

ABSOLUTE RADIOMETRIC CALIBRATION OF THE IKONOS SENSOR USING RADIOMETRICALLY CHARACTERIZED STELLAR SOURCES

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KEY WORDS: IKONOS, Sensor, Multispectral, Radiometric, Calibration, Stellar

ABSTRACT:

Radiometric calibration of remote sensing satellites has traditionally been accomplished by means of vicarious ground calibration techniques. These methods employ extensive modelling algorithms to describe the ground reflectance, atmospheric absorption, etc. The agile-body IKONOS satellite has the capability to maneuver the vehicle such that celestial scenes can be imaged. Hence, several radiometrically characterized stellar sources have been imaged, on three separate occasions at one-year intervals. The data has been used to develop a radiometric calibration that simply correlates the detector counts in the imagery to the energy presented at the telescope aperture. While the results do not yet fully agree with vicarious ground calibration techniques, the stellar data is highly repeatable, easily predictable, the collection activities are easily scheduled and repeatable, and the results extremely linear. This method has established excellent long-term stability. It promises future absolute radiometric calibration.

1. INTRODUCTION

1.1 Historical Background

Traditionally, radiometric calibration of remote sensing systems has been accomplished by on-board calibration sources characterized in the lab prior to launch, and supported by vicarious ground calibration activities that take into consideration the solar spectrum, atmospheric conditions, and surface reflectance. Each of these tasks requires substantial resources in terms of equipment, personnel and opportunity. With the successful launch of the IKONOS satellite and the dawn of the commercial remote sensing industry the resources to perform such calibration activities are constantly held against the profit margin of doing business. Elaborate test facilities and costly excursions to remote sites are becoming more of a cost burden than a data enhancement. Alternative, accurate, and less expensive methods are constantly being pursued as replacement techniques for calibration.

The agile-body IKONOS satellite is capable of pointing at virtually any orientation while on orbit providing the ability to collect non-terrestrial images to support the payload calibration activities. Therefore, celestial scenes are just as accessible as terrestrial sites and offer many advantages that terrestrial sites do not. Solar, lunar and stellar scenes are available on every pass, the only tasking required is that of the satellite, data analysis can begin within hours after collection, and complex modelling schemes are eliminated from the data reduction.

2. ABSOLUTE RADIOMETRIC CALIBRATION USING STELLAR IRRADIANCES

2.1 Orientation of Stellar Image Collections

Typically the satellite is tasked to collect images as it descends across the sun-lit surface of the earth. The stellar images are collected during the 14-minute period while IKONOS passes over the terminator as it crosses the arctic near the North Pole, between the time the satellite exits umbra and before it drops below the northern horizon when the stellar scenes are blocked from view. The only restriction placed upon the stellar imaging activities is that the solar arrays be oriented less than 90° away from sun-point while the images are being collected, as shown in Figure 1, to maintain the Sun's presence on the solar arrays.

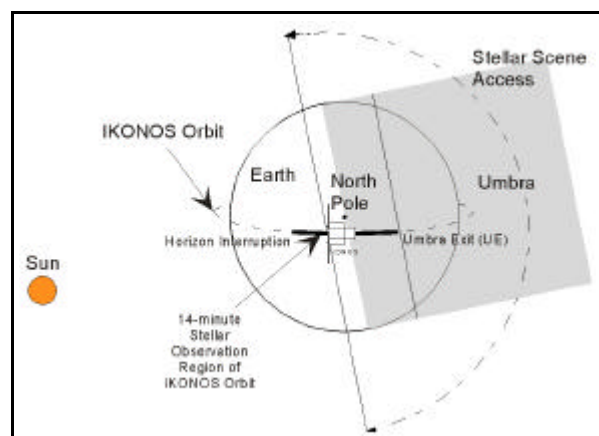


Figure 1. IKONOS stellar imaging collection diagram.

