Applied GIS
a free, international, refereed e-journal
(ISSN: 1832-5505)

URL:
http://www.appliedgis.net

Volume 5, Number 2
September, 2009

CONTENTS:

All papers published during 2009 are part of *Volume* 5.
Each paper constitutes one *Number.*

Hence this paper should be cited as:

Jain, K., Ravibabu, M.V., Shafi, J.A. & Singh, S.P. (2009) – Using Rational Polynomial Coefficients (RPC) to generate digital elevation models - a comparative study, *Applied GIS*, 5(2), 1-11

Using Rational Polynomial Coefficients (RPC) to generate digital elevation models - a comparative study

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Abstract: Models based on Rational Polynomial Coefficients (RPC) have recently sparked considerable interest within the remote sensing community because of their simplicity and accuracy. Indeed, some commercial, high-resolution, satellite imagery data are now supplied with RPC even though they do not disclose their physical sensor model. RPC, with stereo pairs, enable full photogrammetric processing including 3-D reconstruction, generation of digital elevation models (DEMs), orthorectification, block adjustment and feature extraction. In the light of this we here present a complete methodology for generating a DEM from stereo satellite images by using rational polynomial coefficients of the imaging geometry. We also conduct a study of the accuracy and performance, in terms of generating a stereo images-based DEM using RPC within three well known software packages. Our results are evaluated using sample data that was captured by IKONOS.

Keywords: Accuracy, digital elevation model, rational polynomial coefficients, stereoscopic images, IKONOS.

1.0 Introduction

Grid-based Digital Elevation Models (DEMs) are widely used in surveying, mapping, urban planning, engineering, image orthorectification, GIS, land classification and image processing. There are several conventional methods of data acquisition, which include field surveying followed by digitizing contour maps in preparation for inputting. However, DEM generation can be an expensive procedure (Habib et al., 2004), and so usage of these techniques is often limited or even discouraged by project managers.

Nevertheless, using digital photogrammetry with satellite data in order to build a DEM has been a vibrant research and development topic over the last thirty years, and the fundamental task of photogrammetry is to rigorously establish the geometric relationship between the sensor image spaces and ground object space. The latter can be achieved by implementing a physical sensor model from which one can derive, strictly from its imagery, information about the terrain to be modeled.

But such a procedure has various drawbacks. Firstly, it requires explicit understanding of each of the physical parameters and a high level of expertise (Hu et al. 2004). Also, intentional concealment of the physical sensor model by the DEM data provider restricts the confidence with which it can be used.

This is why generalized sensor models based on Rational Polynomial Coefficients (RPC) have recently attracted considerable interest inside the remote sensing community. They are simple and accurate, as demonstrated by the fact that some commercial, high-resolution, satellite imagery data are now supplied with RPC without the need for discoloration of the physical sensor model used to generate it.

1.1 The Rational Polynomial Coefficients (RPC) model

In providing a generic representation of the camera's or sensor's object-image geometry, the RPC model allows derivation of a simple, efficient and accurate DEM. Indeed, it has been demonstrated by Grodecki (2001), Grodecki and Dial (2003), Tao and Hu (2002) and Fraser and Hanley (2003) that RPC provides the end users of high-resolution, satellite imagery with an ability to perform full photogrammetric processing, including block adjustment, 3-D feature extraction, DEM generation and orthorectification. The beauty of using RPC is that it is sensor independent, which means that the user does not need to know all of the specific internal and external camera information. In short, it is simply a lot less complicated than other approaches.

The name "rational polynomial" derives from the fact that the model is expressed as the ratio of two cubic polynomial expressions. It is a simple, empirical mathematical model that relates image space (line and column position) to latitude, longitude, and height above the ground. In other words, it provides a functional relationship between the object space's □*, λ, h* coordinates and the image space (L, S) coordinates, as shown in equation (1):

$$L = \frac{N_s\,(\emptyset,\ \lambda,\ h)}{D_s\,(\emptyset,\ \lambda,\ h)}, \qquad S = \frac{N_l\,(\emptyset,\ \lambda,\ h)}{D_l\,(\emptyset,\ \lambda,\ h)} \qquad (1)$$

where □ is the geodetic latitude, *λ* is the geodetic longitude, *h* is the height above the earth's ellipsoid surface, S is the image sample and L is the line. Hence any single image involves two such rational polynomials, one for calculating the sample position and one for computing the line position.

