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IKONOS satellite, imagery, and products

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Abstract

The IKONOS satellite simultaneously collects 1-m panchromatic and 4-m multispectral images, providing the commercial and scientific community with a dramatic improvement in spatial resolution over previously available satellite imagery. The sun-synchronous IKONOS orbit provides global coverage, consistent access times, and near-nadir viewing angles. The system is capable of 1:10,000 scale mapping without ground control and 1:2400 scale mapping with ground control. The IKONOS ground station produces radiometrically corrected images, georectified images, orthorectified images, stereo pairs, and digital elevation models (DEMs) for image analysis, photogrammetric, and cartographic applications. This article provides an overview of the IKONOS satellite, ground systems, products, and applications.

Keywords: IKONOS satellite; Panchromatic; Imagery

1. Introduction

Space Imaging was formed to explore the commercial prospects of high-resolution satellite imagery. Space Imaging contracted Lockheed Martin to develop the Space Segment and Raytheon to develop the Ground Segment of the Commercial Remote Sensing Satellite (CRSS) now known as IKONOS®. The IKONOS satellite was launched September 24th, 1999 to provide global, accurate, high-resolution imagery to individuals, organizations, and governments for mapping, monitoring, and development.

The design of a high-resolution satellite imaging system proceeds from a series of design trades between spatial resolution and swath width, revisit time and off-nadir viewing angle, image compression and data transmission rates, and other performance specifications. Higher resolution results in a narrower swath width. Waiting for near-nadir opportunities results in long revisit times but short revisit times can be obtained with off-nadir viewing geometries. The vast quantity of collected data and available communications bandwidth require that the imagery be compressed for transmission.

Space Imaging provided high-resolution imagery to NASA under the Scientific Data Purchase (SDP) contract so that NASA could test the utility of commercial imagery for research purposes. The SDP contract licensed NASA to freely redistribute IKONOS imagery to scientists and researchers. SDP products are described later in this article and results of the NASA SDP research are published elsewhere in this journal issue.

2. Basic IKONOS system design

IKONOS performance is summarized in Table 1. The panchromatic sensor with 82-cm ground sample distance (GSD) at nadir provides high resolution, intelligence-quality imagery. Simultaneously, the multispectral sensor collects blue, green, red, and near-infrared (NIR) bands with 3.28-m nadir resolution, providing natural-color imagery for visual interpretation and color-infrared imagery for remote sensing applications. The pan GSD increases to 1 m at 26° obliquity or 60° elevation angle. (Obliquity is the satellite-centric angle from nadir to the line-of-sight. Elevation is the target-centric angle from the horizon to the line-of-sight. These angles would be complementary but for the curvature of the earth.)

On-board gyros, star trackers, and GPS receivers measure attitude and ephemeris for medium-scale mapping without requiring Ground Control Points (GCPs). Higher accuracy mapping can be done with GCPs.

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Table 1
IKONOS performance summary

Specification	Value
Orbit height	681 km
Orbit inclination	98.1°, sun synchronous
Descending node time	~ 10:30 a.m., local solar time
Field of regard	Up to 45° off nadir
Revisit time at mid-latitude	3 days at 60° elevation
	11 days at 72° elevation
	141 days at 89° elevation
Image sensors	Panchromatic and multispectral
Width of panchromatic arrays	13,816 pixels
Width of multispectral arrays	3454 pixels
Field of view	11 km at nadir
Minimum image length	11 km
Maximum mono image length	1000 km
Maximum stereo image length	400 km
Radiometric resolution	11 bits
Panchromatic ground sample distance	0.82 m at nadir
MTF at Nyquist	17%
Multispectral bands	Blue, green, red, NIR
Multispectral GSD	3.28 m at nadir
Blue bandpass	445–516 nm
Green bandpass	506–595 nm
Red bandpass	632–698 nm
NIR bandpass	757–853 nm

The IKONOS sun-synchronous orbit provides global coverage with frequent revisit opportunities between ± 82° latitude. The IKONOS satellite is highly agile. It can pitch and roll to acquire images far away from nadir, so that it can collect long strip images, multiple small images, or even stereo images of the same area on the same orbital pass. The orbit provides daily access to sites within 45° of nadir, 3-day revisit within 26° of nadir, and 141-day revisit within 1° of nadir.

A global network of regional ground stations enable international control and access to IKONOS imagery. Those ground stations automatically process the huge volumes of IKONOS imagery collected daily.

Collection capacity, image quality, radiometric accuracy, mapping accuracy, and ground processing requirements were defined before satellite design. Image quality requirements include modulation transfer function (MTF), signal-to-noise ratio (SNR), and co-registration of the panchromatic and multispectral image detectors. Radiometric accuracy requirements include the absolute calibration of the four multispectral bands and the relative calibration of all pixels. Mapping accuracy requirements include the metric accuracy of stereo models, digital elevation models (DEMs), and orthophotos produced with and without ground control. Ground processing requirements include functional capabilities to operate the satellite and produce products as well as capacity requirements to process large volumes of data per day. These requirements will be described separately in the sections that follow.

3. IKONOS sensor imagery

3.1. Image collection

The IKONOS orbit altitude is approximately 681 km and inclined 98.1° to the equator, providing sun-synchronous operation. The orbit parameters were chosen to provide mid-latitude areas with daily revisit at 45° obliquity, 3-day revisit at 26° obliquity, 11-day revisit at 10° obliquity, and 141-day revisit at 1° obliquity. Ground tracks subdivide the earth as follows: The ground between two successive

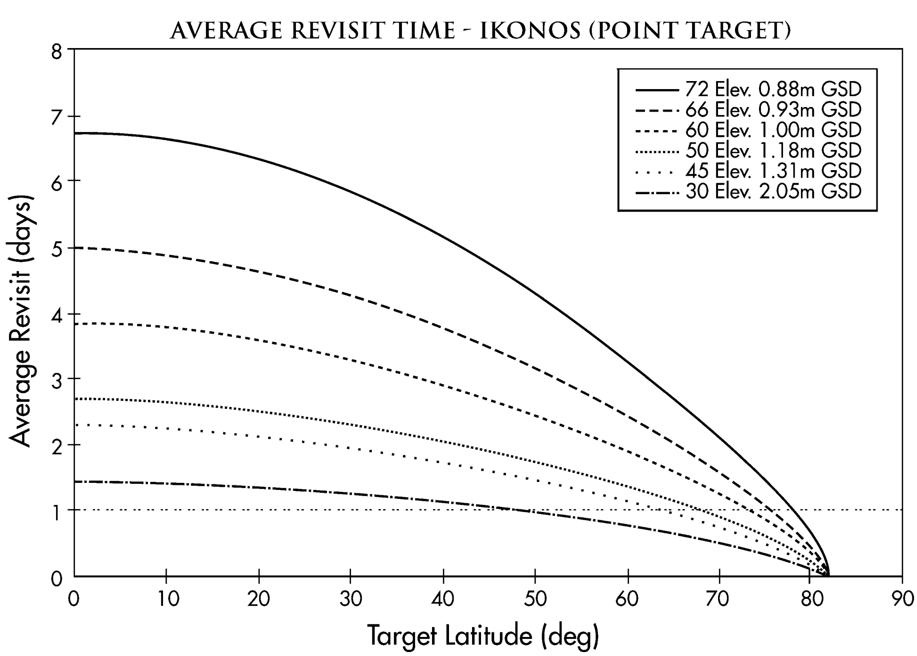

Fig. 1. Relationship between IKONOS revisit intervals, latitude, sensor elevation angles, and GSD.

