ITT

Correction to Method of Establishing the Absolute Radiometric Accuracy of Remote Sensing Systems While On-orbit Using Characterized Stellar Sources

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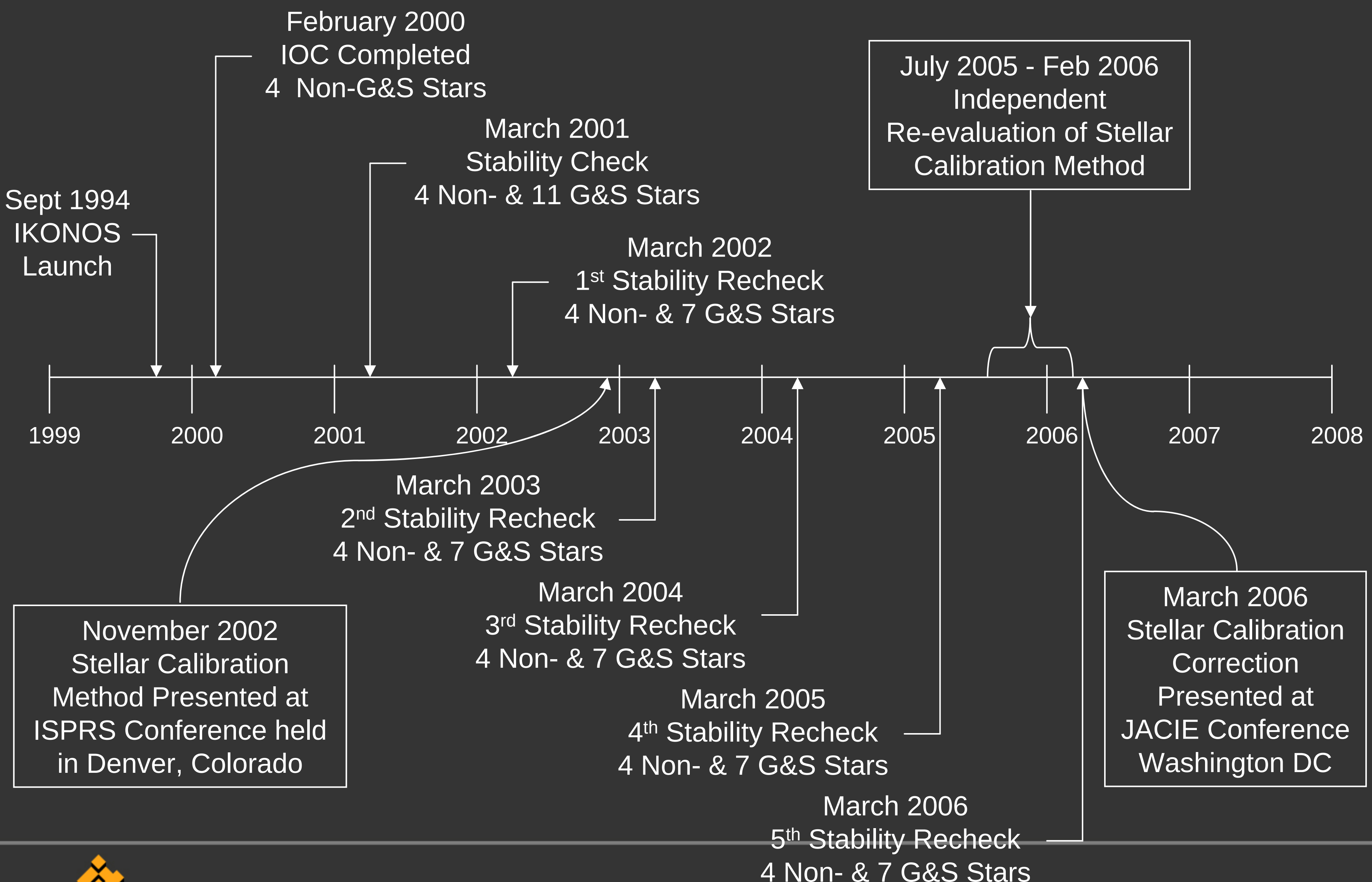
Presentation Outline

- Brief History of Related Events
- Overview of Original Method Used to Establish Absolute Radiometric Accuracy of Remote Sensing Instruments Using Stellar Sources
- Considerations to Improve the Stellar Calibration Approach
- Summary

Brief History of Related Events

Historical Perspective



Absolute Radiometric Calibration

The purpose of absolute radiometric calibration is to determine the expected response for any in-band entrance aperture radiance presented to the telescope.

$$CalCoef_j = \frac{DC_j}{L_j}$$

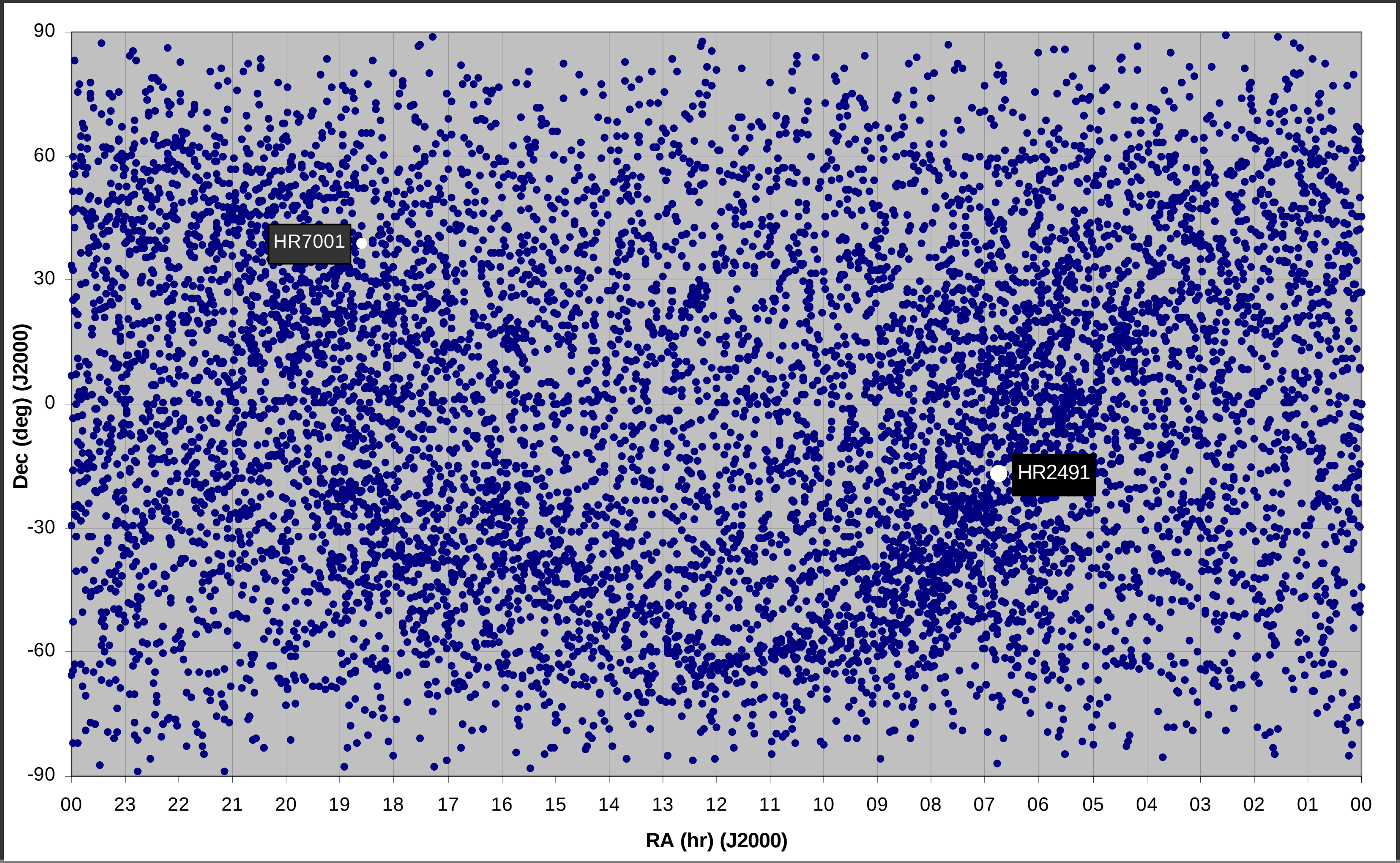
where: CalCoef = In-Band Calibration Coefficient (DC/(W/m^2-sr))
DC_j = Measured Digital Counts in the j^{th} band (DC)
L_j = Entrance Aperture Radiance in the j^{th} band (W/m^2-sr)

Overview of Original Method Used to Establish Absolute Radiometric Accuracy of Remote Sensing Instruments Using Stellar Sources

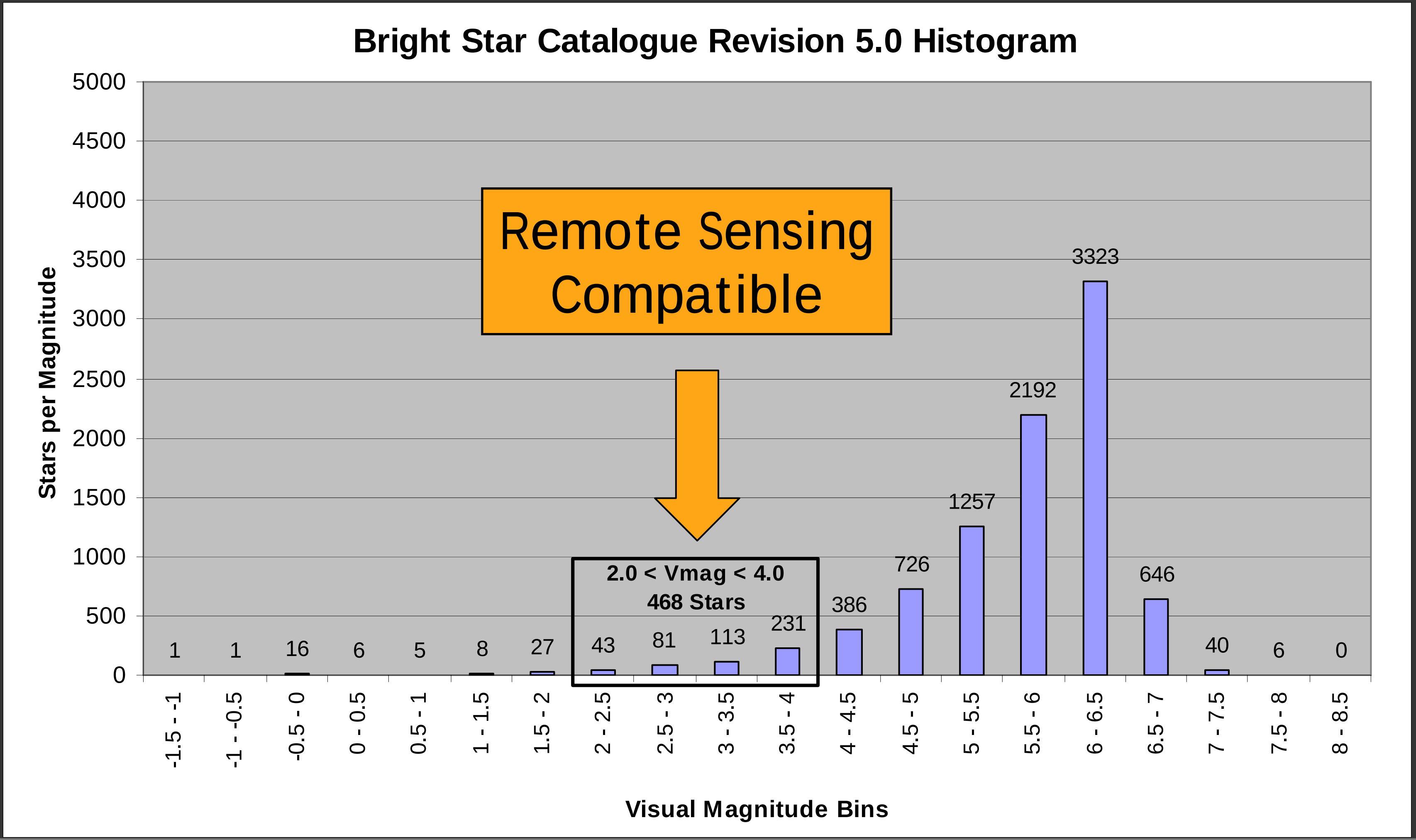
Original Method to Establish Absolute Radiometric Calibration Accuracy Using Stellar Sources

- Identify Acceptable Radiometrically Characterized Stars
  - Compute Broadband Entrance Aperture Flux Density
- Gather Stellar Response Data
  - Extract Stellar Scene Data (sum digital counts)
- Generate Calibration Coefficient
- Verify Results Using Independent Sources
- Determine System Stability
- Determine System Linearity

