Status of the SLIMED model: Converging on the real Moon

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Goal: Exactly how bright (spectral irradiance) is the Moon. Envision an evolving process with more people, additional data, decreasing uncertainty.

SLIMED model of lunar spectral irradiance. Continuous in all 6 dimensions

Concept. Use all available data with appropriate weight.

Implimentation: Source area for each instrument, consistent file formats, segregate control files and arrays, save files between major stages, time-based model names. System that can incorporate all useful data, progressively approach the real Moon.

Some figures are overloaded; Black background improves color separation. Apologies to color-blind folks.

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

Treat the Moon as a cheap ($0), 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 that also lights your science target.

Corollary: Lunar cal is at heart a reflectance-based calibration

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

Summary

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

SLIMED vrs SLIMFIT (2019):

SLIMED, each point has its own geometry and effective wavelength
Avoids the spectral transform matrix

Normalize to a lunar reference spectrum, then fit with polynomials in geometry and "wave" (length λ or $1/\lambda$ or $\ln\lambda$)
Usually omit wide (pan) bands from the fit.
Large matrix, typically 100,000 x 35
In English is simple, math is a little complex

Libration effect has been a major challenge, [most instruments use narrow phase range]
Use global albedo maps from lunar orbiters = MapLib

Evaluate all 24 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 35 terms instead of 328 !

Method

Ingest instrument data into standard formats. Processing all table driven.
Select instruments to include in fit: **Judgement**
Assign uncertainties (teams should do this).

Convert input location and time to photometric angles, adjust to std distances
Do a calibration. If clear indication of trends, fit and apply

Select instruments to include, assign Heft to apply to each.
⇒ ⇒ Make fitReady file: includes empirical gain factors
⇑ Once: Decide whether to apply MapLib correction
⇑ Select basis functions, and what power of wave, to include.
⇑ ⇒ Do the fit. (~30 x 100,000 matrix inversion)
⇑ ⇑ ⇑ Loop 1:4 times with tighter statistics
⇑ ⇑ Key metric, Mean Absolute weighted Residual (MAR)
⇑ ⇑ **Adjust empirical gains**, fit again.
⇑ ⇑ ⇐ Outer fit loop on this until convergence. Typically 15 times
⇑
⇑ Look at results. Can check for trends in calibrated data, apply to irrad. file.
⇑⇐ Modify Heft (and instrument selection) 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

Fit lunar albedo maps for several wavelengths at once

[1, x, y, x^2, y^2, xy] * [1, p, p^2, g,1/p] and each * λ [any of 3 versions] 60 terms

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

Units: x and y in degree/10, p and g in radians

Keep Hlat=0, then p,x,y determine Hlon. Small x can force Hlat ≠ 0 to maintain p.

Can select any subset of terms; 18 do almost as well as 60. MapLib

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

Units: x and y in degree, g in radians

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

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

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

Typically, 20 to 50 terms

SLIMED method: isolate the high-res spectrum

Presume the lunar spectrum is product of high-resolution reference spectra of Sun and Moon, times smooth function TBD of geometry and wavelength.

The core of lunar models is lunar reflectance, the product lunar spectral irradiance in the form

$$E_{\oslash}(t,\lambda) = \underbrace{S_{\odot}(t,\lambda)}_{\text{Sun}} \; \frac{\Omega}{\pi D(t)} \; \bullet \; \underbrace{R_0(\lambda)\;\mathbf{L}(P,w)\;\overbrace{\mathbf{B}(P,w)}^{\text{fit}}}_{\text{Moon}}$$

Ω is the solid angle of the Moon at standard distance.
D is the $1/R^2$ correction to standard distances: Viewer:Moon 384,400 km, Sun:Moon 1 AU.

The 3 terms right of the bullet constitute the lunar model;
the Disk Equivalent Reflectance (DER) $R_{\oslash}(\lambda, P)$,
a function of wavelength and five photometric angles represented by P.

$R_0(\lambda)$ is the reference Moon, a high-resolution nominal surface reflection spectrum.
$\mathbf{L}$ is an optional independent libration model derived from Lunar orbiter data.
$\mathbf{B}$ represents the primary variation of lunar brightness with geometry and wavelength,

B does not have to address the high spectral-resolution features of lunar irradiance.
This is the key to the SLIMED method

Solar and lunar references

Requires a reference lunar spectral reflectance;
still using the Apollo breccia mix used in ROLO.
Requires a reference solar spectral irradiance;
recently adopted the HSRS [Coddington, 2021]
Total Solar Irradiance (TSI) variation based on [Kopp,2120] with recent extension.
Spectral sensitivity to TSI variation based on information from Greg Kopp,
Then fit in log/log space with quadratic in λ that captures 98% of the sensitivity.

Solar spectral irradiance is implimented in SLIM as

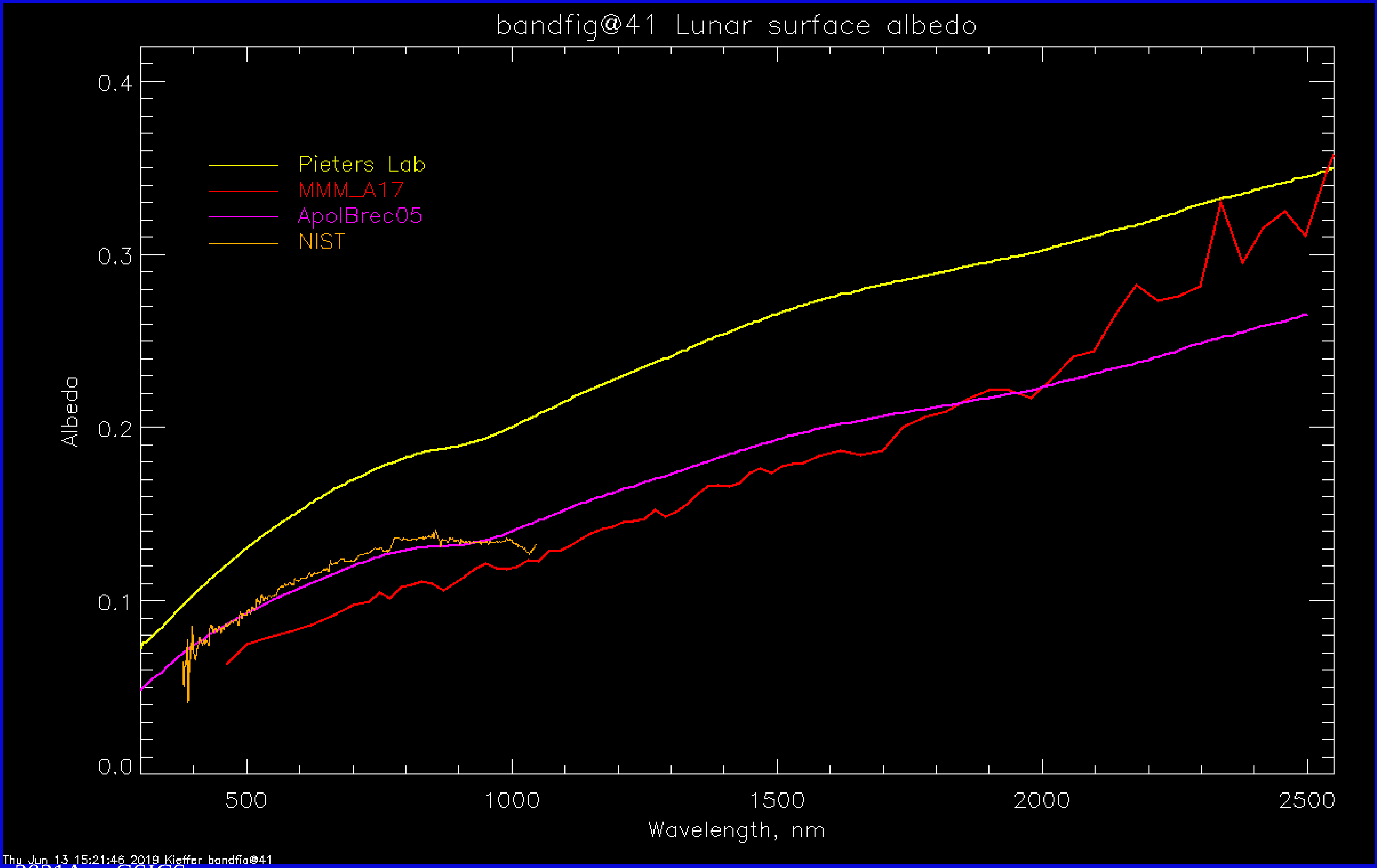
$$S_{\odot}(\lambda, t) = S_0(\lambda) \underbrace{\left[1 + f(\lambda)\left(\frac{H(t)}{H_0} - 1\right)\right]}_{\mathcal{H}(\lambda,t)}$$

$S_0(\lambda)$ is the solar reference spectrum : HSRS [Coddington,2021]
The term in brackets is the solar variation model.
$H(t)$ the total solar irradiance (TSI); linear interpolation of 1-day sampling
with subscript 0 being the long-term average 1361.623 $\mathrm{W/m^2}$.
The relative variation with wavelength $f(\lambda)$ is a
quadratic fit in log/log space over 290:2412 nm to data provided by G. Kopp,
yielding $f = \exp(-0.338752 - 0.785894 \ln \lambda + 0.202152 \ln^2 \lambda)$
where λ is in micrometers; captures 98 % of the spectral variation.