1.2 Objective of this study

Defence department-owned as well as civilian-owned spatial data laboratories are now realizing that there is a great need for fast, economical, accurate and high resolution DEMs, and given that the conventional methods for DEM generation are very time consuming, it is clear that digital, photogrammetric mapping techniques will be adopted more and more widely. Moreover, RPC technology can improve the efficiency and productivity of such techniques, and this is why it has already been implemented within several software packages.

Yet such implementations are not as transparent as would be the case if the programming deployed was "in house", and so there is some interest attached to the result of trials that are designed to compare the accuracy of the DEMs generated by using different software packages. We have decided, therefore, to compare the results obtained from using RPC within three photogrammetric software packages:

1. RSI ENVI (version 4.3) DEM Extraction Module.
2. ERDAS IMAGINE (version 8.7) OrthoBase, and
3. PCI Geomatica (version10) OrthoEngine pro

1.3 Data Used

IKONOS stereo images were used for this study. They were provided in Geo-tiff format along with an RPC metadata file in text format at 0.82 meter spatial resolution. The RPC file contains the 78 coefficients, and the metadata contains the ground control points for both the left and right image. The stereo pairs, which were acquired on March 19, 2001, cover a 9045 meters perimeter area of 4.76 kms^2.

The IKONOS stereo images were taken on the same orbital pass, one from a forward-angled sensor and the other from a backward-angled sensor. This means that given the calibration between the sensor sets, superior image quality can be claimed, because the short time span between the two images ensures that the same lighting conditions, and scene content, is pertain to each of the stereo pair of images.

2.0 Methodology

Whether the data refers to along-track or to across-track acquisition, the DEM extraction process requires a stereo pair of images containing RPC positioning, after which extraction of a DEM typically involves the following steps:

1. sensor camera modelling,
2. tie point collection,
3. epipolar image creation,
4. image matching,
5. DEM geocoding, and
6. DEM editing.

In the sensor camera modelling step, the goal is to construct the geometrical relationship between 2-D image space and 3-D ground space, and here the relationship between image space and ground space is modelled through RPC. RPC is provided with IKONOS, ORBVIEW-3 and QuickBird data, and the coefficients can be computed by software on the fly for SPOT and ASTER data.

The second step involves the tie point selection from the stereo pair. First, a number of evenly distributed, distinct feature points from the left image are extracted, and then an image-matching technique is applied to find their conjugate points in the right image.

Epipolar images are stereo pairs in which the left and right images are oriented so that ground features have the same y-coordinates on both images and epipolar geometry is based on the fact that a ground point and the two optical centres of the stereo images (or in the case of pushbroom sensors, the optical centres of the particular scan lines containing the pixels representing that point) lie on the same plane. This means that a given point in one image, and its conjugate point in the second image, must lie on a known line in the second image. Such reasoning is used to create epipolar images in order to reduce the search space for finding corresponding image points during automatic image matching.

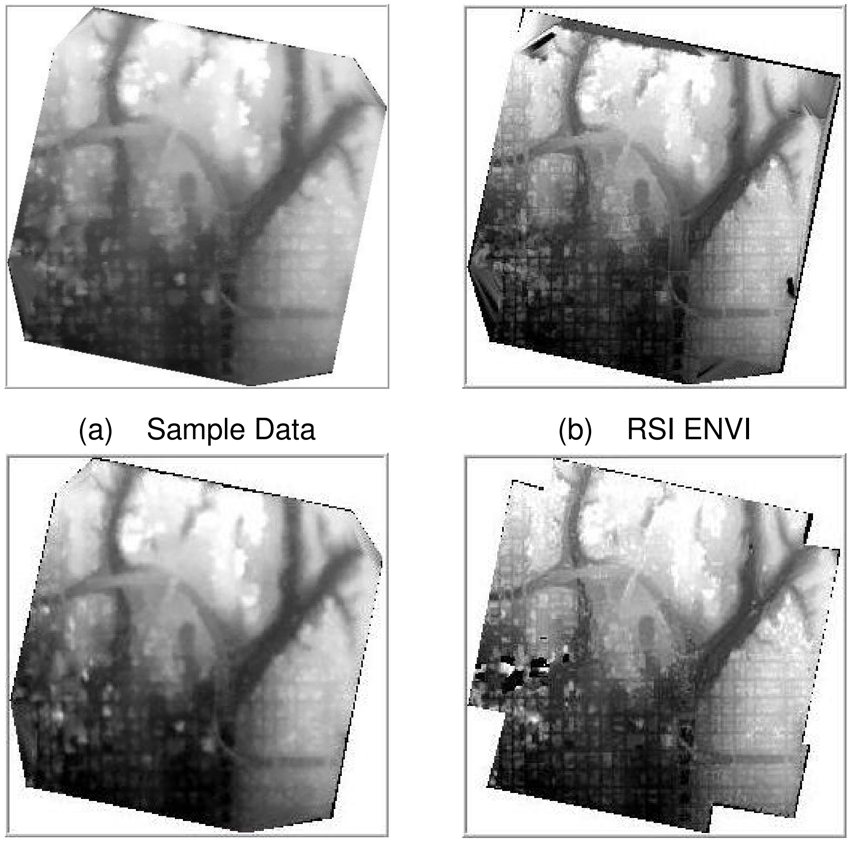
Image matching enables the software to find conjugate points within both left and right images which correspond to the same ground feature. The output of an image-matching procedure is typically called a parallax image, which stores the x-coordinate difference (along epipolar lines) between the left and right images. It is the parallax image that is then used to build a DEM. Hence the quality of the image matching is what largely determines the quality of the output DEM.

