Characteristics of Space Imaging's One-Meter Resolution Satellite Imagery Products

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Key Words : High Resolution Imagery, Metric Accuracy, CARTERRA, IKONOS, Calibration

ABSTRACT

Space Imaging's IKONOS satellite provides imagery products at one-meter panchromatic, one-meter color, and four-meter multi-spectral ground sampled distances, GSD's. The characteristics of the satellite imaging capability, as related to image quality, radiometric resolution and metric accuracy are described. The selection of the orbit and it's parameters as they pertain to image collection efficiency and utility for the creation of precision cartographic image products is discussed, as is the on-orbit calibration and evaluation of the operational system modulation transfer function, MTF, radiometric accuracy and metric verification. A description of the one-meter and four-meter Carterra products offered by Space Imaging, and their attributes as they relate to interpretive, multi-spectral, and cartographic products are presented.

1. Image Collection

1.1 Orbit Geometry

The IKONOS satellite, built by Lockheed Martin in Sunnyvale, California, was launched from Vandenberg AFB, California, on September 24, 1999 at 11:24 AM PDT, on board a Lockheed Martin Athena II launch vehicle, into a sun synchronous orbit with an inclination of 98.1 degrees to the equator at an altitude of 681 kilometers, or 423 nautical miles, and an orbital period of 98.3 minutes. The local crossing time at the descending node is 10:30 AM. The velocity of the satellite over the ground is 6.79 kilometers per second. The altitude was chosen to result in a unique daily revisit or repeat pattern from day to day. At this altitude, for an image collection at the equator, the ground track repeats within 10 degrees of obliquity every 11 days and within 1 degree every 140 days. Orbit maintenance is performed as required to maintain this ground track repetition.

1.2 Revisit and Ground Resolved Distance

The IKONOS satellite / sensor is capable of pointing off nadir to image. Hence, if a customer can tolerate a larger, i.e., poorer GSD, the frequency of revisit increases. This provides for more opportunities to collect low cloud cover images, or more images per unit time to monitor temporal changes in scene content. As the latitude of interest is located farther from the equator, the number of opportunities increases, as represented in table 1

GSD - meters	Target Elevation	Point Target Location Equator	40 Degrees
0.84	79	11	8.5
1.00	60	3.9	2.9
1.18	50	2.8	2.0

Table 1 Revisit frequency as a function of GSD and latitude.

1.3 Image Collection Modes

The number of detectors in the sensor focal plane dictates the instantaneous footprint, or field of view projected onto the Earth. At nadir, this equates to 11 km, while at 1.0 m GSD this is 13 km. However, unlike typical pushbroom sensors, IKONOS has the capability to either pushbroom or whiskbroom imagery. Therefore, on the same pass, adjacent images can be acquired to collect areas larger than the 13 km 1.0 m GSD swath would lead one to believe. In fact, a contiguous image area of 4700 sq. km. can be acquired on a single pass, with the poorest GSD being 1.0 m, for an area of interest below the ground track. This imaging takes about 128 seconds, including maneuver time. Within a single communications cone, three such contiguous areas are capable of being imaged in a 9 minute window. For larger GSD's, larger areas can be imaged. For example, at 45 degrees minimum elevation, or 1.3 m GSD, 10,000 contiguous sq. km can be imaged in 220 seconds, thus allowing for two such contiguous areas in a 9 minute window. In addition, IKONOS can image long 13 km wide stripes up to 1000km long. Same pass stereo images are acquired by pointing the sensor forward of nadir for the first image, then aft of nadir for the second image, forming a stereo pair. These stereo images are epi-polar resampled in ground processing for visual display. Mosaic images up to 12,000 sq. km can be created. The high agility capability of the satellite allows for rapid collection of image targets dispersed off track. For example, for alternate targets located below the ground track and at a cross track distance of 100 km, these can be imaged at a rate of 2.8 per minute for 11 x 11 km images. 22 x 22 km images can be imaged at a rate of 1.0 per minute for the same conditions. Presently the IKONOS satellite is imaging an average 80 to 100K sq. km. Per day in an average operate time of 80 minutes. The satellite is designed to operate 120 minutes per day. As more regional operations centers, ROCS, come on line, the image collection per day will increase proportionally. Figure 1 depicts IKONOS imaging statistics through March 20, 2000. Equivalent images per minute are for the equivalent of an 11 x 11 km image.

