IKONOS Technical Performance Assessment

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ABSTRACT

The world's first high-resolution commercial satellite, IKONOS, was launched by Lockheed Martin for Space Imaging in September of 1999. The IKONOS satellite contains both a 1-meter 11-bit panchromatic sensor and a 4-band 4-meter 11-bit multispectral sensor. After launch a detailed On-Orbit Product Verification program was conducted to verify the IKONOS satellite and ground station products met all design specifications. This paper shares the results of the On-Orbit Product Verification program. Descriptions of the image quality attributes and a comparison between system requirements and on-orbit performance are included. The verified attributes are the Signal to Noise Ratio (SNR), Modulation Transfer Function (MTF), Band to Band Registration, and Radiometric and Geometric Accuracy. The Geometric Accuracy is examined with respect to all ground processed product requirements to produce monoscopic, stereo, orthorectified, and digital terrain matrix products.

The result of this on-orbit testing and subsequent analyses show that all IKONOS system requirements have been met or exceeded.

Keywords: IKONOS, High Resolution, Satellite, Remote Sensing, Panchromatic, Multispectral, Space, Imaging

1. IMAGE QUALITY VERIFICATION

The on-orbit verification program verified several key attributes of the IKONOS Image Quality. Verification of the system Signal to Noise Ratio (SNR), Modulation Transfer Function (MTF), and Band to Band Registration were performed to assure that the IKONOS system met performance requirements.

1.1. Signal to Noise Ratio (SNR)

On-orbit measurements of flat field (zero spatial frequency) SNR are summarized in the Table 1. The flat field SNR was measured using the on-board calibration assembly imaging the Sun at an illumination level approximately equivalent to the peak signal level associated with the specification conditions of a 10% reflective target, 30 degree sun angle, and 2:1 contrast ratio at the aperture. Further analysis indicates that the system is shot-noise limited, as predicted.

1.2. Modulation Transfer Function (MTF)

The panchromatic MTF was measured using an edge target and Fourier techniques during the on-orbit test program. The MTF was evaluated using "tap-point" data, prior to image synthetic array resampling, to provide a true representation of the collection system performance. Evaluation of the MTF at the product level yielded similar results. Table 1 summarizes the IKONOS MTF at Nyquist.

Table 1. IKONOS SNR and MTF

FLAT-FIELD (ZERO SPATIAL FREQUENCY) SNR				**MTF AT NYQUIST**	
Band	Signal (DN)	Noise (DN)	SNR	MTF	MTF Verification Method
Pan	946.8	3.55	88.9	0.17	On-Orbit Test
Blue	1406	5	93.7	0.266	Analysis
Green	1933	4.5	143.2	0.284	Analysis
Red	1395	4.5	103.4	0.290	Analysis
NIR	751.4	3.75	66.8	0.277	Analysis

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1.3. Band to Band Registration

To support the verification of IKONOS image quality, two distinct band to band registration test methodologies were used. One approach utilized stellar collections and offline analyses of the residual errors resulting from application of the IKONOS on-line camera model processing. The second approach was a direct measurement of IKONOS output products using terrestrial scenes and correlation analysis.

1.3.1. Band to Band Registration- Stellar Verification

The following sections document the results of the stellar band to band registration verification. Maintenance order collections of stellar scenes were processed using the offline camera-model calibration software. Since the IKONOS system is capable of collection in both forward and reverse scanning modes, the verification program tested the pan to MSI registration in both collection scenarios.

1.3.1.1. Reverse Pan to MSI Band to Band Registration

Table 2 summarizes the results of the band to band registration error as measured using the stellar verification approach. The stellar verification approach does not include any misregistration contribution due to terrain uncertainty, hence the Adjusted Requirement column. Table 2 also includes the results of several statistical methods used to generate the linear error confidence factor. In all cases, the performance requirement was achieved.

Table 2. Reverse Pan to MSI Band to Band Registration Error Summary

	SYSTEM REQUIREMENT (PP LE90)	ADJUSTED REQUIREMENT (PP LE90)	LINE[Y] (PP)	SAMP[X] (PP)
LE 90% (RMS-based estimate):	1.8	1.62	1.466	1.346
LE 90% (Mean & SD-based estimate):	1.8	1.62	1.226	1.348
LE 90% (actual from Reg. Error Mag. Dist.):	1.8	1.62	1.336	1.331

The detailed numerical summary of the reverse pan to MSI band to band registration is provided in Table 3. This table documents the misregistration summary statistics for each of the reverse pan to MSI band combinations and the confidence factor of the measurement.

Table 3. Reverse Pan to MSI Band to Band Registration

	REVPAN-BLUE REGISTRATION		**REVPAN-GREEN REGISTRATION**		**REVPAN-RED REGISTRATION**		**REVPAN-NIR REGISTRATION**	
	Δ Line[y] (Pp)	Δ Samp[x] (Pp)	Δ Line[y] (Pp)	Δ Samp[x] (Pp)	Δ Line[y] (Pp)	Δ Samp[x] (Pp)	Δ Line[y] (Pp)	Δ Samp[x] (Pp)
Mean	0.70	0.13	0.67	0.12	0.56	-0.08	0.49	-0.34
Standard Deviation	0.63	0.80	0.53	0.77	0.61	0.73	0.79	0.91
RMS Error	0.94	0.81	0.85	0.77	0.82	0.72	0.93	0.97
LE 90% (RMS-based estimate)	1.55	1.33	1.41	1.27	1.35	1.19	1.53	1.59
LE 90% (Mean&SD-based estimate)	1.26	1.32	1.10	1.27	1.15	1.20	1.39	1.54
Prob(Chi-Sq)	0.91	0.97	0.98	0.98	0.94	0.99	0.90	0.83

1.3.1.2. Forward Pan to MSI Band to Band Registration

Table 4 summarizes the results of the forward Pan to MSI band to band registration error as measured using the stellar verification approach. Table 4 also includes the results of several statistical methods used to generate the linear error confidence factor. In all cases, the performance requirement was achieved.

Table 4. Forward Pan to MSI Band to Band Registration Error Summary

	SYSTEM REQUIREMENT (PP LE90)	ADJUSTED REQUIREMENT (PP LE90)	LINE[Y] (PP)	SAMP[X] (PP)
LE 90% (RMS-based estimate):	1.8	1.62	1.315	1.289
LE 90% (Mean & SD-based estimate):	1.8	1.62	1.311	1.274
LE 90% (actual from Reg. Error Mag. Dist.):	1.8	1.62	1.085	1.222

The detailed numerical summary of the forward pan to MSI band to band registration is provided in Table 5. This table documents the misregistration summary statistics for each of the forward pan to MSI band combinations and the confidence factor of the measurement.

