Seeking a consensus evolutionary lunar calibration model

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Many observations, one Moon.

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Celestial Reasonings

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A general discussion of lunar calibration, models, goals and attitudes

Apologies, I have no tech help to make nice charts.

cal con
www.calcon.sdl.usu.edu

The Moon as a Calibration Target

“All you have to do is look at the Moon” 2003

+ Appropriate radiance range for Earth-viewing instruments
+ Reflectance properties are virtually invariant ($<10^{-8}$/yr)
+ Spectrally bland (returned Apollo samples)

– Non-uniform reflectance, complex photometric behavior
  - Requires a spectral-photometric model
  - Potentially knowable to high accuracy

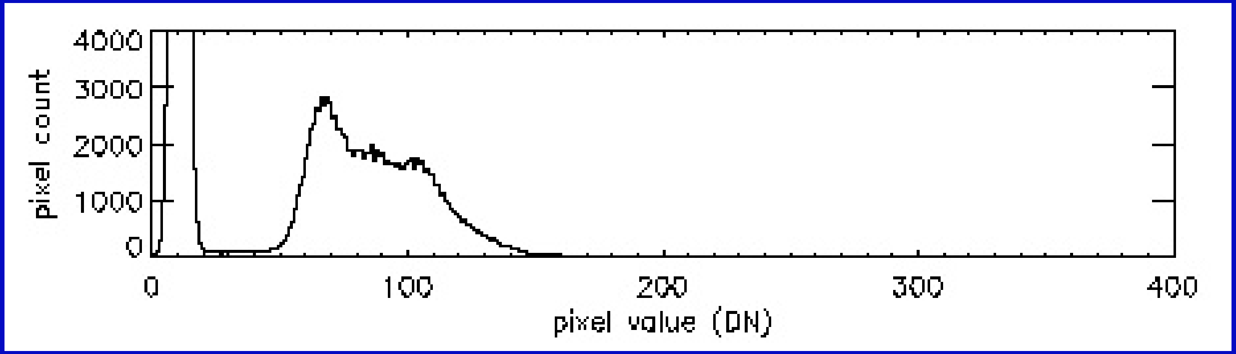
+ Accessible to spacecraft regardless of orbit
  – Commonly requires an attitude maneuver
+ Can be used as a transfer source between spacecraft

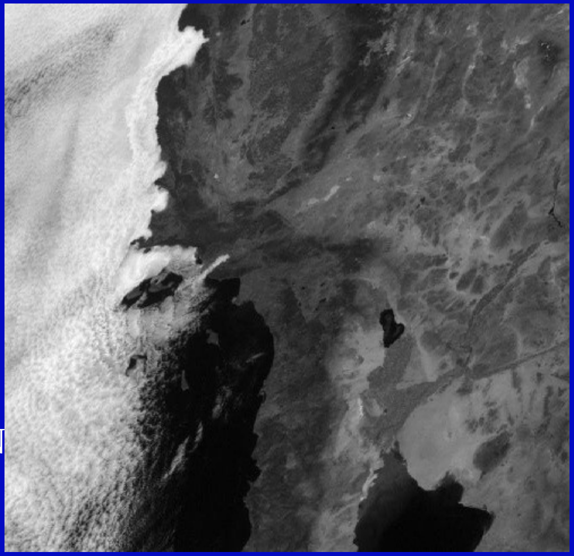
Most stars are variable. None is as well known as the Sun.

Dynamic Range of Moon at small phase ~land
Extracts from GOES-12 image; 9.5° phase

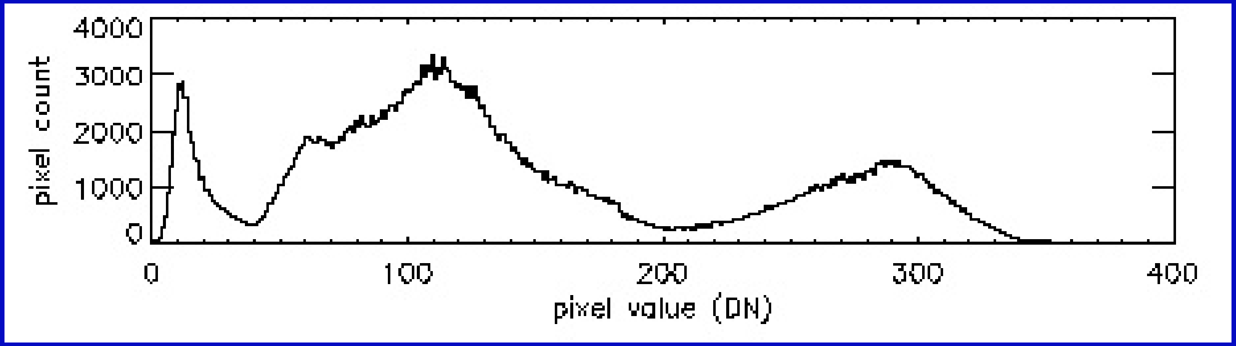
Geometry corrected

Space Moon





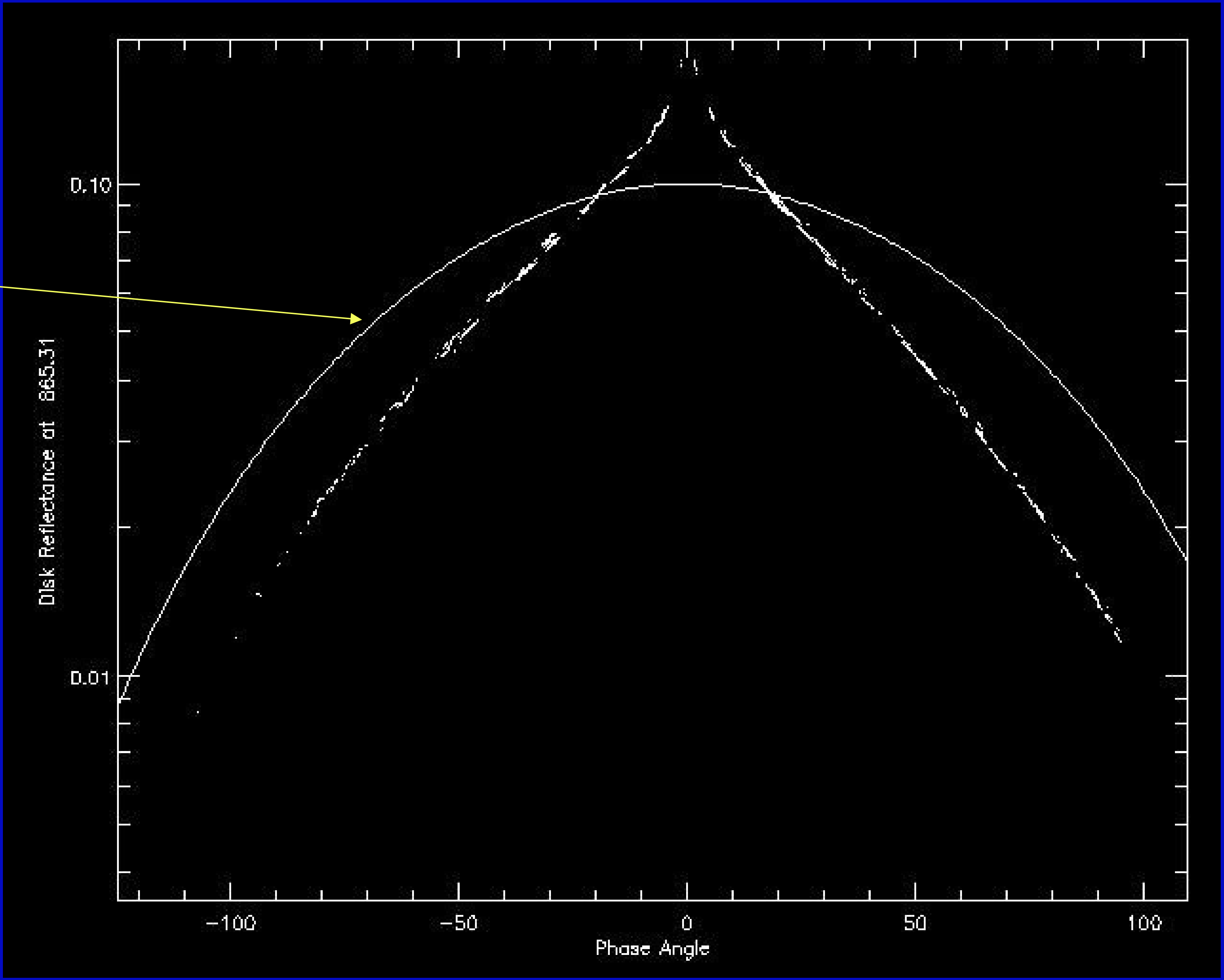
Ocean Land Cloud



ROLO observations for one band: 865 nm

Lambert Sphere

Data spread is libration; Noise is 5 times smaller



Polarization of the whole Moon 90'th anniversary

No whole-Moon observations since!   Max is 8.8%.

Zero near 23 º

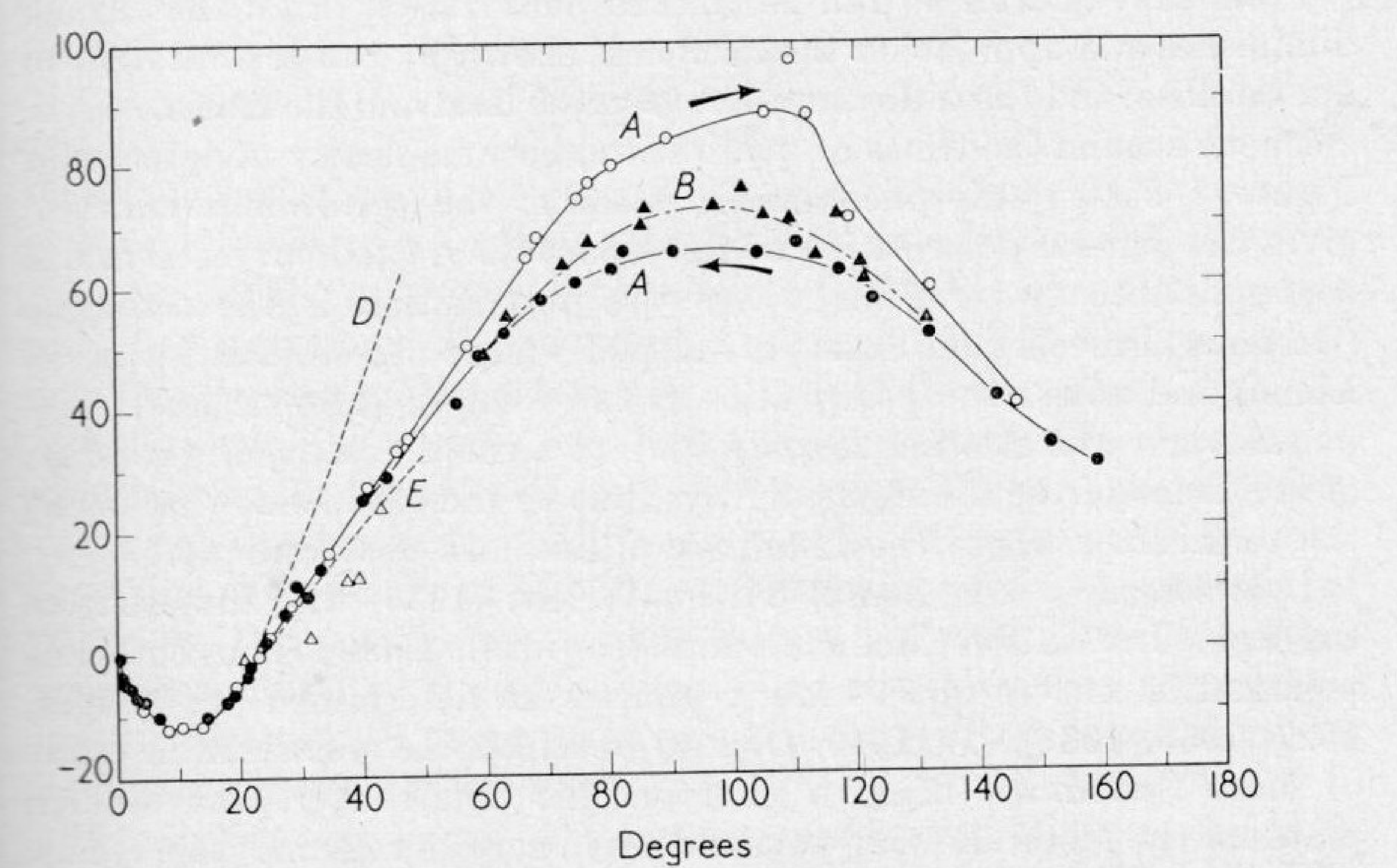


FIG. 1. The polarization curve of the Moon (after Lyot, 1929). Abscissae: proportion of polarized light of the Moon and Mercury (in units of 0·001). Ordinates: phase-angle (in degrees).

Polarization versus wavelength: local areas

Expected to apply to whole Moon

Dollfus, 1971
Fit is linear in log λ

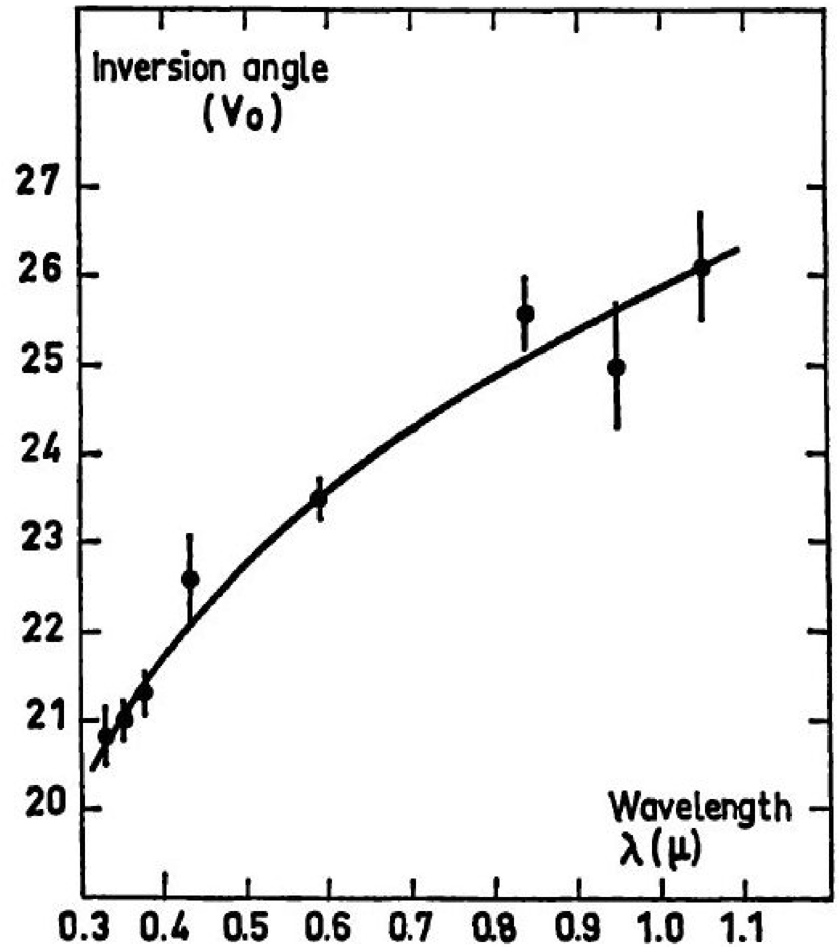


Fig. 18. Phase angle at which the zero polarisation occurs, as a function of wavelength

Basic Sun-Earth-Moon geometry

Due to apsidal,axial and nodal precession, Moons orbit and orientation are complex,
But extremely well known (cm level).