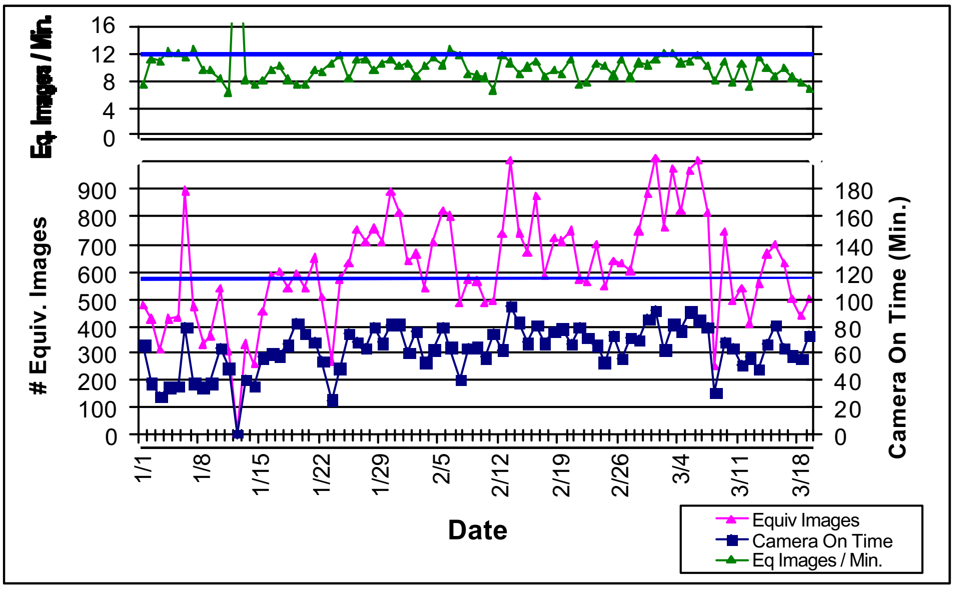


Figure 1 IKONOS Imaging Statistics

2 Sensor System

2.1 General

The camera system, built by the Eastman Kodak Company in Rochester, NY, consists of a one meter panchromatic and four band 4 meter GSD multispectral sensor. The camera field of view for both pan and multispectral are 0.931 degrees and the IFOV's are 1.2 and 4.8 micro-radians for the pan and multispectral bands respectively. At 681 km, this equates to GSD's of 0.82 and 3.26 meters. The pan and multispectral detectors field share the optical system and are collected simultaneously within 0.5 seconds of each other. Both the pan and multispectral imagery is collected at 11 bits per pixel and bandwidth compressed on board the satellite to 2.6 for transmission to the ground. The telescope assembly consists of a 10 meter focal length three mirror anastigmat with on-orbit refocus capability. Both the pan and multispectral detectors incorporate anti-blooming circuitry to limit blooming for 1.5 times the max scene radiance to 1 pixel. However, on orbit experience shows that under unique conditions of collection geometry and reflectivity of objects within the scene, that blooming is unavoidable. The requirement on inoperable detectors is less than or equal to 0.1 %. The IKONOS satellite launched with all detectors operable. The requirement on system radiometric accuracy relative to full scale is 10 % absolute, meaning temporally, 10 % relative, or pixel to pixel, and a linearity of 5 %.

2.2 Panchromatic Sensor

The pan sensor consists of 13,816 unique detectors with 5 ground commandable time delayed integration, TDI, modes to control exposure over a wide dynamic range of input radiance's. TDI is not changed within an image. For the present nominal TDI setting being used by IKONOS, the exposure time is 2.7 milliseconds. The pan CCD's employ a two phase architecture, limiting linear smear due to individual pixel integration to 0.5 pixels. The well capacity is 200,000 electrons, with an average quantum efficiency, QE, of 0.35. The pan CCD spectral QE curve is shown in figure 2. The quantization step equivalence, QSE, represents the exposure change produced by a single quantization step change out of the A/D converter. Although 11 bits equates to 2048 counts, only 1800 are used. For the pan band, at a TDI of 24 steps, a 40 degree solar elevation, 80% target reflectivity, and 20% background reflectivity, results in an input radiance at the aperture of 8.44 mW/cm/sr, or a nominal QSE of 0.55 micro Joules / sq. meter and 170,000 electrons. The nominal QSE is 94.4 electrons

