

A least-squares approach was utilized to determine the RPC model coefficients a_i, b_i, c_i, and d_i from a 3-dimensional grid of points generated using the physical IKONOS camera model. The 3-D grid of object points was generated by intersecting the rays emanating from a 2-D grid of image points – computed using the physical IKONOS camera model – with a number of constant elevation planes (see Figure 2). The estimation process, identical in principle for both the line and sample RPCs, was performed independently for each of the RPC models (i.e. line and sample RPC models).

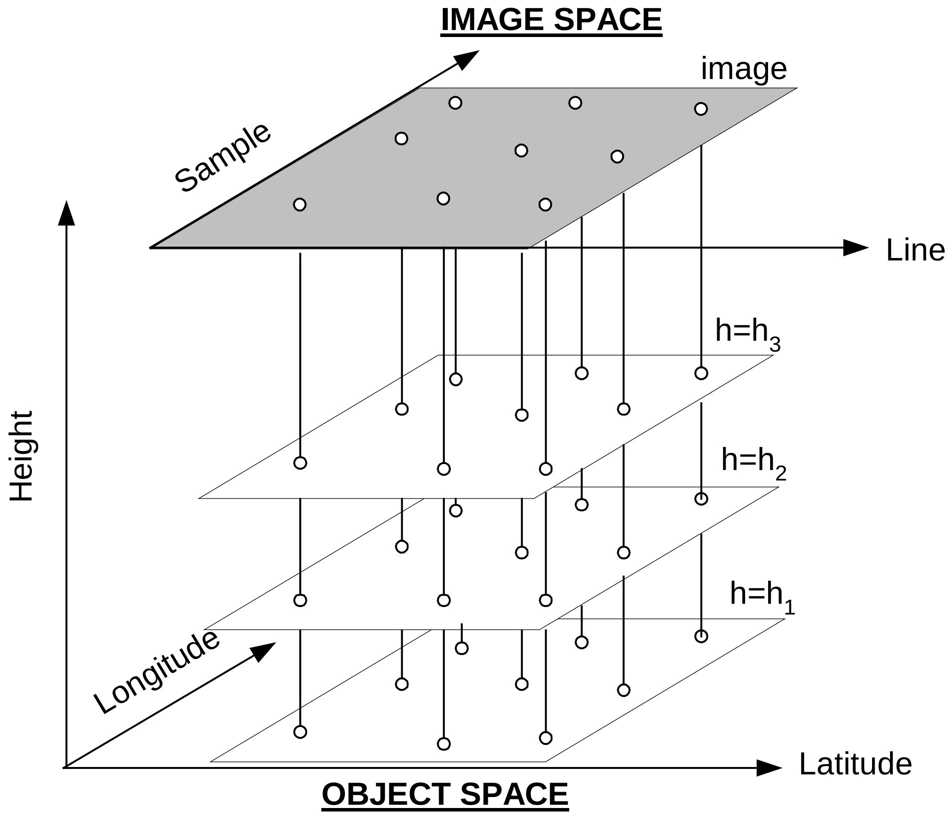

Figure 2. RPC Generation

RPC Accuracy Determination

The results of accuracy analysis of the RPC sensor model are given in this section. Accuracy of the RPC model was assessed using the physical IKONOS camera model as a reference. RPC models were fitted to a data grid generated using the physical IKONOS camera model, utilizing the math model given above. The accuracy of RPC models was subsequently computed from a grid of independent check points.

RPC accuracy was computed for a strip length of 100 km – for a series of imaging scenarios:

- roll angle of the camera was varied between $0^o$and 30^o,
- pitch angle of the camera was varied between 0^o and 30^o),
- scan azimuth ranged from 0^o through 360^o,
- latitude ranged from $0^o$to 60^o.

The results of RPC accuracy analysis are given in Table 2.

Table 2. RPC Accuracy

RPC model	**Post-fit RMS error [pixels]**	**RMS error using independent check points [pixels]**	**Max error using independent check points [pixels]**
line	0.01	0.01	0.04
sample	0.01	0.01	0.03

STEREO FEATURE EXTRACTION

IKONOS stereo images are taken on the same orbital pass, one in a forward and the other in a backward direction. This results both in a superior image quality because of a short time span between the two images resulting in same lighting conditions and scene content, and better metric accuracy that that of the "cross-track" stereo satellite systems which acquire stereo pairs from different orbital passes [Dial, 2000].

IKONOS stereo images are block adjusted by Space Imaging with or without ground control -- using the physical IKONOS camera model -- prior to generating the RPCs. Since, as shown above, the RPC sensor model is as accurate as the physical IKONOS camera model, the end user always gets the stereo product that maintains full accuracy of block adjustment performed at Space Imaging.

The block adjusted stereo images are always resampled to epipolar geometry. As a result they can be used directly for stereo feature extraction without the any additional adjustment and resampling.