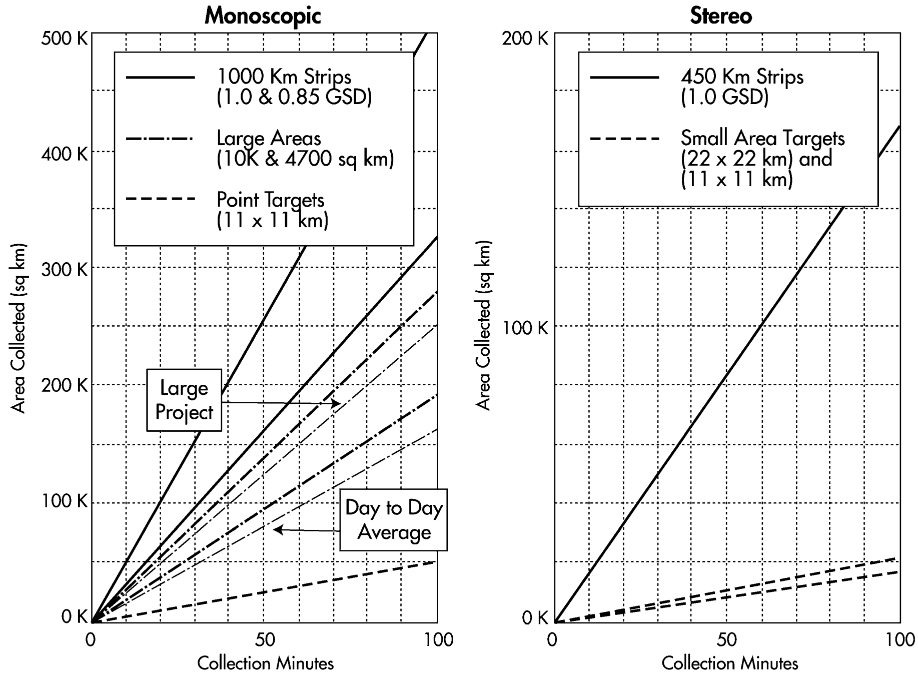

Fig. 2. Area collection rates for monoscopic and stereo images.

passes on 1 day are divided in thirds on days 2 and 3, providing a 1-m GSD every 3 days. These passes are further divided approximately in quarters during an 11-day period, providing 11-day revisit with obliquity less than 10°. This pattern of 3- and 11-day cycles walks around the earth to provide access within 1° of nadir every 141 days. This sophisticated orbit provides a workable compromise between desires for short revisit times and low obliquity angles at regular intervals. The 10:30 a.m. local mean solar time of the descending node provides good illumination and shadow definition. Fig. 1 shows the relationship between revisit time, latitude, sensor elevation angle, and GSD.

The IKONOS satellite is a monolithic pointing body. The camera is rigidly attached to the satellite bus. The entire satellite rotates from image to image without articulation, scanning mirrors, or other moving parts. The optical field-of-view of the telescope provides a nadir swath of 11 km with an 82-cm GSD. The sensor line rate produces an area collection rate at 1-m GSD of almost 5390 km^2/min in the strip mode, the greatest and most efficient method of imaging. For large, contiguous area collection the satellite must maneuver between image strips, causing the imaging efficiency to decrease. Finally, small image collection is the least efficient due to the small area per image and maneuver time from image to image. Fig. 2 illustrates the area collection rates for the various imaging modes along with the average historical collection rate and the collection rate achieved for large area mapping. During a single orbital pass, IKONOS can image a contiguous area of 4700 km^2 at a 1-m GSD or 10,000 km^2 with GSD < 1.2 m.

The maneuver capability of the IKONOS satellite allows for same pass stereo collection of significant area, a feature that differentiates IKONOS in the high-resolution, commercial satellite-imaging arena. Fig. 2 also shows the stereo area rate capability. Note that IKONOS can image a strip as long as 450 km and then rotate back to collect the entire area in stereo on the same pass.

From launch to August of 2003, Space Imaging collected over 162,000,000 km^2 of the earth's surface and archived over 400 terabytes of data.

3.2. Image quality

Image quality can be described by SNR, MTF, and National Imagery Interpretability Rating Scale (NIIRS) ratings (Ryan et al., 2003). SNR and MTF were measured during On Orbit Acceptance Tests (OOAT) under conditions that approximated a 10% reflective target with a 30° sun elevation angle. Table 2 shows the OOAT measurements of SNR and MTF. As expected, the system was found to be shot-noise limited. MTF was measured with the edge target shown in Fig. 3 with the results shown in Fig. 4. Exo-atmospheric measurements of IKONOS MTF are discussed in Bowen and Dial (2002).

Table 2
IKONOS SNR and MTF measurements

Band	SNR	Nyquist MTF
Pan	89	17%
Blue	94	26%
Green	143	28%
Red	103	29%
NIR	67	28%

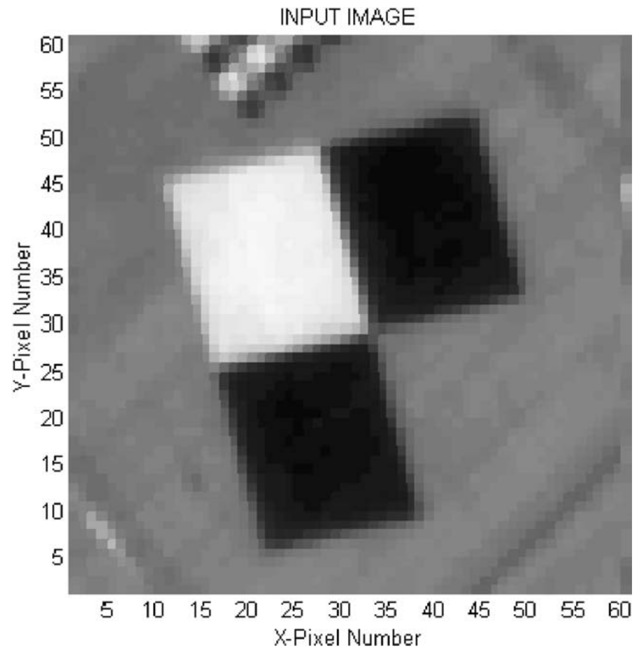

Fig. 3. IKONOS image of edge target used for modulation transfer function measurements (Imagery© Space Imaging).

