Advances in the SLIM Lunar Spectral Irradiance Model;

Many Observations, One 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.

This is an update; with repeat of the fundamentals

Charts designed for later study

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.

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 of SLIMFIT

Normalize to a lunar reference spectrum, then fit with polynomials:
In geometry and "wave" (length λ or 1/λ or lnλ)
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 fit to 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 smaller than ROLO model
About 35 terms instead of 328 !

SLIMED method: isolate the high-res spectrum

Presume the lunar spectrum is product of high-resolution reference spectra of Sun and Moon, times a 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 Basis Functions

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:
$g \equiv | p |$ is the absolute value of p and $q \equiv 1/ | p |$

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

Instruments that provided irradiance

Instrument	Acro-nym	Number of band	Number of Luna	Number of time	Number of points	Launch date	Obs. Date First (yymondd)	Obs. Date last	phase angle min	phase angle min-Abs	phase angle max	Number Wax	Number 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	1
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

Model flexibility: joy and curse

Based on many [12] 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

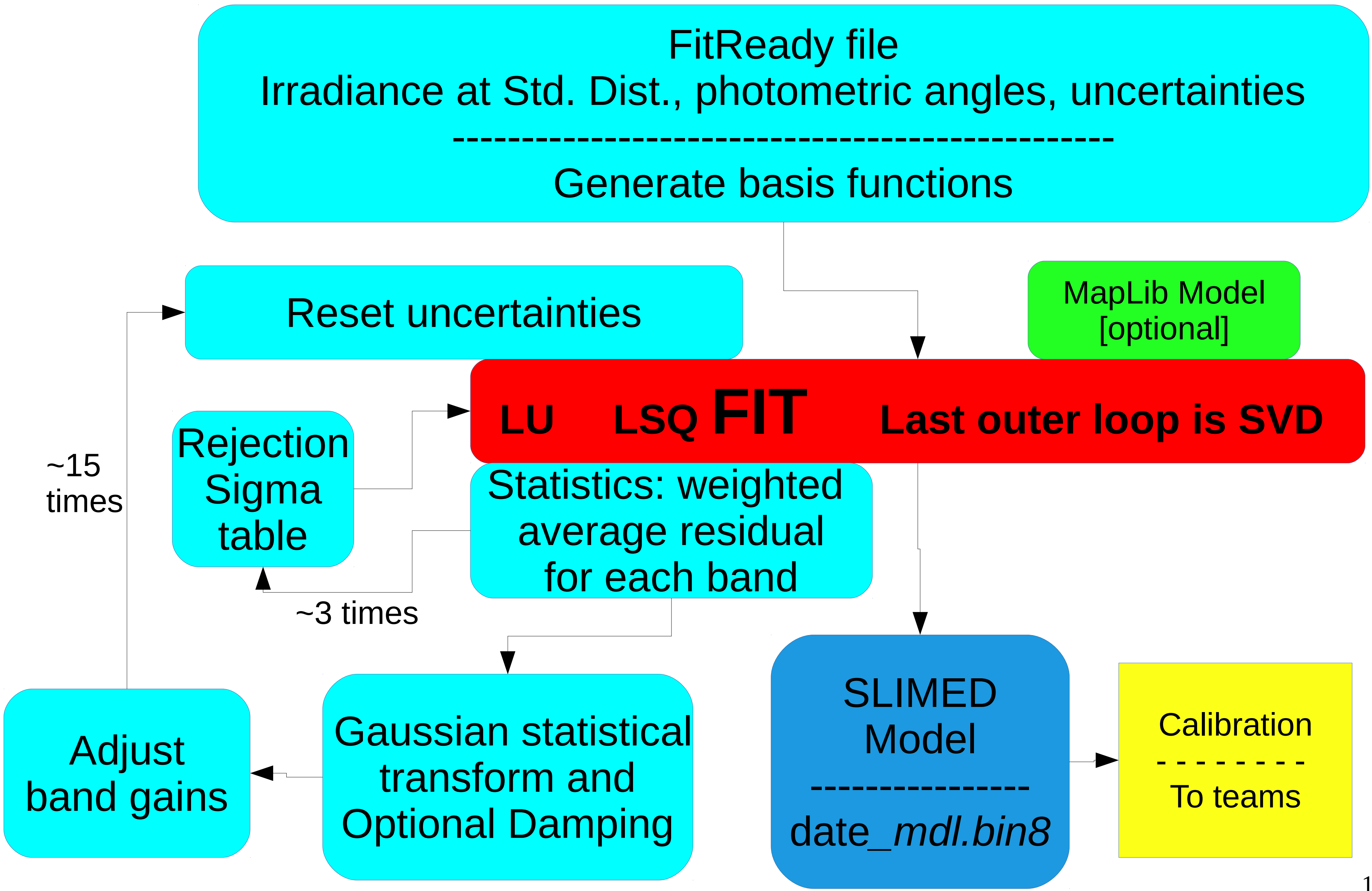
Decisions: some of the categories

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?**
5) **Include solar variation?**
6) **Which of the thousands of possible BF combinations to use.**
7) **Dozens of fit control parameters**

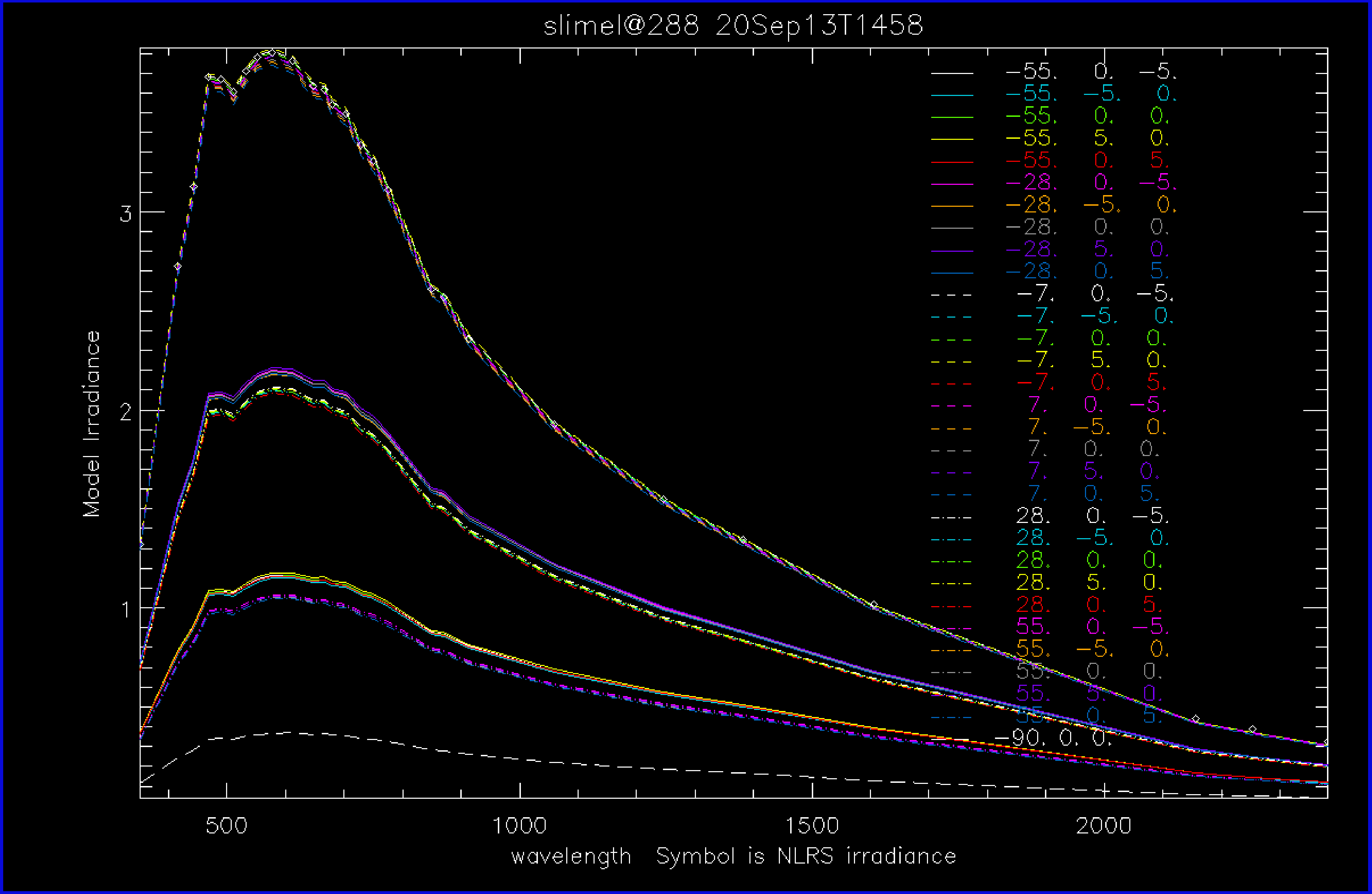
Nested fit iterations for outlier rejection and gain of each instrument band.
Typical model has 20:40 Basis Functions. [ROLO=GIRO has 328]
Mean absolute residual ∼0.65%

Calibrate all instruments in inventory, and some fabricated models.