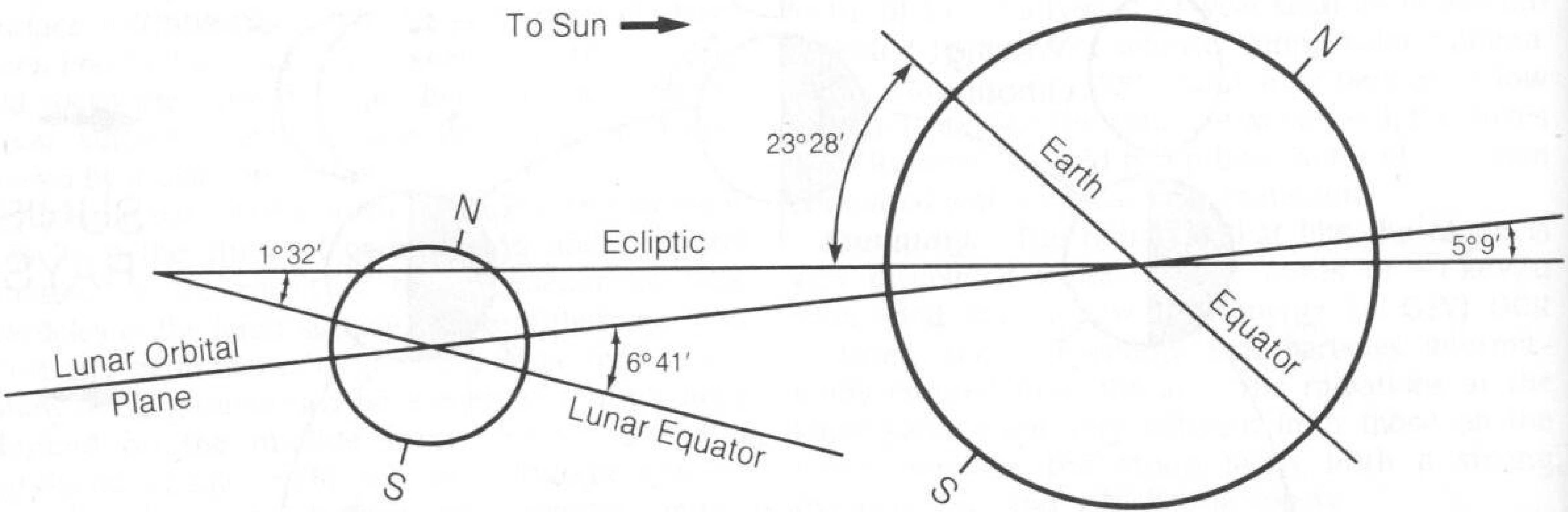
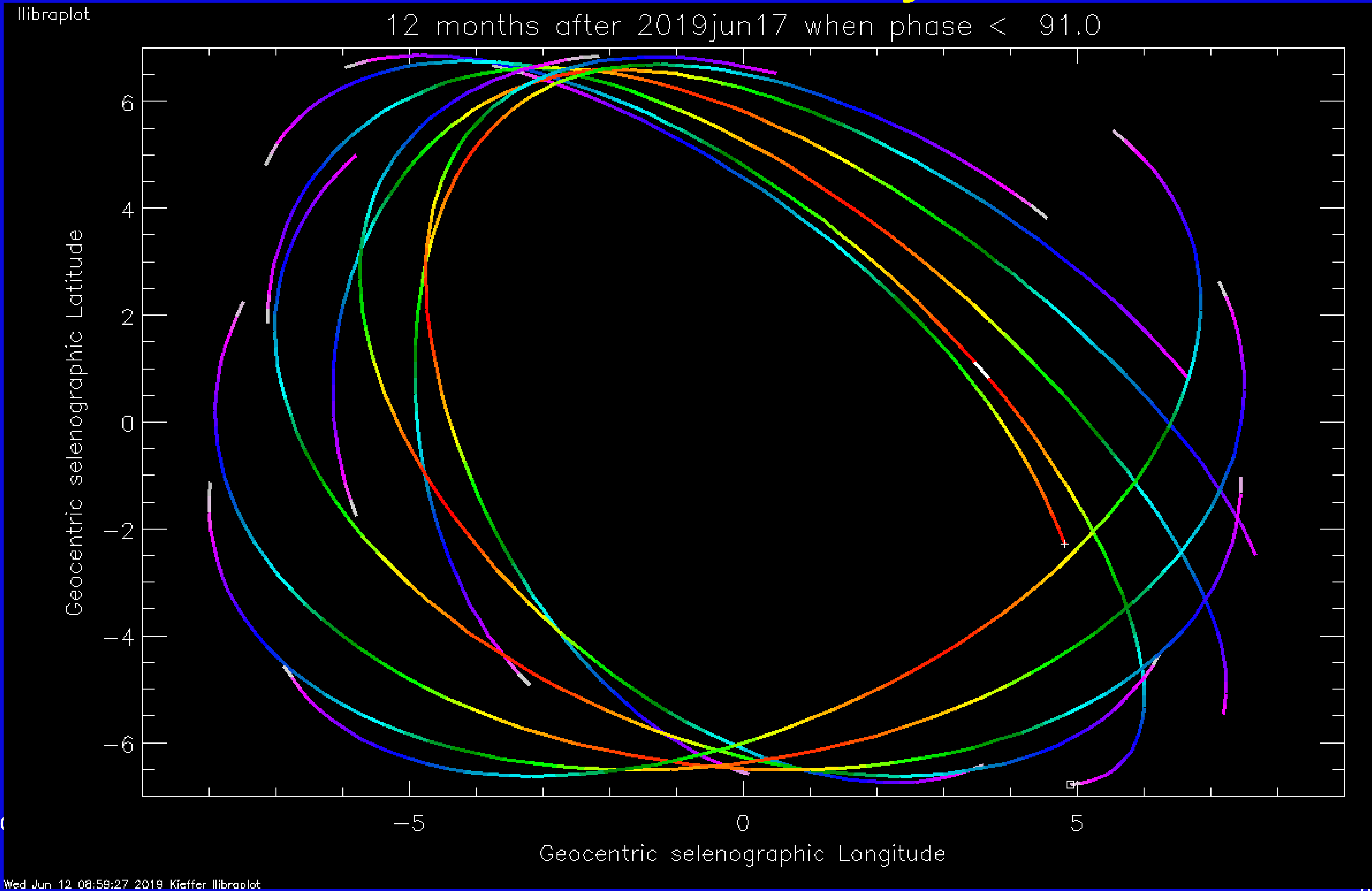


Fig. A3.2. Geometric relationship between the planes of revolution and rotation in the Earth–Moon system. Note that angular relationships have been exaggerated (from *Mutch,* 1970).

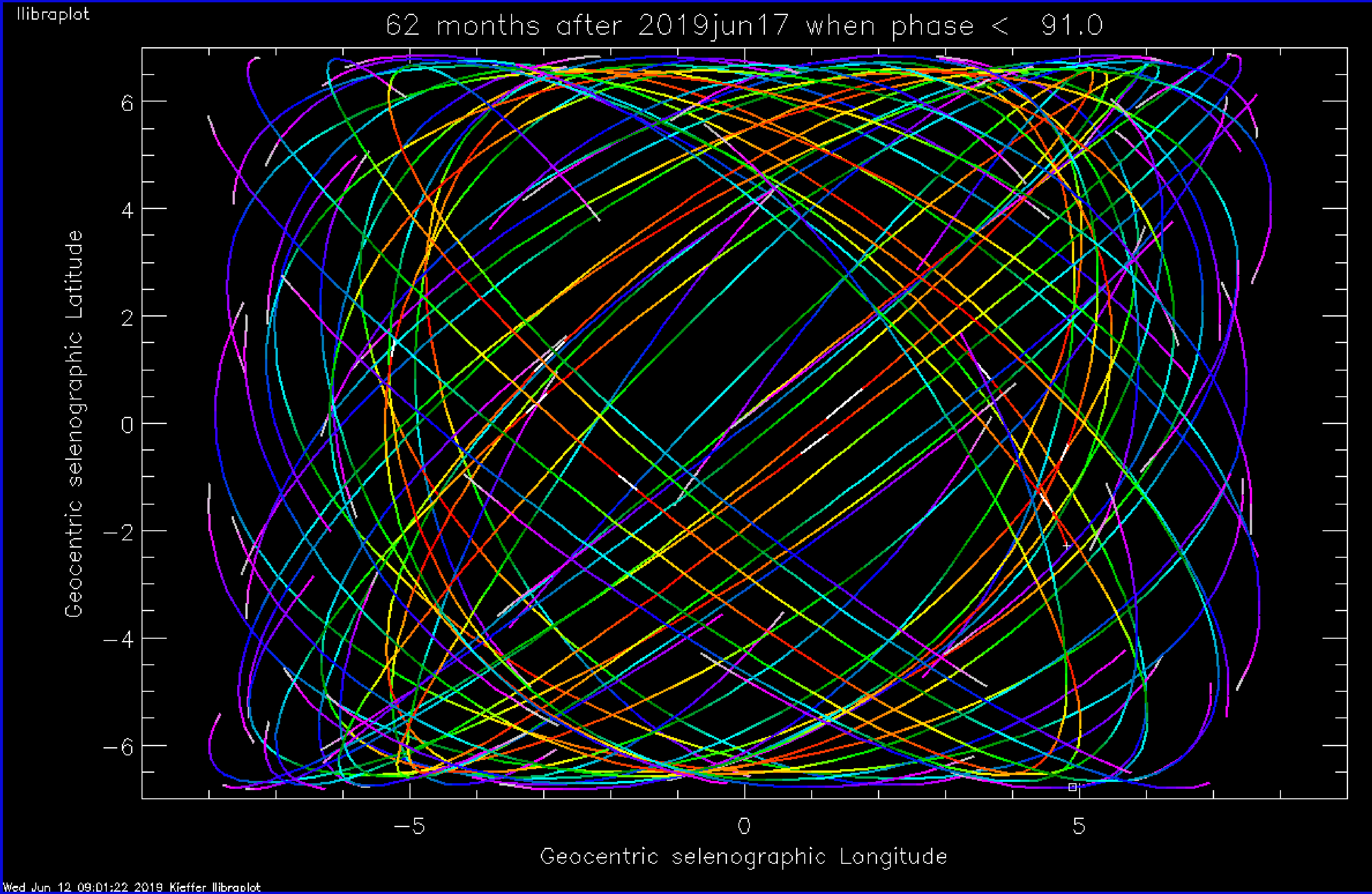
From Lunar Sourcebook

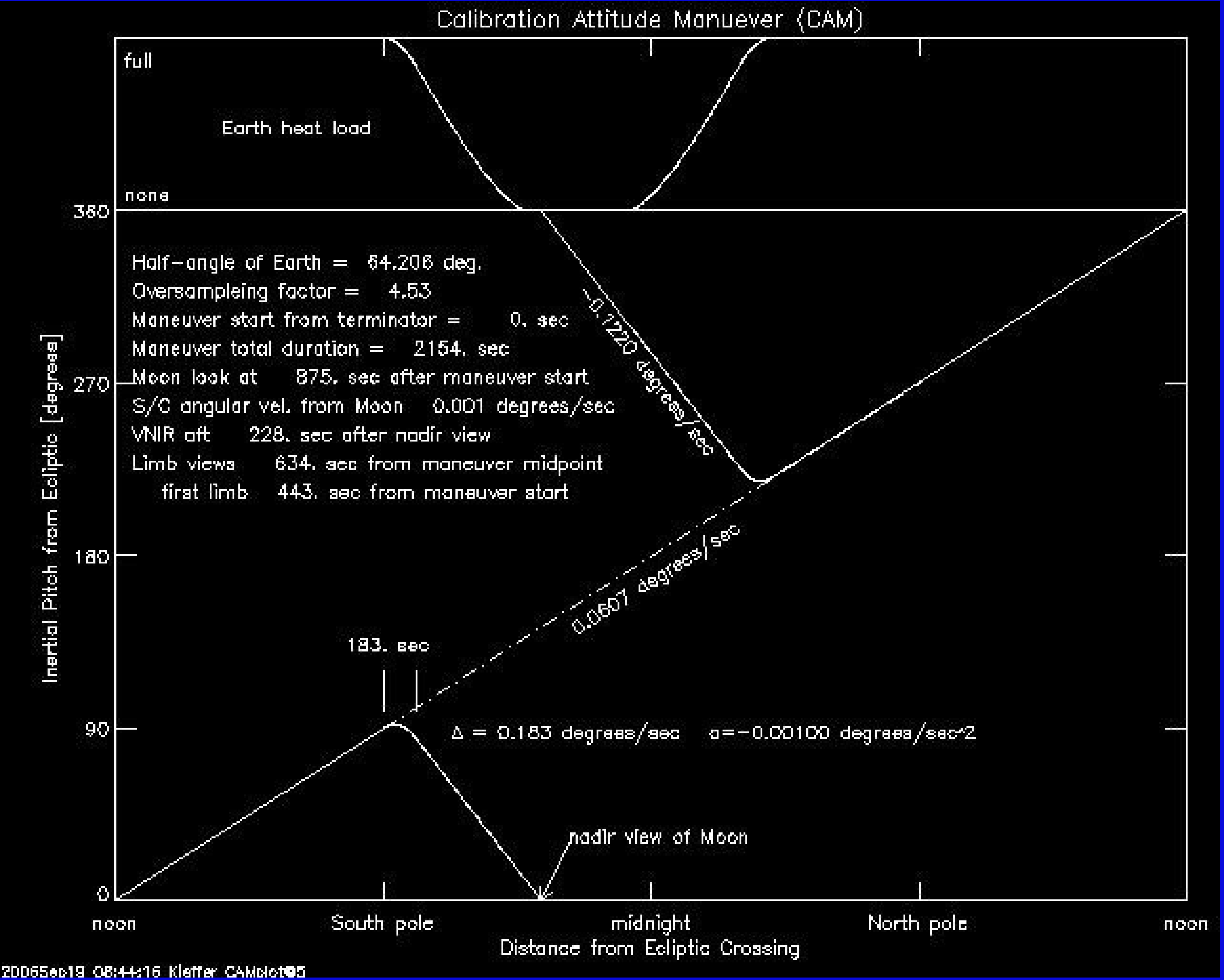
Libration over a year



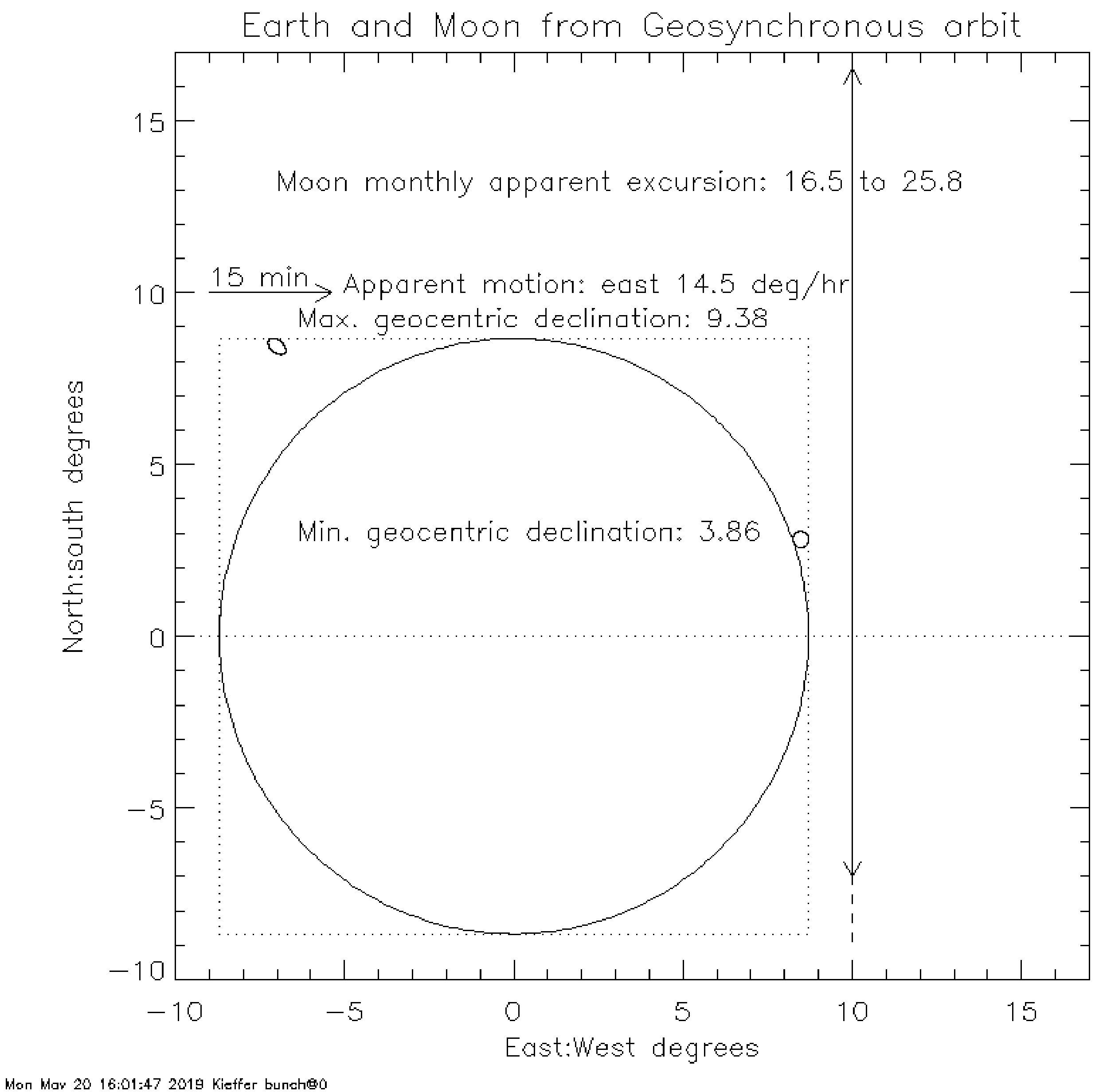
Color is absolute phase angle, white is near eclipse