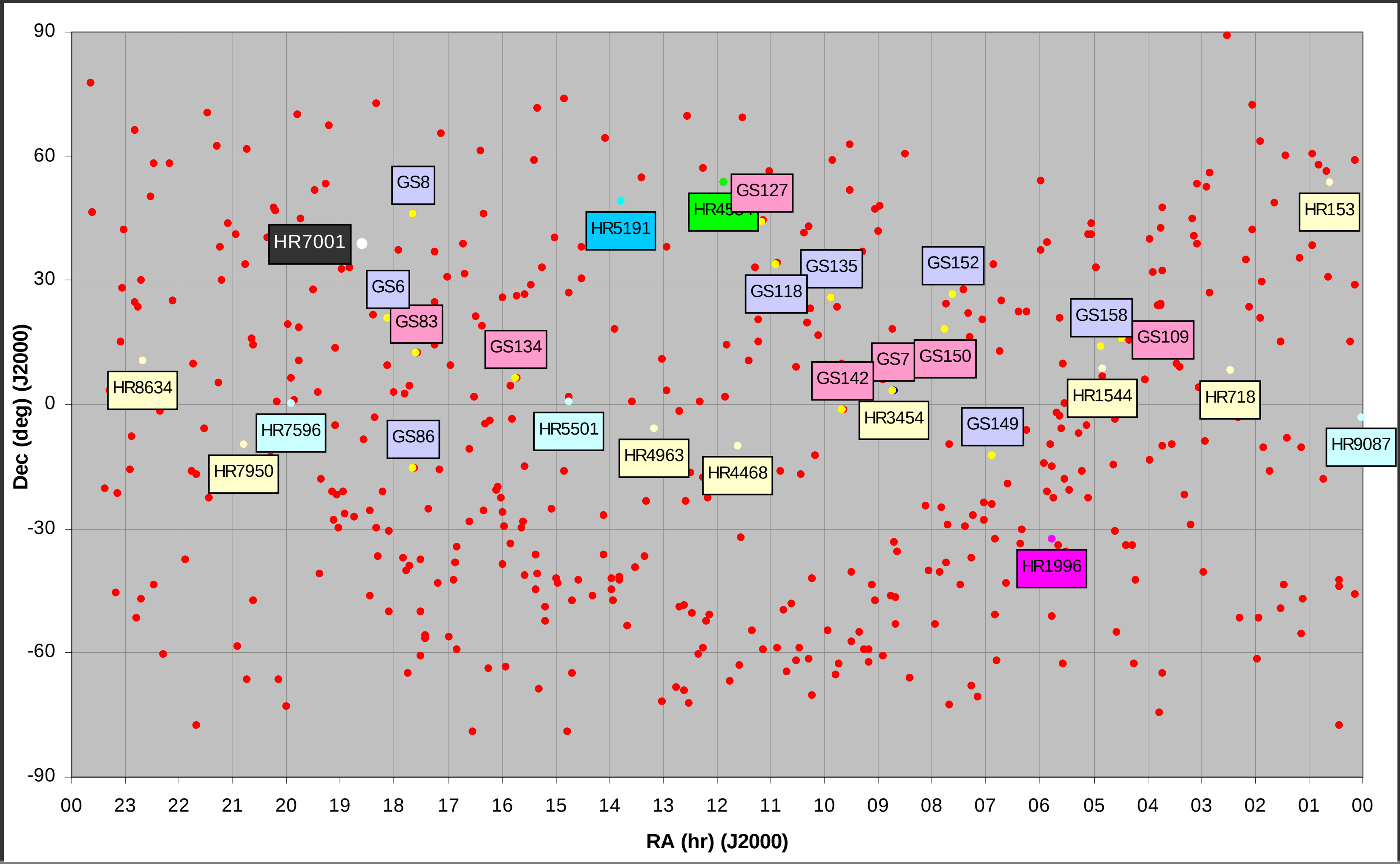
Bright Star Catalogue Stars
-1.46 < Vmag < 8.0 = 9110 Items



Bright Stars most likely to be compatible with IKONOS-like Remote Sensing Instruments



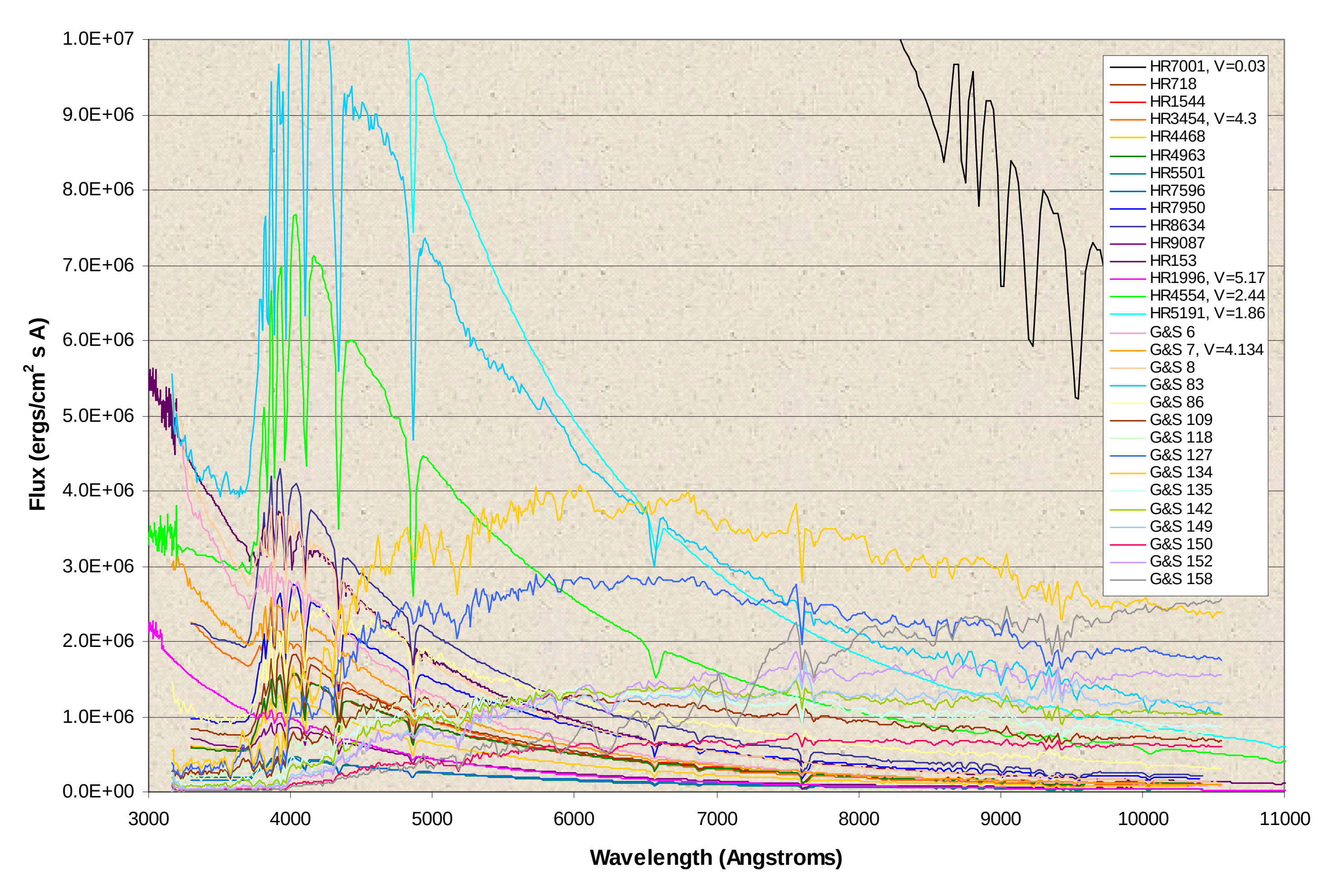
BSC Remote Sensing Compatible Stars (468) and Spectrophotometric Standard Stars (28)



Remote Sensing Compatible Spectrophotometric Standard Stars (28) (Excluding Vega and 1 repeated star)

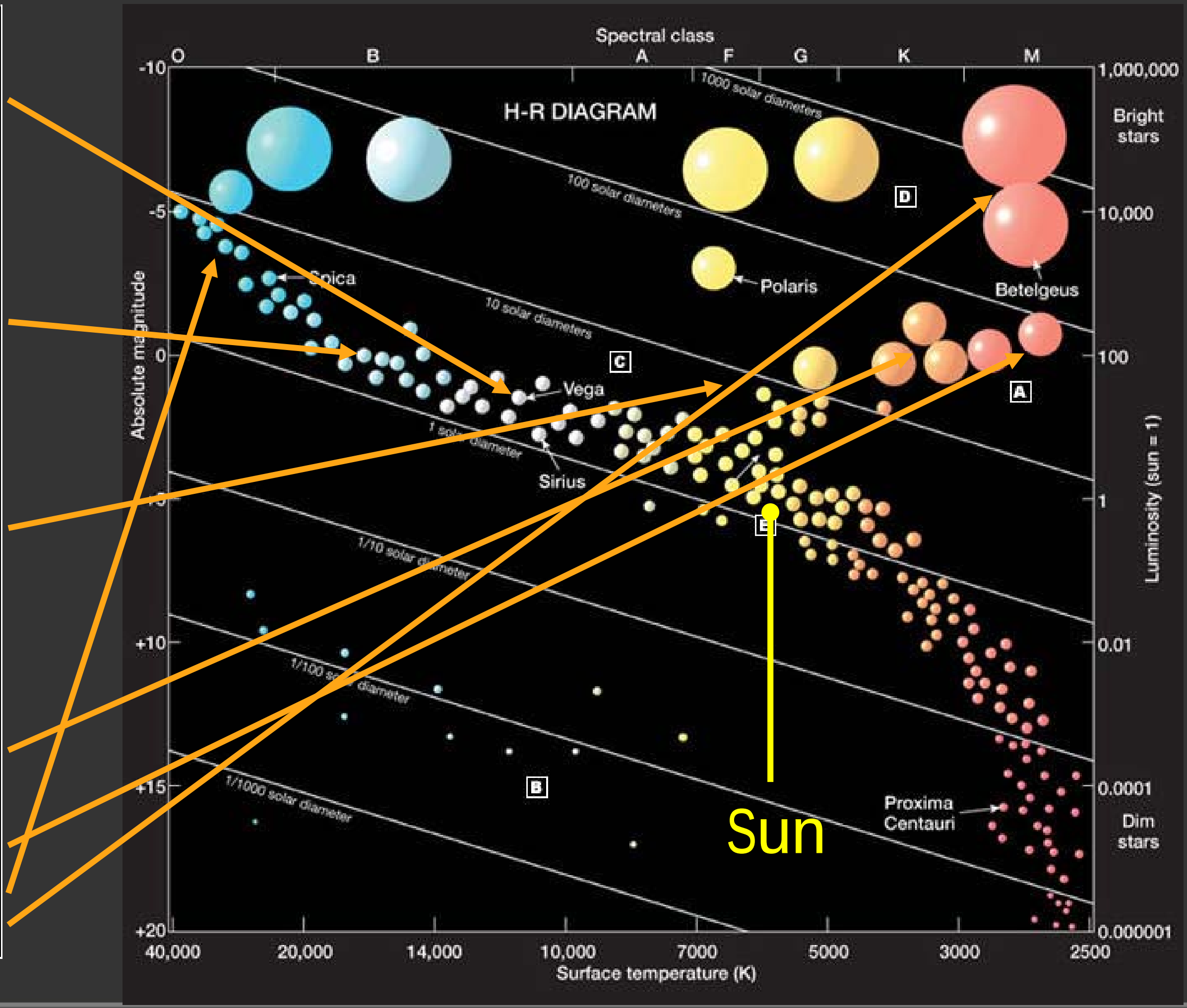
RS ID	BSC ID	RA (J2000)	DEC (J2000)	Proper Name	Vmag	Spectral Type
HST 1	HR7001	18:36:56	38.7836	Alpha Lyrae	-0.03	A0V
HST 2	HR718	2:28:09	8.4601	Xi 2 Ceti	4.28	B9III
HST 3	HR1544	4:50:36	8.9002	Pi 2 Orionis	4.36	A1V
HST 4	HR3454	8:43:13	3.3986	Eta Hydrae	4.30	B3V
HST 5	HR4468	11:36:40	-9.8023	Theta Crater	4.70	B9.5V
HST 6	HR4963	13:09:56	-5.5390	Theta Virginis	4.38	A1IV
HST 7	HR5501	14:45:30	0.7174	108 Virginis	5.68	B9.5V
HST 8	HR7596	19:54:44	0.2735	58 Aquilae	5.62	A0III
HST 9	HR7950	20:47:40	-9.4958	Eta Aquarii	3.78	A1V
HST 10	HR8634	22:41:27	10.8314	Zeta Pegasi	3.40	B8V
HST 11	HR9087	0:01:49	-3.0275	29 Piscium	5.12	B7III
HST 12	HR153	0:36:58	53.8969	Zeta Cassiopeiae	3.66	B2IV
HST 13	HR1996	5:45:59	-32.3065	Mu Columbae	5.17	O9V
HST 14	HR4554	11:53:49	53.6948	Gamma Ursae Majoris	2.44	A0V
HST 15	HR5191	13:47:32	49.3133	Eta Ursae Majoris	1.86	B3V
G&S 1	HR6787	18:08:45	20.8144	102 Her	4.36	B2IV
G&S 2	HR3454	8:43:13	3.3986	Eta Hydrae	4.30	B3V
G&S 3	HR6588	17:39:27	46.0064	85 Iot Her	3.80	B3IV
G&S 4	HR6556	17:34:56	12.5600	55 Alp Oph	2.08	A5III
G&S 5	HR6561	17:37:35	-15.3986	55 Xi Ser	3.54	F0IVDel Sct
G&S 6	HR1411	4:28:34	15.9622	77 The1 Tau	3.84	K0IIIbFe-0.5
G&S 7	HR4247	10:53:18	34.2150	46 LMI	3.83	K0+III-IV
G&S 8	HR4335	11:09:39	44.4986	52 Psi UMa	3.01	K1III
G&S 9	HR5854	15:44:16	6.4256	24 Alp Ser	2.65	K2IIIbCN1
G&S 10	HR3905	9:52:45	26.0069	24 Mu Leo	3.88	K2IIICN1Ca1
G&S 11	HR3845	9:39:51	-1.1428	35 Iot Hya	3.91	K2.5III-IIIbBa0.3
G&S 12	HR2574	6:54:11	-12.0386	14 The CMa	4.07	K4III
G&S 13	HR3003	7:46:07	18.5100	81 Gem	4.88	K4III-IIIb
G&S 14	HR2905	7:35:55	26.8958	69 Ups Gem	4.06	M0III-IIIb
G&S 15	HR1556	4:52:32	14.2506	4 Omi 1Ori	4.74	S3.5/1-