The Lunar Reference Spectrum

Telescope and Lab measures. ROLO and SLIM use ApolBrec05;

Depend upon shape only, not the absolute level.



The Basis Functions

$\mathbf{B}$ carries the variation of the lunar irradiance over angles and wavelength in the form

$$B_{ij}(P_i, w_j) = \sum_{k=0}^{K} F_k(P_i) \underbrace{\sum_{m=0}^{M_k} c_{km} w_j^m}_{b_{jk}} \qquad \text{and} \qquad \mathbf{B}(P, w) = \exp B_{ij}(P_i, w_j)$$

i is an observation index
j is a band index
k runs over the selected geometric basis functions F
The F_k terms are the angles comprising P, and some cross-products,
each may be polynomials of low degree.
M_k is the degree in wave for each of the k terms
c_{km} are the model coefficients

The individual terms in the right-hand sum are required to generate the model, however the b_{jk} can be used in evaluating the model.

The fit process derives c_{km}. Finding the band gains is minimization in a 168 dimensional space. Hard to ensure one has found the global minimum; hence approach slowly!

Lunar orbiter based libration model: MapLib

A libration model based on lunar orbiters maps has the form

$$L(P_i, w_j) = \sum_k d_k \underbrace{\left[1, p, p^2, g, q\right] \# \left[1, x, y, x^2, y^2, xy\right]}_{\mathcal{L}} + \sum_k d'_k w \mathcal{L}$$

$$\mathbf{L}_{ij} = \exp L(P_i, w_j)$$

where $\mathcal{L}$ represents the 30 cross-terms of the two sets in brackets.
Any subset of the 60 terms can be selected to include in a fit.

Five angles, with 4 independencies, comprise P;
p is the signed phase angle, increases through each lunation,
changes sign (discontinuously) at full Moon
x and y (or Vlon and Vlat): selenographic longitude and latitude of viewer
h and z (or Hlon and Hlat): selenographic longitude and latitude of the Sun
only odd powers of h are allowed to avoid near-degeneracy with $-p$.

Two varients of p are used for convenience in notation:
$g \equiv \mid p \mid$ is the absolute value of p and $q \equiv 1/ \mid p \mid$

Doing a fit

The task is to choose the basis functions and find least-squares best coefficients of c_{km} for

$$\mathbf{B}(P, w) \Longleftarrow \frac{\frac{\pi D_i}{\Omega} E_{ij}(P_i, \lambda_j)}{S_0(\lambda_j)\ \mathcal{H}(\lambda_j, t_i)\ R_0(P_0, \lambda_j)\ \mathbf{L}_{ij}(P, w)}\ G_j$$

Uncertainties are assigned to all measurements E_{ij}
Everything on the right is known except the emperical gains G_j ;
which are found from the residuals by iteration.

Always represent band by its effective or equivalent wavelength:
RSR weighted by Sun * Moon reference spectra
$= \int T(\lambda)\, S_0(\lambda)\, R_0(\lambda)\, d\lambda \,/\, \int S_0(\lambda)\, R_0(\lambda)\, d\lambda$

Limit the change of emperical gain $\Delta \ln G_j$ for each band based on a probablility that is scaled to the weighted mean fit residual δ in that band:

$$\Delta \ln G_j = \pm\sqrt{2\pi}U' \left(P\left(\frac{|\,\delta\,|}{U'}\right) - \frac{1}{2} \right)$$

Have since included a damping factor

U' is $N_\sigma U_j$ with U_j the uncertainty in band j
N_σ is a pragmatic likelyhood estimate, typically 3.
$P(x)$ is the Gaussian probability function $\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-t^2/2} dt$

This function is one-to-one for small values of δ and approaches $\pm N_\sigma U_j$ for large values.

Instruments that provided irradiance

Instrument	Acro-nym	band	Luna	time	points	Launch date	Obs. Date First	last	phase angle min	Abs	max	Number Wax	Wane
LEO													
Terra-MODIS	MODT	20	192	993	19860	99Dec18	00Mar24	19Feb23	47.9	47.9	81.5	0	993
Aqua-MODIS	MODA	19	175	743	14117	02May04	02Jun20	19Feb15	-79.9	36.9	-36.9	743	0
SeaWiFS	SeaW	8	144	204	1632	97Sep20	97Nov14	10Nov21	-48.9	5.1	65.5	117	87
Landsat-8-OLI	OLI	9	70	1080	9720	13Feb11	13Mar26	19Jan21	-8.4	5.4	9.7	30	1050
Suomi-VIIRS	VIIRS	14	70	71	994	11Oct28	12Jan03	20Mar05	-56.2	49.8	-49.8	71	0
NOAA-20-VIIRS	VIIRN	14	28	28	392	17Nov18	17Dec28	21Mar24	-52.0	50.1	-50.1	28	0
PLEIADES-A	PleA	5	61	141	705	11Dec17	12Jan02	17Apr07	-94.5	2.1	111.9	66	75
PLEIADES-B	PleB	5	42	339	1695	12Dec02	13Feb17	17Apr07	-101.5	1.4	101.6	169	170
EO1-Hyperion	HypM	26	18	20	520	00Nov21	13Feb25	16Feb22	-28.3	6.9	29.4	3	17
GEO													
GOES-8	GS8	1	38	44	44	94Apr13	95Jan08	03Feb20	-91.1	4.3	84.1	19	25
GOES-9	GS9	1	7	9	9	95May23	95Dec12	98Apr12	-70.4	10.0	82.5	5	4
GOES-10	GS10	1	40	49	49	97Apr25	98Aug09	06Jun06	-89.3	7.3	89.6	26	23
GOES-11	GS11	1	49	77	77	00May03	06Sep08	11Dec04	-87.6	4.5	89.9	47	30
GOES-12	GS12	1	38	49	49	01Jul23	03Apr14	10Mar02	-83.4	6.8	66.5	25	24
GOES-13	GS13	1	26	47	47	06May24	10Jul30	13Nov14	-76.9	6.4	74.3	25	22
GOES-15	GS15	1	14	28	28	10Feb05	12Mar06	13Nov14	-52.8	2.6	69.0	16	12
GOES-16-ABI	ABI16	6	15	115	690	16Nov03	19May14	20Jul10	-76.0	5.6	69.9	67	48
GOES-17-ABI	ABI17	6	15	121	726	18Mar01	19May14	20Jul10	-73.6	5.0	72.3	69	52
MSG-1-SEVIRI	SEV1	4	183	1209	4836	02Aug28	03Nov03	19Dec30	-153.0	1.5	156.1	613	577
MSG-2-SEVIRI	SEV2	4	162	1152	4608	05Dec22	06Jul03	19Dec30	-154.6	1.3	153.7	579	567
MSG-3-SEVIRI	SEV3	4	81	556	2224	12Jul05	13Jan01	19Dec19	-152.4	1.6	153.1	291	255
MSG-4-SEVIRI	SEV4	4	31	199	796	15Jul15	15Aug28	19Dec21	-145.4	3.6	147.6	105	96
Other													
ROLO-v.3 2148m	ROLOG	32	30	1249	39968	96Mar01	98Jul02	00Dec17	-124.7	1.4	109.3	491	758
Cramer 2367m	NIST	9	1	2	18	12Nov	12Nov29	12Nov29	19.8	19.8	19.8	0	2
AeroNetMaunaLoa	AerN	7	20	50	350	16Feb26	16Mar27	21Jun26	-73.9	4.3	86.8	26	24
MRO-HiRISE Mars	HiRIS	3	1	4	12	05Aug12	16Nov19	16Nov19	69.6	69.6	69.6	0	4

Several LEO have narrow range of phase angle

Into the model: all LEO, ROLOG, NIST and AerN. GEO all have more scatter

Preparation: Wild points and Trends

Look for points that are statistically unlikely (actually a huge nuisance), assign huge uncertainty

Five kinds of trend fits: use simplest 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**

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

Estimate libration effect using Clementine maps

Sources:
Clementine: all nadir, so shadows increase pole-ward 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: [3,8,14,20,30,40,50,60,70,80,90-] and – these, 22 points
Total of 550 points / band