Libration over 1/4 node precession cycle; 62 months




Calibration Attitude Manuever (CAM)
full
Earth heat load
none
360
270
180
90
0
Half-angle of Earth = 64.206 deg.
Oversampleing factor = 4.53
Maneuver start from terminator = 0. sec
Maneuver total duration = 2154. sec
Moon look at 875. sec after maneuver start
S/C angular vel. from Moon 0.001 degrees/sec
VNIR aft 228. sec after nadir view
Limb views 634. sec from maneuver midpoint
first limb 443. sec from maneuver start
-0.1220 degrees/sec
0.0607 degrees/sec
183. sec
Δ = 0.183 degrees/sec a=-0.00100 degrees/sec^2
nadir view of Moon
Inertial Pitch from Ecliptic [degrees]
noon
South pole
midnight
North pole
noon
Distance from Ecliptic Crossing
2006Sep19 08:44:16 Kieffer CAMplot95

Moon as seen by Geosynchronous scanner



If off-nadir:
Max Delta libration
Geocentric to
Geosynchronous:

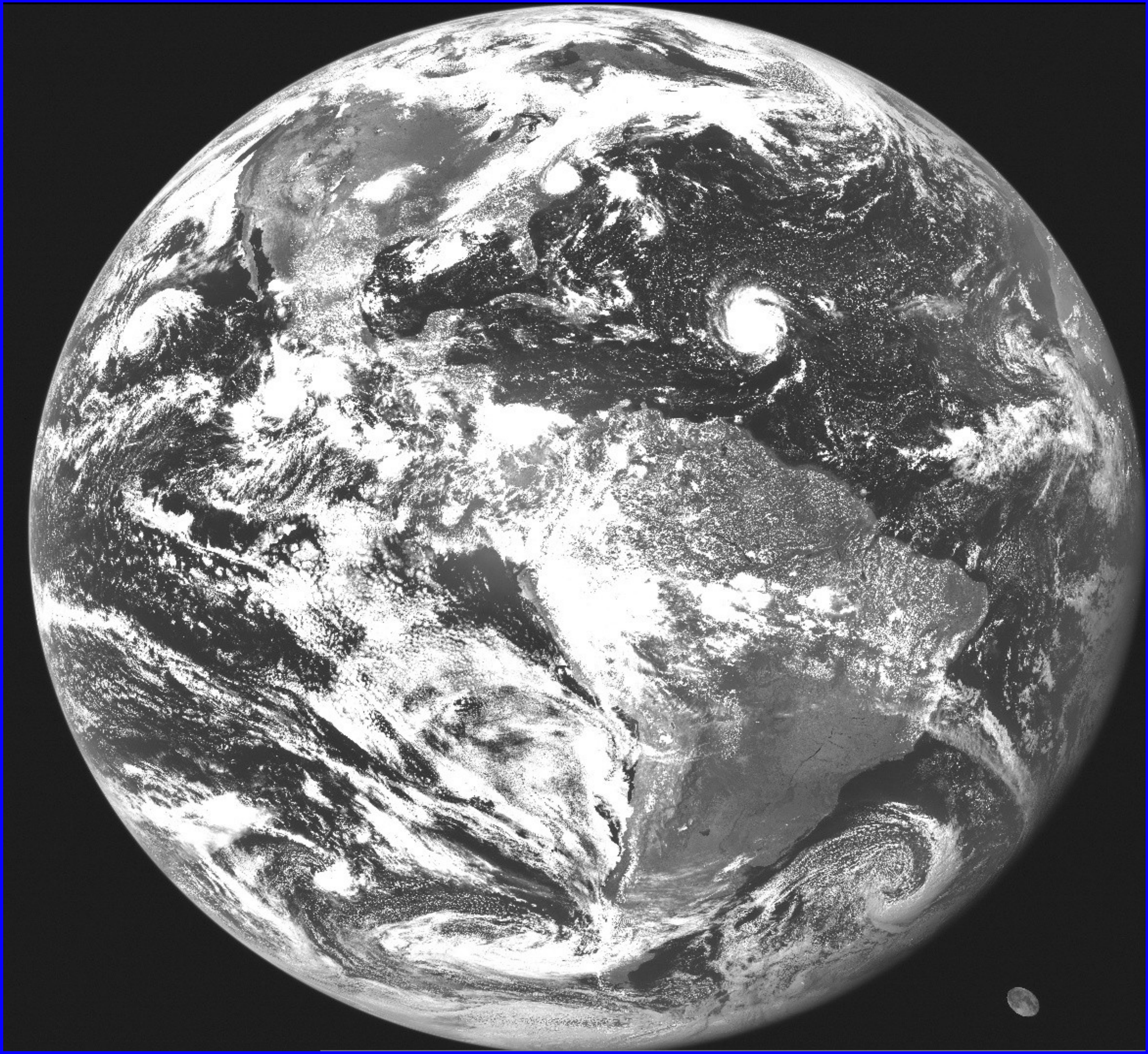
Vlon=6.27°
Vlat=3.32°

Raw GOES-12 image 2004Aug30 17:45:14

Shifted

Over-sample correct.

20

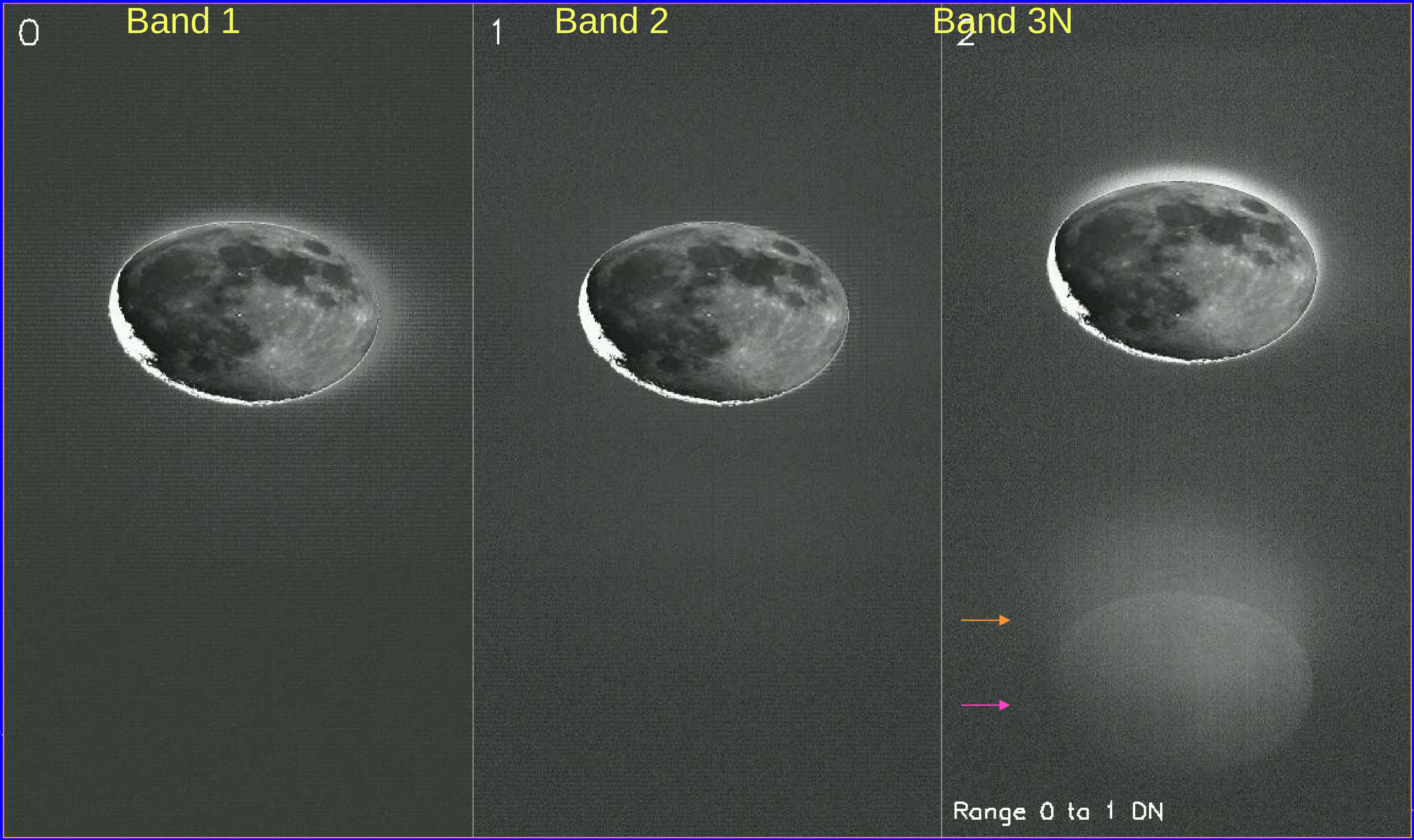


ASTER VNIR scattered light: 1 DN stretch

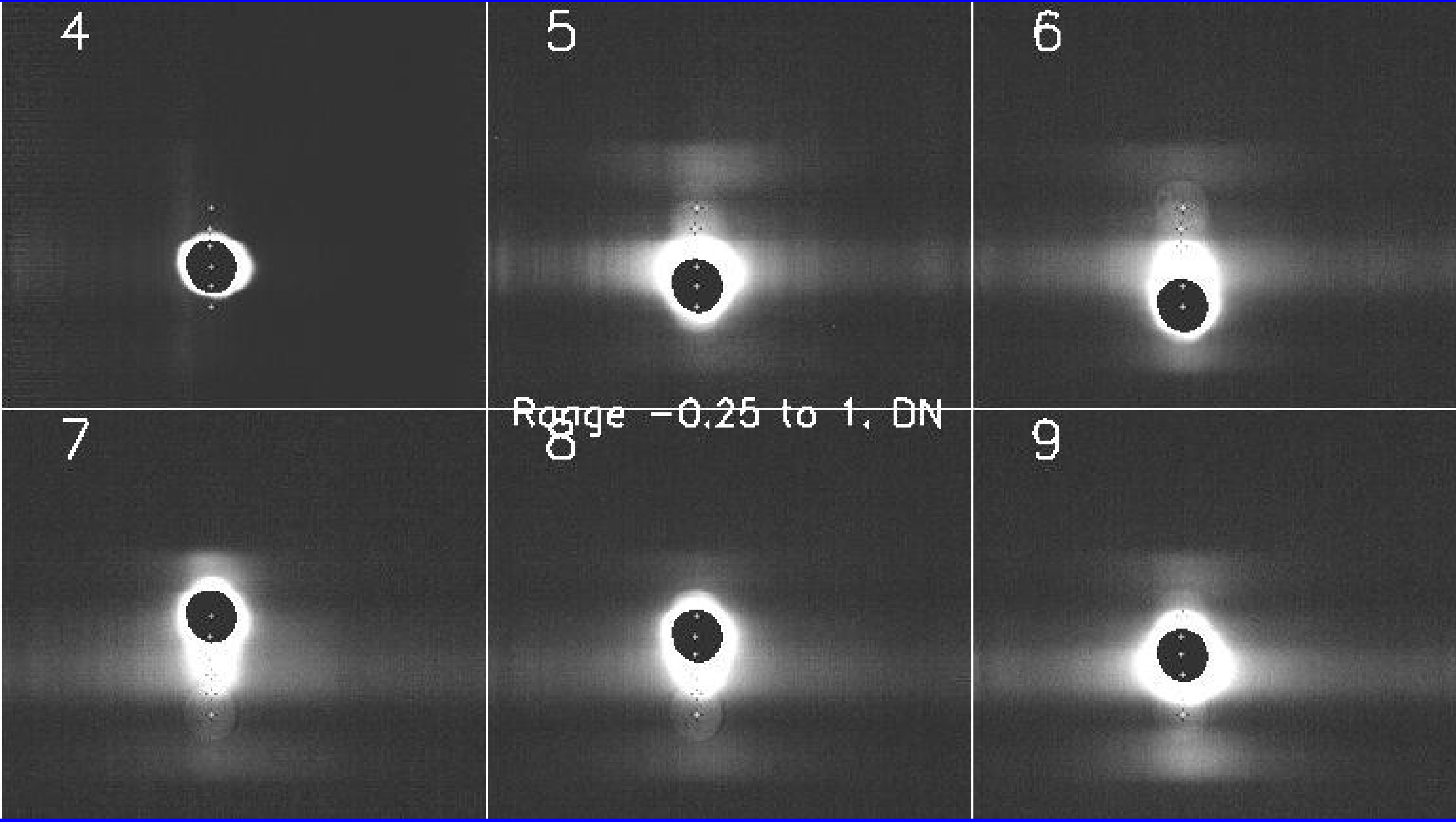
Primary image dimmed from ~ 50 DN

Band 3N: Offset ghosts: diffuse ~0.5 DN

Sharp-erect ghost ~ 0.12 DN !!!