SLIMED fit   Double iteration loops

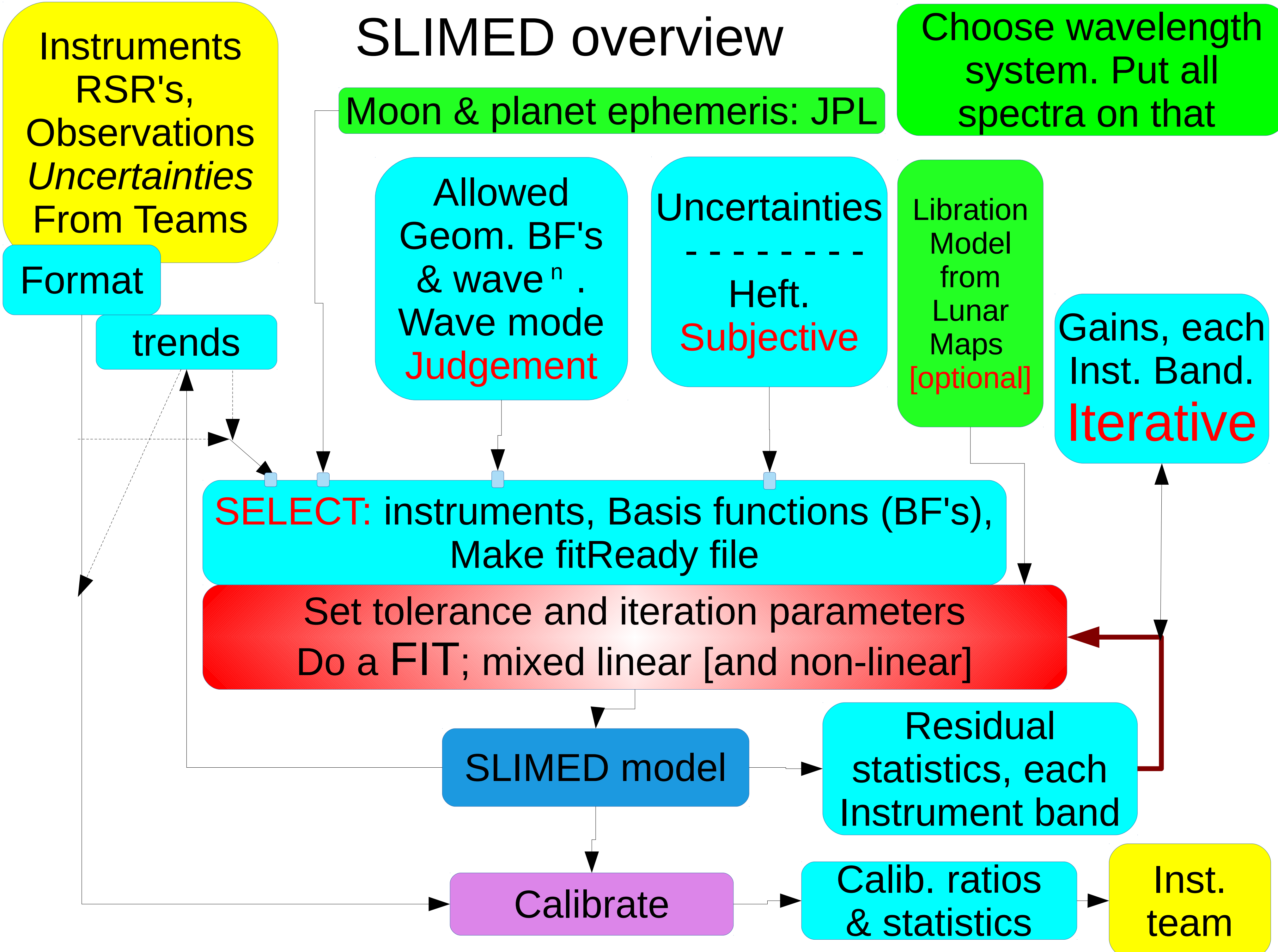


A SLIMED model: 34 terms, no MapLib



A 22-term model using MapLib correction is indistinguishable from this

SLIMED overview



Different Hefts => Weights: %

		Heft					resulting weight %					
Model name		22T1035	22T1039	22T1043	22T1052	23T1649						
“ alias		HAm2f62	H8m2f57	Hum2f60	H1m2f64	HBm2f62						
'what'		HiPleaB	low_ROLO	Uniform	Unity	Base	HiPleB	loROLO	Unif	all_1	Base	~
Inst.	UncAve	A	8	u	1	B	A	8	u	1	B	
ROLOG	0.05	0.32	0.033	0.211	1.0	0.335	19.15	2.07	8.34	39.53	20.00	20
OLI	0.03	0.3	0.5	0.391	1.0	0.310	9.67	16.88	8.34	21.30	9.97	10
HypM	0.10	5.7	5.0	73.0	1.0	5.936	0.96	0.88	8.12	0.11	1.00	1
MODT	0.05	0.364	1.0	0.479	1.0	0.379	9.58	27.62	8.36	17.38	9.96	10
MODA	0.05	0.465	1.0	0.69	1.0	0.432	8.57	19.42	8.42	12.09	7.95	8
VIIRS	0.05	3.7	1.0	9.7	1.0	3.856	4.8	1.36	8.32	0.86	4.99	5
VIIRN	0.05	18.4	2.0	24.0	1.0	19.250	9.56	1.09	8.25	0.34	9.98	10
SeaW	0.03	1.57	2.0	2.1	1.0	1.644	9.56	12.75	8.45	4.02	9.99	10
PleA	0.05	4.6	2.0	17.3	1.0	10.974	3.36	1.53	8.34	0.48	7.99	8
PleB	0.05	9.2	2.0	7.6	1.0	4.777	15.42	3.5	8.42	1.10	7.99	8
NIST	0.006	1.65	2.0	4.3	1.0	1.722	4.79	6.08	8.26	1.92	4.99	5
AerN	0.03	3.5	5.0	9.7	1.0	4.000	4.57	6.83	8.38	0.86	5.21	5

Only VIRRS (Suomi) is trend-corrected

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
Any systematic calibration bias over all instruments would be incorporated into a model

21Aug23T1645=a45 a58=21Aug23T1649 LibMod=21Aug13T1720 jit=16