2.2 Equivalent Radiance Calculation

Absolute calibration of the IKONOS satellite's payload sensors is performed by comparing the total digital numbers found in the stellar image, to the absolute in-band spectral radiance of several radiometrically characterized stars. The method is somewhat complicated by spatial differences between the calibration stars, which are essentially point sources, versus the extended ground scenes, which are the usual targets. Because of this difference, absolute calibration needs to address the relationship between the irradiance from the stars (given in Watts/cm² at the telescope aperture) and its equivalent radiance from an extended target (given in Watts/cm²-sr) as shown in Figure 2.

The radiometric calibration method that has been developed for IKONOS is performed post-launch. Once on-orbit, images of radiometrically characterized stars are collected and the actual digital numbers (DN) are determined for each multispectral band from each of the images collected. Separately, the absolute at-aperture in-band radiance is calculated from the absolute stellar spectrum. The ratio of calculated at-aperture in-band radiance per measured DN then becomes the primary calibration factor for the IKONOS satellite's payload sensors. This method of calibration simply correlates the system output to the input.

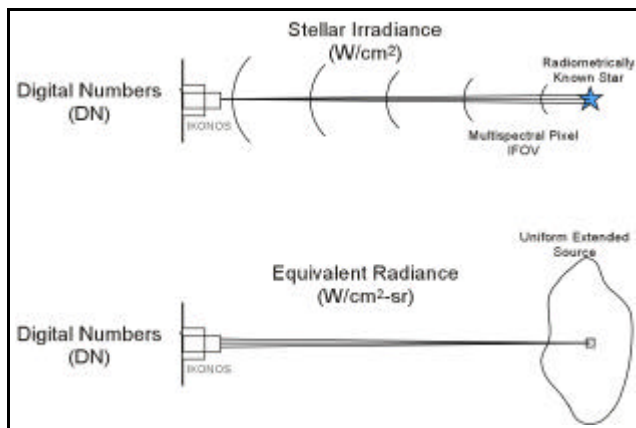


Figure 2. Radiometric calibration equivalent radiance.

The Gunn & Stryker, Stellar Spectrophotometric Atlas, 1983, was used to identify and select the stars that could be used in the IKONOS radiometric calibration activities. These data represent the source for spectrophotometric measurements, which cover the full spectrum of the IKONOS satellite's payload detectors. According to an April 21, 1988 private communication from J. E. Gunn, the uncertainty in the knowledge of the absolute spectroradiometric brightness of these stars is estimated to be no greater than 3 percent.

Of the 175 stars included in the Gunn and Stryker Atlas, 11 of those found to have acceptable properties for IKONOS response characteristics were also accessible during the period when the calibration was performed. These are listed in Table 3 (along with their astronomical identifications, and the Hipparcos catalogue identification).

Table 3. Stars from the Gunn & Stryker Atlas selected for IKONOS radiometric accuracy calibration.

G&S	HIP	Star Name	V mag	Av mag
7	42799	Hya Eta-7	4.130	0.030
83	86032	Ras Alhague	2.035	0.014
109	20885	Tau Theta1-77	3.694	0.027
118	53229	LMi 46	3.672	0.025
123	53740	Crt Alpha-7	3.964	0.030
127	54539	UMa Psi-52	2.861	0.018
134	77070	Unukalhay	2.508	0.015
135	48455	Leo Mu-24	3.733	0.026
142	47431	Hya Iota-35	3.741	0.037
149	33160	CMa Theta-14	3.888	0.044
150	37908	Gem 81	4.650	0.067

3. DERIVATION OF IKONOS CALIBRATION COEFFICIENTS

The absolute calibration coefficients were determined for each band in four steps, summarized as below, and explained in detail in the subsequent paragraphs.

1. Measure, on-orbit, the digital numbers (DN) generated in the stellar image;
2. Calculate at-aperture in-band irradiance for the imaged star (Watts/cm²);
3. Using the results of Step 2, calculate the equivalent at-aperture in-band radiance for the imaged star (Watts/cm²-sr);
4. Divide the results of Step 1, by results of Step 3, to obtain DN/(Watts/cm²-sr) and apply a linear fit to the results.

