SLIMED: A lunar calibration model based on many instruments and one Moon

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Status of the SLIM lunar calibration model

Introduction: see CALCON 2019 invited talk

https://digitalcommons.usu.edu/calcon/CALCON2019/invitedspeaker/1/

30 sec Intro. What are Lunar Calibration and a Lunar Model?

Treat the Moon as a cheap, aged, mottled but stable (10^{-8} /year)
diffuse reflector that is routinely (monthly) available
with wobbly but exactly known (<0.0000015° viewing, 4×10^{-12} illumination) geometry
(compliments of Newton, Einstein and JPL)
illuminated by a fairly stable lamp (the Sun) that also lights your science target.

Goal: What is the effective reflectance of this gift
as a function of the illumination and viewing angles.

SLIM Summary

There is only one Moon; its reflectance must be smooth in all photometric and spectral dimensions.

Initial SLIMFIT mapped each instrument band onto a fixed set of model bands
Using a spectral transform matrix for each instrument
SLIMED, each point has its own geometry and effective wavelength; no spectral transform

Normalize to fixed solar and lunar reference spectra, then fit with polynomials in 'wave'
Select intrmumnts to include in fit; usually omit wide (pan) bands.
Large matrix inversion, typically 100,000 x 35
In words is simple, math is a little complex

Libration effect has been a major challenge,
Use global albedo maps from lunar orbiters to model libration effect.

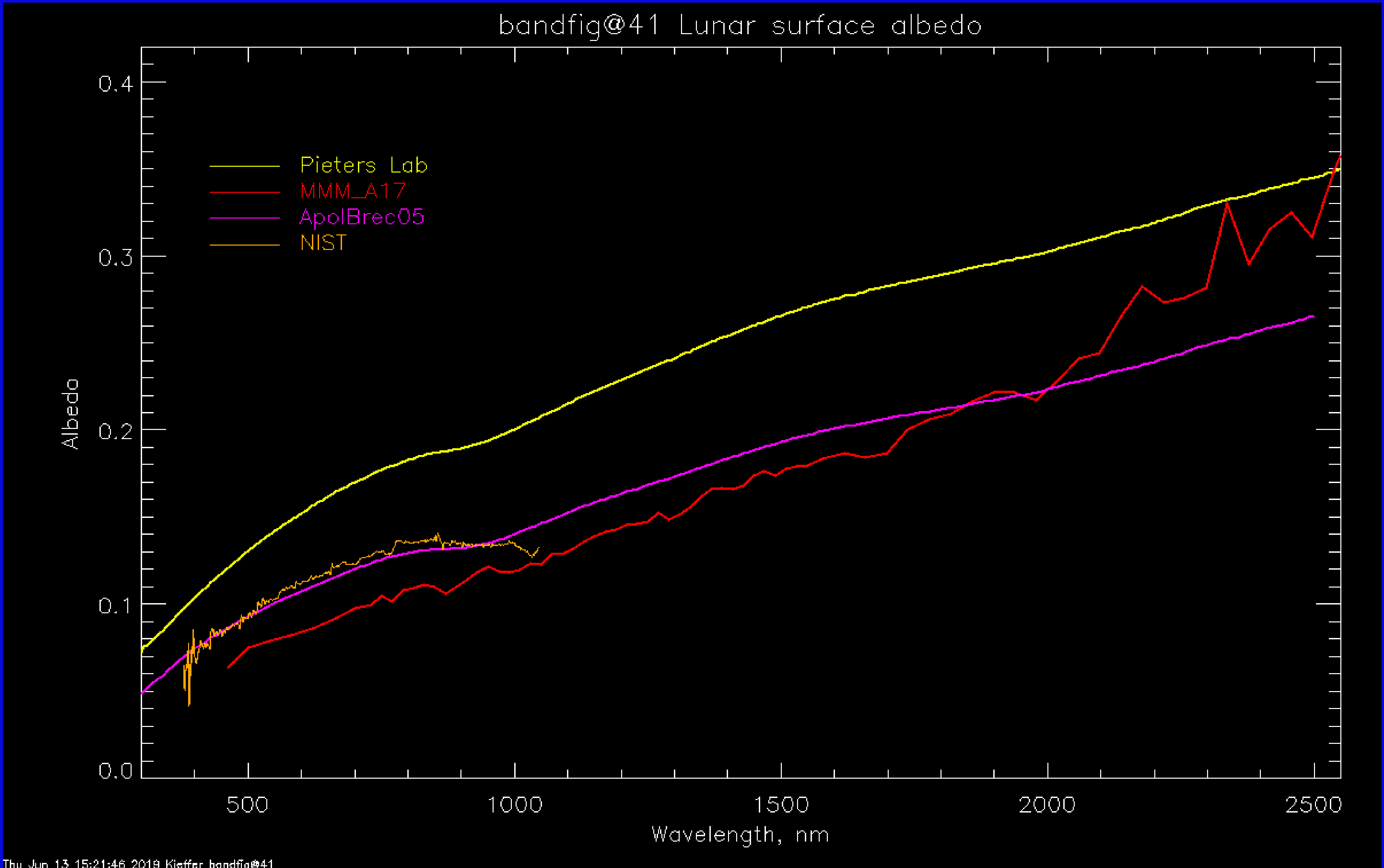
Evaluate all instruments on hand with one model
Useful for relative response comparisons; large differences