Table 3
Radiometric performance requirements and results

Description	Requirement	OOAT results	Post OOAT results
Absolute radiometric accuracy (multispectral bands only)	± 10%	± 10%	± 10%
Relative radiometric accuracy (all bands)			
Tap-to-tap (banding)	± 5%	± 5%	< 1%
Pixel-to-pixel (streaking)	± 5%	± 5%	< 1%
Linearity	± 5%	± 5%	± 1%, 1-σ
Stability	± 10%	NA	± 3%, 1-σ
Failed pixels	Compensation	None	None

For image analysts, numerical measurements such as GSD, SNR, and MTF are not as significant as the ability to extract information from images. In an effort to quantify image interpretability, a U.S. Government/Contractor team created the NIIRS (IRARS, 1996). The visible NIIRS rating scale consists of 10 levels from 0 to 9 defined by interpretation tasks or criteria, with 9 being the most demanding and requiring the highest-quality imagery. For example, analysts should be able to count railroad tracks in a NIIRS 4 image and be able to identify the type of rail car (flat car, box car, etc.) and engine (diesel, steam, etc.) in a NIIRS 5 image. NIMA has rated IKONOS panchromatic imagery at NIIRS 4.5 (Baldridge, 2002). That rating would have been higher if the evaluation had been restricted to imagery with a GSD less than 1 m; as it happens, oblique imagery with GSD up to 1.2 m was included in the evaluation.

The optical stability and focus are crucial to image quality. Trained image analysts can detect small focus differences when comparing side-by-side image samples collected under good conditions from a well-behaved imaging system. Periodically, a through focus set of images is collected with IKONOS and evaluated to determine if focus adjustment is required to maintain image quality.

Because IKONOS is an agile imaging satellite that collects imagery at varying obliquities and target distances

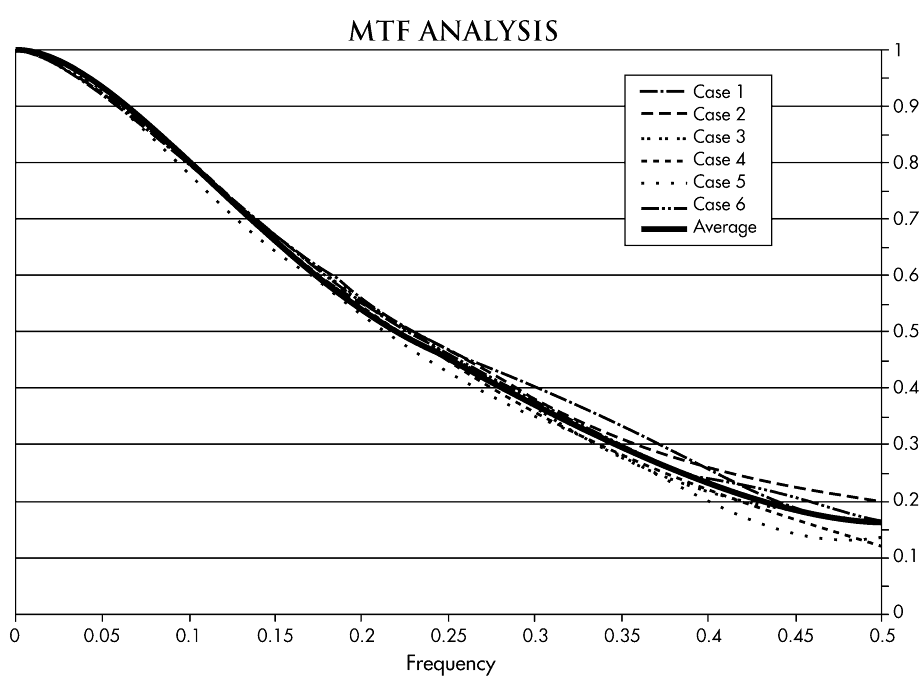

Fig. 4. Modulation transfer function measurements during OOAT.

Table 4
Radiometric calibration coefficients ((cm^2 sr DN)/mW)

Product type	Production date	Bands			
		Blue	Green	Red	NIR
11-bit	Pre 22 Feb. 2001	633	649	840	746
	Post 22 Feb. 2001	728	727	949	843
8-bit	Pre 22 Feb. 2001	79	81	105	93
	Post 22 Feb. 2001	91	91	119	105

or slant ranges, analysts often ask if there's a defocus effect. The difference in focus for an image at nadir vs. one at 60° elevation is a small fraction of the depth of focus.

The angular relationship between the collector, the area of interest, and the sun has a dramatic impact on overall image quality (Gerlach, 2001). Specular reflections of the sun off water bodies, tin roofs, and other reflectors can saturate the sensor. Acquiring images with the sun on the opposite side of the target results in forward scatter that fogs the image. Images at low elevation angles have long atmospheric path lengths and large GSD. Space Imaging schedules satellite image collection to avoid specular reflections from water bodies, to avoid looking towards the sun, and typically above 60° elevation angle (or less than 26° off-nadir) to reduce atmospheric path effects.

3.3. Radiometry

The IKONOS satellite was designed to meet radiometric requirements for calibration to an absolute standard, uniform relative response across the scene, linearity, and stability over time. These same general specifications were established several decades ago when remote sensing systems were first being implemented. IKONOS radiometric calibration is discussed in Bowen (2002) and Bowen and Oleszczuk (2002). The importance of radiometry to automated classification is discussed in Dial, Gibson, and Poulsen (2001). Table 3 compares the radiometric calibration requirements, set before satellite design, with performance measurements during and after OOAT. Banding and streaking were within specification but visually distracting. Streaking is pixel-to-pixel variation in detector response. Banding is variation between detector arrays or between electronic readouts, called taps, within those arrays. Calibration improvements have reduced banding and streaking to be virtually imperceptible.

3.3.1. Absolute radiometric accuracy

Within the first year after launch, with the assistance of the NASA Commercial Remote Sensing Program (now called the Earth Science Applications Directorate), several vicarious ground calibration activities were conducted to independently verify the radiometric accuracy of the IKONOS system (see Pagnutti, 2002; Pagnutti et al., 2003). In February 2001, a change was made to increase the gain of each multispectral array to eliminate saturation banding in images produced by extremely bright scenes. The calibration coefficients were adjusted to compensate for this gain change. Table 4 shows IKONOS radiometric calibration coefficients.

3.3.2. Relative radiometric uniformity

The requirement for relative radiometric uniformity was taken directly from the specifications for the Landsat systems. This is a reasonable specification for large area data capture with a broad range of image content and a dynamic range of only 256 counts. However, at the completion of OOAT, it was clear that this requirement was not sufficient for IKONOS 11-bit imagery.

Fig. 5 shows a uniform scene of an Antarctic snowfield with an average response of ~1200 counts and a range of

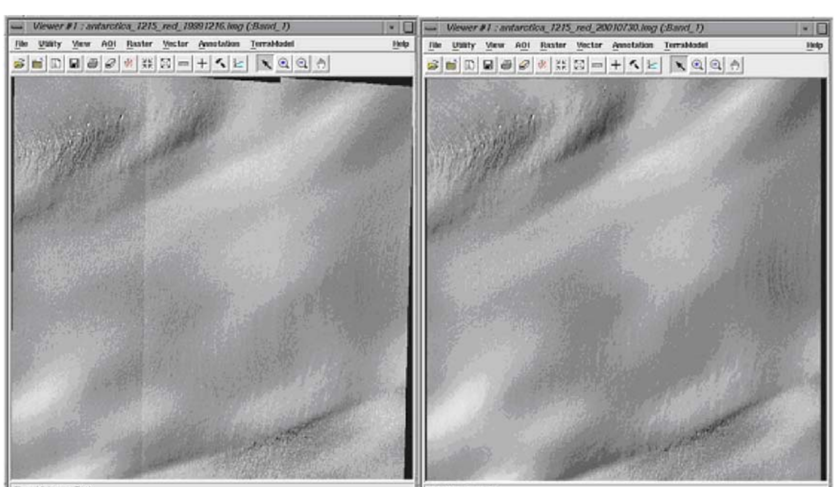

Fig. 5. Relative radiometric uniformity requirements demonstrated on Antarctic snowfield uniform scene. Left: Visible banding artifacts still visible after radiometric correction to better than 10 counts or 0.8%. Right: Radiometric uniformity is now better than 0.5% over the dynamic range of the detectors (Imagery© Space Imaging).