5500 points. About 20 terms models most of the effect

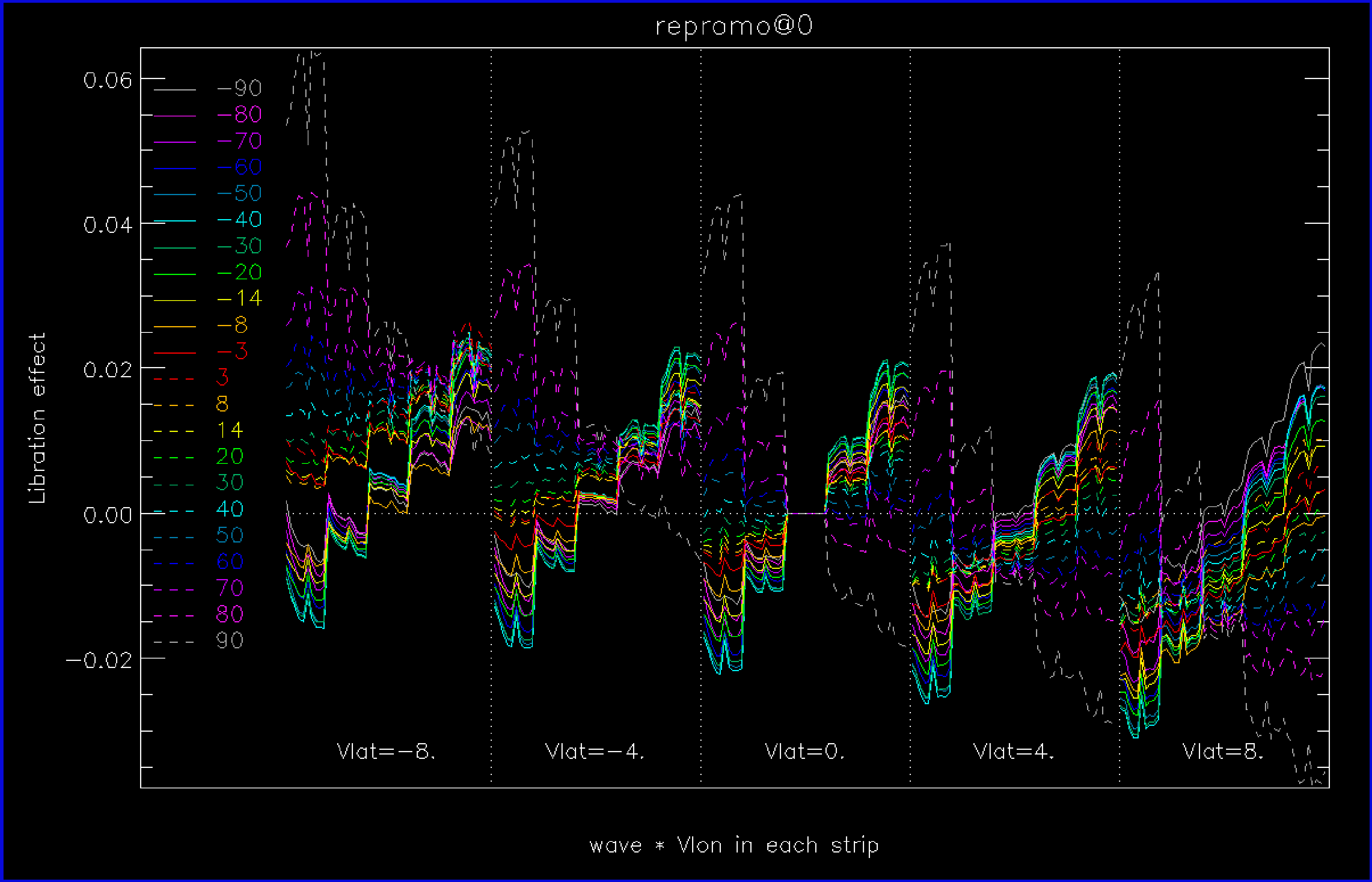
Synthetic Moon based on LOLA albedo

8 pixel/deg
Simple cylindrical map
Re-projected
to 700 pixel diameter

Phase -45°
Vlon +8
Vlat -4
Hlat 0

Actually bypass the projection and use pixel apparent solid angles

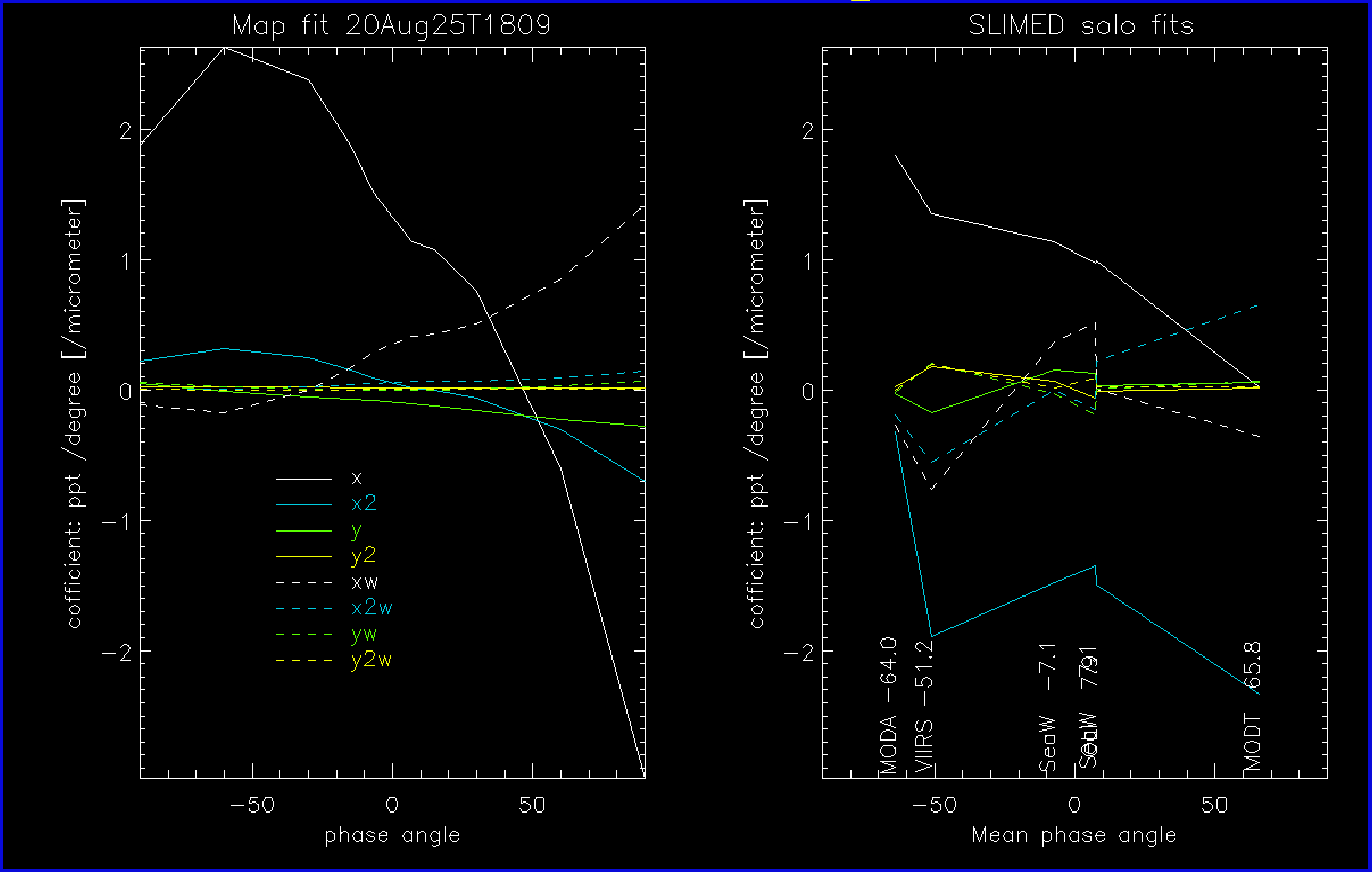
MapLib: Libration effect, 4 dimensions
Wavelength, phase, Viewer longitude and latitude



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**

Model flexibility: joy and curse

Based on many [11] instruments, 90,000 measurements. Includes TSI and SSI variation.
Optional: libration model derived from 10 maps by Lunar orbiters. ⇖ ⇧ 0.1% effect
Basis functions (BF): abs. phase angle; Viewer Longitude, latitude; Solar lat., lon.
Selected polynomials and cross-products of each, and those times polynomials in λ

Decisions: some of the categories

1) **Which instruments to include in model.**
2) **Teams rarely provide uncertainties, must be assigned.**
3) **Heft: Overall weighting factor for each instrument to address abundance of points, apparent consistency, ...**
4) **Use MapLib? Include solar variation?**
5) **Which of the thousands of possible BF combinations to use.**
6) **Dozens of control parameters**

Nested fit iterations for outlier rejection and gain of each instrument band.
Typical model has 20:40 Basis Functions. [ROLO=GIRO has 328]
Mean absolute residual ∼0.7%