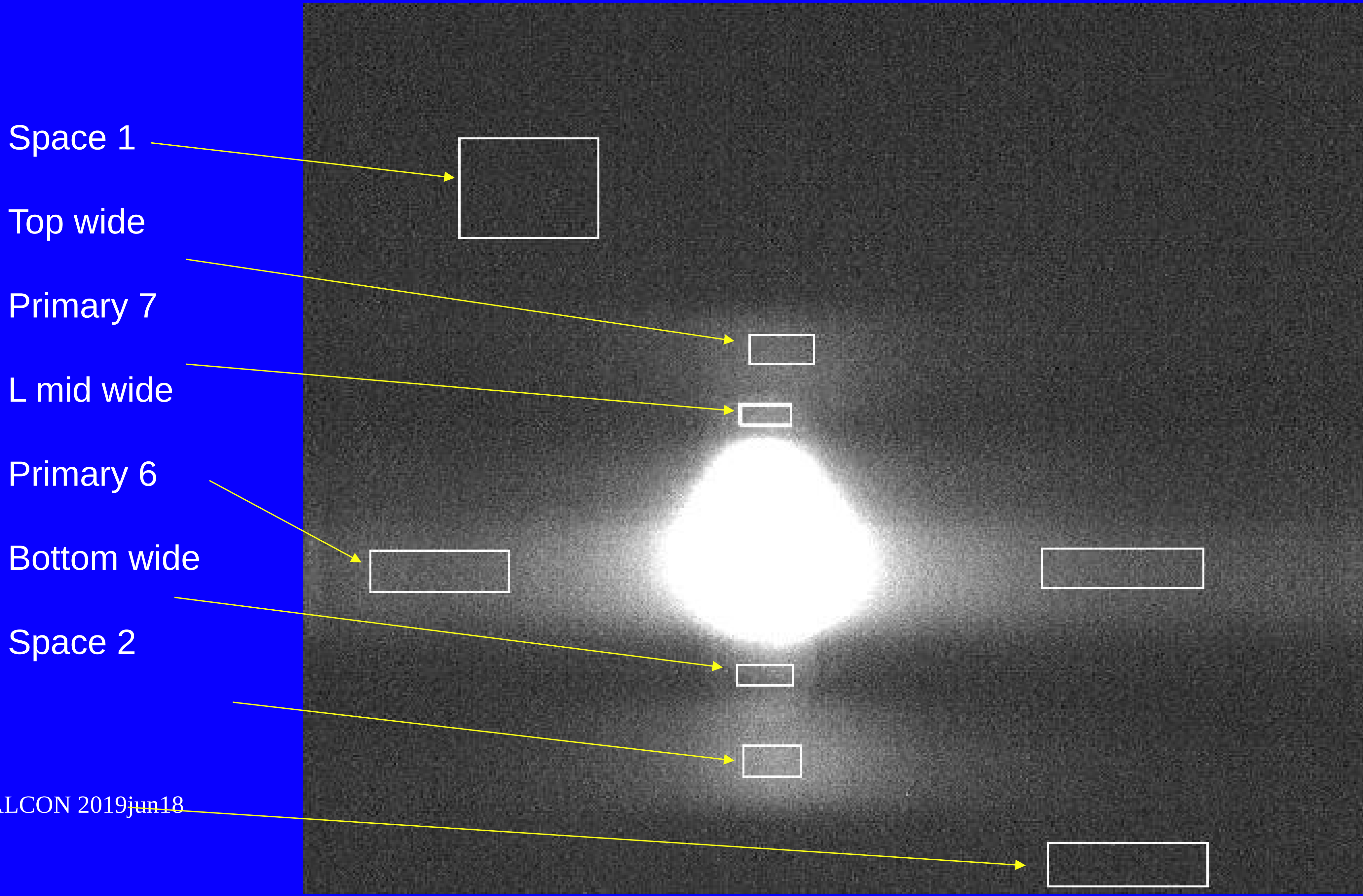


ASTER SWIR bands: extreme stretch



Crosses at locations of the primary images, which are masked

Region Averages. Shown on Band 9



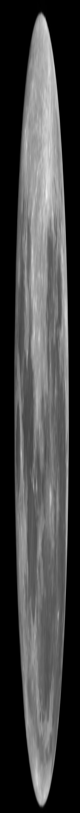
CALCON 2019jun18

ASTER Rectangular Region Averages

Band:	4	5	6	7	8	9
On Moon	38.58	47.63	55.92	54.76	70.97	81.93
Space 1	0.01	0.02	0.02	0.01	0.02	0.02
Top wide	0.01	0.31	0.21	0.56	0.19	0.29
Bot wide	0.03	0.19	0.40	0.19	0.20	0.48
L mid wide	0.06	0.16	0.18	0.17	0.17	0.23
R mid wide	0.00	0.14	0.15	0.15	0.16	0.21
Primary 7	0.03	0.26	0.25	56.71	1.12	0.47
Primary 6	0.04	18.97	58.66	0.22	0.24	0.35
Space 2	-0.00	0.01	0.01	0.01	0.01	0.02

Lunar Cal view: OLI

Raw.
Oversampled
by ~8
494 x 8581



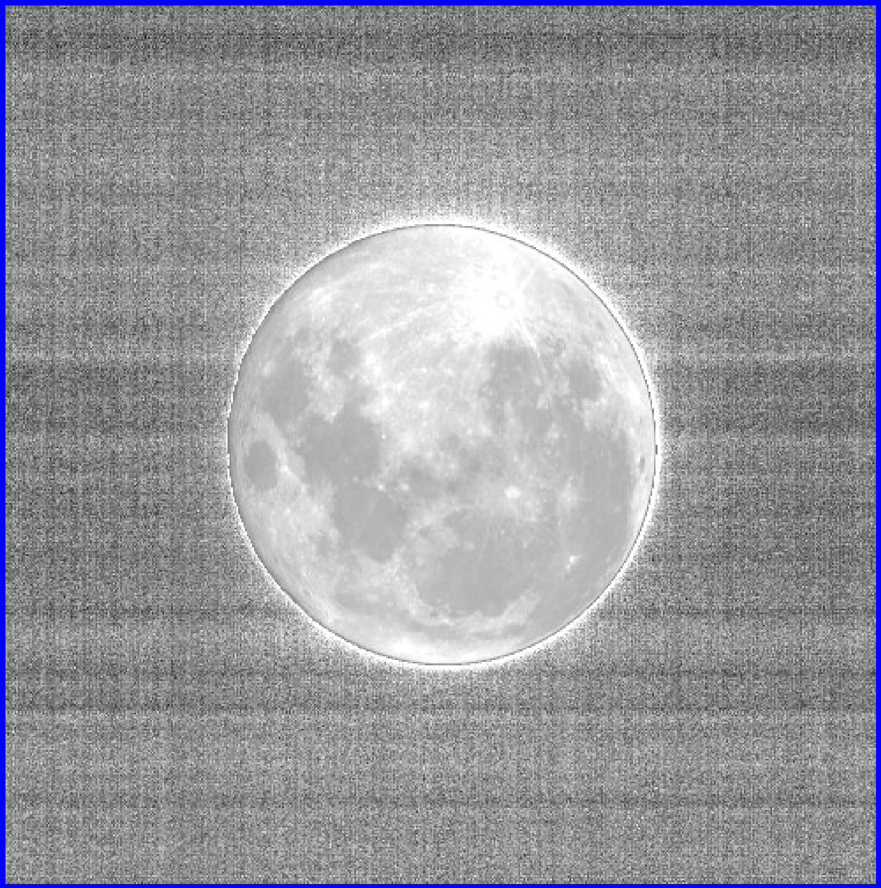
Cube, Average line by 4
494 x 996.
Pan also as 4 bands

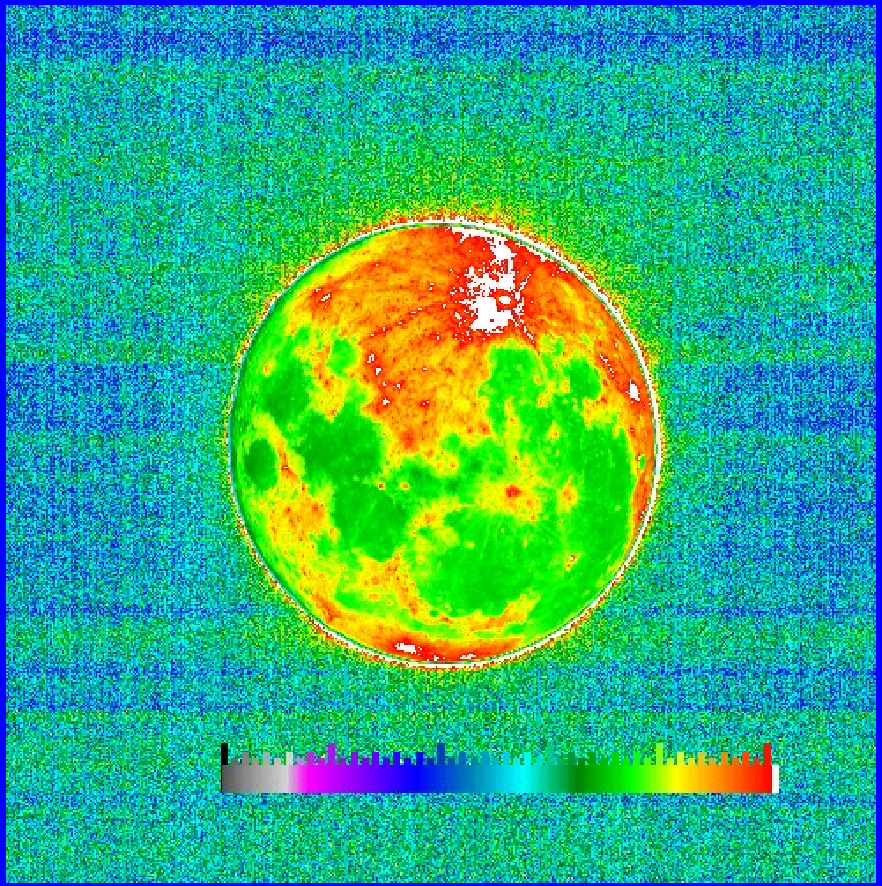
North ~ up
Outside tonight

Display:
Y/2, ~ round

Flare: Extended response

Moon attenuated by 400





Display range, +/-0.2 DN

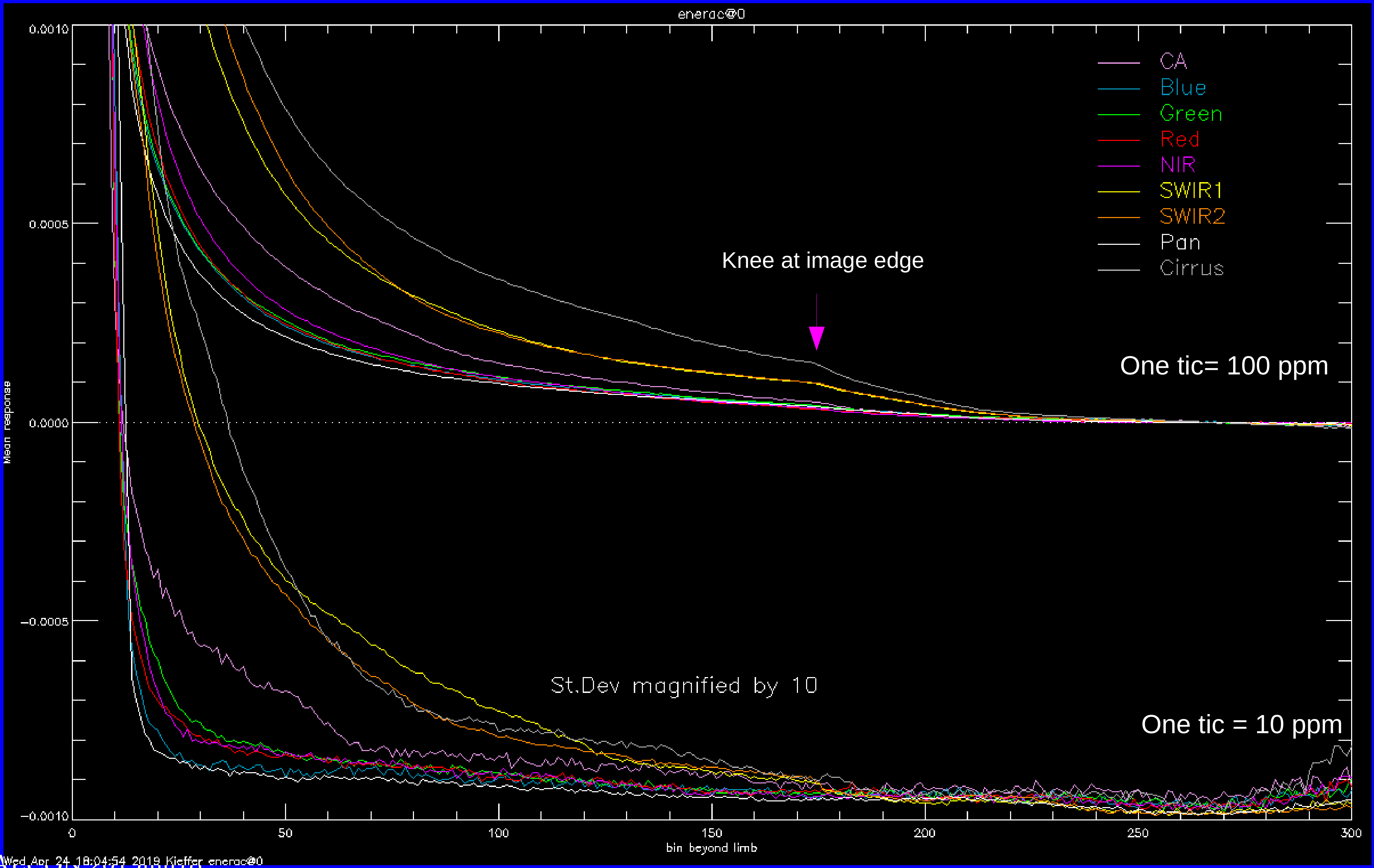
Importance of integrated radial response
"Encircled energy"

Pre-launch cal typically uses effectively large angular source, e.g., integrating sphere. Rarely measures encircled energy in an image; difficult to do, requires finite source with virtually zero background.

Moon is a about 1/2° diameter. Difference between this and an extended source may be small, but can exceed 0.1% and be unknown; maps into a calibration change.

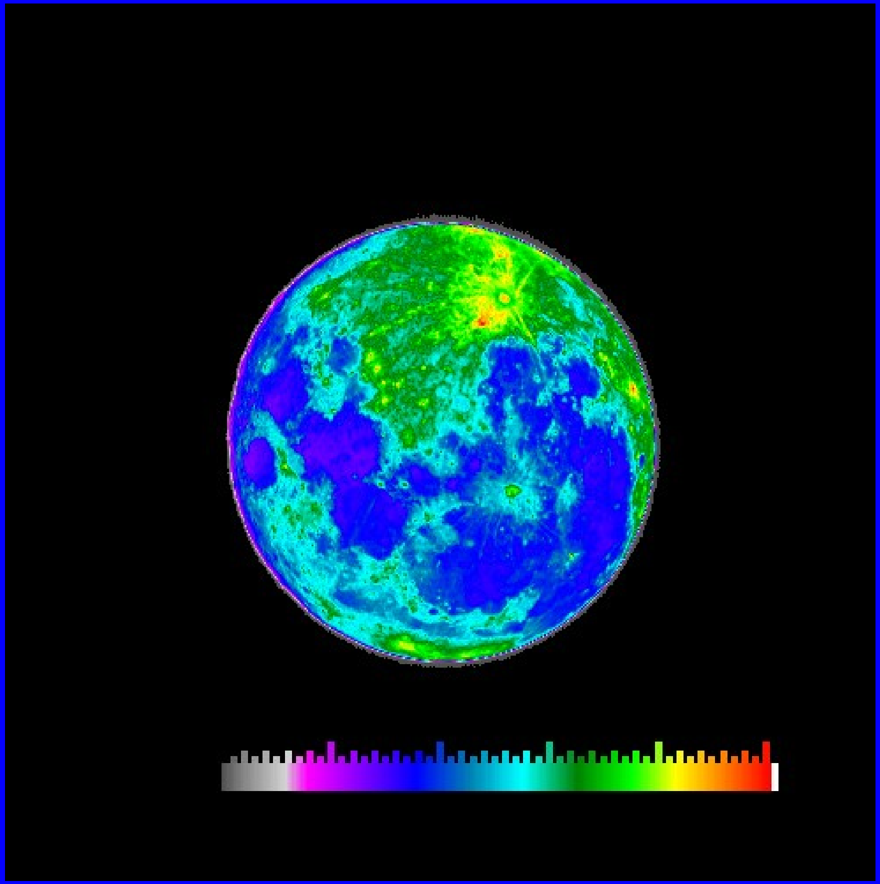
Radial Response: OLI

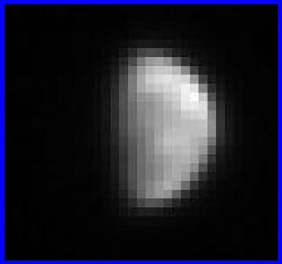
Average over 59 observations, all FPMs
Moon radius over time is 152:170 bins. Bin is 0.7 compressed pixels



Example of OLI image, color to show range of brightness

South up. **and Our mystery guest**





Vlon=-0.2 Vlat=-0.8 g=-70

Use of the lunar Model

Spacecraft Team provides:

- System Relative Spectral Response for all bands [once]
- Time (UTC) and place (J2000 XYZ) of Spacecraft observations
- Measured lunar irradiance in standard calibrated image

Effective wavelength versus spectral transform matrices

Model returns:

- Instrument/Model ratio or Difference from the model in percent.
- Full geometry of the observation: photometric angles, distance factor

ROLO data from star-calibrated-to-exoatmospheric radiance images, spatially integrated to irradiance I_k and converted to disk-equivalent reflectance A_k: >1200 data points per band.

$$I_k = A_k \cdot \Omega_M E_k / \pi$$

E_k = Solar spectral irradiance

Ω_M = 6.4236×10^{-5} sr

- **Empirically-derived model form, a function of the primary geometric variables of phase and lunar libration:**

$$\ln A_k = \sum_{i=0}^{3} a_i g^i + \sum_{j=1}^{3} b_j \Phi^{2j-1} + c_1\theta + c_2\phi + c_3\Phi\theta + c_4\Phi\phi$$
$$+ d_1 e^{-g/p_1} + d_2 e^{-g/p_2} + d_3 \cos((g - p_3)/p_4)$$

g = phase angle

θ = observer selenographic latitude

ϕ = observer selenographic longitude

Φ = selenographic longitude of the Sun

311g Mean absolute residual is 0.0096 in ln A, or ~ 1%

ROLO Model coefficients & effect

14 coefficients for each band, 4 are wave-length coupled. 4 non-linear terms constant over wavelength.