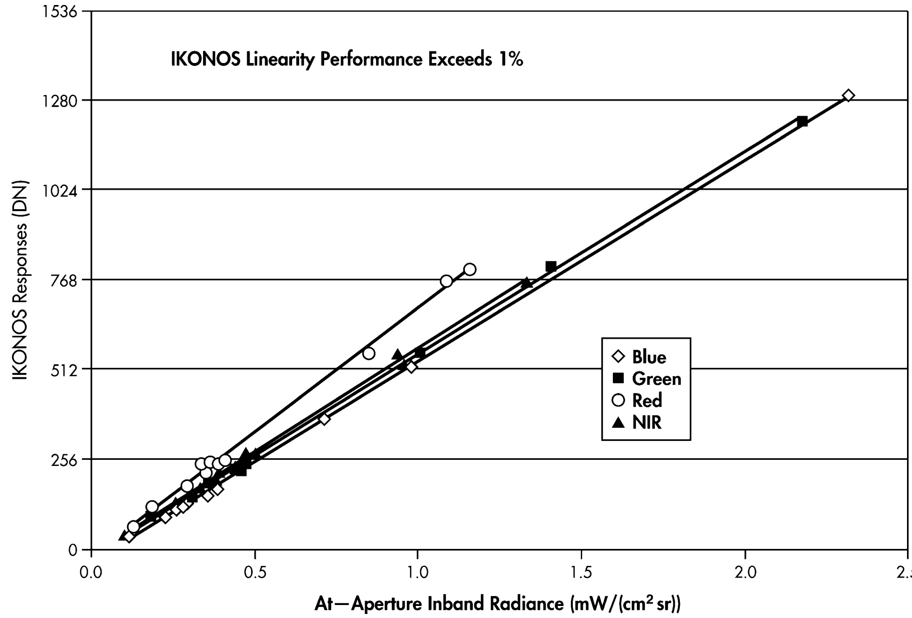

Fig. 6. IKONOS radiometric linearity.

less than ± 50 counts. Radiometric calibration that just meets the $\pm 5\%$ specification could result in variations of as much as ± 60 counts. The left image shows that radiometric correction to better than 10 counts or 0.8% still leaves clearly visible banding artifacts. With continued relative radiometric uniformity assessments and updates, it has been possible to reduce and eliminate the perceived non-uniform variations in IKONOS imagery as shown in the image on the right. Relative radiometric uniformity is now better than 0.5% over the dynamic range of the detectors.

3.3.3. Linearity

The response of the IKONOS system has been shown to be linear throughout the dynamic range of the detectors. The technique used to demonstrate this capability is to image several stable, radiometrically characterized stars. The at-aperture radiance for each star is calculated. The star is imaged and the total DN generated by the star is measured. Fig. 6 shows the calculated versus measured response values. This technique shows the linearity of the IKONOS system to be better than 1% of full scale.

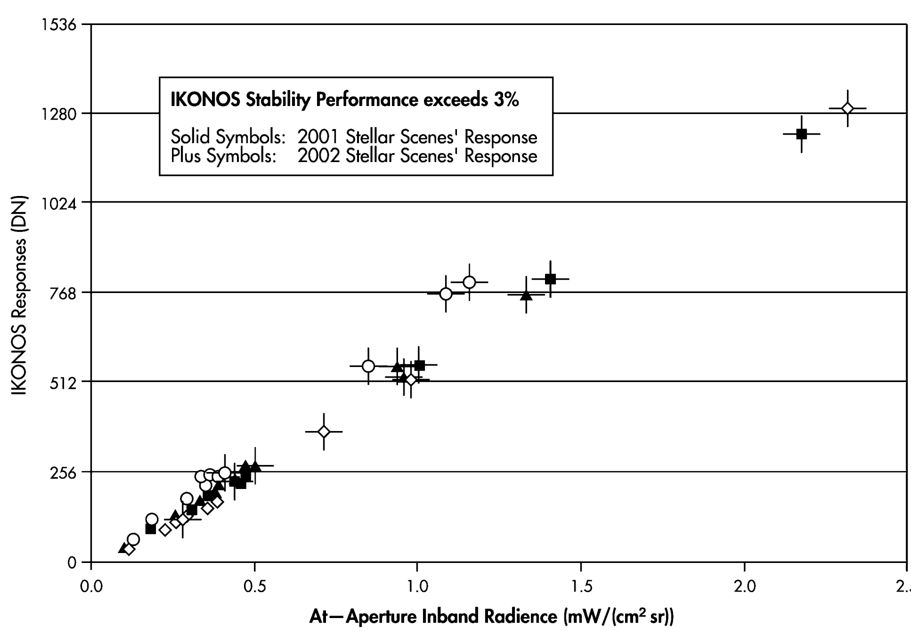

Fig. 7. IKONOS radiometric stability.

Table 5
Geometric performance requirements and OOAT results

Product	Requirement	OOAT results
Stereo without GCP (level 2 stereo)	25.4 m CE90, 22.0 m LE90	4.8 m, 7.8 m CE90, 5.2 m, 1.3 m LE90
Stereo with GCP (level 3 stereo)	2.0 m CE90, 3.0 m LE90	1.5 m, 1.7 m CE90, 1.5 m, 1.6 m LE90
Ortho from one stereo pair without GCP (level 4a)	25.4 m CE90	6.9 m, 12.3 m, 18.8 m CE90
Ortho from three stereo pairs without GCP (level 4a)	12.2 m CE90	8.8 m CE90
Ortho from stereo with GCP (level 4b)	2.0 m CE90	1.4 m CE90
DEM from stereo without GCP (level 5b)	30 m CE90	5.8 m LE90
DEM from three side-by-side stereo pairs without GCP (level 5c)	7 m RMSE	4.3 m RMSE
DEM from stereo with GCP (level 5e)	3 m LE90	2.0 m, 2.1 m LE90

Multiple OOAT results shown for multiple test cases.

3.3.4. Radiometric stability

Radiometric stability ensures that the imagery collected over a period of time is consistent. Annual measurements by Space Imaging verify that the same stars produce the same response from year to year. Fig. 7 shows the results of the stellar imaging that occurred in 2001 as solid markers and the results 2002 as cross hairs. The results show that the IKONOS system has been stable within $\pm 3\%$, 1-σ since launch.

3.3.5. Failed pixels

The 923,250 detectors that make up the IKONOS panchromatic and multispectral arrays function without a single failure. If a pixel were to fail, ground software can replace that pixel with interpolated data.

