Correlation of Target-dependent Calibration Methods used to Determine Absolute and Relative Radiometric Accuracy, Monitor Long-term Stability, Assess Stray Light Performance, Measure MTF Performance and Estimate Effective Focal Length for the IKONOS Space-based Remote Sensing Payload

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Martin Taylor, PhD – GeoEye
Kurt Thome, PhD – NASA GSFC

JACIE 2009 Workshop – Fair Oaks, Virginia
April 1, 2009

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Correlation of Target-dependent Calibration Methods Outline

- Acknowledgements
- Overview
- Introduction and Historical Background
- Target-dependent Calibration Methods Results Correlation
  - Radiometric: Absolute and Relative
  - Stray Light
  - Modulation Transfer Function
  - Effective Focal Length
- Summary

Acknowledgements

- Dr. Martin Taylor of GeoEye in Thornton, Colorado
- Dr. Kurt Thome of NASA GSFC (formerly associated with the University of Arizona, Optical Sciences Center, Remote Sensing Group)
- Mr. Jim Erwin of ITT
- Mr. Doug Cunningham, Mr. James Hardy, Dr. Rick Herbert (retired), Mr. David House, Mr. Michael Jacobs, Dr. Alan Marchant (retired), Mr. James Mooney, Mr. Donald Oinen, Dr. Karl Sweitzer, Dr. Dennis Thompson and Mr. Noah Block of ITT
- Ms. Mary Pagnutti, Ms. Kara Holekamp, Mr. Robert Ryan, et. al. of Lockheed Martin Space Operations, NASA Stennis Space Center
- Mr. Tim Goodwill, Dr. Carl Lutzer, Dr. David Ross, and Dr. Manuel Lopez, of the Rochester Institute of Technology, School of Mathematical Sciences
- Dr. Dennis Helder of the University of South Dakota
- Dr. Tom Stone of ROLO in Flagstaff, Arizona

IKONOS FPA: 2 Panchromatic Arrays (Fwd and Rev)
4 Multi-spectral Arrays (BLU, GRN, RED, NIR)

9 years On-orbit - 923,250 Detectors in 6 Arrays
Zero (0) Failed or Non-calibrateable Detectors

LM Spacecraft Specifications
- 3-axis Stabilized Spacecraft
- LM900 Satellite Bus System
- Two Star Trackers
- Inertial Reference Unit
- Four Reaction Wheels
- Sun Sensor
- Three Solar Panels
- GPS Receiver
- Design life is 7 years
- S/C Body = 1.83 m x 1.57 m
- S/C Mass = 726 kg (1600 lbs)
- S/C Power = 1.5 kW

ITT Optical Payload
- 70 cm Diameter, 3-mirror Anastigmat
- 10m Focal Length (f/14.3)

Spatial Resolution
- 0.8 m Panchromatic (1-m PAN)
- 4.0 m Multispectral (4-m MS)
- 1.0 m Pan-sharpened (1-m PS)

Temporal Resolution
- Revisit is 3 to 5 days for off-nadir
- Repeating is 144 days for true-nadir

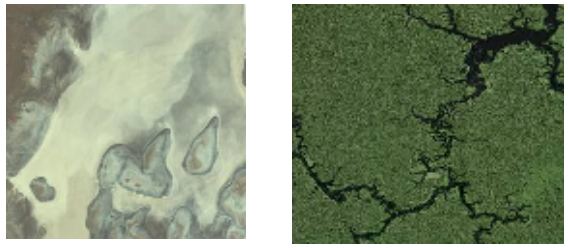
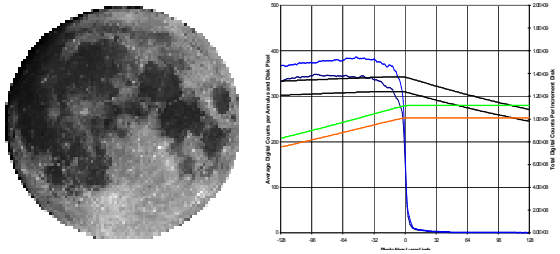
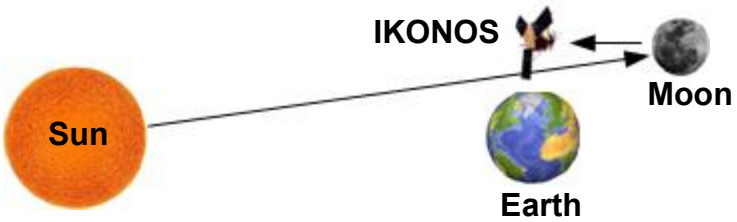
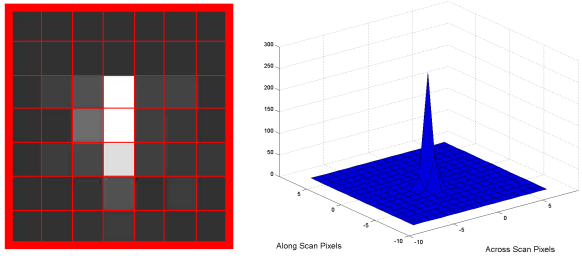
Swath Width and Coverage
- 11 km x 11 km (Single Scene)
- 11 km x 1000 km (Long Strip)
- 100 km x 100 km (Large Area)

Launch and Orbit:
- September 24, 1999
- 98° Inclined, Sun-synchronous
- 681 km Orbit (424 mi)
- 7 km/s Velocity (4 mi/s)

IKONOS Target-dependent Calibration Correlation Matrix

	Target Type			
Calibration / Assessment	**Vicarious Ground Sites**	**Stellar Point Sources**	**Full Lunar Disk**	**Lunar Limb**
Absolute Radiometric Accuracy	**Yes**	**Yes**	**Yes**	**na**
Long-term Radiometric Stability	**Yes**	**Yes**	**Not in ConOps**	**na**
Intra-band Relative Radiometric Accuracy	**Unknown**	**Not in ConOps**	**Yes** P-Fwd vs. P-Rev	**na**
Inter-band Relative Radiometric Accuracy	**Yes**	**na**	**Yes**	**na**
Stray Light Assessment	**Unknown**	**Not in ConOps**	**Yes**	**Yes**
MTF Assessment	**Yes**	**Yes**	**na**	**Yes**
Effective Focal Length	**Yes** Gnd Control Points	**Yes** Stellar Separation	**na**	**Yes** Limb-to-Limb

Correlation between Target-dependent Calibration Methods Require Unique Considerations for Each Analysis Type

Method	Response	Stimulus
Ground		
Lunar		
Stellar		

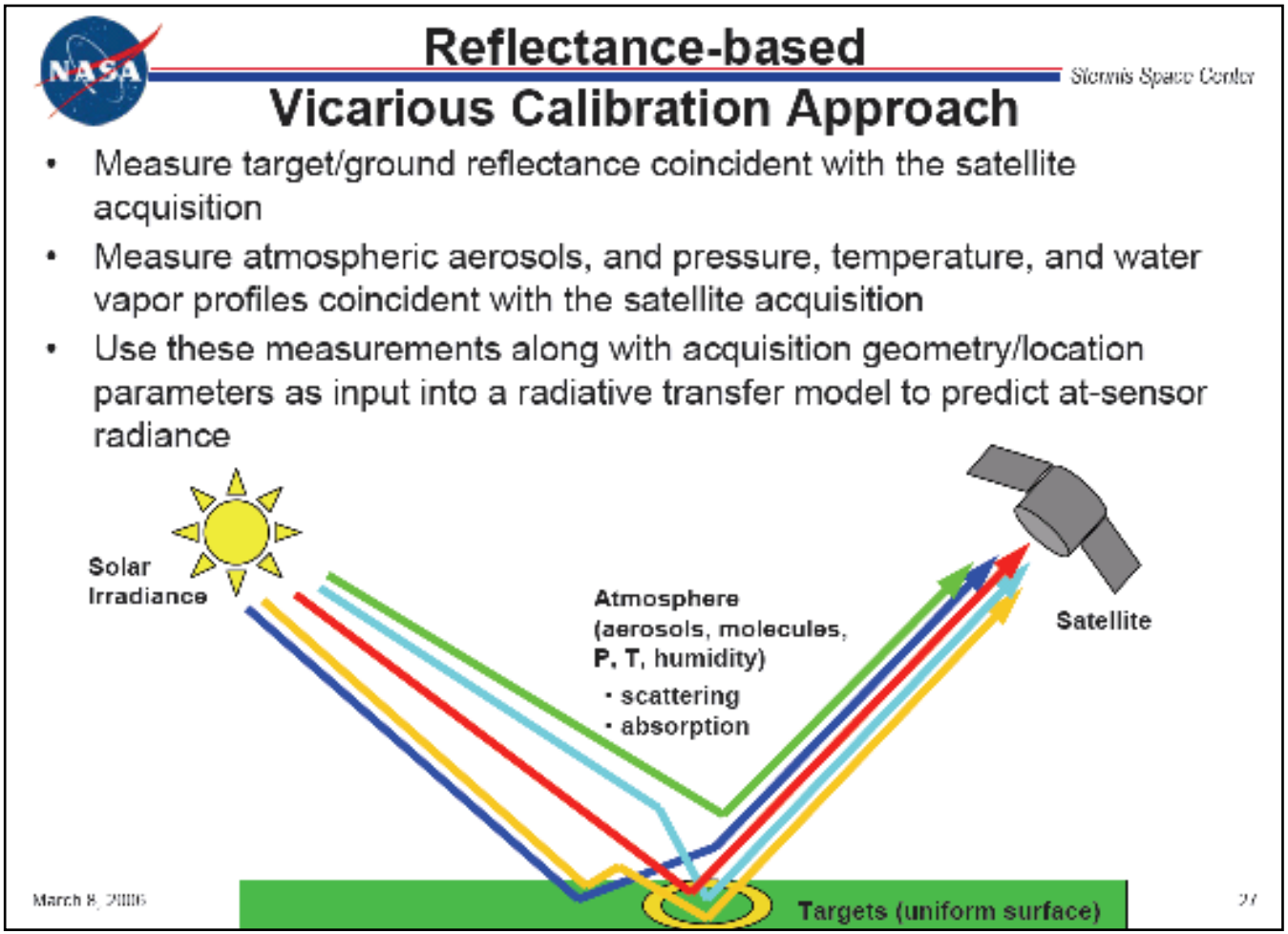
Absolute Radiometric Accuracy Targets

Earth-based Uniform Scene Targets (over-filled telescope FOV)

Point Source Stellar Imaging (point source at infinity)

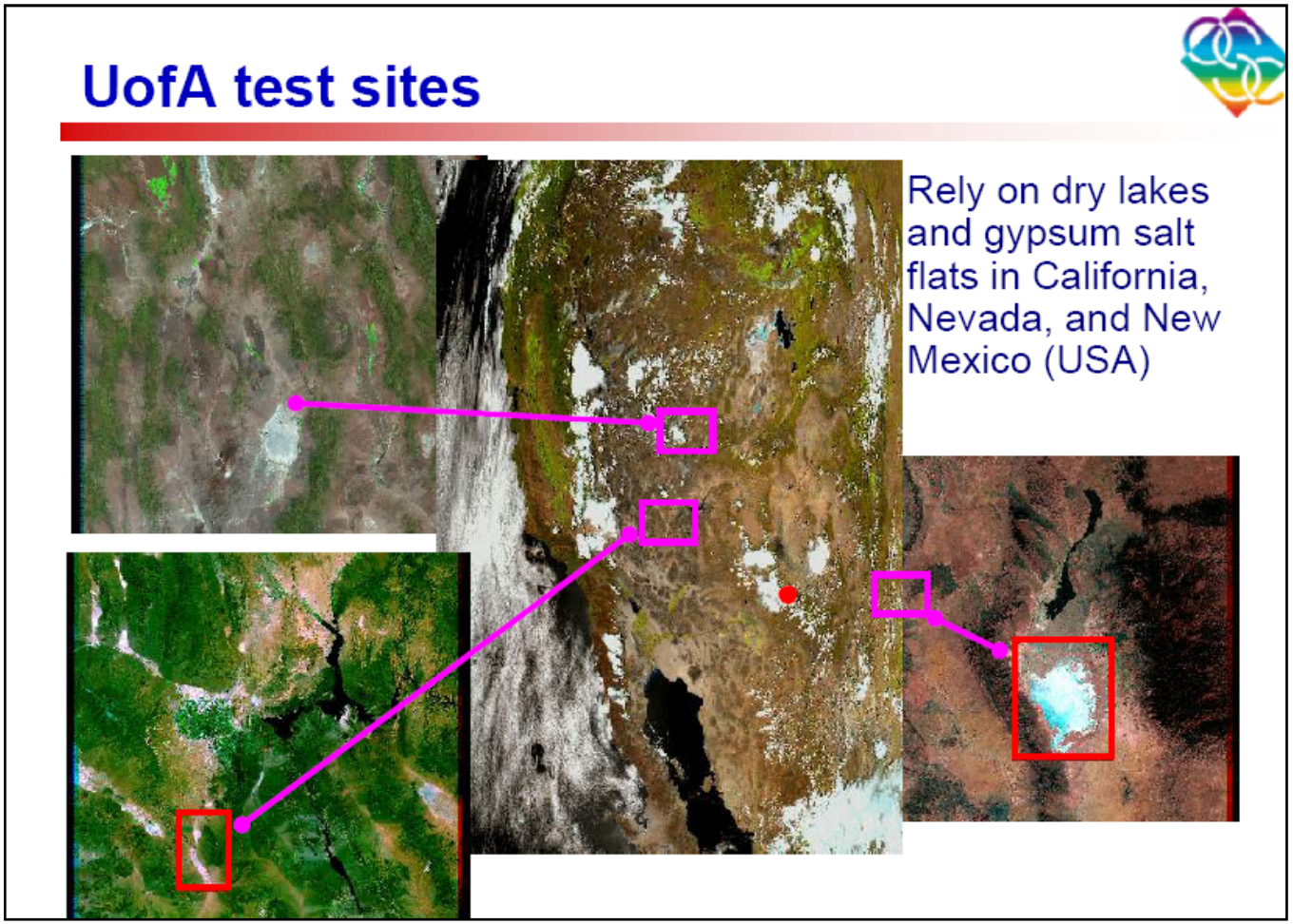
Full Disk Lunar Imaging (under-filled telescope FOV)

Absolute Radiometric Accuracy – Vicarious Ground Calibration Analysis Considerations



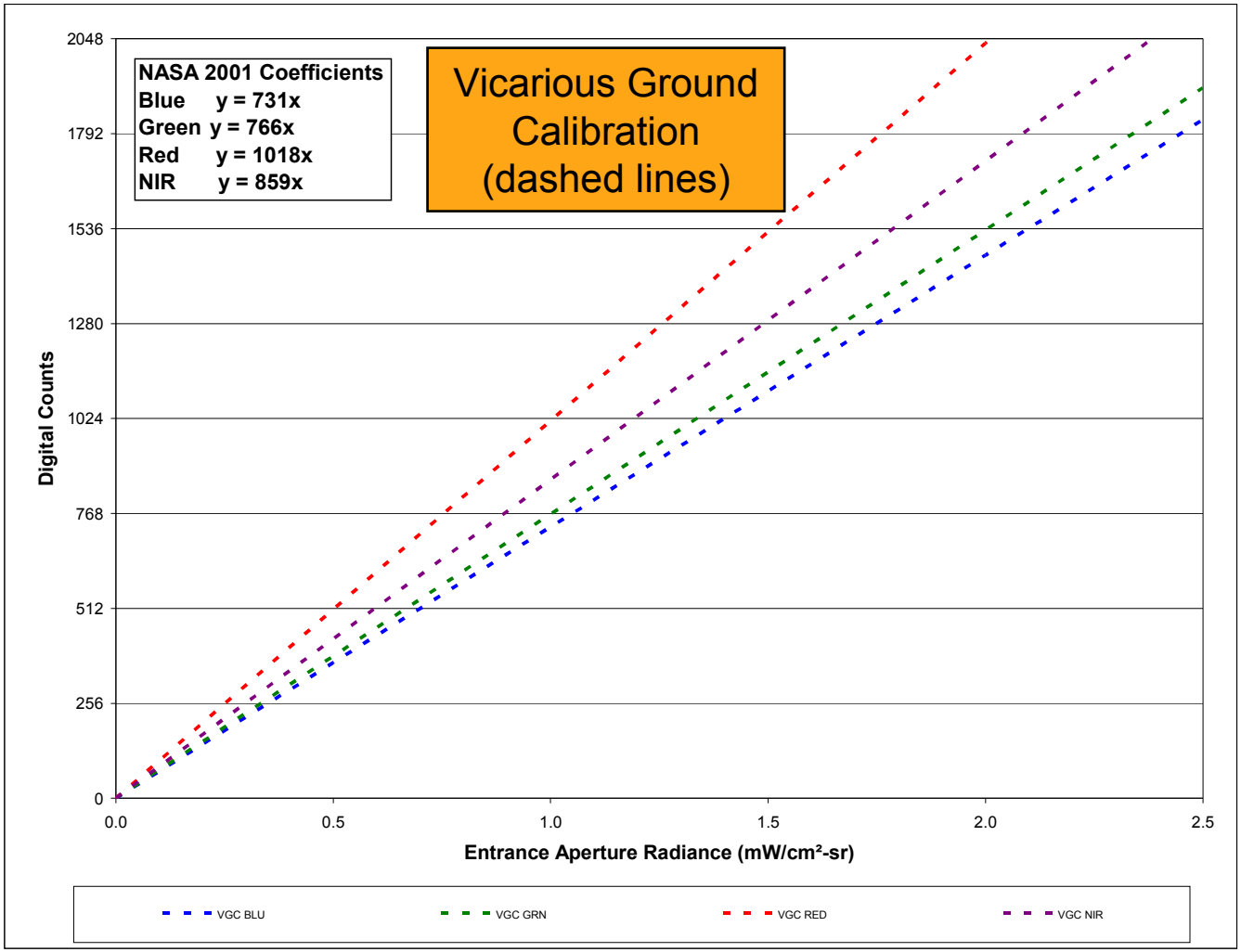
Pagnutti, Mary; Measurement Sets and Sites Commonly Used for High Spatial Resolution Image Product Characterization, 2006 EO/IR Calibration and Characterization Workshop, Science Systems and Applications, Inc., John C. Stennis Space Center, Stennis, Mississippi, March 8, 2006.

Absolute Radiometric Accuracy – Dry Lakebeds & Salt Flats Typical of Earth-based Uniform Scene Targets



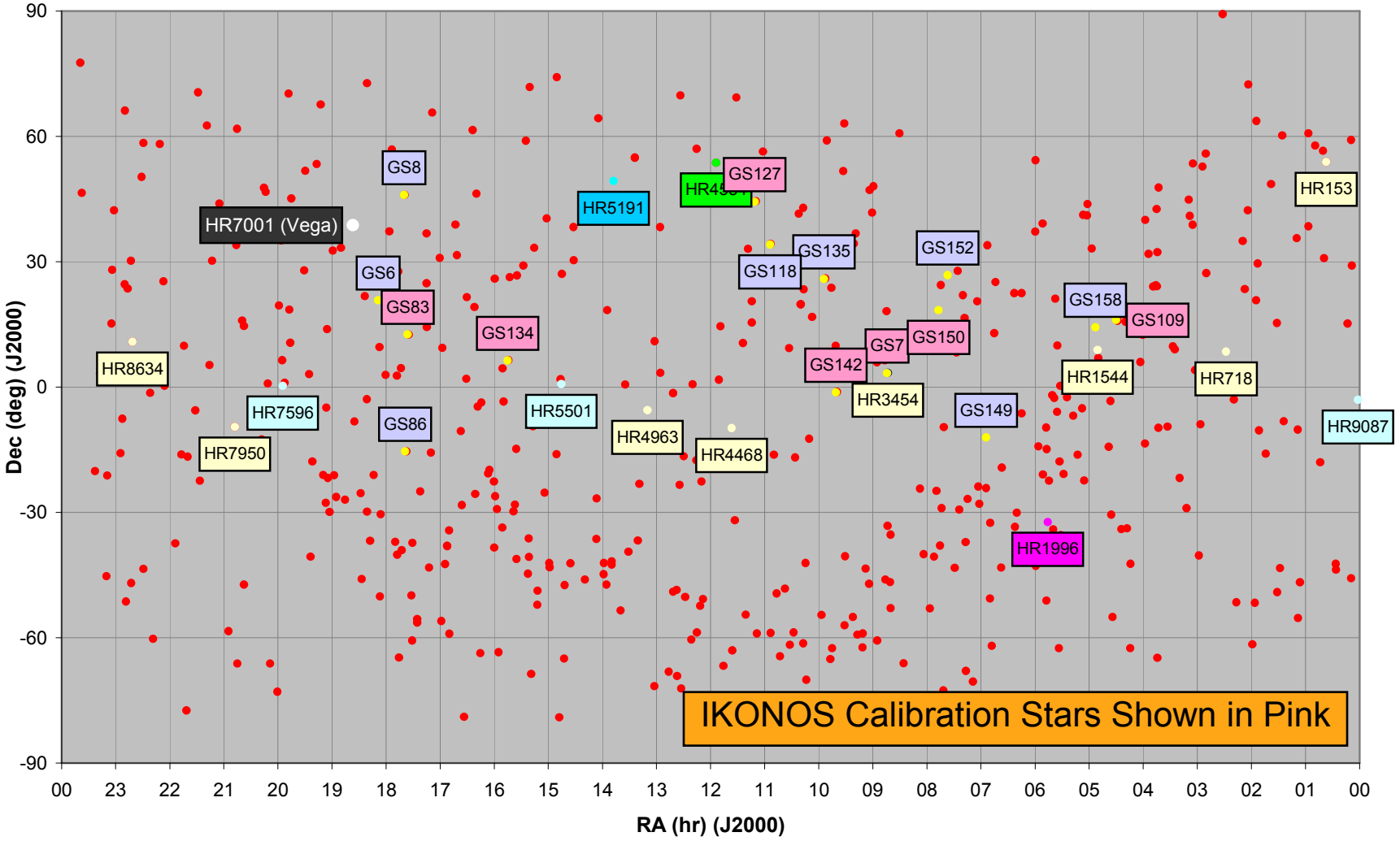
Thome, K., Leisso, N., Buchanan, J..; Radiometric Calibration Assessment of Commercial High Spatial Resolution Multispectral Image Products, Civil Commercial Imagery Evaluation Workshop, Joint Agency Commercial Imagery Evaluation (JACIE) Team, Laurel, Maryland, March 14-16, 2006

Absolute Radiometric Accuracy – Vicarious Ground Calibration Published Calibration Coefficients