>1200 data points per band.

324 coefficients total (all are given in the AJ article).

Smooth wavelength interpolation.

Mean absolute residual is 0.0096 in ln A or ~ 1%

¿ Due to rapid variations of atmospheric extinction that are not, and probably cannot be, modeled

Lunar Irradiance Model *Band-Averaged* Coefficents

Symbol	Term	Name	Value	Units	Effect
a_0	g^0	Constant	-1.889	–	
a_1	g^1	Phase 1	-1.627	$radian^{-1}$	2.811
a_2	g^2	Phase 2	0.438	$radian^{-2}$	1.309
a_3	g^3	Phase 3	-0.235	$radian^{-3}$	1.212
b_1	Φ^1	SunLon 1	0.0425	$radian^{-1}$	0.147
b_2	Φ^3	SunLon 3	0.0132	$radian^{-3}$	0.137
b_3	Φ^5	SunLon 5	-0.005	$radian^{-5}$	0.157
c_1	θ	Libr X	0.0003*	deg^{-1}	0.005
c_2	ϕ	Libr Y	-0.0014*	deg^{-1}	0.028
c_3	$\Phi\theta$	SunLon*LibX	0.0010*	deg^{-1} $radian^{-1}$	0.026
c_4	$\Phi\phi$	SunLon*LibY	0.0008*	deg^{-1} $radian^{-1}$	0.017
d_1	e^{-g/p_1}	1st expon.	0.389	–	0.264
d_2	e^{-g/p_2}	2nd expon.	-0.148	–	0.130
d_3	$\cos((g-p_3)/p_4)$	cosine	-0.0035	–	0.004
p_1		1st expon.	3.08*	degree	
p_2		2nd expon.	12.10*	degree	
p_3		phase	-43.48*	degree	
p_4		period	18.73*	degree	
			* =	constant over	band

Libration effect is 5%.

Lunar calibration concept, and complications

1. Image the whole Moon anytime during the bright half of a month
   Note the time and the place
   Usually involves an off-nadir attitude maneuver; safety considerations
   Possible change in instrument behavior

2. Convert the image to irradiance in each band.
   Takes some care. Must determine any oversampling factor

3. Submit the system RSR (once only), the time and location, and the irradiances
   Human nature, politics, inertia. There are many more data sets out there.

4. Run the magic model to get 'true' lunar irradiance for the instrument situation.
   Determining the model !!! I have started. Residuals still significant. Lots to do.

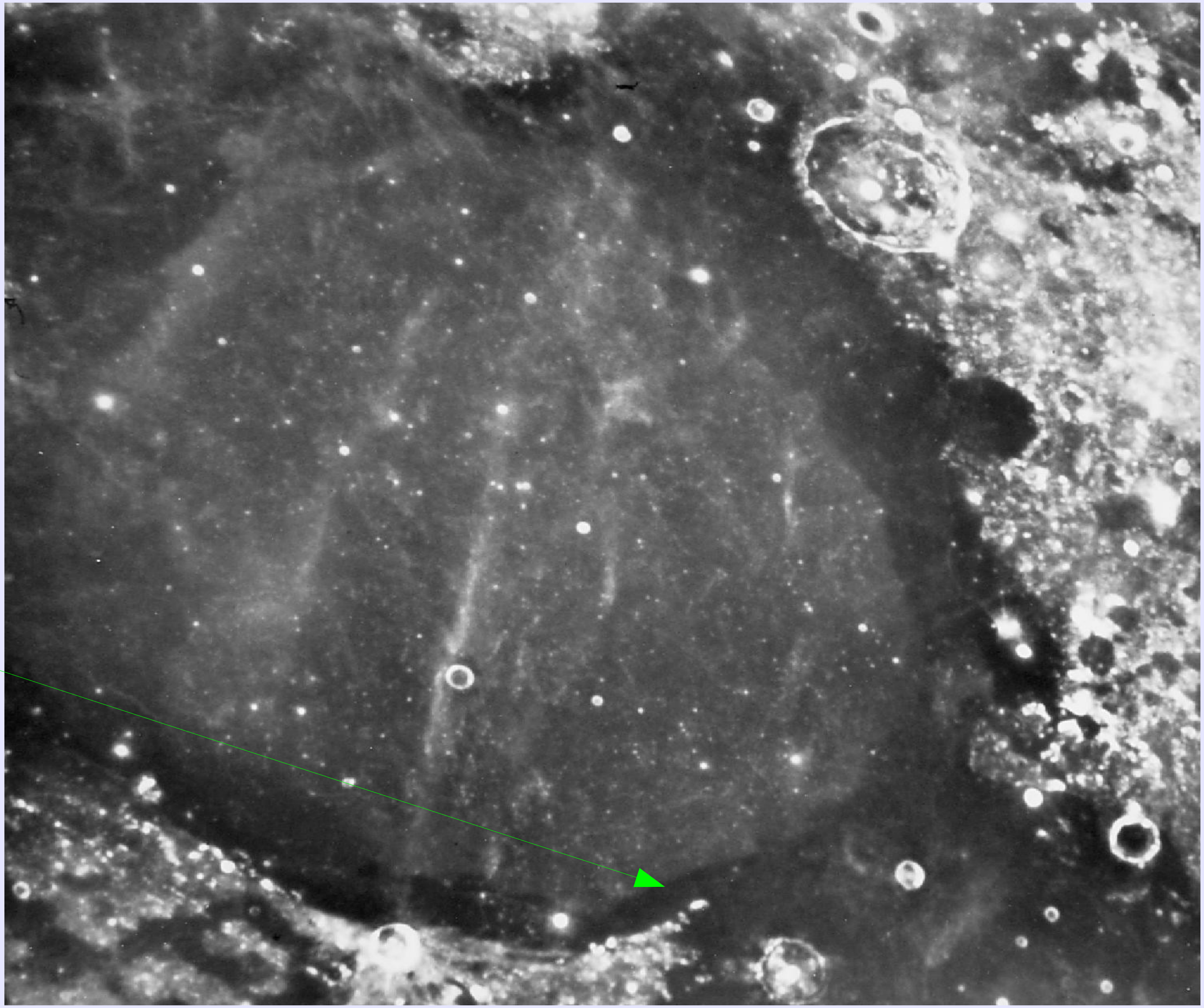
5. Report back the gain calibration ratio: measured/model.
   Virtually none. Maybe a little politics

Consideration of a radiance model

Some instruments have adequate resolution to look at small areas on the Moon.There are relatively uniform areas in the mare; all are dark. Some are well-studies spectroscopically. E.g., Mare Serenitatis 2: long. -21.4, lat 18.7
However, Precise location and instrument MTF are likely problems!

Modeling would be similar.
The issue is the nature of the target.
I am not encouraged.

Photo: near Full Moon
Pretty hard stretch.



SLIM data inventory

ROLO	32	1249	Observatory, 7 years
OLI	9	885	Landsat 8 Operational Land Imager.
			15 scans in orbit pairs on 59 dates
HypM	26	20	EO-1 Hyperion Spectrometer,
			242 bands,196 useful; 7:56 and 78:223
MODA	12	53	MODIS-Aqua 1:4,8:12,17:19 of 1:19,26
VIIRS	14	27	Suomi-NPP M1:11, I1:4
PleA	5	141	PLEIADES-A
PleB	5	339	PLEIADES-B; phase runs with 1-rev. separation
GS8	1	44	GOES-8 Vis
GS9	1	9	
GS10	1	49	
GS11	1	77	
GS12	1	49	
GS13	1	47	
NIST	9	1	Observatory, traceable
HiRIS	3	4	HiRISE, in orbit at Mars

Lead-in warning

Some of the charts will be extremely busy.
Don't worry, I do not expect you to retain any details.

Recently became aware of the extensive ground-based observing program in China. None of that is included, but it should be.

My goals

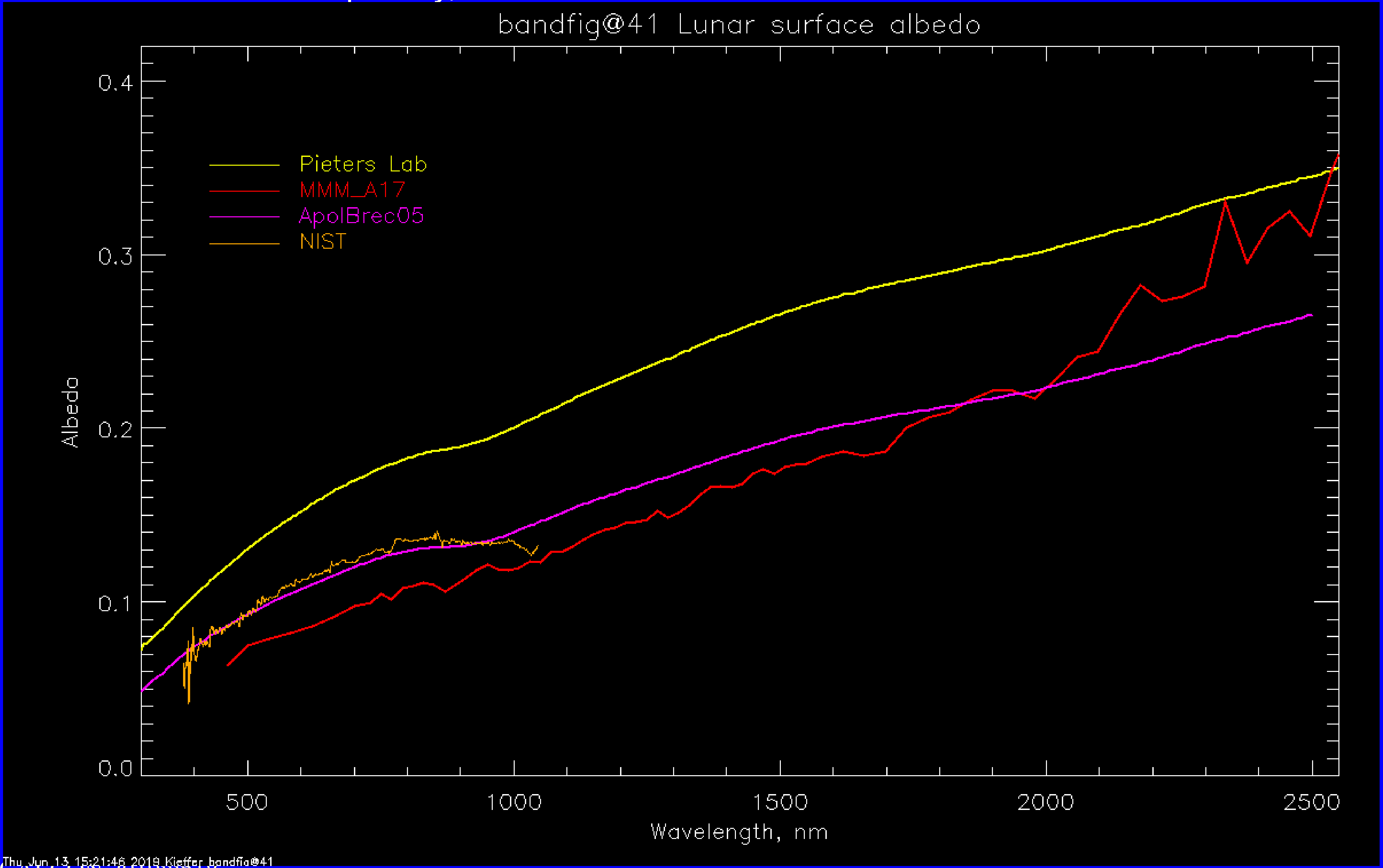
- Introduce you to the magnitude of the task
- Propagate some hope that there is a solution, and it is important to get there.

This whole mathematical mess may someday be replaced by extensive observations (> 4.7 years) with a dream on-orbit instrument:
stable, traceable spectrophotometer with order of 0.1% accuracy.

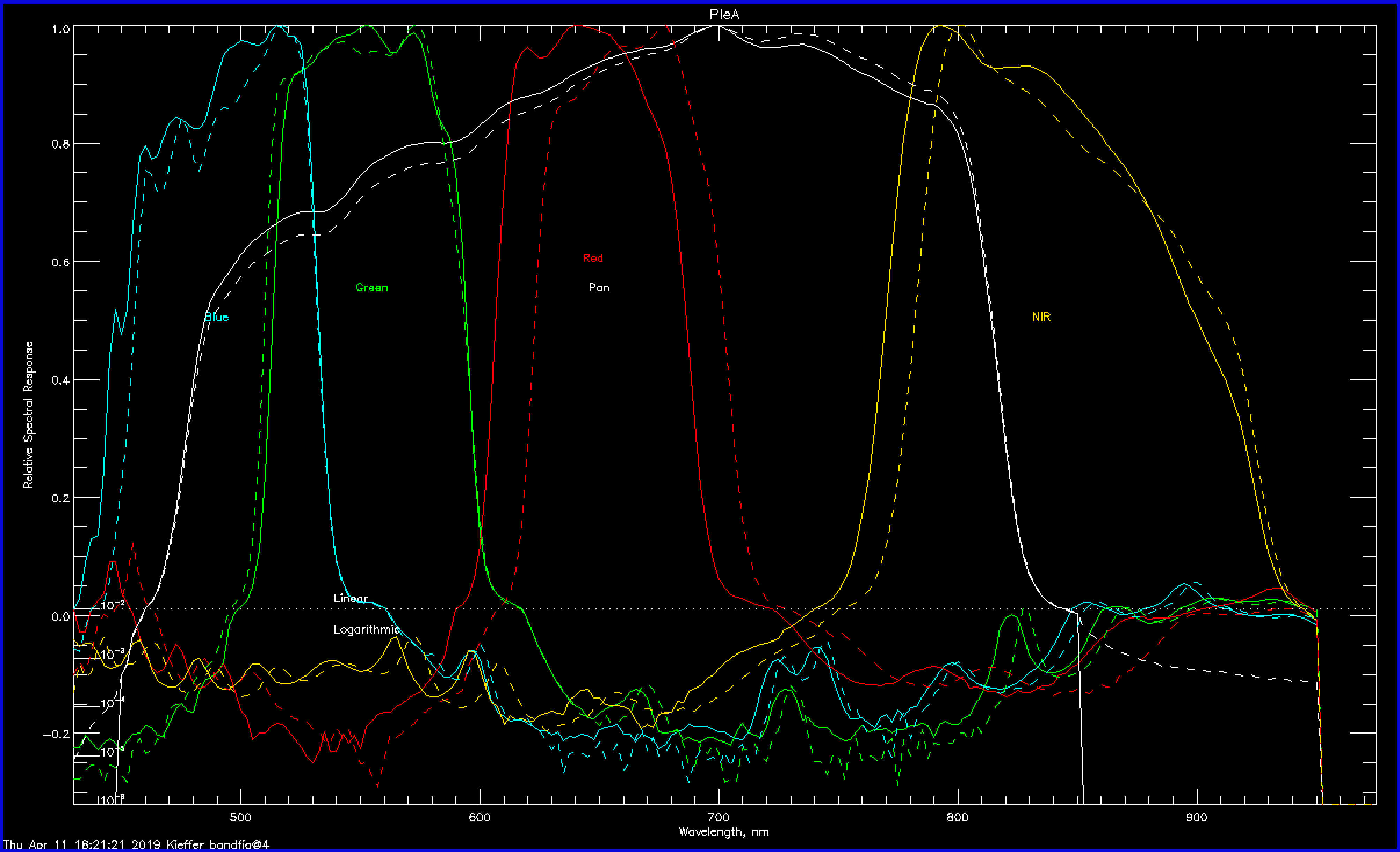
However, till then .....

