Redesign of the SLIM lunar model *development* system

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The Software system that creates the SLIM model(s) was developed incrementally over a period of more than 20 years. It predates the availabilty of NetCDF and the JPL-NAIF-SPICE system. It includes combined IDL & FORTRAN code for direct access to the JPL planetary ephemeris and 'home-brew' techniques for solution of mixed linear and non-linear equations. The system accesses 280 custom routines, all written by a single individual. Only two people had looked inside; one retired, the other is Tom Stone, who has been a close associate of this software since the start of ROLO.

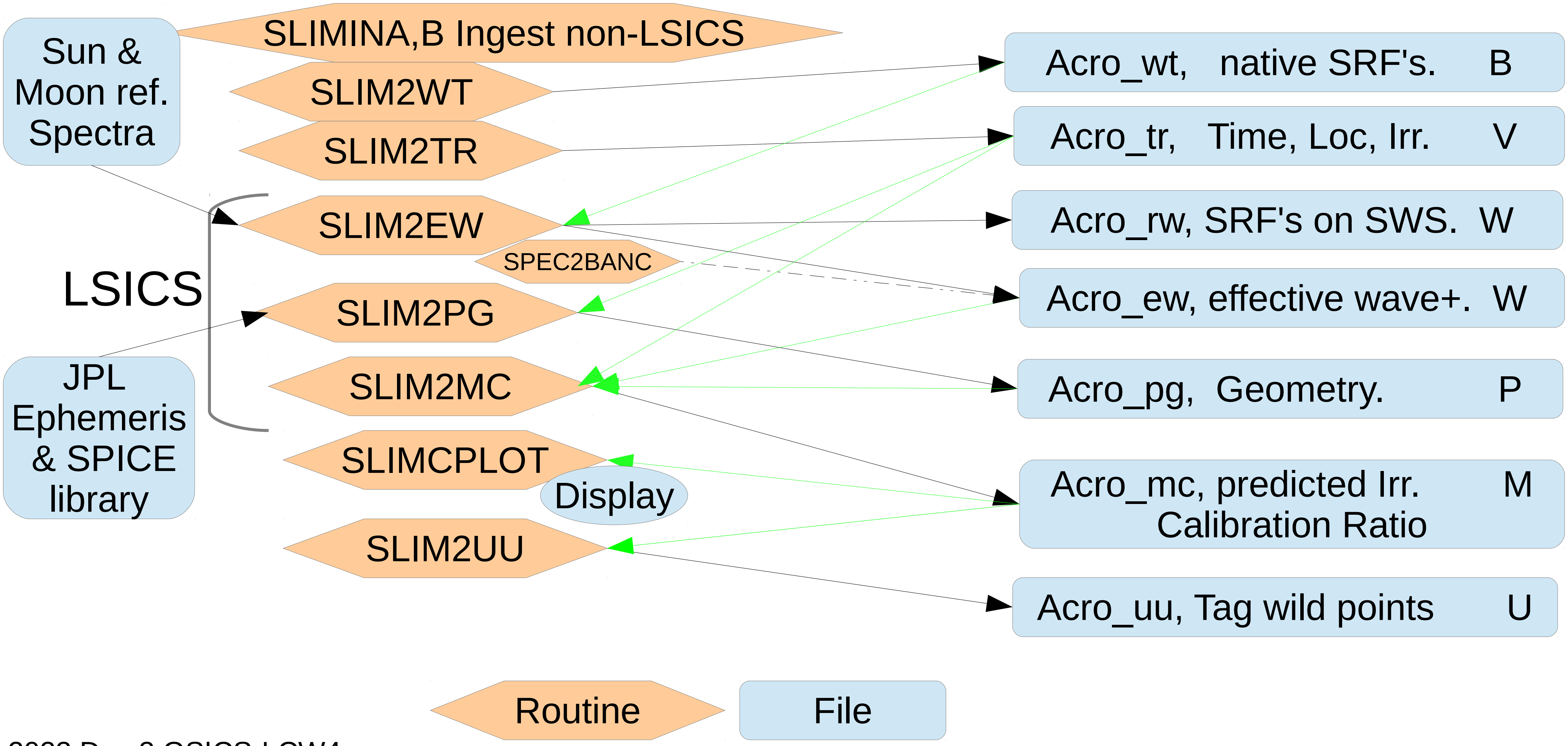
Many of the high-level routines were large case statements with numeric targets directed by editable sequence of integers; some of the targets allow editing the system parameters. This allowed great flexability is what data went into the model, how it was treated, what statistics were available, how results were displayed ,... At the time, this was deemed essential to the concept of a model based on many sources of information. And it has been a success.

However, the system could not be managed by anyone else.