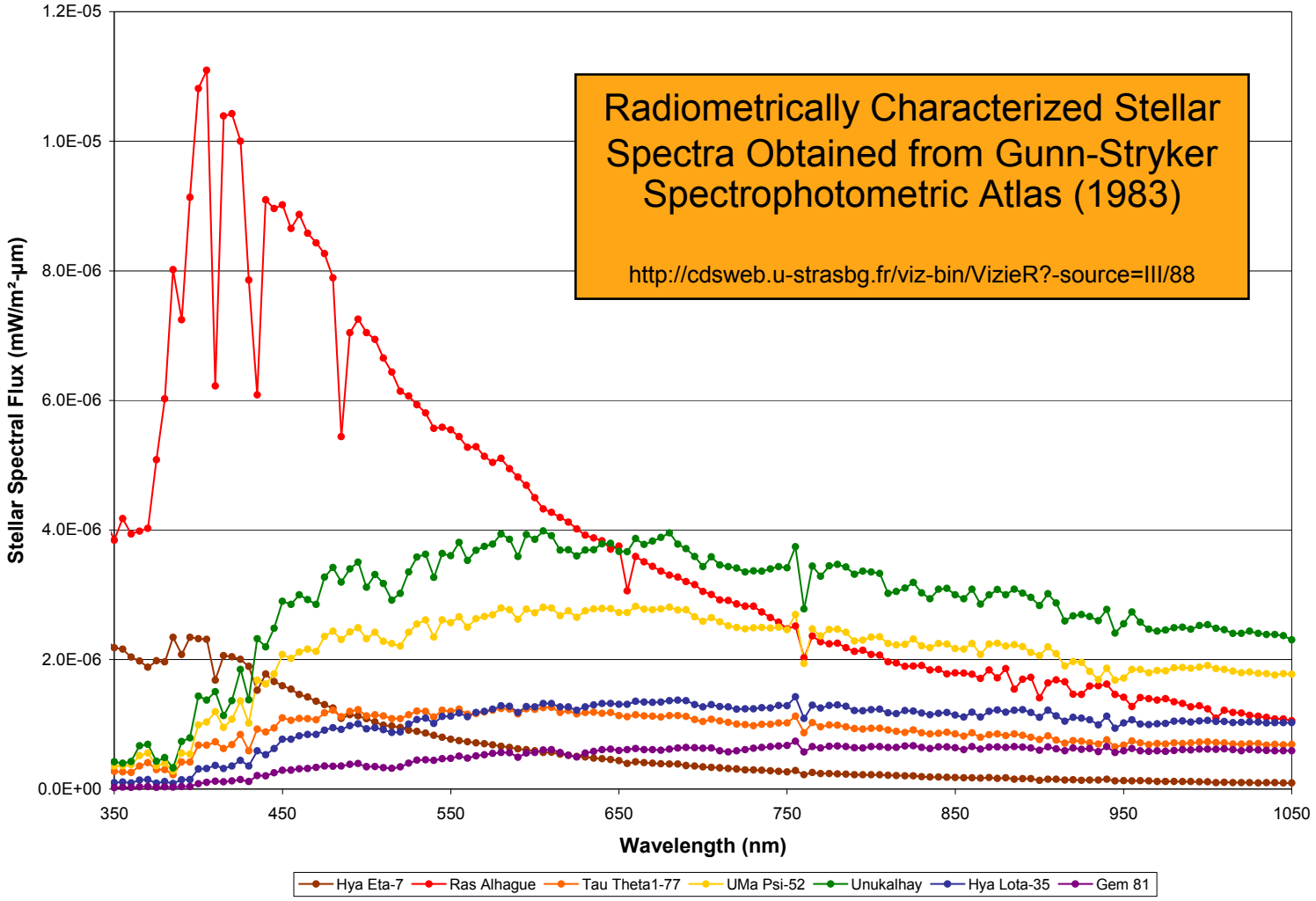


Vicarious Ground Results Based Upon Band Average Radiance Multiplied by Computed Bandwidth

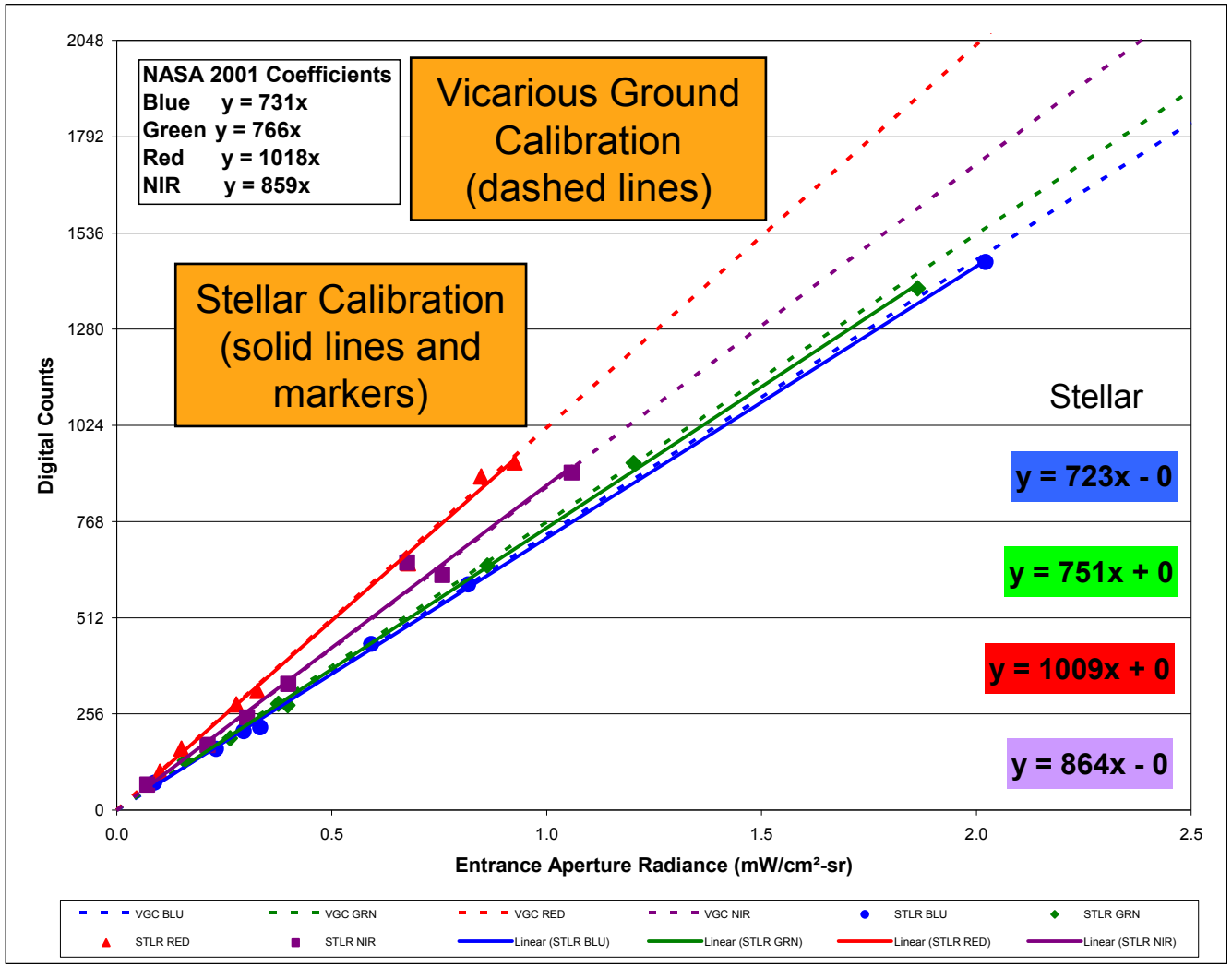
Absolute Radiometric Accuracy – Radiometrically Characterized Stars versus BSC Stars of $2 < V_{mag} < 4$



Absolute Radiometric Accuracy – Spectra for IKONOS Radiometrically Characterized Stellar Sources



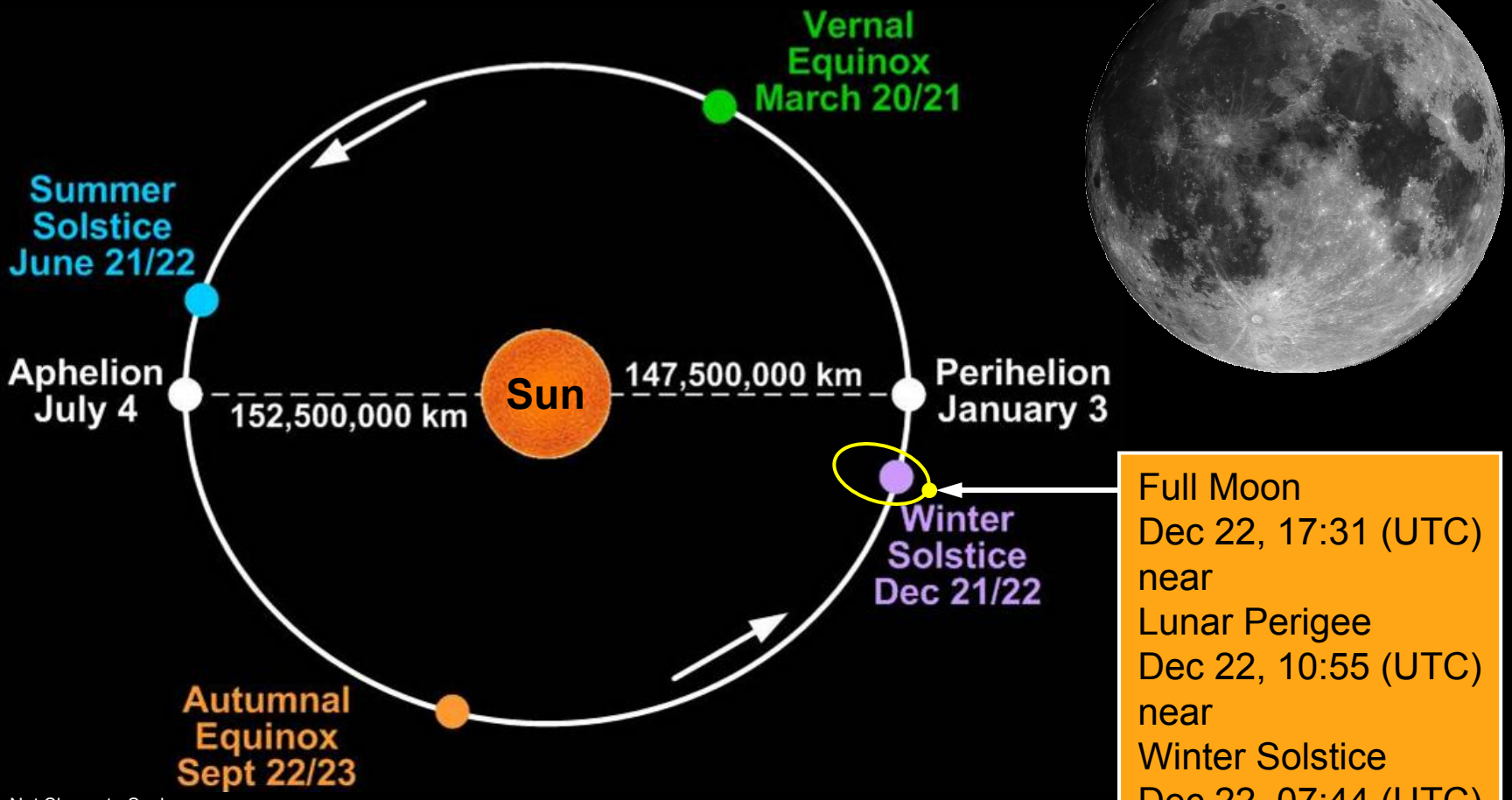
Absolute Radiometric Accuracy – Vicarious Ground Calibration and Revised (2007) Stellar Calibration Results



Revised Stellar Results Based Upon FWHM In-band Radiance

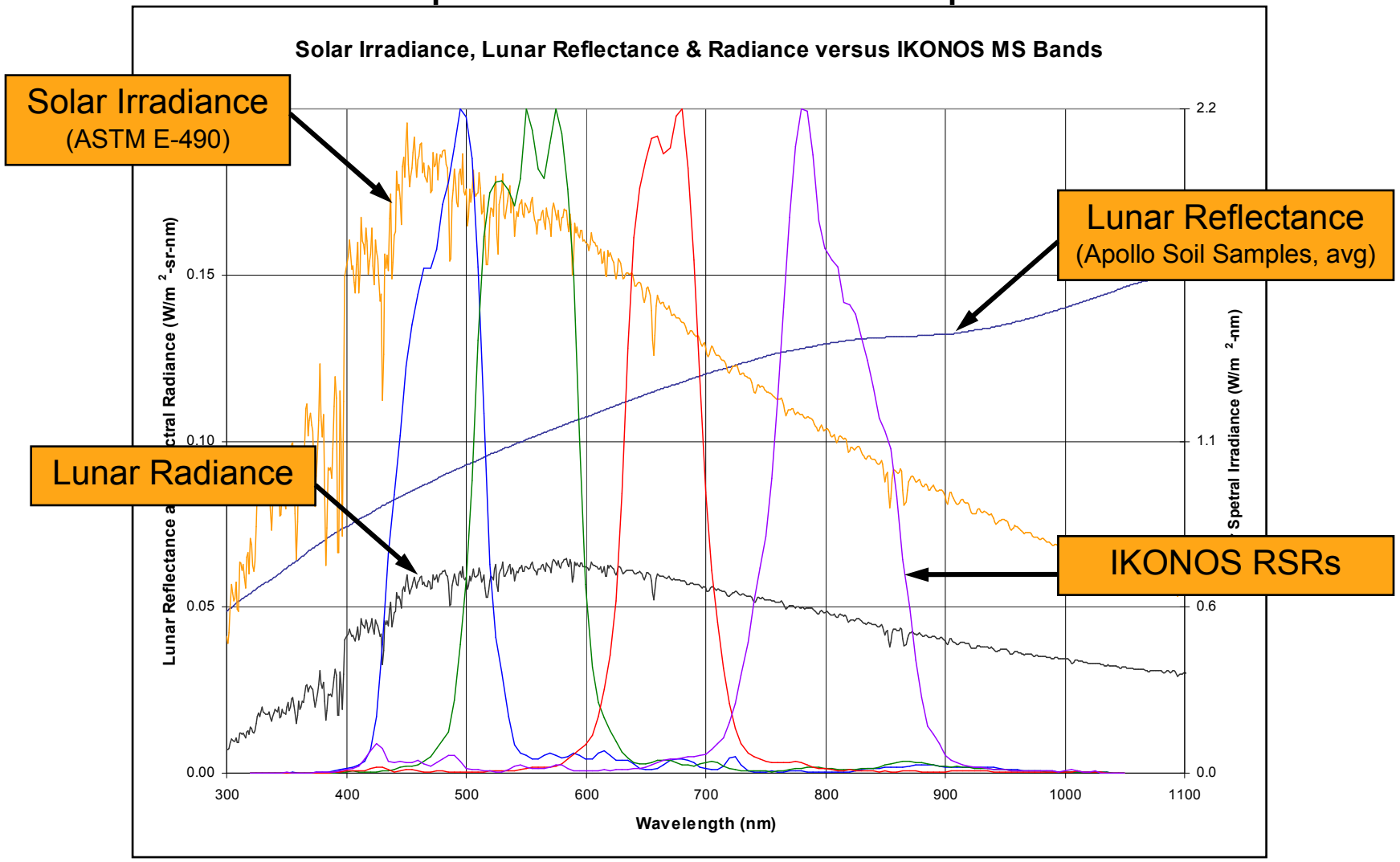
Previous stellar results had been reported in terms of FW In-band Radiance

Absolute Radiometric Accuracy – Historic IKONOS Moon: Brightest, Largest Full Disk Lunar Imaging Opportunity

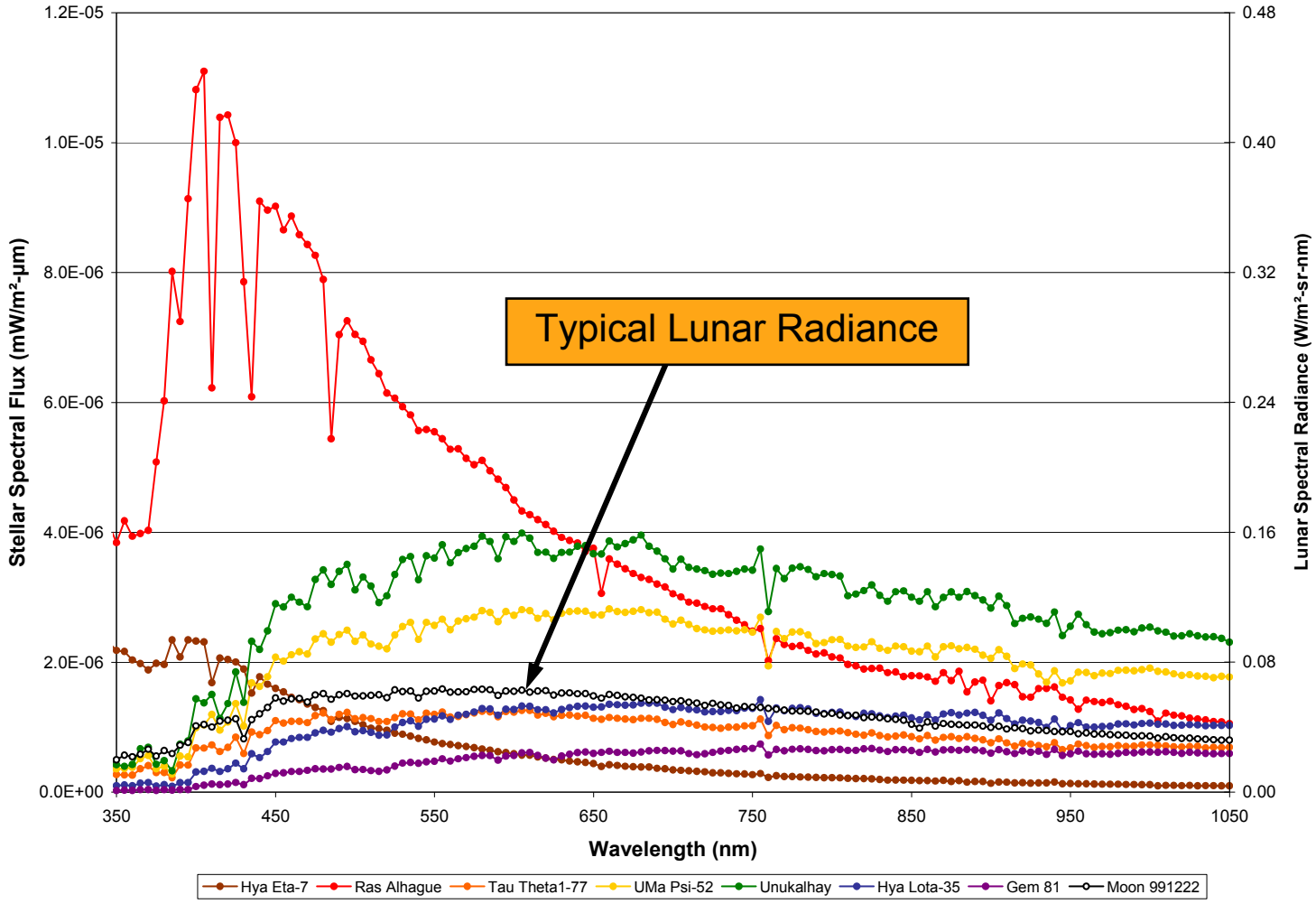


Full Moon
Dec 22, 17:31 (UTC)
near
Lunar Perigee
Dec 22, 10:55 (UTC)
near
Winter Solstice
Dec 22, 07:44 (UTC)

Absolute Radiometric Accuracy – Exoatmospheric Lunar Radiance with respect to IKONOS Multispectral Bands



Absolute Radiometric Accuracy – Comparison of Exoatmospheric Lunar Radiance and Stellar Flux



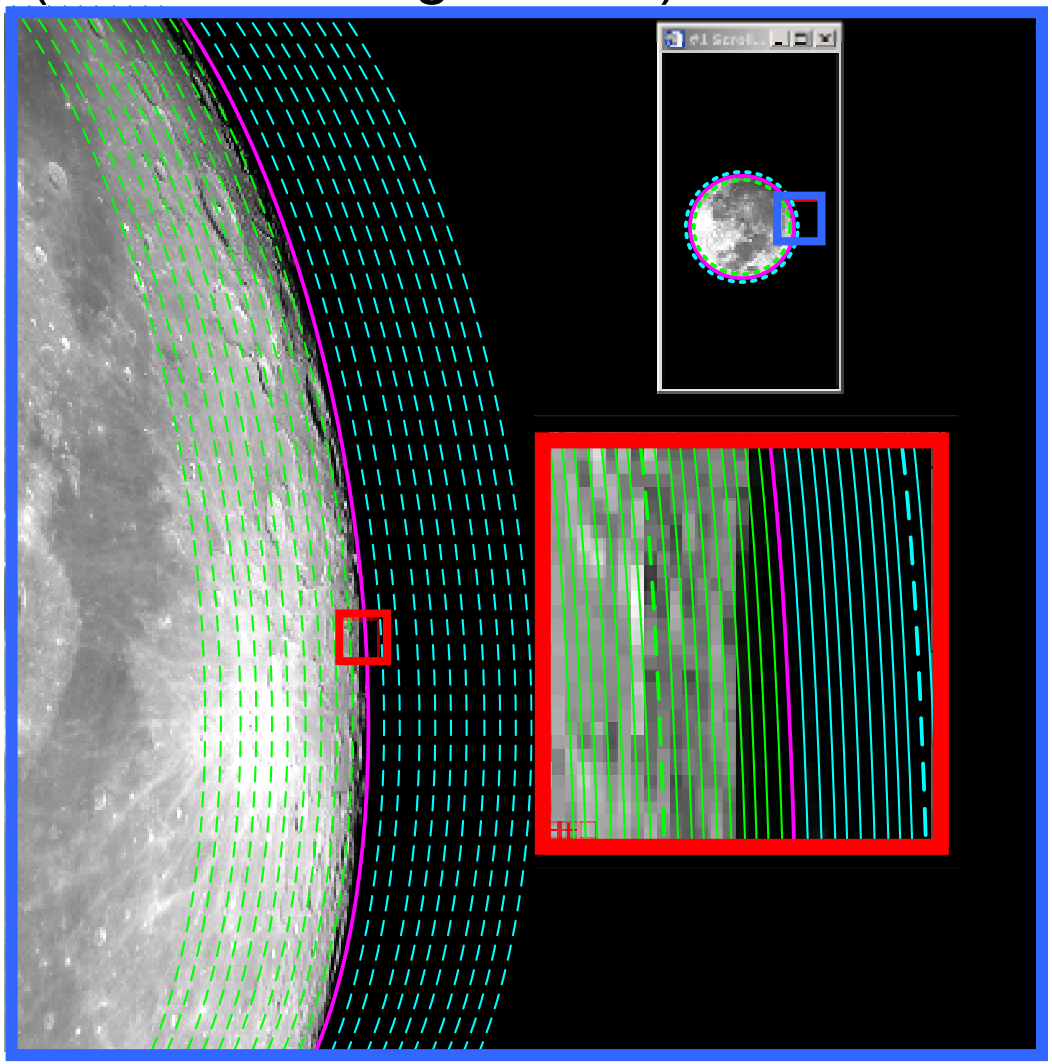
Absolute Radiometric Accuracy – Lunar Limb Determination Using Full Disk Imagery (lunar limb edge detail)