Remote Sensing Compatible Spectrophotometric Standard Stars Spectral Data

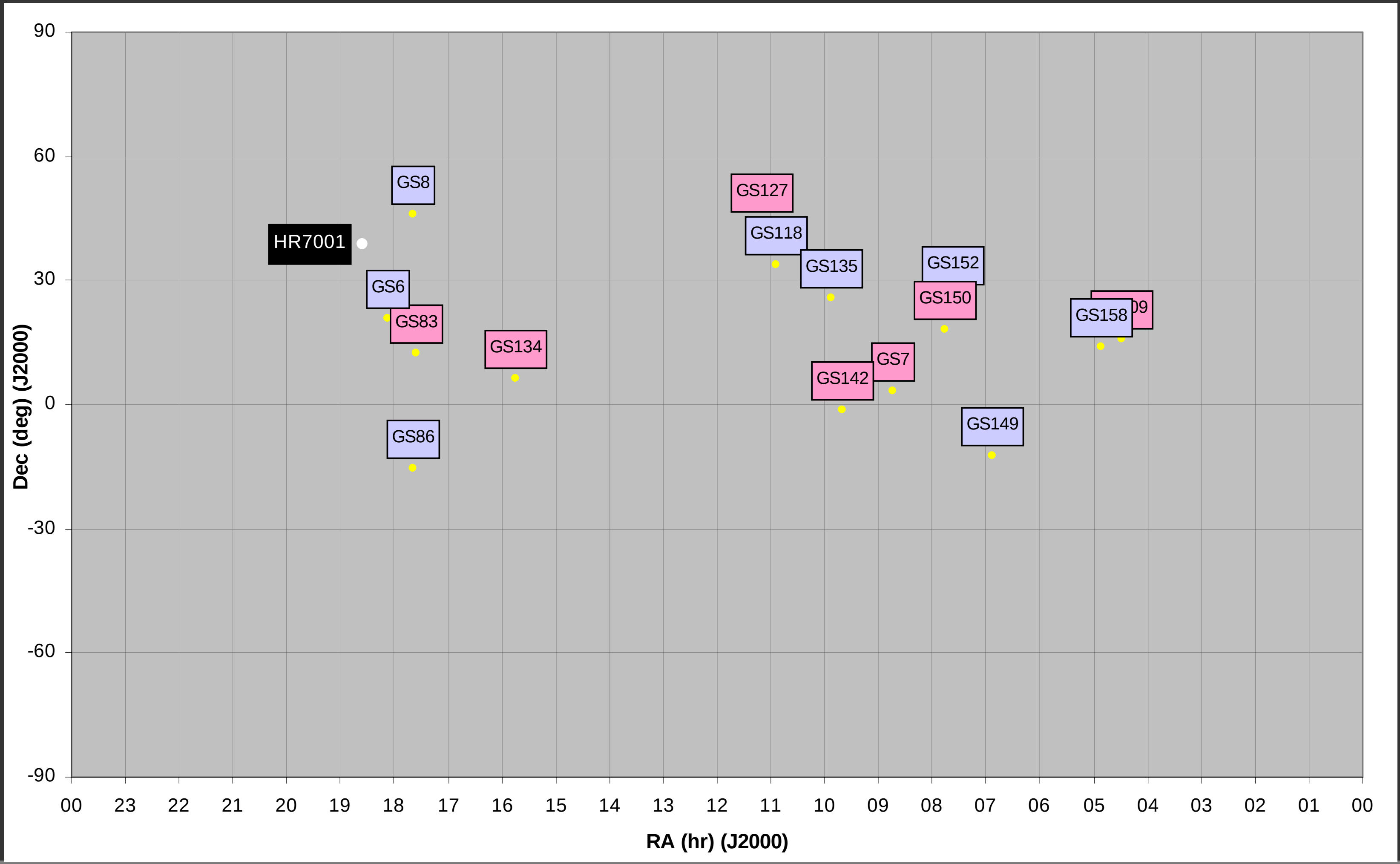


Hertzprung-Russell Diagram Showing Remote Sensing Characterized Star Categories

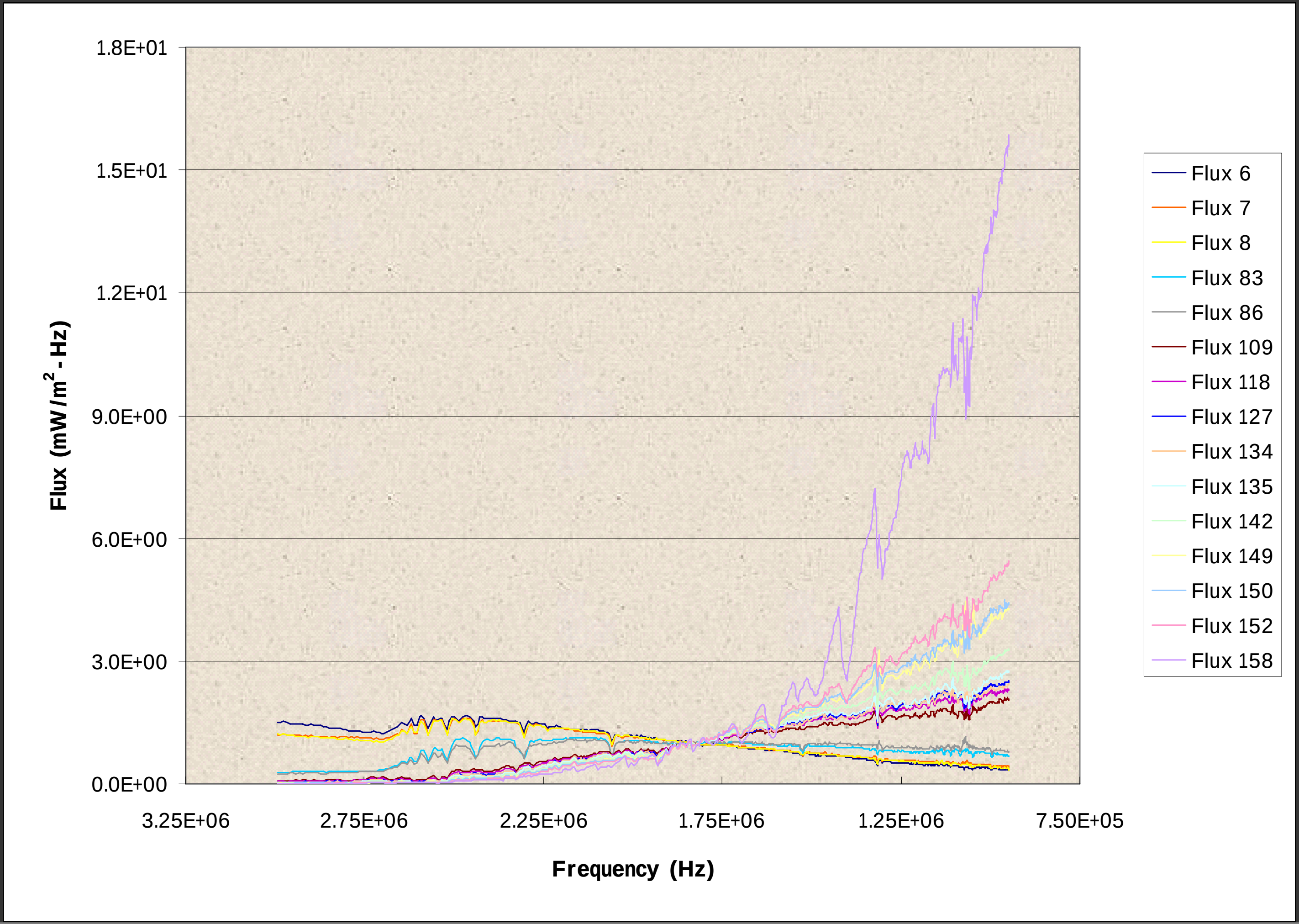
Star ID (s)	Category
HR7596	A0III
HR7001, HR4554	A0V
HR4963	A1IV
HR1544, HR7950	A1V
HR6561	A5III
HR153, HR6787	B2IV
HR6556	B3IV
HR1591, HR3454	B3V
HR9087	B7III
HR8634	B8V
HR4468, HR550	B9.5V
HR718	B9III
HR1411	F0IV
HR4247	K0III
HR4335	K1III
HR3845	K2.5III
HR5854	K2IIIb
HR3095	K2IIIC
HR2574	K4III
HR3003	K4IIIb
HR2905	M0III
HR1996	O9V
HR1556	S3.5



Brightest G&S Stars and Those Used for IKONOS Absolute Radiometric Accuracy Assessment (7)

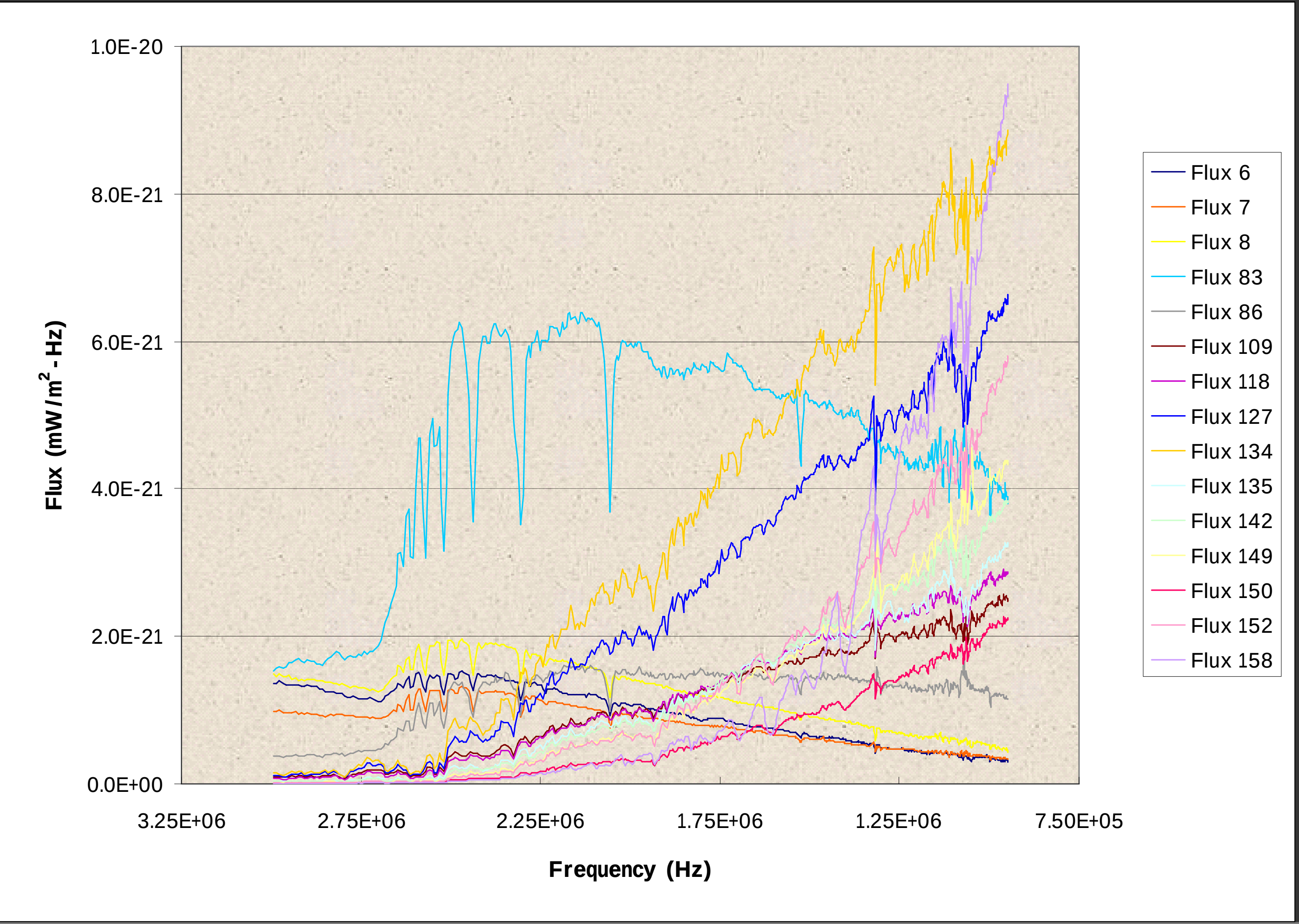


J.E. Gunn & L.L. Stryker – Stellar Spectrophotometric Atlas 3130 < λ < 10800 Å (1983), Remote Sensing Stellar Subset



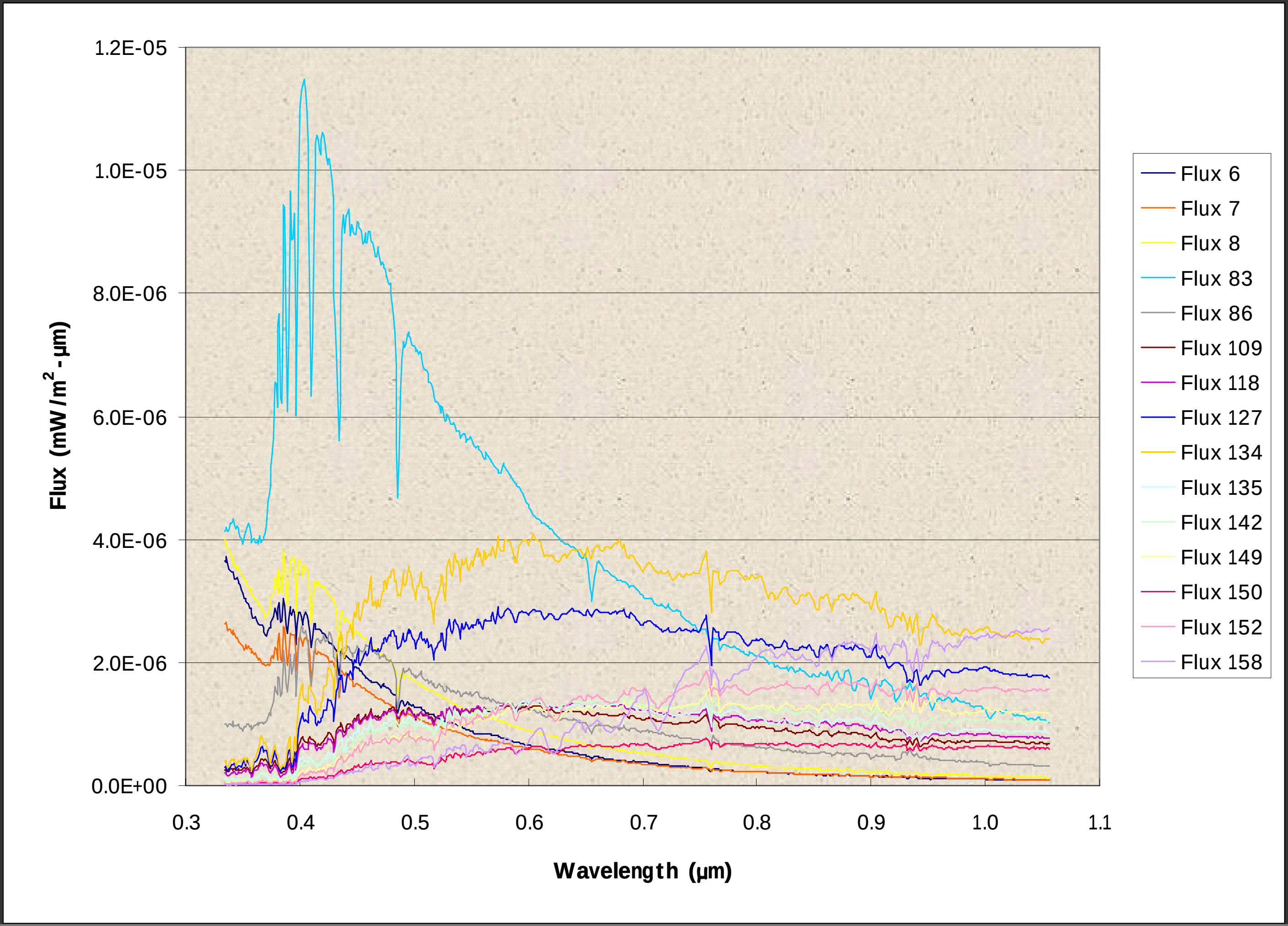
Un-normalized Stellar Spectral Data v. Frequency