The object-to-image relationship for each stereo image is expressed by a sample RPC and a line RPC. To determine 3-dimensional object coordinates of a point one needs to measure its line and sample coordinates on both stereo images. This results in following set of equations

$$l^{left} = \frac{Num_L^{left}(U,V,W)}{Den_L^{left}(U,V,W)}$$

$$s^{left} = \frac{Num_S^{left}(U,V,W)}{Den_S^{left}(U,V,W)}$$

$$l^{right} = \frac{Num_L^{right}(U,V,W)}{Den_L^{right}(U,V,W)}$$

$$s^{right} = \frac{Num_S^{right}(U,V,W)}{Den_S^{right}(U,V,W)}$$

where

s^{left}, l^{left}, s^{right} and l^{right} are the measured (normalized) image coordinates of a point on the left and the right image, respectively,

and U, V, and W are the unknown (normalized) object space coordinates.

Since there are four equations and only three unknowns, the above system of equations is overdetermined. The least-squares criterion minimizing the second norm of the residual errors can be used to find the solution (see Figure 3).

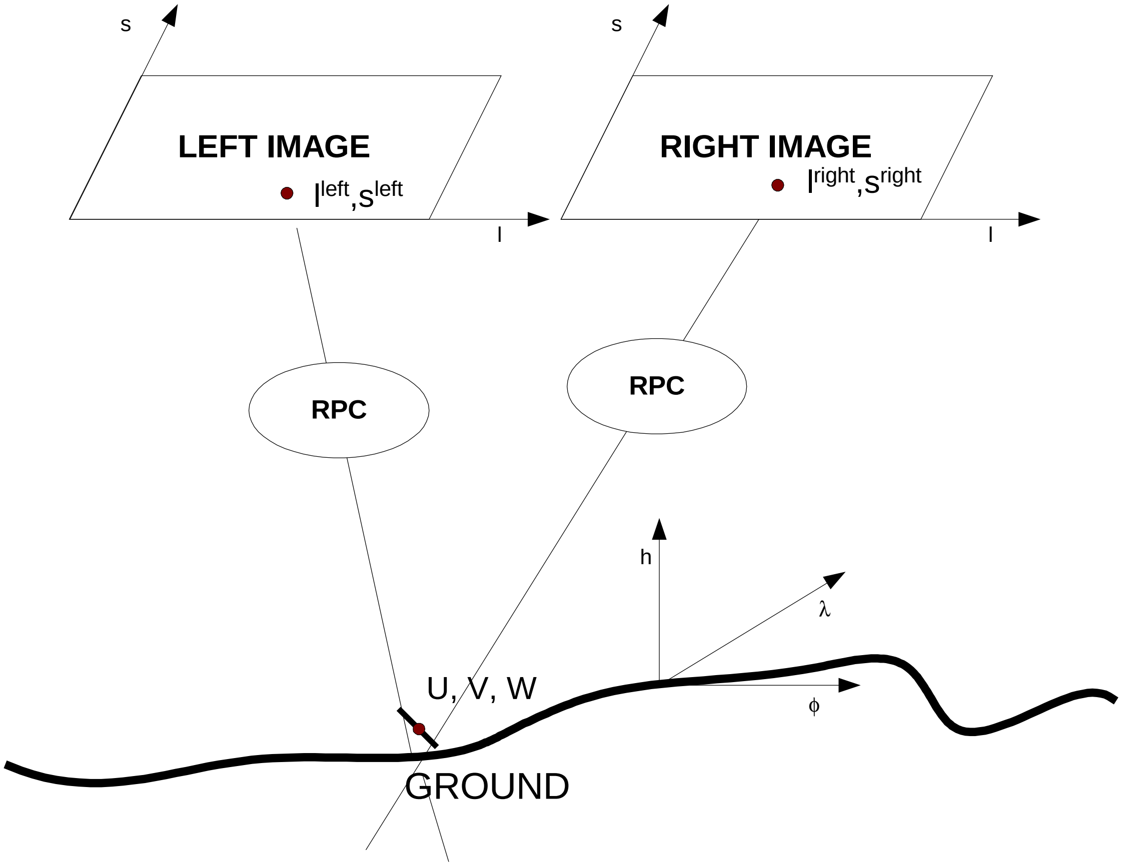

Figure 3. Stereo Feature Extraction

It should be noted that a number of COTS softcopy photogrammetric software packages support IKONOS stereo products, including the RPC sensor model. These are LH-Systems SOCET SET, ERDAS Stereo Analyst and Z/I Image Station. Thus the end user can now perform stereo feature extraction, DEM generation and orthorectification using IKONOS stereo data, with the metric accuracy being the same as the accuracy of the Space Imaging physical IKONOS sensor model.

CONCLUSIONS

The sophisticated geometric and radiometric characteristics of the IKONOS stereo imagery make it particularly well suited for 3-D feature extraction.

The very complex physical IKONOS sensor model is efficiently communicated to the softcopy photogrammetric software by the Rational Polynomial Camera (RPC) model.

The RPC model contains enough degrees of freedom to maintain full accuracy of the physical IKONOS sensor model. The paper demonstrates that the RPC IKONOS model differs by no more than 0.04 pixel from the physical model, with the RMS error below 0.01 pixel.

Since IKONOS RPC sensor model provides a generic interface it facilitates software development. It is currently supported by a number of COTS softcopy photogrammetric software packages.

REFERENCES

Dial, G. (2000). IKONOS Satellite Mapping Accuracy. In: *Proceedings of ASPRS 2000*. Washington DC, May 26th.