SLIMED model is continuous in all dimensions.
Residuals over all instruments are comparable to ROLO
About 30 terms instead of 328 !
Many little things still to be addressed, but the basic result is firm.

The Lunar Reference Spectrum

Telescope and Lab measures. ROLO and SLIM use ApolBrec05;

Depends upon shape only, not the absolute level.



Method

Ingest instrument data into standard formats
    All table driven. Define each instrument data set
Select instruments to include in fit: **Judgement** **Judgement**
  Assign band or point uncertainties (teams should do this).
  Assign instrument 'Heft' to account for number of data points
Convert input location and time to photometric angles, adjust to std distances
    Do ROLO calibration. If indication of trends, fit and apply
  Select geometric and wave basis functions to fit.
⇒ ⇒ Make fitReady file: all points, bands (unity gain), selected instruments
⇑ Decide whether to apply Libration Model correction
⇑ Select basis functions, and what power of wave for each, to include.
⇑ ⇒ Do the fit. (~30 x 111,019 matrix inversion) Look at results.
⇑ ⇑ Key metric, Mean absolute weighted residual
⇑ ⇑ Also: check symmetry to perturbations of each coefficient
⇑ ⇑ Mean weighted residual for each band is the gain factor: apply it
⇑ ⇑ ⇐ Loop on this until convergence. First N loops automatic, then query.
⇑ Calibrate the instruments,
⇑
⇑ Can check for trends in calibrated data, apply them.
⇑⇐ Do again
Output: A lunar model, and empirical gain factor for every instrument band.
 Can then use this model to calibrate any/all instrument observations

pseudo-Equations

In both cases, can select any subset of terms.

Fit lunar albedo maps by band: [1, x, y, x^2, y^2, xy] * [1, p, p^2, g,1/p]   30 terms

x=Viewer lon., y=Viewer lat., p=signed phase, g=absolute phase

Units [for numerical stability]: x and y in degree/10, p and g in radians

Fit all bands at once, using all these * λ [select 1 of 3 versions] , total 60 terms.