Remote Sensing Stellar Subset



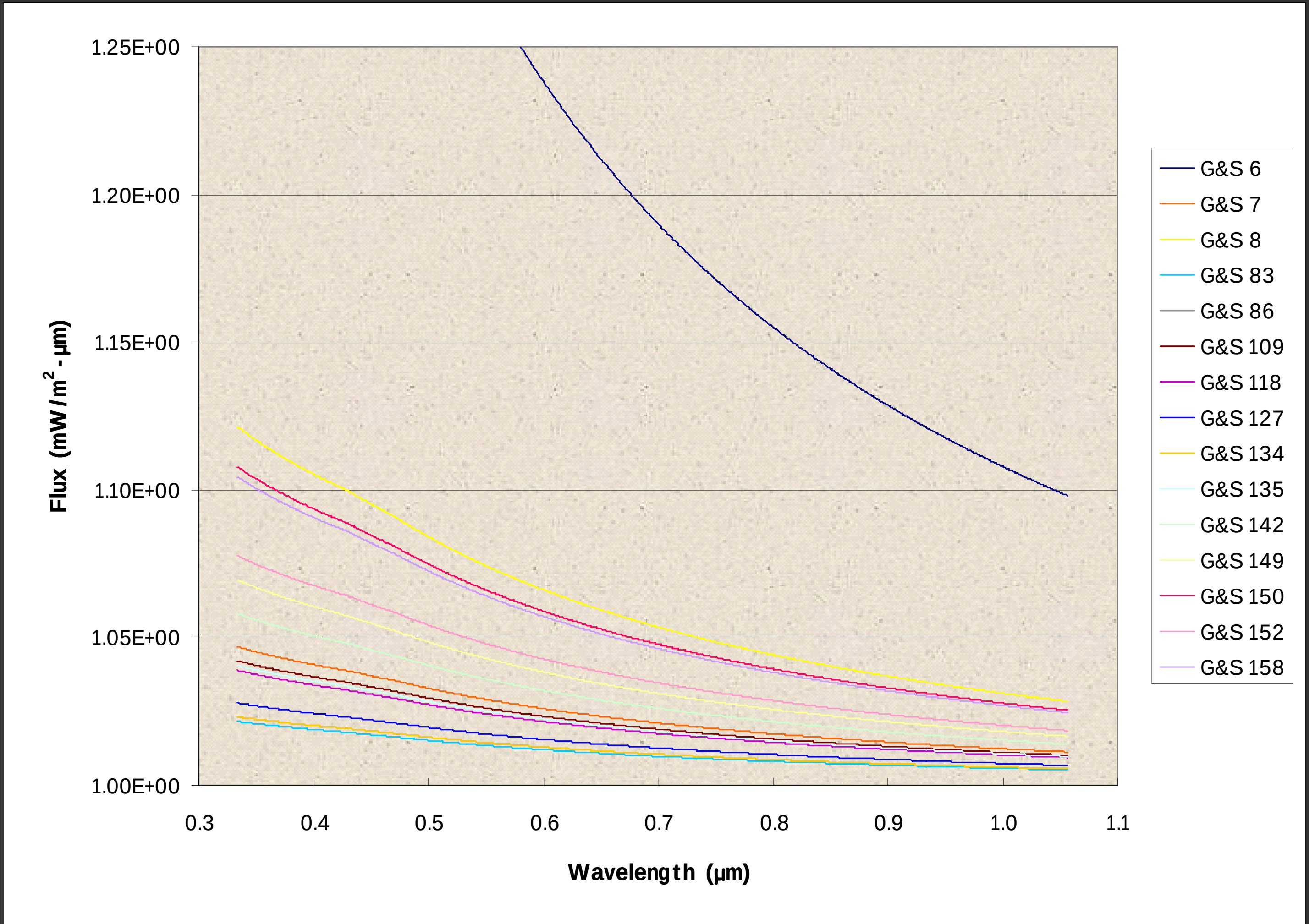
Un-normalized Stellar Spectral Data v. Wavelength

Remote Sensing Stellar Subset



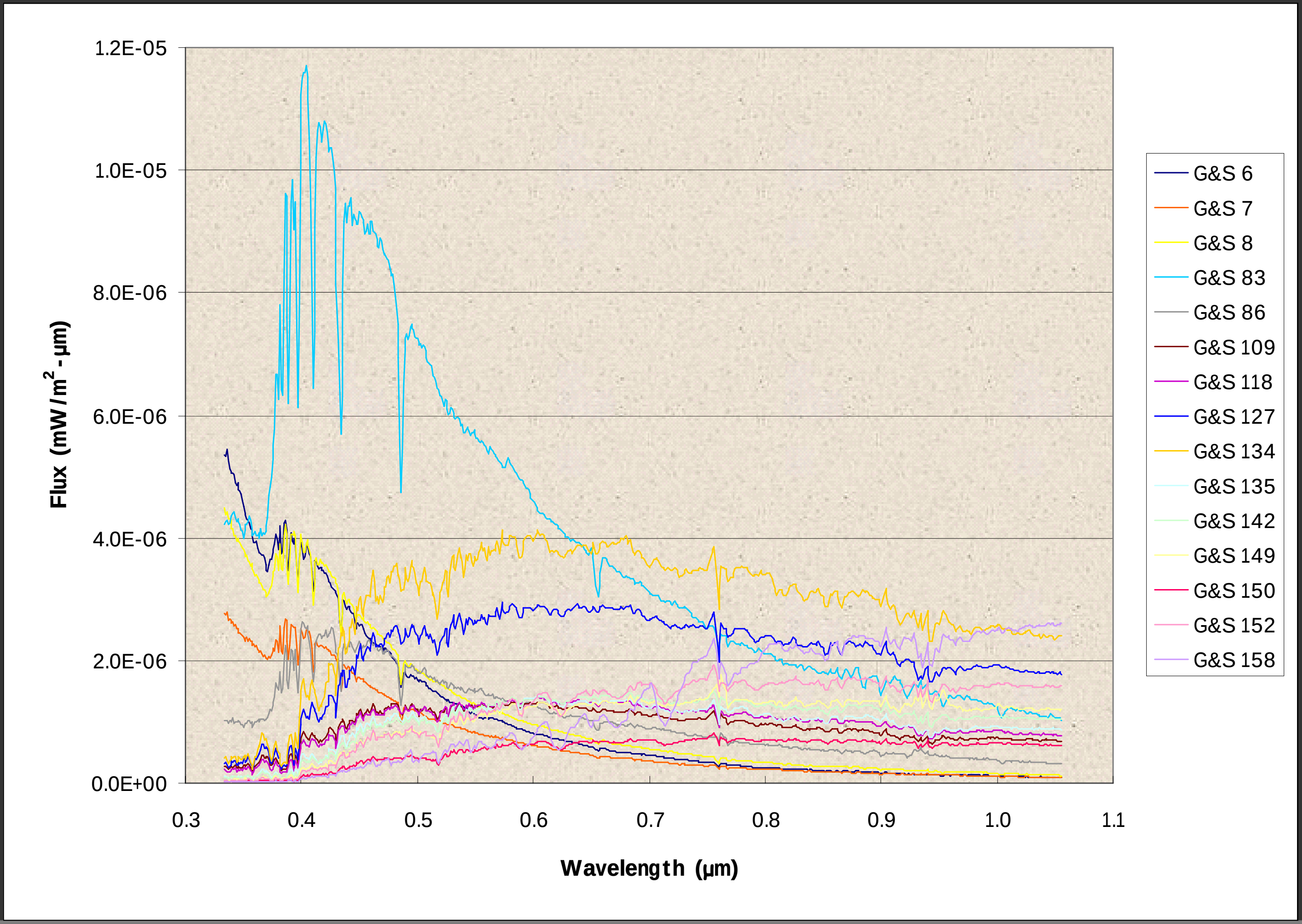
De-reddening Coefficients for Stellar Spectral Data

Remote Sensing Stellar Subset

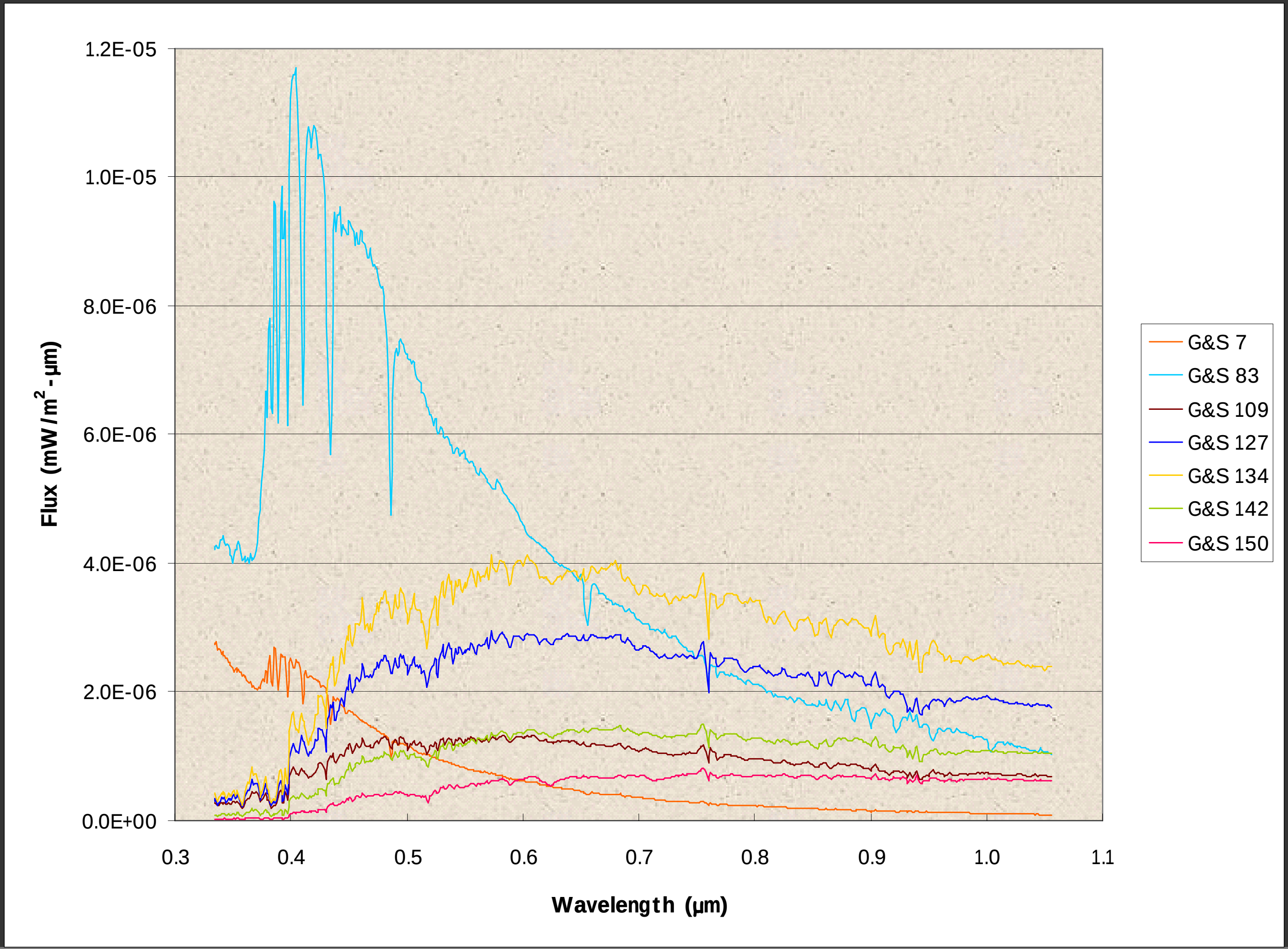


Re-reddened Stellar Spectral Data v. Wavelength

Remote Sensing Stellar Subset



Subset of G&S Stellar Spectra Used To Assess IKONOS Absolute Radiometric Accuracy



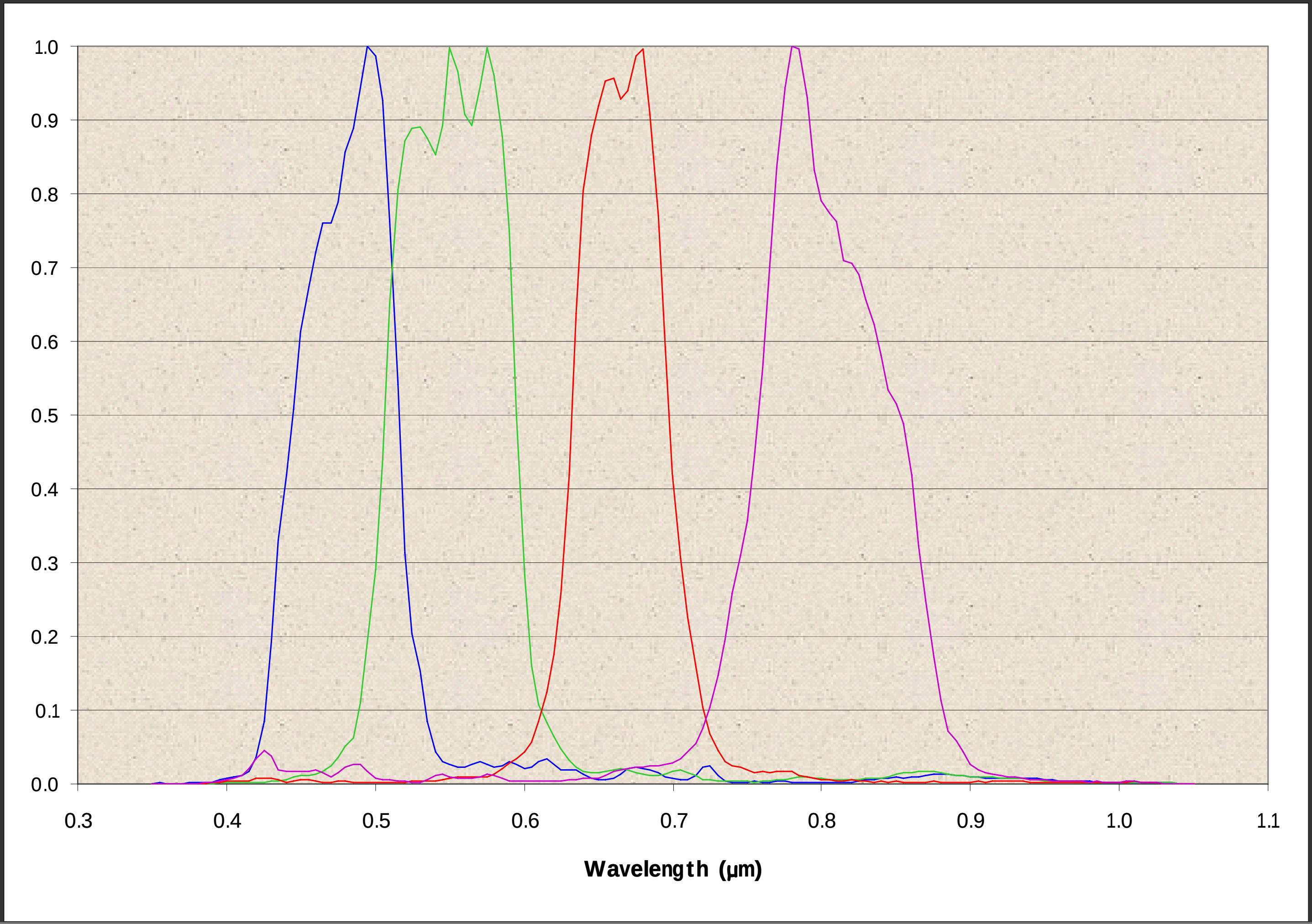
IKONOS MS Bands Relative Spectral Response (RSR) (http://www.spaceimaging.com/products/ikonos/spectral.htm)