Calibrate all instruments in inventory, and some fabricated models.

```
 21Aug04T1738=a45  a58=21Aug04T1803  LibMod=21Jul09T1512  jit=16
Slim?.inp ?_unc.bin8 heft?.tab *_eg.bin8 H wP= c 1 9 unity 0 f
 ROLOG OLI HypM MODT MODA VIIRS VIIRN SeaW PleA PleB NIST AerN
      MARwei   0.0063359
```

i	name	symbol	value*E3	uncert*E3	Magnitude val*StD*E3
0	const	1	131.711	0.37623	0.000
1	const.1	1w	53.995	3.27755	30.837
2	const.2	1w^2	-28.603	2.70299	49.635
3	phase:	p	-982.137	5.67299	418.835
4	phase:2	p^2	86.643	3.81209	51.730
5	phase:3	p^3	-156.085	4.15818	124.189
6	phase:.1	pw	-273.843	20.74507	206.482
7	phase:.2	pw^2	19.366	9.62237	32.041
8	phase:2.1	p^2w	64.859	11.48883	64.290
9	1/g:	q	-5.833	28.30255	17.872
10	1/g:2	q^2	0.546	4.96367	17.271
11	1/g:.1	qw	12.042	2.87932	65.538
12	1/g:.2	qw^2	-1.842	2.38153	21.572
13	1/g:2.1	q^2w	-0.209	4.39311	11.306
14	Hb:	h	48.919	2.35988	38.133
15	Hb:3	h^3	10.080	1.99306	10.124
16	Hb:5	h^5	-3.894	9.66328	6.588
17	Hb:.1	hw	2.836	15.14767	3.437
18	Hb:.2	hw^2	-2.665	15.24759	6.097
19	Hb:3.1	h^3w	-0.078	2.89292	0.122
20	Hlat	z	-1.891	1.16756	2.059
21	Hlat.1	zw	0.179	0.48487	0.311
22	LibraX	x	-0.951	0.23997	4.203
23	LibraY	y	0.216	0.12172	1.043
24	LibraX:2	x^2	-0.018	0.19995	0.304
25	LibraY:2	y^2	-0.005	0.36218	0.090
26	LibraX.1	xw	0.018	0.07406	0.126
27	LibraY.1	yw	-0.044	0.06209	0.342
28	Hb*LibX	(hx)	-0.668	0.13353	2.564
29	Hb*LibY	(hy)	-0.225	0.02811	0.877
30	Hb*LibX:2	(hx)^2	0.006	0.12914	0.142
31	Hb*LibY:2	(hy)^2	0.003	0.03785	0.067
32	Hb*LibX.1	(hx)w	0.150	0.01259	0.897
33	Hb*LibY.1	(hy)w	0.159	0.01636	0.973

Uncert*E3 is formal SVD uncertainty

Typical model

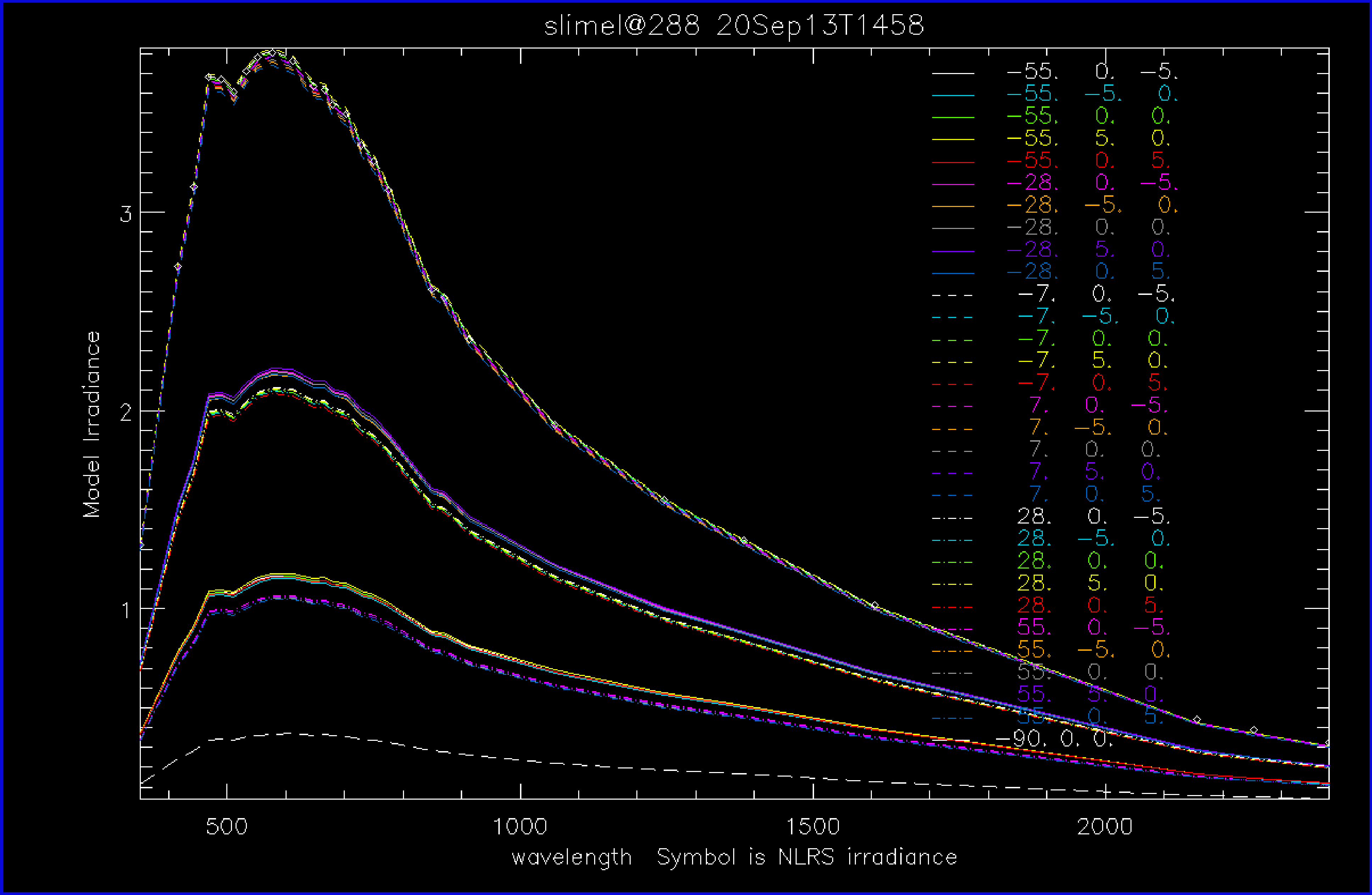
This is the Base model: (for this talk) 21Aug04T1738 or Hm92f63

34 coefficients,
  18 are pure geometric
  16 involve wave
With MapLib
 No Solar variation
MAR= 63 pptt = 0.63%

Columns 3 and 4,
Symbol and value,
Are a complete specification
of the SLIMED model !

Magnitude == importance:
Absolute magnitude of the coefficient times the standard deviation of the basis function

A SLIMED model: 34 terms, no MapLib



A 22-term model using MapLib correction is indistinguishable

Different Hefts => Weights: %

	Heft			resulting_weight_%			
	05T0544	05T0547	04T1803				
Inst	7	8	9=base	7	8	9=base	~
ROLOG	0.066	0.033	0.023	39.53	26.38	19.67	20
OLI	0.312	0.500	0.437	5.95	12.70	11.86	12
HypM	30.000	5.000	13.900	2.99	0.66	1.97	2
MODA	0.546	1.000	0.628	8.50	20.76	13.94	14
MODT	0.388	1.000	0.459	4.21	14.56	7.16	7
VIIRS	7.800	1.000	5.400	5.99	1.02	5.90	6
VIIRN	19.400	2.000	23.000	5.96	0.82	10.06	10
SeaW	1.700	2.000	1.900	6.12	9.60	9.74	10
PleA	13.800	2.000	4.800	5.95	1.15	2.95	3
PleB	6.000	2.000	4.900	5.95	2.64	6.91	7
NIST	1.700	2.000	1.600	2.92	4.58	3.91	4
AerN	7.700	5.000	5.400	5.93	5.13	5.93	6

