ORTHORECTIFICATION AND PANSHARPEN RAPIDEYE, IKONOS AND ALOS OPTICAL IMAGERY USING HIGH RESOLUTION NEXTMAP® DATA

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ABSTRACT

A plethora of medium to high resolution multi-spectral imagery is available from a host of commercial optical satellites. However, image data acquired by satellite image sensors are affected by systematic sensor and platform-induced geometry errors, which introduce terrain distortions when the image sensor is not pointing directly at the Nadir location of the sensor. Image orthorectification can accurately remove the image distortions related to sensor collection. This study presents the orthorectification multispectral imagery from several satellites (ALOS, Rapid Eye and IKONOS) with high resolution NEXTMap® data over Colorado, California and Alaska test sites, respectively. Orthorectification has been demonstrated using a Rational Functions method which involves the collection of GCPs from the NEXTMap® high resolution ORI (1.25 m pixel; 2 m horizontal accuracy) used in conjunction with the NEXTMap® DTM and off-the-shelf orthorectification software. The resulting orthorectified satellite imagery is processed further to derive pan sharpened imagery.). The accuracy of the orthorectified pan sharpened images was tested against National Geodetic Survey (NGS) verification check points (VCPs). The ALOS derived products achieve mapping scale accuracies of 1:10,000, while the Rapid Eye and IKONOS are suitable for 1:4,800 mapping scales.

Key words: NEXTMap®, accuracy, pan sharpening, radar image, Rapid Eye IKONOS, ALOS, DTM

INTRODUCTION

“Raw” remotely sensed images, such as those from IKNONS, RapidEye and ALOS; contain geometric distortion due to sensor motion, platform attitude and viewing perspective, earth rotation and curvature, and terrain relief displacement, which introduce terrain distortions when the image sensor is not pointing directly at the Nadir location of the sensor. These distortions vary within the image, as well as from image to image. In order to use such images for mapping, change detection and other applications, various levels of correction must be applied since terrain displacement can be hundreds of meters. Orthorectification is a form of correction for raw imagery to correct for terrain displacement and sensor collection parameters. It is a process whereby an image (such as that from optical satellites) is geometrically corrected to correspond to real-world map projections and coordinate systems. This process removes distortions in the imagery due to topography and sensor collection parameters. The result is an image accurate product that can be used in GIS and other mapping applications. Orthorectification requires ground control points, an accurate digital elevation model and commercial software to process the data. The resultant orthorectified image (ORI) is then, essentially is a map, with the scale uniform throughout the image and from one ORI to the next. As such, the utility of the image is greatly increased, as the ORI can be easily overlaid on other, similarly orthorectified images or maps in geographic information systems or other software, for mapping or further analysis purposes. Orthorectification has been effectively implemented in several mapping programs, including orthorectification of digital airborne imagery over 3,000 square miles of L.A. County, California where the existing USGS DEMs were of insufficient accuracy to meet the orthorectification specifications (Corbley, 2002).

Traditional orthorectification of aerial photography, for example, requires detailed information about the sensor (camera model), sensor platform (to correct for motion, attitude and viewing angle), ground elevation (to correct for terrain, or relief displacement), ground control points (for improving absolute accuracy) and a pair of stereo images (to perform the terrain correction). However, the use of IFSAR in the orthorectification of satellite imagery is somewhat streamline, requiring less information than traditional methods. The IFSAR method requires one satellite sensor image (e.g. no need for stereo image pairs), a digital elevation model of appropriate quality (vertical accuracy and horizontal resolution) to do the terrain correction and an orthorectified image (IFSAR ORI) to create ground control reference points between the satellite imagery and the IFSAR ORI. This paper presents the results of using IFSAR elevation and radar imagery data to test and demonstrate orthorectification of IKONOS, RapidEye and ALOS over test sites in Colorado, California, and Alaska, respectively. Together with input of GCPs (Ground Control Points) taken from the NEXTMap Orthorectified Radar Images (ORIs) that accompany the DEMs, mapping scale accuracies suitable for 1:4800 (IKONOS and RapidEye) and larger (ALOS) have been achieved. Several examples of pan-sharpening of the satellite data performed using the NEXTMap ORI and optical orthorectifed satellite images are presented.

DATA AND STUDY AREA

Study Areas

Three study sites located in the United States of America (California and Morrison) were selected for this research due to the availability of the satellite optical imagery.