First step computes the average digital counts per pixel within an ellipse beginning at -128 pixels inside the Lunar Limb to +128 pixels beyond the Lunar Limb

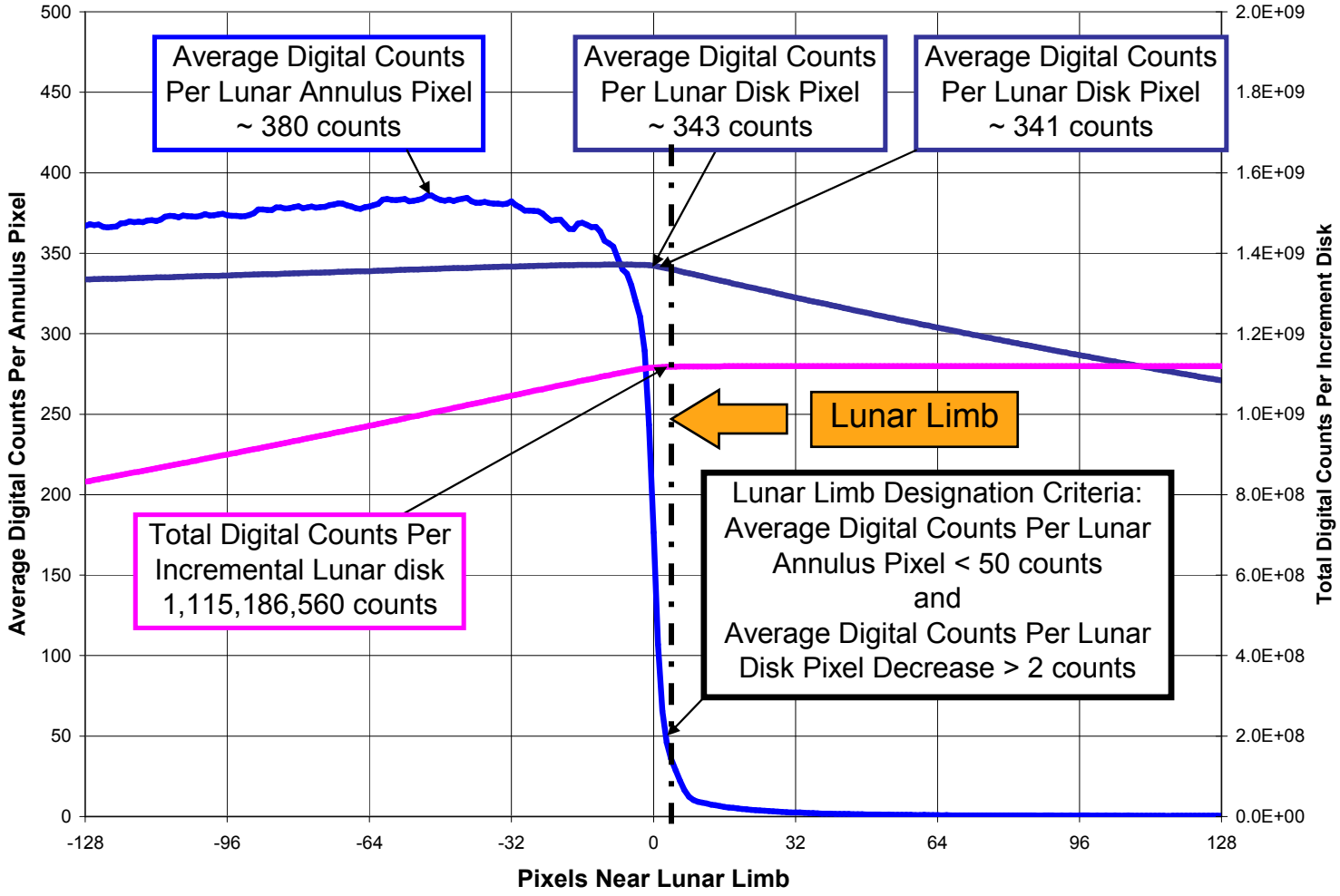
Second step computes the difference between the average digital counts for each ellipse beginning from -128 to +128

Third step computes the increase in signal for each ellipse beginning from -128 to +128 to find lunar limb

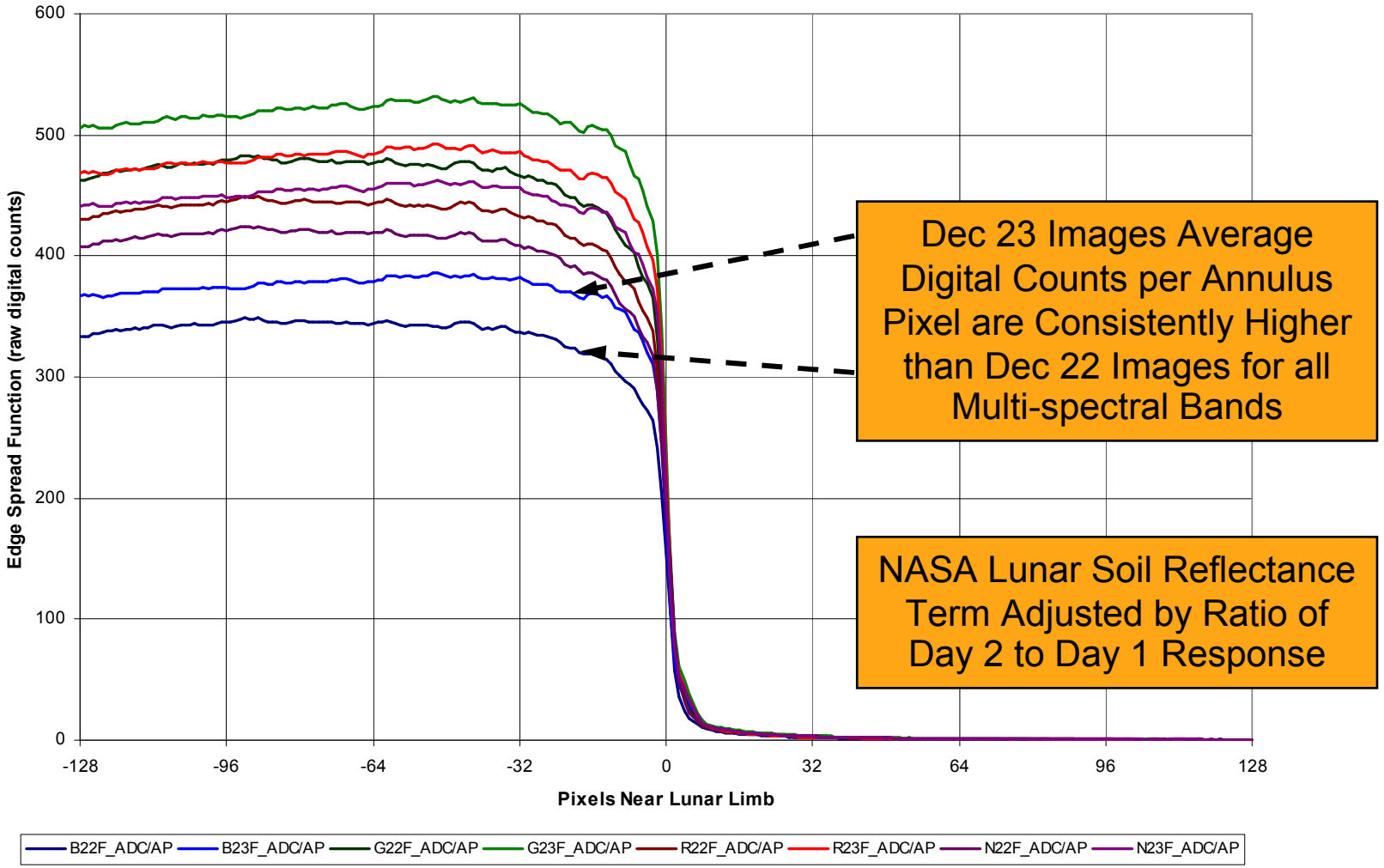
Forth step computes the total digital count contribution to the image within the lunar limb



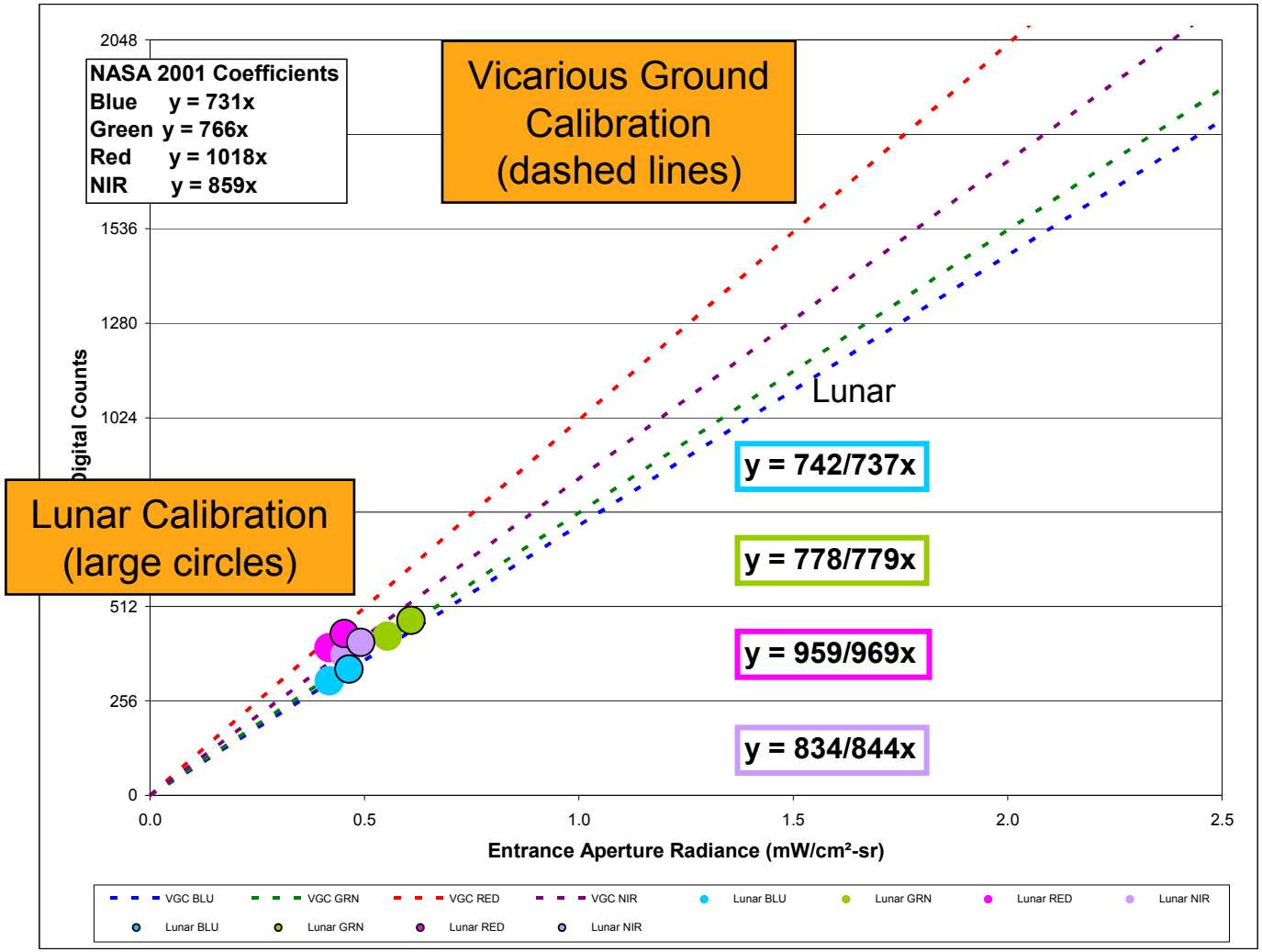
Absolute Radiometric Accuracy – Lunar Disk Average Digital Counts per Pixel Determination Strategy



Absolute Radiometric Accuracy – Average Digital Counts per Annulus Pixel for Multispectral Images Separated by 1 day

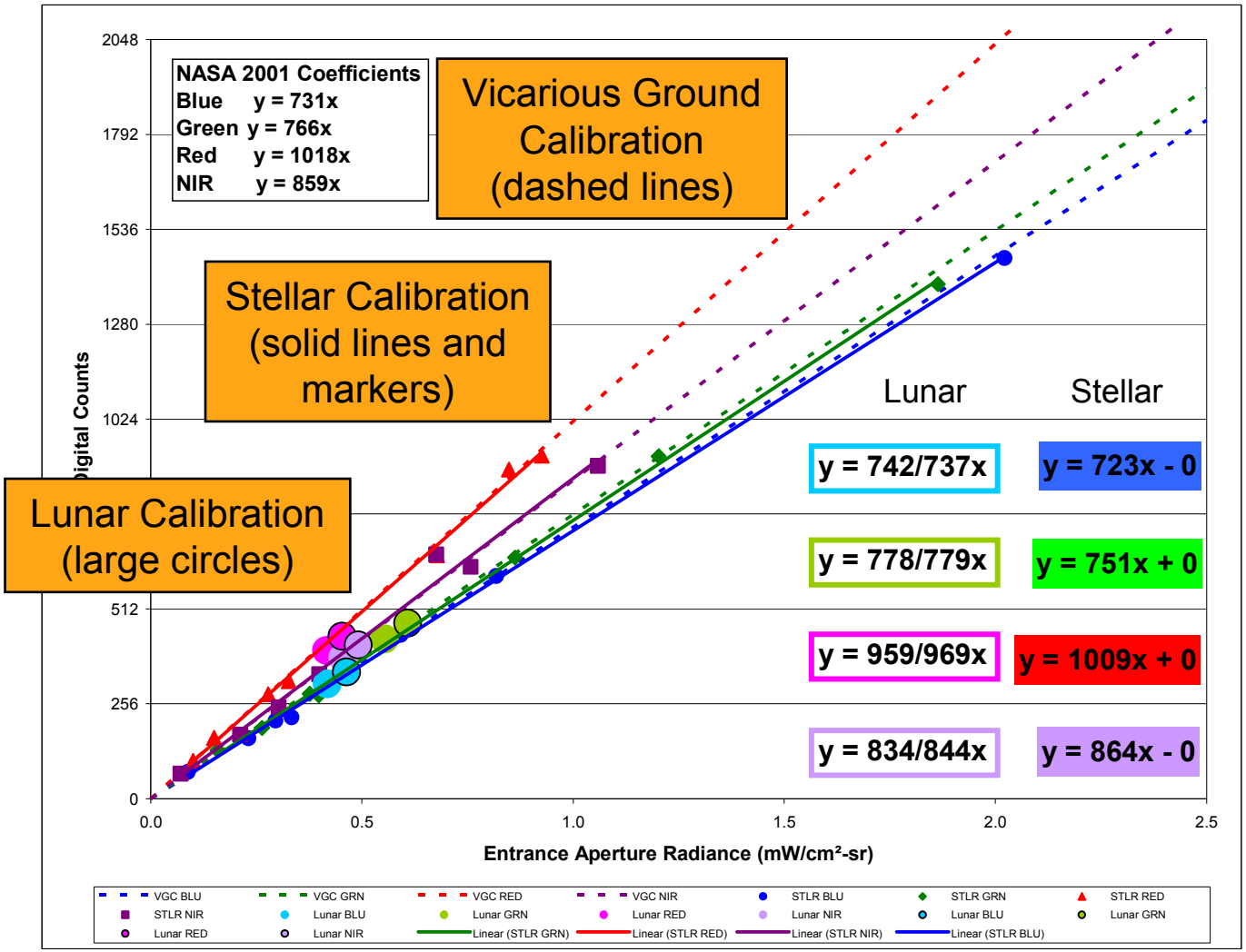


Absolute Radiometric Accuracy – Full Disk Lunar Calibration Coefficients (First Publication CalCon 2008)



Lunar Calibration Results Based Upon Band Average Radiance Multiplied by Computed Bandwidth

Absolute Radiometric Accuracy – Current (2008) Vicarious Ground, Stellar and Lunar Calibration Coefficient Correlation



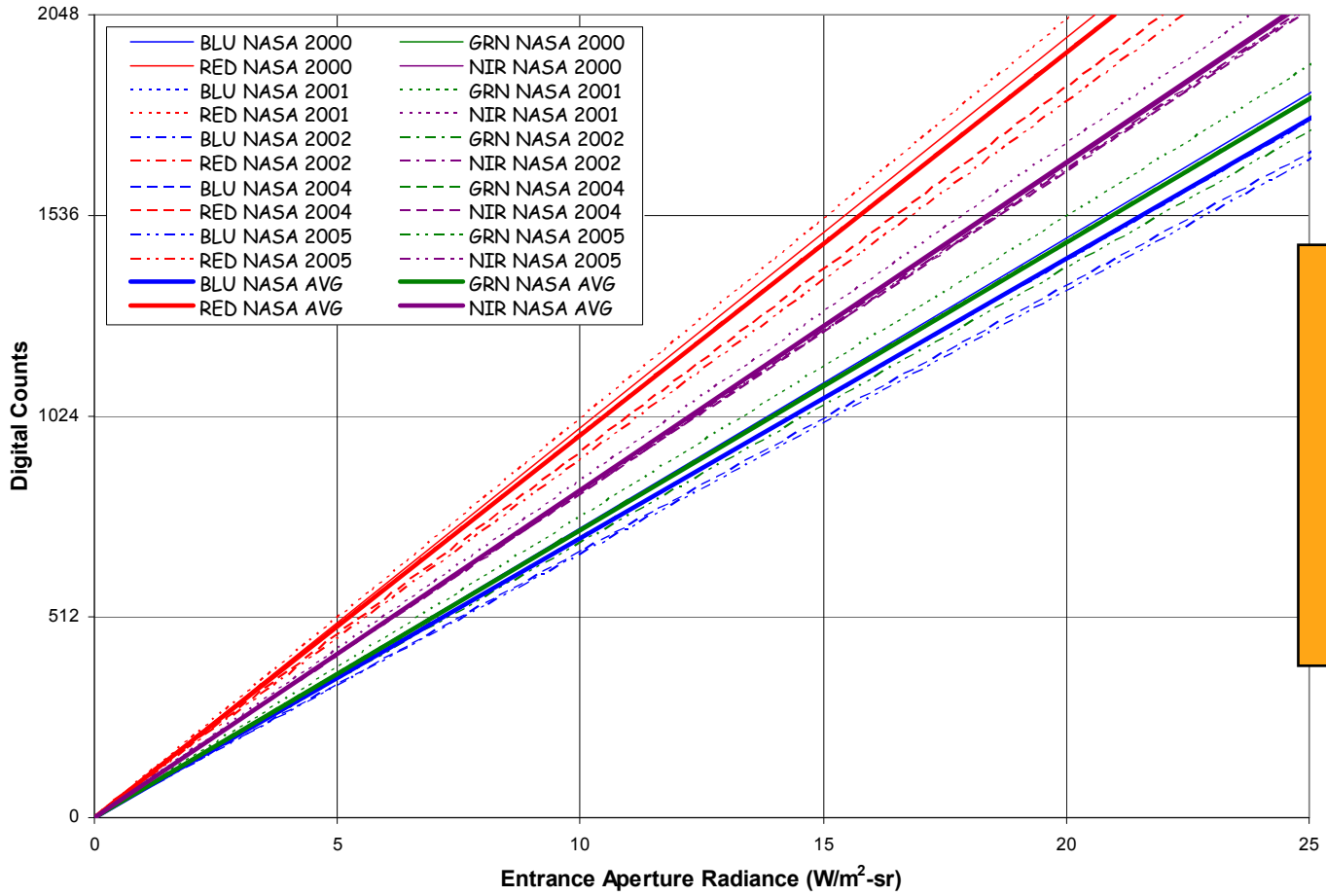
Correlation Between Ground, Stellar and Lunar Methods In Agreement When Similar Terms and Definitions are Applied

Long-term Stability Assessment Targets

Earth-based Uniform Scene Targets (over-filled telescope FOV)

Point Source Stellar Imaging (point source at infinity)

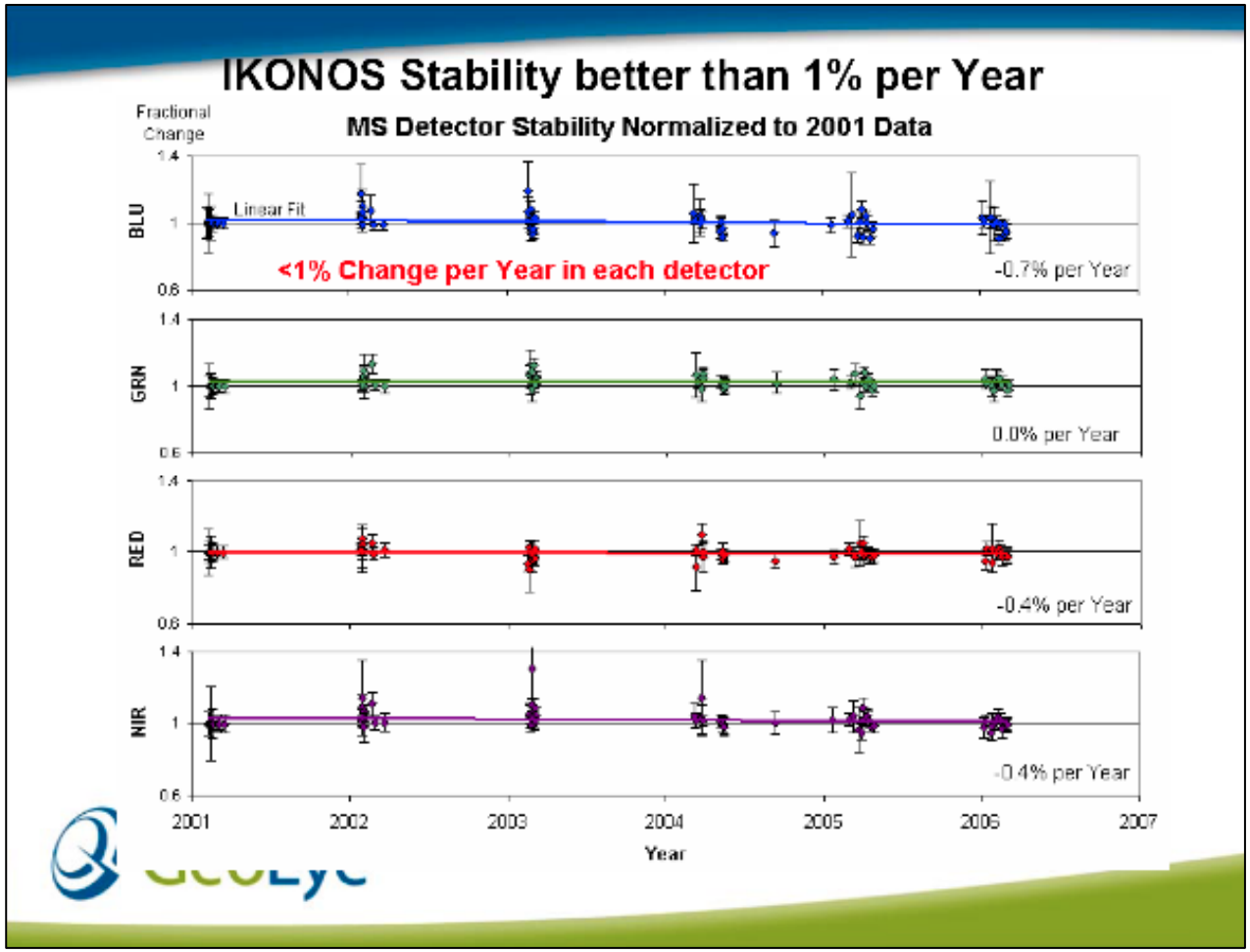
Long-term Stability - Annual Vicarious Ground Calibration Revisits covering 6-year Time Period