Basis of the new design

- Division into three major stages.
- Use of NetCDF or plain-text files for everything except interface between stages.
  - Files compatible with the LSICS system (once it is firm).
- Use of standard math routines for matrix inversion.
- Removal of as much idiosyncratic code as possible.
- Simplifying and generalizing specification of basis functions.
- Pipelining the code in each stage (removal of case statements).
- Consistent interface documentation format (retained from the ROLO era)

Instrument Routines of Redesigned SLIM



SLIM routines before or similar to LSICS

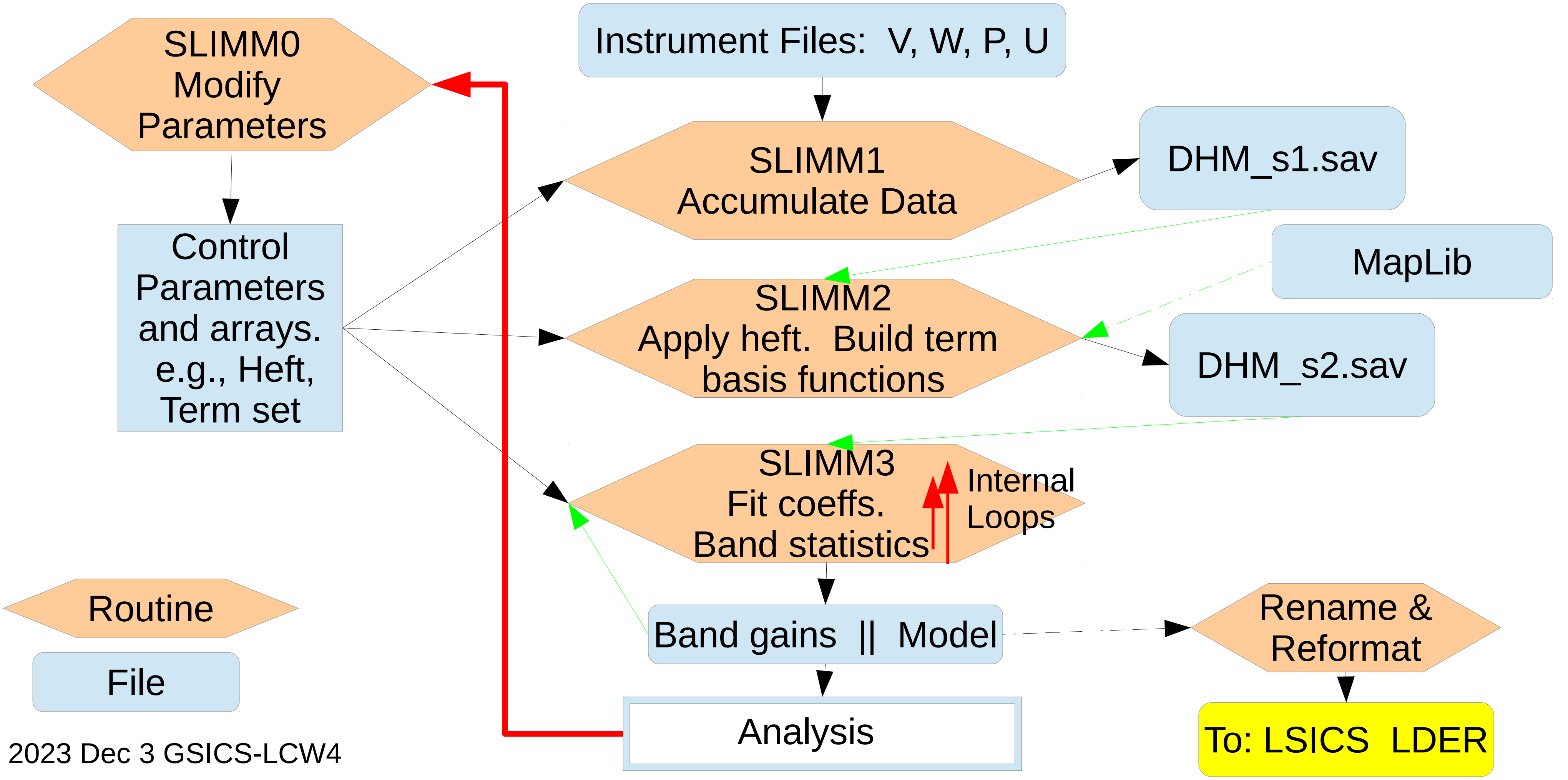
- SLIMINA, SLIMINB. Routines with custom sections for each instrument to read:
  - RSR's. Calls SLIM2WT ≡≡> Acro_wt.nc
  - Observation time, locations and measured irradiances, calls SLIM2TR ≡≡> _tr
- SLIM2EW: interpolates onto a standard wavelength grid ≡≡>_rw,
  - calculates effective wavelength and mean in-band reference lunar irradiance ≡≡> _ew
- Spectrometers only: SPECTOBANC Reduce the number of bands from hundreds to dozens by averaging sets of contiguous bands,. Alter acronym, ≡≡> _tr
- SLIM2PG Generate the photometric geometry. ≡≡> _pg
- SLIM2MC Compute the model and calibration ratio: ≡≡> _mc
- SLIMCPLOT Look at the results, calls CLOT, quality check.
- SLIM2UU Use calibration ratio to tag wild points: ≡≡> _uu
  - First: AI using statistics and absolute 2^{nd} difference: WILD4