California. The study site focuses on a five 7.5 minute tiles of approximately 150 km^2 area each, south of the village of Sanger, California. Geographically, the region is centered on 36^{o}40’42” N latitude and 119^{o}33’30” W longitude. It was selected because it represents a range of terrain conditions (coastal environment to mountainous terrain). There are some gentle hills that are interspersed with boulders and open rock surfaces and a vast amount of agriculture fields. The topography of this site is dominantly rolling with irregular slopes (0^o-36.5). Altitude ranges from 0 m along the coast to 3060 m in the mountains. The region consists of mountains running NW – SE located along the right side of the image strip with agriculture fields in the central valley and residential and commercial areas located in the eastern section. An extensive transportation network is present. Forests are dominated by evergreen and occur mainly on the west facing slopes whereas shrubs occur mainly along the east facing slopes. The region also contains urban, suburban, grassland, and deciduous land cover.

Morrison. The study site focuses on a 180 km^2 area located near the town of Morrison Colorado, USA. It was selected because it represents a semi-arid environment. There are some gentle hills that are interspersed with boulders and open rock surfaces. The topography of this site is dominantly rolling with irregular slopes (0^o-46.5) and many outcrops of bedrock. Geographically, the region is located between 39^{o}45’09” N and 39^{o}37’20” N latitudes and 105^{o}06’36” W and 105^{o}15’55” W longitudes. Altitude ranges from 1660 m in the foothills to 2435 m in the mountains. The region consists of the Rocky Mountain Range running NW – SE located along the left side of the imagery with residential and commercial areas located in the eastern section. An extensive transportation network is present. Forests are dominated by evergreen and occur mainly on the west facing slopes whereas shrubs occur mainly along the east facing slopes. The region also contains urban, suburban, grassland, and deciduous land cover.

Data

NEXTMap. Intermap Technologies (Intermap, 2009) generates three core products using its interferometric synthetic aperture radar (IFSAR for short) technology. They are an orthorectified radar image (OR) and two corresponding elevation models: namely a digital surface model (DSM) and a digital terrain model (DTM). The orthorectified radar image (ORI) is an 8 bit grayscale image of the terrain as sensed by the IFSAR sensor. This product looks similar to a black-and-white aerial photograph. The difference is that instead of being created from visible light, the radar pulses the ground with “flashes” of radio waves, which then return from the ground (or whatever they strike, including buildings and trees) to the antennae to give distance and intensity measurements. This information along with the digital elevation data is then processed to produce the ORI. The digital surface model (DSM) is a digital representation of the earth’s surface as “seen” by the sensor. It is comprised of elevation measurements that are laid out on a grid, posted every 5 m. These measurements are derived from the return signals received by the two radar antennae on the aircraft. The signals bounce off the first surface they strike, making the

DSM a representation of the height of any object large enough to be resolved. This includes buildings, vegetation, and roads, as well as natural terrain features. The digital terrain model (DTM) is a digital representation of the bare earth that is derived from the DSM. Thus, the DTM has had the heights of vegetation, buildings, and other cultural features digitally removed, leaving just the elevations of the underlying terrain. This is achieved by using Intermap's proprietary three dimensional software to interpolate terrain elevations based on measurements of bare ground contained in the original DSM.

IKONOS. IKONOS is a high-resolution, multi-spectral satellite sensor operated by GeoEye. It was launched in 1999, making it the first commercially available satellite imagery available at less than 1 m pixel resolution. The sensor has a swath width of 11.3 km when pointing straight down (nadir), 13.8 km when pointing off nadir (off to the side) operating 4 multispectral bands (blue, green, red, infrared) and 1 panchromatic band. Data used in this study had a 3.2 m multispectral and was collected in nadir mode (Dial, 2000; Grodecki, 2001). The satellite has an altitude of 681 km.

RapidEye. Launched in August 29th, 2008, RapidEye operates a constellation of 5 optical satellites, all of which have identical sensors, orbits, and calibrations. They are quite small (about 1sq m) in comparison to many of the other satellites in operation today. These identical satellites provide a product with a 5m resolution, which can be collected in 5 different optical bands. (Blue (440-510 nm), Green (520-590 nm), Red (630-685 nm), Red Edge (690-730 nm) and Near Infrared (760-850 nm). Revisits times are quick due to the 5 satellites identical orbits. Additionally, RapidEye can collect a substantial amount of data within a single day (roughly 4 million sq km per day). The RapidEye constellation uses reaction wheels to move the satellite instead of gyros. As a result, the native accuracy of the sensor is only 500 m CE90 / 590 m CE95. However, 12 m CE90 / 13.7 m CE95 accuracies can be met (equivalent to 1:24,000 NMAS) using appropriate ground control and a DTED Level 2 terrain model.