Table 5. Forward Pan to MSI Band to Band Registration

	FWDPAN-BLUE REGISTRATION		FWDPAN-GREEN REGISTRATION		FWDPAN-RED REGISTRATION		FWDPAN-NIR REGISTRATION	
	Δ Line[y] (Pp)	Δ Samp[x] (Pp)	Δ Line[y] (Pp)	Δ Samp[x] (Pp)	Δ Line[y] (Pp)	Δ Samp[x] (Pp)	Δ Line[y] (Pp)	Δ Samp[x] (Pp)
Mean	-0.11	0.01	-0.03	-0.06	0.03	-0.27	-0.28	-0.45
Standard Deviation	0.78	0.83	0.76	0.73	0.75	0.71	0.89	0.68
RMS Error	0.78	0.83	0.75	0.73	0.75	0.75	0.93	0.81
LE 90% (RMS-based estimate)	1.29	1.36	1.24	1.20	1.23	1.24	1.53	1.34
LE 90% (Mean&SD-based estimate)	1.29	1.37	1.25	1.20	1.24	1.19	1.49	1.21
Prob(Chi-Sq)	0.98	0.96	0.99	0.99	0.98	0.98	0.90	0.94

1.3.1.3. MSI to MSI Band to Band Registration

Table 6 summarizes the results of the MSI to MSI band to band registration error as measured using the stellar verification approach. Table 6 also includes the results of several statistical methods used to generate the linear error confidence factor. In all cases, the performance requirement was achieved.

Table 6. MSI to MSI Band to Band Registration Error Summary

	SYSTEM REQUIREMENT (PP LE90)	LINE[Y] (PP)	SAMP[X] (PP)
LE 90% (RMS-based estimate):	1.4	0.646	0.839
LE 90% (Mean & SD-based estimate):	1.4	0.646	0.840
LE 90% (actual from Reg. Error Mag. Dist.):	1.4	0.630	0.793

The detailed numerical summary of the MSI to MSI band to band registration is provided in Table 7. This table documents the misregistration summary statistics for each of the forward pan to MSI band combinations and the confidence factor of the measurement.

Table 7. MSI to MSI Band to Band Registration Error Details

	BLUE - GREEN REGISTRATION		BLUE - RED REGISTRATION		GREEN - RED REGISTRATION	
	Δ Line[y] (Pp)	Δ Samp[x] (Pp)	Δ Line[y] (Pp)	Δ Samp[x] (Pp)	Δ Line[y] (Pp)	Δ Samp[x] (Pp)
Mean	0.00	0.00	0.00	0.00	0.00	0.00
Standard Deviation	0.32	0.36	0.41	0.63	0.44	0.53
RMS Error	0.32	0.36	0.41	0.63	0.44	0.53
LE 90% (RMS-based estimate)	0.53	0.60	0.68	1.03	0.73	0.87
LE 90% (Mean&SD-based estimate)	0.53	0.60	0.68	1.04	0.73	0.87
Prob(Chi-Sq)	1.00	1.00	1.00	1.00	1.00	1.00

Note that the stellar verification approach was unable to generate registration data for the IKONOS NIR band. The cataloged stars imaged in the Maintenance Order imagery had very dim responses in the NIR band. The analysis software was unable to accurately locate, identify, and centroid the NIR stellar responses.

1.3.2. Band to Band Registration – Terrestrial Verification

Terrestrial verification of image registration accuracy was performed by means of image correlation. For each pair of images, the image correlation program correlates on a fixed grid of points, eliminating those points at which the correlation peak is either too wide or too low. The offsets between the two images at each successful correlation point were recorded. This data was then analyzed to derive a statistical description of the registration accuracy. Tables 8 and 9 summarize the results of the correlation-based terrestrial misregistration assessment.

Standard statistics are computed for the offsets. Except where otherwise noted, CE90 and LE90 errors are computed using the empirical distributions.

Table 8. Forward Scan Band to Band Registration Summary

	Δ X LE90	**Δ Y LE90**	**CE90**	**TOTAL COUNT**
Pan-Blu	0.930	1.290	1.521	6932
Pan-Grn	0.837	1.191	1.381	9599
Pan-Red	0.856	1.137	1.336	9218
Pan-NIR	0.759	0.929	1.129	12684
Blu-Grn	0.181	0.233	0.303	40377
Blu-Red	0.198	0.258	0.332	39973
Blu-NIR	0.378	0.483	0.647	34667

Table 9. Reverse Scan Band to Band Registration Summary

	Δ X LE90	**Δ Y LE90**	**CE90**	**TOTAL COUNT**
Pan-Blu	1.028	1.677	1.117	12565
Pan-Grn	0.940	1.523	1.022	19443
Pan-Red	0.915	1.436	0.971	20232
Pan-NIR	0.803	1.287	0.903	25796
Blu-Grn	0.088	0.107	0.081	41600
Blu-Red	0.113	0.153	0.113	41214
Blu-NIR	0.893	0.974	0.648	14889

2. RADIOMETRIC ACCURACY

The Radiometric Accuracy of the IKONOS System has been determined through a combination of pre-launch and on-orbit testing. The Relative Spectral Response of the system was determined pre-launch based upon laboratory measurements of the payload components. The on-orbit test program determined the radiometric calibrations coefficients, the absolute calibration accuracy, the relative calibration accuracy, and linearity of the IKONOS system.

2.1. Relative Spectral Response

The relative spectral response (RSR) of the IKONOS system was determined by analysis based upon laboratory measurements. The RSR for each IKONOS band was calculated from a straight-forward combination of the spectral responses of the telescope and the focal plane.

The spectral response of the telescope was determined empirically based upon measurement of the spectral reflectivity of the mirror coating witness samples. The optical path consists of 5 reflective surfaces, each coated with the same enhanced-silver mirror coating.

The focal plane included both the spectral filters and the detector elements. The spectral response of the focal plane was determined by laboratory measurement of the flight unit and by analytically adjusting the measured response for the air to vacuum shift of the spectral filters. The spectral response of the focal plane was measured at three locations across the field of view to determine uniformity of system response.

The measured focal plane spectral response at full-width-half-maximum varied across the focal plane by 2% on average. The spectral response was measured using a monochrometer in an optical convergence cone similar to that resulting due to the f# of the system. Spectral "spreading" due to fast optics is not a contributor to potential RSR uncertainty. The air to vacuum shift of the spectral filters was measured using coating witness samples. The final spectral response of the focal plane includes the air to vacuum shift exhibited by the spectral filter.

The final RSR curves were determined by cascading the spectral responses of the telescope and the focal plane. The values are the average of the system response at the three different locations across the field of view. Table 10 provides a numerical summary of the IKONOS relative spectral response. Figure 1 is a plot of the panchromatic band spectral response, and Figure 2 shows the spectral curves of the MSI bands.