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

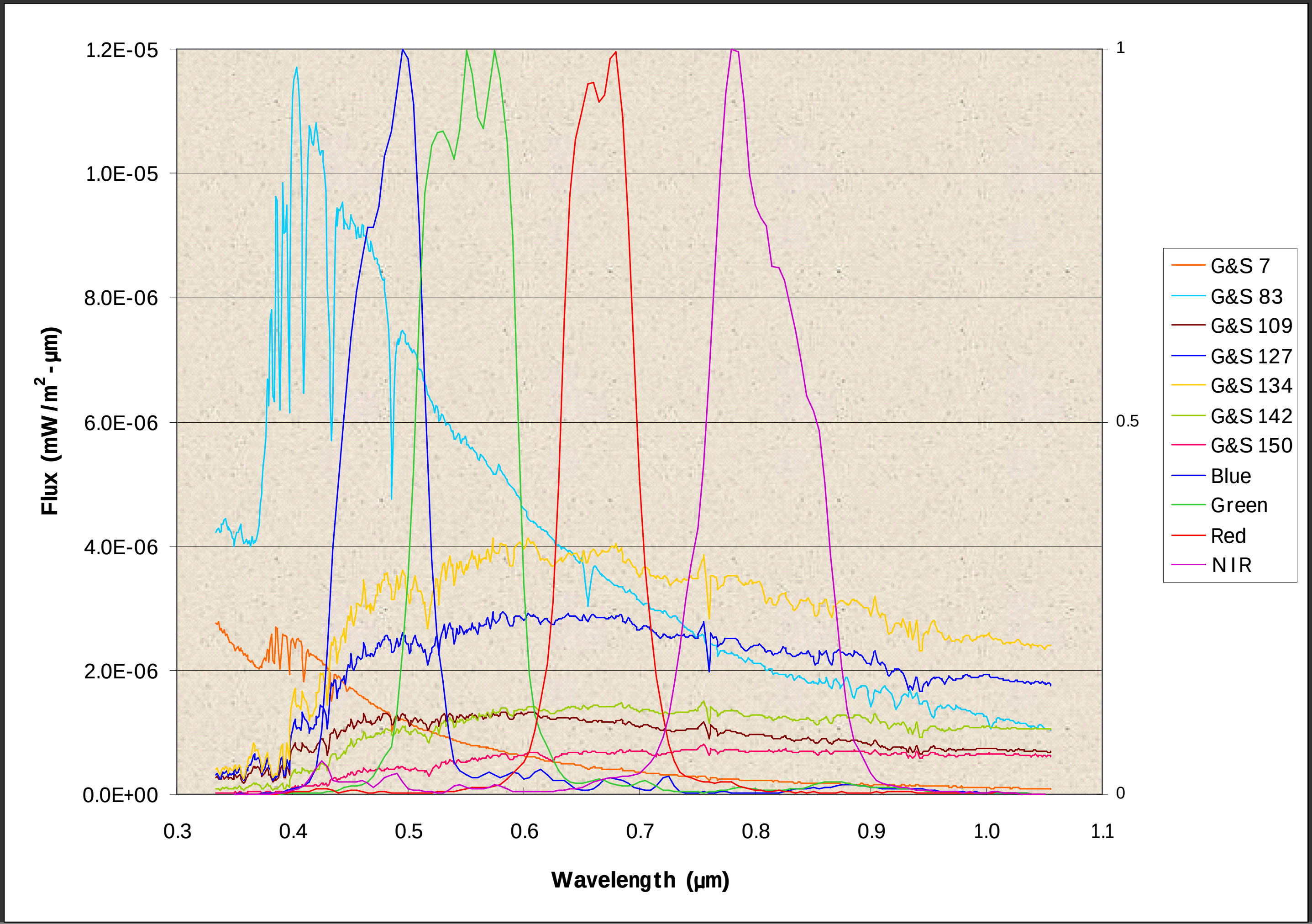
Note:
1. Spectral Bandwidths are Full-Width at Half-Max (FWHM)
2. Panchromatic Band does not incorporate spectral filtering - response is that of optics/detector only

Values Shown in Color are Bandpass Definitions Using 50nm-interval Datasets Without Interpolation

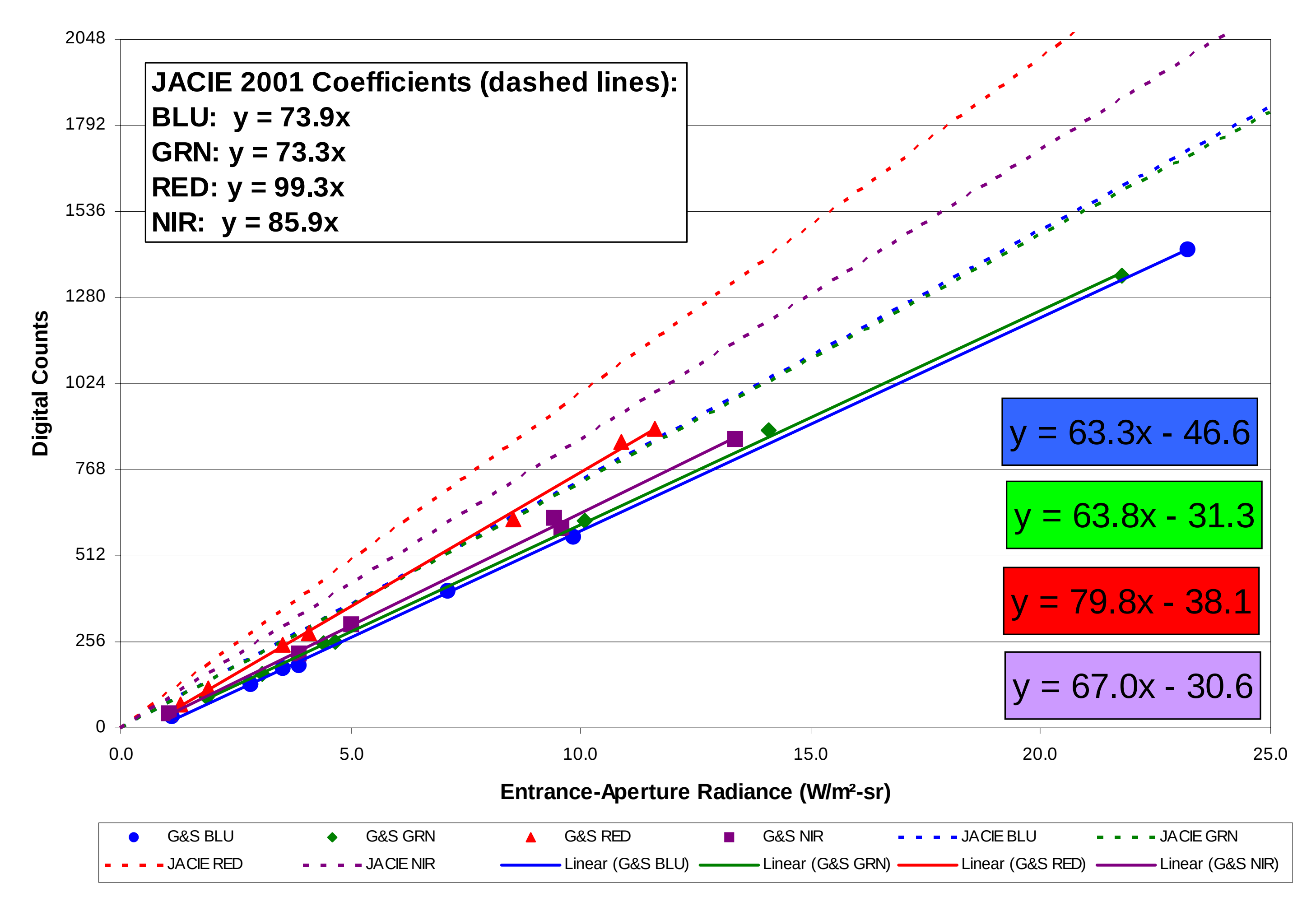
IKONOS Multi-spectral Bands RSR - 50nm Intervals
(as published on GeoEye website)



G&S Stellar Spectra and IKONOS MS Bands RSR



IKONOS Stellar Calibration Coefficients 2001 Compared with JACIE 2001 Results

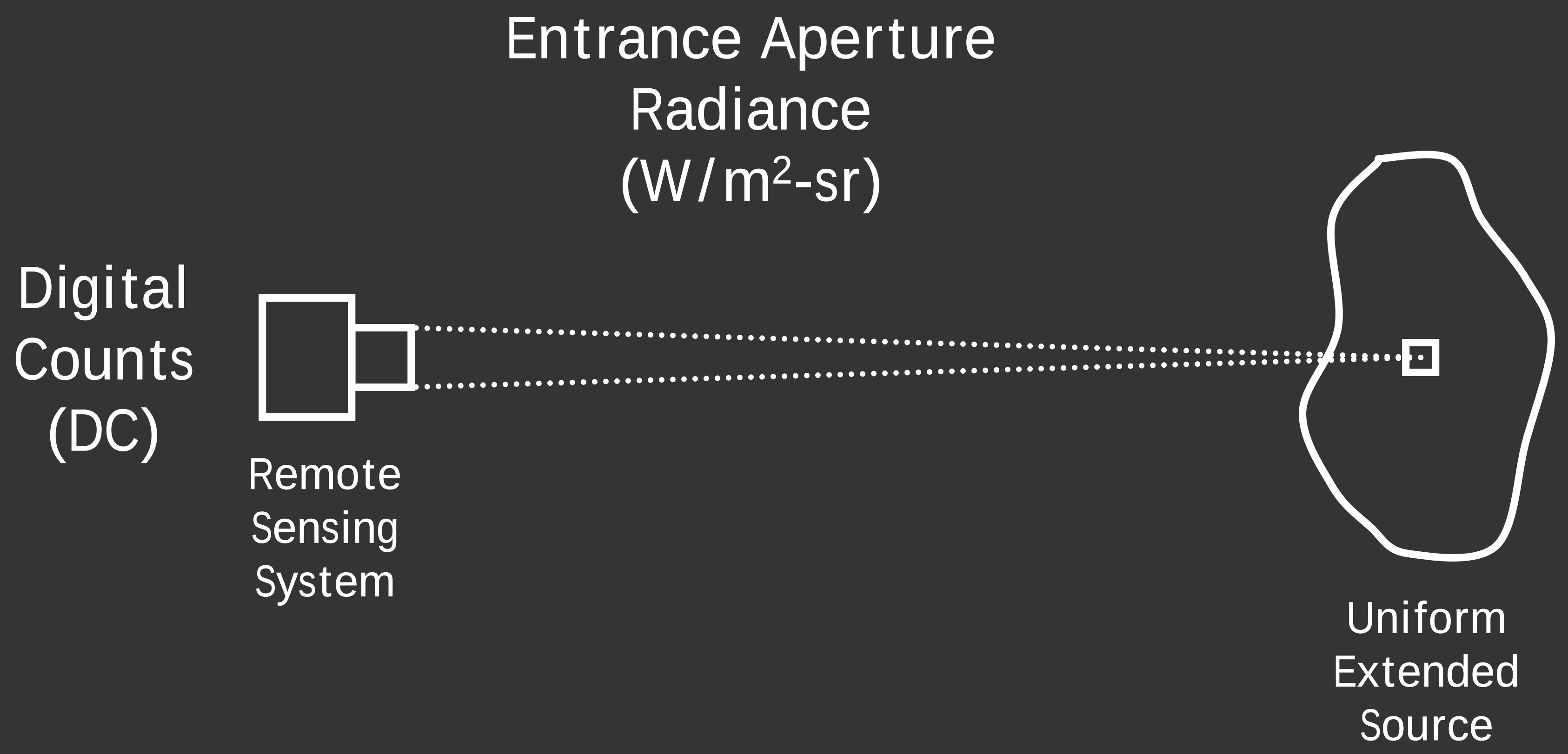


IKONOS Stellar Calibration Coefficients 2001 Compared with JACIE 2001 Results

MS Band	JACIE 2001	Stellar 2001 FW	Δ Gain
Blue 445-516 nm	72.8	63.3x – 51	Δ = 14%
Green 506-595 nm	72.7	63.8x – 31	Δ = 13%
Red 632-698 nm	94.9	79.8x – 40	Δ = 20%
NIR 757-853 nm	84.3	67.0 – 31	Δ = 21%