The Lunar Reference Spectrum

Telescope and Lab measures. ROLO and SLIM use ApolBrec05;
Shape only, not absolute level.

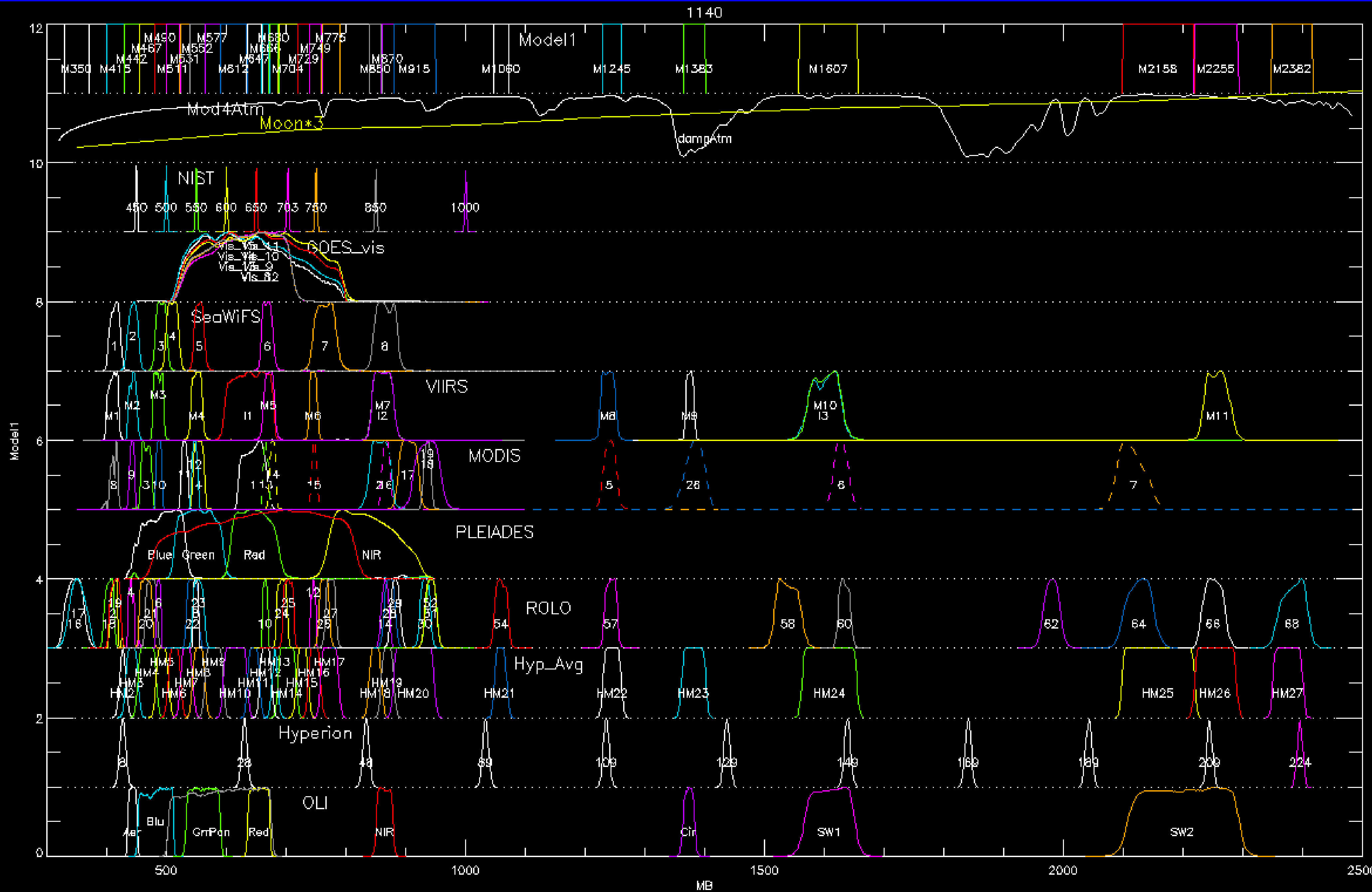


Example of Instrument bands

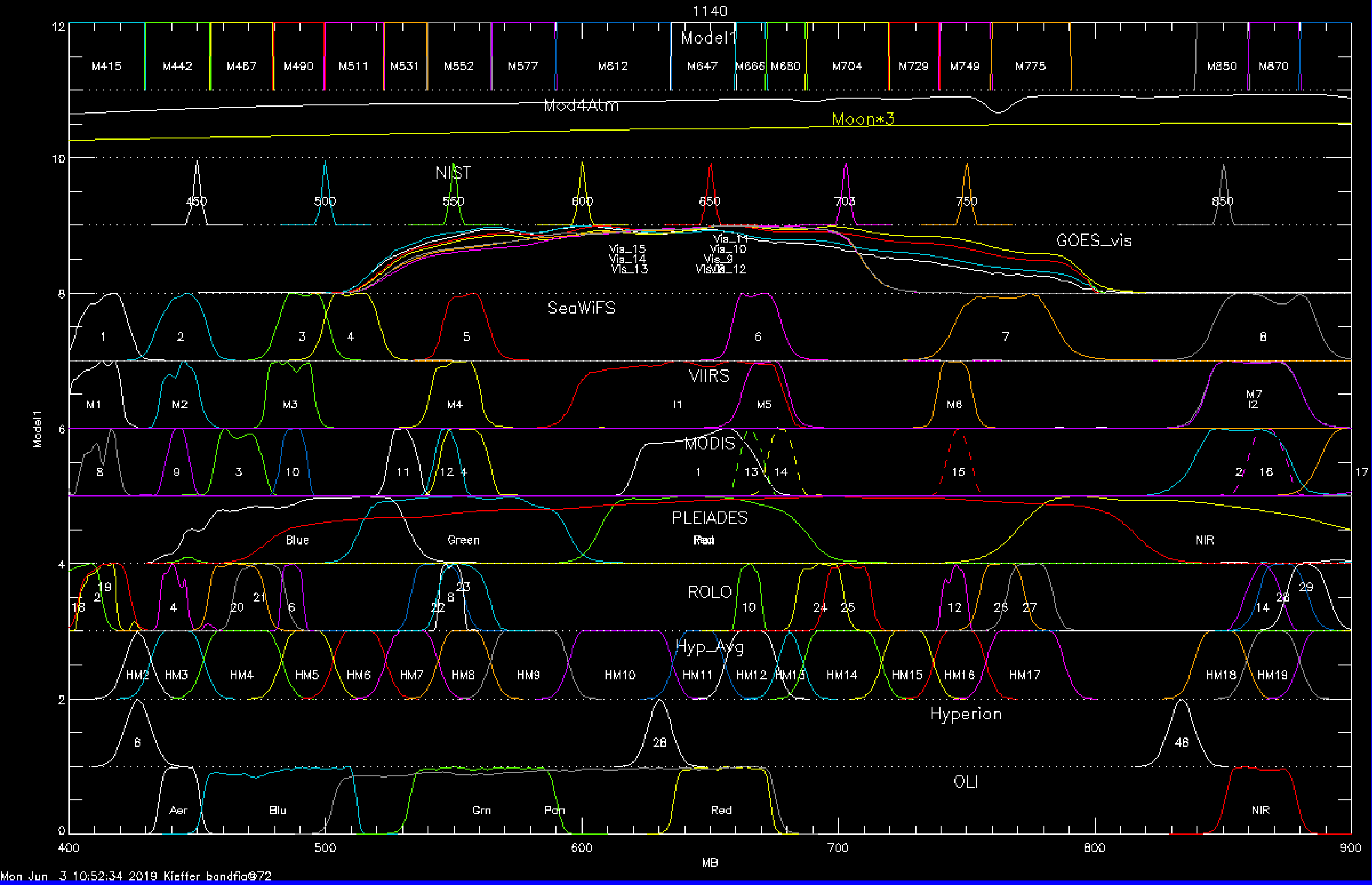


PLEIADES HR-A and -B (dashed) Relative spectral response (RSR) as provided. Bands wings given to 1.e-6 level. Generally, RSR data should extend until all bands are below at least 0.001

Spectral response for several instruments and SLIM bands



Bands in the Silicon region



SLIM overview

Sun, Moon, common instrument bands => Define model bands, wavelength system

Ground calibration, RSR's => Inst:Model bands transformation matrix **X,** once

On orbit: time, place, observed irradiance, in each band

Convert to standard formats. Mix in prejudice as: Gain and Weight tables, badPoints

Make Fit Ready: Photometric geometry=PG, adjusted irradiances=**MI**, Uncertainties

Select Basis Functions and tolerance controls.

Do a fit => coefficients for each model band; timeless

Calibrate every instrument: Evaluated the model at PG, transform with X, ratio with MI.

Report to Team, Generate statistics; feedback into Gain table.

Basis Functions:
most as power series up to cubic

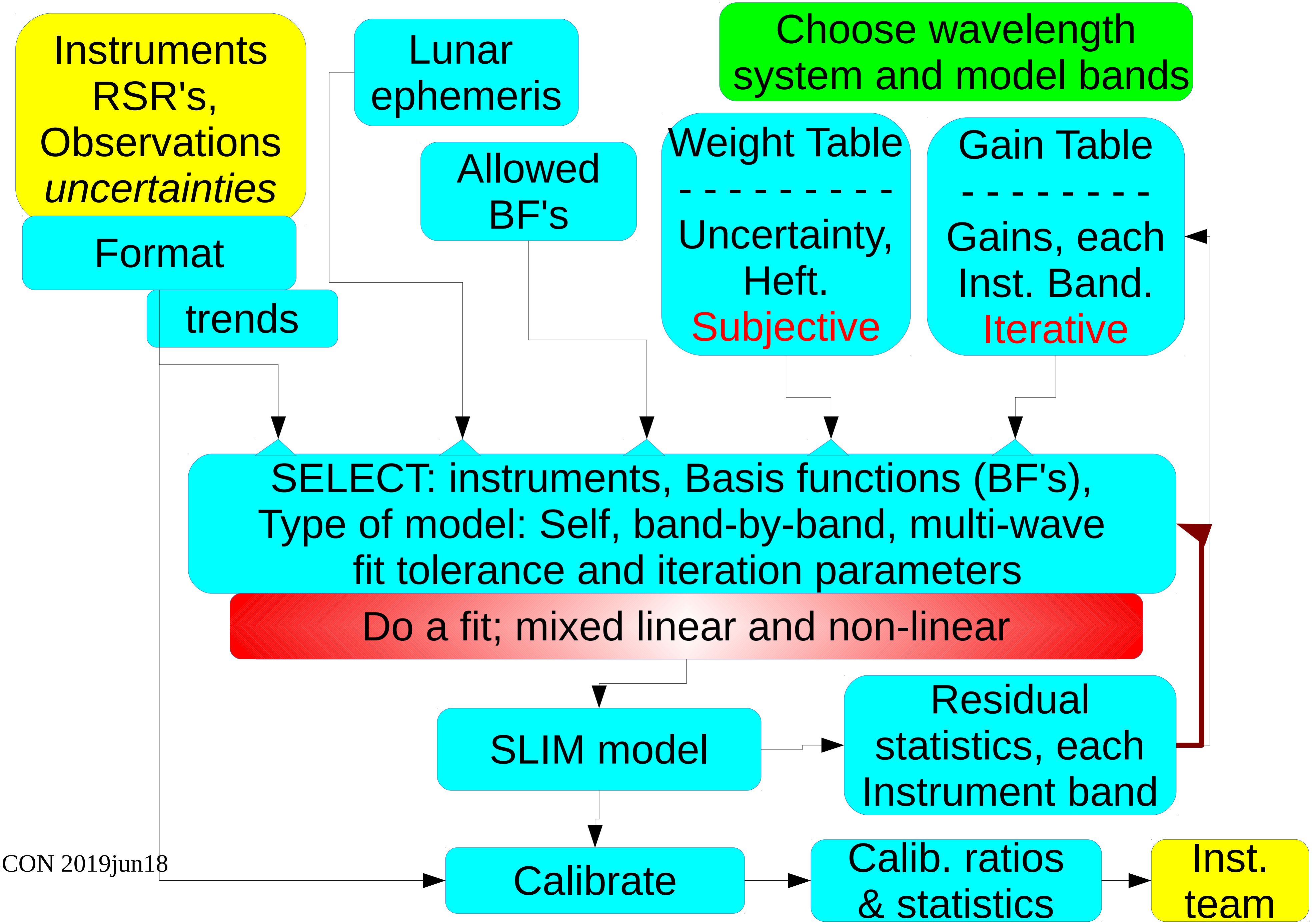
Constant (no other degree)
Unsigned Phase angle (g), to degree +13 and to -7
Sub-solar longitude, odd powers only. Hlon, to +5
Sub-solar latitude (range ± 1.6 °) Hlat
Sub-view longitude Vlon
Sub-viewer latitude Vlat
Hlon × Vlon and Hlon × Vlat

In multi-wave models, each term may be polynomial
in wave: λ in μ, or 1/λ or ln λ

[time: MJD/1000] for trends]

non-Linear terms (same as in ROLO)
Opposition effect: exp($-c_2$ g) [multiple non-overlapping]
Hemisphere, emperical: cos ((Hlon-c_2)/c_3)

SLIM overview



SLIM Design starters

Desire to include many instruments means that some compromise set of bands is required. Currently SLIM uses a set of non-overlapping bands with gaps where no-one looks. Need to fill the gap near 820 nm for PLEIADES near-IR

Corollary is need for spectral transformation matrices between SLIM bands and bands of an instrument.

Also, greatly simplified by using a common set of wavelength points for all spectra.
SLIM chose: constant resolution of 1000.

Must decide on which photometric basis functions to allow; seem to have enough.

Is the formulation: In DER = sum of angle basis functions the best ??
What else to try?

SLIM modeling

Self models, each instrument band, no spectral transforms.
Instruments with limited phase-angle range can attack the libration terms.

SLIMED models, avoid spectral transforms. All instruments and bands at once. - - Under development.

Transform actual instrument observations onto SLIM model bands

Band-by-band modeling. Some SLIM bands are poorly supported.
Large phase-angle range requires more geometric basis functions (BF's)
Inversion can be sensitive.

Multi-wave modeling; each geometric BF can be polynomial in **wave.**
Fit all bands at once.
Very large inversions. Not much progress yet.

Empirical / Subjective Parameters

Technical details you may ignore

Which instruments to include?

What weight to assign to each instrument?   Use “heft” to account for abundance
  And the relative weight of each band

The gain assigned to each instrument band
  This can evolve with repeated fits

How to redistribute uncertainties when mapping instrument bands to model bands?

Method of matrix inversion: currently 50,000 x 27, things can go awry.
Current options are:
- LU-decomposition
- Singular Value Decomposition on normal equations (commonly fails)
- SVD on the design matrix.

Insurance. Check the curvature and symmetry of residuals for perturbations of each derived coefficient.

SLIM system issues

The assumption that the detailed **shape** of the lunar irradiance spectrum, not its level or slope, is the same at all geometries.
There may be a better set of basis functions.