Down-select to about 20 most important terms

Fit instrument irradiance: polynomial in: g, 1/g, x, y, Hlon*x and Hlon*y

Units: x and y in degree, g in radians

Hlon, sub-solar longitude (~=p) , radians, to odd powers

Hlat, sub-solar latitude, degree, linear only (small range)

Any of these terms may be polynomial in wave: λ or 1/λ or ln λ

Typically, 20 to 50 terms

Estimate libration effect using Clementine maps

Sources:
Clementine: all nadir, so shadows increase poleward relative to Earth view
UVVIS (5 bands) to the poles, noisy beyond ±59°
NIR (6 bands, omit longest two; thermal influence), to ±70°
Lunar Orbiter Laser Altimeter, LOLA, 1.084 µm, to the poles, nadir, 0-phase

Source maps generally high resolution; reduce to 8 pixels/degree
Fill poles with bland average where needed; 6% of view
Synthesize orthographic image assuming Lunar-Lambert photometry
A mix of Lambertian and Lommell-Seeliger photometric function
Lambert fraction increases with absolute phase angle
Normalize to zero libration

Compute grid of irradiance:
Vlon and Vlat: [-8, -4, 0, +4, +8] , 25 points
p=Phase angle: [3, 8, 14, 20,3 0, 40, 50, 60,7 0, 80, 90] and – these, 22 points
Total of 550 points / band