3.1 Collection of digital numbers from stellar images

To begin, the number of counts or DN resulting from the (on-orbit) imaging of a star is determined. These numbers are simply the measured output of the sensor, the calibration factors in the remaining steps being calculated values.

Six images are collected of each star during a single imaging opportunity. Figure 4 shows a 7-pixel by 7-pixel area, bounded by an inner box, of one stellar image containing the star scene, this area collects all of the pixels illuminated by the star. To obtain the total number of DN produced by the stellar illumination, the DN of each of the pixels within the box are summed to obtain DN_{Total}. Also, the DN for all the pixels outside of the box are averaged to obtain the noise within the image in terms of DN_{Noise/pixel}. Then, any pixel within the box presenting a value equal to, or less than, the noise per pixel is subtracted from DN_{Total} to reduce the noise of the scene, the result DN_{Scene} being the total digital counts produced by the stellar illumination onto the focal plane for that image.

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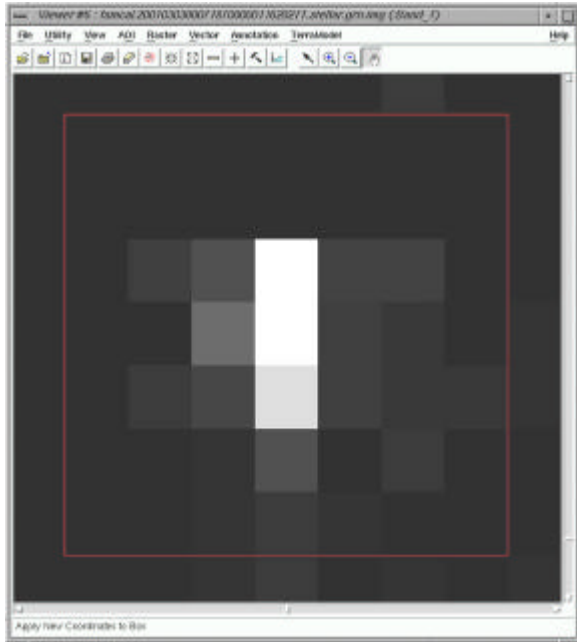


Figure 4. Typical star scene in a stellar image.

This process is repeated for each of the six images collected for each multispectral band (j) and the results are averaged together to obtain the average detector numbers per star (i) per band (j) or DN_{ij} . Table 5 gives the DN of the stellar image evaluations.

Table 5. Averaged DN_{ij} from star (i) for each band (j) from the IKONOS stellar images collected in 2001/2002.

G&S	HIP	Star Name	BLU (DN)	GRN (DN)	RED (DN)	NIR (DN)
7	42799	Hya Eta-7	169/ 178	145/ 144	62/ 66	38/ 44
83	86032	Ras Alhague	1295/ 1281	1223/ 1227	763/ 775	556/ 565
109	20885	Tau Theta1-77	160/ 173	224/ 263	222/ 234	194/ 216
118	53229	LMi 46	149/ NC	244/ NC	242/ NC	217/ NC
123	53740	Crt Alpha-7	108/ NC	182/ NC	179/ NC	172/ NC
127	54539	UMa Psi-52	371/ 366	559/ 560	557/ 566	523/ 545
134	77070	Unukalhay	515/ 511	805/ 811	797/ 790	760/ 762
135	48455	Leo Mu-24	135/ NC	225/ NC	238/ NC	238/ NC
142	47431	Hya Iota-35	117/ 129	228/ 242	254/ 253	271/ 265
149	33160	CMa Theta-14	88/ NC	188/ NC	241/ NC	274/ NC
150	37908	Gem 81	35/ 42	91/ 96	117/ 119	130/ 142

NC – Not collected as part of 2002 data set.

3.2 Calculate the at-aperture in-band stellar irradiance

Using the G&S Atlas spectral data, the in-band irradiance was calculated for the imaged star (Watts/cm²) arriving at the telescope aperture.

Processing the Gunn & Stryker Stellar Spectrophotometric Atlas tabulated data.

Before being used however, the stellar flux data published in the Gunn & Stryker Atlas required three adjustments and corrections.