Libration coefficients are similar in overall effect to ROLO, but different in detail.

Overall measure of model quality: mean absolute weighted residual in ln DER
ROLO version 311g: .009
SLIM self fits .002 typical
SLIM Jun11T0752: .007 6 instruments without ROLO

Considerations

Perhaps close your eyes and just listen

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

Possible causes of disparity of fits between bands and instruments:

Possible change of instrument response when maneuvered to view the Moon.
  If so, need to reconsider instrument design.
Instruments have substantial spatial extended response.
Conversion of a lunar image to irradiance is unfaithful.
Instrument scales are wrong.
Ensure that relative spectral response is full system level.
Photometric basis functions being used are inadequate.
Lunar calibration concept is flawed.
Something else.

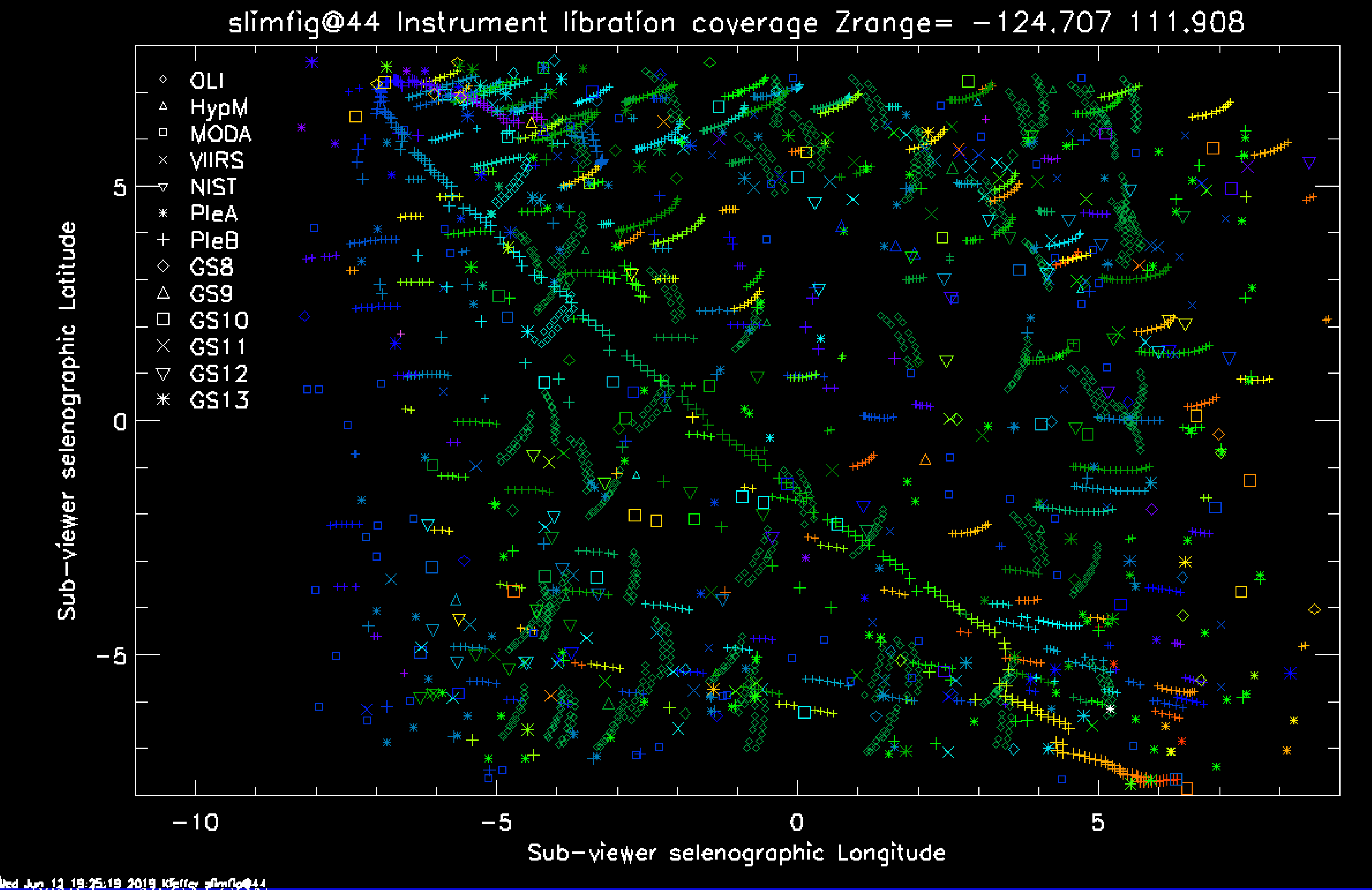
As fidelity improves, will need to accounting for solar variation.

How to make available a lunar model that should/will be periodically updated.
    ROLO 311g has been in use for 14 years
Gaining acceptance of the concept of a concensus model

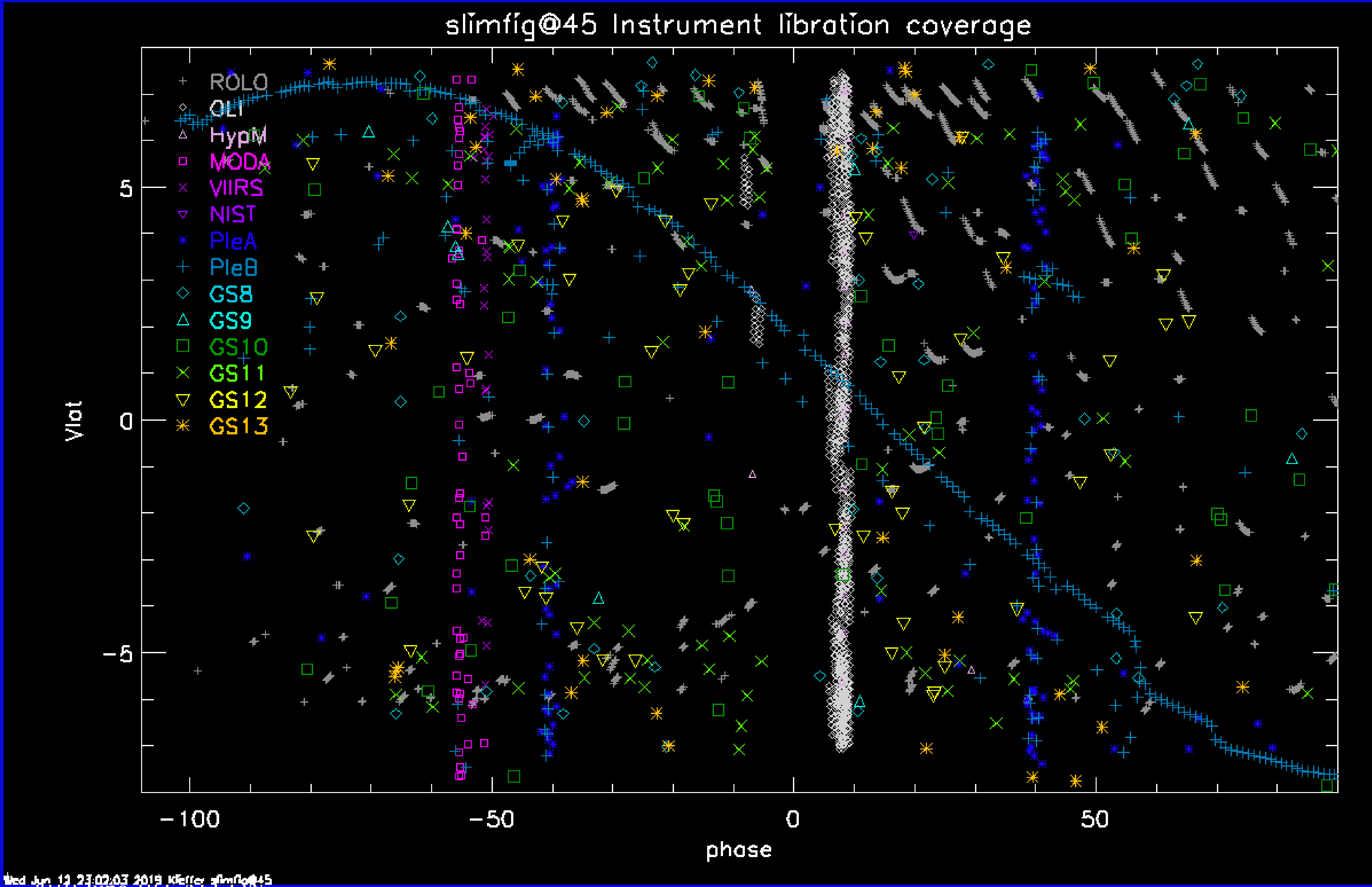
Sources of error

Item	expression	Native	in ppm 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

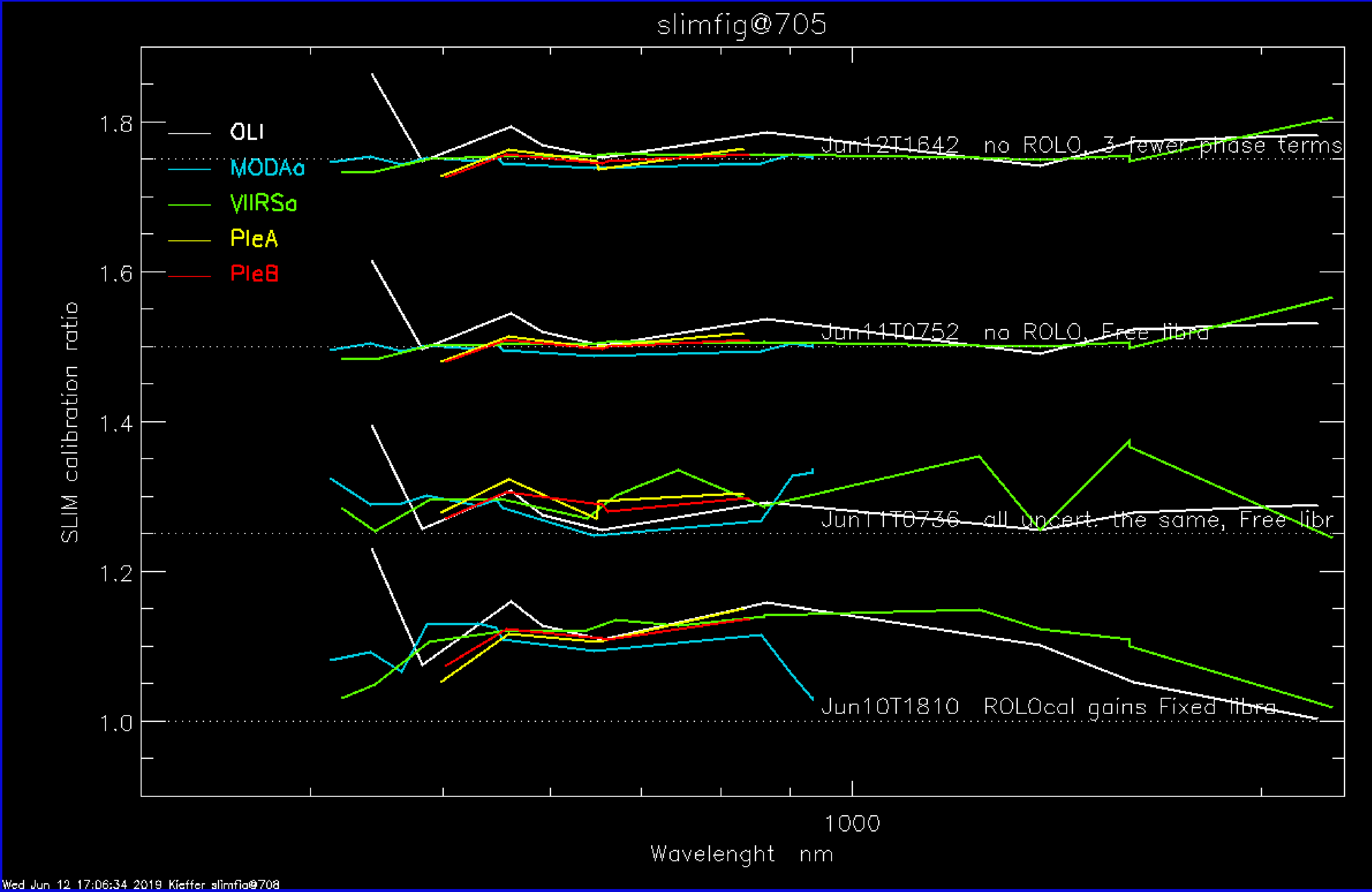
Geom. Coverage, Viewer libration. Color is phase



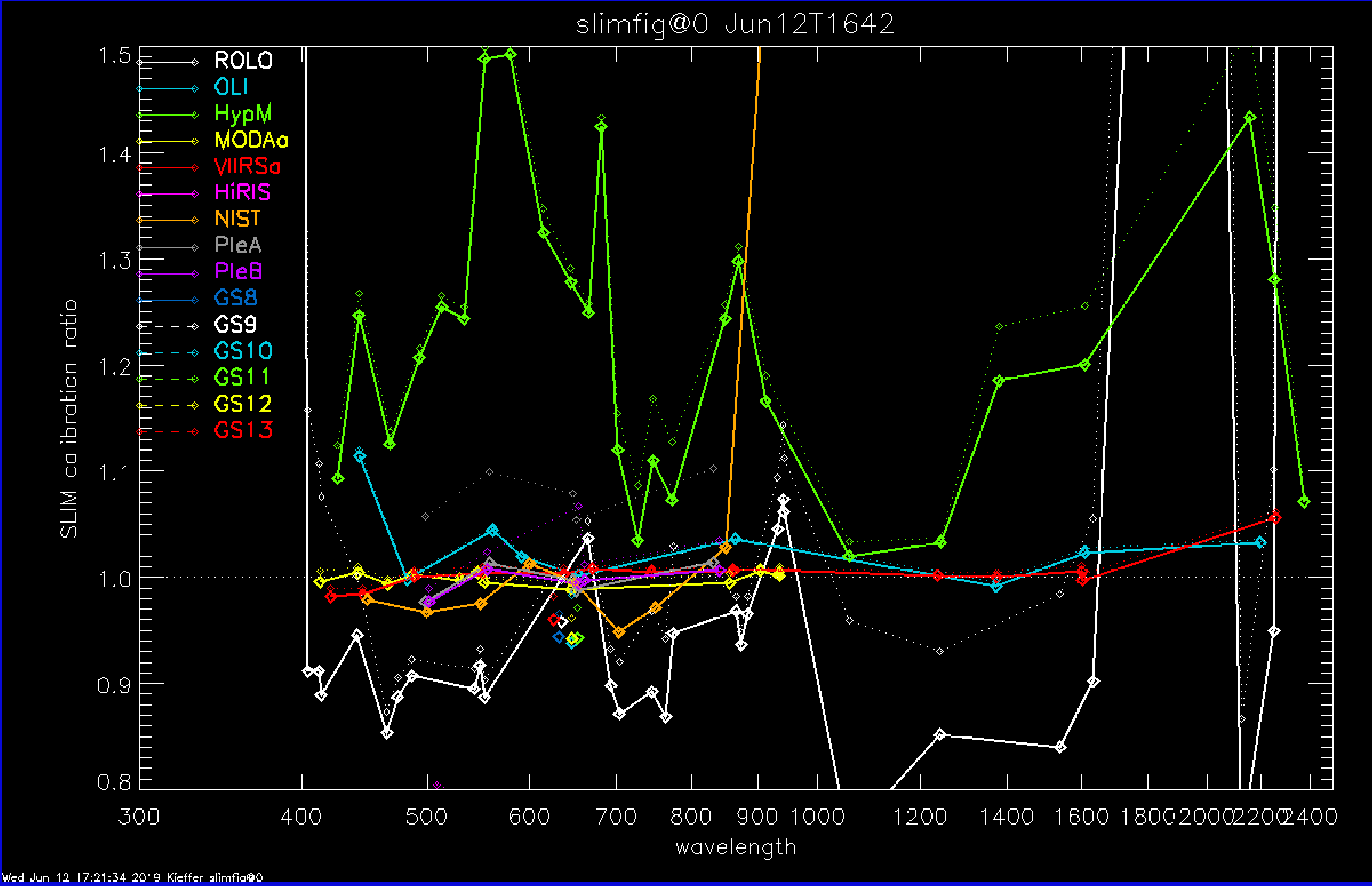
Geom. Coverage, Viewer latitude versus phase



Calibration of 5 instruments with 4 SLIM models



Calib. of 15 instruments with a SLIM BB model



Standard Protocol: Once

Pre-Launch

Ensure RSR's are system level.