ALOS. ALOS PalSAR is a Japanese land observation satellite launched on January 25th, 2006 from Tanegashima Island, Japan. ALOS has a wide range of capabilities, as it has three different sensors on board. The Panchromatic Remote Sensing Instrument (PRISM) allows for stereo mapping, while the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) give ALOS earth observation with 4 different optical bands. (Blue, green, red, near-IR.) ALOS also has an active sensor on board with the Phased Array L-band Synthetic Aperture Radar (PALSAR) system. ALOS has a resolution of 2.5 m panchromatic, 10 m multispectral, and 10 or 100 for the radar component. PALSAR operates in the L-Band, with a frequency of 1.3. (GHz).

METHODS

To orthorectify optical satellite data, first, NEXTMap IFSAR ORI (either newly acquired, or from the radar archive) are utilized to provide the ground control points (GCPs) required to register the satellite imagery. Second, the NEXTMap DTM is required to remove terrain related distortion. The use NEXTMap ORI and DTM eliminates the need to collect GCPs on the ground, a costly and often difficult process, particularly in remote areas. All information is then used as inputs to a modified commercial version of rational functions solution software to perform the orthorectification. This approach is particularly suitable for the class of high-resolution satellites typified by IKONOS, RapidEye and ALOS which are agile pointing and characterized by potentially large off-nadir viewing angles which are relatively uniform across each image. Figure 2 provides a generalized process flow of the othorectification process utilized in this study for all optical satellite data sets. Pan-sharpening, the process whereby the colour (hue) of the multispectral imagery (ranging from 5 m – 15 m resolution) and the high resolution of the panchromatic imagery (1.25 m resolution) are merged together to create a new imagery product whereby the Hues of the Satellite data and the resolution of the NEXTMap ORI are maintained.

Overall Orthorectification Method

Most commercial off-the-shelf software (COTS) for software (i.e. Erdas Imagine, PCI Geomatics, ENVI, ZI Imagine, LH System, TNT products, etc) contain comprehensive suite of products designed for performing tasks required in producing high quality, seamless digital orthophoto imagery products from aerial (standard and digital) and commercial satellite imagery. These software products include programs required to produce the input components for orthorectification including project setup, DEM interpolation/formatting, and GCP and tie point collection. These products can also be used to create imagery mosaics, and they have the ability for orthorectification using RPF. Most of these software products currently support processing of ephemeris data and orthorectification for the following commercial imaging satellites referenced in this study. PCI Geomatics software was utilized for the orthorectification of all satellite imagery. The general orthorectified workflow utilized in this paper was as follows:

1. Importing raw satellite imagery, including orbital metadata for a variety of airborne cameras and sensors;
2. Collection of ground control points from the ORI (existing geocoded image) and the optical satellite imagery;
3. Refining the ground control points based on criteria such as high residual error;
4. Calculating the updated model (orthorectification) for the images with the refined GCPs;
5. Given the model and the elevation data provided by the NEXTMap data sets, the orthorectification process is preformed.

Rational Function Model Rectification

The use of the Rational Function sensor Model (RFM), a generalized senor model (Tao and Hu, 2001; Mercer et al., 2003), have alleviated the requirement to obtain a physical sensor model, and with it, the requirement for a comprehensive understanding of the physical model parameters. RFM has been successfully implemented in various high-resolution sensors, such as IKONOS and QuickBird (Croitoru et al., 2004; Mercer et al., 2003). The RFM sensor model describes the geometric relationship between the object space and image space. It relates object point coordinates (X,Y,Z) to image pixel coordinates (r,c) or vice versa using 78 rational polynomial coefficients (RPCs). For the ground-to-image transformation, the defined ratios of polynomials have the following form (Croitoru et al., 2004):

$$r_n = \frac{p_1(X_n,Y_n,Z_n)}{p_2(X_n,Y_n,Z_n)} = \frac{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{j=0}^{m3} a_{ijk}X_n^iY_n^jZ_n^k}{\sum_{i=0}^{n1}\sum_{j=0}^{n2}\sum_{j=0}^{n3} b_{ijk}X_n^iY_n^jZ_n^k} \qquad (1)$$