3.4. Geometric accuracy

3.4.1. Interior and exterior orientation

Interior and exterior orientation of the IKONOS satellite are derived from sophisticated attitude and ephemeris determination systems, a stable optical assembly, and a solid state focal plane, enabling IKONOS to achieve high geometric accuracy with or without ground control.

The Field Angle Map (FAM) describes the interior orientation of the IKONOS camera. FAM allows one to determine the line-of-sight vector in the camera coordinate system for each image pixel.

The on-board star trackers and gyros determine satellite attitude. The exterior orientation of the camera is defined by the interlock angles, which relate camera orientation angles to the satellite attitude. The initial interlock angles were determined by pre-launch assembly measurements and further refined by in-flight calibrations.

3.4.2. RPC camera model

Photogrammetric users require a camera model to make measurements from the imagery. A camera model provides a mathematical relationship between object and image coordinates. For high-resolution pushbroom sensors such as IKONOS, the physical camera model, based on the interior and the exterior geometry and other physical properties of the sensor, becomes complicated. To simplify interface with the end users of IKONOS imagery, Space Imaging distributes the Rational Polynomial Camera (RPC) model (Grodecki, 2001) with IKONOS photogrammetric

Fig. 8. IKONOS geometric accuracy testing range over San Diego consisting of 140 ground control points over a 22 × 22-km area (Imagery© Space Imaging).

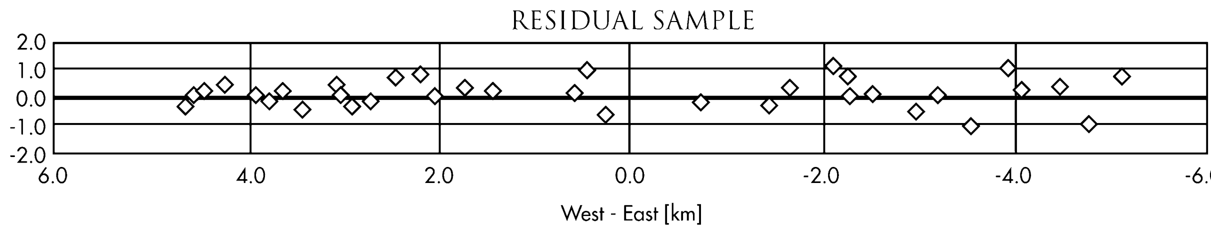

Fig. 9. Post-FAM-calibration residual errors over the Denver test range displayed against the GCP layout; no significant systematic error pattern.

products. To ensure that using the RPC camera model in lieu of the physical model causes no discernable accuracy loss to the end user, Space Imaging performed rigorous accuracy analysis, validation, and testing of the RPC model. The evaluation methodology and the results of the RPC accuracy analysis are given in Grodecki (2001) and Grodecki and Dial (2001), and show that, for all possible imaging scenarios, the RPC camera models do not differ from the physical camera model by more that 0.04 pixel. Rational function camera models are also discussed in Tao and Hu (2001).

3.4.3. Pre-operational (OOAT) calibration

Table 5 compares IKONOS geometric accuracy requirements, set prior to satellite design, with accuracy test results during OOAT. Circular error at 90% confidence (CE90) describes horizontal accuracy, while linear error at 90% confidence (LE90) describes vertical accuracy. The IKONOS geometric accuracy was tested during the OOAT, using the San Diego test range consisting of 140 GCP over a 22 × 22-km area shown in Fig. 8 (Grodecki & Dial, 2001). GCPs were derived from large-scale controlled aerial photography and have 0.5-m CE90 horizontal and 1-m LE90 vertical accuracy. As shown in Cook et al. (2001), Grodecki and Dial (2001), and Fraser, Hanley, and Yamakawa (2002), accuracy requirements have been met or exceeded for all IKONOS geometric products.

3.4.4. In-flight calibrations

Space Imaging endeavored to further improve geometric accuracy through FAM and interlock in-flight calibrations (Grodecki & Dial, 2002b). The main goal of the in-flight calibrations was to reduce systematic errors of the interior orientation, improve panchromatic-multispectral registration, and improve accuracy of the interlock angles.

3.4.5. FAM calibration

The in-flight FAM calibration was performed over the Denver test range consisting of 33 GCPs surveyed with differential GPS to 0.5-m CE90/0.9-m LE90 accuracy. The FAM parameters determined over the Denver test range were later verified over the Southern test range, comprising over 200 GCPs and covering 100 × 100-km area in south-western Australia. It is seen that the post-FAM-calibration residual errors over the Denver test range, shown in Fig. 9 against the GCP layout, exhibit no significant systematic error pattern. Moreover, they are all within ± 1 pixel, which is the expected combined GCP and pick accuracy. The residual errors over the Southern test range are shown in Fig. 10. As before, no significant systematic error pattern can be observed in the residual plot.

3.4.6. Interlock calibration

Space Imaging used a set of independent images, taken repeatedly over the Space Imaging MTF target, to improve interlock angle calibration. The interlock angle errors for

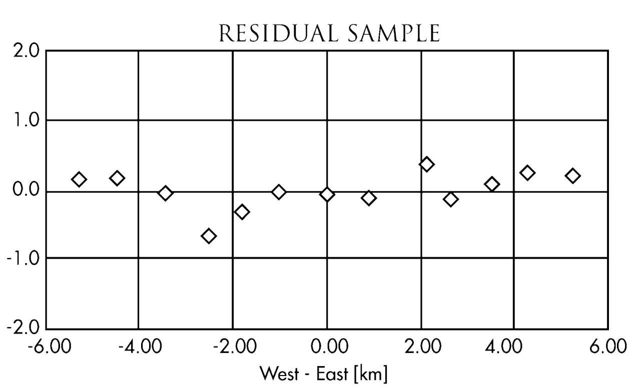

Fig. 10. Post-FAM-calibration residual errors over the southern test range displayed against the GCP layout; no significant systematic error pattern.

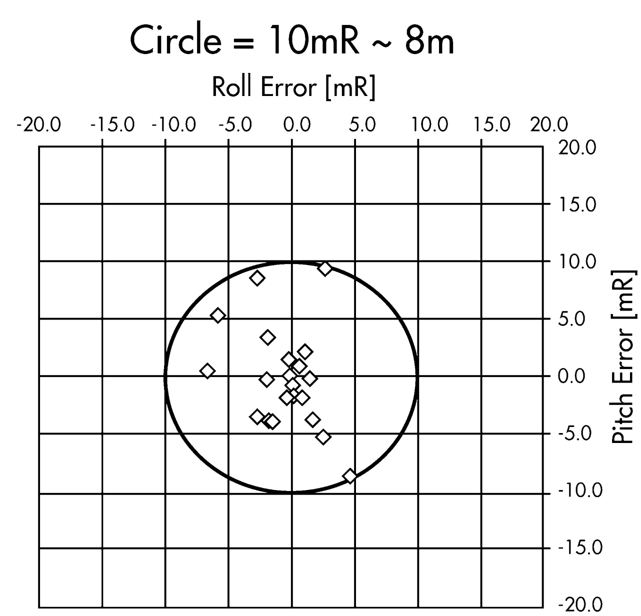

Fig. 11. Error distribution after corrections applied to improve interlock angle calibration.