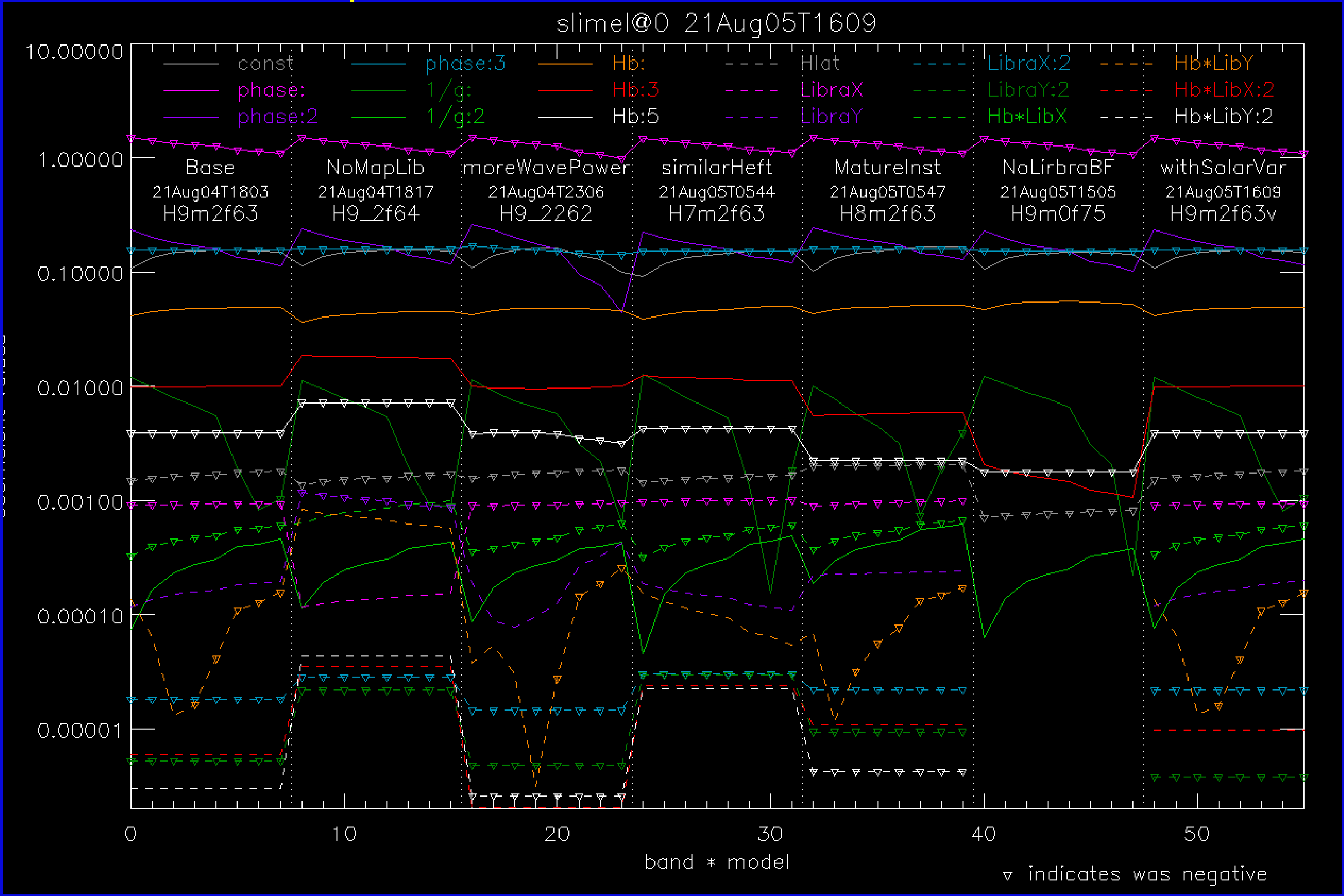
Only VIRRS (Suomi) is trend-corrected

7: ROLO 40%, Hyperion & NIST 3%, rest ~6%

8: ROLO 26%, other instruments more uniform

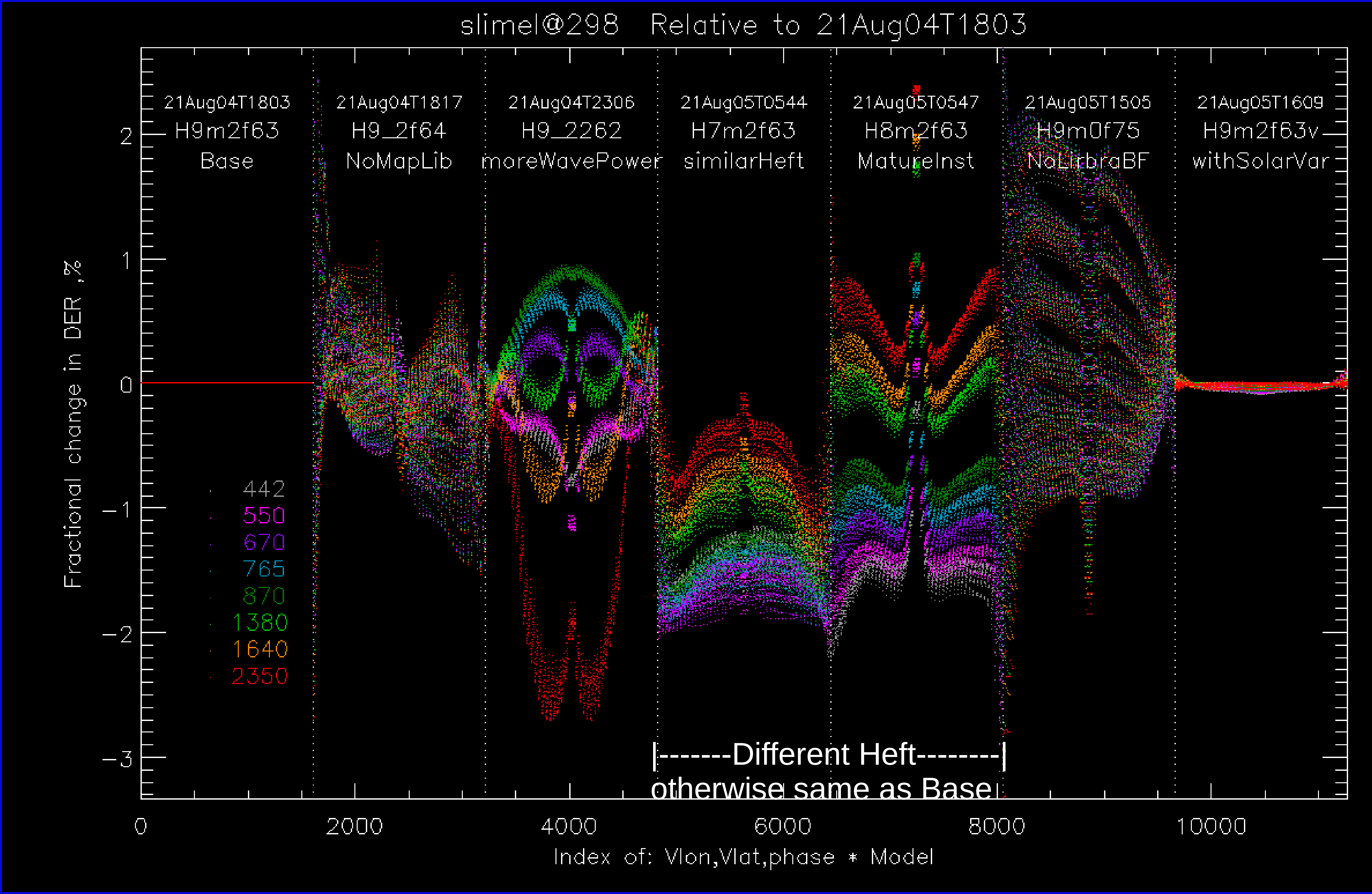
9: ROLO 20%, less MODIS, more both VIIRS and PLEIADES

Comparison of coefficients for 7 models



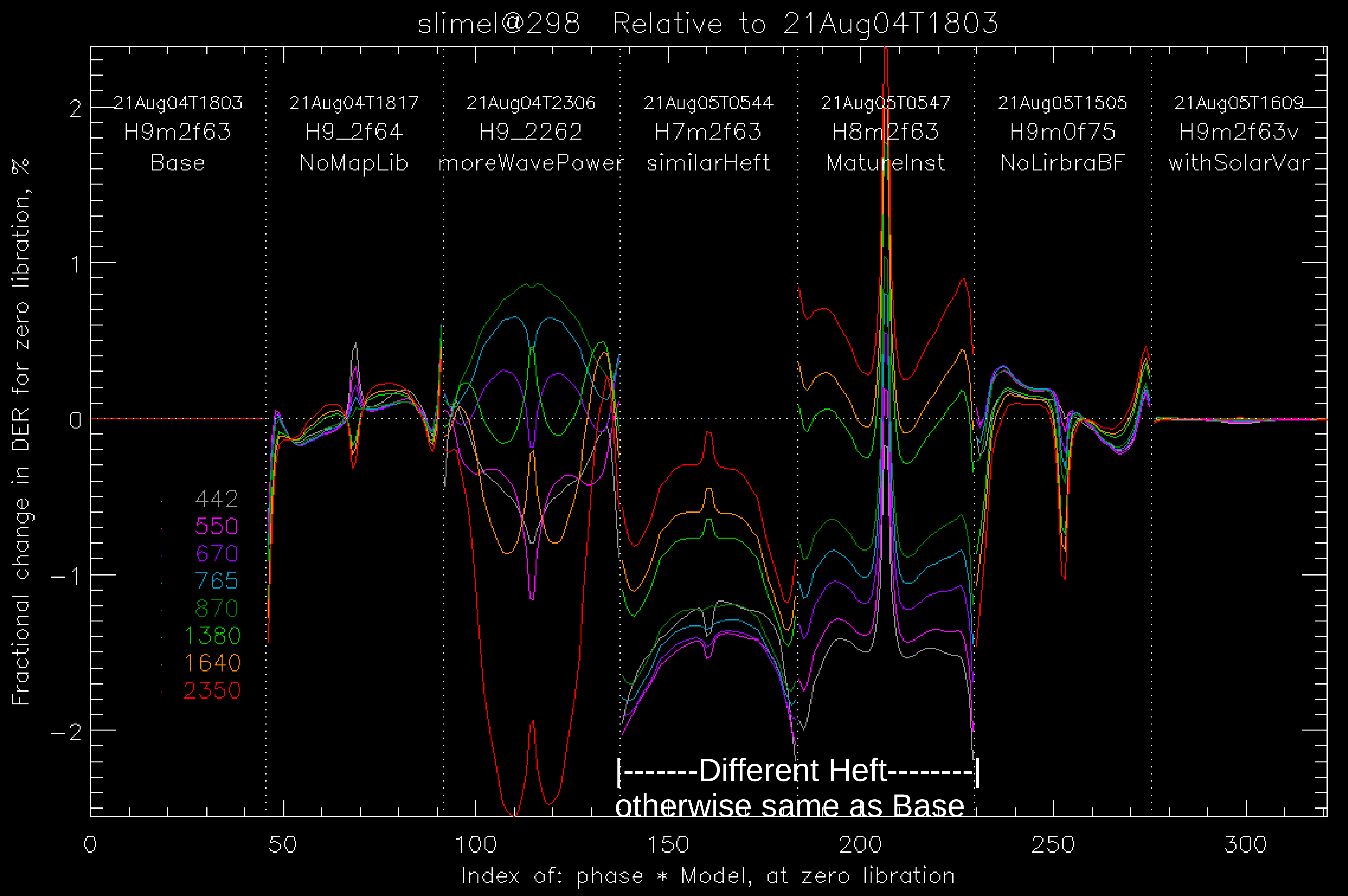
All H9 (left 3,right 2) have same heft. H7 and H8 have same BF as base