First: The stellar flux data presented in the G&S Atlas is normalized and scaled to the stellar flux of Vega and presented in units of frequency. It was un-normalized using Equation 1:

$$F_{i, \text{u}dered} (?) = F_{i, \text{u}dered} (?) * 10^{-20} * 10^{-0.4V(i)} \quad (1)$$

where: $F_{i, \text{u}dered}(v)$ = Un-normalized spectral flux of dereddened star i (mW/m²-Hz)

$F_{i, \text{u}dered}(v)$ = Normalized spectral flux of dereddened star i (mW/m²-Hz)

V(i) = Visual magnitude of star i

Converted to flux in units of wavelength using Equation 2:

$$F_{i, \text{u}dered} (\lambda) = F_{i, \text{u}dered} (v) * \frac{c}{\lambda^2} * 10^{-4} * 10^{-6} \quad (2)$$

where: $F_{i, \text{u}dered}(\lambda)$ = Un-normalized spectral flux of dereddened star i (mW/cm²-μm)

$F_{i, \text{u}dered}(v)$ = Un-normalized spectral flux of dereddened star i (mW/m²-Hz)

c = Speed of light in a vacuum 2.9998x10⁸ (m/s)

λ = Wavelength (m)

And, corrected to absolute flux using Equation 3:

$$F_{i, \text{abs-dered}} (?) = F_{i, \text{u}dered} (?) * Zp_{\text{vega}} \quad (3)$$

where: $F_{i, \text{abs-dered}}(\lambda)$ = Absolute spectral flux of dereddened star i (mW/cm²-μm)

$F_{i, \text{u}dered}(v)$ = Un-normalized spectral flux of dereddened star i (mW/cm²-μm)

Zp_{vega} = Zero Point of Vega correction factor of 3.67

Second: In the G&S Atlas the stellar flux values are given for wavelengths at 10-Angstrom intervals for the short wavelength range (3180 - 5750 Angstroms), and at 20-Angstrom intervals for the remainder of the range (5780 - 10,560 Angstroms). To accommodate integration at 10-Angstrom intervals, additional

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data points were generated by linear interpolation between data point pairs with 20-Angstrom intervals.

And, because the relative spectral response values for IKONOS are given in 50-Angstrom intervals the interpolated flux values were reduced to the set containing only those at the same 50-Angstrom intervals as the IKONOS response values.

Third: In the G&S Atlas the stellar flux values are dereddened values, meaning that the attenuation due to scattering by intergalactic dust has been removed, which is more pronounced in the blue end of the spectrum than at the red end (thus reddening the stars). For the IKONOS calibration that attenuation needs to be replaced, accomplished using a formula given in the Appendix to the G&S Atlas, referenced here as Equation 4:

$$\text{Flux}\lambda(\text{dered}) = \text{Flux}\lambda(\text{red}) * \text{dex}(0.4 * A_v * A\lambda) \quad (4)$$

where: dex is the decimal exponent (i.e. $10^{(0.4 * A_v * A\lambda)}$)
 A_v is a factor given for each star along with the irradiance data
 $A\lambda$ is the function returned by the following FORTRAN algorithm, presented in the G&S Atlas:

```

FUNCTION ABSORP(WAVE)
  ABSORP=0.0
  IF(WAVE.LE.900..OR.WAVE.GT.2.E4)RETURN
  F=1.E4/WAVE + 0.1
  DO 1 K=1,2
    E1 = -0.28 + 0.725 * F
    E2 = 0.40 + 0.42 * F
    A = E1
    IF(E2.LT.E1)A = E2
    ABSORP = 0.5 * A + ABSORP
  1 F = F - 0.2
RETURN
END
  
```

Figure 6 shows the plotted dereddening factors and their spectral dependence for the stars used from the G&S Atlas versus their A_v values.