Table 6
Mississippi block adjustment results

GCP	Average error ϕ (m)	Average error λ (m)	Average error h (m)	CE90 (m)	LE90 (m)
None	− 2.9	2.5	1.0	4.4	2.7
1	− 1.5	0.7	0.0	2.7	2.5

each image were determined by block adjusting the IKONOS images in our ground station and later used to compute the mean interlock angle corrections. Fig. 11 shows the error distribution after applying the interlock angle corrections. It is seen that the resulting geometric accuracy of an uncontrolled IKONOS imagery is better than 10-m CE90.

3.4.7. Validation

A Space Imaging project located in a relatively flat area of Mississippi, with six stereo strips and a large number of well-distributed GCPs, was used to validate the FAM and interlock calibrations. Each of the 12 source images was produced as a georectified image with RPC camera model data. The images were then loaded onto a SOCET SET® workstation running a Space Imaging developed RPC block adjustment model, described in more detail in Dial and Grodecki (2002a) and Grodecki and Dial (2002a). To quantify block adjustment accuracy, GCPs were selectively changed between control and check points. Horizontal and vertical accuracy for the case with no GCP and the case with one GCP are given in Table 6. Vertical and horizontal error distribution for a case with a single GCP is shown in Fig. 12. More detailed results can be found in Grodecki and Dial (2002b).

Several statistical tests of IKONOS accuracy have been performed since the completion of OOAT. IKONOS mono accuracy, exclusive of terrain displacement, was measured

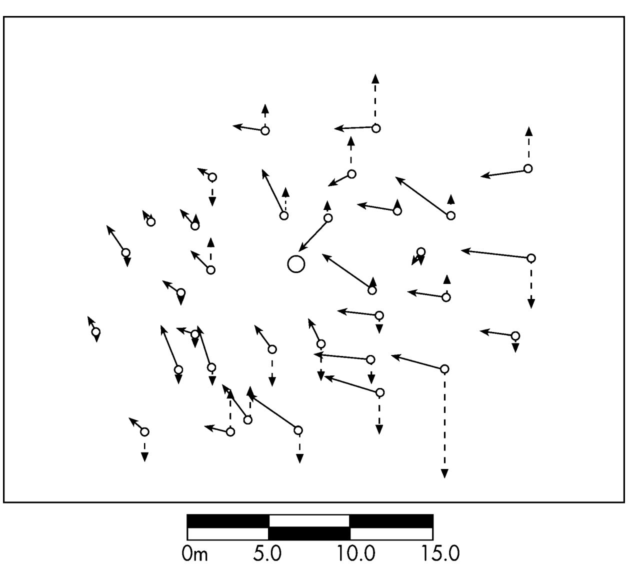

Fig. 12. Validation of FAM and interlock calibrations, and quantification of block adjustment accuracy: vertical and horizontal errors shown by dotted and solid arrows, respectively, for a case with a single GCP.

at 4-m RMS per axis (9-m CE90) with RMS relative errors of 50 parts per million (Dial & Grodecki, 2002b). IKONOS stereo accuracy without control has been reported at 6.2-m CE90 horizontal with 10.1-m LE90 vertical by Dial and Grodecki (2003a) and 7.9-m CE90 horizontal with 7.6-m LE90 vertical by Ager (2003).

4. IKONOS system products and applications

After successful completion of satellite launch, calibration, and test, Space Imaging began meeting the needs of government and commercial customers by delivering the products that interface the IKONOS satellite to the user community. These products meet customer needs for image analysis, cartography, and photogrammetry.

4.1. NASA Scientific Data Purchase

The NASA Scientific Data Purchase contract specified the products described in Table 7. Accuracy of the Standard Original, specified pre-launch at 250-m CE90, turned out to be considerably better with an accuracy of 15-m CE90 exclusive of terrain displacement. The Precision Original product was problematic. Intended only for flat (± 3 m) regions where orthorectification would not be necessary, it was sometimes ordered in hilly regions where large terrain displacement errors were not corrected by orthorectification but small satellite positioning errors were corrected with ground control. Both the Precision Original and the Precision Master products required high satellite elevation angles leading to long collection times. Space Imaging does not market an equivalent to the Precision Original Product because of these issues. Instead of Precision Plus orthorectified products with 2-m CE90 accuracy, Space Imaging

Table 7
Scientific data purchase products

SDP product name	Description	Nearest commercial product name
Standard Original	Georectified image with 250 m CE90 accuracy exclusive of terrain displacement.	Geo
Precision Original	Georectified image collected above 80° elevation with ground control and 3 m CE90 pan accuracy, 5 m CE90 MSI accuracy exclusive of terrain displacement.	None
Standard Master	Orthorectified image, 12.2 m CE90 accuracy.	Pro (10 m CE90)
Precision Master	Orthorectified image, 2 m CE90 pan accuracy, and 5 m CE90 MSI accuracy.	Precision Plus
Model	Bundle with a stereo pair (25 m CE90 horizontal, 22 m LE90 vertical accuracy) and a DEM (7 m RMSE).	Reference Stereo + IKONOS Terrain Model

Table 8
Scientific data purchase parameters

Parameter	Value
Bits	11
DRA	No
MTFC	Yes
Mosaic	No
Pan sharpen	No
Resampling	Cubic convolution
GSD	1 m pan, 4 m MSI
Bands	Pan + blue, green, red, and NIR
Datum	WGS84
Projection	UTM
Format	GeoTIFF
Media	CD-ROM

recommends Precision orthorectified products at 4-m CE90 because they can be delivered much more quickly.

One area where the SDP product specifications excelled was the uniformity of product delivery parameters. Where commercial products can be delivered in a variety of bit, band, processing, and format options, the SDP established consistent standards shown in Table 8. The uniform SDP delivery parameters facilitate testing algorithms and software across the entire SDP archive. This is a model for future archives of satellite image data.

4.2. Image analysis

IKONOS Geo images are designed to meet the image analysis needs of customers on a budget. Geo images are collected with sensor elevation angles as low as 60°, providing 3-day revisit cycle for rapid image collection. Geo images are rectified to a map projection at a constant height without the use of a DEM. Not requiring a DEM speeds delivery but hurts accuracy, so Geo images are suitable for image analysis applications, that do not require a positional accuracy, but do require fast response or low price. Typical applications are emergency response, national defense/intelligence, and environmental monitoring applications.

Geo images are produced in a variety of formats according to the needs of the application and data handling capabilities of the user. Different band combinations are available: panchromatic (black and white), multispectral, pan-sharpened (color), or a bundle of panchromatic and multispectral imagery. Only three bands can be simultaneously displayed on computer monitors for visual interpretation. Common band combinations are natural color red–green–blue (RGB) displays and color infrared (CIR) with sensor NIR displayed as red, sensor red displayed as green, and sensor green displayed as blue. Natural color may be preferred for general use and color infrared preferred for remote sensing applications.

Imagery can be delivered in 8-bit formats for ease of use on small computer systems or 11-bit formats for full dynamic range. Dynamic range adjust (DRA) modifies grayscale values to enhance visual interpretability, while multispectral imagery with DRA off maintains absolute radiometric accuracy (Oleszczuk, 2000). Automatic machine classification favors 11-bit DRA-off products, while human visual interpretation favors DRA-on products with 8 or 11 bits. Fig. 13 illustrates stretching an 11-bit image to reveal shadow detail on an 8-bit display.