Slim?.inp, ?_unc.bin8, heft?.tab, *_eg.bin8, H, wP= d 1 B unity 1 f
ROLOG OLI HypM MODT MODA VIIRS VIIRN SeaW PleA PleB NIST AerN

Typical model

This is the Base model: (for this talk) 21Aug23T1649 or w3Base

i	name	symbol	value*E3	uncert*E3	val*StD*E3
0	const	1	175.193	2.82517	-----
1	const.1	1w	6.186	2.47899	2.690
2	const.2	1w^2	-97.138	3.02284	24.677
3	phase:	p	-1264.620	1.73289	524.196
4	phase:2	p^2	175.427	3.26259	103.076
5	phase:3	p^3	-163.152	4.20912	129.636
6	phase:.1	pw	274.706	1.85347	96.983
7	phase:.2	pw^2	-29.183	2.91562	6.432
8	phase:2.1	p^2w	-88.165	9.14899	34.954
9	1/g:	q	3.266	10.91622	9.806
10	1/g:2	q^2	0.388	9.69891	12.233
11	1/g:.1	qw	-9.962	1.83193	22.465
12	1/g:.2	qw^2	0.680	9.92877	1.052
13	1/g:2.1	q^2w	0.390	23.25776	7.862
14	Hb:	h	49.751	27.97480	38.201
15	Hb:3	h^3	10.623	3.04355	10.383
16	Hb:5	h^5	-4.296	0.39852	7.158
17	Hb:.1	hw	3.695	1.15352	1.484
18	Hb:.2	hw^2	-8.151	0.96292	2.316
19	Hb:3.1	h^3w	-0.277	0.66905	0.141
20	Hlat	z	-1.629	0.87916	1.751
21	Hlat.1	zw	-0.403	0.78774	0.238
22	LibraX	x	-0.926	0.53844	4.082
23	LibraY	y	0.146	0.47195	0.707
24	LibraX:2	x^2	-0.018	0.12164	0.292
25	LibraY:2	y^2	-0.003	0.12506	0.058
26	LibraX.1	xw	0.022	0.24905	0.052
27	LibraY.1	yw	0.272	0.22677	0.723
28	Hb*LibX	(hx)	-0.494	0.16705	1.855
29	Hb*LibY	(hy)	-0.012	0.11757	0.046
30	Hb*LibX:2	(hx)^2	0.007	0.04689	0.159
31	Hb*LibY:2	(hy)^2	-0.001	0.03278	0.027
32	Hb*LibX.1	(hx)w	-0.210	0.01490	0.415
33	Hb*LibY.1	(hy)w	-0.178	0.03186	0.361