Annual Ground Calibration Revisits Show Less Than ±5% Drift of IKONOS MS Response Over 6-year Period

Reference: Several Presentations Given at Civil Commercial Imagery Evaluation Workshop, Joint Agency Commercial Imagery Evaluation (JACIE) Team, 2000 through 2006

Long-term Stability - Annual Stellar Scene Calibration Revisits covering 6-year Time Period



Annual Stellar Calibration Revisits show Less Than 1% Drift of IKONOS MS Response per year Over 6-year Period

Dial, G., Cole, A., Lutes, J., McKune, J., Martinez, M., Rao, R.S., Taylor, M.; The GeoEye Satellite Constellation, Civil Commercial Imagery Evaluation Workshop, Joint Agency Commercial Imagery Evaluation (JACIE) Team, Laurel, Maryland, March 14-16, 2006

Relative Intra-band Radiometric Accuracy Targets

Full Disk Lunar Imaging (under-filled telescope FOV)

Relative Intra-band Radiometric Accuracy – Multiple Lunar Imaging Collection Opportunities for Fwd and Rev Arrays

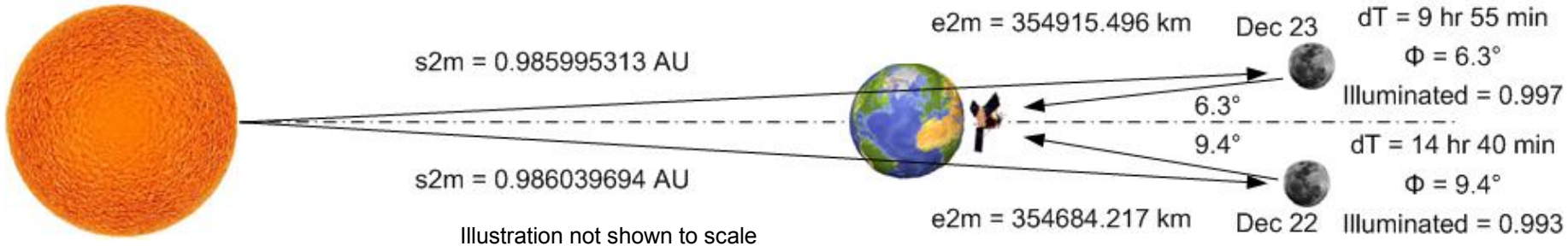
- Waxing Lunar Image Collect #1: Delta from Full Moon = 14h 40m
  - 19991222025054475.pan.fwd.TDI13
    - Delta between fwd and rev images = 17 s
  - 19991222025111475.pan.rev.TDI13

Astronomical Data Obtained from USNO Multiyear Interactive Computer Almanac (MICA), Version 2.1 (2006)

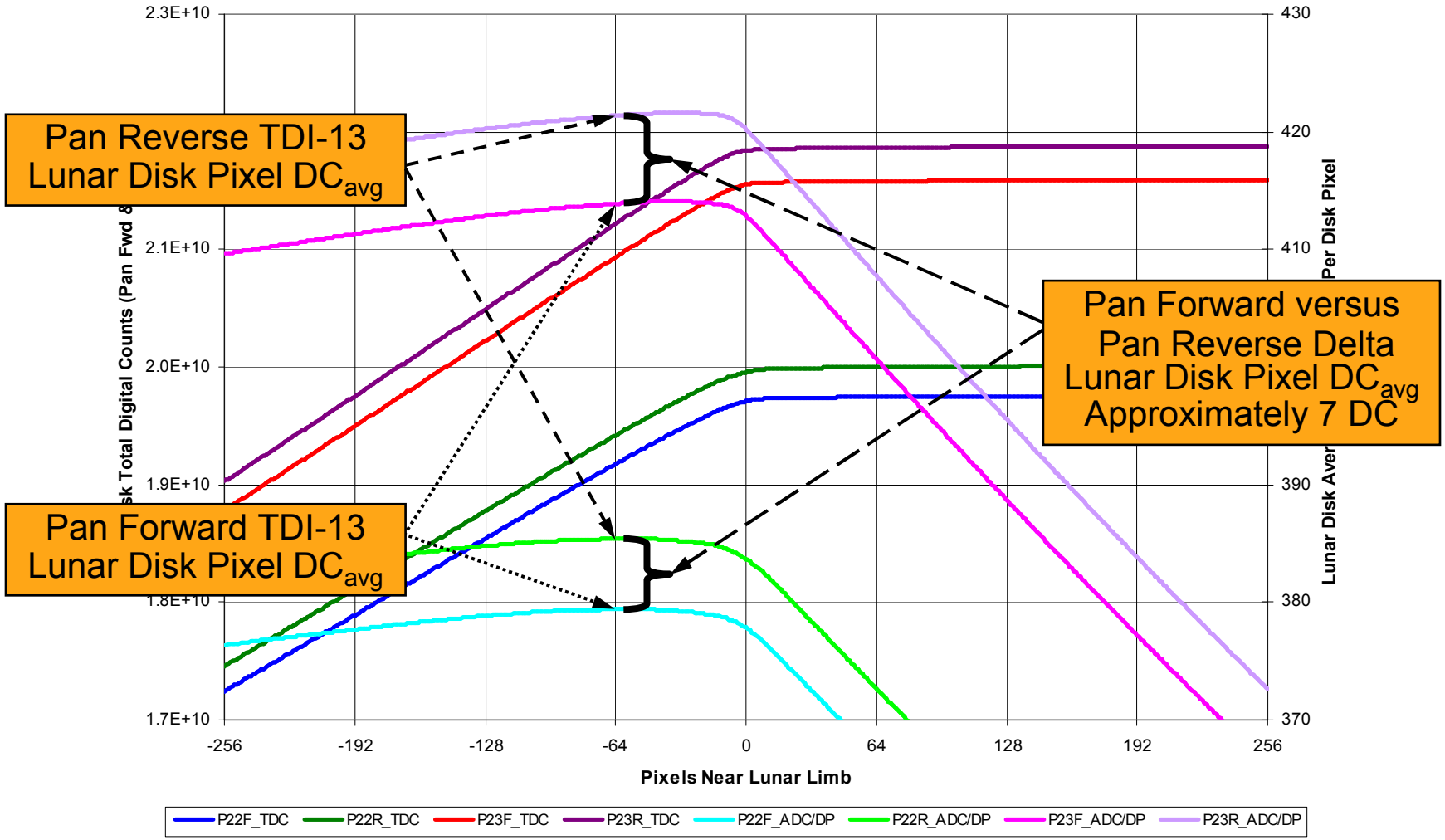
http://www.willbell.com

- Full Moon December 22, 1999, 17:31 (UTC)

- Waning Lunar Image Collect #2: Delta from Full Moon = 09h 55m
  - 19991223032646375.pan.fwd.TDI13
    - Delta between fwd and rev images = 17 s
  - 19991223032703375.pan.rev.TDI13



Relative Intra-band Radiometric Accuracy – Results Show 6-7 Count Difference between Fwd and Rev Arrays at 20% DR



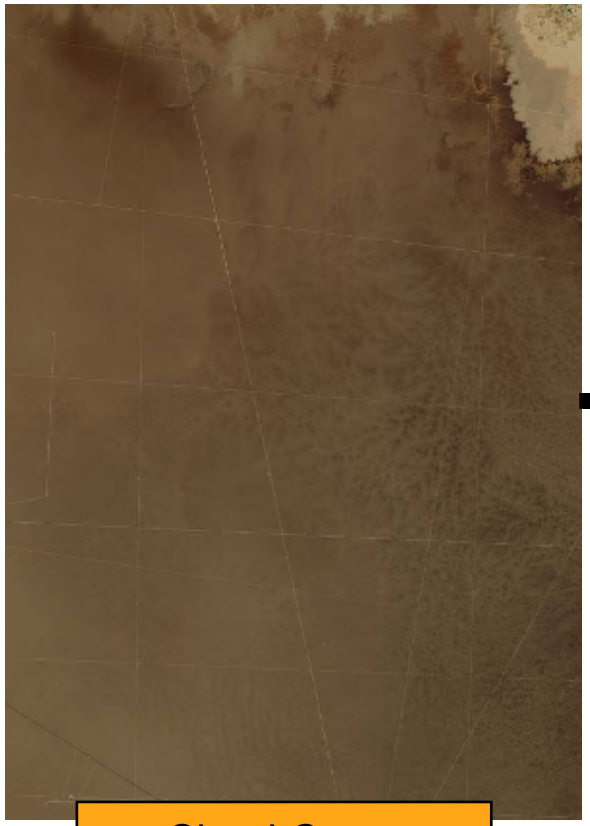
Relative Inter-band Radiometric Accuracy Targets

Earth-based Uniform Targets (spatially uniform scene, side-slither)

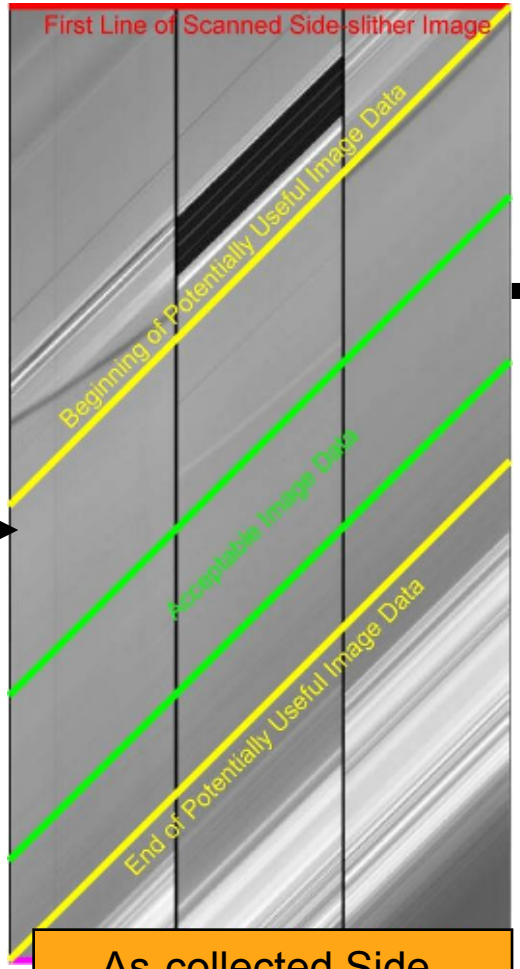
Full Disk Lunar Imaging (uniform lunar mare, side-slither)

Relative Inter-band Radiometric Accuracy - Earth-based Uniform Scene Target, Imaged in Side-slither Mode

Site: Salar de Atacama, Chile

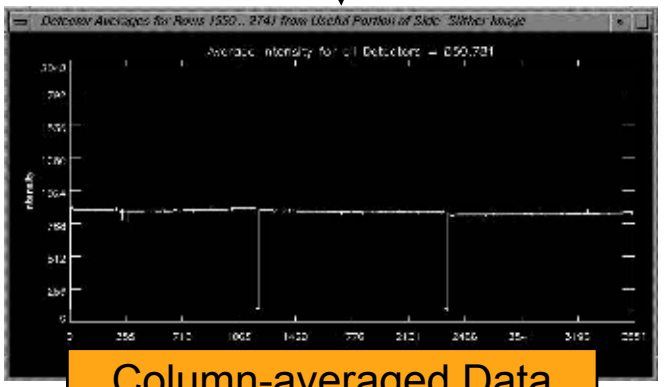


Cloud Cover Assessment Image



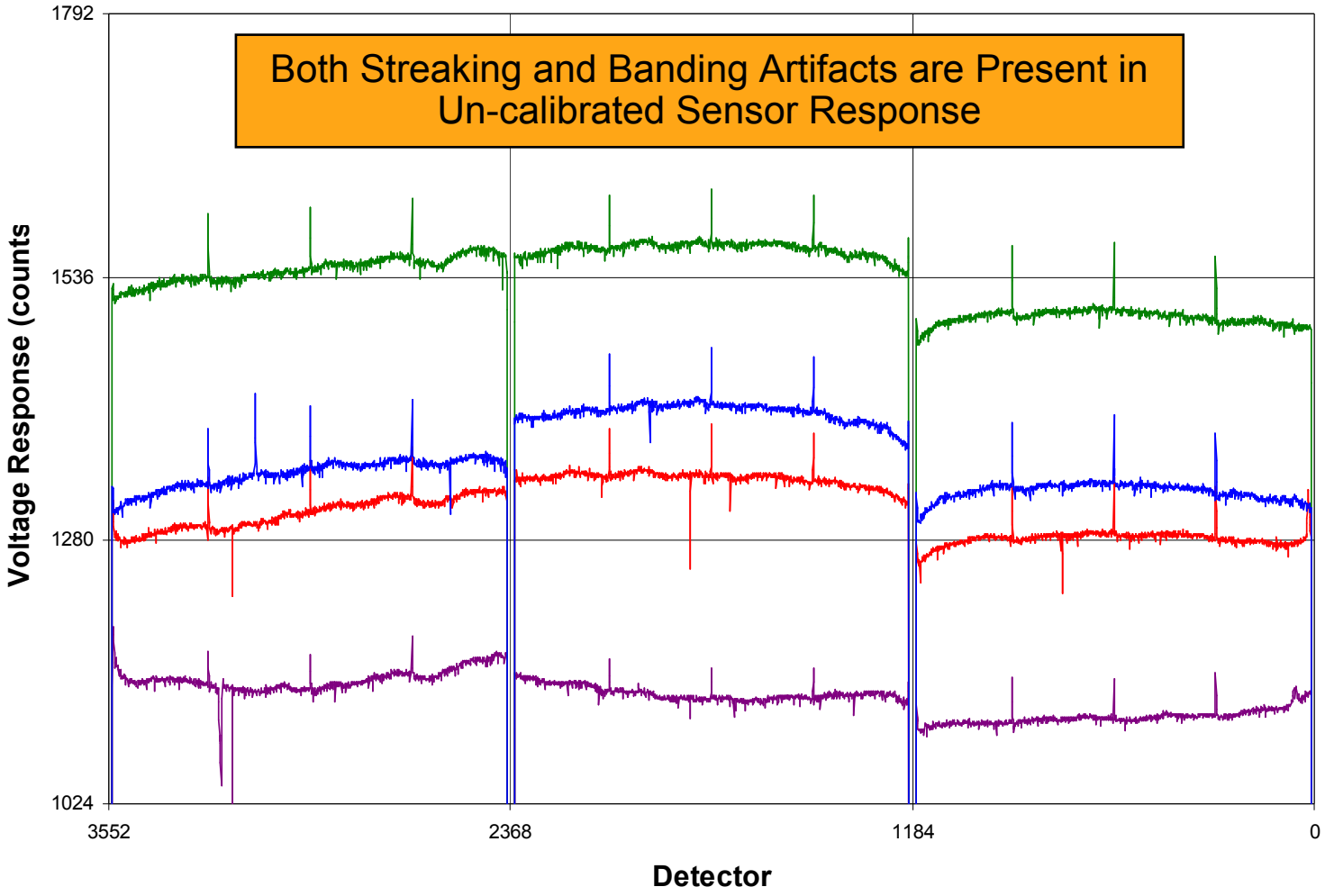
As-collected Side-slither Image Data

Rectangular Presentation of Raw Data

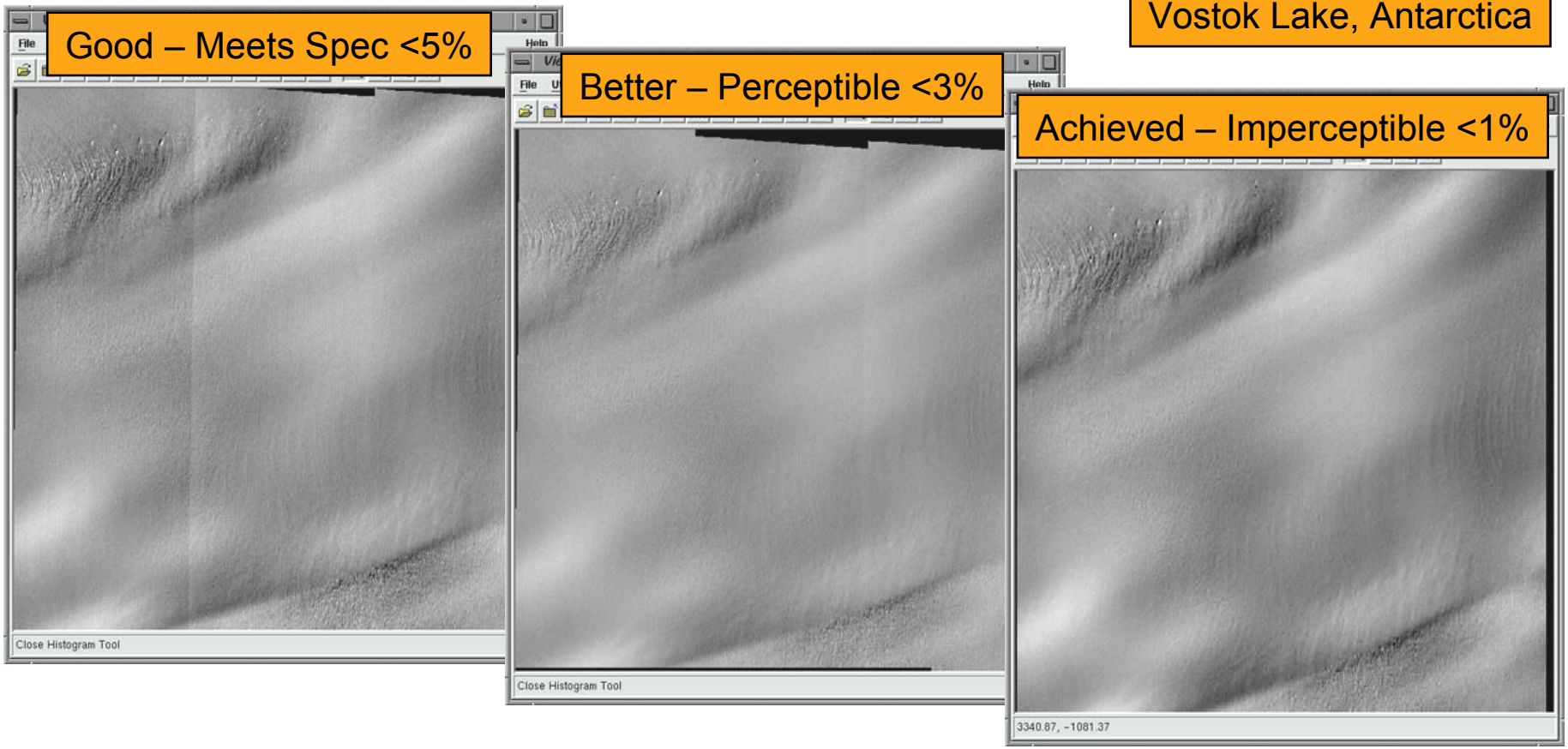


Column-averaged Data

Relative Inter-band Radiometric Accuracy – Non-uniform Response for IKONOS Multispectral Bands

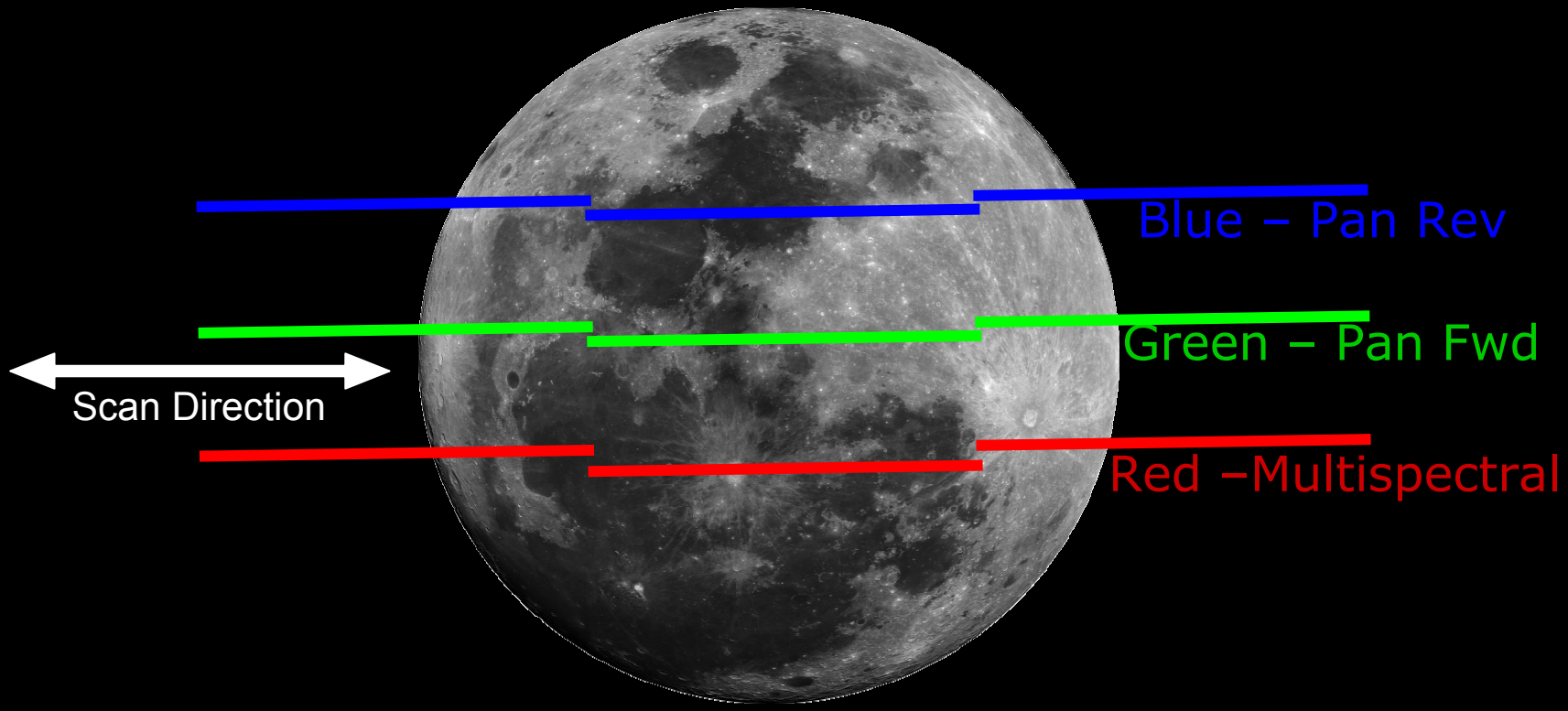


Relative Inter-band Radiometric Accuracy – Equalized Imagery Shows Quality of Calibration Solution



IKONOS sensor response has shown excellent long-term stability such that all imagery is processed using only ONE set of image equalization coefficients.