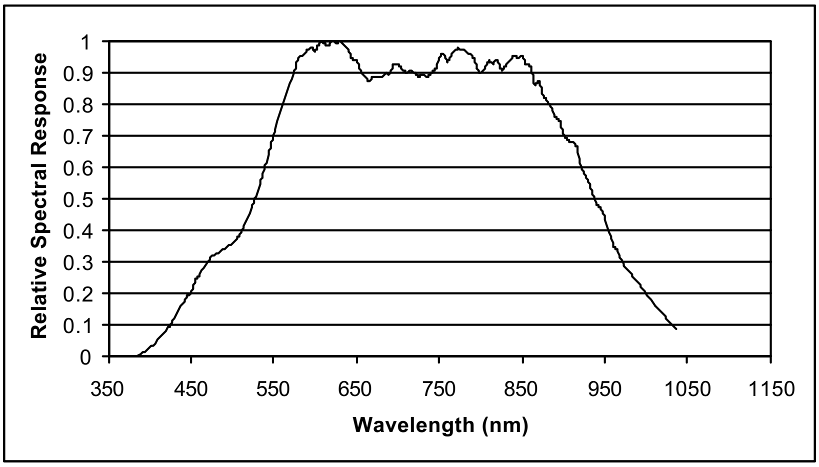


Figure 2 Pan CCD relative spectral response

Figure 3 shows the typical resolution of the IKONOS pan imagery. Note people in the square.

2.3 Multispectral Sensor

The bandpasses of the multispectral sensor are intended to be similar to those of the Landsat Thematic Mapper, Bands one through four.

Band 1	Blue	0.45 - 0.52 micrometers
Band 2	Green	0.52 – 0.60
Band 3	Red	0.63 - 0.69
Band 4	Near IR	0.76 - 0.90

Figure 4 shows the relative spectral response for the four multispectral filters.
The multispectral detectors have a well capacity of 250,000 electrons, with a one phase arcitecture.
For the multispectral band, the QSE's for bands 1 through 4 are 100.0, 100.6, 72.2, and 109.2 electrons.