Table 10. IKONOS Spectral Band Characteristics

BAND	LOWER 50% (NM)	UPPER 50% (NM)	BANDWIDTH (NM)	CENTER (NM)
Pan	525.8	928.5	403	727.1
MS-1 (Blue)	444.7	516.0	71.3	480.3
MS-2 (Green)	506.4	595.0	88.6	550.7
MS-3 (Red)	631.9	697.7	65.8	664.8
MS-4 (VNIR)	757.3	852.7	95.4	805.0

Note: 1. Spectral Bandwidths are Full-Width at Half-Max
2. Panchromatic Band does not incorporate spectral filtering - response is that of optics/detector only

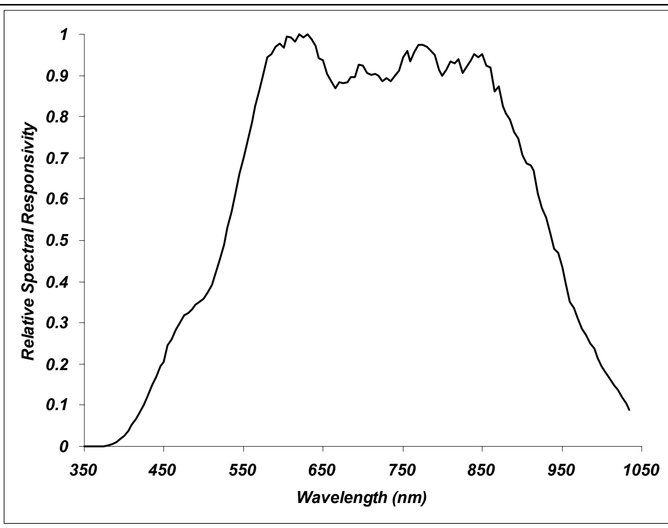

Figure 1. IKONOS Panchromatic Band Relative Spectral Response

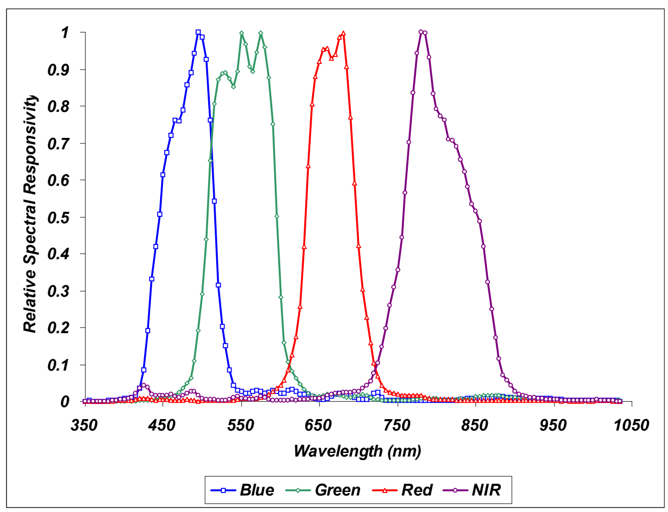

Figure 2. IKONOS Multispectral Band Relative Spectral ResponsesRadiometric Calibration

2.1.1.1. Determination of IKONOS Calibration Coefficients

The IKONOS radiometric calibration coefficients were determined through combined measurements of the sun using an on-board calibration assembly, homogenous terrestrial flat-field targets using a side-slither imaging maneuver, and multiple stellar irradiance targets.

Calibration coefficients were determined for converting IKONOS digital image values to in-band radiance at the sensor aperture. In-band radiance, the power density actually measured within each spectral band of IKONOS, is computed by integrating the relative spectral response and the source spectral radiance over all wavelengths:

$$L_k = \int L(\lambda) R_k'(\lambda)\, d\lambda \qquad (1)$$

where: L_k = in-band radiance at the sensor aperture for IKONOS band k (mW/cm^2-sr)
$L(\lambda)$ = spectral radiance at the sensor aperture (mW/cm^2-sr-µm)
$R_k'(\lambda)$ = peak-normalized spectral response for IKONOS band k from Figure(s) 3.2.1-1 and 3.2.1-2
λ = wavelength (µm)

The calibration coefficients for each band k were then computed as follows:

$$CalCoef_k = G_k^{-1} A_{opt}\, \Omega_k \int L(\lambda) R_k(\lambda) L_k^{-1}\, d\lambda \qquad (2)$$

where: G_k = gain coefficient for IKONOS band k (e^-/DN)
Aopt = clear aperture area of the IKONOS telescope (cm^2)
Ω = IKONOS instantaneous field of view in band k (sr)
L_k = in-band solar radiance at the sensor aperture for IKONOS band k (mW/cm^2-sr)
$L(\lambda)$ = solar spectral irradiance at the sensor aperture (mW/cm^2-sr-µm)
$R_k(\lambda)$ = spectral responsivity of IKONOS band k (e^-/mW)
λ = wavelength (µm)

2.1.1.2. Calibration of IKONOS Imagery to In-Band Radiance

IKONOS products are radiometrically corrected by rescaling the raw digital data transmitted from the satellite. All IKONOS image products are radiometrically corrected as one of the first steps in the production process. Imagery products, which have not been generated with Dynamic Range Adjustment (DRA) to enhance image interpretability, retain radiometric accuracy.

Image product digital values (DN) are converted to physical units of in-band radiance (mW/cm^2-sr) using equation (3).

$$L_{i,j,k} = DN_{i,j,k} * [CalCoef_k]^{-1} \qquad (3)$$

where: i,j,k = IKONOS image pixel i,j in spectral band k
$L_{i,j,k}$ = in-band radiance at the sensor aperture (mW/cm^2-sr)
$CalCoef_k$= In-Band Radiance Calibration Coefficient (mW/cm^2*sr-DN)
$DN_{i,j,k}$ = image product digital value (DN)

Table 11 provides the band-specific calibration parameters for the IKONOS 11 bit/pixel products computed from equation (2). Table 11 also documents the Full Scale Dynamic Ranges of the bands computed as the in-band radiance at 1900 digital counts.

Table 11. IKONOS Product Radiometric Calibration and Dynamic Range

SPECTRAL BAND	**$CALCOEF_K$ $DN*[MW/CM^2-SR]^{-1}$**	**FULL SCALE DYNAMIC RANGE (MW/CM^2-SR)**
Pan (TDI 13)	161	11.80
Pan (TDI 18)	223	8.52
Pan (TDI 24)	297	6.39
Pan (TDI 32)	396	4.79
MS-1 (Blue)	637	2.98
MS-2 (Green)	573	3.32
MS-3 (Red)	663	2.87
MS-4 (VNIR)	503	3.75

2.1.2. Radiometric Calibration Accuracy

2.1.2.1. Absolute Calibration Accuracy

The absolute accuracy of the IKONOS system was characterized during the On-Orbit Verification testing. Absolute accuracy was verified by computing the relative error between measured IKONOS in-band counts versus the expected in-band counts (Note: For convenience, in-band counts were used for assessing radiometric accuracy. The calibration coefficients cited in Table 11 provide the translation between in-band counts and in-band radiance).

In the original calibration plan, stellar targets with well-characterized irradiances were selected for evaluation of the radiometric accuracy. However, these well-characterized stars were not available for viewing from IKONOS during the On-Orbit Verification test period. As such, lesser-characterized calibration targets were selected from Hipparcos catalog stars within the available IKONOS imaging field.