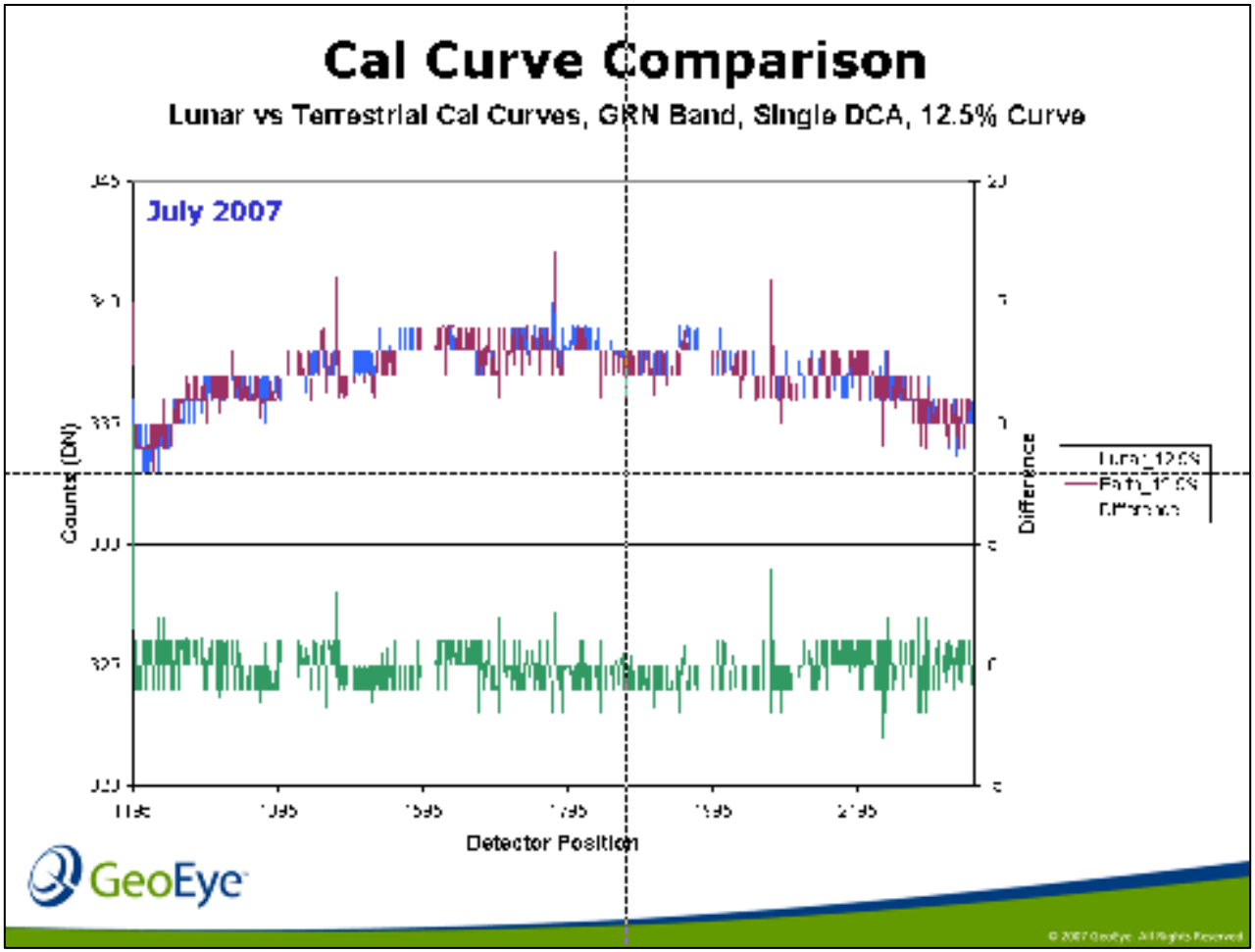
Relative Inter-band Radiometric Accuracy – Side Slither Lunar Imaging Equalization Solution



Lunar Side Slither Image Collected: 7 Sep 2006

IKONOS Focal Plane Arrays shown at midpoint of Side Slither Maneuver

Relative Inter-band Radiometric Accuracy – Equivalent Results Using Side-slithered Lunar and Earth Scenes

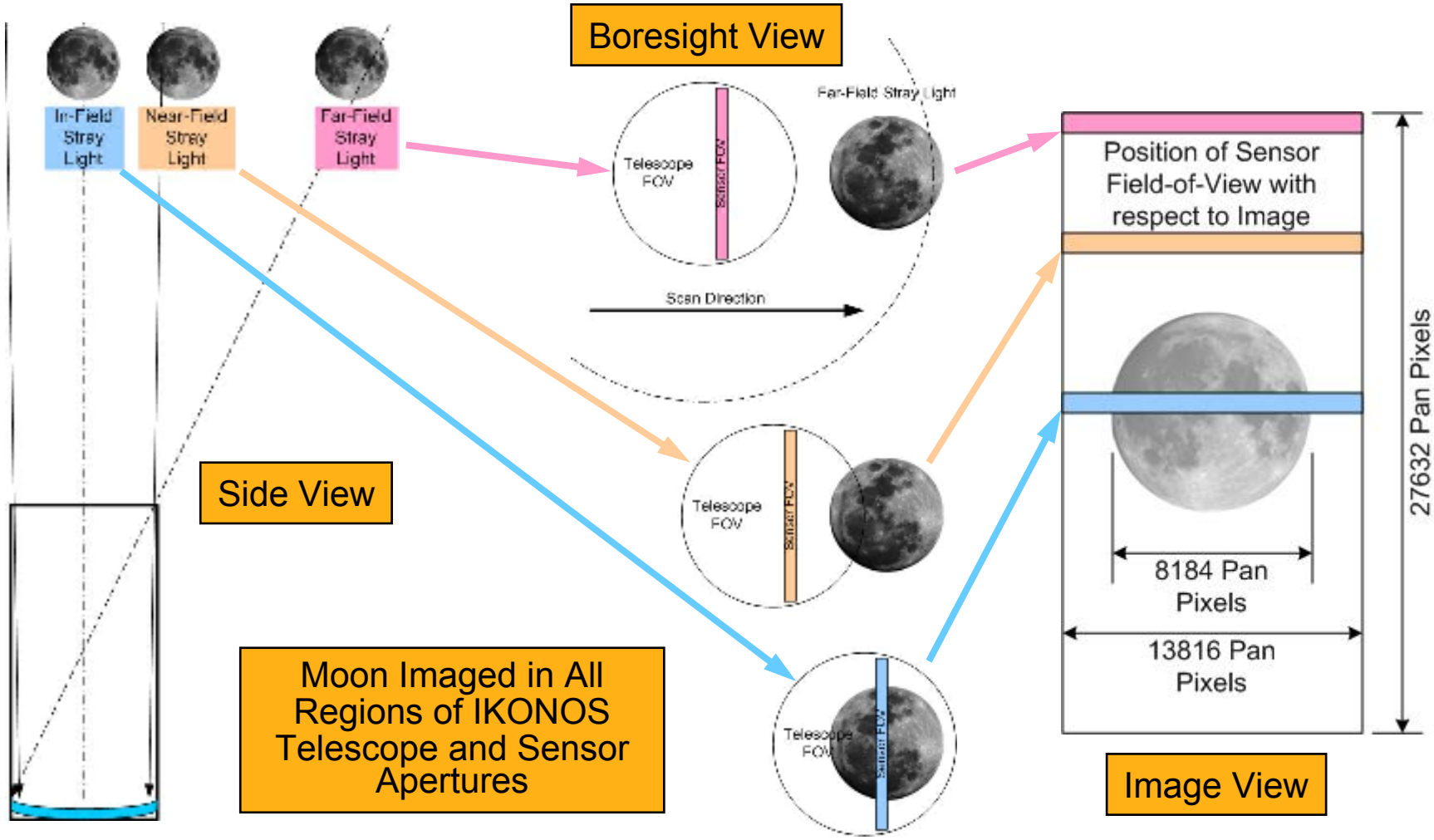


Taylor, Martin, Bowen, Howard; Lunar Side Slither: A Novel Approach for IKONOS Relative Calibration, 2007 CALCON Technical Conference, Space Dynamics Laboratory & University of Utah, Logan, Utah, September 10-14, 2007.

Stray Light Assessment Targets

Full Disk Lunar Imaging (lunar limb edge detail)

Stray Light Assessment – Strategy Maps Photons Arriving at Sensor Image Plane via Secondary and Tertiary Light Paths



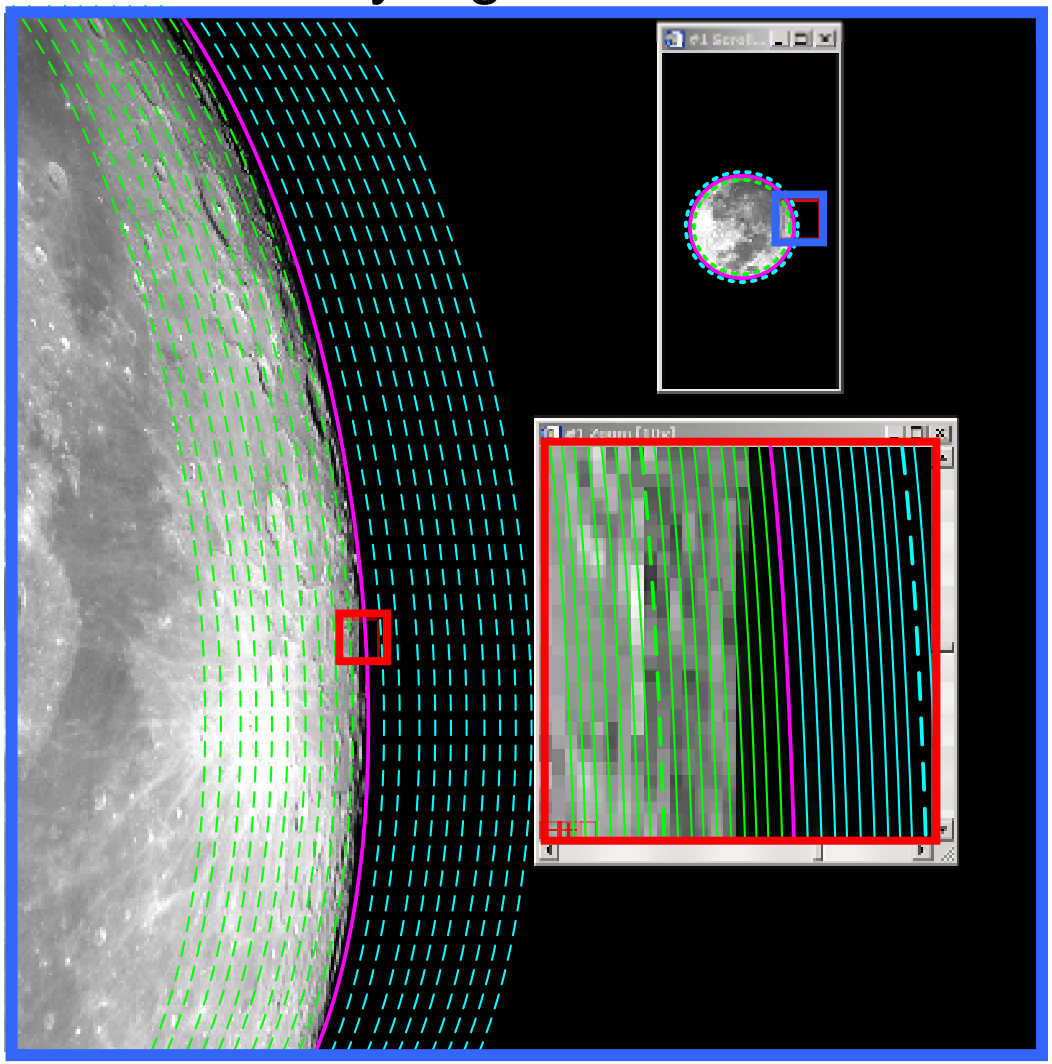
Stray Light Assessment – Counts Beyond the Limb in Full Disk Lunar Imagery Represents Stray Light Contribution

First step computes the average digital counts per pixel in each annulus beginning at -128 pixels inside the Lunar Limb to +128 pixels beyond the Lunar Limb

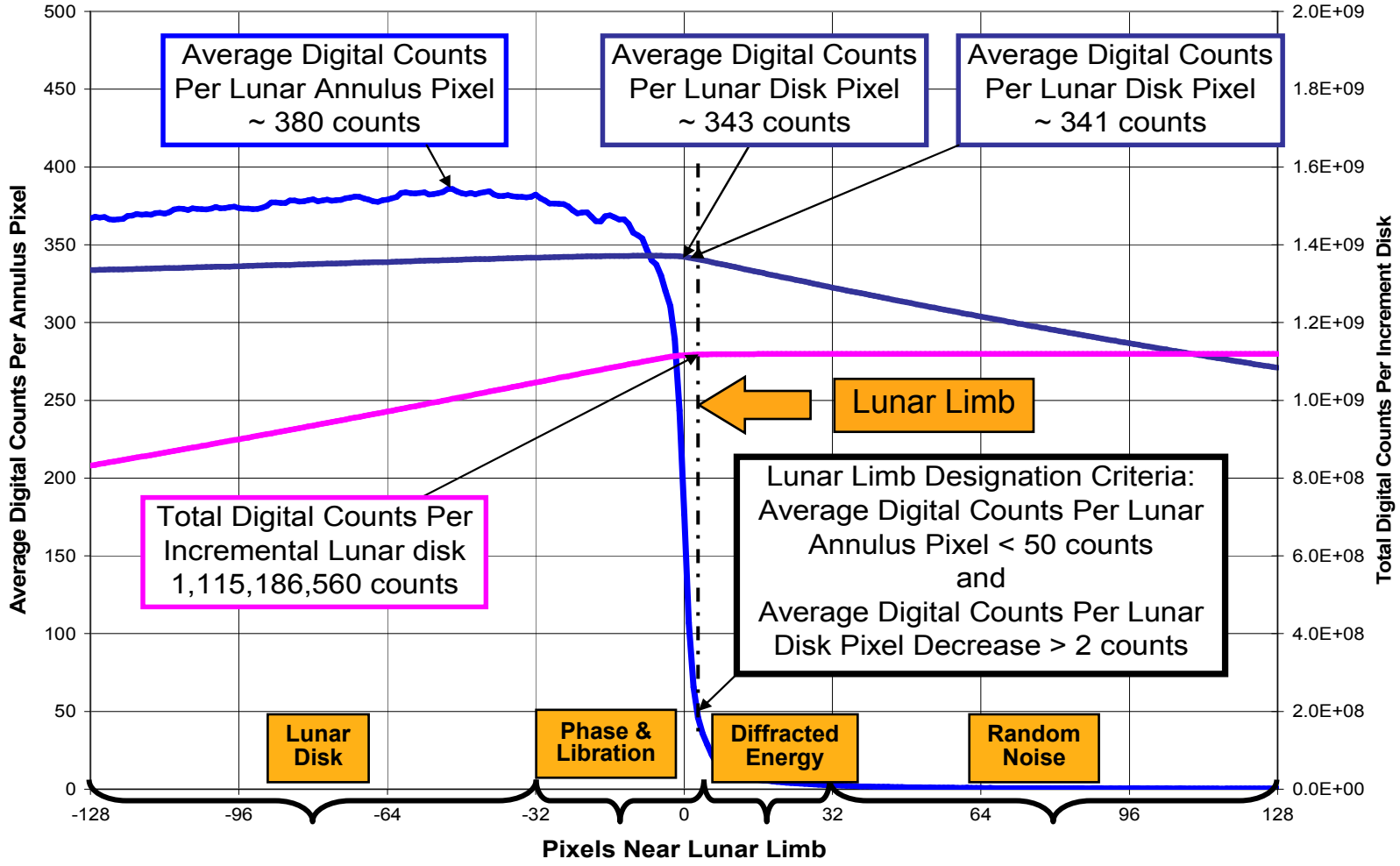
Second step computes the difference between the average digital counts for each annulus beginning from -128 to +128

Third step computes the increase in signal for each annulus beginning from -128 to +128 to find lunar limb

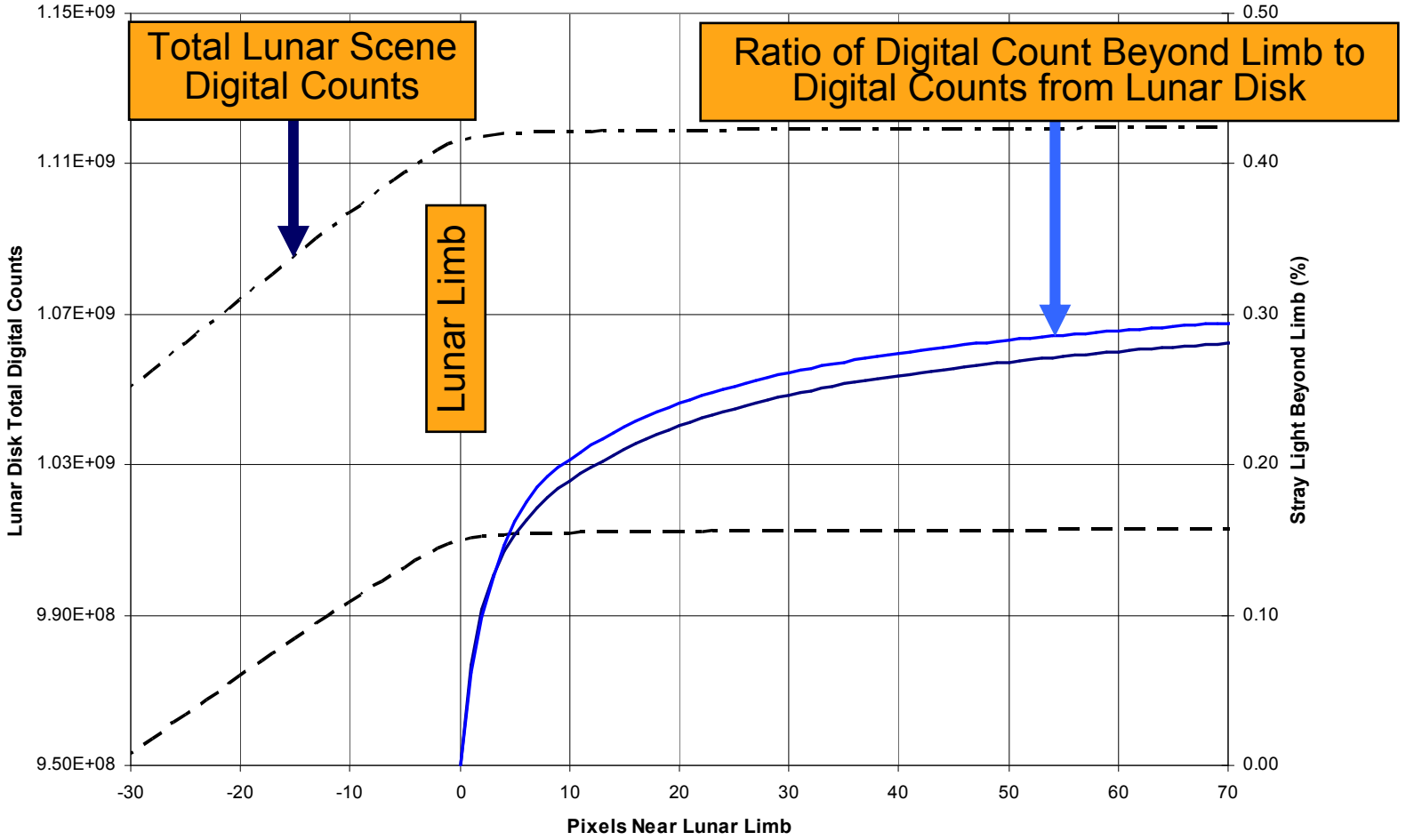
Forth step computes the total stray light contribution to the image beyond the lunar limb



Stray Light Assessment – Determining Lunar Limb versus Scene Background

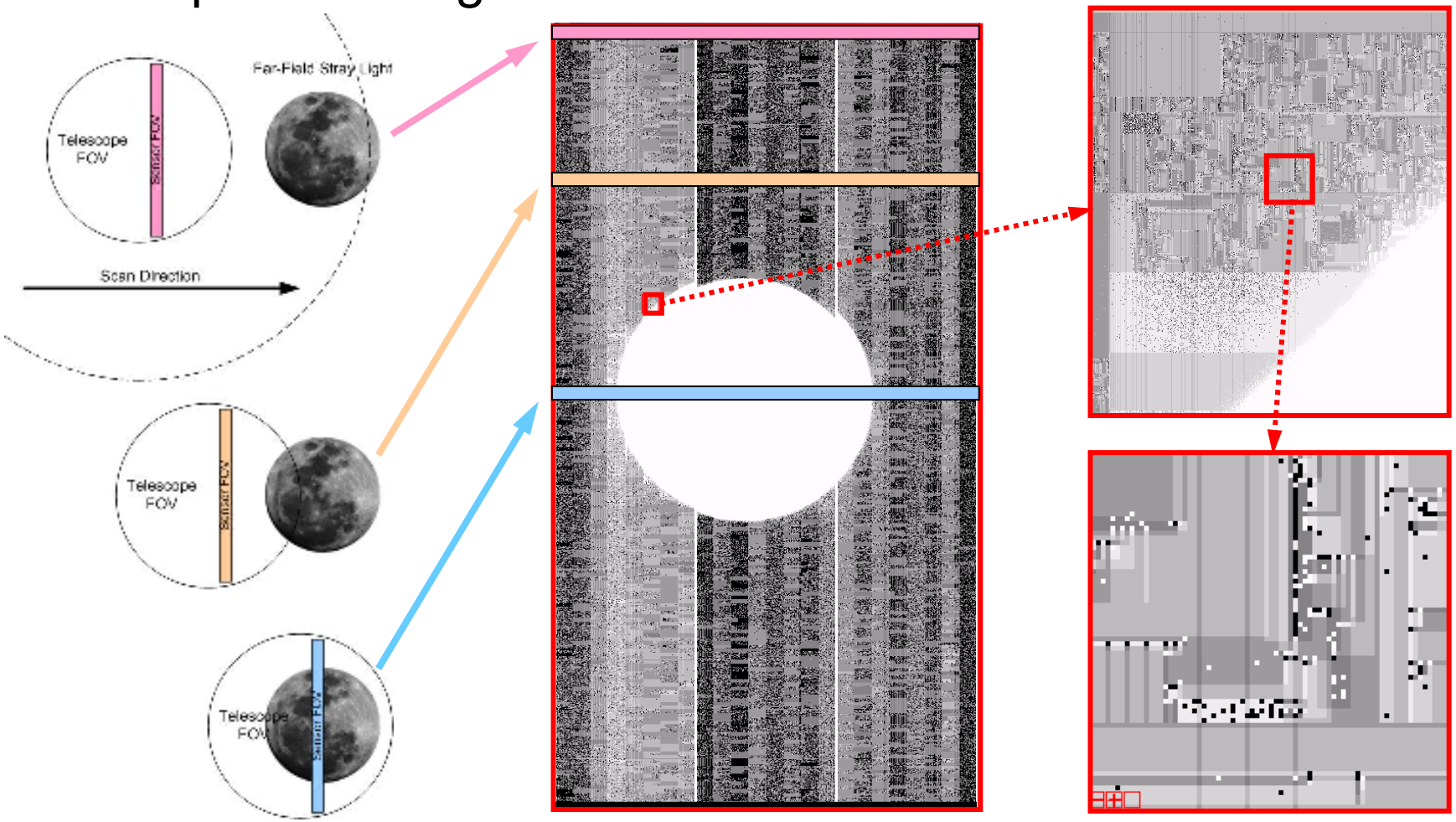


Stray Light Assessment –Stray Light Accumulates in Scene Background of Lunar Images