Uncert*E3 is formal SVD uncertainty

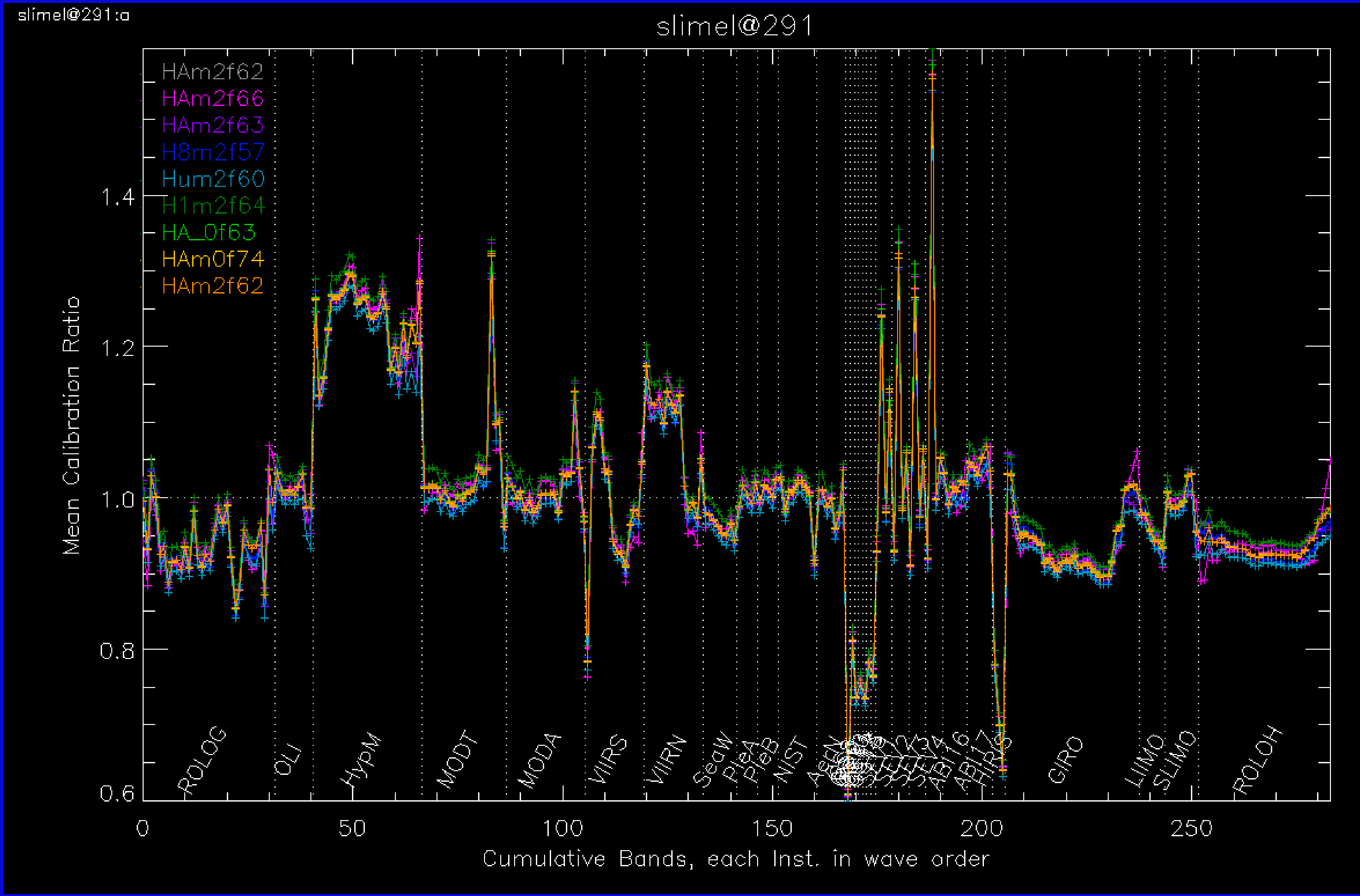
34 coefficients,
- 18 are pure geometric
- 16 involve wave, here ln λ

With MapLib and Solar variation
Mean absolute residual: MAR= 0.62%

Columns 3 and 4, Symbol and value, +MapLib, are a complete specification of this SLIMED model !