$$c_n = \frac{p_3(X_n,Y_n,Z_n)}{p_4(X_n,Y_n,Z_n)} = \frac{\sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{j=0}^{m3} c_{ijk}X_n^iY_n^jZ_n^k}{\sum_{i=0}^{n1}\sum_{j=0}^{n2}\sum_{j=0}^{n3} d_{ijk}X_n^iY_n^jZ_n^k} \qquad (2)$$

where (r_n,c_n) are the normalized row (line) and column (sample) index of pixels in image space; X_n) ,Y_n) and Z_n) are normalized coordinate values of object points in ground space; and the polynomial coefficients a_{ijk}, b_{ijk}, c_{ijk}, are called Rational Function Coefficients (RFCs). Four GCPs, as a minimum is required for each satellite image, although six to eight are recommended, 30 GCPs were used for each satellite image. Tie points are produced by identifying the same pixel location in two or more images within their overlap areas. These software products can process tie points for an unlimited number of input images.

RESULTS/DISCUSSION

To demonstrate the accuracy and feasibility of the orthorectification method presented herein, tests have been using the three representative satellite image sources. The accuracies of the resulting products are given in Table 1, and several examples are shown in the following figures (Figures 2-4). The orthorectified IKONOS, Rapid Eye and ALOS imagery achieved a horizontal accuracy of about 1.8 m RMSE, 3.0 m RMSE, and 4.5 m RMSE, respectively. The horizontal offset of the un-orthorectified IKONOS, Rapid Eye and ALOS imagery was compared to 34, 36, and 30 independent ground control points (from several different sources), respectively. Preliminary results indicate that there is an average of a 30.76 m offsite in the X direction (East-West) and an 8.64 m offset in the y direction (North-South) when comparing the un-orthorectified Rapid Eye imagery to the 36. Intermap is in the progress of conducting additional analysis (e.g. analysis on the 4 other 150 km square tiles) to provide results of statistical vigour.

Table 1. Accuracy of Image Products Orthorectified using Intermap IFSAR DEMs

Image Source (Optical Satellite Sensor)	NEXTMap DTM Post/Vertical Accuracy	Ground Control Points Used	RMSE (m)	CE95%	NMAS Equivalent Scale
IKONOS	5 m/1 m	34 per scene	1.8	3.5388	1:3,600 & 1:4,800
RapidEye	5 m/1 m	36 per scene	3	5.898	1:4,800
ALOS Optical Sensor	5 m/1 m	30 per scene	4.5	8.847	1:10,000

The following illustrations provide a visual depiction of the orthorectified versus the satellite-NEXTMap pan sharpened images for the ALOS (Figure 1), RapidEye (Figures 2-4) and IKONOS (Figure 5) imagery. There are some cases where the addition of the multispectral hues in a optical-radar pan sharpened image makes it easier to interpret features, provided the resolution of the optical and the radar imagery is similar (e.g. a few meters difference – like that of 1.25 m orthorectified radar imagery and 5 m RapidEye multi-spectral optical imagery). This is evident in Figure 1, where the addition of the higher resolution NEXTMap ORI (1.25 m pixel) and the hue provided by the ALOS imagery (10 m pixel; green tones for the vegetation) allows for easier depiction of the golf course and residential area then if only the ALOS imagery were available. Figure 2 provides demonstrates the high resolution in the NEXTMap ORI in agriculture landscape, and the tones in the RapidEye imagery help to provide information about the status of the agriculture fields.

Figure 1. ALOS on left – 10 m pixel resolution (courtesy of ASF) compared with a Pan-sharpened ALOS – Intermap Orthorectified Radar Image on the right (courtesy of Intermap) 1.25 m pixel resolution.

1.25 m Pixel NEXTMap® ORI

5 m Rapid Eye Orthorectified True Color

1.25 m Rapid Eye Pan Sharpen True Color

Figure 2. Right Image - Intermap's NEXTMap® Orthorectified radar Image (2 m RMSE horizontal accuracy; 1.25 m pixel); Middle Image – Orthorectified (using NEXTMap® Data) Rapid Eye True Color Image (5 m pixel); Left Image – pan-sharpened Rapid Eye/ NEXTMap® Data.