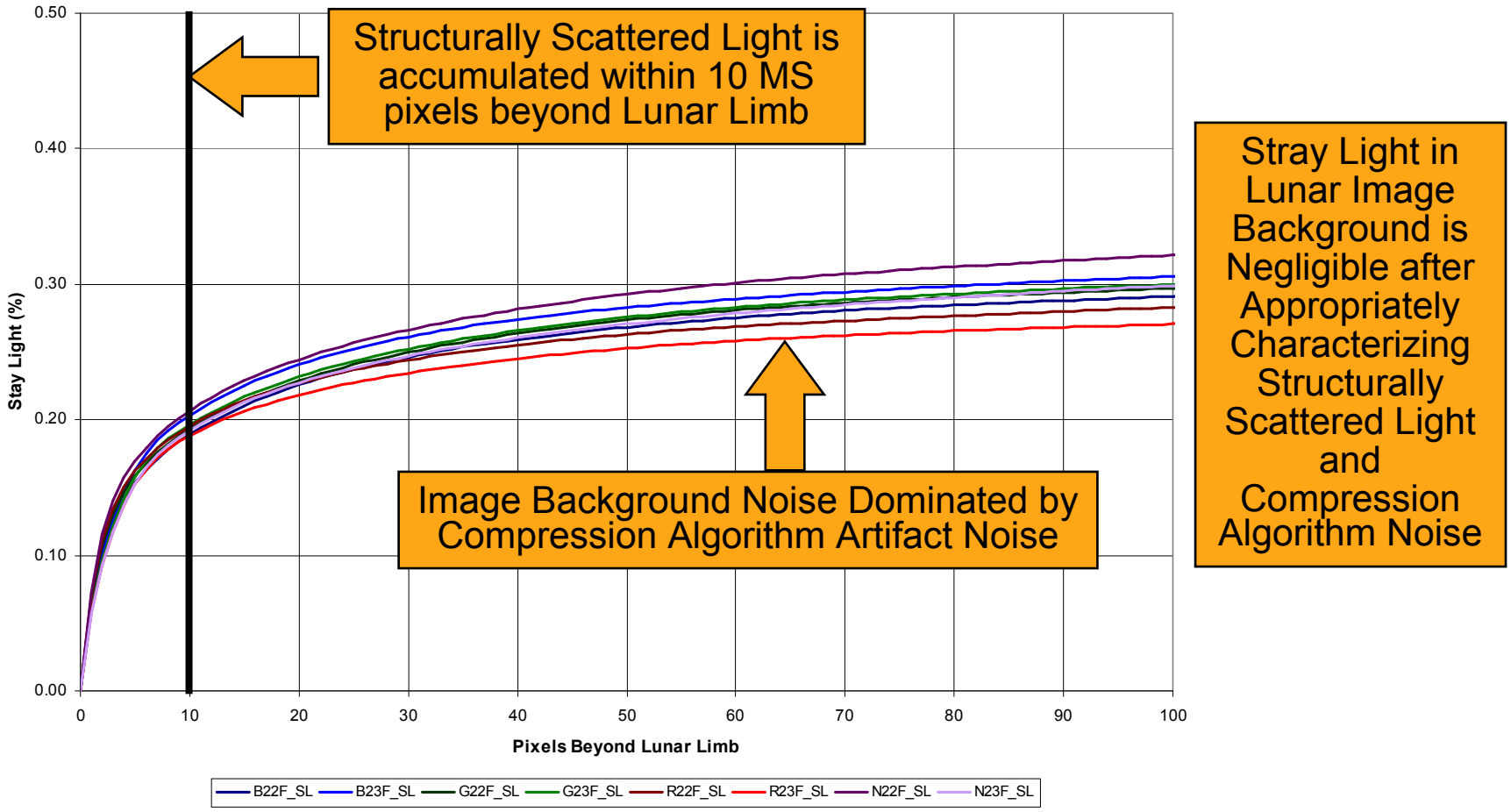
IKONOS (BLU) Stray Light <0.3% is Sum of Response 50-pixels Beyond Lunar Limb

Stray Light Assessment – Investigation Revealed Presence of Compression Algorithm Artifact in Low-contrast Areas



Noise in IKONOS lunar image background is a result of on-board compression algorithm

Stray Light Assessment – Results Show Negligible Stray Light Present in IKONOS MS Band Lunar Images



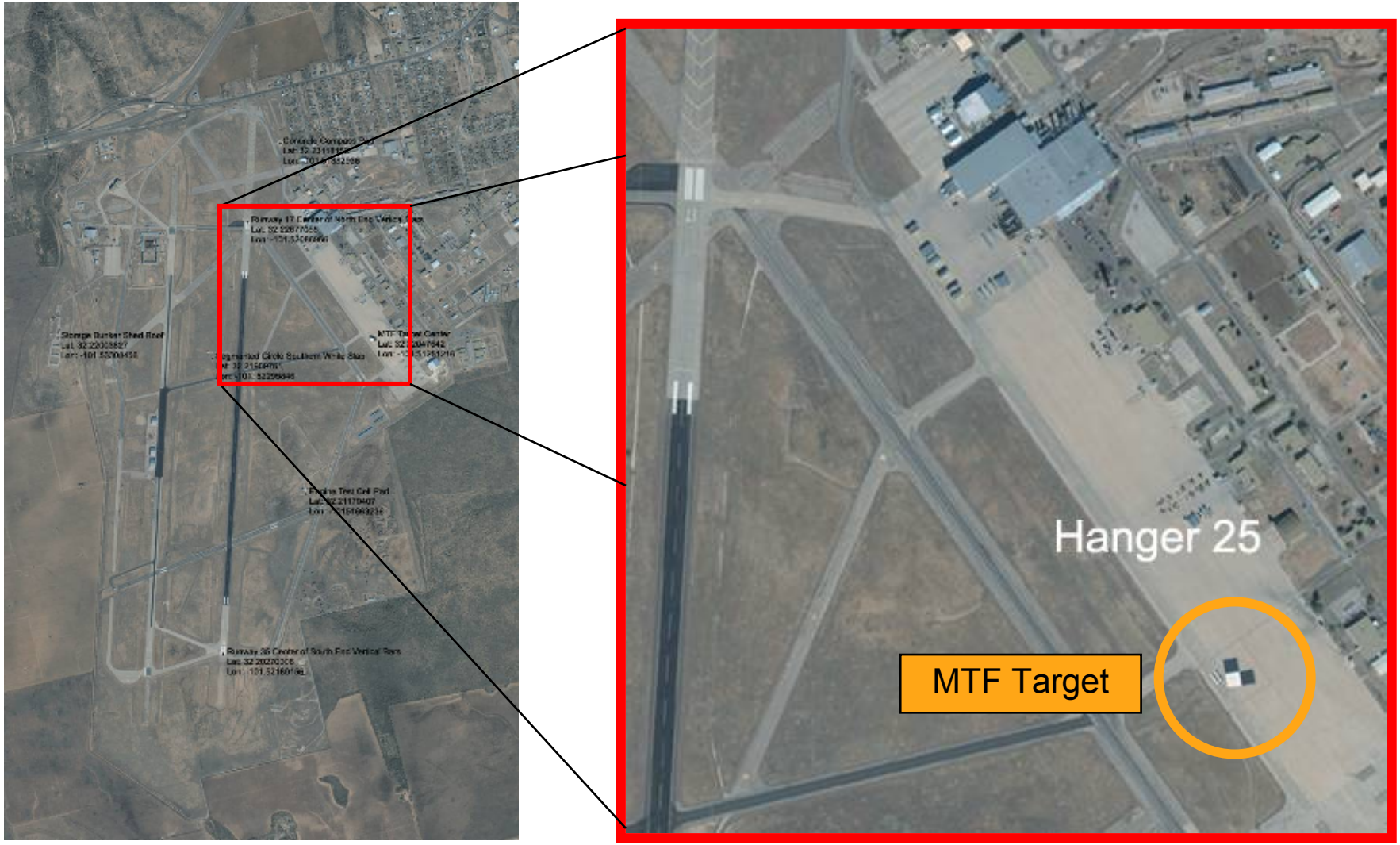
MTF Assessment Targets

Earth-based Uniform Targets (knife-edge detail)

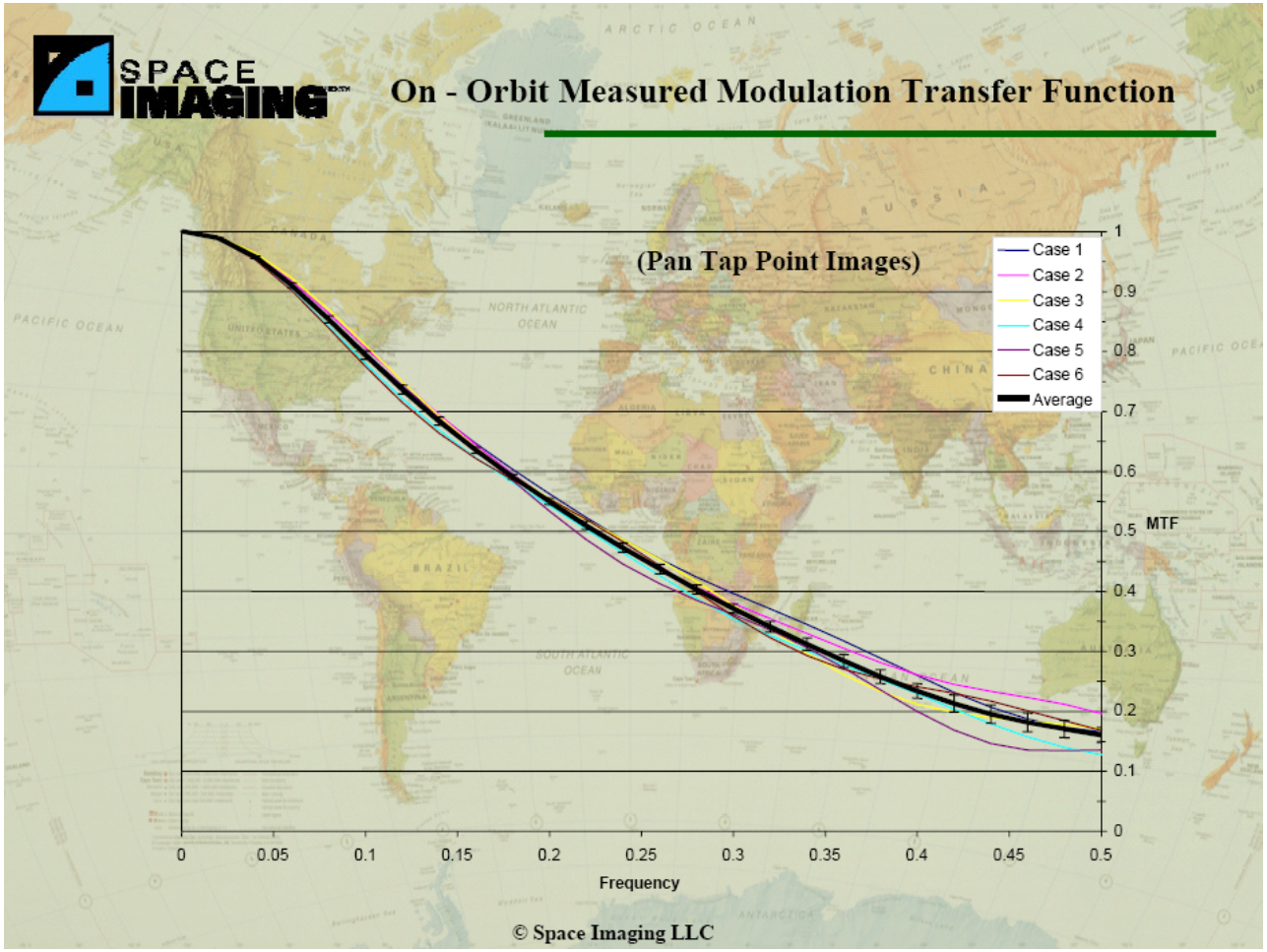
Point Source Stellar Imaging (point source at infinity)

Full Disk Lunar Imaging (lunar limb edge detail)

MTF Assessment – High Contrast Knife-edge Target Painted at Big Spring, Texas, Municipal Airport



MTF Assessment – Earth-based Cultural Detail Edge Target Results Obtained During IKONOS Initialization

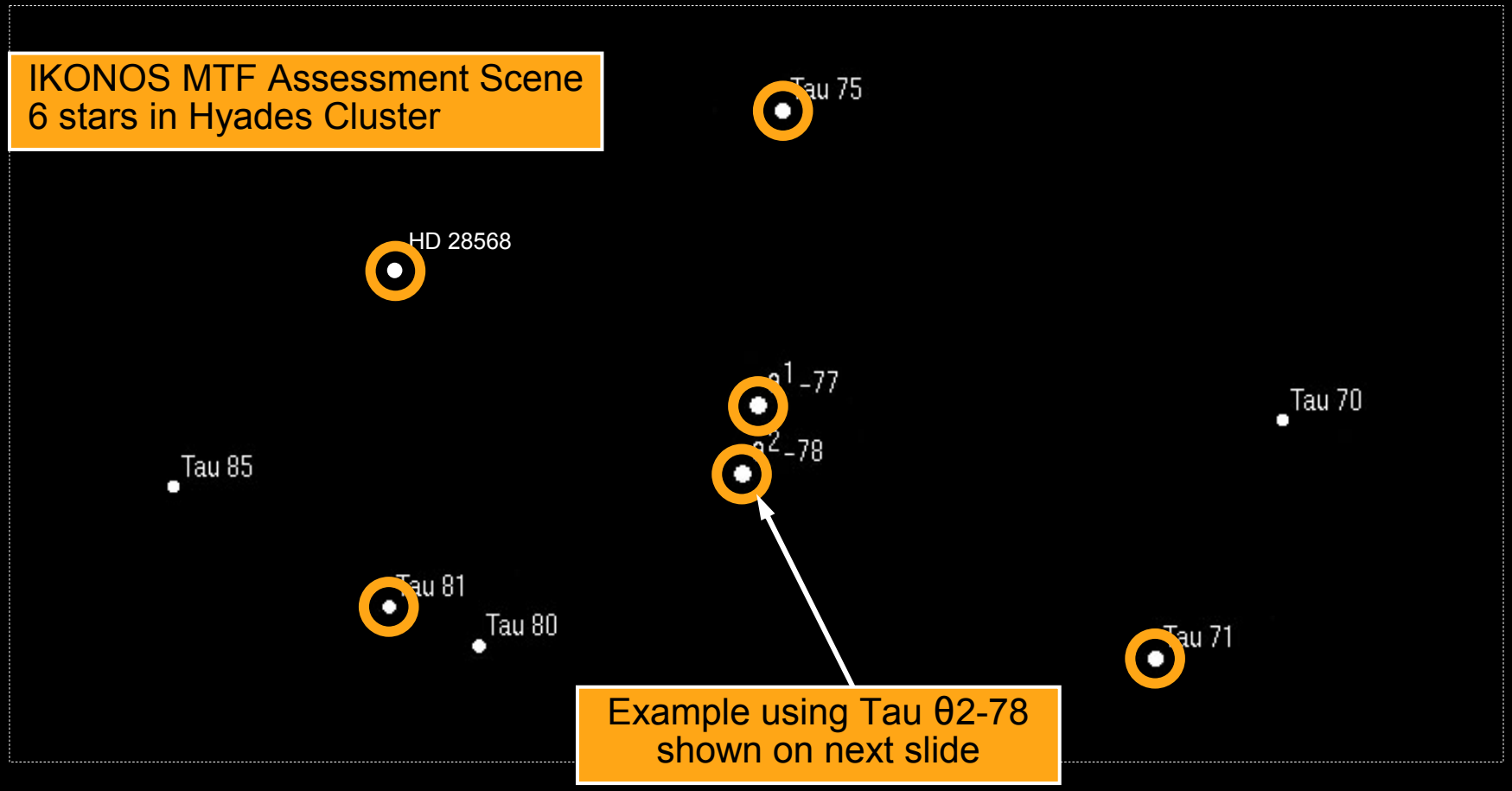


Initial Ground MTF Assessment Performed Using High-contrast Edge Targets

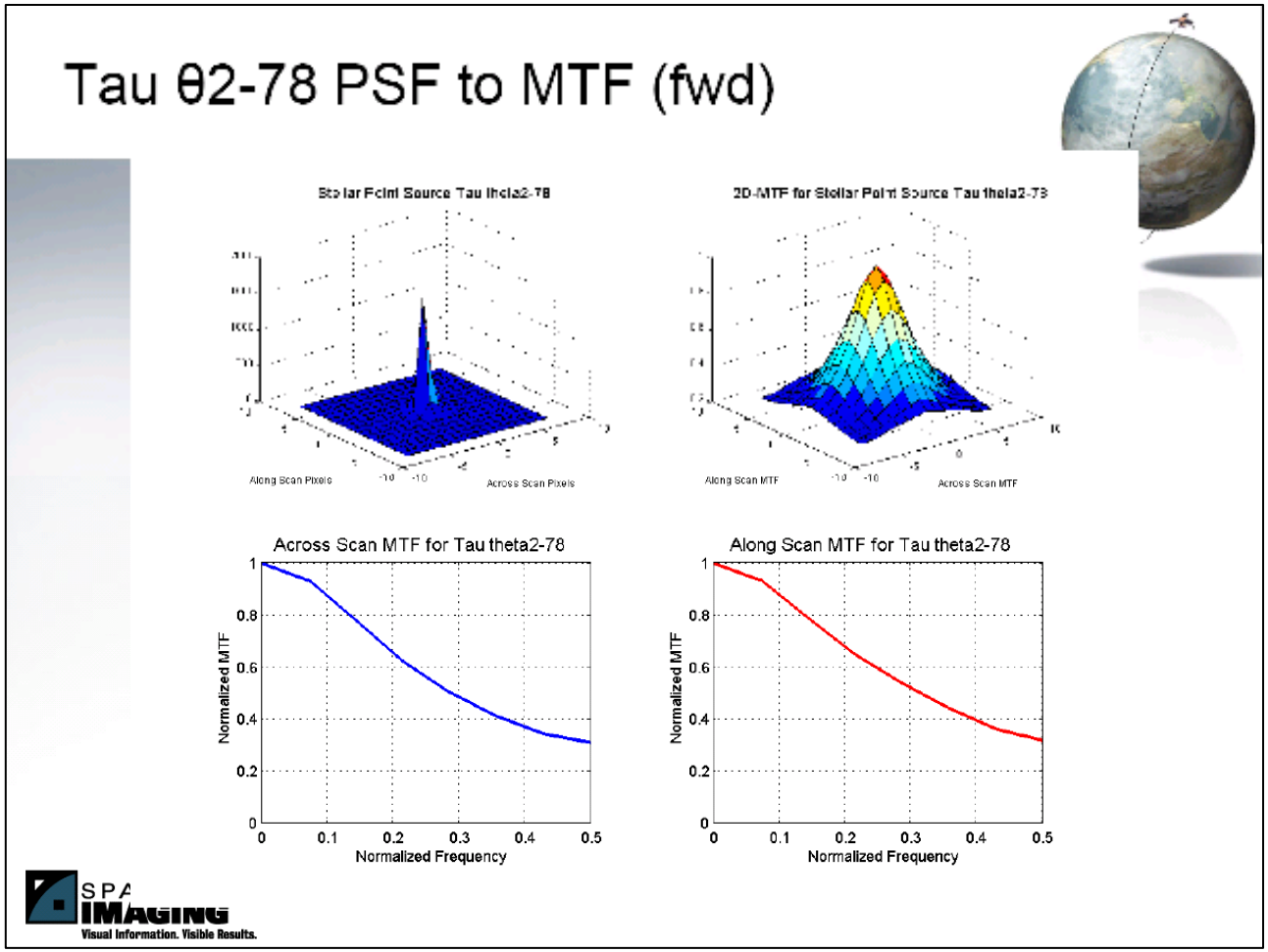
(atmospheric impact was not backed out)

Gerlach, Frank; Space Imaging IKONOS Spatial Characterization, High Spatial Resolution Commercial Imagery Workshop 2001, Joint Agency Commercial Imagery Evaluation (JACIE) Team, Greenbelt, Maryland, March 19-21, 2001.