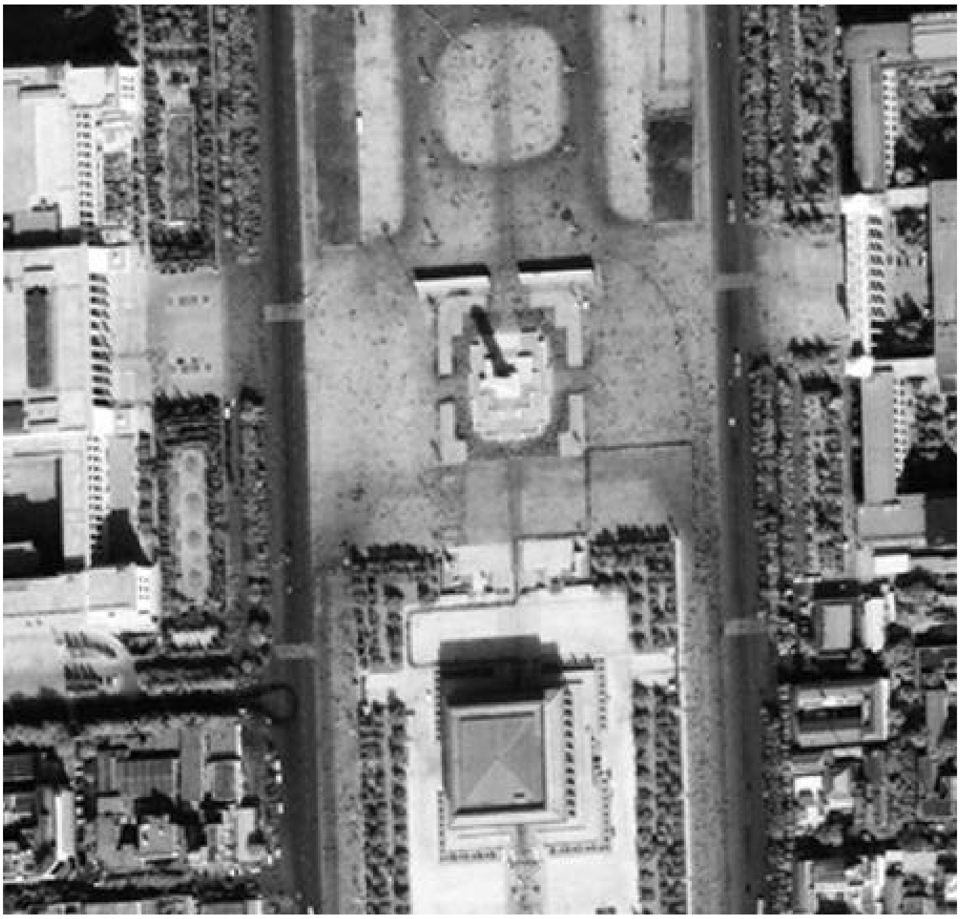


Figure 3 Example of IKONOS Pan image taken of Tiennamen Square

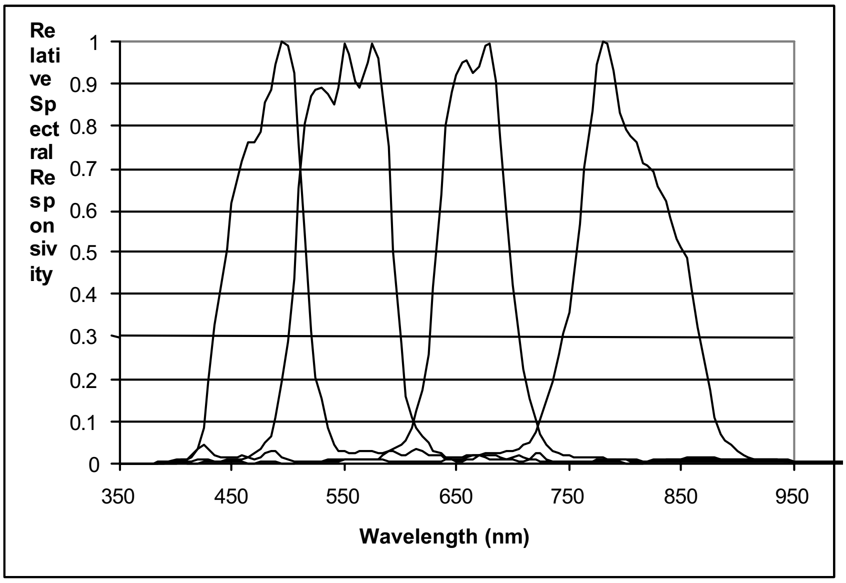


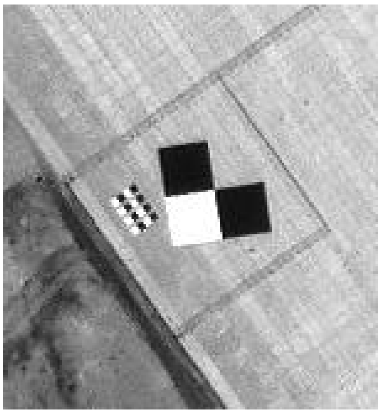
Figure 4 Normalized multispectral filter response

3. Calibration

3.1 On-orbit MTF measurement

The end to end system requirement for MTF is 0.10 measured at the Nyquist frequency of 41.6 cy/mm for the pan system. This includes a display multiplier of 0.91. Therefore, one would expect a system MTF exclusive of display of 0.11. This is for a target contrast ratio at the entrance aperture of 2 to 1, with 24 TDI. . The MTF's for the multispectral system are 0.17, 0.19, 0.21, and 0.23. Figure 5 shows the deployed edge target. The ground measured contrast ratio is about 6.5 to 1. The contrast ratios measured at the focal plane from six images collected on four different dates varied from 3.6 to 5.7

Figure 6 shows the on orbit measured MTF for the pan system, where a relative spatial frequency of 0.5 represents the Nyquist frequency of 41.7 cy / mm. The flat field MTF, i.e., calculated at zero spatial frequency, is 89 to 1 for the pan band. The MTF's for the MS bands 1 through 4 are: 0.26, 0.28, 0.29, and 0.27 respectively.