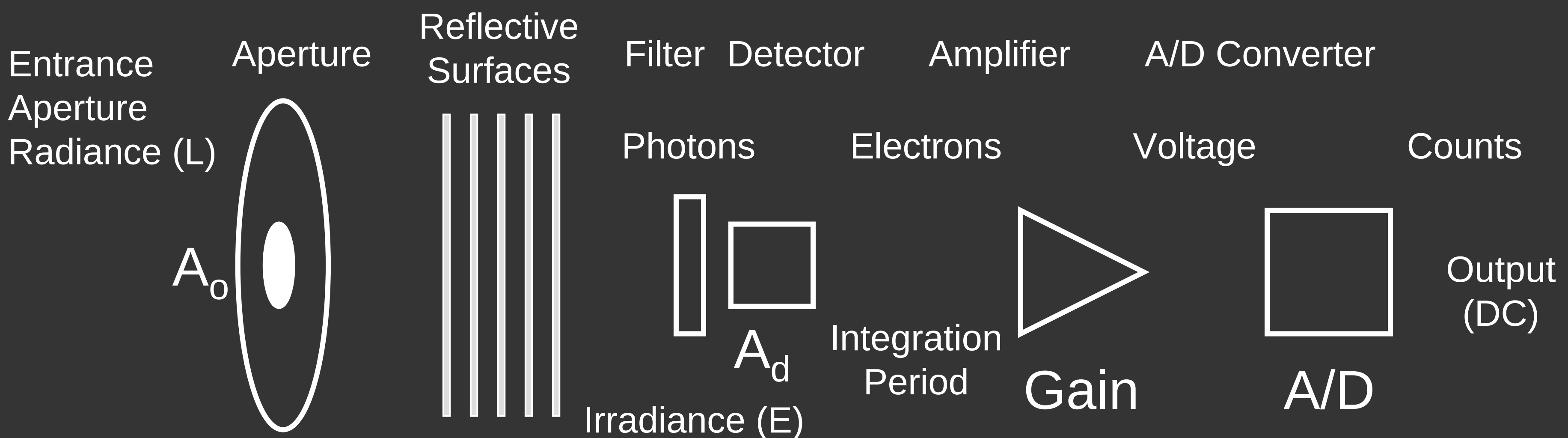
Considerations to Improve the Stellar Calibration Approach

Traditional Remote Sensing System Calibration Methods Determine Entrance Aperture Radiance



Typically the System Response Function Takes Into Consideration All of the Components of the System

$$SRF = A_o \Omega_{\mathrm{det}} \tau_{\mathrm{ota}}(t,\alpha)\tau_{\mathrm{fltr}}(\lambda)R_{\mathrm{det}}(\lambda, T_{fp})R_{elec}(\lambda, T_{elec})$$
$$R_{A/D}(\lambda, DC)\tau_{NL}(\lambda, DC, DC_0)\tau_{noise}(\lambda, L)\Delta\lambda$$

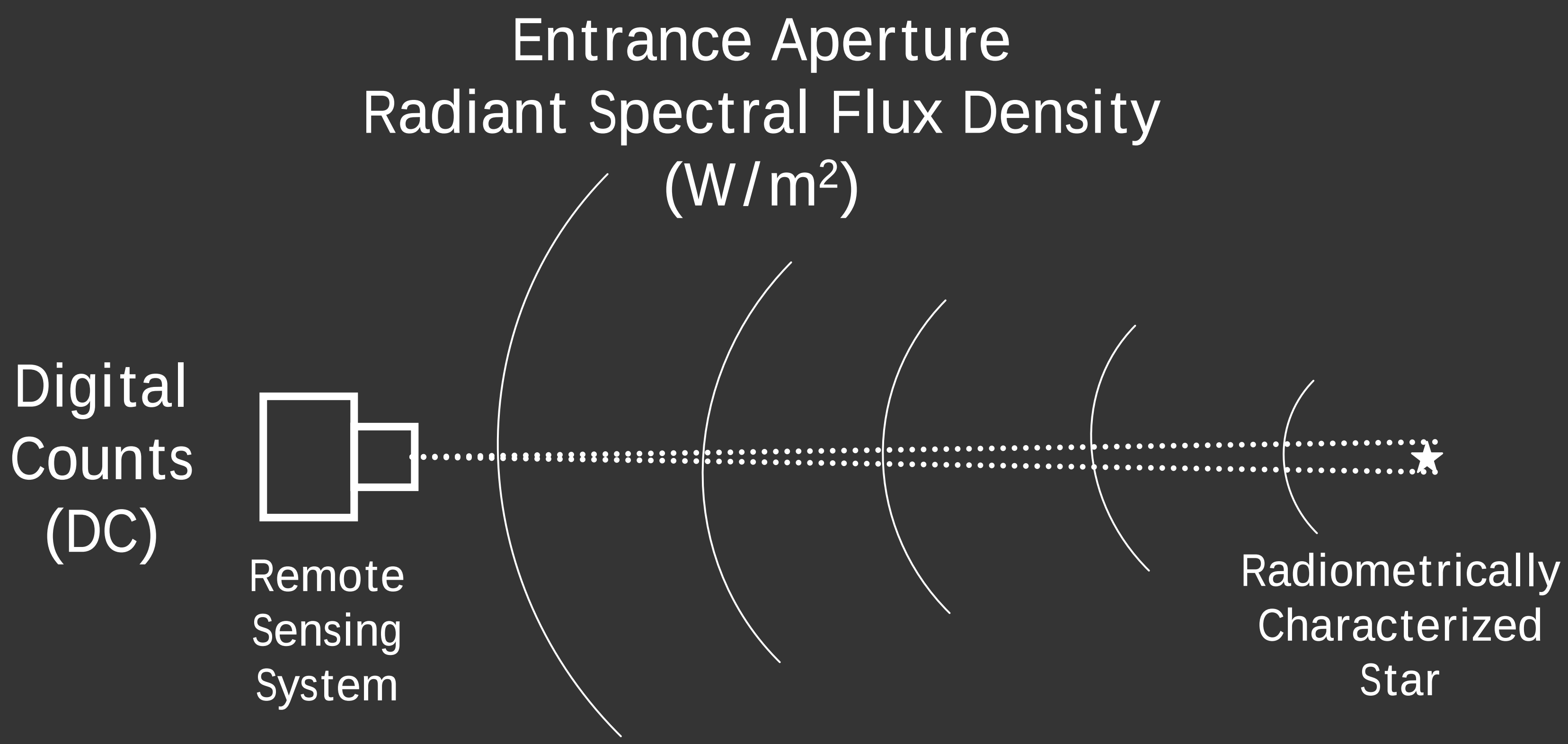


Calibration Coefficient is the Relationship between Entrance Aperture Radiance and Digital Counts

$$\text{Calibration Coefficient}\left(\frac{DC}{\frac{W}{m^2-sr}}\right)=\frac{\text{Digital Counts}\,(DC)}{\text{Entrance Aperture Radiance}\left(\frac{W}{m^2-sr}\right)}$$

Calibration Coefficient [DN/(W/m^2-sr)]

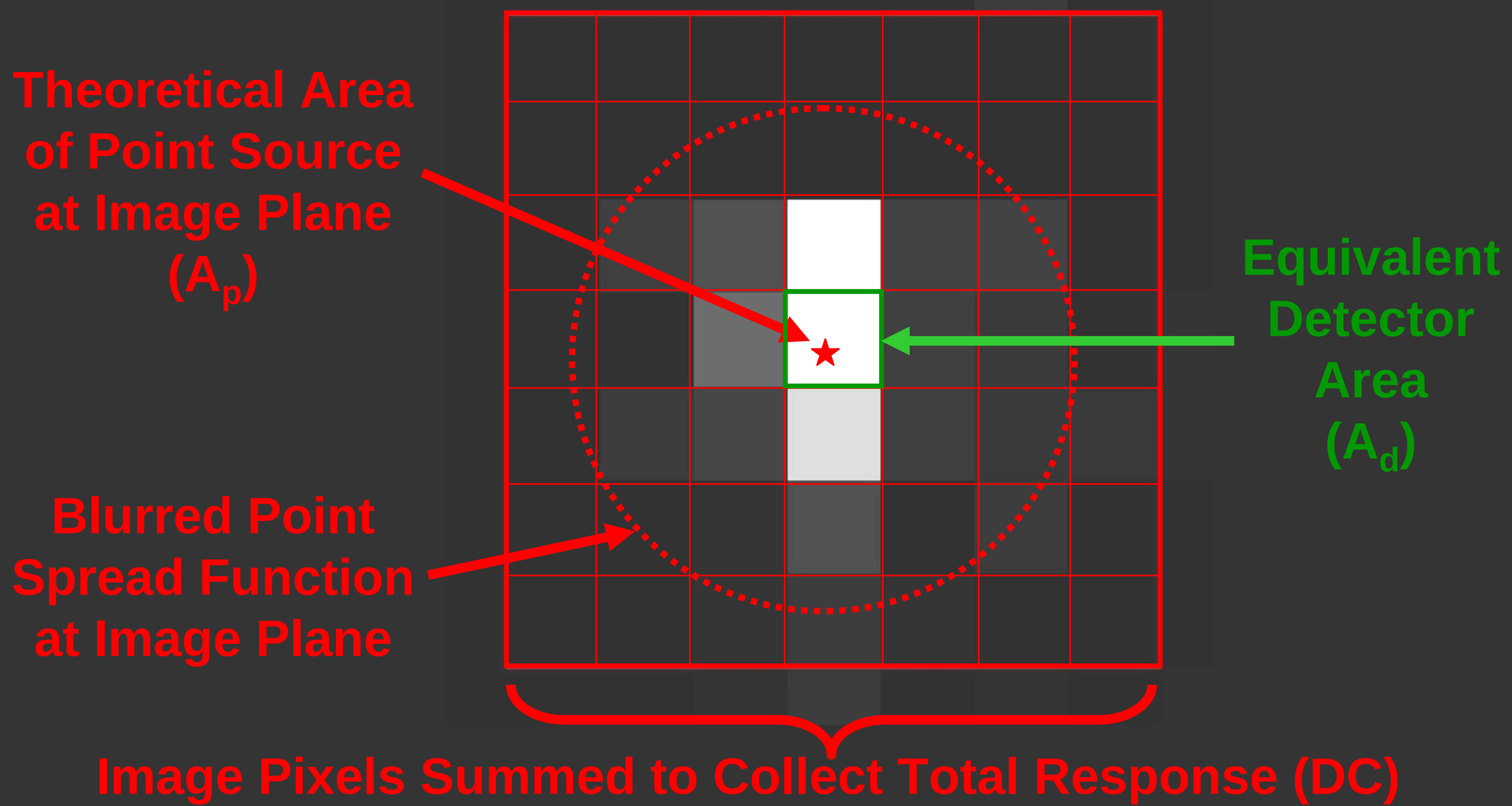
Stellar Calibration Uses Well-characterized Stellar Flux Densities Arriving at the Payload Aperture



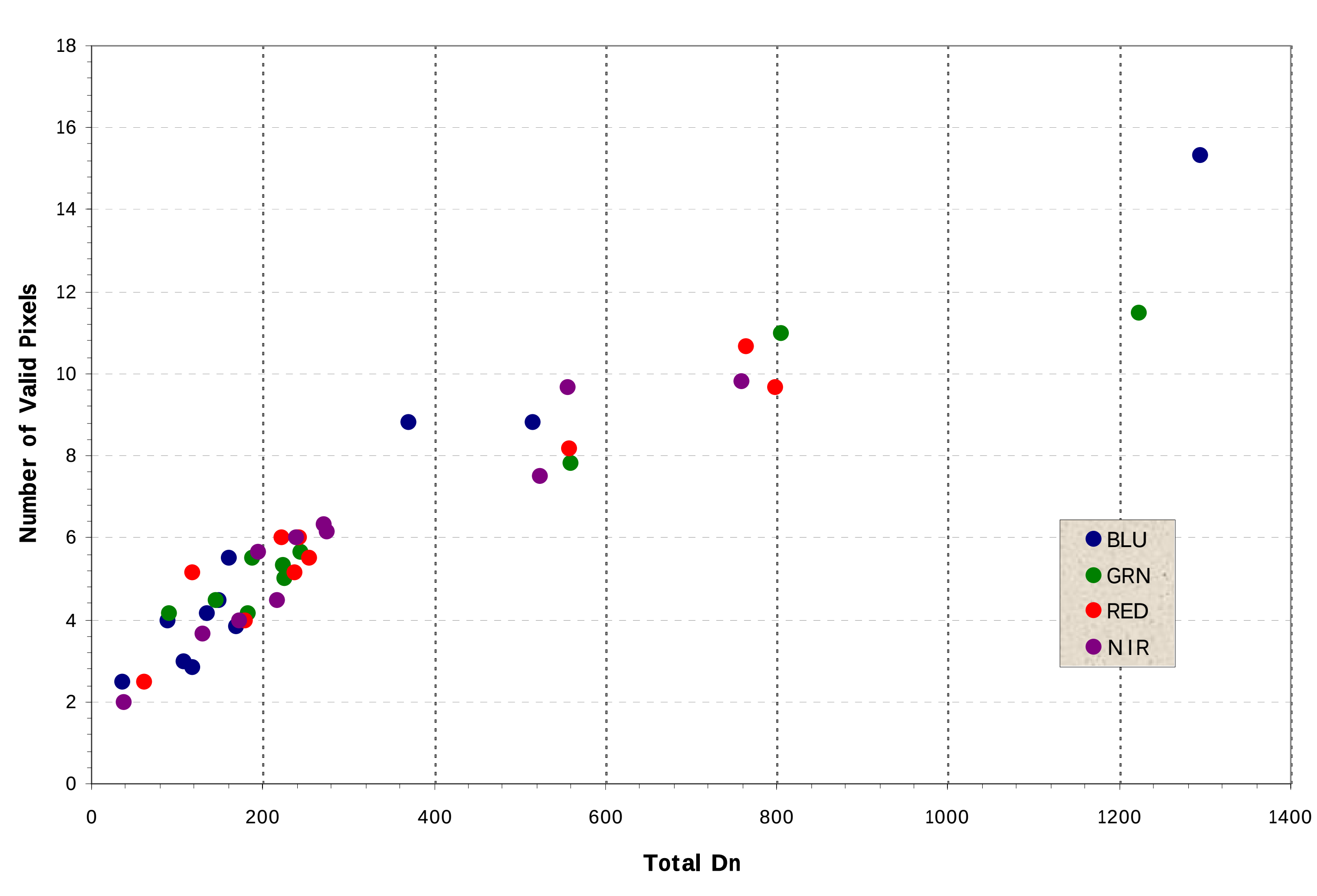
Stellar Calibration Method as Presented in 2002 ISPRS Paper

- Assumed
  - All of the energy was represented as if it was being captured within a single Instantaneous Field of View (IFOV) of the detector
- Did not consider Encircled Energy (ε_f) function for the optical system
  - Encircled Energy Function determines the amount of energy falling on the focal plane that is higher than the response threshold of a detector circuit
- Did not consider compression artifacts imposed on stellar scene data
  - Older Compression Algorithms and Points Sources don't play well
- Did not include an absolute spectral reference associated with the vicarious ground calibration approach
  - Stellar Spectral Content versus Solar/2xAtmosphere/Ground Spectral Content

All Pixels with Measurable Response Summed to All Energy Contained Within Point Spread Function



Average Number of Detectors within 7x7 pixel Area Summed to Produce the Total Digital Counts