Typically, the DEM generated at this stage is not in the projection system and the output pixel spacing that is eventually desired. Therefore, the output DEM from the epipolar projection is re-projected into the desired output map projection and resolution.

However, the results often benefit from a manual review and editing to remove errors, and so DEM editing tools allow the user to modify DEMs by defining regions to which one or other of the DEM modification processes should be applied.

Note that all the software tools deployed for DEM generation in this study call for evenly-distributed tie points. Accordingly, they are generated automatically, or semi-automatically, and then edited to minimize parallax error. The maximum number of tie points generated by ERDAS and by Geomatica tools is limited, but the number generated by the ENVI tool is only limited by the configuration of the computer being used. Moreover, Geomatica and ENVI provide full image-matching support, which is why they can generate all tie points automatically, but in deployment of the ERDAS tool, the first tie points have to be selected manually, and then the automated procedure can begin.

Figure 1 shows the result of applying the various DEM generators, and on visual analysis it seems that the DEM generated using ERDAS and DEM provided with IKONOS data is the same in terms of the clipped area.



(a) Sample Data (b) RSI ENVI

(c) ERDAS Imagine (d) PCI Geomatica

Figure 1 - DEMs generated using different software packages

3.0 Results and analysis

Table 1 makes a statistical comparison between the DEMs by listing their minimum and maximum elevations, along with their means and standard deviations. It can be seen that the result generated by ERDAS is similar to that of the sample DEM that was provided by the IKONOS Geo-Ortho kit.

Serial No	DEM Source	Elevation Range		Mean	Std deviation
		Minimum	Maximum		
1.	Sample Data	-29.807718	66.452492	3.227595	24.55971
2.	ENVI	-50.000000	77.000000	-0.380813	25.583584
3.	ERDAS	-28.767096	64.477707	4.193706	24.658877
4.	Geomatica	-30.000000	80.000000	-6.985711	26.041936

Table 1 - Mean and Standard Deviation of DEM

Note also that the (slight) difference between the ENVI and Geomatica DEMs must result from the Geomatica tool's input requirement that the minimum and maximum elevation values (shown in Table 1) must be provided by the user before DEM generation can start. The ENVI tool, on the other hand, takes the height offset and the scale factors from the RPC file in order to calculate the minimum and maximum scene elevation.

The corresponding Root Mean Square (RMS) errors are shown in Table 2.

	Sample Data	ENVI	ERDAS	Geomatica
Sample Data	-	6.835854	6.589727	8.303025
ENVI	6.835854	-	5.504751	8.081811
ERDAS	6.589727	5.504751	-	7.996158
Geomatica	8.303025	8.081811	7.996158	-

Table 2 - Root Mean Square errors of the elevations given by different software packages

It can be seen that the ERDAS model is the most accurate of the three generated for this study. That is, the mean and the standard deviation of the DEM generated using ERDAS is close to the mean and standard deviation of the sample data DEM (Table 1) and the RMS error is lowest for the elevations from the DEM generated by ERDAS (Table 2).

Variations in elevation obtained from the different sources are plotted in Figure 2.