A model was developed, which used the stellar visual magnitude (Mv) and color index (B-V) extracted from the Hipparcos catalog, to estimate the in-band IKONOS counts for each calibration star. The model was built by relating the astronometric parameters (i.e., visual magnitude and B-V color) to the expected in-band counts of a large pool of well-characterized stellar targets (i.e., those unavailable for viewing from IKONOS). Using a large pool of well-known stars helps reduce the uncertainty associated with each individual star. Only those stars with expected in-band counts greater than 100 counts and less than 4000 counts were kept for analysis to avoid interference with the noise floor or the saturation level, respectively, of the detectors.

Figure 3 presents the expected in-band counts for the selected calibration stars versus the in-band counts measured by IKONOS. If the estimated radiometic accuracy were perfect, the data points would all fall on the dashed line. It should be pointed out that the error bars shown represent a uncertainty in the measured IKONOS in-band counts only.

Figure 4 presents a more complete representation of the IKONOS absolute radiometric accuracy. Plotted on this figure is the ratio of the measured to expected in-band counts. A ratio value of 1 would indicate that the radiometric calibration was 100% accurate. As can be seen from the plot, the absolute radiometric error (distance from a ratio of 1) in any band is much smaller than the system absolute accuracy specification of 10%. However, the total uncertainty in the measured/expected ratio, as represented by the error bars, is much greater, especially in the near-infrared band. The total uncertainty was estimated from the root-sum-squares (RSS) of the uncertainty in the IKONOS stellar measurements, the uncertainty in the model used to predict the expected in-band counts, and the bias in the well-characterized stars used to generate the model.

As might be expected, the uncertainty in the model far exceeded the measurement uncertainty. As such, it is clear that the use of lesser-characterized calibration targets was the limiting factor in the demonstration of the absolute radiometric accuracy. The impact of the model uncertainty was more apparent for the near-infrared band due to two factors.

First, the model to estimate stellar in-band counts assumes that the radiative properties of the calibration stars can be uniquely described in all bands by the two astronometric properties Mv and B-V. Since both of these parameters describe the radiative behavior in the visible portion of the spectrum, there is an assumption that the stars act like perfect blackbodies. Violations of this assumption can result in large variations, particularly in the near-infrared which is not measured in the astronometric parameters. This may help explain some of the larger variability observed in the spectral ratios discussed in the next section.

Second, even if the stars behave as blackbodies, most stars are not cool enough to be exceptionally bright in near-infrared. As observed in Figures 3 and 4, the IKONOS stellar measurements in the near-infrared band tend to be tightly clustered in the low end of the range. This would like increase the uncertainty in the model used to predict the expected near-infrared stellar counts.

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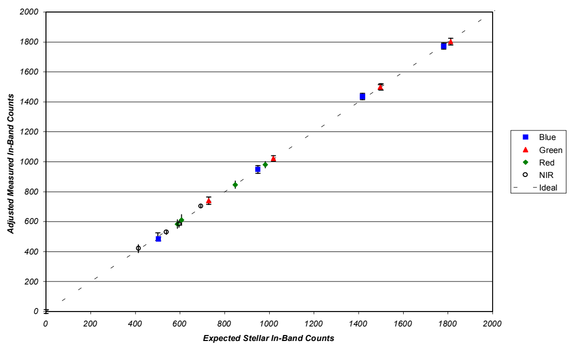


Figure 3. Measured in-band Calibration Star Counts versus Expected in-band Calibration Star Counts

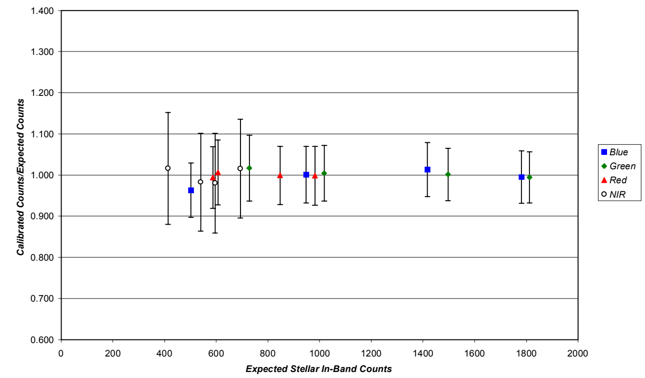


Figure 4. Ratio of Measured to Expected In-band Counts

The table below summarizes the estimated system absolute accuracy and the total system accuracy demonstrated on-orbit including test uncertainty.

Table 12. IKONOS Calibration Accuracy

	BLUE	GREEN	RED	NIR
Estimated RMS Accuracy (%)	2.7	2.8	2.8	5
Total RMS Uncertainty (%)	6.6	6.9	7.4	12.4

The accuracy verification requirements were achieved in all but the NIR band. Based on further analysis, the NIR band is believed to meet the system performance requirements, however the dynamic range and the knowledge of the radiance of the stars used in the verification activity was not adequate to fully demonstrate NIR absolute accuracy without caveat.

Initial IKONOS radiometric calibration performed during On-Orbit Acceptance Testing has since been supplemented with additional testing by both NASA and by Space Imaging. Results of these tests are not reported here, but will be used to update radiometric processing LUTs to improve relative calibration and image quality.

2.1.2.2. Relative Calibration Accuracy

Table 13 presents the RMS relative error for each spectral ratio. As with the absolute accuracy, the uncertainty in the stellar model would increase the uncertainty in the relative (band-to-band) accuracy. While not presented in Table 13, the total uncertainty can be computed for the spectral ratios as follows:

$$(\varepsilon_\pi / \pi_{ij})^2 = (\varepsilon_e(\lambda_i)/I_e(\lambda_i))^2 + (\varepsilon_e(\lambda_j)/I_e(\lambda_j))^2 + (\varepsilon_m(\lambda_i)/I_m(\lambda_i))^2 + (\varepsilon_m(\lambda_j)/I_m(\lambda_j))^2;\ \pi_{i,j} = \lambda_i/\lambda_j$$

Neglecting the uncertainty in the calibration methodology, the spectral ratios appear to be accurate to within the specification. Of note, the largest RMS errors in the spectral accuracy are systematically attributed to spectral ratios of the NIR band. In particular, the RMS error of the G/N and R/N ratios exceeds the specification. This is in-line with the overall uncertainty in the model prediction for the NIR band.