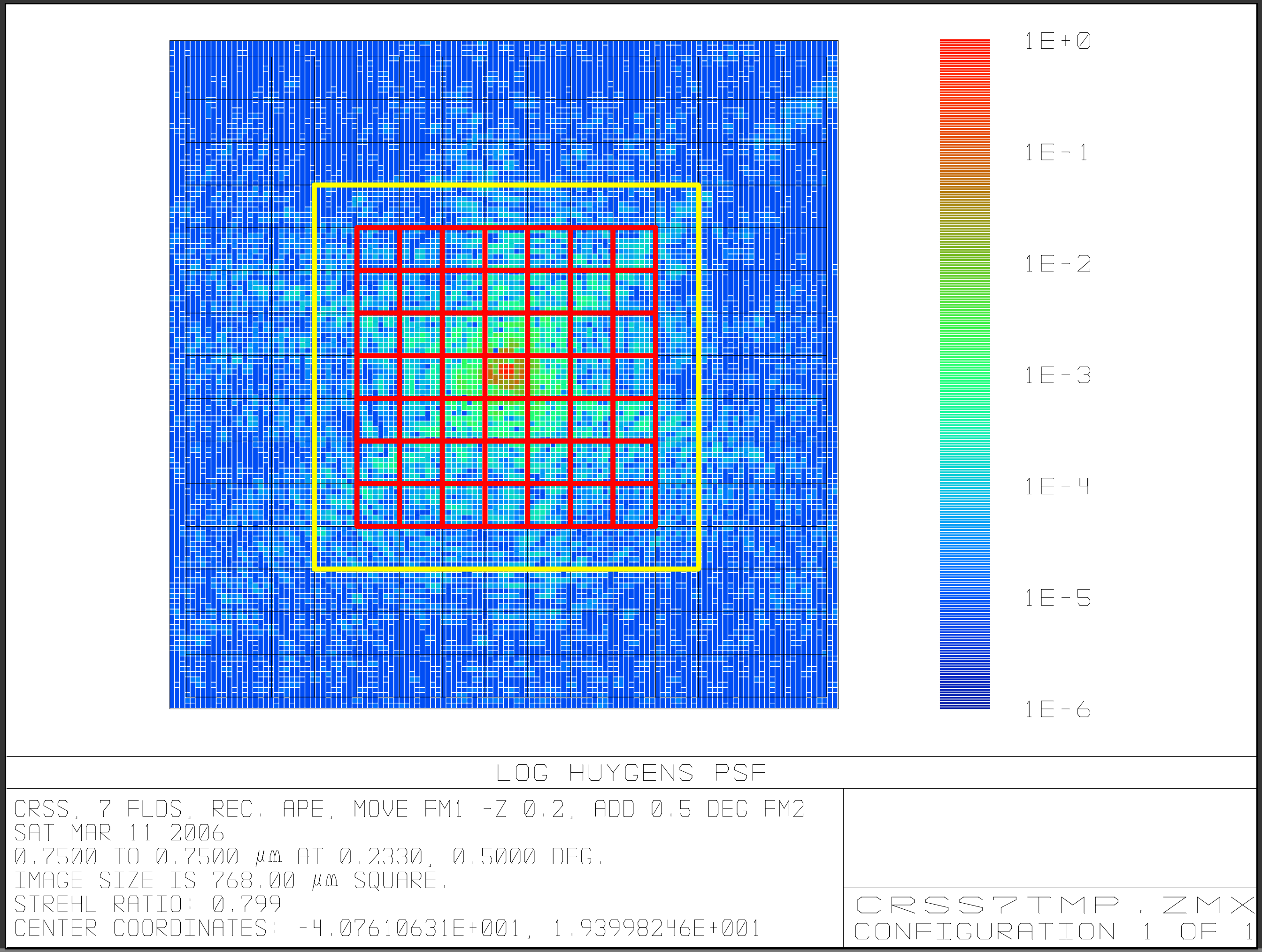


Stellar Calibration Sensor Response Function Algorithm

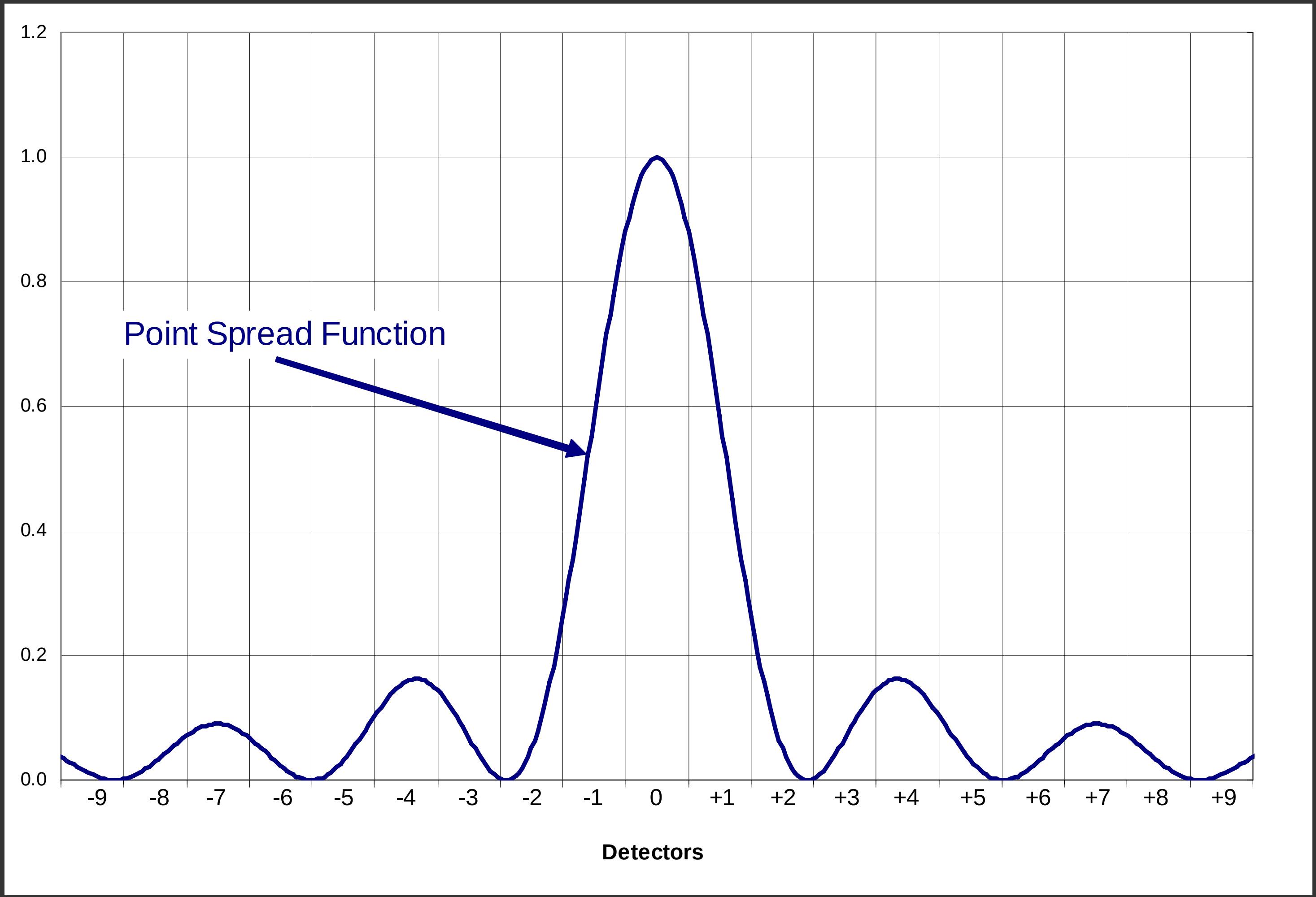
$$L_{i,j} = \int_{350nm}^{1100nm} \frac{F_i(\lambda)}{\Omega_{do}} * RSR_j(\lambda) * \varepsilon_{f_j}(A_m) * SCF_{i,j} * d\lambda$$

where: $L_{i,j}(\lambda)$ = Equivalent Radiance of Star at the Aperture (W/m^2-sr)
$F_i(\lambda)$ = Spectral Flux Density at Entrance Aperture (W/m^2-μm)
Ω_{do} = Solid Angle of a single Detector (sr)
$RSR_j(\lambda)$ = Relative Spectral Response of jth Band (%)
ε_{fj} (A_m) = Encircled Energy Function of jth Band (%)
$SCF_{i,j}$ = Spectral Correction Function of jth Band (%)

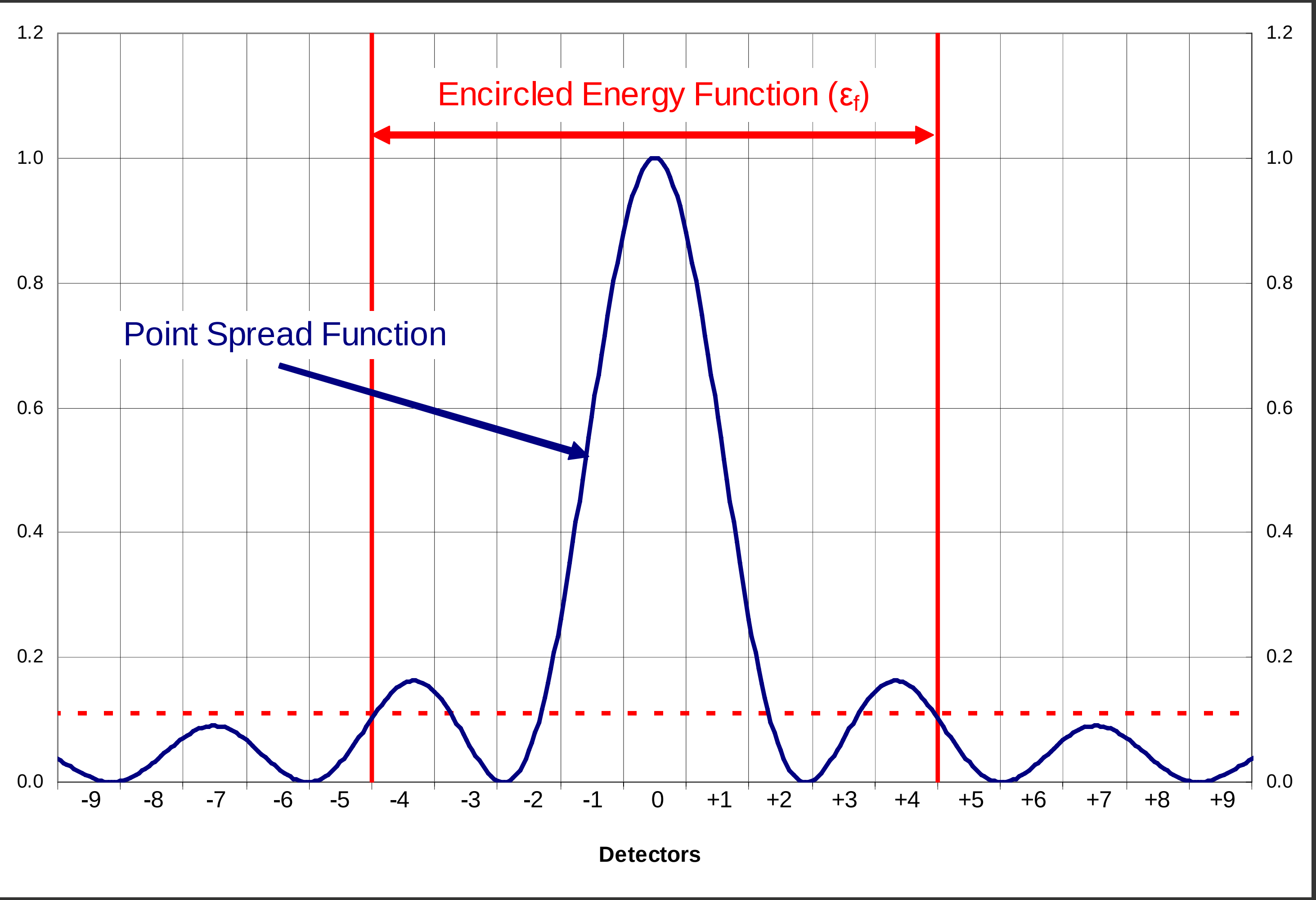
CRSS w/simulated stellar PSF (log scale)
15x15, 48um pixels, λ = 0.75 um, Focus at 700 km



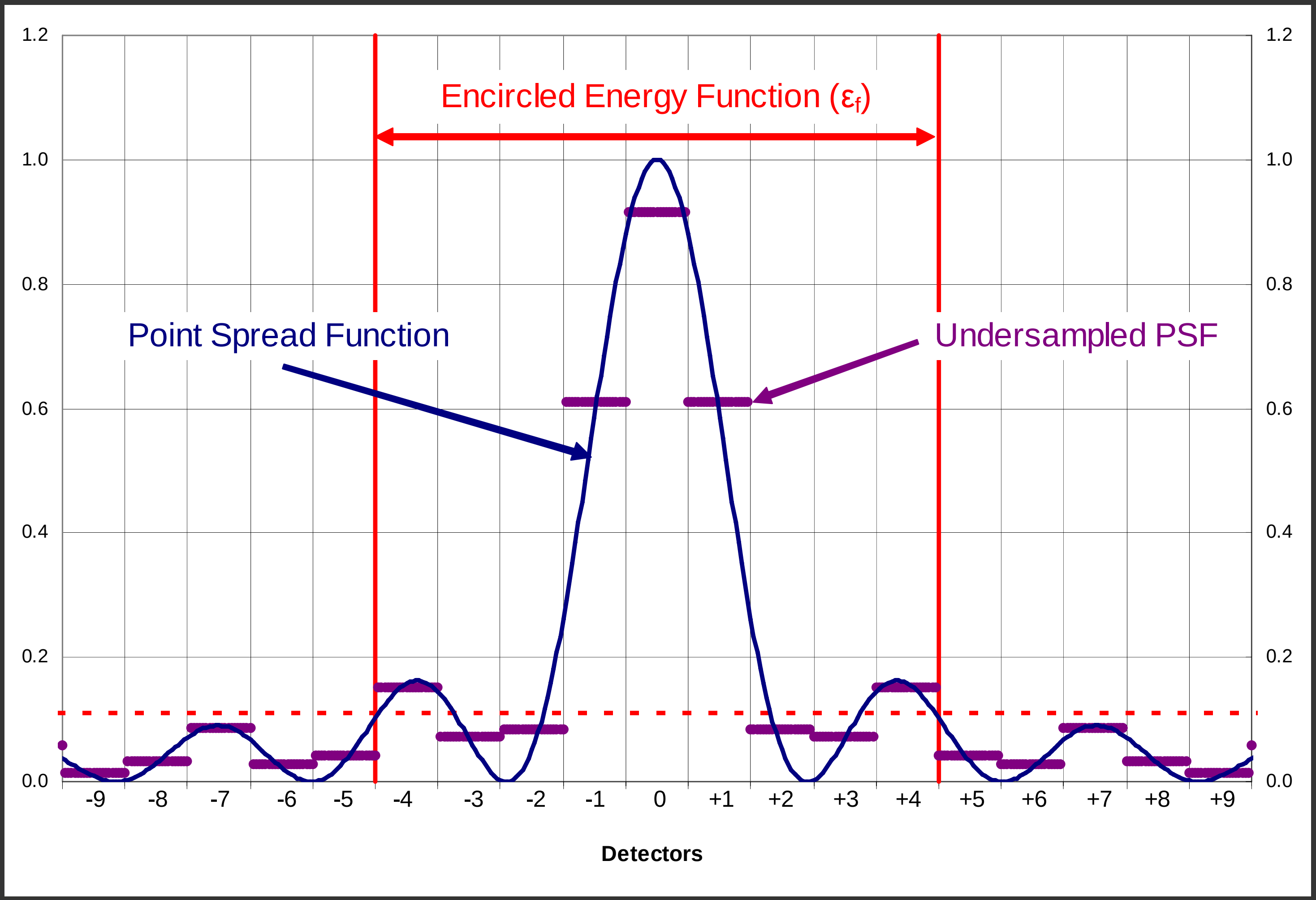
Point Source Illumination at Focal Plane Is Distributed According to Optical Transfer Function