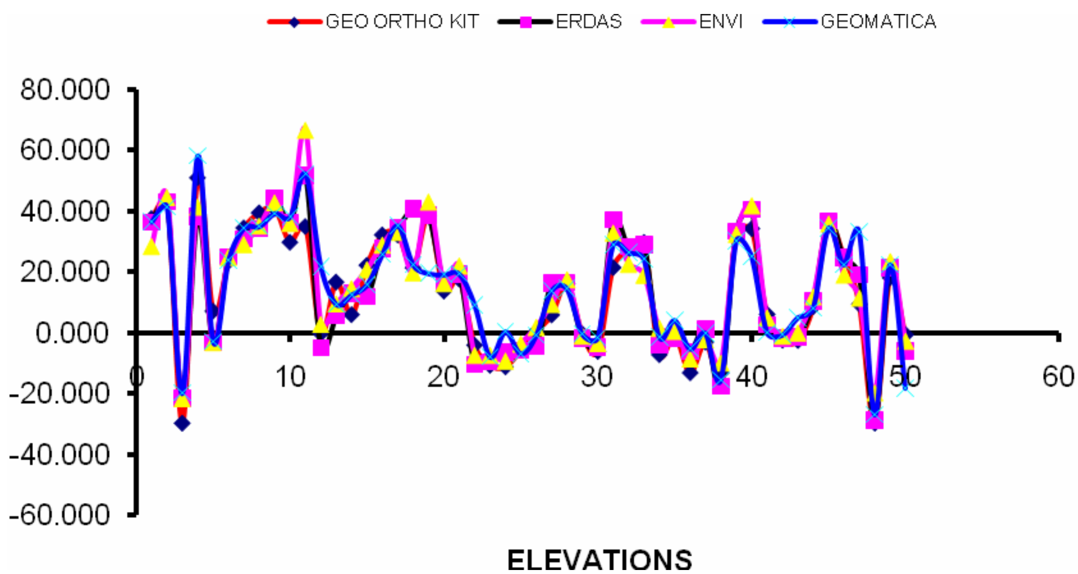


Figure 2 - Graph showing the elevations of the DEMs' changes when using the different software packages

Fifty evenly-distributed points were then selected from the sample DEM, as shown in Table 3, and the corresponding line, sample and elevation values were recorded manually. Corresponding to the selected line and sample values, elevation values were sampled manually from each DEM. Root Mean Square (RMS) errors, model by model, were then calculated from the sample data's elevations and the observed elevations from the DEM.

Note that elevations were very high for all software packages where there are building and river edges. This was because the ENVI and Geomatica software packages failed to pick the same points in both images – serial numbers 4, 11, 18, 33, 40, 47, 50.

Serial No	Sample	Line	Sample Data	ERDAS	ENVI	Geomatica
1	466	34	37.768	36.508	28.600	36.600
2	708	200	43.617	43.200	44.687	41.500
3	942	62	-29.808	-21.600	-21.600	-19.730
4	1208	109	51.237	38.200	41.500	58.400
5	1450	179	7.208	-3.100	-3.100	-2.730
6	1653	265	23.598	25.000	25.000	23.900
7	1623	328	34.678	30.900	29.210	34.600
8	295	148	39.672	34.300	35.261	35.100
9	647	250	41.079	44.400	42.950	39.428
10	905	507	29.953	36.135	36.639	38.250
11	1123	554	35.147	51.795	66.792	52.360
12	1475	640	-0.202	-4.900	2.873	21.900
13	1412	859	16.807	5.600	9.647	9.543
14	826	914	6.043	13.100	14.654	12.638
15	537	492	22.354	12.000	20.900	15.968
16	686	570	32.364	27.753	29.011	25.963
17	436	429	32.384	34.562	33.164	35.430
18	717	679	21.493	40.900	19.867	22.530
19	1162	718	38.550	38.748	43.194	19.658
20	1428	781	13.816	17.059	16.298	19.254
21	1772	1648	17.796	19.431	22.164	19.470
22	1186	1593	-4.050	-10.260	-7.287	9.300
23	826	1562	-10.673	-9.513	-7.267	-7.796
24	757	1516	-11.219	-6.300	-9.163	0.500
25	506	1477	-5.540	-5.697	-3.591	-6.718
26	147	1133	0.496	-4.264	1.900	-0.670
27	561	883	5.959	6.400	6.457	9.953
28	1031	1008	16.193	16.638	17.598	14.638
29	350	1141	-0.342	-1.717	-0.987	-0.285
30	710	1313	-6.091	-4.636	-3.364	-1.456
31	374	829	21.582	31.200	32.987	29.100
32	1085	727	27.532	28.303	27.684	26.458
33	1585	977	29.893	28.987	19.100	24.400
34	1116	1274	-7.185	-3.878	-1.587	-1.254
35	686	1227	-0.638	-1.870	0.563	4.222
36	1170	1350	-13.145	-16.134	-12.511	-6.135
37	303	1235	-3.040	1.192	-2.186	0.025
38	491	1750	-13.171	-17.500	-9.864	-15.360
39	920	610	32.774	33.506	32.547	30.258
40	1170	766	34.437	40.700	41.932	25.300
41	1516	485	6.147	2.622	5.017	0.259
42	139	1094	-2.381	-1.797	-0.987	-0.564
43	678	1274	-2.482	-1.406	0.099	5.100
44	381	715	8.706	10.546	11.956	8.259
45	990	535	35.579	36.769	35.987	34.562