MTF Assessment – Visible Stars in Hyades Cluster Used in Method Developed to Analyze 2D MTF Performance



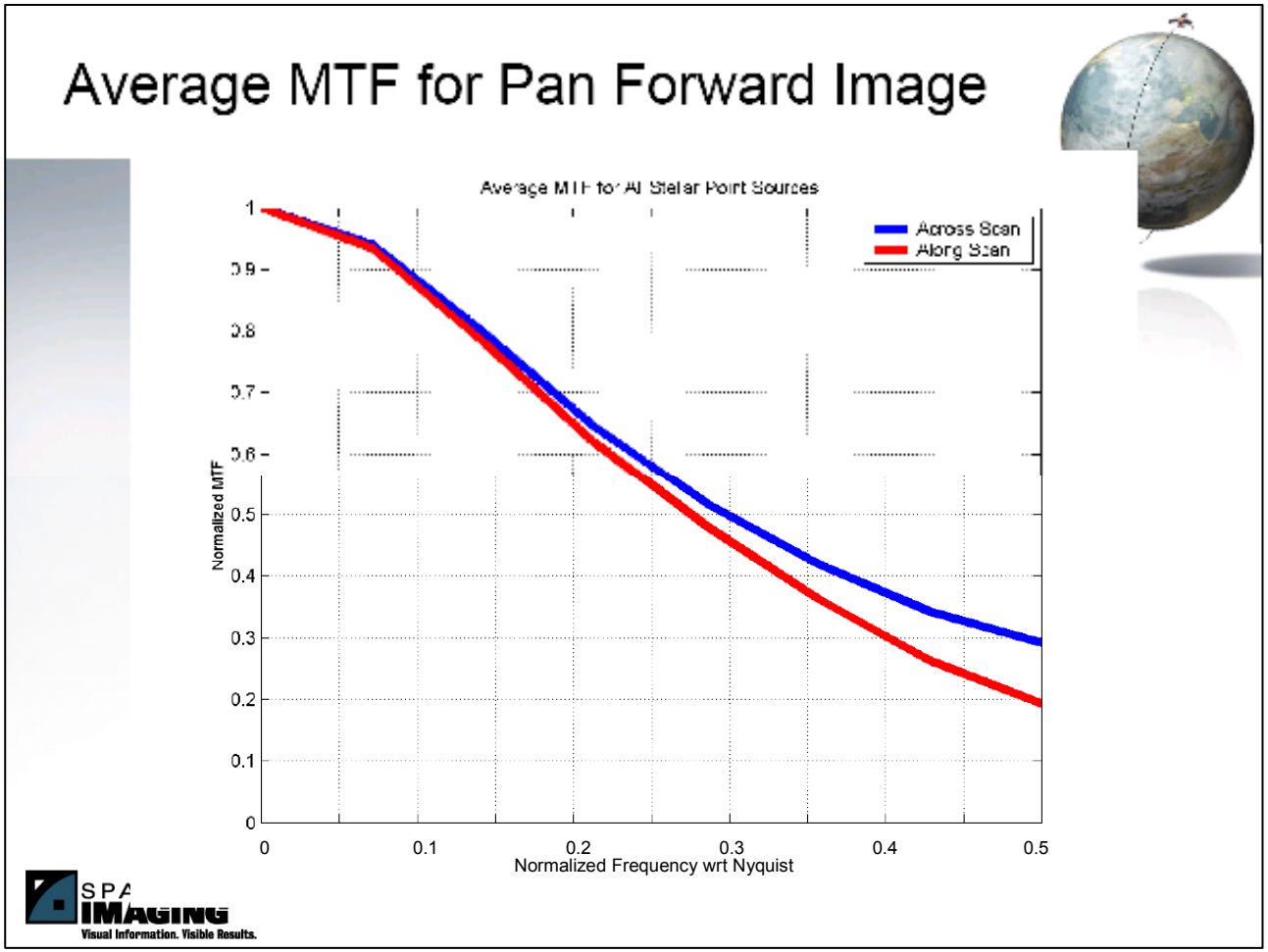
MTF Assessment - IKONOS Hyades Cluster Stellar Image, Brightest Star Tau θ2-78



Stellar MTF Assessment Provides Simultaneous 2-dimensional Analysis

Bowen, H.S, Dial, G.; IKONOS Calculation of MTF using Stellar Sources, Civil Commercial Imagery Evaluation Workshop 2002, Joint Agency Commercial Imagery Evaluation (JACIE) Team, Reston, Virginia, March 25-27, 6

MTF Assessment – Results for IKONOS Panchromatic Arrays (Fwd and Rev) using Stellar Targets (2002)

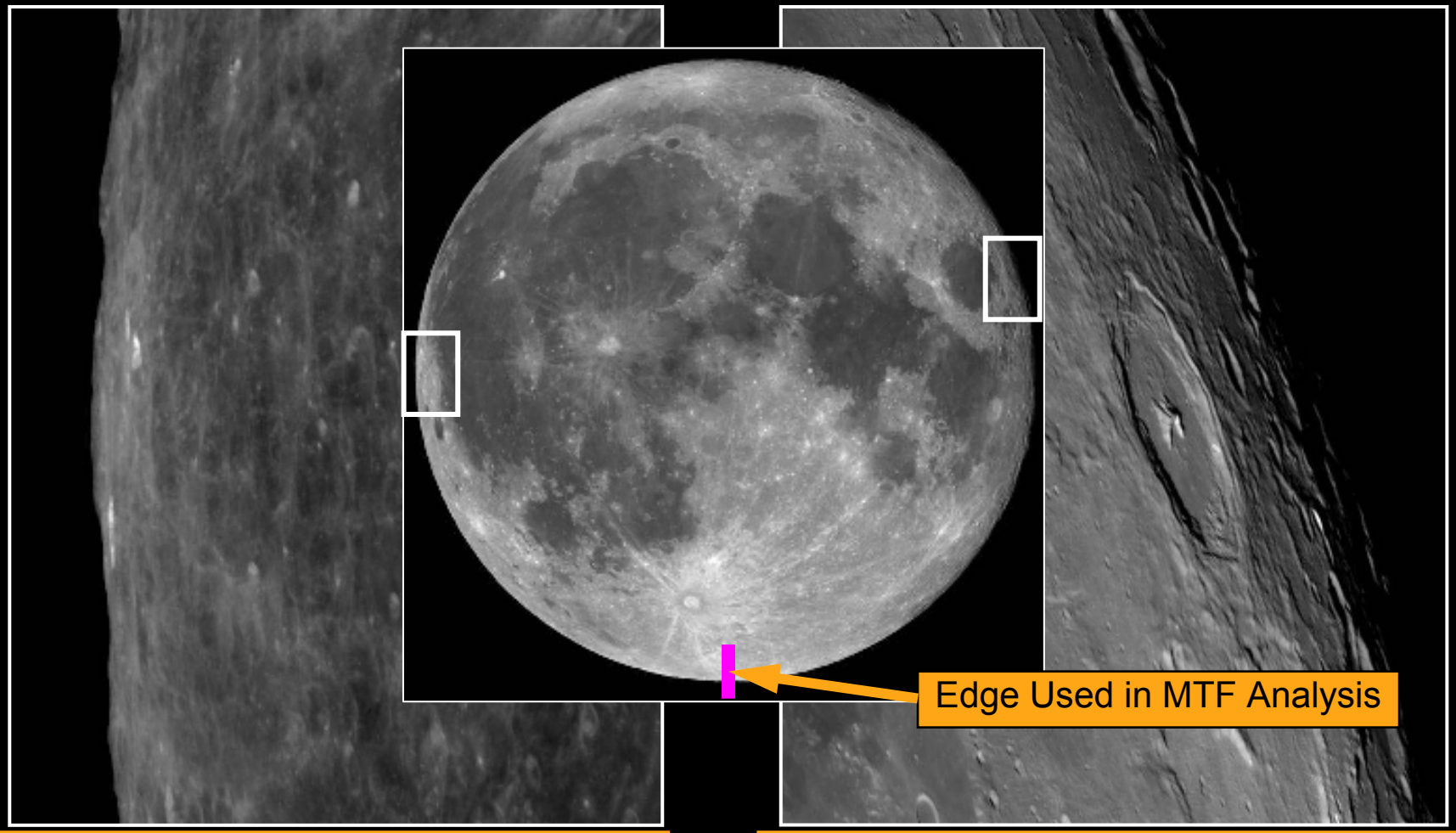


Initial Stellar MTF Assessment Performed Using High-contrast Hyades Point Source Targets

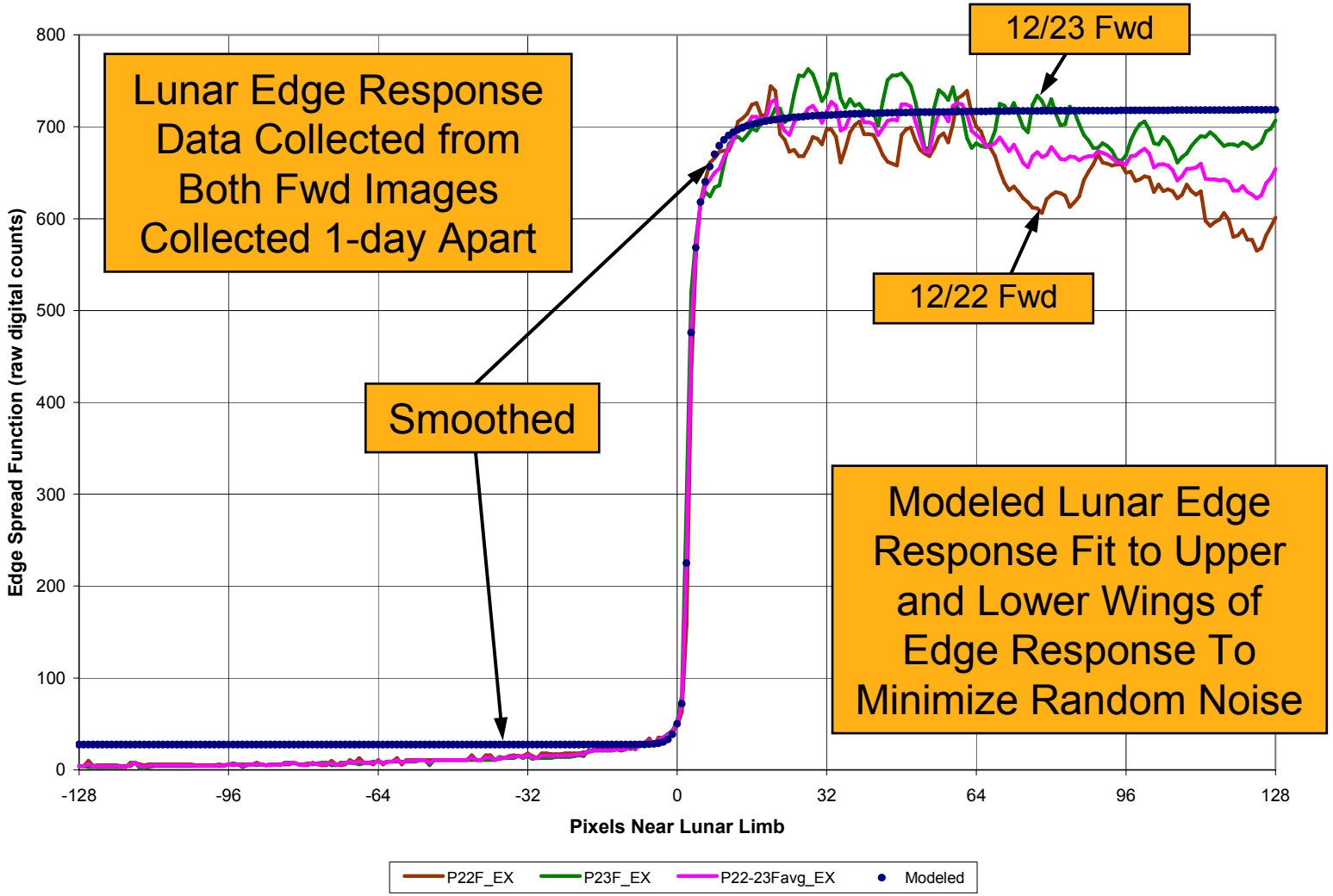
(no atmosphere)

Bowen, H.S, Dial, G.; IKONOS Calculation of MTF using Stellar Sources, Civil Commercial Imagery Evaluation Workshop 2002, Joint Agency Commercial Imagery Evaluation (JACIE) Team, Reston, Virginia, March 25-27, 15

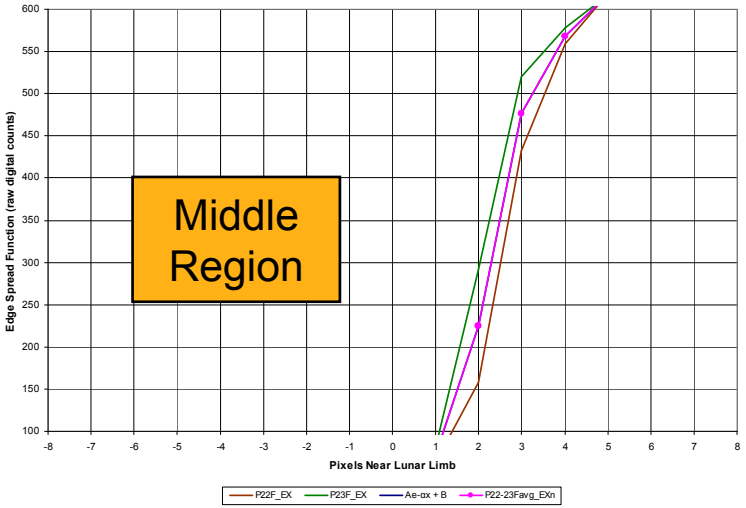
MTF Assessment – Examination of Lunar Limb Edge Details Leads to Brightest-edge MTF Assessment Approach

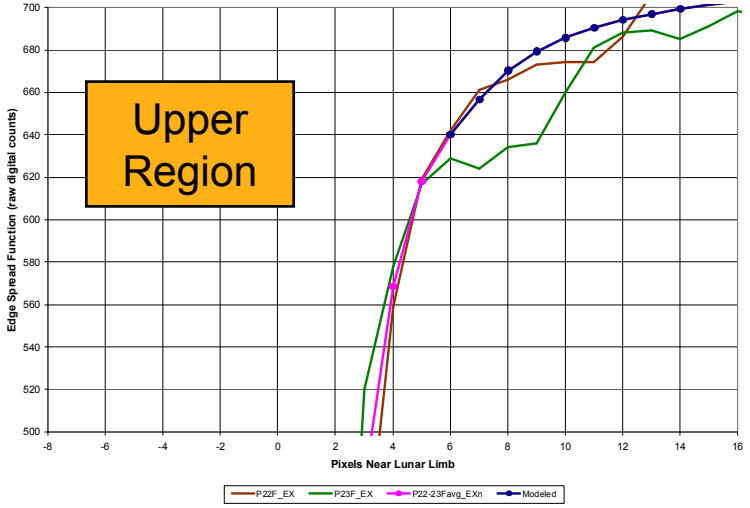


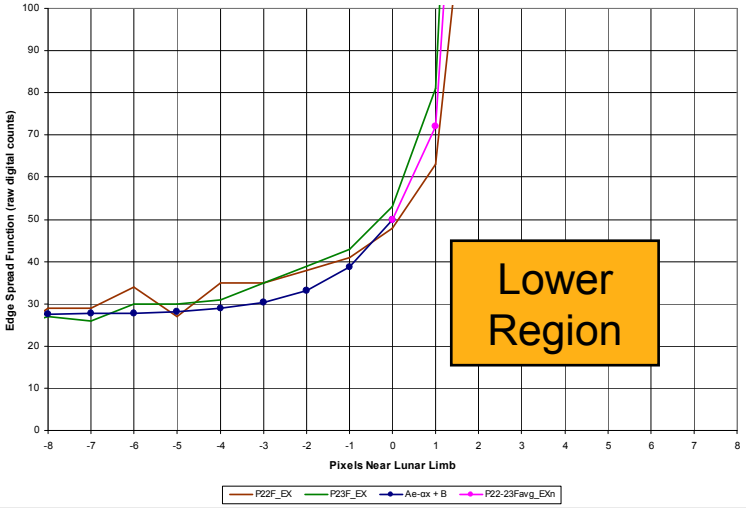
MTF Assessment – PAN Fwd TDI-13 Lunar Limb Edge Spread Function Smoothed using Exponential Function

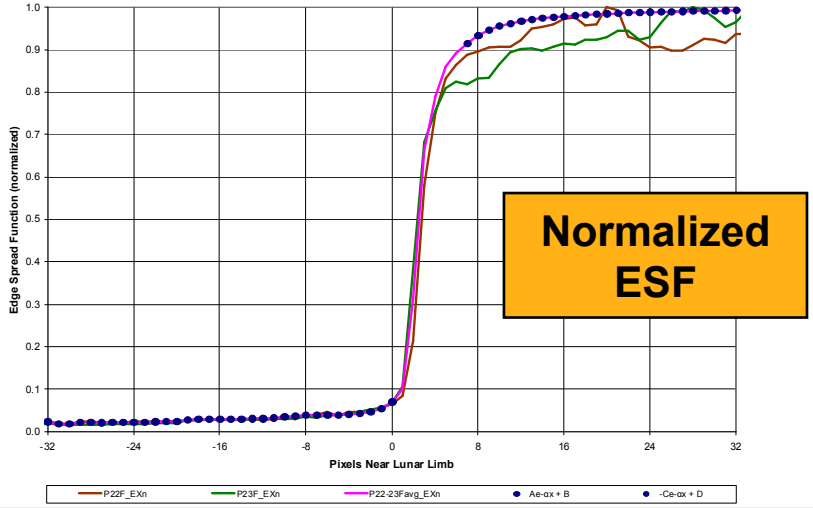


MTF Assessment – Lunar Limb Smoothed Edge Spread Function Detail Shows Transition Region Not Disturbed

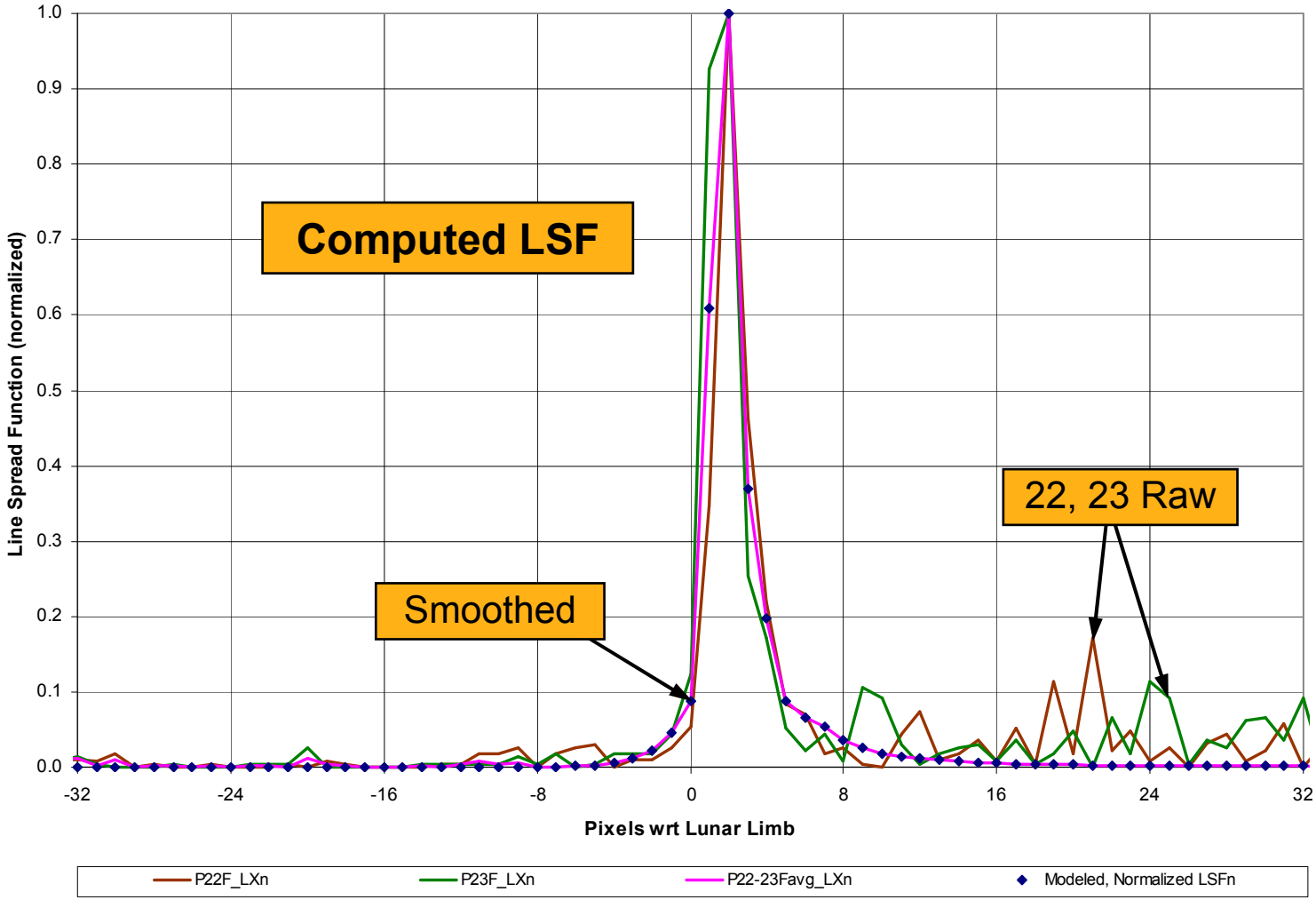




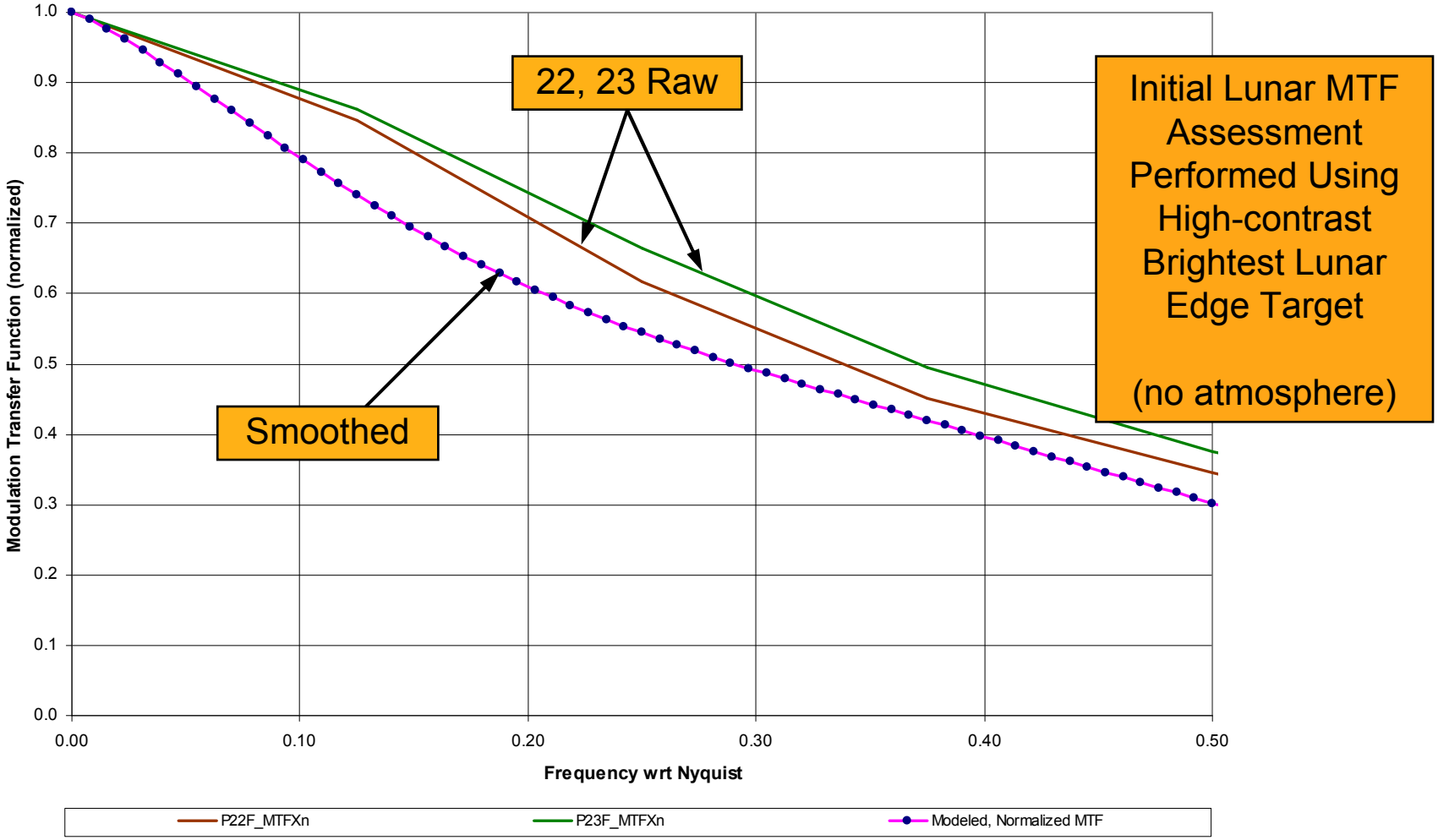




MTF Assessment – Lunar Limb Computed Line Spread Function for Raw Data Sets and Smoothed Function