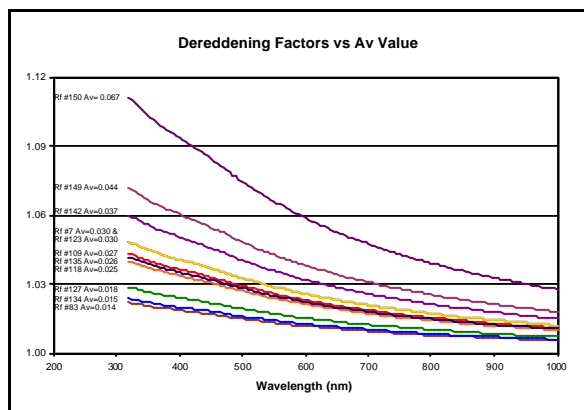


Figure 6. G&S dereddening factors versus wavelength.

The absolute flux values were calculated by converting the dereddened flux to reddened flux using Equation 5 in the following form:

$$F_{i,abs-red}(I) = F_{i,abs-dered}(I) * R_i(I) \quad (5)$$

where: $F_{i,abs-red}(\lambda)$ = Absolute flux of reddened star i (mW/cm²-μm)
 $F_{i,abs-dered}(\lambda)$ = Absolute flux of dereddened star i (mW/cm²-μm)
 $R_f(\lambda)$ = Spectral dereddening factor, $10^{(-0.4 * A_v * A\lambda)}$
 A_v = published value for each star
 $A\lambda$ = the function returned by the dereddening algorithm

Figure 7 shows the dereddening spectral flux versus the reddened spectral flux for star #83 (ALPHA OPH 85111) in the G&S Atlas, as star #86032 in the Hipparcos catalogue, and also known as Ras Alhague.

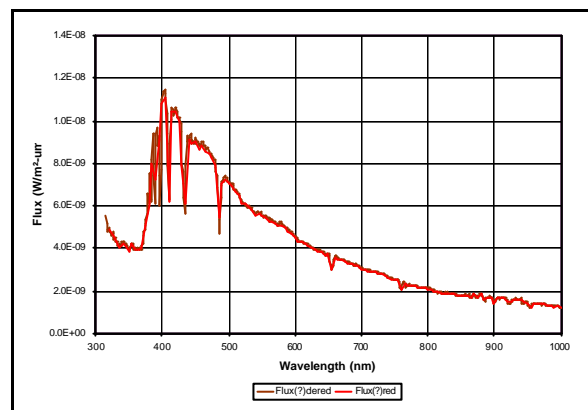


Figure 7. Calculated flux for Gunn & Stryker Star #83, Ras Alhague.

IKONOS Relative Spectral Response.

Data providing relative spectral response (RSR) for the IKONOS satellite's payload were measured by the vendor, Eastman Kodak (Figure 8). For the pan band, an average of the six pan band detectors (3 sub-arrays for each array, for forward and reverse directions) for flight vehicle 1 was used. For the multispectral bands, an average of the flight vehicle 1 arrays for each band was used. The RSR spectral data furnished by Eastman Kodak are given at 50-Angstrom intervals.

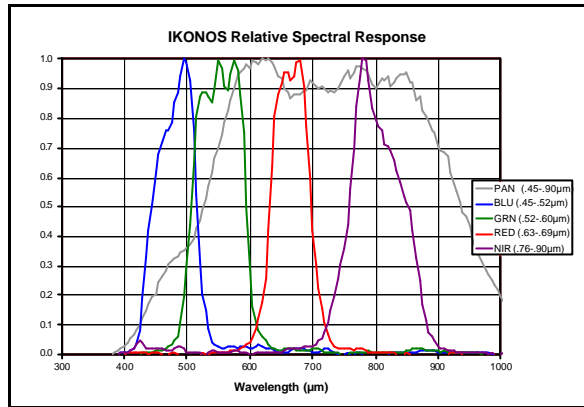


Figure 8. Relative spectral response of IKONOS bands.

Arriving the at-aperture in-band stellar irradiance.