4.3. Cartography

Cartographers have long used aerial photography for map making. Making maps requires the extraction of

Fig. 13. Extracting detail from shadows in 11-bit imagery. Left: Image displayed with full radiometric range. Right: Same image stretched to show detail in shadows.

topography, hydrology, transportation, and other features from imagery. Two approaches are employed-monoscopic and stereoscopic.

Fig. 14 diagrams stereoscopic extraction. Stereoscopic extraction provides three-dimensional feature coordinates for 3-D Geographic Information System (GIS) systems and databases. Working with softcopy stereo display systems, the cartographer extracts contours and 3-D feature coordinates directly from the stereo imagery, assuring correct cartographic relationship of contours and features. While stereo workstations are more expensive than monoscopic systems, stereo imagery costs less than the combination of DEM and ortho images derived from that stereo, so economics may favor stereo extraction. The stereo products required for stereo map making will be discussed in the next section with photogrammetric products.

Fig. 15 diagrams monoscopic extraction from DEM and ortho imagery. Automatic software generates contour lines from DEM and the cartographer extracts features from the ortho image. Feature extraction uses low-cost, eye-friendly monoscopic displays. DEM and ortho products to support monoscopic extraction are discussed in this section.

4.3.1. Orthorectified images

Orthorectified images are the fundamental products for image maps, GIS image base, and cartographic extraction. Image maps show imagery with marginalia, scale, and grids, just like a regular map, except the image itself is shown instead of features represented by icons and vectors. GIS systems commonly show hydrographic, transportation, and other information as vector layers. Displaying those vectors on top of a base image adds context to the vector information.

Image features in orthorectified imagery are terrain corrected to planimetrically correct coordinates. Map vectors such as transportation, vegetation, and cultural features can be digitized from the ortho image.

Positional accuracy is increasingly important in today's GPS-enabled world. IKONOS orthorectified images are commonly produced in accuracy grades shown in Table 9 so that clients can order accuracy appropriate to their needs.

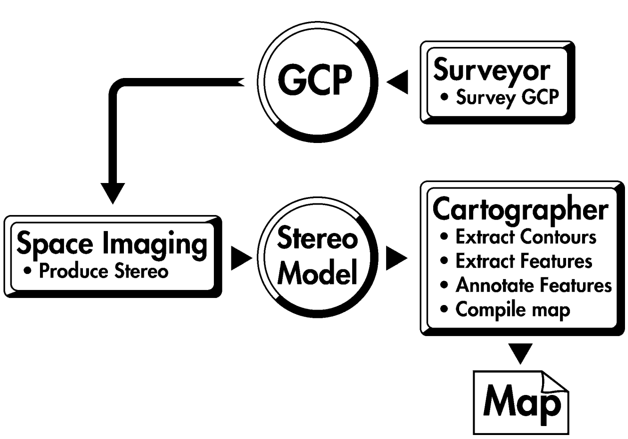

Fig. 14. Cartographic extraction from stereo images.

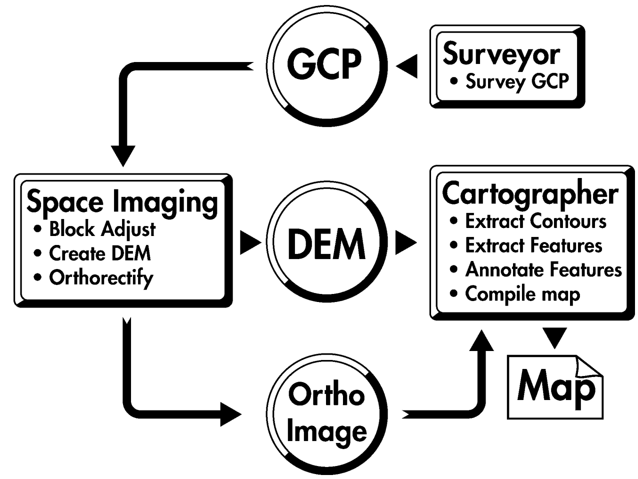

Fig. 15. Cartographic extraction from ortho images and DEM.

IKONOS accuracy without control is sufficient to make Reference products from a single stereo pair. Pro products can be produced from a multi-image block adjust solution or from a single image with ground control. Precision products require ground control. IKONOS product accuracy is controlled by CE90; corresponding RMS accuracy and scale values are shown for reference. The standardization of accuracy grades simplifies ordering, collection, processing, and quality control of ortho images.

4.3.2. Digital elevation models

A DEM representing the surface of the earth is used to assess flood dangers, communication lines of sight, airport safety, and other applications. An important application of DEM is to correct imagery for terrain displacement during orthorectification. DEM can be created from IKONOS stereo imagery in various accuracy grades and resolutions corresponding to DTED-1, DTED-2, USGS 7.5′ quad DEM. IKONOS best DEM is specified at 3-m LE90.

Automatic software generates the DEM that is then edited by operators at stereo workstations. DEM can be edited to the terrain surface, the top surface, or for orthorectification. Terrain DEMs, edited to the surface of the earth without trees and buildings, are best for hydrological studies. Top surface DEMs, edited to building and treetops, are best for line of sight analysis and aircraft navigation. DEMs for orthorectification are terrain edited except that they are edited to correctly show roads and bridges during orthorectification. IKONOS DEMs can be terrain edited, top surface edited, or

Table 9
IKONOS commercial ortho accuracy specifications

Product name	CE90 (m)	RMS (m)	Scale	GCP
Standard	50	25	1:100,000	No
Reference	25	12	1:50,000	No
Pro	10	5	1:12,000	Optional
Precision	4	2	1:4800	Yes
Precision Plus	2	1	1:2400	Yes

edited for orthorectification according to the application requirement. The lower accuracy DEM grades require less editing to meet their accuracy requirements.

4.4. Photogrammetry

The Ortho-Kit and Stereo image products include camera model data along with the imagery. The camera model data in RPC format enables users with suitable software to photogrammetrically process the imagery. Accuracy can be improved with ground control. Images can be orthorectified with external DEMs or stereo images can be used to create DEMs. Monoscopic images with RPC camera model are called Ortho-Kit images. The principal application of Ortho-Kit images is to allow users to orthorectify IKONOS images with their own DEM. Precision and Reference Stereo images refer to stereo images processed respectively with and without ground control. Image orientation is described by RPC data for both Precision and Reference Stereo, the difference being that RPC coefficients for Precision Stereo images have been updated by use of ground control and so are more accurate.

Fig. 16 shows an anaglyph visualization made from an IKONOS stereo pair. Both images of an IKONOS stereo pair are collected on the same orbital pass as illustrated in Fig. 17. Typically, one image is collected above 72° elevation angle and the other above 60° with 30–45° convergence angle between the two images. The convergence angle facilitates three-dimensional measurement, while the high-elevation leg is suitable for orthorectification. Same-pass stereo collection results in the identical scene content and lighting conditions for both images and facilitates automatic terrain extraction of DEMs. After DEM extraction, the image of the stereo pair with the higher elevation angle can then be orthorectified with the DEM. Stereo accuracy can be improved with ground control, either by Space Imaging with Precision Stereo or by the users with commercial software.