Table 13. IKONOS Band-to-Band Spectral Accuracy

	B/G (RMSE)	B/R (RMSE)	B/N (RMSE)	G/R (RMSE)	G/N (RMSE)	R/N (RMSE)
RMS Average Error	0.038	0.031	0.048	0.037	0.057	0.053
Requirement	0.05	0.05	0.05	0.05	0.05	0.05

2.1.2.3. IKONOS System Linearity

The linearity of each IKONOS band was tested by computing a linear regression fit between the expected and measured in-band counts. The intercept was forced to zero for the regression as the measured data had been preprocessed through equalization and dark noise removal. The results are presented for the four IKONOS multispectral bands in Table 14. The table shows the equation of the fitted curve, the linear correlation coefficient, the RMS relative error, and the RMS error relative to the system full-scale exposure (FSE). As can be seen from the figures, the IKONOS system response is highly linear. All four multispectral bands easily exceeded the On-Orbit Acceptance criteria of 5% of FSE. Further, using a more stringent analysis of the RMS relative error (e.g., computing the relative error between the calibrated value and the fit) indicates that the system is linear to better than 2% throughout the measured dynamic range in all four bands.

Table 14. IKONOS Band-to-Band Spectral Accuracy

BAND	EQUATION	R^2	RMSE	RMS FSE
Blue	y=1.000x + 0	0.9992	1.98%	0.73%
Green	y=0.9992x + 0	0.9997	0.45%	0.14%
Red	y=0.9999x + 0	0.9996	0.93%	0.44%
Near IR	y=0.9986x + 0	0.9908	1.72%	0.52%

3. GEOMETRIC ACCURACY

The geometric accuracy of the IKONOS products as verified by the On-Orbit Verification program is summarized in Table 15. The geopositional accuracy was measured directly by evaluating system output products for accuracy with respect to known ground control in the metric test ranges. Each product was evaluated using approximately 20 GCP to ensure adequate confidence in the result. In the majority of the verification cases, measurements were performed in both the Forward and Reverse collection modes to ensure stable system performance across the operational envelope of the collection system.

Table 15. IKONOS On-Orbit Geometric Accuracy Verification Summary

PRODUCT LEVEL	REQUIRED	ON-ORBIT VERIFICATION
Level 2 Mono	N/A	< 50 meters Evaluated for many collections in support of release of GEO product.
Level 2 Stereo	25.4m CE90 22m LE90	FWD 4.84m CE90, 5.24m LE90 REV 7.77m CE90, 1.27m LE90
Level 3 Mono	2.0m CE90	<2.0m CE90 Not measured in OOAT program. Given metric performance demonstrated by other products, analysis indicates performance requirements satisfied.
Level 3 Stereo	2.0m CE90 3.0m LE90	FWD 1.66m CE90, 1.52m LE90 REV 1.50m CE90, 1.65m LE90
Level 4a 1:50,000	25.4m CE90	FWD 6.87m CE90; REV 18.81m CE90; FWD 12.33m CE90
Level 4a 1:24,000	12.2m CE90	8.77m CE90
Level 4b 1:2,400	2.0m CE90	1.40m CE90
Level 5b DEM	30m CE90	5.78m LE90
Level 5c DEM	7.00m RMS	4.30m RMS
Level 5e DEM	3.0m LE90	FWD 1.96m LE90; REV 2.13m LE90
Level 7 1:24,000 Mosaic	12.2m CE90	6.40m RMS

3.1. Level 1 Radiometrically Corrected Products

IKONOS Level 1 products were not assessed for geometric accuracy. Evaluation of the Level 1 products consisted of a visual examination to verify that the products did not exhibit detectable shear at the focal-plane boundaries. The IKONOS system Level 1 products were verified to meet the requirements.

3.2. Level 2 Standard Geometrically Corrected Products

Level 2 mono and stereo products were evaluated for geometric accuracy during the on-orbit verification program.

3.2.1. Level 2 Mono Accuracy

The Level 2 mono products, released commercially as the Carterra Geo product, was examined periodically during the on-orbit verification program as a fundamental benchmark of system metric accuracy. Figure 5 plots the various measurements of Level 2 mono accuracy during the test program.

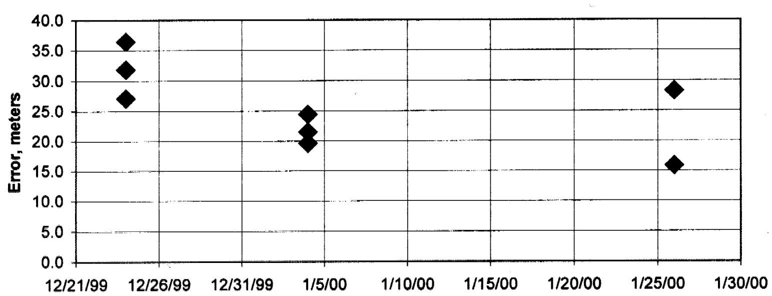


Figure 5. Level 2 Mono Accuracy (Including Terrain Displacement Error)

3.2.2. Level 2 Stereo Accuracy

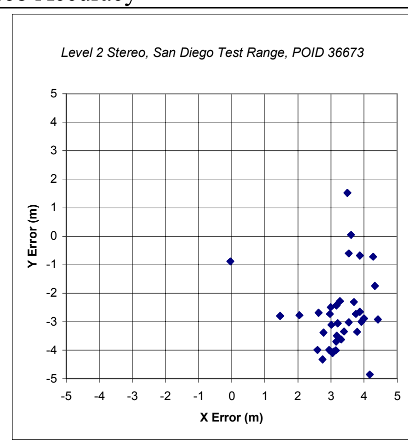
The Level 2 stereo accuracy was verified during the on-orbit verification program. The Level 2 stereo is the fundamental verification of uncontrolled system product accuracy. Verification of the stereo accuracy was performed in both the forward and reverse scan directions. Both stereo products were confirmed to have met all metric accuracy requirements (see Table below).

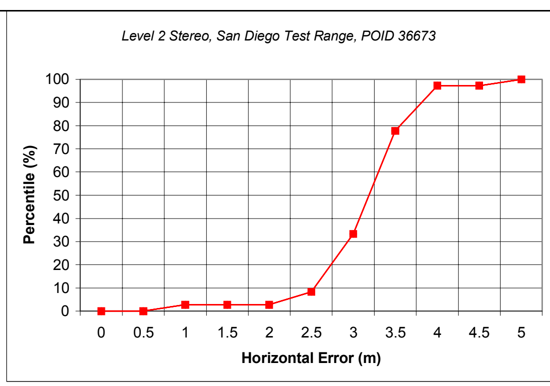
Table 16. IKONOS Level 2 Stereo Metric Accuracy Verification Summary

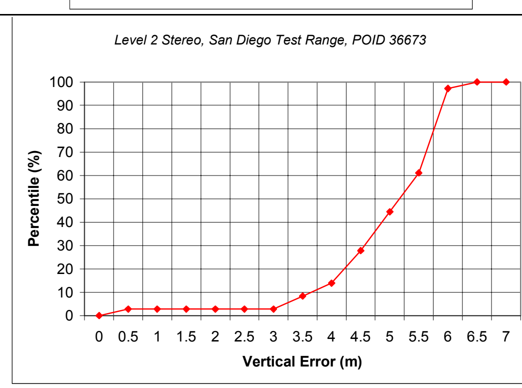
DESCRIPTION	HORIZONTAL ACCURACY REQUIREMENT (METERS, CE90)	MEASURED HORIZONTAL ACCURACY (METERS, CE90)	VERTICAL ACCURACY REQUIREMENT (METERS, LE90)	MEASURED VERTICAL ACCURACY (METERS, LE90)
Forward Scan	25.4	4.8	22.0	5.2
Reverse Scan	25.4	7.8	22.0	1.3