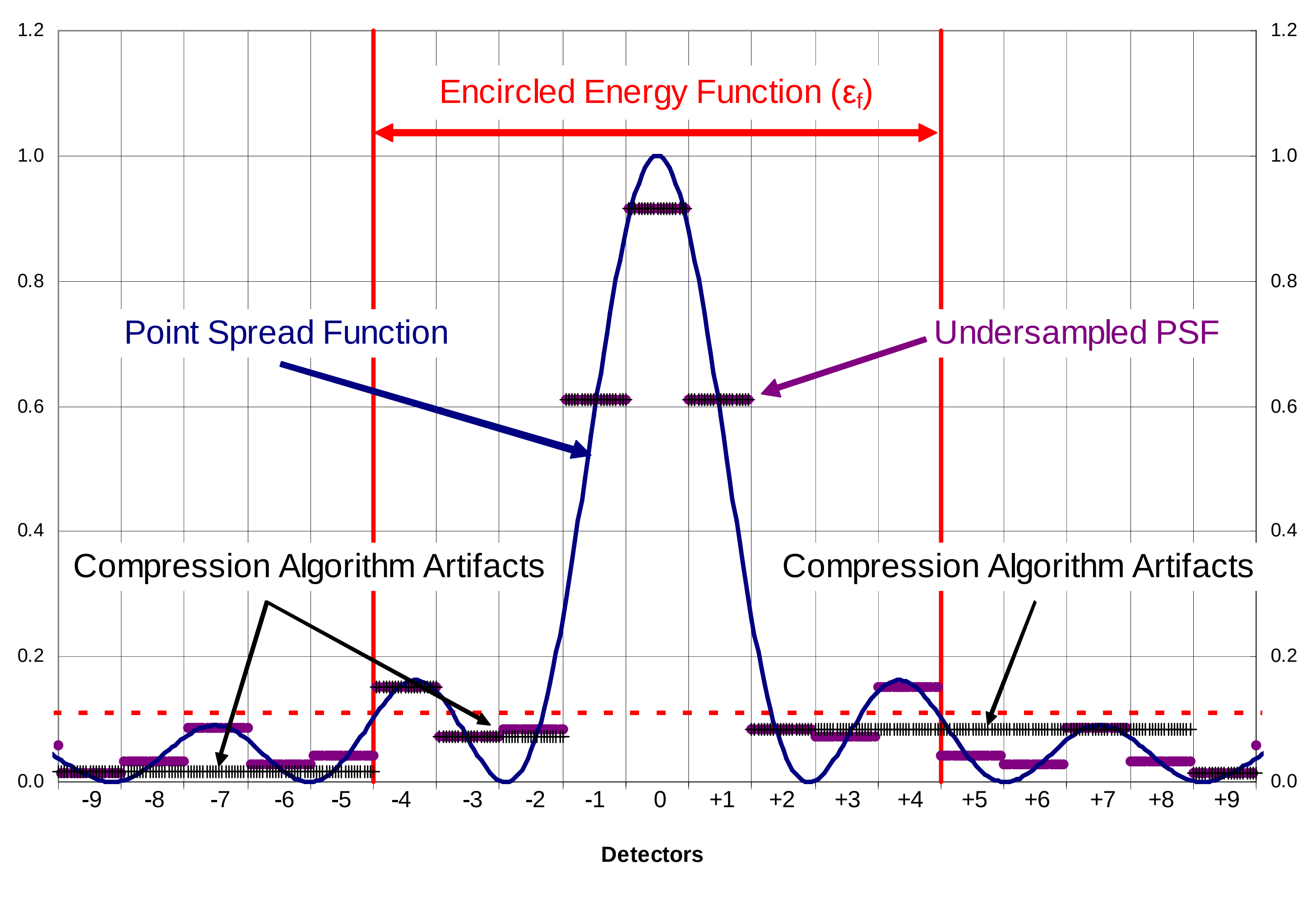
Encircled Energy Function Describes Unaccounted Energy Due to Spatial Distribution at Focal Plane



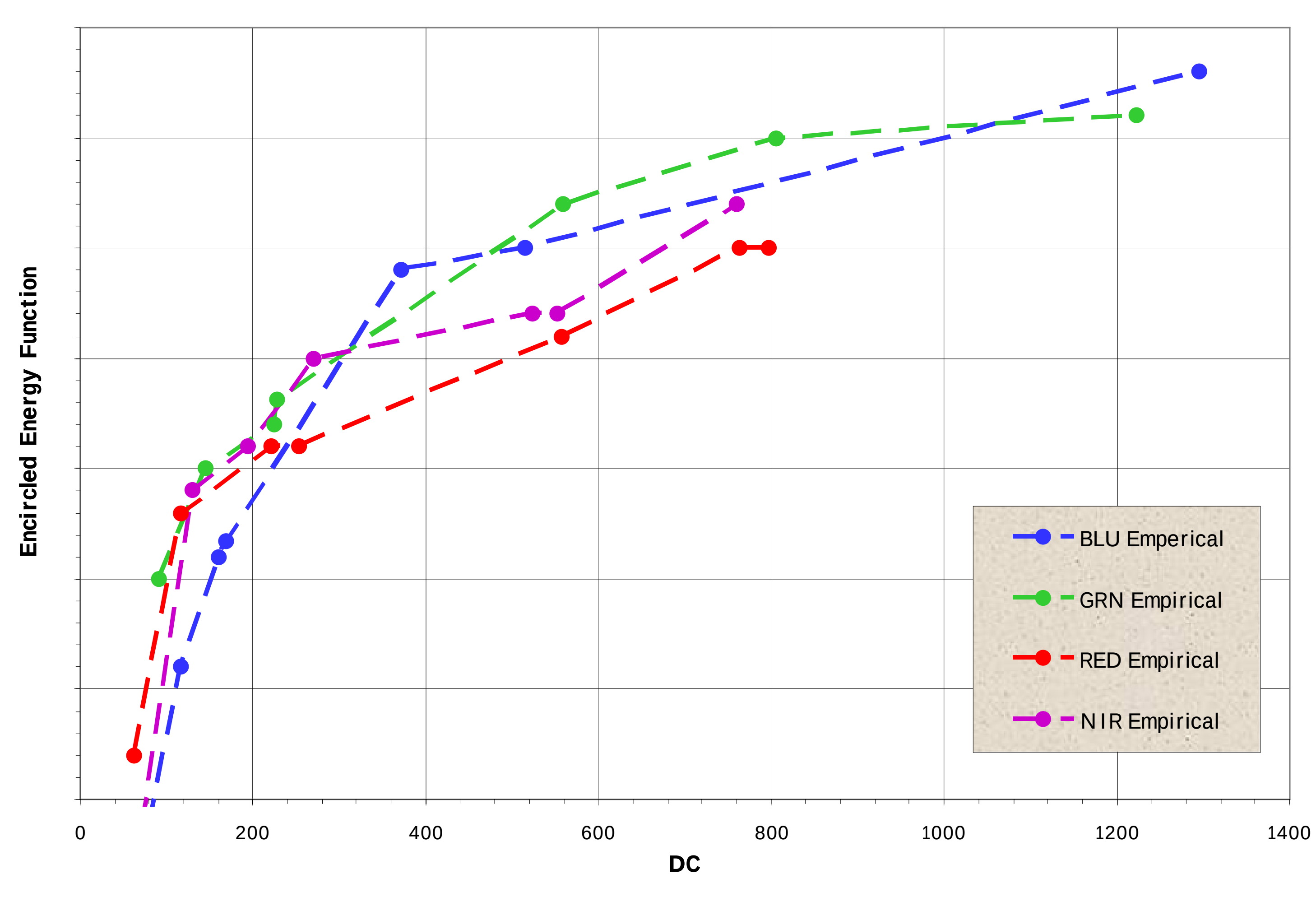
Discrete Detectors in the Focal Plane Under-sample the Point Source Energy Distribution



Low-contrast Stellar Scenes Cause Compression Artifacts that Contribute to Algorithm Uncertainty



Empirical Encircled Energy Functions that Provide Match Between Stellar and Ground Results

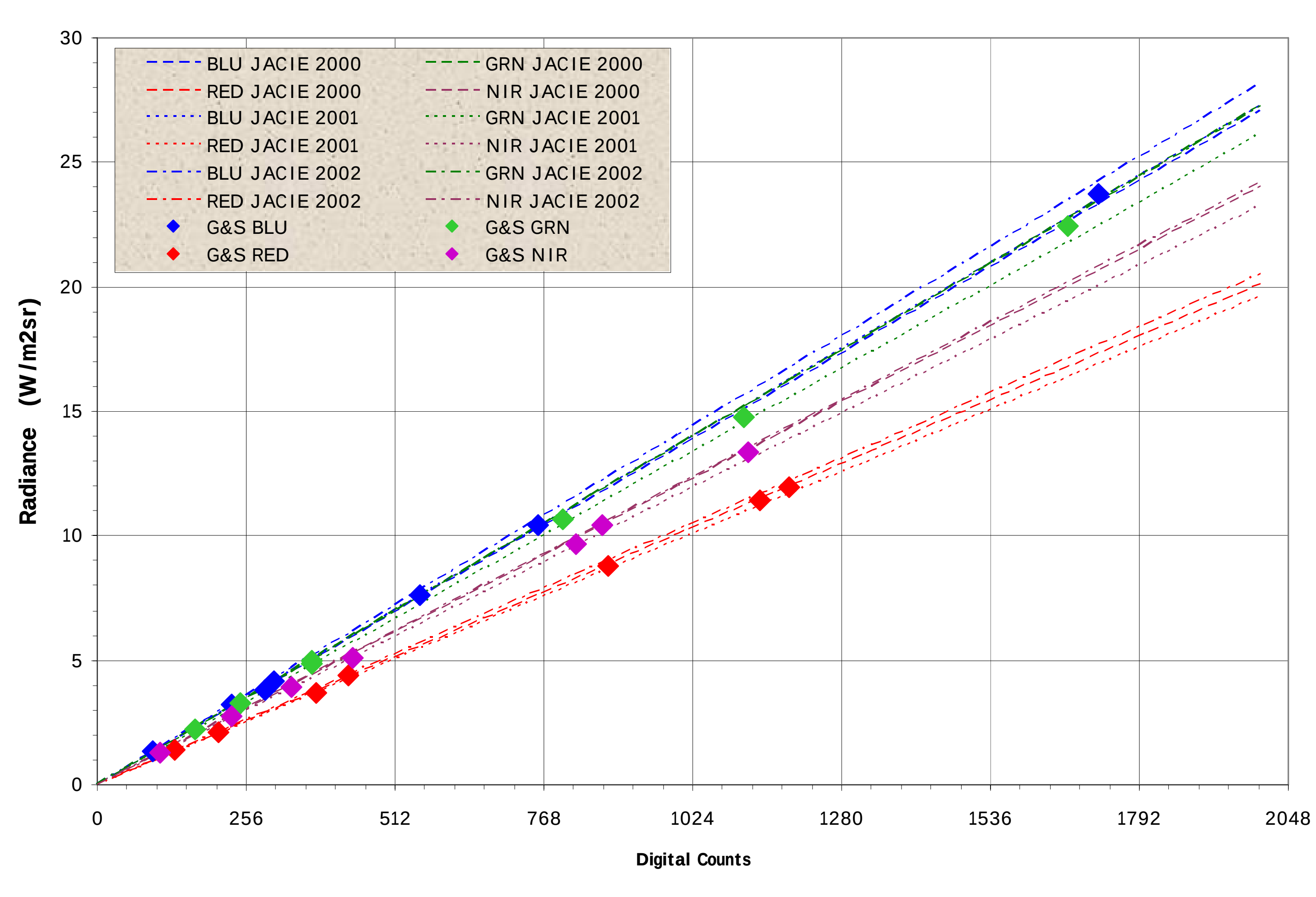


Spectral Correction Function can be Employed to Reference the Stellar to a Solar/Ground Spectra

$$SCF_j = \frac{\dfrac{\int_{350nm}^{1100nm} L_{star}(\lambda) RSR(\lambda) d\lambda}{\int_{\lambda_l}^{\lambda_h} L_{star}(\lambda) d\lambda}}{\dfrac{\int_{350nm}^{1100nm} L_{gnd}(\lambda) RSR(\lambda) d\lambda}{\int_{\lambda_l}^{\lambda_h} L_{gnd}(\lambda) d\lambda}}$$

where: $L_{star}(\lambda)$ = Equivalent Radiance of Star at the Aperture (W/m^2-sr)
$L_{gnd}(l)$ = Radiance of Reference Ground Scene at the Aperture (W/m^2-sr)
$RSR_j(\lambda)$ = Relative Spectral Response of jth Band (%)
$SCF_{i,j}$ = Spectral Correction Function of jth Band (%)

Correlation between Corrected Stellar Calibration and Vicarious Ground Calibration Results



Topics for Future Investigations

- Add New Characterized Stars to Collection Plans
- Revisit Stellar Imaging Scenario
  - Develop Encircled Energy Function
    - Linear Array
    - Push-broom Scanning Systems
  - Separate data from compression noise
  - Determine uncertainty of measurement
- Collect and Analyze Additional Stellar Imagery
  - Analysis primarily uses only 7 stellar collects

Summary

- Additional research needed to further refine the algorithm