5500 points. About 20 terms model most of the effect

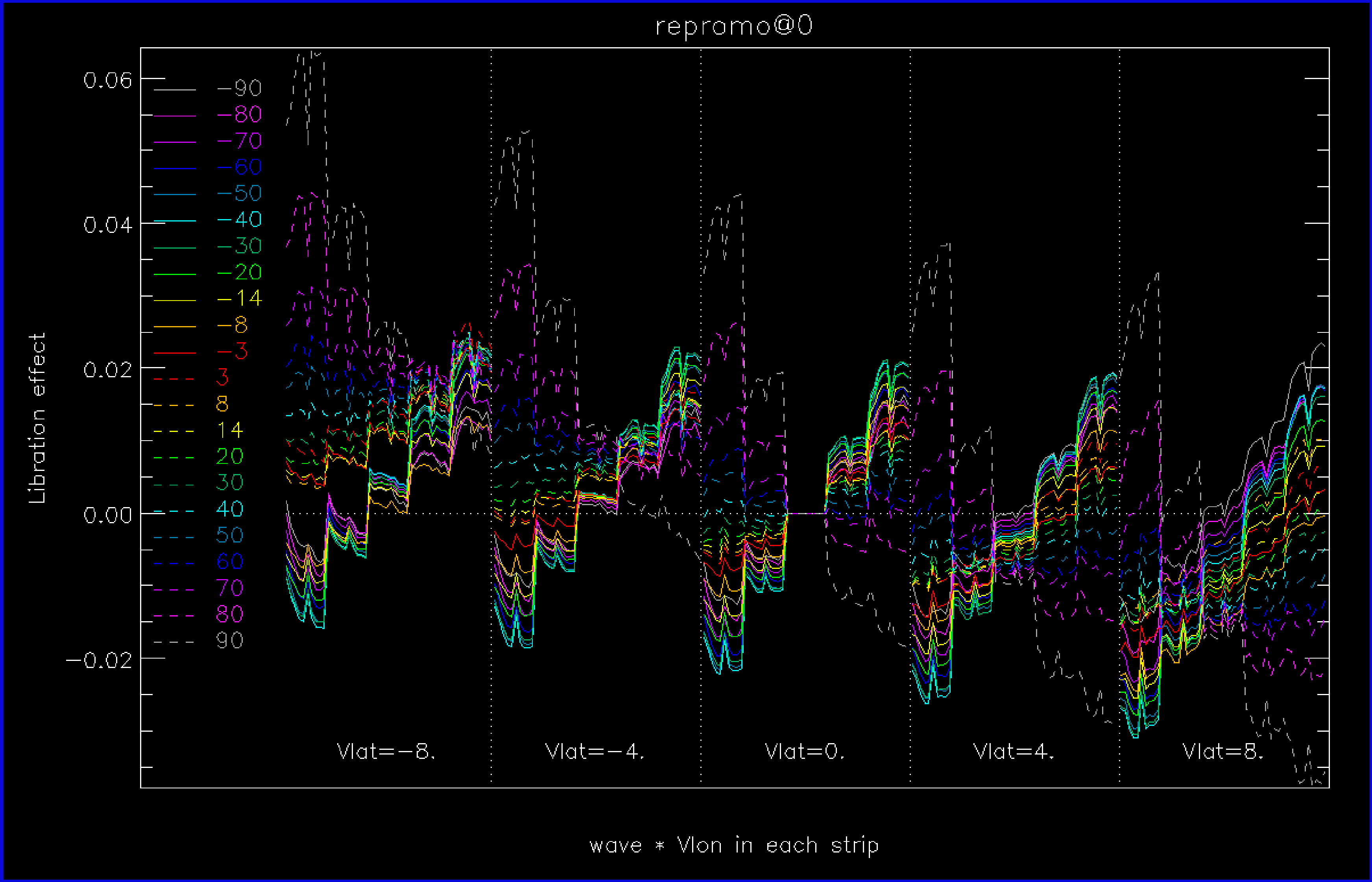
Synthetic Moon based on LOLA albedo

8 pixel/deg
Simple cylindrical map
Reprojected
to 700 pixel diameter

Phase -45˚
Vlon +8
Vlat -4
Hlat 0

Actually bypass the projection and use pixel apparent solid angles

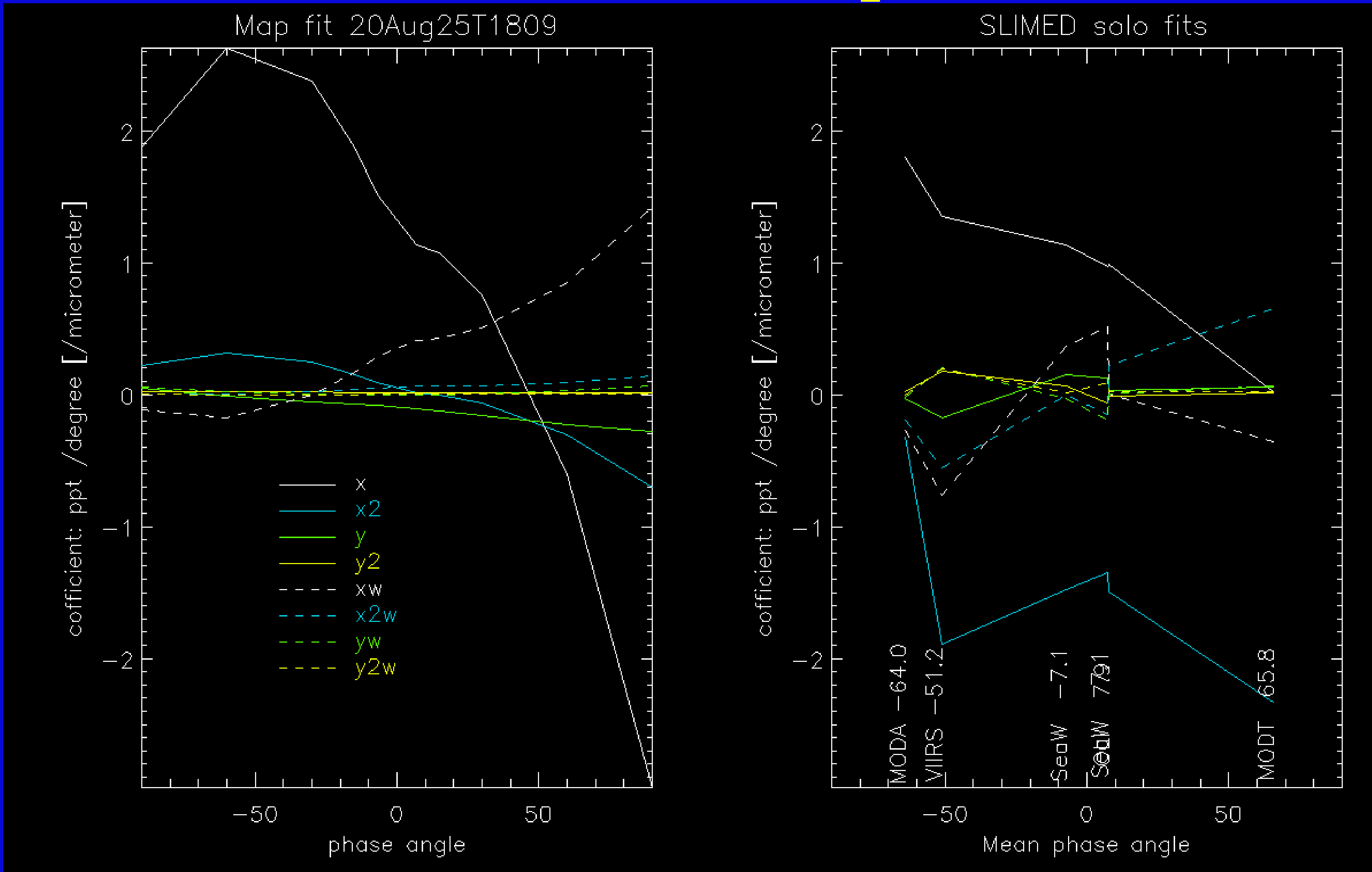
Libration effect, 4 dimensions
Wavelength, phase, Viewer longitude and latitude