MTF Assessment – Modulation Transfer Function Calculated for Raw and Smoothed Lunar Limb LSFs



Effective Focal Length Assessment Targets

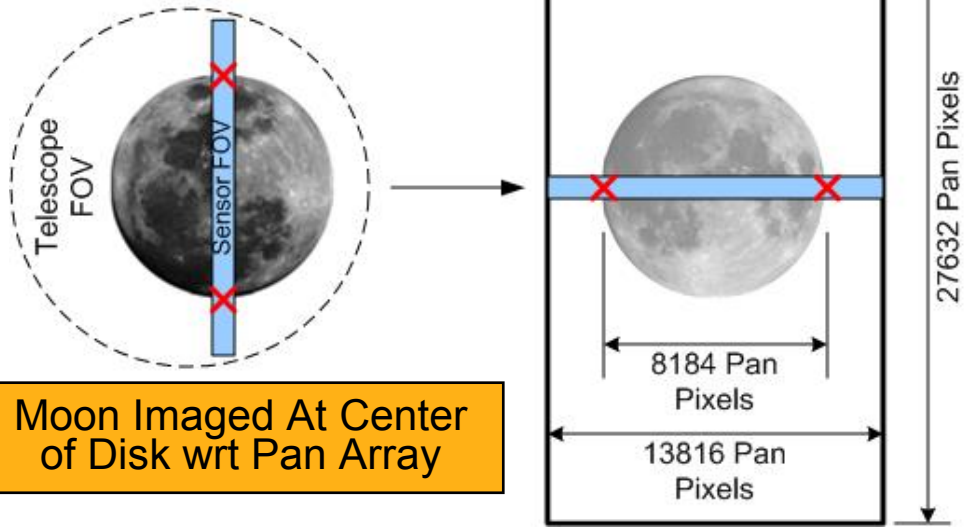
Earth-based Uniform Targets (ground control points) (not presented)

Full Disk Lunar Imaging (lunar limb-to-limb diameter)

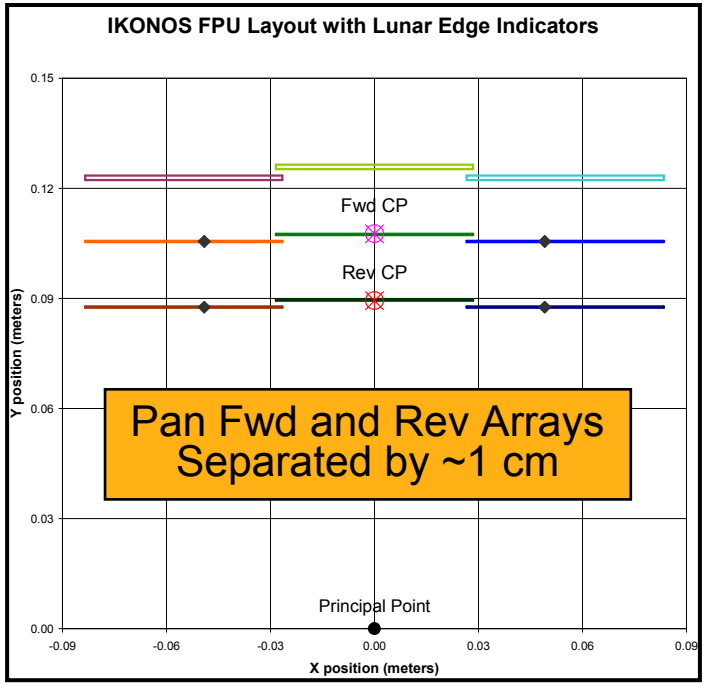
Point Source Stellar Imaging (separated point sources at infinity)

Effective Focal Length Assessment Strategy – Two Points Separated Across the Focal Plane Imaged Simultaneously

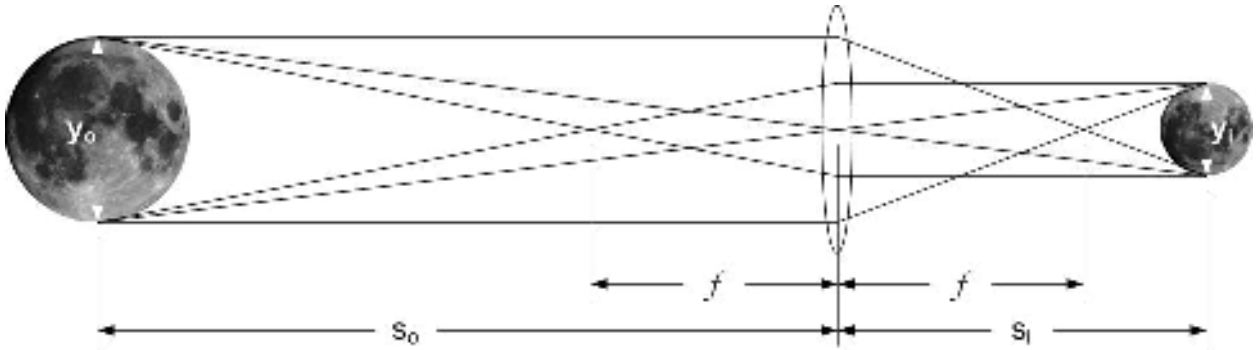
Boresight View



Moon Imaged At Center of Disk wrt Pan Array



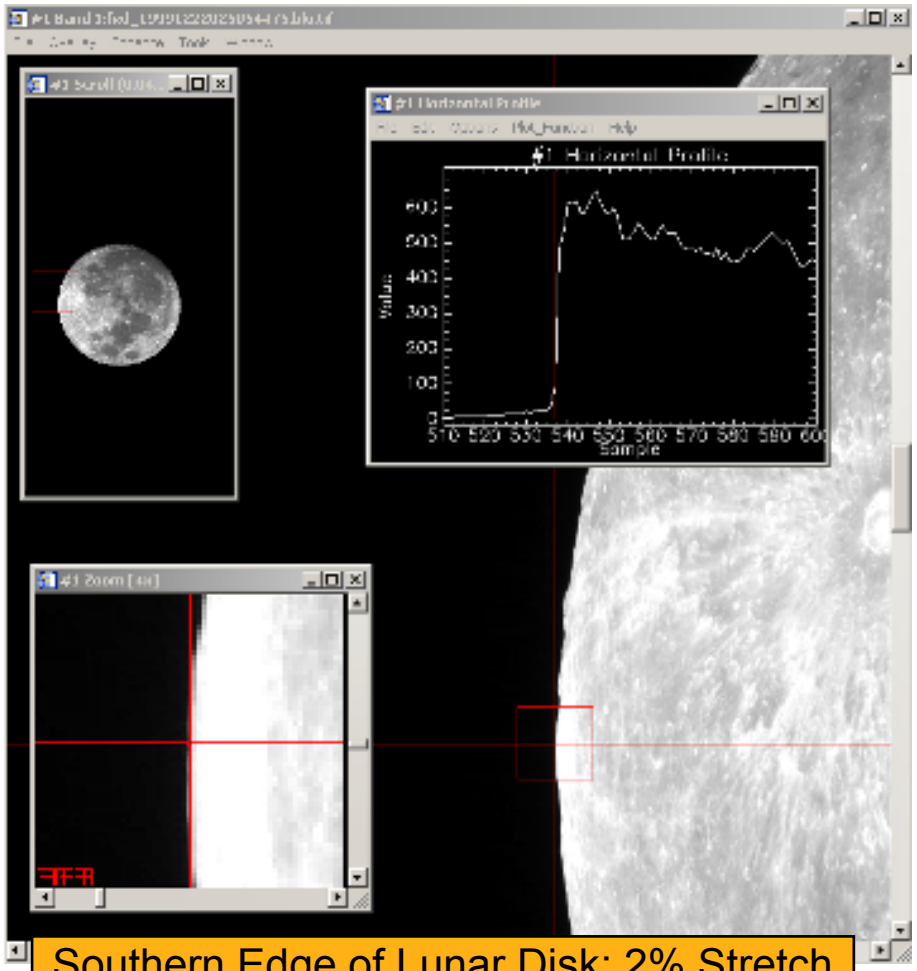
Pan Fwd and Rev Arrays Separated by ~1 cm



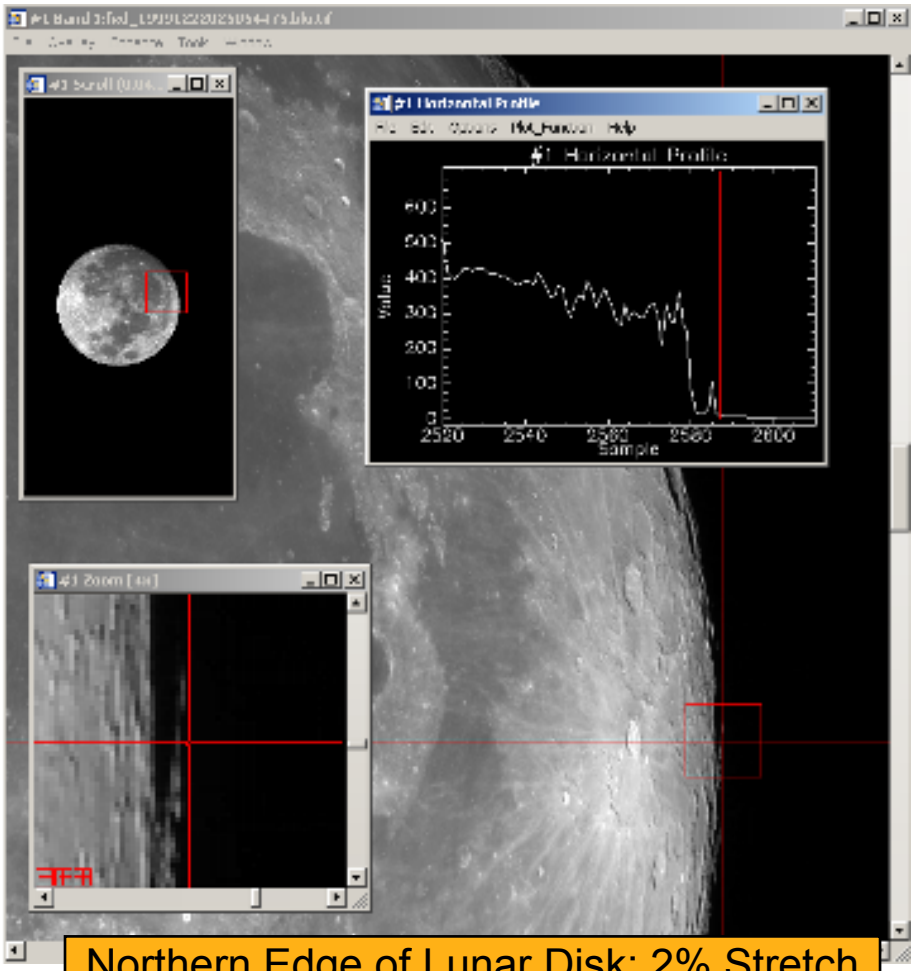
$$f_{effective} = \frac{|y_i| * s_o}{(y_o + |y_i|)}$$

Lens Equation used to Determine Effective Focal Length

Effective Focal Length Assessment – Lunar Limb Detail



Southern Edge of Lunar Disk: 2% Stretch

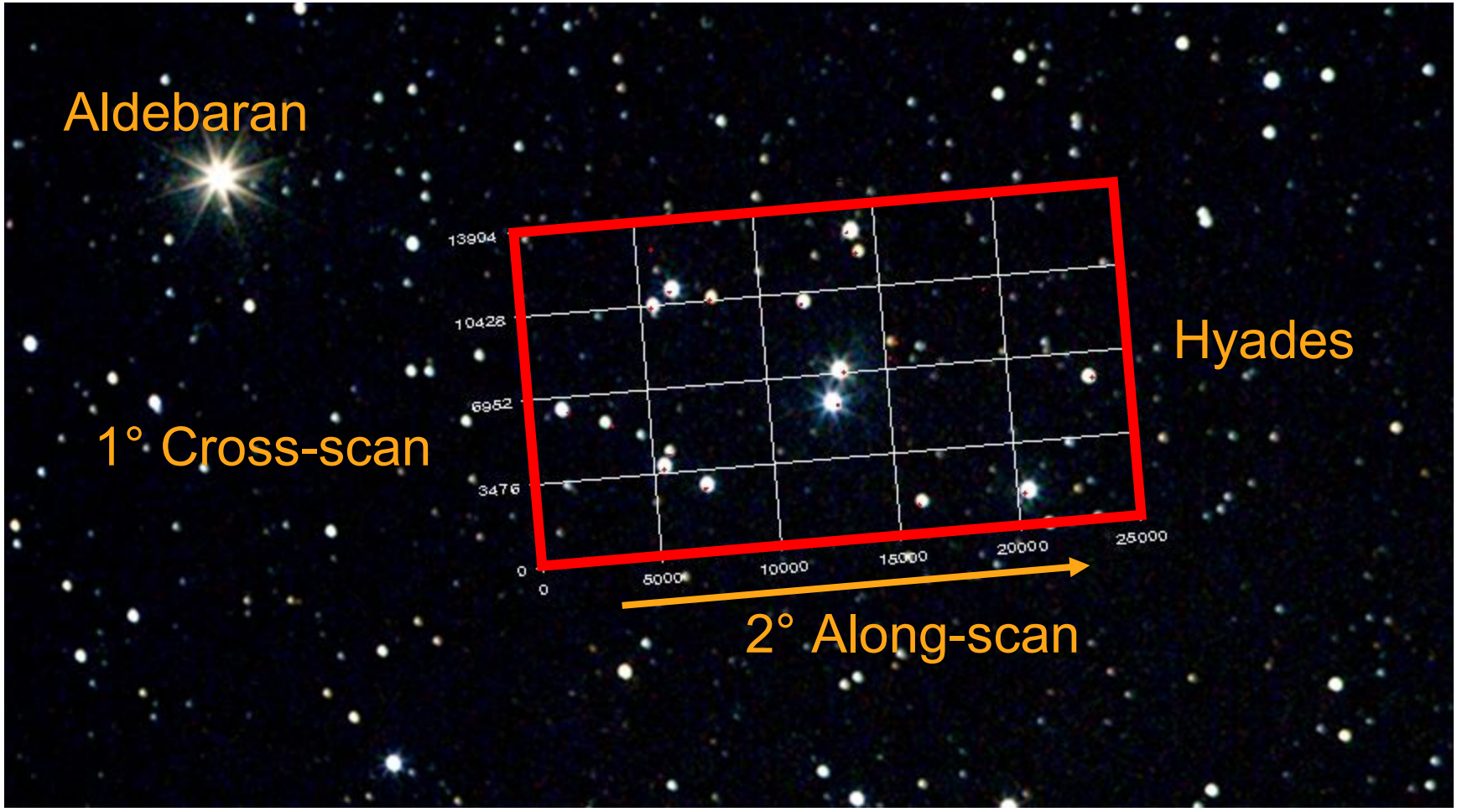


Northern Edge of Lunar Disk: 2% Stretch

Effective Focal Length Assessment – Results Using Lunar Disk Diameter in both Polar and Equatorial Directions

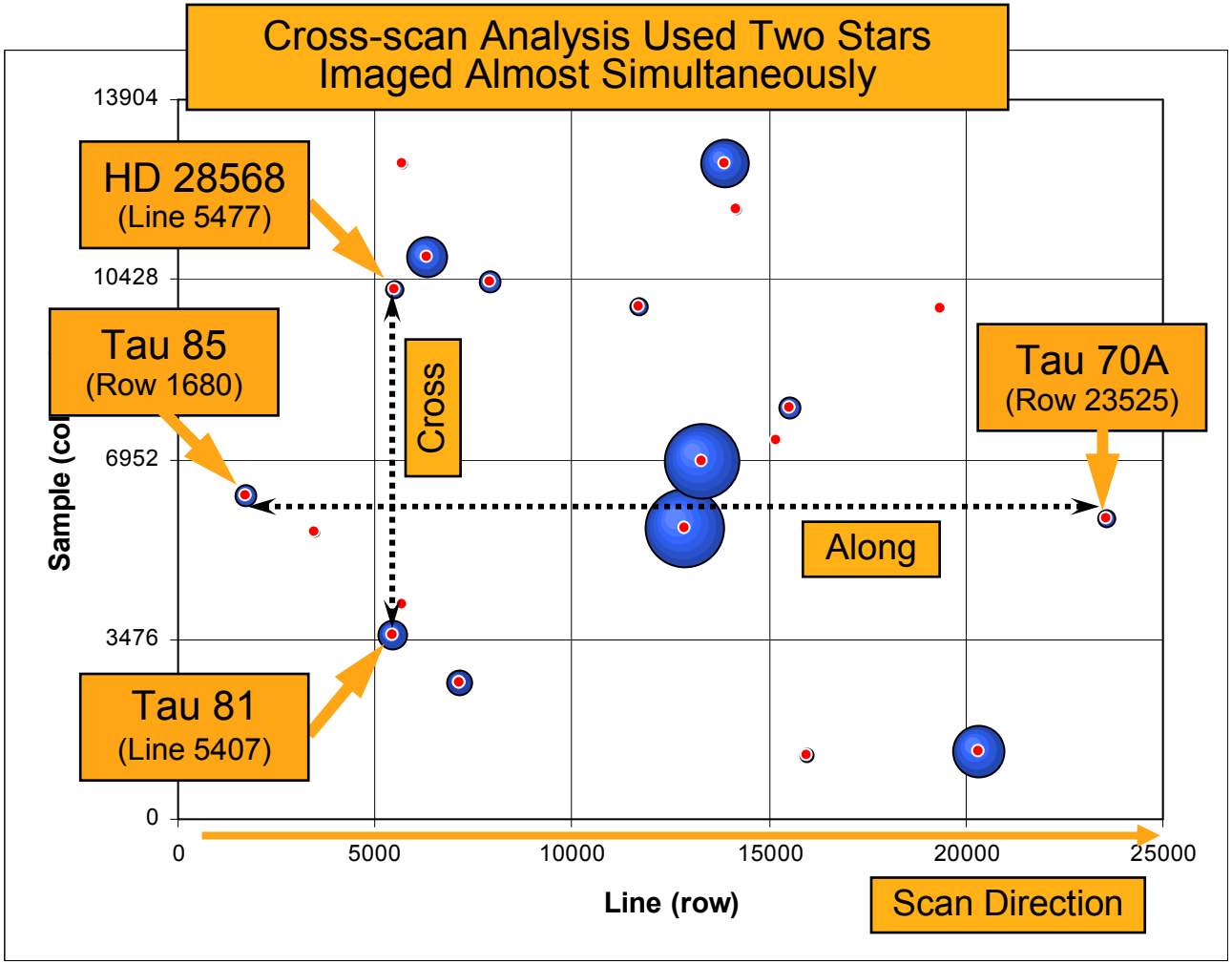
Image	Cross-Track Diameter (y_i, pan pixels)	Moon Polar Diameter (y_o, km)	Earth-to-Moon Distance (s_o, km)	Effective Focal Length ($f_{effective}$, m)
1991222 Forward	8184	3471.94	354684.217	10.033
1991223 Forward	8174	3471.94	354684.217	10.027
Forward	Δ = 10 pp			Δ = 5 mm
1991222 Reverse	8170	3471.94	354915.496	10.016
1991223 Reverse	8162	3471.94	354915.496	10.012
Reverse	Δ = 8 pp			Δ = 4 mm
Fwd v. Rev	Δavg = 13 pp		Δs_o = 231.279 km	Δavg = 16 mm

Effective Focal Length Assessment – Stellar Point Source
IKONOS Pan Fwd TDI-13 Image Region of Hyades Cluster



Hyades Open Cluster, taken with Canon EOS Digital Rebel XTi, 20 frames @2sec each, F/5.6, 55mm focal length, ISO-400, taken December 20, 2006 at 7:36pm EST by Todd Vance.

Effective Focal Length Assessment – Hyades Cluster Stellar Point Source Placement in IKONOS Pan Fwd Image



Along Scan Analysis Used Two Stars Imaged Near the Beginning and End of Scan

Effective Focal Length Assessment – Results Using Stellar Separations in both Cross-scan and Along-scan Directions

20020221 IKONOS Pan Fwd Stellar Image	Image Coordinates (column, row)	Point Source Separation (y_i, pan pixels)	Stellar Scene Separation (α_o, degrees)	Effective Focal Length ($f_{effective}$, m)
Tau 81	3582, 5407	6683.36	0.45793	Cross-scan 10.035
HD28568	10265, 5477			
Tau 85	6252, 1680	11601.3	0.79811	Along-scan Fore 9.994
Tau 77B	6938, 13261	wrt Tau 77B		wrt Center of Scan
Tau 70A	5841, 23525	10322.5	0.71040	Along-scan Aft 9.990

Results Correlate well with Lunar Method and Show Excellent Scan Rate Stability

Remote Sensing System Target-dependent Calibration Method Correlation Summary

- Instruments demonstrating stable performance can be used to assess results obtained by independent target-dependent calibration methods
- Correlation of target-dependent calibration methods requires cooperation between separate entities performing independent assessment strategies
- Discrepancies between calibration methods must not be misinterpreted as a failure of the method itself, rather a lack of knowledge of the unknowns
- Thorough investigations into each method's strategies, assumptions, algorithms, models and processing steps will eventually resolve discrepancies between calibration methods

Demonstrated IKONOS Performance Provides a Stable Reference Making it Possible to Correlate a Variety of Target-dependent Calibration Methods