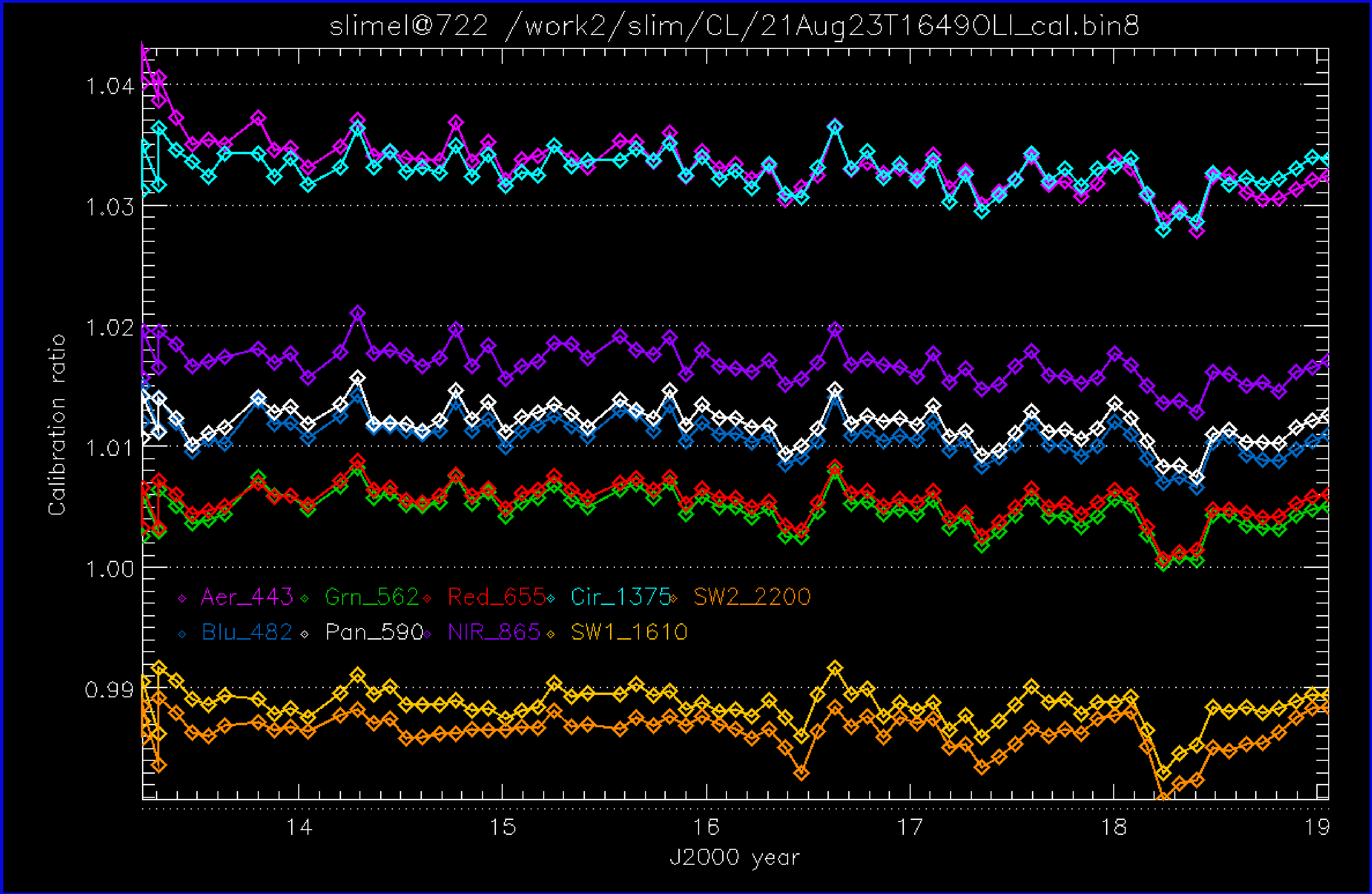
Last col: Magnitude == importance:
Absolute magnitude of the coefficient times the standard deviation of the basis function