Small variation with wavelength, and shape is suspicious

ROLO treated this as 2-D, linear in Vlon and Vlat

Libration coefficients: Maps and SLIMED



+7, SeaWIFS and OLI

- **Some agreement**

Instruments that provided Lunar irradiance

Instrument	Acro-nym	Num band	Lunations	Num Times	Num. pts	Obs. Date First	Obs. Date Last	phase angle min	phase angle min.Abs	phase angle max
LEO										
SeaWIFS	SeaW	8	143	145	1160	97Nov14	10Nov22	-7.9	5.1	10.1
Hyperion	HypM	26*	18	20	520	13Feb26	16Feb23	-28.3	6.9	29.4
MODIS-Terra	MODT	20	192	949	18980	00Jul22	19Feb23	47.9	47.9	81.5
MODIS-Aqua	MODA	19	175	743	14117	02Dec13	19Feb15	-79.9	36.9	-36.9
Suomi-NPP	VIIRS	14	70	71	994	12Jan04	20Mar05	-56.2	49.8	-49.8
Landsat-8	OLI	9	70	1080	9720	13Mar26	19Jan21	-8.4	5.4	9.7
PLEIADES-A	PleA	5	61	141	705	12Jan02	17Apr07	-94.6	2.1	111.9
PLEIADES-B	PleB	5	42	339	1695	13Feb17	17Apr07	-101.5	1.4	101.6
		*242 raw bands, 204 useful, averaged into 26 bands								
GEO										
GOES-8	GS8	1	38	44	44	95Jan08	03Feb20	-91.1	4.3	84.1
GOES-9	GS9	1	7	9	9	95Dec12	98Apr12	-70.4	10.0	82.4
GOES-10	GS10	1	40	49	49	98Aug09	06Jun06	-89.3	7.3	89.6
GOES-11	GS11	1	49	77	77	06Sep08	11Dec04	-87.6	4.5	89.9
GOES-12	GS12	1	38	49	49	03Apr14	10Mar02	-83.4	6.8	66.5
GOES-13	GS13	1	26	47	47	10Jul30	13Nov14	-76.9	6.4	74.3
GOES-15	GS15	1	14	28	28	12Mar06	13Nov14	-52.8	2.6	69.0
other										
2148m	ROLO	32	30	1249	39968	98Jul03	00Dec17	-124.7	1.4	109.3
2367m	NIST	9	1	2	18	12Nov30	12Nov30	19.8	19.8	19.8
HiRISE Mars	HiRIS	3	1	4	12	16Nov20	16Nov20	69.6	69.6	69.6