Table 17. Forward Scan Level 2 Stereo Accuracy

POID	36673		
Image ID	2000010818095180000010109325		
Image ID	2000010818090260000010109323		
Num. Pts.	36		
	X Error (m)	Y Error (m)	Z Error (m)
Mean	3.2	-2.7	-4.9
Maximum	4.4	1.5	-0.3
Minimum	0.0	-4.9	-6.1
Std. Dev.	0.8	1.3	1.1
RMS	3.3	3.0	5.0
Product Horizontal Accuracy (CE90) Mean & Std. Dev. Based			4.8 (m)
Product Horizontal Accuracy (CE90) Actual Error Distribution			3.6 (m)
Product Horizontal Accuracy (CE90) RMS Based			6.8 (m)
Product Vertical Accuracy (LE90) Mean & Std. Dev. Based			5.2 (m)
Product Horizontal Accuracy (CE90) Actual Error Distribution			5.7 (m)
Product Horizontal Accuracy (CE90) RMS Based			8.3 (m)







3.3. **Level 3 Precision Geometrically Corrected Products**

3.3.1. Level 3 Mono Accuracy

The on-orbit verification program did not test the Level 3 mono products. The elevation uniformity requirements for the Level 3 mono products were deemed overly restrictive for a meaningful verification.

3.3.2. Level 3 Stereo Accuracy

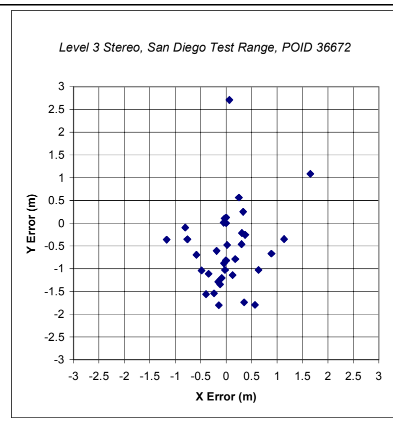
Verification of the Level 3 stereo accuracy was performed in both the forward and reverse scan directions. Two Level 3 stereo products, generated from the source data collected over the San Diego metric range, were used for this verification:
POID 36672 (Western Strip, Forward Scan)
POID 36681 (Center Strip, Reverse Scan)
Both stereo products were confirmed to have met all metric accuracy requirements (see Table below).

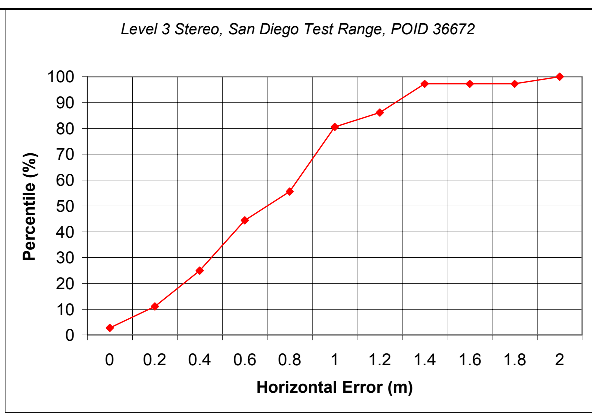
Table 18. IKONOS Level 3 Stereo Metric Accuracy Verification Summary

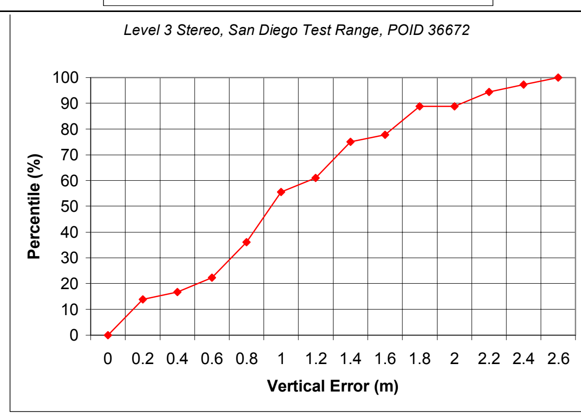
DESCRIPTION	HORIZONTAL ACCURACY REQUIREMENT (METERS, CE90)	MEASURED HORIZONTAL ACCURACY (METERS, CE90)	VERTICAL ACCURACY REQUIREMENT (METERS, LE90)	MEASURED VERTICAL ACCURACY (METERS, LE90)
Forward Scan	2.0	1.7	3.0	1.5
Reverse Scan	2.0	1.5	3.0	1.6

Table 19. Forward Scan Level 3 Stereo Accuracy

POID	36672		
Image ID	2000010818095180000010109325		
Image ID	2000010818090260000010109323		
Num. Pts.	36		
	X Error (m)	Y Error (m)	Z Error (m)
Mean	0.0	-0.6	-1.0
Maximum	1.7	2.7	0.4
Minimum	-1.2	-1.8	-2.5
Std. Dev.	0.5	0.9	0.7
RMS	0.5	1.0	1.2
Product Horizontal Accuracy (CE90) Mean & Std. Dev. Based			1.7 (m)
Product Horizontal Accuracy (CE90) Actual Error Distribution			1.3 (m)
Product Horizontal Accuracy (CE90) RMS Based			1.8 (m)
Product Vertical Accuracy (LE90) Mean & Std. Dev. Based			1.5 (m)
Product Horizontal Accuracy (CE90) Actual Error Distribution			2.0 (m)
Product Horizontal Accuracy (CE90) RMS Based			2.0 (m)







3.4. Level 4a Standard Orthorectified Products (no Ground Control)

3.4.1. Level 4a 1:50,000 Orthorectified Products (no Ground Control)

The IKONOS system Level 4a 1:50,000 Orthorectified products were verified to meet all accuracy requirements during the on-orbit testing. Three separate products were generated for this verification, including collection using both forward scans and reverse scans. The products for this verification use source imagery of the 3 adjacent stereo collections of the metric test range. Table 20 summarizes the test results.