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



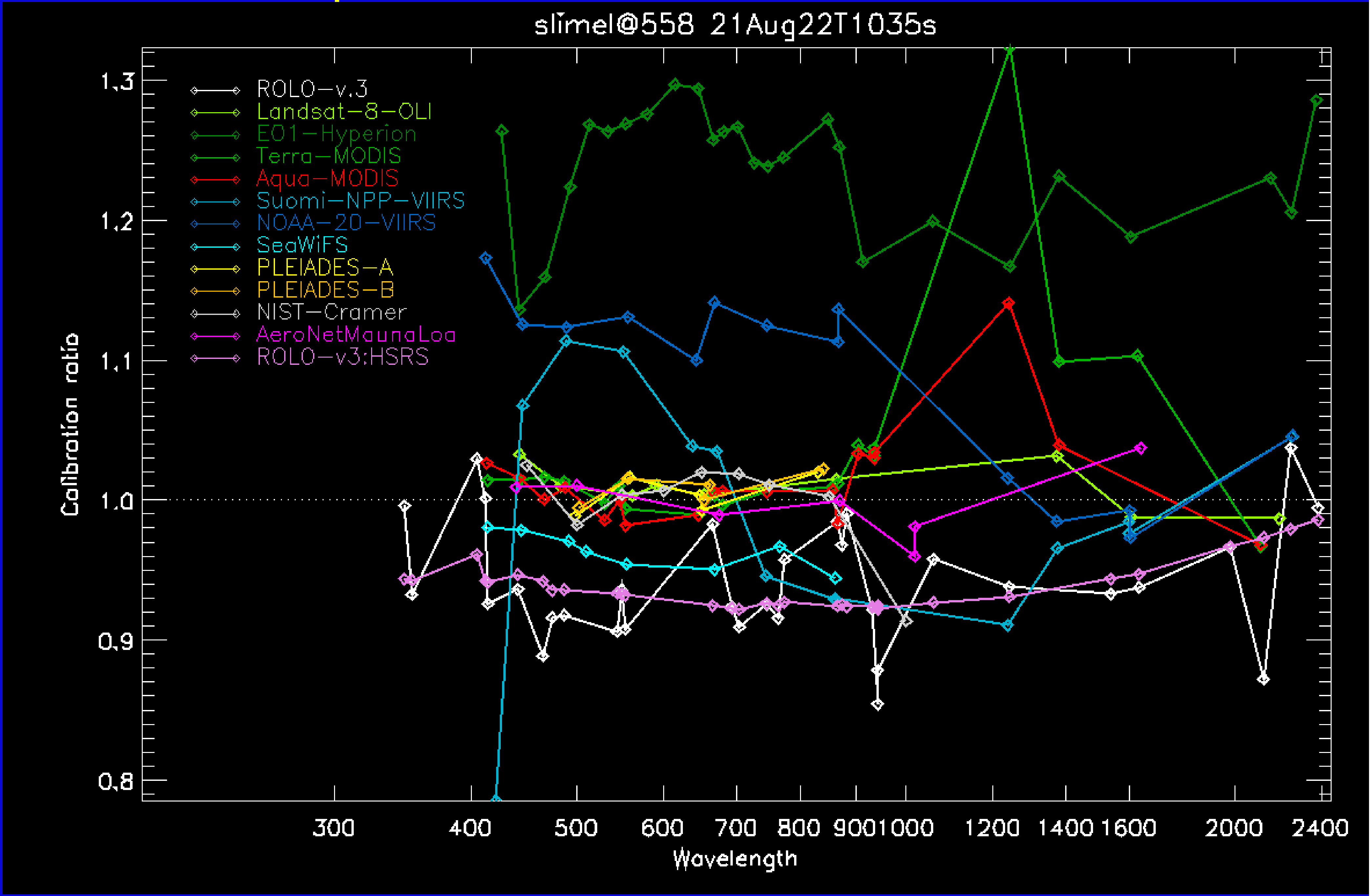
ROLOH is version 3 data with new reference solar model