    Display and list bad points. May reinstate.
  - Second: Visual examination and hand-pick bad points with cursor: PICKPNT3

Stage overview: Nobody said this was easy!

- [-2] Ingest of data not in LSICS format
- [-1] Preparation of data for each instrument
- 0: a: Setup: load default parameters.   b: allow modification
- 1: Accumulate the data to be fit. ≡≡> save file 1
- 2: Generate the term Basis Functions. ≡≡> save file 2
- 3: Do a fit (multiple nested Loops). ≡≡> save file 3
- [4] Post-fit: Analysis.
- Redo any of Stage 0b 1, 2, 3, over and over until done.

Model Development part of Redesigned SLIM



Stage 0: Setup

- Define file name parts for local computer, load with default values.
- Define file name parts for the SLIM system, load with local default values.
- Define numeric control parameters, load with default values.

- At each stage, may modify relevant control parameters.
- Arrays of string and numeric control parameters are the same for all stages.

Stage 1: Accumulate the data to be fit

- Read the “master” table of Instruments.
  - Columns for: acronyms, # bands, # dates, trend type, launch time.
  - Includes a “suitablilty” index for default inclusion in fit.
- For each “suitable” instrument.
  - Read the _ew, _tr, _pg, _uu files.
  - Adjust for distanceFactor & SolarVariability.
  - Increase the uncertainty for any wide bands.
  - If using trends, adjust each band for them.
- Output a “dataSave” IDL save file named with UTC time to the minute ≡≡> DHM_s1.sav .

Stage 2: Generate the term Basis Functions

- Read the control parameters; may modify.
- Read the table of “terms” for Basis Functions.
- Select & restore a DHM_s1 save file.
- Read the “Heft” table.
- Option: Read the file with MapLib coefficients.
  - Compute the Maplib corrections and apply them.
- Compute all the term Basis Functions.
- Output a “fitReady” IDL save file ≡≡> DHM_s2.sav   .

Stage 3: Do a fit

- Read the control parameters; may modify.
- Select & restore a DHM_s2 save file .
- Start with gains all unity or with results of prior fit.
- N fits using relatively rapid methods (LU inversion.)
  - Within each “fit”, several loops for outlier rejection.
  - Adjust band gains based on weighted average residuals.
- Major challenge is finding the global minimum in a space of dimensionality = total number of bands (~200).
- 1 (or more) fits with SVD inversion to get uncertainty of coefficients.
- Last fit, compute statistics and save model. ≡≡> DHM_s3.sav

After a Fit

- Analysis of the found coefficients and uncertainties.
- Calculate the Calibration Ratio for the entire inventory.
- Analysis of calibration results.
- Fit trend functions for each band, chose a form for each instrument
  - Human time-intensive
- Option: Incorporate trends at Stage 1 .
- Refit: stages 1,2,3 again.

Status

- All the instrument routines are done.
- Stage 0,1,2,done. Debugging Stage 3 .
- Virtually all the data and results display is incorporated in a call to a single (highly competent) routine, which calls a few more routines, AND a 'common' for handling colors. These could straight-forwardly be replaced.
- Has 29 numeric parameters.
- Backup slides provide a little history.

Future Advances / Modifications

- Experiment with weighting and sub-division of panchromatic bands.
- Use Chebyshev polynomials for phase angle and wave.
- Try rational functions for phase terms to avoid the non-physical infinity at p=0 .
- A few different lunar reference spectra to represent different lunar regions.
  - Initially, mare and highlands, then pyroxenes.

Goal: reduce residuals, with presumed improvement of accuracy.
Attainment: Better data sources: some exist, some planned. Improved modeling.
Young enthusiasm.