The total in-band irradiance of the j th band presented at the aperture of the IKONOS telescope by the i th star, located near the telescope optical axis, was then calculated for each IKONOS band by integrating over the relative spectral response of each multispectral band using Equation 6:

$$E_{i,j} = \int_{0.320}^{1.055} F_{i,abs-red}(\lambda) RSR_j(\lambda) d\lambda$$

where: $E_{i,j}$ = In-band irradiance of reddened star i in the j th band (W/cm^2)
 $F_{i,abs-red}(\lambda)$ = Spectral flux of reddened star i ($W/cm^2-\mu m$)
 $RSR_j(\lambda)$ = Relative Spectral Response of the j th band as a function of wavelength
 $d\lambda$ = Wavelength increment (μm)

3.3 Calculate the equivalent at-aperture in-band radiance

Since calibration factors are usually stated as radiance in terms of $DN/(Watt/cm^2-sr)$ at the OTU aperture, or DN per pixel per $Watt/cm^2-sr$ at the OTU aperture, the radiance is calculated by dividing the irradiance presented to the aperture by the pixel solid angle or the instantaneous field of view (IFOV) of an IKONOS multispectral pixel.

The total equivalent in-band radiance of the j th band presented at the aperture of the IKONOS telescope by the i th star, located near the telescope optical axis, was then calculated for each IKONOS band. This was calculated by dividing the total in-band flux by the instantaneous field of view (IFOV) for a multispectral pixel using Equation 7; the results are presented in Table 9.

$$L_{i,j} = \frac{E_{i,j}}{IFOV_{multispectral}} \quad (7)$$

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where: $L_{i,j}$ = In-band radiance of reddened star i in the j th band (W/cm^2-sr)
 $E_{i,j}$ = In-band flux of reddened star i in the j th band (W/cm^2)
 $IFOV_{multispectral}$ = Instantaneous Field of View of a multispectral pixel (steradians)

Table 9. At-aperture in-band radiance of reddened stars.

G&S	Star Name	BLU (*)	GRN (*)	RED (*)	NIR (*)
7	Hya Eta-7	0.386	0.309	0.131	0.106
83	Ras Alhague	2.321	2.175	1.089	0.941
109	Tau Theta1-77	0.352	0.465	0.352	0.386
118	LMi 46	0.359	0.475	0.359	0.394
123	Crt Alpha-7	0.258	0.362	0.295	0.339
127	UMa Psi-52	0.712	1.010	0.852	0.959
134	Unukalhay	0.983	1.407	1.162	1.335
135	Leo Mu-24	0.303	0.450	0.392	0.446
142	Hya Iota-35	0.283	0.442	0.411	0.501
149	CMa Theta-14	0.228	0.382	0.344	0.479
150	Gem 81	0.110	0.187	0.189	0.264

* - Units are mW/cm^2-sr .

3.4 Calculate the IKONOS calibration coefficients

⁽⁶⁾ The calibration coefficients for each IKONOS band were calculated by dividing the average detector numbers per star (i) per band (j) or $DN_{i,j}$, obtained from Section 3.1, by the total in-band radiance (L), obtained in Section 3.3 using Equation 8:

$$CalCoef_j = \frac{DN_{i,j}}{L_{i,j}} \quad (8)$$

where: $CalCoef_j$ = In-Band Calibration Coefficient ($DN/(mW/cm^2-sr)$)
 $DN_{i,j}$ = Measured Digital Numbers for the imaged star i in the j th band (DN)
 $L_{i,j}$ = Calculated radiance of reddened star i in the j th band (W/cm^2-sr)

The solution describing the linear fit through the individual stellar data for each multispectral band is the absolute radiometric calibration coefficient for that band, which are shown in Figure 10 which plots each star's measured output versus the calculated at-aperture in-band radiance.

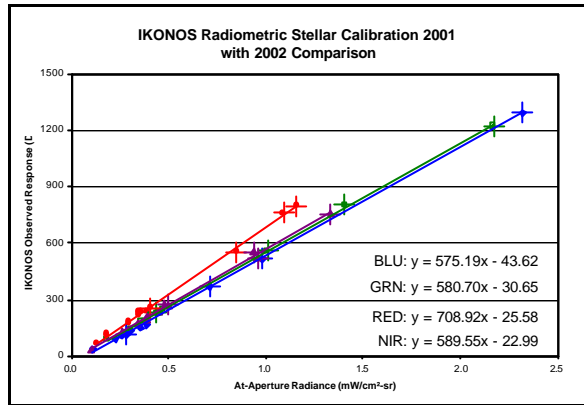


Figure 10. Plotted at-aperture radiance vs measured DN for 2001 and 2002 stellar data sets.