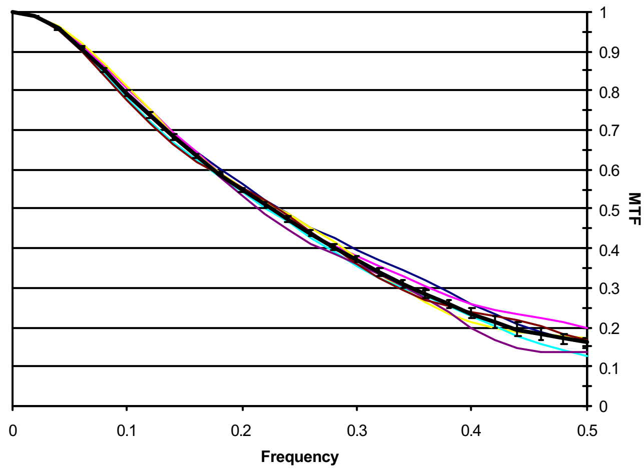


Figure 5 Edge target

Figure 6 On orbit measured system MTF (exclusive of display)

In addition, imagery products can be ordered with transfer function compensation, MTFC, either on or off. MTFC applies the inverse of the known system induced point spread function, governed by the laws of physics, to remove the blurring introduced primarily by the optics and detector. Even with a perfect camera system, some blurring is induced. IKONOS is a diffraction limited, Shot noise limited system with a sampling ratio of approximately two pixels per Airy disk. Figure 7 shows a comparison of the same image both with (right image) and without MTFC. It is suggested that imagery be ordered with MTFC on, even for multispectral products, the rationale being that the energy is being placed back into the pixels that it should have originated from.

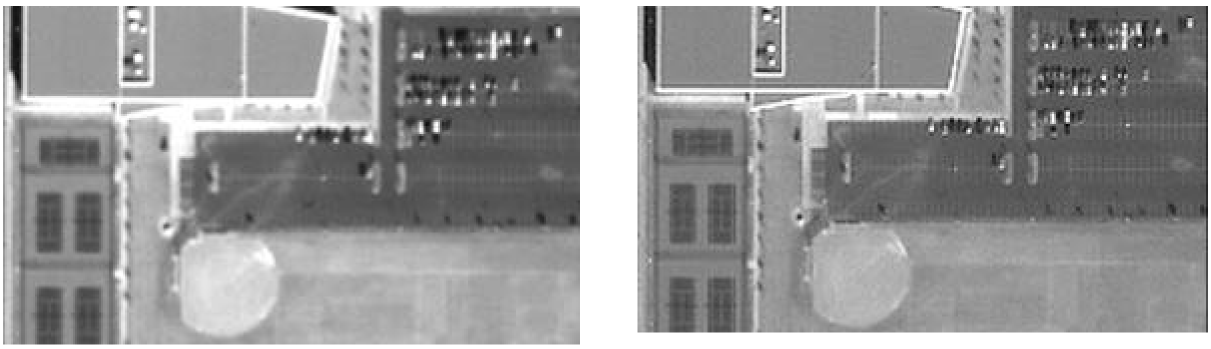


Figure 7 IKONOS one meter image without and with MTFC

3.1 Signal to Noise Ratio

The end to end system requirement for SNR is 10 : 1 for the pan system. This is for a target contrast ratio at the entrance aperture of 2 to 1, measured at the Nyquist frequency, with 24 TDI. The MS SNR's are spec'd at 13.0, 14.0, 11.5, and 13 to 1 for the blue through NIR bans respectively. The measured SNR for the pan band is 14 to 1 average with a variance of 1.0. The MS band SNR's at nyquist are 24, 40, 30, and 18 to 1.The corresponding flat field SNR's for the MS bands 1 through 4 are: 94, 143, 103, and 67 to 1 respectively. The measured noise across all five bands is about 4 digital counts, making the system shot noise limited. All specs and measured data are without transfer function compensation, MTFC.

3.2 Radiometric Calibration

The on-orbit radiometric calibration of the IKONOS system is performed in three ways. First, a passive on-board calibration assembly is used to fully and uniformly irradiate the focal plane sequentially through a series of Waterhouse stops in the calibration assembly, using the sun as the source. The range in size of the aperture stops provides for calibration data over the full dynamic range of the multispectral detectors and pan detectors for all 5 TDI settings. This processed calibration data results in a five point cal curve per detector per TDI setting. At this time it is too early to have sufficient data to measure the absolute or temporal radiometric accuracy. However, there are no indications that the system will not meet the spec value of 10%. The relative accuracy was measured using four stars, one of which was questionable, to verify that the system is equal to or better than the 5 % relative accuracy spec. The linearity is specified at 5% of full scale. The measured value is in the order of tenths of a percent, and when calculated as a percent of the measured value, about 2% on the average. Figure 8 depicts the result of the gain adjusted cal curve for the multispectral bands using this data. The preliminary QSE's for the MS bands, using this very limited data set are: 132.17, 151.79, 146.07, and 138.17 electrons per digital count.