Instruments

inst	band	date	Uncert	heft	effUnc	Tot.W%
ROLO	32	2462	0.025	0.05	0.112	16.12
OLI	9	1080	0.03	1.00	0.030	27.61
HypM	26	20	0.10	1.00	0.100	0.13
MODA	19	743	0.05	1.00	0.050	14.44
MODT	20	949	0.05	1.00	0.050	19.41
VIIRS	14	71	0.05	2.00	0.035	2.03
SeaW	8	145	0.03	4.00	0.015	13.18
PleA	5	141	0.05	5.00	0.022	3.61
PleB	5	339	0.05	2.00	0.035	3.47

| my estimate | Help me out here

Calibrated, but not used in model construction

Inst	#band	#date	
GS8	1	44	
GS9	1	9	
GS10	1	49	
GS11	1	77	
GS12	1	49	
GS13	1	47	
GS15	1	28	
NIST	9	1	Mountaintop
HiRIS	3	4	from Mars

SEVIRI-1:4, 4 bands, 181 to 34 dates

Prep.: Trends and wild points

Look for points that are statistically unlikely, assign huge uncertainty

Five kinds of trend fits: use simplist that works well

$Y = c_0 + c_1 t$

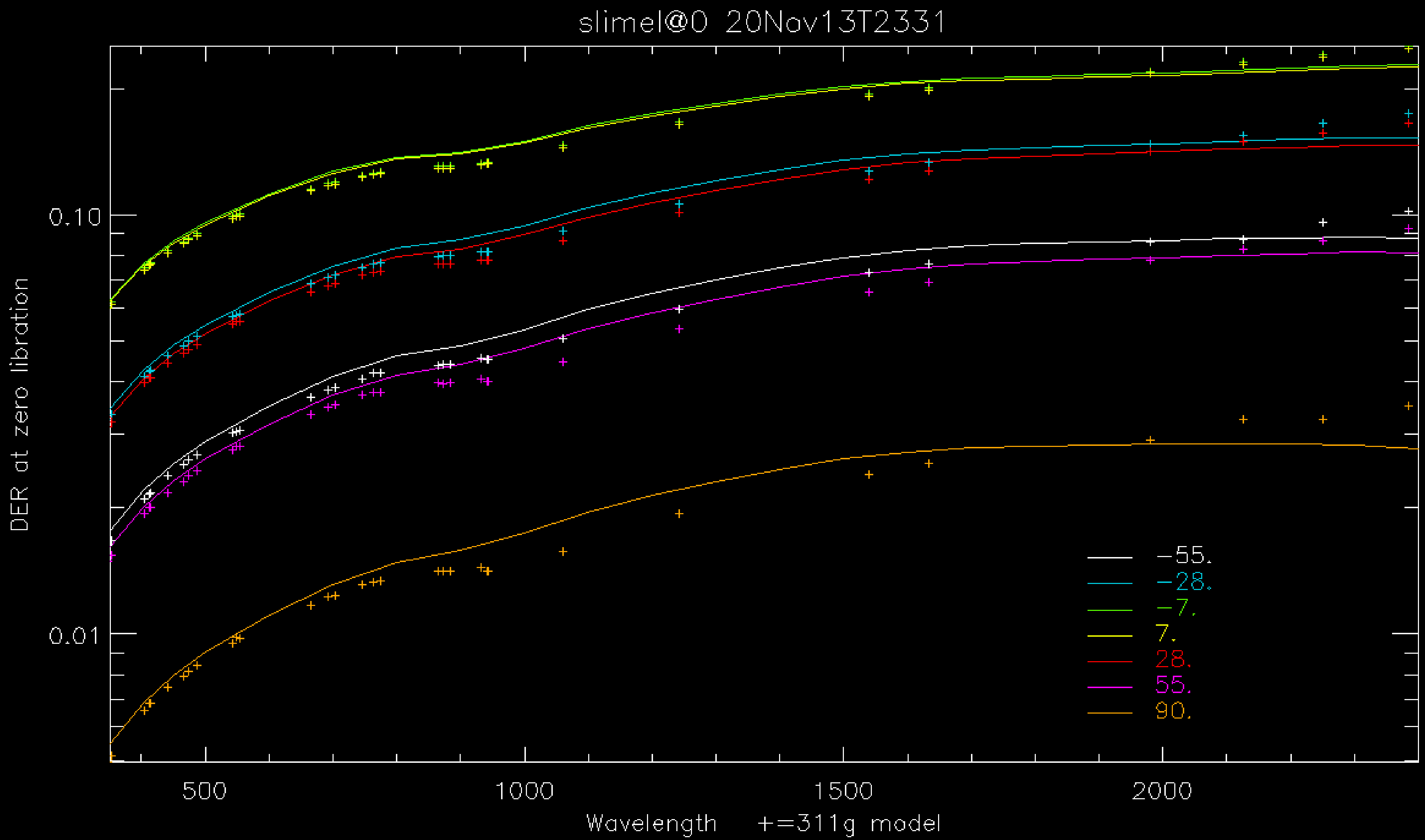
$Y = c_1 e^{-t/\tau}$

$Y = y_1 + (y_2 - y_1) e^{-t/\tau}$

$Y = c_0 + c_1 t + c_2 e^{-t/\tau}$ **Used for VIIRS**

$Y = c_0 + c_1 e^{-t/\tau} + c_2 e^{-t/\tau'}$

A SLIMED model: 22 terms, with LibModel



A 34-term model with LibModel is indistinguishable from this

Reality plot implications

Lunar calibration differences between instrument datasets are significant.

Probable Causes:

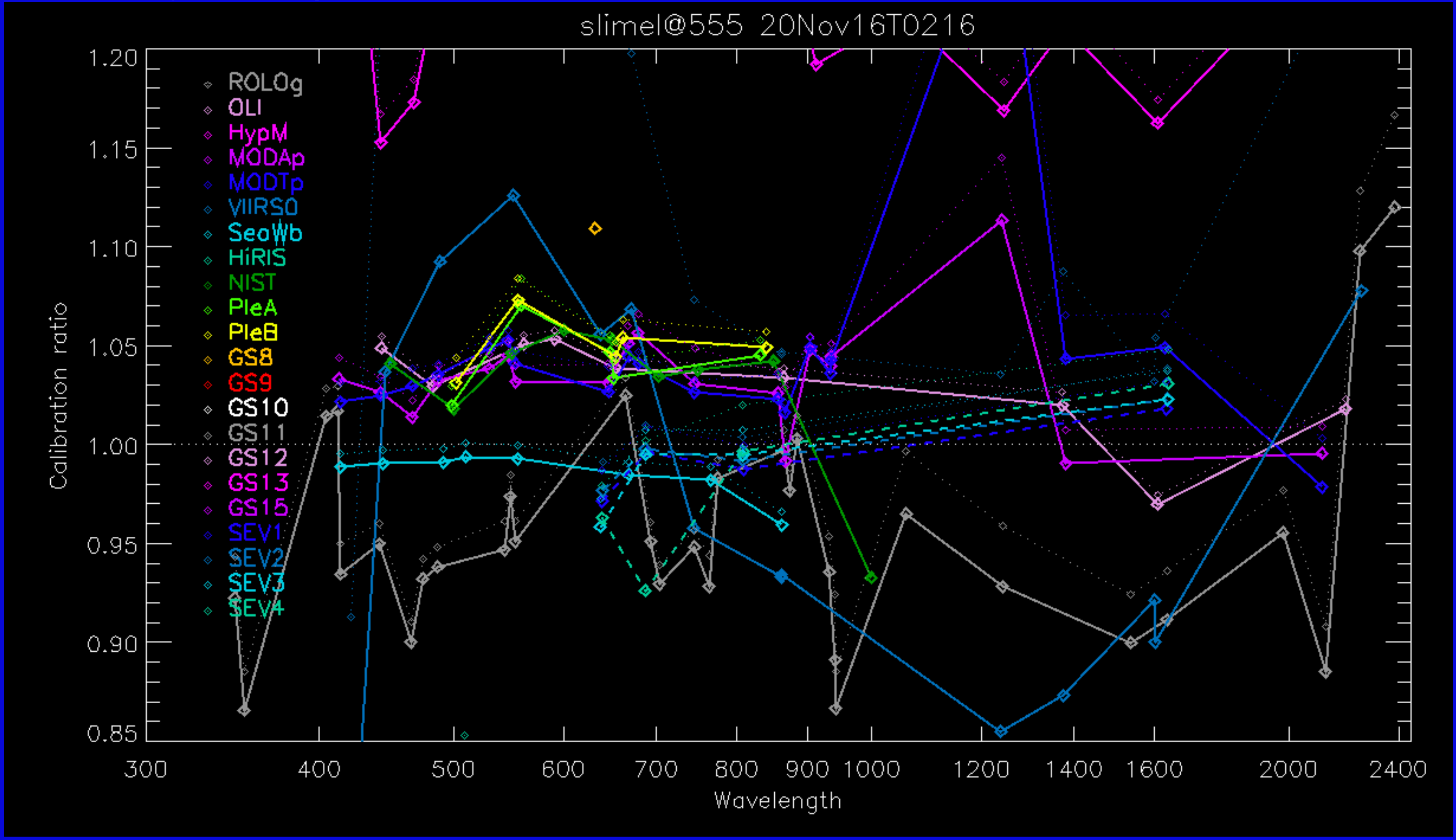
Hardware techniques: Changes between nadir look and lunar look