Figure 3, middle image (Rapid Eye), portrays red, white and blue hues which actually represent clouds in the region during the time of imagery collection. The process of pan-sharpening, allows for the reduction of the influence of the clouds and the enhancement of the terrain is given by the NEXTMap ORI to offer a better representation of the region over the Rapid Eye or NEXTMap ORI images alone. To add the final pan-sharpened images all maintain the spatial resolution of the NEXTMap ORI (1.25 m pixel), which improves the usage of the combined optical and radar datasets.

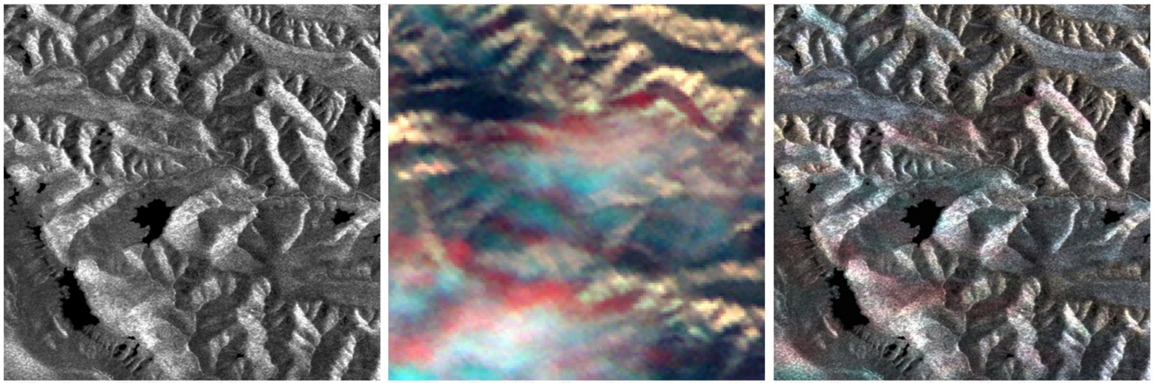
1.25 m Pixel NEXTMap® ORI
5 m Pixel Rapid Eye True Color
1.25 m True Color Rapid Eye Pan Sharpened

Figure 3: Right Image - Intermap's NEXTMap® Orthorectified radar Image (2 m RMSE horizontal accuracy; 1.25 m pixel); Middle Image – Orthorectified (using NEXTMap® Data) Rapid Eye True Color Image (5 m pixel); Left Image – pan-sharpened Rapid Eye/ NEXTMap®.

In Figure 4, we can see a temporal difference between the orthorectified radar image (right image – collected in 2007) and the RapidEye imagery (middle image – collected in 2009). The final pan sharpened image (left image, Figure 4) uses the NEXTMap ORI as the master image to reduce the effects of temporal differences. Equally, the RapidEye imagery could have been selected as the master image to enhance the temporal differences in order to use the date set for applications such as changed detection.


1.25 m Pixel NEXTMap® ORI
5 m Pixel Rapid Eye True Color
1.25 m True Color Rapid Eye Pan Sharpened

Figure 4. Right Image - Intermap's NEXTMap® Orthorectified radar Image (2 m RMSE horizontal accuracy; 1.25 m pixel); Middle Image – Orthorectified (using NEXTMap® Data) Rapid Eye True Color Image (5 m pixel); Left Image – pan-sharpened Rapid Eye/ NEXTMap®.

Figure 5 presents an illustration of the distribution of the ground control points selected to orthorectify the IKONOS winter scene (not the snow covered lake in the bottom right hand corner of the image). A total of 36 GCPs were collected using the NEXTMap ORI as the source. Figure 6 offers a comparison in the different resolution of the ALOS and IKONOS sensor data over the Morrison study cite in Colorado.