Space Imaging has certified several commercial software packages for photogrammetric processing of IKONOS data: ERDAS IMAGINE®, OrthoBase Pro®, and Stereo Analyst®; PCI OrthoEngine®; INTERGRAPH ImageStation®; and BAE SOCET SET®. Used appropriately, these software packages can accurately perform block adjustment, terrain

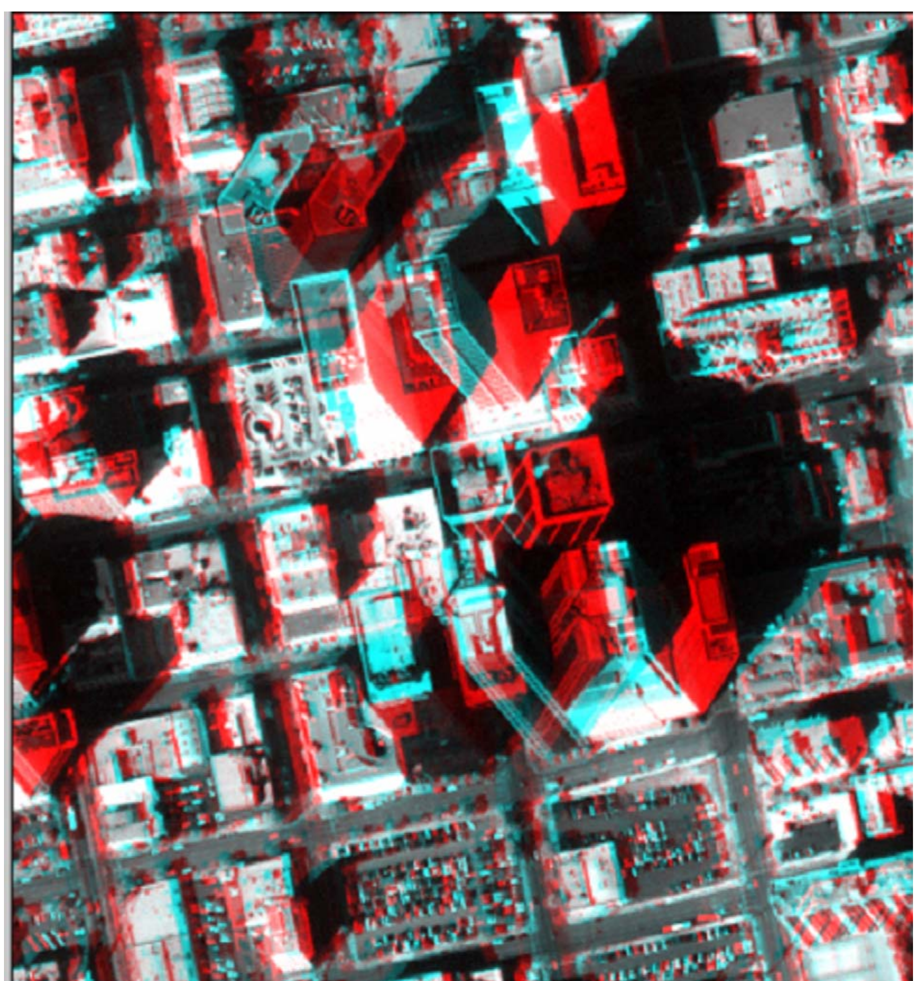

Fig. 16. Anaglyph visualization made from an IKONOS stereo pair (Imagery© Space Imaging).

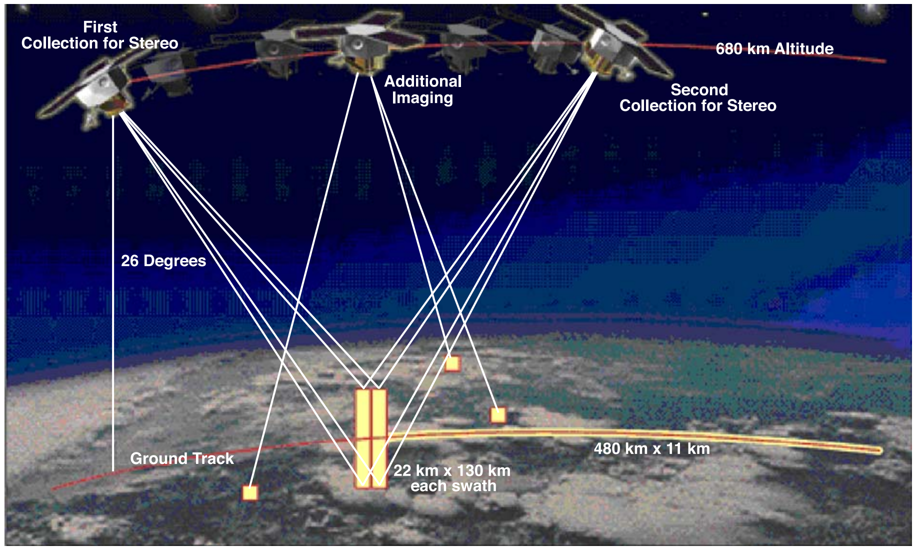

Fig. 17. Same-pass collection of IKONOS stereo images.

extraction, orthorectification, and cartographic extraction from IKONOS imagery (Dial & Grodecki, 2003b).

5. The space imaging IKONOS Block II system: the next step

Having described the IKONOS satellite performance and products, we conclude with a glimpse into plans for the next generation, high-resolution commercial image satellite system, described for now simply as "Block II".

The planned orbit for the IKONOS Block II satellites is 681 km, the same as Block I. The present license is for a nadir GSD of 0.50 m. However, Space Imaging has applied for a license that would permit 0.40 m at nadir so that we could provide a 0.5-m GSD over a field of regard of 700 km centered about the ground track. IKONOS today is 0.8-m GSD at nadir increasing to 1.0 m at 26° obliquity for a 700-km field of regard. So Block II provides a 2 × improvement in GSD from the same orbit as Block I with the same high perspective, 141-day repeat cycle and 3- and 11-day subcycles.

The satellite and payload design have been significantly improved to leverage advances in technology since the IKONOS design and build timeframe of 1994. The payload field of view and line rate have been increased and the detector size decreased. This increases the area collection rate to twice that of IKONOS today. A 2 × decrease in GSD increases the data rate by 4 × . Combined with the doubled area collection rate, Block II will generate pixels at a rate eight times that of Block I. This will provide a significant advantage in reducing the cost to produce products and shortening delivery timelines. The large contiguous coverage will image areas faster when clear weather occurs.

The agility of the satellite will be significantly increased to both improve the area collection efficiency and point target collection. It is expected that Block II will collect point targets at a rate nearly twice that of Block I. The nadir swath will be increased from 11 to 15 km. The area rate collection for Block II in the strip mode will be >12,000 km^2/min at a GSD of 0.5 m. The higher collection rates and maneuvering capability will allow the Block II satellite to completely image a one degree cell of 110 × 110 km in mono on a single pass all at a GSD < 0.55 m. The Block II system will provide a significant improvement over Block I in image resolution, large area mapping, and point target collection.

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