46	1592	457	25.215	24.850	19.118	22.568
47	1795	621	9.500	19.100	11.527	33.300
48	1850	1519	-29.801	-28.767	-19.648	-26.782
49	1710	1635	18.232	21.366	23.591	22.553
50	991	1261	-0.567	-5.911	-2.671	-18.100

Table 3 - Elevations values (in meters) corresponding to line and sample values, picked from the DEM, as obtained from the different models

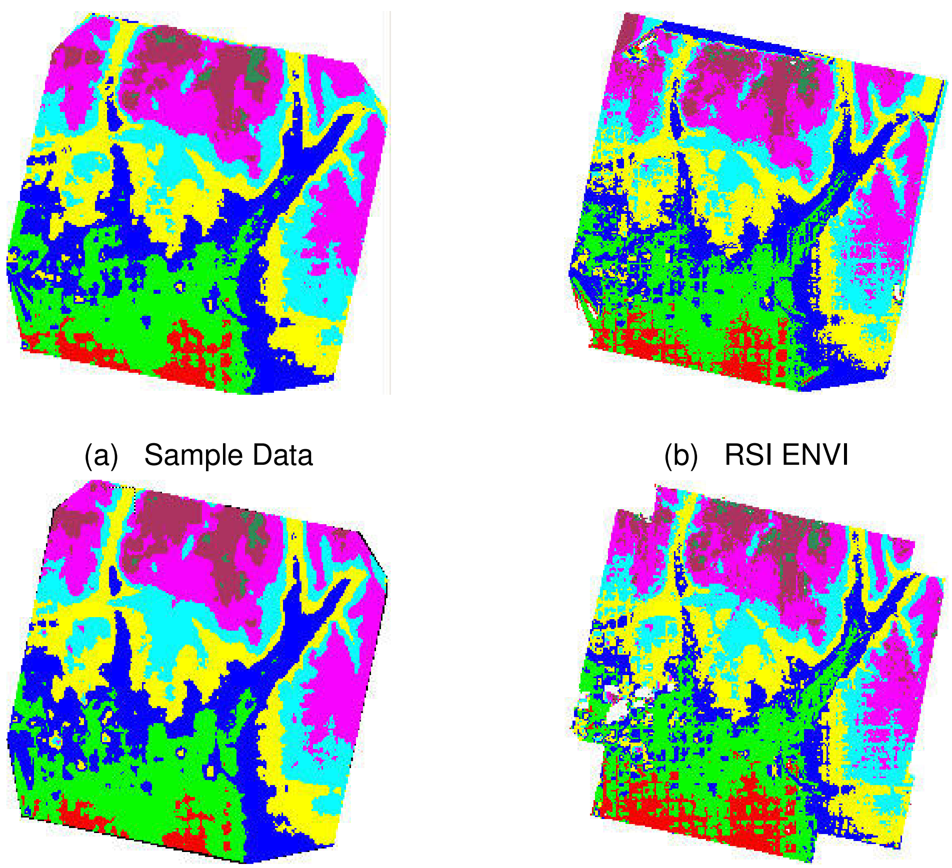
The range of DEMs generated from the same basic data set would, if subjected to density slicing, produce a range of models, the nature of which would reflect differences among the input DEMs. Accordingly, Figure 4 below shows the density sliced pattern, using eight classes/colours, with the same colours being assigned to the classes for each of the DEMs. These colours are shown in Table 4.