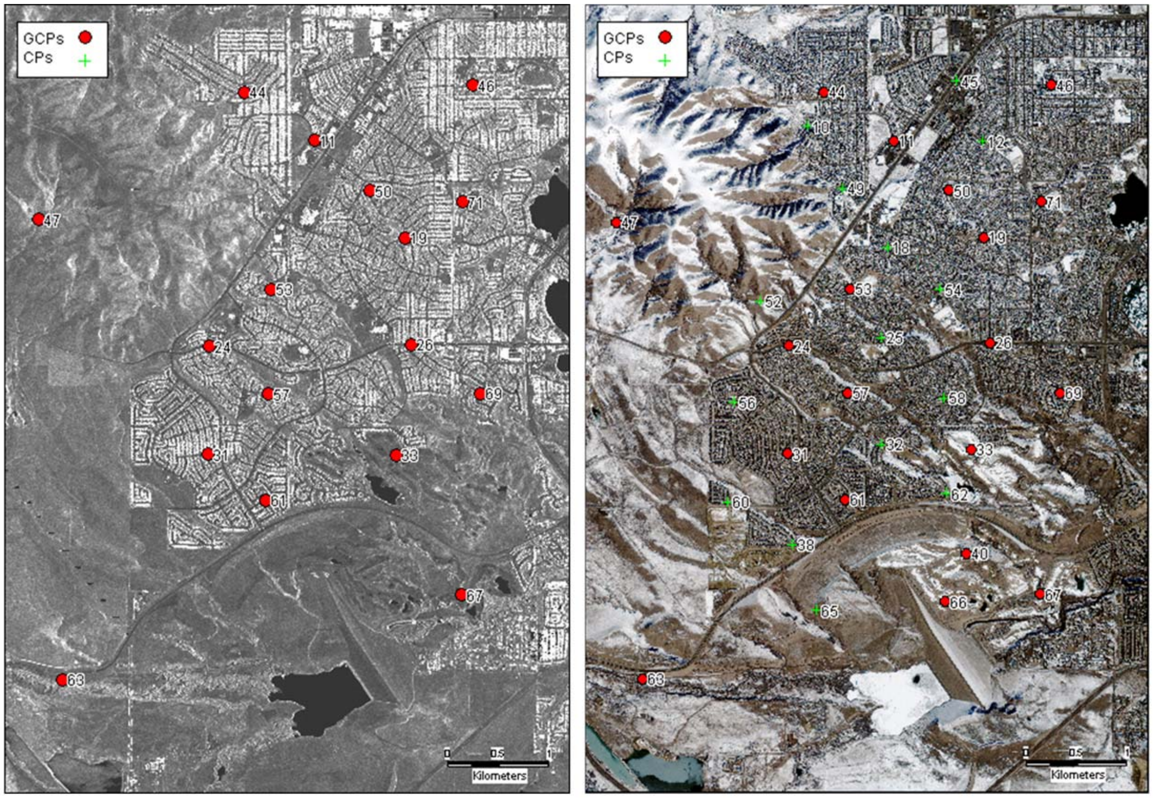

Figure 5. Right Image - Intermap's NEXTMap® Orthorectified radar Image (2 m RMSE horizontal accuracy; 1.25 m pixel); Left Image – Orthorectified IKONOS image; both the 34 GPCs superimposed.

Figure 6. Right Image ALOS Orthorectified Image (10 m pixel) taken in the summer time; Left Image – Orthorectified IKONOS image (4 m pixel) taken in the winter time.

CONCLUSIONS AND FUTURE RESEARCH

This paper presents the results of using high resolution NEXTMap elevation and orthorectified imagery and commercial off-the-shelf (COTS) software to orthorectify and pan sharpen IKONOS, RapidEye and ALOS satellite imagery, using the state-of-the-art RFM method. IFSAR data offers a cost-effective image orthorectification solution for use with IKONOS, RapidEye and ALOS satellites sensors. IFSAR-derived DEMs have been tested for high-resolution satellite image orthorectification to NMAS levels as large as 1:3,000 scales. The densely posted IFSAR DEMs can provide more accurate elevation information than is publicly available in most areas of the world, thus increasing the accuracy of the final ORI and the orthorectified satellite imagery. Cost savings are realized in several areas of the process: requirement for only a single (not stereo) image; reduction or elimination of the need for GCP collection on the ground; and provision of a full product set, rather than just an ORI from the source image. Prices for orthorectification of either satellite or airborne images are competitive when the IFSAR data have to be newly acquired, and are much lower when the data are already in Intermap's extensive archive. As the need for detailed mapping consistently develops worldwide, and as practical budget constraints continue to rise, the requirement for an efficient satellite and airborne image orthorectification approach is rapidly growing. Intermap's research and development, and several operational programs to date, have demonstrated that the use of its IFSAR terrain data provides a timely, cost-effective, high-accuracy, globally consistent orthorectification solution.

REFERENCES

Corbley, K. 2002. L.A. County combines IFSAR with digital imaging to produce accurate orthos and DEMs, *Earth Observation Magazine*, September 2002:14-16.