Table 20. IKONOS Level 4a 1:50,000 Orthorectified Product Accuracy Summary

POID	DESCRIPTION	ACCURACY REQUIREMENT (METERS, CE90)	HORIZONTAL ACCURACY (METERS, CE90)
30933	Western Strip, Forward Scan	25.4	6.87
31835	Center Strip, Reverse Scan	25.4	18.81
31834	Eastern Strip, Forward Scan	25.4	12.33

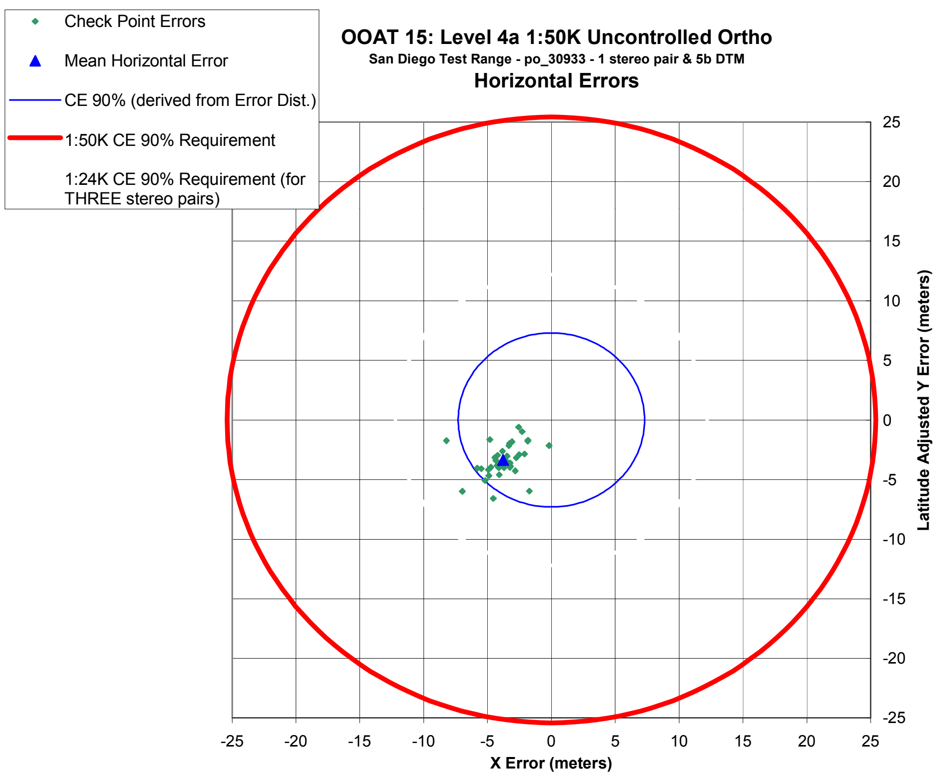


Figure 6. Level 4a Forward Scan 1:50K Latitude Adjusted Y versus X Error Distribution (PO_30933)

3.4.2. Level 4a 1:24, 000 Orthorectified Products (noGround Control)

The on-orbit testing program verified the capability of the system to produce an uncontrolled 1:24,000 orthorectified product using 3 stereo collections in the bundle adjustment process. Table 21 summarizes the results of the product verification. The requirement of 12.2 meters CE90 was achieved.

Table 21. 1:24,000 Orthorectified Product Accuracy

Product Horizontal Accuracy (CE90) Actual Error Distribution	8.77 meters

The following figures further characterize the results of the verification of the 1:24,000 orthorectified product.

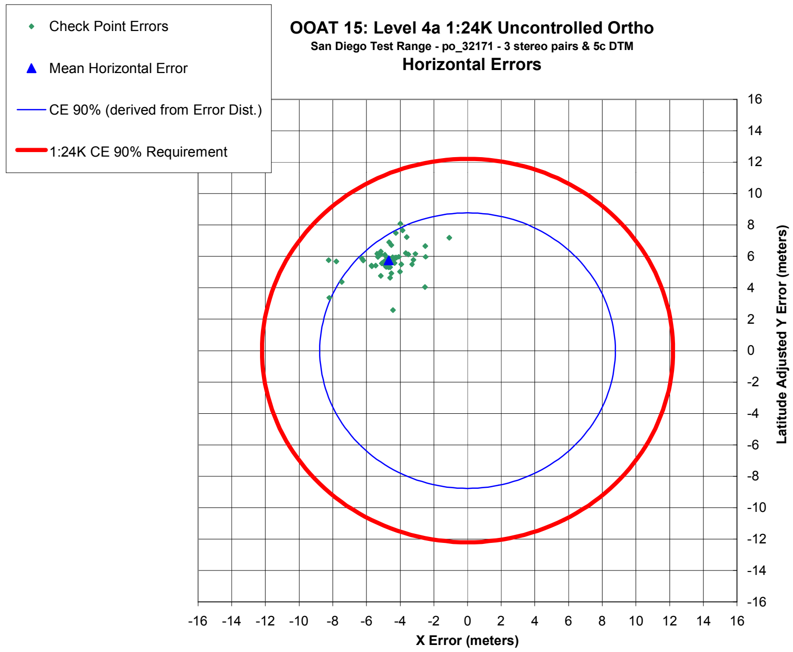


Figure 7. Level 4a 1:24K Horizontal Error Distribution (PO_32171)

3.5. Level 4b Precision Orthorectified Products (with Ground Control)

The on-orbit testing program verified the capability of the system to produce controlled 1:2,400 orthorectified product using a single high-elevation collection and ground control. Table 22 summarizes the results of the product verification. The requirement of 2.0 meters CE90 was achieved.

Table 22. 1:2400 Orthorectified Product Accuracy

Product Horizontal Accuracy (CE90) Actual Error Distribution	1.40 meters

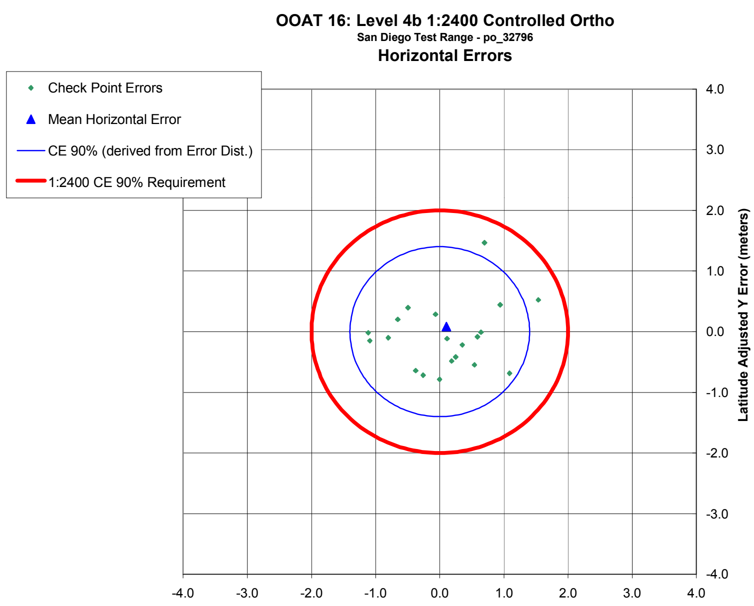


Figure 8. Level 4b Reverse Scan 1:2400 Latitude Adjusted Y versus X Error Distribution (PO_32796)

3.6. Level 5 Digital Terrain Matrix Products

The capability of the IKONOS system to generate Digital Terrain Matrix products was verified during the on-orbit verification activities. A subset of the available DTM products was produced and verified. Table 23 summarizes the DTM accuracy performance verified on-orbit.