Visual interpretation of the density slice reveals that the result obtained from ERDAS and from the IKONOS data is same in terms of the clipped area, resolution and elevations. Moreover, in the case of the ERDAS application of density slicing (Figure 4c), the detail is blurred compared to that of the ENVI implementation (Figure 4b) where even the roads, streets and houses can easily be distinguished.

Also, the pattern generated by application of the density slicing algorithm in Geomatica is somewhat similar to that generated by ENVI, but “white pixels” in the left lower region (Figure 4d) indicate some uncertainty in achieving useful pixel assignment. Here it is to be noted that the maximum elevation in the image is 66.4525 meters and the minimum elevations is -29.8077 meters. These elevations are ellipsoidal height, and to convert them into orthometric heights one needs to add geoid height of the image area.

Serial No.	Elevation Range		Color Slice	
	From	To	Name	Color
1.	-29.8077	-17.7752	Red	
2.	-17.7752	-5.7427	Green	
3.	-5.7427	6.2899	Blue	
4.	6.2899	18.3224	Yellow	
5.	18.3224	30.3549	Cyan	
6.	30.3549	42.3874	Magenta	
7.	42.3874	54.4200	Maroon	
8.	54.4200	66.4525	Sea Green	

Table 4 - Defined density-slice ranges



(a) Sample Data

(b) RSI ENVI

(c) ERDAS Imagine

(d) PCI Geomatica

Figure 3 - Density slices of the DEMs generated

Performances of all three software packages were then checked for their speed, accuracy and user friendliness. DEM generation was carried out on the same PC to check the time taken for each one, and all the steps of automatic DEM generation were analysed individually for all three software packages.

3.1 Data Input

In terms of data input, ENVI provides fast and easy selection of data, there is no need to specify either the sensor types or the projection system. Data input is similar for all types of sensor model (RPC), but in ERDAS and Geomatica the sensor type and output file projection both have to be specified.

3.2 Tie points selection

Tie-point selection in ENVI and Geomatica (but not ERDAS) is automatic via deployment of image-matching techniques after the first few points have been selected. The tie point-selection number is limited in Geomatica and ERDAS, but this is not the case with ENVI. Although all three software packages provide a tie points editing tool, the ENVI one is the most versatile. This is because ENVI gives the error rank of each and every tie point in increasing order, thereby providing easy editing of the tie points because those with a higher rank are more easily identified.

3.3 Epipolar image generation

Epipolar image generation capability is available in ENVI and in Geomatica. These packages first build epipolar images and then perform parallax image generation in order to extract elevation from the parallax image. In the case of ERDAS, triangulation is performed using the stereo pair and selected tie points and it gives the ground coordinates as output.

3.4 DEM extraction

After generation of the triangulation results, ERDAS rapidly proceeds forward to DEM generation. ENVI and Geomatica, on the other hand, first build the epipolar image and then proceed forward to DEM generation. At this stage, the Geomatica user is prevented form further progress until minimum and maximum model elevations have been provided. This step may confuse non-technical and inexperienced users.

3.5 DEM editing

All the three packages provide editing tools. However, in terms of providing region-selection tools and interpolation techniques, ENVI stands out as the most versatile.

4.0 Conclusions

It has been demonstrated how the RPC framework provides a comprehensive photogrammetric solution in a variety of applications. It offers greater flexibility and enables non-technical users to exploit the full potential of high-resolution imagery. As such, the RPC sensor model provides full accuracy as a replacement for a rigorous sensor model. Moreover, modelling procedures and algorithms, for the 3-D ground coordinates reconstruction from 2-D image coordinates using an RPC approach, have been elaborated upon.

The basic statistics we have provided give an indication of the relative performance levels of the three DEM generators. The RMS error between the sample data and the DEM generated using the software packages was found to be between 6.589727 and 8.303025. Versatility and limitations of the different generators using the RPC model have been studied and discussed.

Finally, it needs to be stressed that it is the user who must match project requirements and project tools. For maximizing accuracy within minimum time it is perhaps ERDAS that offers the most, but the user must be a technically (stereo capable) expert (Jain K et al, 2008). A less expert user might be better off using the ENVI tools, but he or she must be prepared to allow time for improving accuracy via the use of the editing tools.

Acknowledgment

The authors would like to thank anonymous reviews for their comments and suggestions to improve our manuscript's technical strength. Thanks also to journal editors Professor Ray Wyatt and Professor Jim Peterson (Director, Centre for GIS, School of Geography and Environmental Science, Monash University, Vic.) for suggestions about standardizing our English expression.

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