Croitoru, A., et al., 2004. The rational function model: A unified 2D and 3D spatial data generation scheme, in *Proceedings of ASPRS Annual Conference*, Denver, Colorado, USA.

Di, K., R. Ma, and R.X. Li, 2003. Rational functions and potential for rigorous sensor model recovery, *Photogrammetric Engineering and Remote Sensing*, 69(1):pp. 33-41.

Dial, G., 2000. IKONOS satellite mapping accuracy, in *ASPRS 2000 Proceedings*, Washington DC, 22-26 May 2000.

Dowman, I., and J.T. Dolloff, 2000. An evaluation of rational functions for photogrammetric restitution, *International Archives of Photogrammetry and Remote Sensing,* 3(B3/1):252-266.

Grodecki, J., 2001. IKONOS stereo feature extraction - RPC approach, in *ASPRS 2001 Proceedings*, St. Louis, MO, 23-27 April 2001.

Grodecki, J., and G. Dial, 2001, IKONOS geometric accuracy, in *Proceedings of Joint International Workshop on High Resolution Mapping from Space*, 19-21 September 2001, Hanover, Germany, pp. 77-86 (CD ROM).

Hemmleb, M., and A. Wiedemann, 1997. Digital Rectification and Generation of Orthoimages in Architectural Photogrammetry, *CIPA International Symposium, IAPRS, XXXII* (Part 5C1B): 261-267, Göteborg, Sweden.

Fraser, C.S., H.B Hanley, and T. Yamakawa, 2001. Sub-metre Geopositioning with IKONOS *Geo* Imagery, *Proc. Joint ISPRS Workshop "High Resolution Mapping from Space 2001,"* 19-21 September, Hannover, Germany, (on CD ROM).

Intermap, 2009. www.intermaptechnologies.com/products.htm

Li, X. and B. Baker. 2003. Characteristics of airborne IFSAR elevation data, in *Proceedings ASPRS Annual Conference*, 5-9 May 2003, Anchorage AL, CD-ROM.

Mayr, W., and C. Heipke, 1988. A contribution to digital orthophoto generation, *International Archives of Photogrammetry and Remote Sensing*, 27(Part B11-IV): 430 - 439.

Mikhail, E.M., J.S. Bethel, and J.C. McGlone, 2001. *Introduction to Modern Photogrammetry*, Wiley, New York.

Mercer, J.B., and S. Schnick, 1999. Comparison of DEMs from STAR-3i interferometric SAR and scanning laser, in *Proceedings of the Joint Workshop of ISPRS III/5 and III/2*, La Jolla, November, 1999.

Mercer, J.B., J. Allen, N. Glass, J. Rasmussen, and M. Wollersheim. 2003. Orthorectification of satellite images using external DEMs from IFSAR, in *Proceedings Joint ISPRS Workshop High Resolution Mapping from Space 2003*, Hanover, Germany, 6-8 October 2003.

Novak, K., 1992. Rectification of digital imagery, *Photogrammetric Engineering and Remote Sensing*, 58(3): 339-344.

Rosenholm, D., and D. Akerman, 1998. Digital orthophotos from IRS - Production and utilization, *GIS - Between Visions and Applications*, ISPRS, 32, Stuttgart, Germany.

Tao, C.V., and Y. Hu, 2001. The rational function model: A tool for processing high resolution imagery, *Earth Observation Magazine* (EOM), 10(1).

Tao, C.V., and Y. Hu, 2001. 3D reconstruction algorithms with the rational function model and their applications for IKONOS stereo imagery, in *Proc. Joint ISPRS Workshop "High Resolution Mapping from Space 2001,"* 19-21 September, Hannover, Germany, 12 p. (on CD ROM).

Toutin, T., 2003, Error tracking in IKONOS geometric processing using a 3D parametric model, *Photogrammetric Engineering & Remote Sensing,* 69(1):43-51.

Wang, Y., B. Mercer, V.C. Tao, J. Sharma, and S. Crawford, 2001. Automatic generation of bald earth digital elevation models from digital surface models created using airborne IFSAR, in *ASPRS 2001 Proceedings*, (on CD ROM).

Zhang, Y., V. Tao, and J.B. Mercer, 2000. Assessment of the influences of satellite viewing angle, earth curvature, relief height, geographical location, and DEM characteristics on planimetric displacement of high-resolution satellite imagery, in *ASPRS 2000 Proceedings*, (on CD ROM).