Optional: Calculate sensitivity to outer planets and stars.

Know your linearities (lunar levels), hard to check on orbit.

Assess calibration uncertainty

[These are needed in modeling, but rarely provided so far]

Commissioning

Longs scans across the Moon and to the side

Fill out possible stray responses space

Quantify any stray response.

Philosophical: how to treat stray response?

L0: Determine signature of cosmic ray hits

L0d = Detector geometry corrected: Find the Moon and its limb

Develop encircled energy curves

Decide on space-correction and irradiance integration zones.

Standard protocol: periodic

Scan / image the Moon.
Get enough space for the space-correction

L0d: optional: Rough location of Moon
Search for cosmic-rays hits
Check for stars and planets: catalog and ephemeris

L1d:
Optional: remove cosmic-ray hits.   Remove planets/stars
If scans: space levels for each detector-element, and subtract.
Precision Locate Moon and limb; critical if needed for over-sample
Check for drift
Build the elliptical radius mask and the encircled-energy curve
Extract the Moon-center time (and derive the spacecraft location)
Extract the space-corrected lunar irradiance

Community

Similar to what has been done for ROLO model ?

Find a home for the modeling effort. GSICS Lunar group?

Library of RSR's and Derived effective wave parameters.
Refresh if a new reference Moon or solar spectrum.

Repository of Lunar observations: ROLO or new format?
How to avoid trending incest?
Transmit both irradiance measured with constant calibration and gain versus time.

Periodic updates to the concensus model? (a lot of work)
Make available the models and code to apply them.

I have software for everything mentioned here.
Unfortunately mostly in IDL, proprietary
Could/should/can be converted to Python (or ?)
Or, find better algorithms.
(Be humble. Limb-finding algorithm developed over 15 years.)

What you can do

Express your opinion about the whole concept.
If thumbs-up, then ---

Examine your image-to-irradiance process.
Submit data: officially through: Lawrence.Ong@gsfc.nasa.gov
[I am happy to accept data]

Support whoever takes over this task.

Thanks for your attention.

Backup

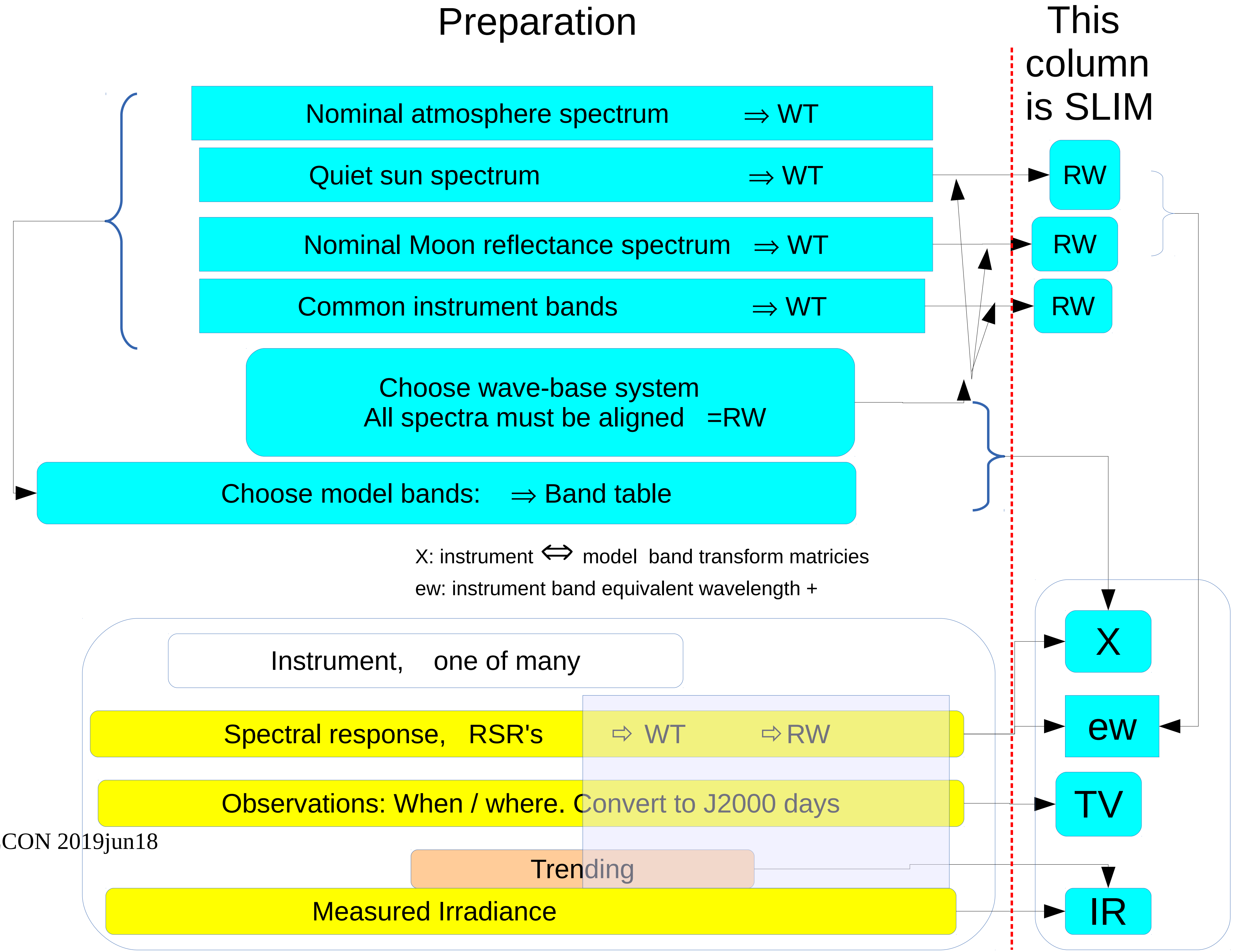
Error Table: Notes

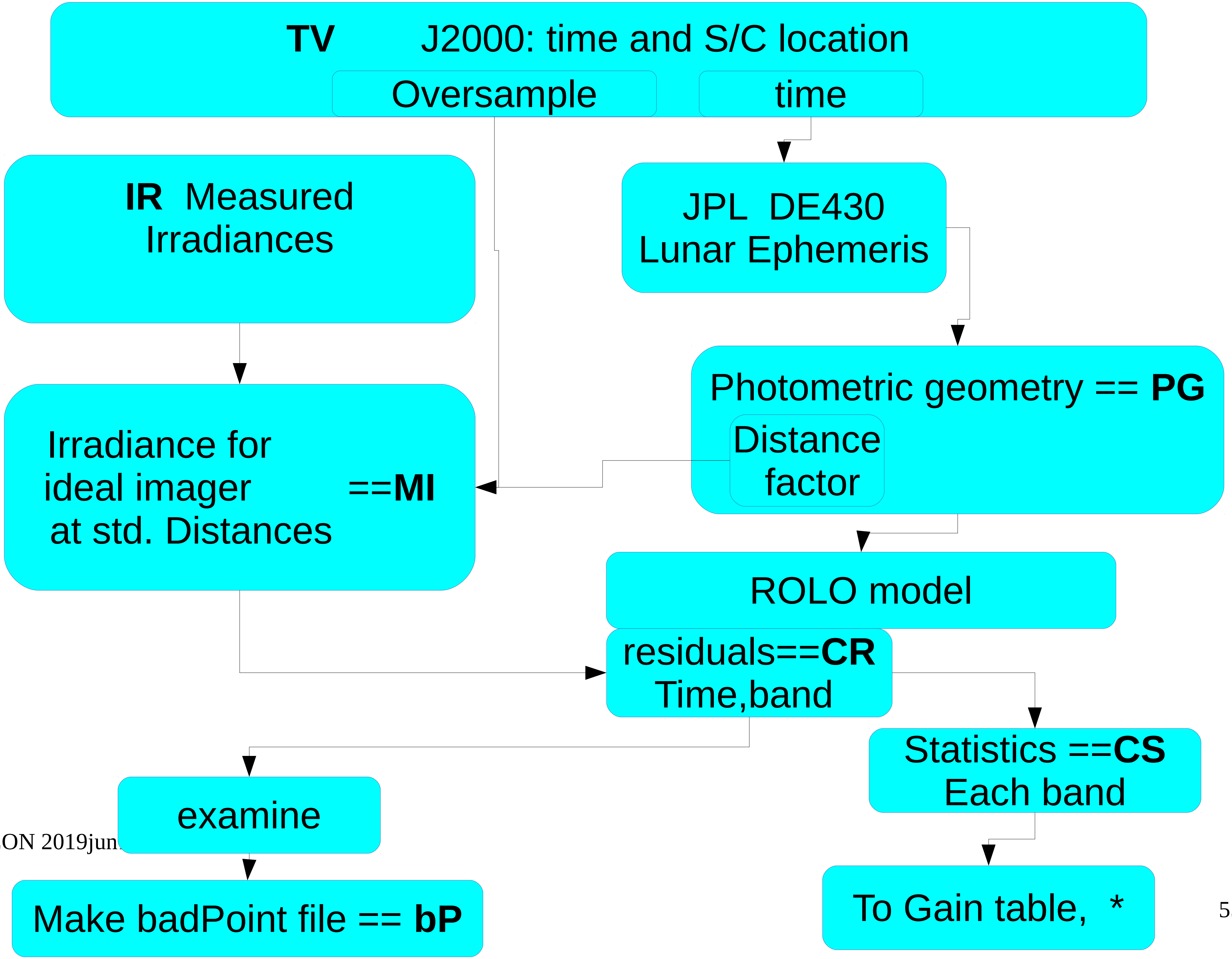
1: Accounted for in libration terms in model, if adequately high resolution in angle.
2: Non-linearity in $1/\cos\theta$ over 7°[1.2e-3]; times the fractional circumference,
Arbitrarily set a 1/4 $\Delta h/R$
3: Fractional rate change while crossing the Moon.
e.g., Change in mean scan rate over first 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.

Status

Expecting more OLI and GOES data.
  Hope for lots more; 2+ PLEIADES-B phase-angle runs
Need to run MW models and assess value.
Debugging of no-spectral-transform system nearly finished (Ha!).
Plan to publish the SLIM concept and the “best” model.

Preparation




TV J2000: time and S/C location
Oversample
time
IR Measured Irradiances
JPL DE430 Lunar Ephemeris
Photometric geometry == PG
Distance factor
Irradiance for ideal imager at std. Distances
==MI
ROLO model
residuals==CR Time,band
Statistics ==CS Each band
examine
Make badPoint file == bP
To Gain table, *

Stage 3   Make a file ready for fit

Inst. 1: PG, MI, X, bP

Inst. 2: PG, MI, X, bP

....   PG, MI, X, bP

Inst. N: PG, MI, X, bP

Gain Table, divide MI by gain

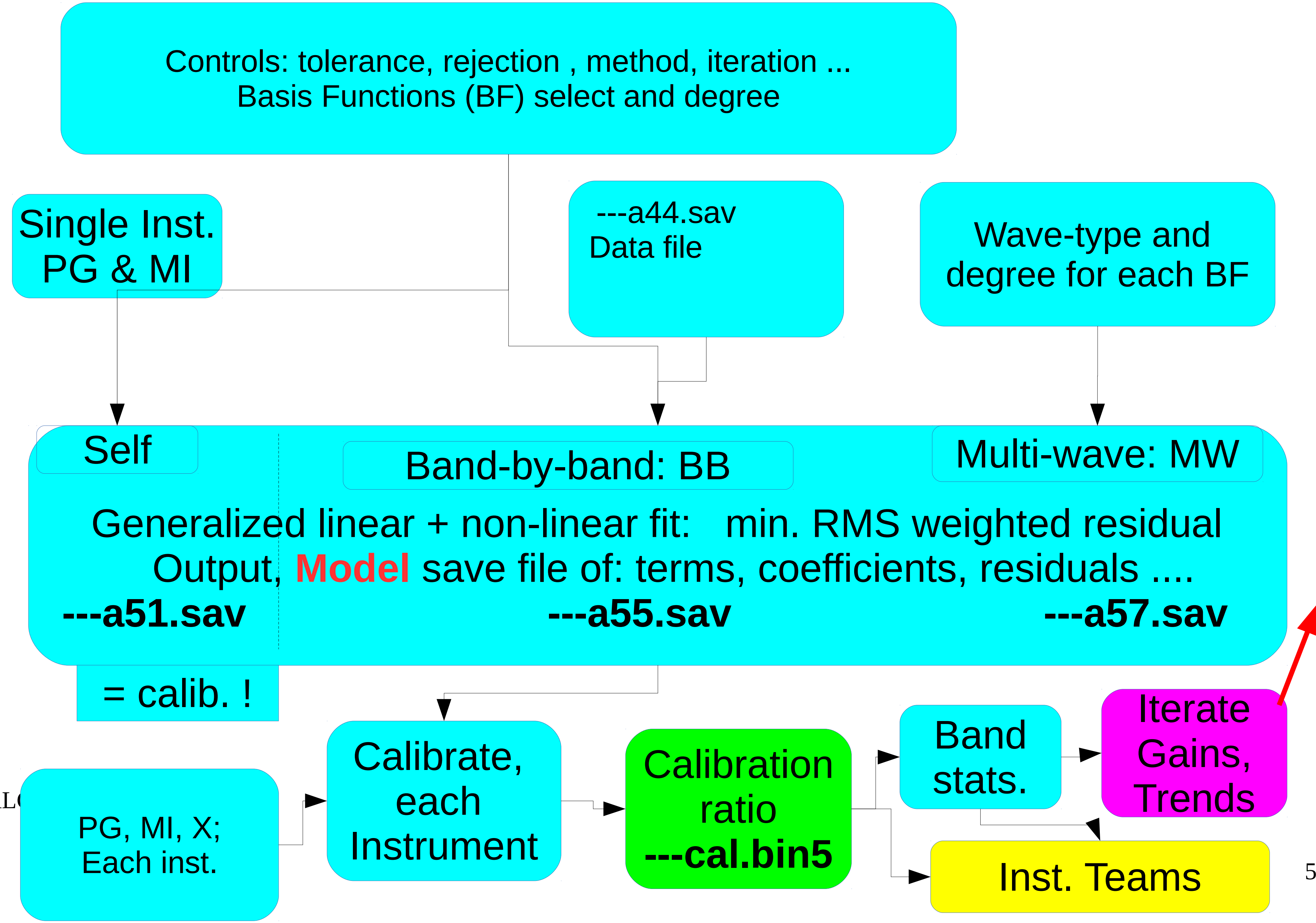
Weight table.   Uncertainty = Inst. Unc × Band relative Unc. × Heft

Instrument-to-model spectral transform

Save data: PG_ij, MI_ij, U_ij   concatonated == **---a44.sav**

i=instrument obs. Index   j=model band. This file is “ready for fit”

Stage 4 and 5: Generate Model and Calibrate Instruments



CAL

Pragmatics

I have found it useful retain wild points so that the data for an instrument stay in alignment across bands. This is done by adding a large number to the uncertainty, retaining the point but giving it virtually no weight in a fit.

[done @55 and 51]

BadPoints are applied in making the Fit-Ready file, not earlier, to avoid having another type of instrument file. BadPoints are omitted in modeling.

Currently used only for PLEADIES

Trend information supplied by a team are normally applied at the ingest stage for data to be used in modeling. However, such trends can be ignored during calibration to derive SLIM-based trends.

SLIM-derived trends are applied at the stage of distance correction; do not want to change source irradiances.