% change in flux for 7 models, GSICS grid and bands



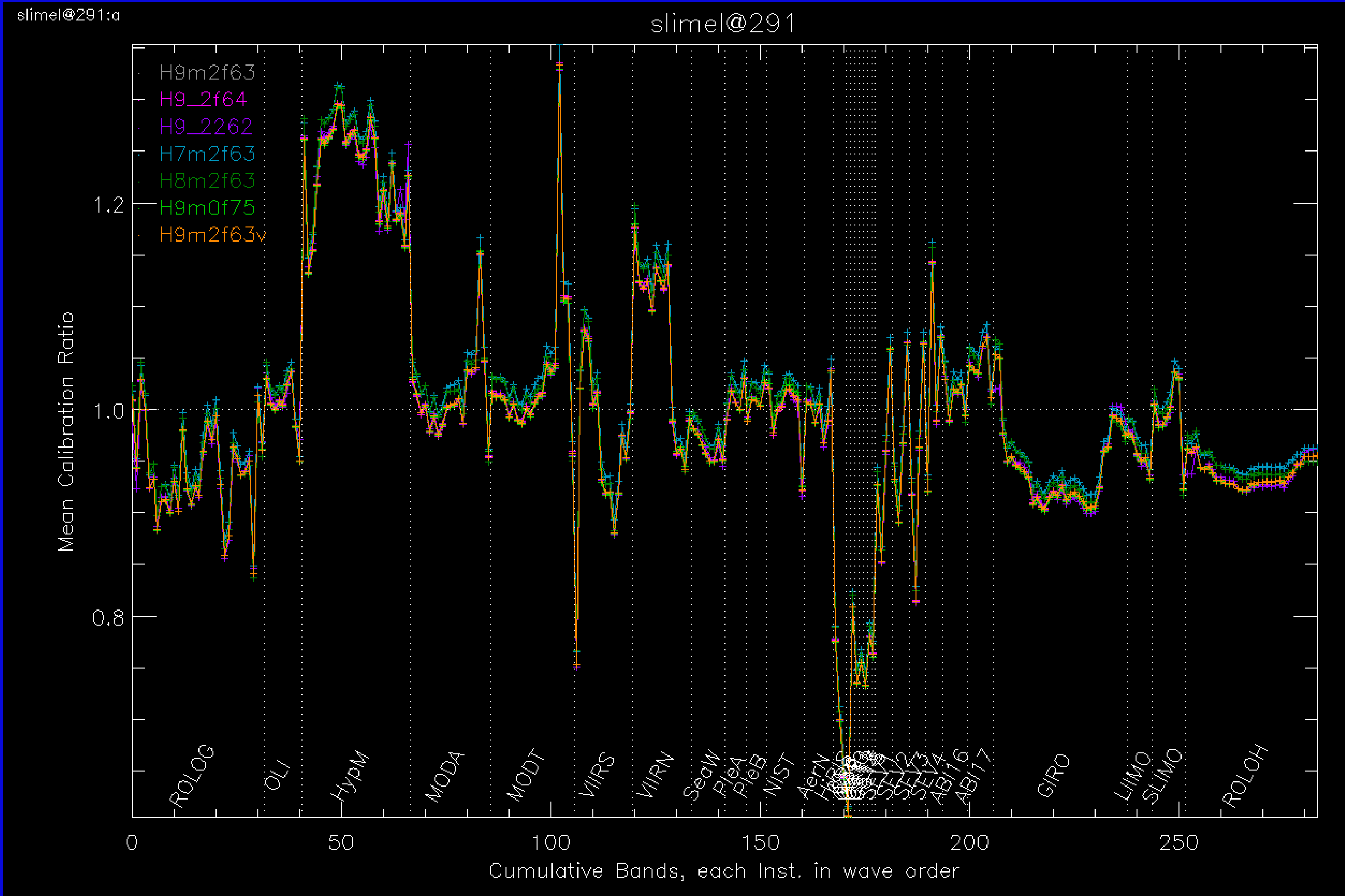
All but ⇑--------⇑ have 34 coefficients

% change in flux for 7 models, GSICS grid and bands



All but ⇧--------⇧have 34 coefficients

7 model calibration results for all instruments and models on GSICS geometry grid



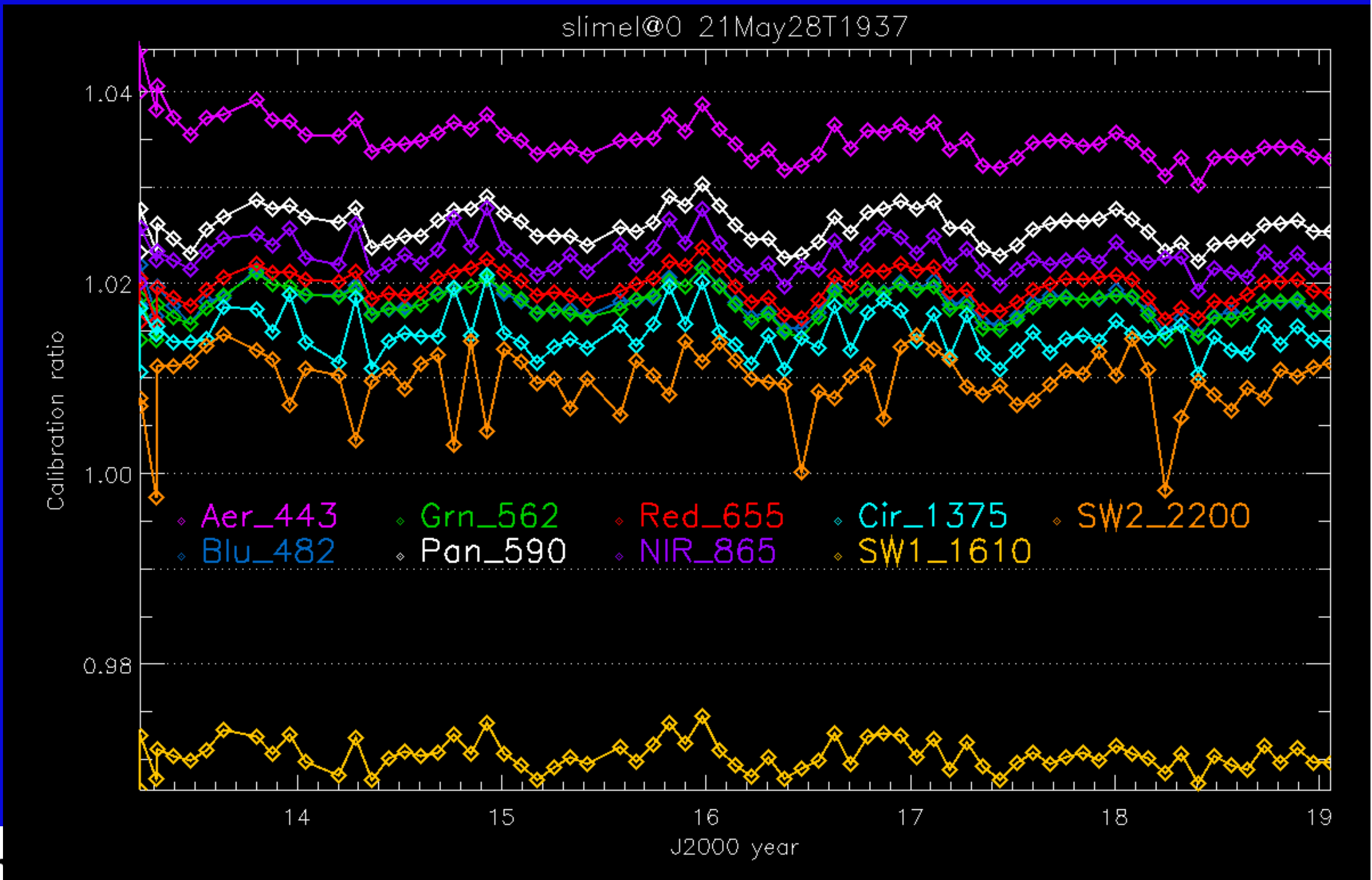
ROLOH is version 3 data with new reference solar model