4. VERIFICATION METHODS

To verify the accuracy of the predicted spectral flux calculations a comparison was made against the spectral flux held in the Space Telescope Science Institute (STSI) database for the G&S Atlas Star #83, the brightest G&S star imaged by IKONOS. Also, the process was used to predict the values that should be present in an image of the star Vega, the primary calibration standard in the optical spectrum that is used by the astronomical community.

4.1 Comparison of Calculated Spectral Flux with STSI Database Values

To determine the uncertainty in the absolute flux calculated from the G&S tabulated data the spectrum for G&S star #83, Ras Alhague, was obtained from the STSI database (Jeff Pedelty, NASA Goddard, personal communication) and compared to the calculated absolute flux using the process outlined in Section 3 of this document. The difference across the spectrum between 300 nm and 1000 nm is less than 1 percent as shown in Figure 11.

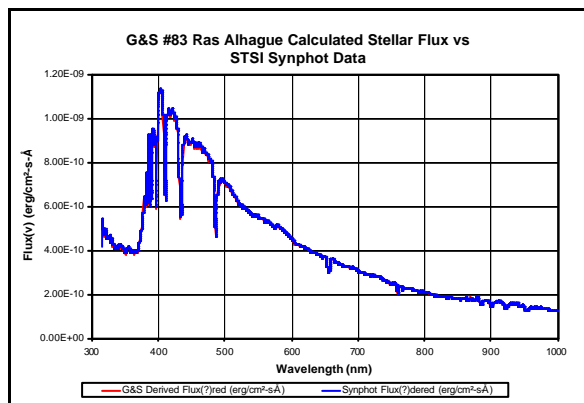


Figure 11. Plotted values of SI calculated vs. STSI Synphot flux for G&S Star #83 (Ras Alhague).

4.2 Comparison of predicted and measured counts for Vega

Being able to predict the number of counts that should be found in an image is as important as being able to recreate the absolute spectrum. The star Vega was used to validate the procedure of predicting the counts in an image. Vega is the astronomical primary calibration standard in the optical spectrum. Once again, NASA Goddard provided the Vega spectrum as described in L. Colina, R. Bohlin, F. Castelli, STSI Instrument Science Report CAL/SCS-008, "Absolute Flux Calibrated Spectrum of Vega", April 22, 1996. The only manipulation performed on the data was to multiply the data by a factor of 10 to convert from units of ergs/sec-cm²-Å into units of W/m²-µm. Integrating the Vega flux through the IKONOS passbands and dividing by the IFOV of a single pixel provided the at-aperture radiance. And, multiplying the at-aperture radiance by the calibration coefficients obtained from processing the G&S stars gives a predicted DN for each multispectral band.

It was clear from the predicted DN values that the Blue and Green bands would be severely saturated if the center of the star point spread function (PSF) was centered exactly on the common corners of four adjacent pixels. Only the Red and NIR band images would be usable, and then, only if the center of the PSF was centered between at least two pixels. This expectation was realized when the data in the images were evaluated. The results of the image evaluation showed that the DN for Vega in the Red and NIR bands could be predicted to within 3.9% and 4.4% respectively, shown in Figure 12, using the calibration coefficients obtained from the G&S Atlas stellar sources given in Figure 10 above.