Trends: sensitivity ~0.1%. OLI example



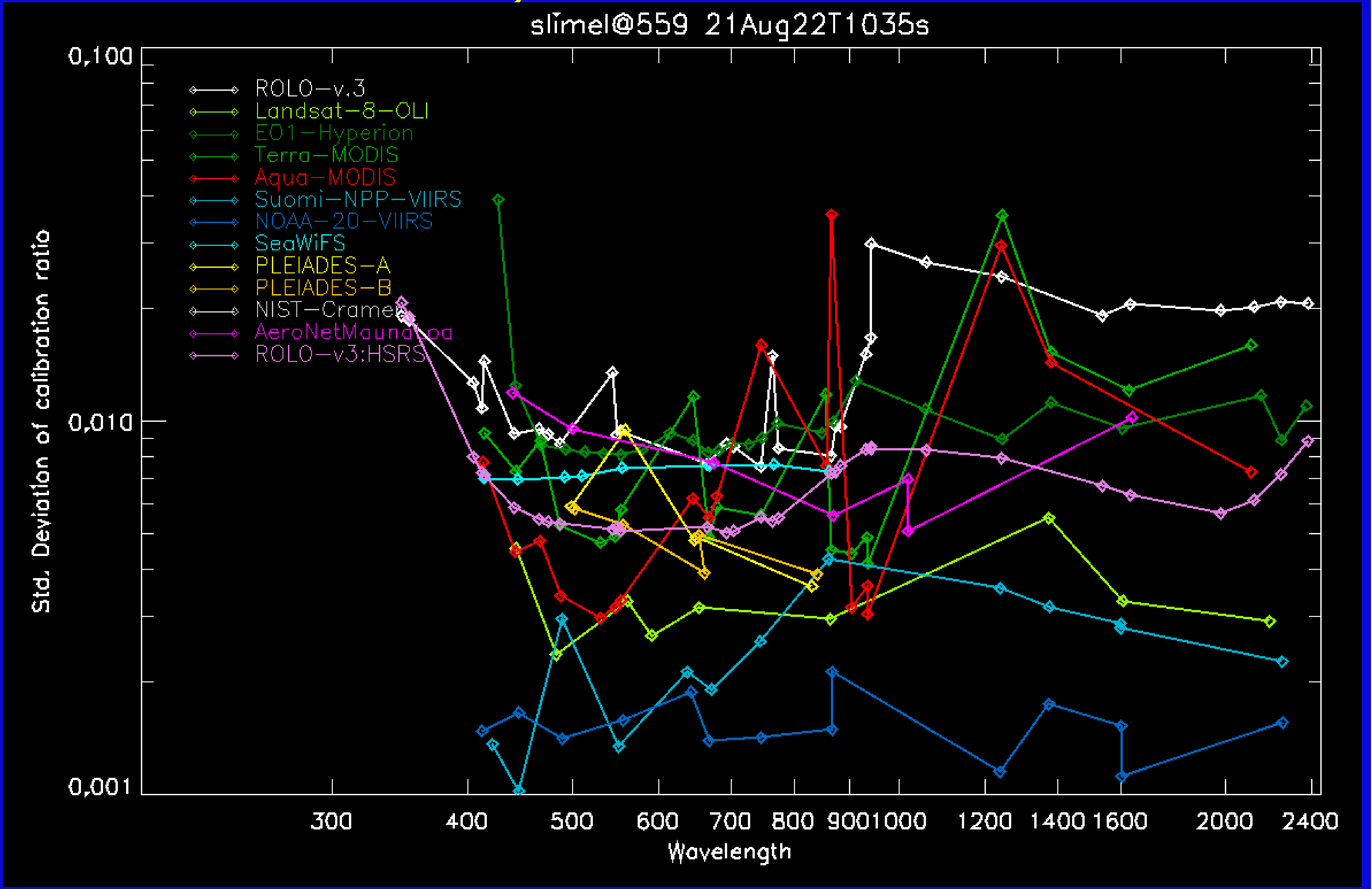
Only Aerosol band shows decline; first 1/2 year
With ROLO model, SW1 ~1.5% scatter, SW2 ~0.8% annual

Empirical Gains: LEO and surface obs.



Model: ln λ , MapLib, Solvar. MAR=0.62%. "Reality plot"

Consistency of observations to model



NOAA-20 VIIRS best. HSRS ROLO better than version 3. Some MODIS bands poor

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. ABI-17 excepted.

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

Some conclusions

A lot of decisions are required

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

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%

Serious need for high-accuracy lunar irradiance measurements at any phase:
Spectral resolution 1/ 15 or better
Eagerly await upcoming higher accuracy observations.
SLIMED models indicate need of a better lunar reference spectrum.
All 3 wave methods drop at extreme wavelenghts, ln λ the least.

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.
If instrument irradiance is suspect, then any trending is suspect.

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