OLI trends

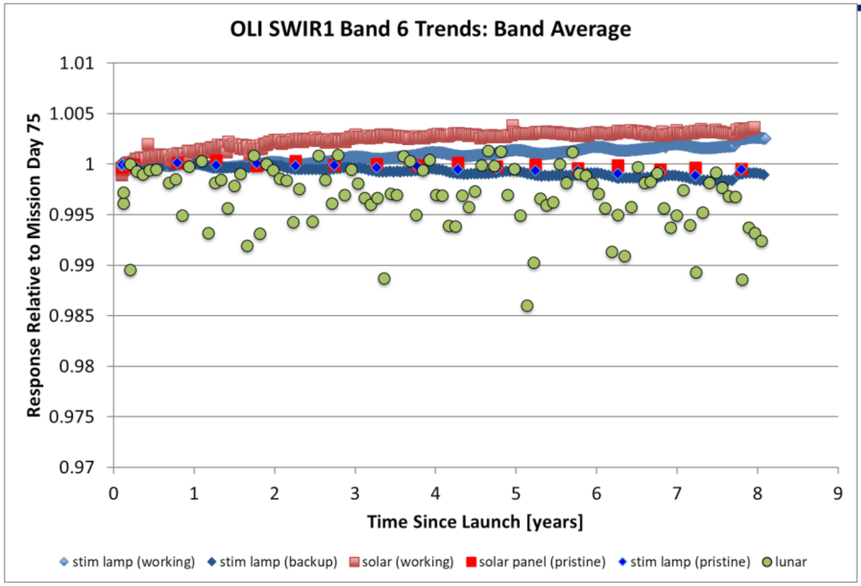
Amplitude: 6=SW1, 1610 nm
Lunar=ROLO: ~1%
SLIM Hbase: ~ 0.2%

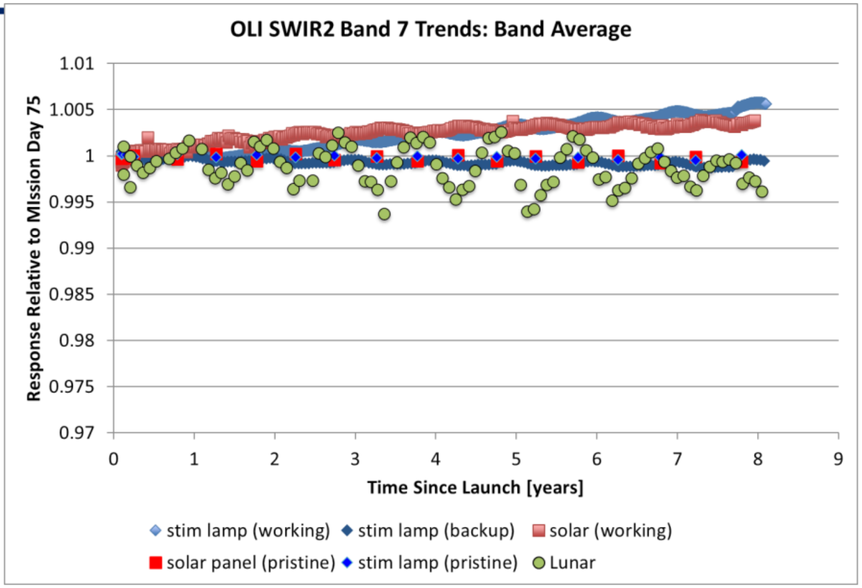
7=SW2, 2200 nm
Lunar=ROLO: 0.4%
SLIM Hbase: similar, period less clear

Only Aerosol shows decline

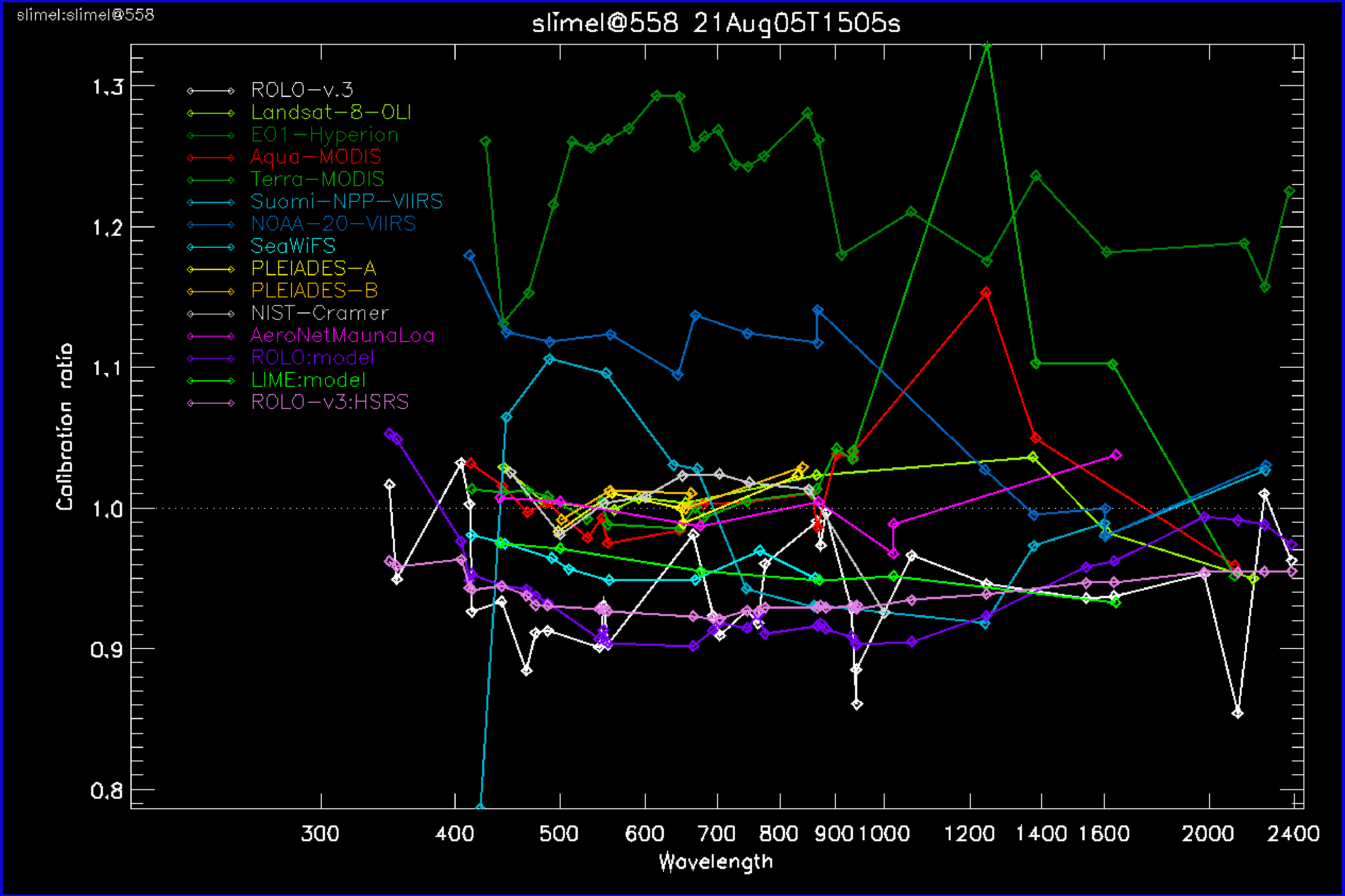


L8 OLI SWIR1 and SWIR2 Lun... With Onboard Calibration Solar Diffusor Panels and Lamps





Empirical Gains: LEO, surface, and models on GSICS



SLIMED is Base + Solar Variation MAR=0.633%. "Reality plot"

Aspects of SLIM calibration

Some major disagreements.
VIIRS very different than MODIS, but the same folks.?