Change in optics from a Z-axis observation

Response changes, thermal load effect.

Processing techniques: Extracting the lunar irradiance from an lunar observation

Myriad of possibilities, all addressable!



A few comments

Model fine for trending

Still big uncertainty in absolute levels
    Need absolute above-atmosphere observations
Would help to have reference spectrum of undisturbed lunar soli

SeaWIFS about 5 % below others.
Below 850 nm general agreement except for VIIRS.
Some MODIS bands long of 1μ are inconsistent.

Done: Thank you

Backup slides follow

Sources of error

			in ppm	
Item	expression	Native	Typical	Best
Nadir vrs Moon	attitude, hardware	-	? 10,000	
Oversampling	$\propto$ calib.	Y size	†7 ? 1000	100
Image artifacts	ghosts, flare	1% ?	? 10,000	? 1000
Solar variability	most in UV	1/	1000	300
Scan uniformity †3	$\epsilon \cdot \nabla I$	1/100 ?	†4 1000	?
Cross-track pixel scale	$\Delta\alpha/\alpha$	-	OLI 5800	? 10
Frame image distortion	$\propto \theta^3$	?	? 10	? 10
Image time	-	1 sec =7.6 km	20	†6 ? ~ 1
Moon not a sphere	$\Delta h/R$	1/1737 local	†1	†2 0.2
Lunar surface	Global reflectance	0.01 ppm/yr	$\ll 1$	$\ll 1$
Spacecraft ephemeris	U, one axis	1 KM ?	2.6	$\ll 1$
Lunar ephemeris	ME distance	10 cm	2.6e-5	$\ll 1$
Relativity: c	d/c	1.3 sec	0.4	$\ll 1$
" Abberation	v/c	2.e-8 radian	0.003	$\ll 1$
Model: Absolute		5% ?	50,000	? 1000
Model: Relative		1% ?	10,000	? 100

Error Table: Notes

1: Accounted for in libration terms in model, if adequately high resolution in angle.
2: Non-linearity in $1/\cos\theta$ over $7°$[1.2e-3]; times the fractional circumference,
Arbitrarily set a $1/4\ \Delta h/R$
3: Fractional rate change while crossing the Moon.
e.g., Change in mean scan rate over first 1/2 Moon to second 1/2
4: Depends upon scan direction. Typical fractional radiance difference
between two halves of a lunar image may be 0.1
5: Change in mean scan rate over first 1/2 Moon to second 1/2
6: If scan direction and angle across Moon are consistent
7: May vary widely between instruments.