Table 23. DTM Accuracy Verification Summary

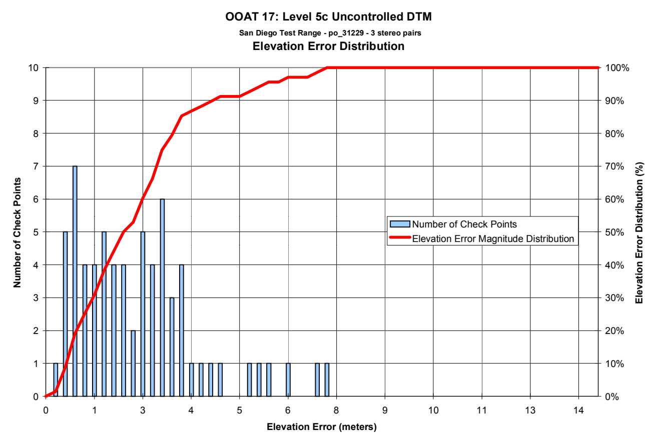
PRODUCT LEVEL	VERTICAL ACCURACY REQUIREMENT	ON-ORBIT VERTICAL ACCURACY
5b DTM	30.0 meters LE90	5.78 meters LE90
5c DTM	7.0 meters RMS	4.30 meters RMS
5e DTM	3.0 meters LE90	2.06 meters LE90 Forward Scan 2.16 meters LE90 Reverse Scan

3.6.1. Level 5c Digital Terrain Matrix

The capability of the IKONOS system to produce a Level 5c DTM meeting a vertical accuracy of 7 meters RMS error was verified during the on-orbit test program. The Level 5c DTM was generated using image data from the 3 stereo collections of the metric test range. Table 25 demonstrates analysis results of the 5c DTM accuracy.

Table 24. Level 5c Accuracy

Product Order Number	31229
Required Image 2000020718025380000010116784 2000020718034550000010116785	
Collateral Image 2000010818090260000010109323 2000010818095180000010109325 2000020218201960000010114367 2000020218211040000010114368	
Number of Diagnostic Pts	68
Mean	2.13
Min	-2.32
Max	7.15
Std. Dev	1.80
Sum Sq.	524.98
RMS_vertical (m)	2.78
Product Horizontal Accuracy (RMS) RMS Based	4.57
Product Horizontal Accuracy (RMS) Mean & SD Based	3.64
Product Horizontal Accuracy (RMS) Actual Error Distribution	4.30



3.6.2. Level 5e Digital Terrain Matrix

The on-orbit test program verified the capability of the IKONOS system to produce Level 5e DTM products using a single stereo collection and ground control points. Level 5e DTM production was verified using both forward and reverse collections (Tables 25 and 26). In both collection and production configurations, the vertical accuracy of 2.0 meters LE90 was achieved.

Table 25. Level 5e DTM – Forward Scan

Product Order Number	36556
Required Image 2000020718025380000010116784 2000020718034550000010116785	
Required GCPs SD-GCP-87 SD-GCP-109 SD-GCP-114 SD-GCP-116	
Number of Diagnostic Pts	27
Mean	0.05
Median	0.63
Min	-2.37
Max	2.29
Std. Dev	1.32
Sum Sq.	45.3
RMS_vertical	1.30
Product Vertical Accuracy (LE90) RMS Based	2.13
Product Vertical Accuracy (LE90) Mean & SD Based	2.17
Product Vertical Accuracy (LE90) Actual Error Distribution	2.06

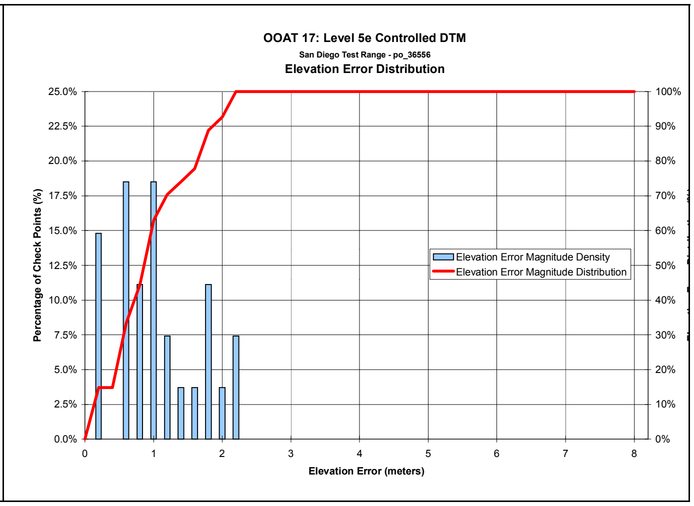
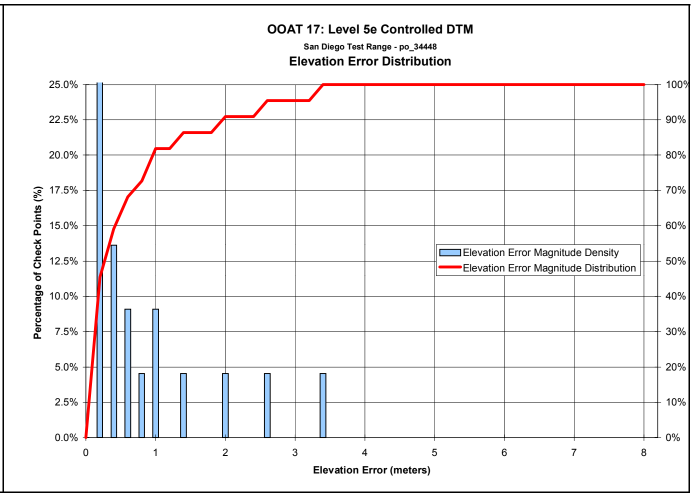


Table 26. Level 5e DTM Reverse Scan

Product Order Number	34448
Required Image 2000010818090260000010109323 2000010818095180000010109325	
Required GCPs SD-GCP-54 SD-GCP-56 SD-GCP-75 SD-GCP-82	
Number of Diagnostic Pts	22
Mean	-0.30
Median	-0.185
Min	-3.44
Max	2.66
Std. Dev	1.18
Sum Sq.	31.2
RMS_vertical	1.19
Product Vertical Accuracy (LE90) RMS Based	1.96
Product Vertical Accuracy (LE90) Mean & SD Based	1.97
Product Vertical Accuracy (LE90) Actual Error Distribution	2.16



4. ACKNOWLEDGEMENTS

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5. REFERENCES

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3. B. Peterson, “IKONOS On-Orbit Band to Band Registration, 1:2,400 Orthorectified and DTM Product Verification Summary”, *Space Imaging Internal ISO-9001 Reference Document SE-REF-019*, November 2000.