Cluster below 880 nm of MODIS & PLEIADES & NIST
Relative to these, SeaWiFS about -5%, GIRO≡ROLO model about -10%

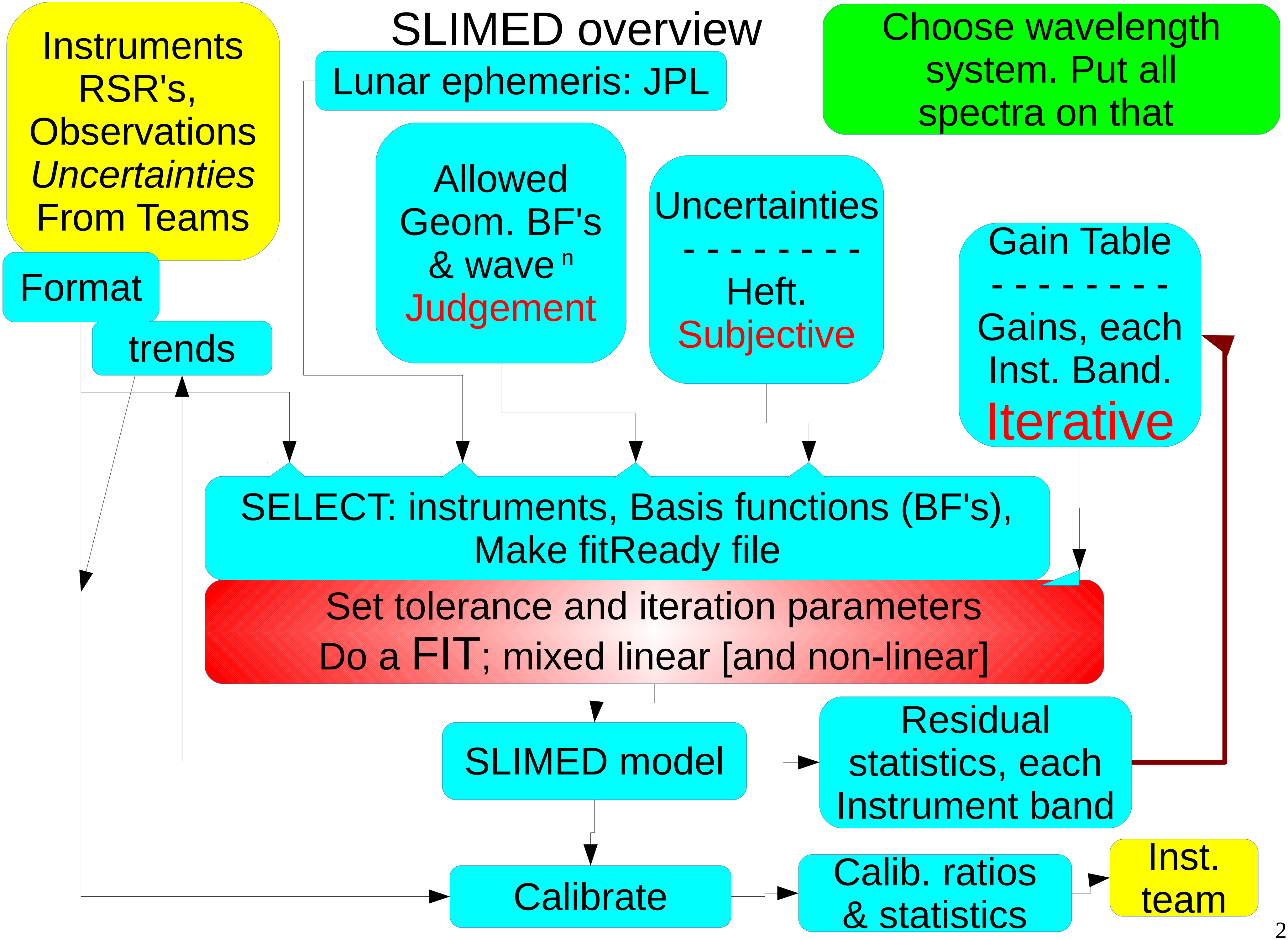
Using MapLib or SLIM ~12 libration basis functions yield similar models

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

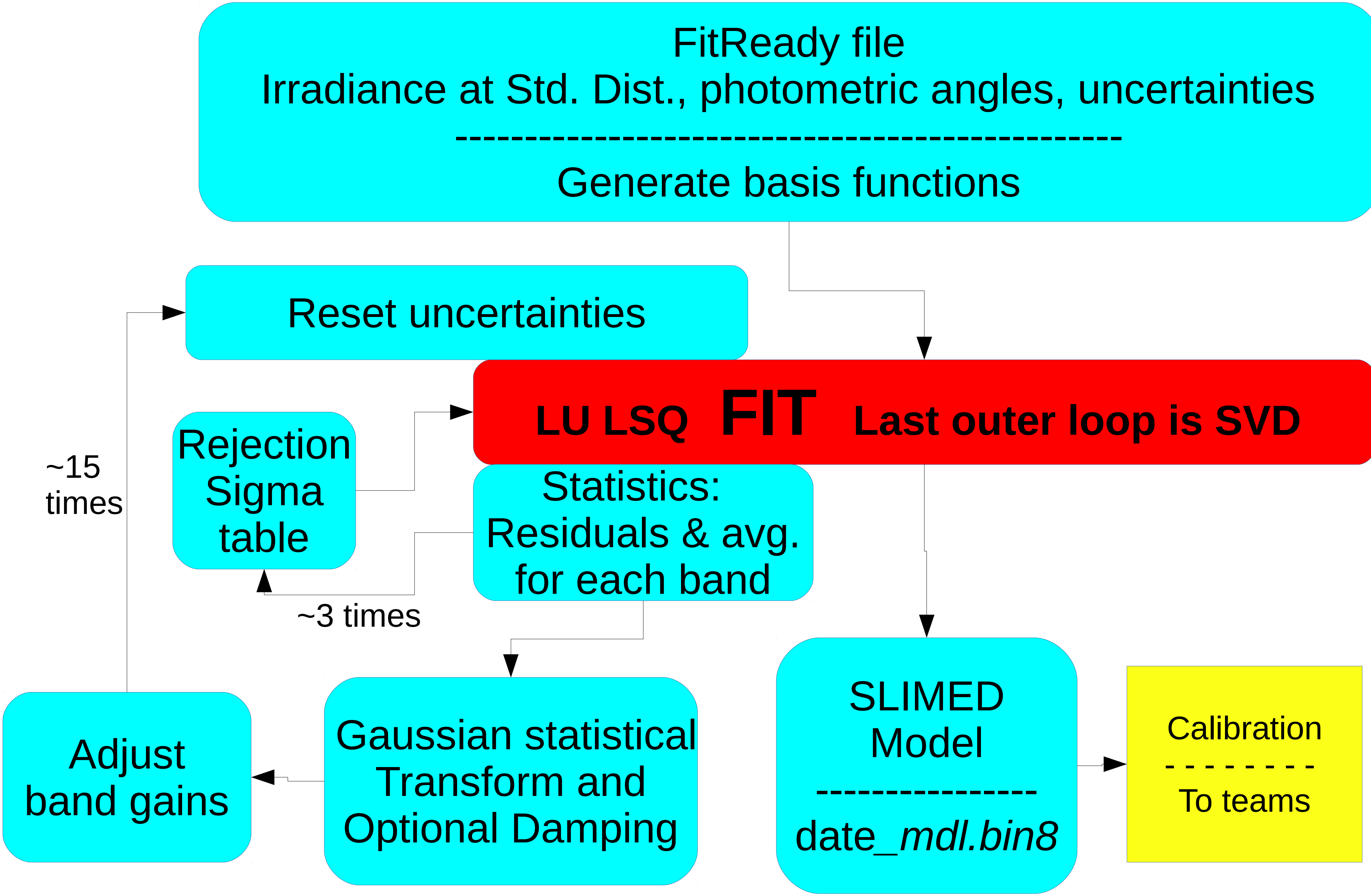
GEO calibrations are [much] more noisy than LEO.

Possible causes of large Lunar calibration differences
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!
Misunderstandings and blunders

SLIMED overview



SLIMED fit   Double iteration loops



Some conclusions

Believe that SLIM model is closer to true moon than ROLO
Absolute scale still uncertain, but differences between instruments are solid.

LEO's mostly within a few %, outliers may be due to maneuver or team procedures.
Fit trends; look for periodic behavior, sensitivity ~0.01%

Substantial problems exist in lunar calibration for a few instruments.
Instrument calibration must be better than indicated by lunar calibration.
∴ Irradiance extraction techniques need work.
Current irradiance is suspect, hence trending is suspect.

Serious need for high-accuracy lunar irradiance measurements at any phase:
Spectral resolution ≤ 1/ 15
Eagerly await upcoming higher accuracy observations

Teams should re-examine the image-to-irradiance methodology.
E.g., What is limiting GEO consistency?

Onward: External help and internal hints

By looking at calibration results for several models for many instruments versus phase or other angles, can get a sense of any unreality in the models and what direction to pursue.   (there are hundreds of figures)

Tuning the judgment areas is expected to get closer to the true Moon.
Higher power wave terms; inclusion of opposition effect terms.
Perhaps using rational functions.

This talk has been a solution for method,
the model is transitory.

Paper in progress. Plan to seek consensus on a specific model.
Start with base model shown here.

Needs: Better lunar reference spectrum
Uncertainty values from the instrument teams
Some good candidate instruments exist for inclusion.

Done: Thank you

Backup slides follow

Estimated sources of error

Item	expression	Native	in ppm Typical	in ppm 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.

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