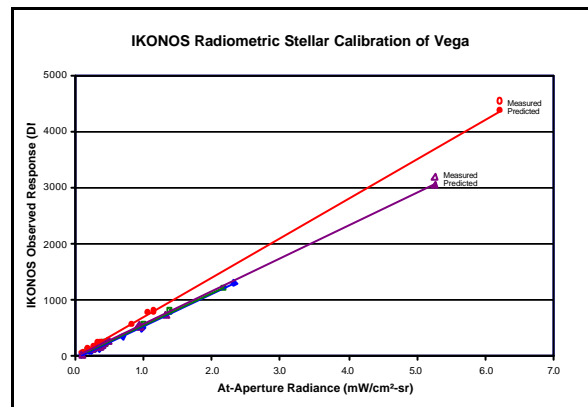


Figure 12. Predicted vs. measured DN values for Vega.

4.3 Comparison between Space Imaging and NASA results

Mr. Jeff Pedelty, of NASA Goddard, with the aid of the Synphot program predicted the results using the IKONOS stellar image data provided by Space Imaging. The independent analysis showed reasonable correlation to Space Imaging's results previously presented in Figure 10, and here alongside the NASA results shown as Table 13.

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Table 13. NASA Goddard versus Space Imaging calculated calibration coefficients using stellar image data

Band	NASA Goddard	Space Imaging
Blue:	$y = 595.04x - 48.023$	$y = 575.19x - 43.62$
Green:	$y = 595.08x - 35.311$	$y = 580.70x - 30.65$
Red:	$y = 721.13x - 31.486$	$y = 708.92x - 25.58$
NIR:	$y = 600.59x - 27.485$	$y = 589.55x - 22.99$

5. IKONOS PERFORMANCE REPEATABILITY

As the mission of the IKONOS satellite continues towards its fourth year, three stellar image collection/analysis activities have been completed. The most recent occurring between January and March of 2002, when a subset of the calibration stars collected in 2000 and 2001 were re-collected to determine the repeatability of the collection and data extraction techniques.

5.1 Annual data comparison

The total DN from the multispectral bands stellar image collections that occurred during the first quarter of 2002 versus those from 2001, given previously in Table 5, and here in Table 14 in terms of percent difference between the two data sets. The greatest differences correspond to stars whose total DN count is less than 50 counts, indicating that for the dimmest stars a few DN shifted about the pixel pattern of the stellar image has a much greater influence on the outcome than the same shifting for the patterns of the brighter stars. Taking this into consideration it is reasonable to conclude that the repeatability of the IKONOS sensor is less than a few percent per year in each of the multispectral bands.

Table 14. Repeatability of IKONOS stellar image collections.

G&S	Star Name	BLU (%)	GRN (%)	RED (%)	NIR (%)
7	Hya Eta-7	4.9	0.4	7.5	14.3
83	Ras Alhague	1.0	0.2	1.0	0.7
109	Tau Theta1-77	7.8	13.3	5.3	11.0
118	LMi 46	NC	NC	NC	NC
123	Crt Alpha-7	NC	NC	NC	NC
127	UMa Psi-52	1.1	0.2	1.5	4.3
134	Unukalhay	0.7	0.8	0.9	0.3
135	Leo Mu-24	NC	NC	NC	NC
142	Hya Iota-35	10.0	5.9	0.3	2.2
149	CMa Theta-14	NC	NC	NC	NC
150	Gem 81	17.5	6.0	1.7	8.7

NC – Not collected as part of 2002 data set.

6. CONCLUSION

Stellar images are easily scheduled, collected, and evaluated. The published stellar irradiance can be converted to an equivalent at-aperture radiance. The extremely linear, repeatable, and stable results have made it possible to use this method of calibration to establish the long term stability of the IKONOS sensor with future hopes for absolute radiometric calibration.

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Pecora 15/Land Satellite Information IV/ISPRS Commission I/FIEOS 2002 Conference Proceedings

Acknowledgements

The author would like to acknowledge the efforts of Max Dahler, Gerry Kerbyson, Laury Smith, Jim VanPernis and Amy Maddox, of LMMS, who developed the original concept for stellar-based absolute radiometric calibration; Jeff Pedlty of NASA Goddard for his support in providing the comparisons of computed stellar data; and, Gene Dial, Kevin Hutchins, Rick Oleszczuk, and Frank Gerlach of Space Imaging, for their continued contributions towards IKONOS calibration activities.

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