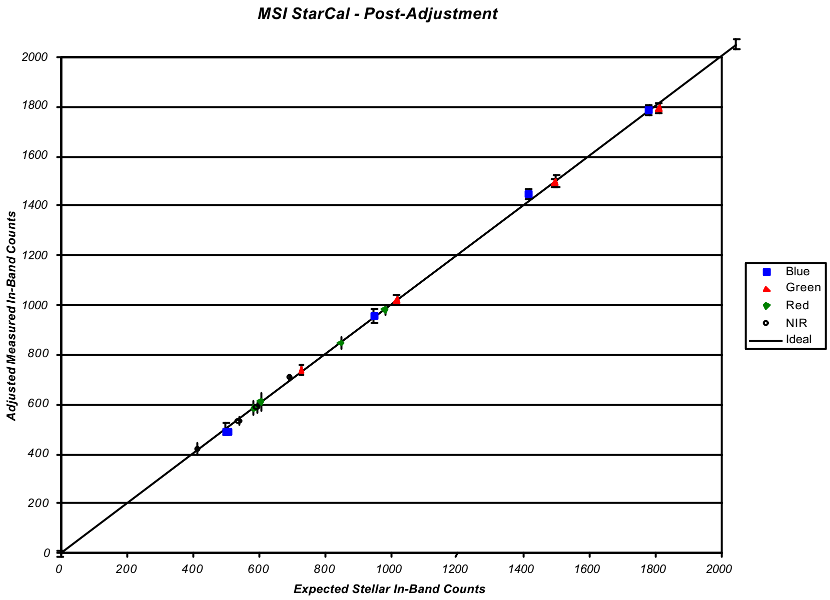


Figure 8 Multispectral calibration from star data

3.1 Metric Accuracy Assessment

The IKONOS satellite system was designed to meet the metric accuracy requirements specified both with and without the use of ground control points, GCP's.

3.1.1 Stereo Accuracy without Ground Control

Accuracy without ground control requires accurate knowledge of orbital ephemeris, satellite attitude (pointing direction), and interlock angles between the telescope bore-sight and star trackers. On-board GPS receivers and ground processing determine orbital ephemeris. Star trackers determine satellite attitude. Combining ephemeris, attitude, and interlock information enables ground processing to triangulate on ground features and determine their position. The requirements in Table 2 on 1, 3, and 5 models are three specification points on a curve of asymptotically improving accuracy as the number of models is increased.

Number of Stereo Models	Horizontal Accuracy, CE90	Vertical Accuracy, LE90
1	25.0m	22.0m
3	12.2m	not specified
5	not specified	10.0m

Table 2 Metric Accuracy Specification without Ground Control

3.3.2 Stereo Accuracy with Ground Control

Use of Ground Control Points (GCP) improves accuracy, largely by eliminating bias errors. The requirements for stereo model accuracy with ground control are shown in Table 3.

Horizontal Accuracy	2m CE90
Vertical Accuracy	3m CE90

Table 3 Metric Accuracy Specification with Ground Control Points

3.3.3 Operational Metric Accuracy Verification

Space imaging uses ground test ranges to verify the operational metric accuracy of the system. Test ranges have been surveyed in Phoenix, San Diego, and Western Australia. These geographic regions provide geographic diversity, differing terrain conditions and high probability of cloud free imaging. The Phoenix test range consists of 150 photo identifiable ground control points, GCP's. The points are fairly uniformly distributed over a 30km East-West by 20km North-South area. This range permits a mapping block of 3 side-by-side image strips. The San Diego test range consists of 140 GCP over a 22 by 22km area and offers more vertical relief, hence a more rigorous test of terrain extraction and orthorectification. The Southern Hemisphere Test Range consists of 200 GCP's over a 100 by 100km area in Western Australia. This area is relatively. Located in the Southern Hemisphere, this range is an important test that accuracy is independent of position along the orbital path. Being in the Eastern Hemisphere also tests that accuracy is independent of longitude. The GCP layout for this test range provides for measuring a larger mapping block, as well as independent analysis of pixel field angle mapping and along track low frequency oscillation. Table 4 shows the accuracy for Carterra

Carterra Product	CE90	RMS	NMAS (1)
Geo (2)	50.0 m	23.3 m	1:100,000
Reference	25.4 m	11.8 m	1:50,000
Map	12.2 m	5.7 m	1:24,000
Pro	10.2 m	4.8 m	1:12,000
Precision	4.1 m	1.9 m	1:4,800
Precision Plus	2.0 m	0.9 m	1:2,400

Table 4 CARTERRA products and associated metric accuracy (3)

Notes:
(1) Meets National Map Accuracy Standard for scale shown. Pixel size is 1m.
(2) Geo products are not orthorectified; accuracy values do not include effect of terrain displacement.
(3) Not all products in the table have been released as of the date of publication. See section 4.1

products, both released and planned.

4. Product Descriptions

Product Availability as of March 28,2000, Space Imaging has released the following CARTERRA products based on IKONOS imagery, described below.

1) CARTERRA™ Geo Pan and Multispectral 11 bit
2) CARTERRA™ Reference Pan 11 bit
3) CARTERRA™ Precision Pan 11 bit
4) CARTERRA™ Precision Plus Pan 11 bit, only as a non-standard quote with customer supplied DEMs

Products are delivered as 11-bit black-and-white and 11-bit color images. 11-bit imagery corresponds to 2048 shades of gray per pixel, compared to 256 shades of gray per pixel in traditional 8-bit imagery. The value of 11 bit data for customers is that it has a richer dynamic range, providing an enhanced ability to distinguish detail in shadows and brightly lit areas. Future product releases will include Pan Sharpened imagery. These products will consist of 1 meter natural color and false color imagery for various products such as Geo, Reference and Precision. The IKONOS satellite can produce digital elevation models from stereo images. The corresponding Carterra DEM product has not yet been released. The proposed DEM has a post spacing of one arc-second and a vertical accuracy requirement of 12m LE90.

4.1 Product Options

Format - GeoTIFF and NITF 2.0
Projections – UTM, State Plane, Albers Conical Equal Area, and Lambert Conformal Conic
Datum / Ellipsoid – WGS 84, NAD 83 / GRS 1980, Tokyo, and NAD 27
Media – CD-ROM and 8 mm tape

4.2 CARTERRA Geo

On January 3, 2000, Space Imaging introduced CARTERRA Geo ™ , high-resolution, geo-corrected imagery collected by IKONOS. CARTERRA Geo is ideal for projects not requiring a high degree of positional accuracy but which require quick delivery. Carterra Geo products are georectified and map projected. No terrain model is used so these images are not orthorectified. These images are collected with elevation angles as low as 50° (to permit rapid revisit), so terrain displacement can be significant. Accuracy of the Carterra Geo products is specified as 50m CE90 exclusive of terrain displacement. This accuracy was primarily tested operationally using relatively flat well-known terrain, so that terrain displacement is not an issue. On-orbit test results are consistently better than the product accuracy specification of 50m CE90 exclusive of terrain displacement.

4.3 CARTERRA Reference

Carterra Reference products are ideally suited for applications where quick delivery and less positional accuracy is crucial, including large-area or regional mapping, GIS backdrops, real estate planning, change monitoring, agricultural monitoring, site evaluation, insurance assessments, natural disaster assessments, media reporting and other applications. Carterra Reference products are orthorectified to a terrain model. The collection elevation angle can be as low as 60° depending on the accuracy of the available terrain model. The 60° elevation angle constraint reduces building lean and other orthorectification artifacts. The accuracy of Carterra Reference products was tested on-orbit. A terrain model of the Coterminous US (CONUS) was used. Test results are consistently better than the 25m Carterra Reference product accuracy specification.

4.4 CARTERRA Precision

Carterra Precision products are designed for provincial, state and local government projects, as well as transportation, utilities, telecommunications, real estate and other traditional geographic applications. These products are ideally suited for applications requiring a high degree of positional accuracy, such as base mapping, cadastral mapping, city planning, geographic information system (GIS) updates, change management, site selection and development. Carterra Precision products are orthorectified with a terrain model and ground control. Carterra precision products are specified to have an accuracy of 4m CE90, satisfying National Map Accuracy Standards for 1:4800 mapping. To reduce terrain displacement, the image acquisition elevation angle is higher than for Carterra Reference. This further reduces building lean and other orthorectification artifacts. Operational tests show it to be satisfying the 4m CE90 product specification.