Absolute: 2025: 1%
2035: 0.3 %
2050: 0.1%

Backup Slides

- Backup

String & Array control parameters

```
LSICS-related file names: all ext will be .nc: parf
  0 Instrument base acronym        = ABI16
  1  " serial number               =
  2 Unique run version             =
  3 Top directory for netCDF       =/work2/slimnet/
  4 Sub-dir for team-based files   = S/
  5 unique before type             =
  6 spare                          =
  7 Sub-dir for SLIM-based files   = L/
  8 unique before type             =
  9 Sub-dir for reference files    = refer/
 10 Sun & Moon file name           = SlimSpec_ref
 11 Model file name (dhm)          = 22Apr16T1827
 12 FILEUNIQ outfile conflict code = 0
 13 READ_NC keyword quiet          = 2
```

Master table of instruments

Heft Table (# instruments)

Basis Function term table

```
SLIMM related file names: pars
  0 Top DIR                        =
/work2/slim/
  1 original sub-dir               =
  2  Instrument table     +.tab = slimaster
  6 Control sub-dir                = C/
  9  numerical params     +.tab = control
 20 Big files sub-dir              = B/
```

Numeric control parameters

0	0	[debug: +1=stop each inst +2=print +4=plot
1	1	[0/1 include solar variation
2	0	[+1=include trends +2=print trend coef
3	25	[Maximum band width in %
4	4	[Min master col 5 to include in fit
5	3	[Wave mode
6	1	0/1 double precision
7	1	[Debug for SLIMM2
8	0	0/1 start with prior model gains
9	15	LU auto-iteration number
10	2	SVD iterations after LU
11	3	iteration before last to show gain evolution
12	7	LOCALMINCHECK 5-bit Verbosity
13	3	[Number iterations with initial damping f2
14	7	[SLIMM3 verb ---------last integer--------

15	3.00000	[minimum allowed g [degree]
16	95.0000	[maximum " " "
17	0.500000	[maximum normalized uncertainty
18	5.00000	[Uncert multiplier for wide band
19	1.00000e-06	noise to add 0=none
20	1.00000e-08	SVD tolerance
21	1.00000e-06	delx for LOCALMINFIT 0=none
22	0.0300000	Eq 5a: U=Nominal uncertainty
23	0.333000	" f1= gain damping: minimum
24	0.700000	" f2= " " maximum: first few
25	0.900000	" f2= " " maximum: later
26	6.00000	Reslim 0 \ Residual trim
27	5.00000	Reslim 1 | +=sigma
28	3.50000	Reslim 2 | -=in units
29	0.00000	Reslim 3 / First 0 stops
30	1.0000	[Spare

Foundation of SLIM

- Combines lunar observations from many sources
  - Contributes to good libration coverage
- Each source band is scaled by a single factor to minimize residuals
- Uses team uncertainties where available; else U is assigned
- Several stages of wild-point rejection, about 1% of 100,000 points
  - Custom AI, then human assessment of every point, multiple fit loops
- Solar spectral features incorporated in detail, including TSI variation and increasing sensitivity toward the UV. 300:2380 nm
- Libration model based on Lunar spectral mapping (MapLib), 24 coefficients
  - Decreases the work to be done by the main fit. 34 coefficients
- Model is continuous in all geometry and wavelength dimensions. ±3:95° phase

LSICS Design Goals

- Allow calibration to be run at any institution.
- Minimize the instrument team effort required.
- Accommodate observatories and aircraft, as well as spacecraft.
- Run 1-to-many observations at one time.
- Keep file sizes small enough for email transfer between institutions.
- Optionally allow separation of information based on its permanence.
- Allow easy update of the reflectance model, without changing other modules.
- Current detailed design based on SLIM and the use fo effective wavelengths
- Any model specified by polynomials of the lunar angle set and 'wave' using standard symbols.
- Accommodate oversampling factor; pre-applied or not.
-
- Note: Requires use of the JPL NAIF SPICE system..
-
- Note: The SLIM system uses an effective wavelength for each band, which is adequate and efficient
- for narrow bands; and required for model development
- However, the translated system could easily use the original RSRs for each band,
- or RSRs on a common waveset.

Advances in the SLIM Lunar Spectral Irradiance Model;

Many Observations, One Moon

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

Goal: Exactly how bright (spectral irradiance) is the Moon. Find a model of lunar spectral irradiance that is continuous in wavelength and all 5 geometric dimensions with the minimum number of terms.

Use all available data with appropriate weight. Assume instruments are consistent but allow an empirical gain factor for each band.

New: Include: AeroNet Mauna Loa, 4 SEVIRI, 2 ABI. Use of ln λ wave mode.

Use HSRS solar model. Option for actual solar variation in time and wavelength.

GSICS grid simulation of models, e.g. LIME, then can calibrate them!

Auto-iteration on empirical gains. Lots of testing.

SLIM 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.

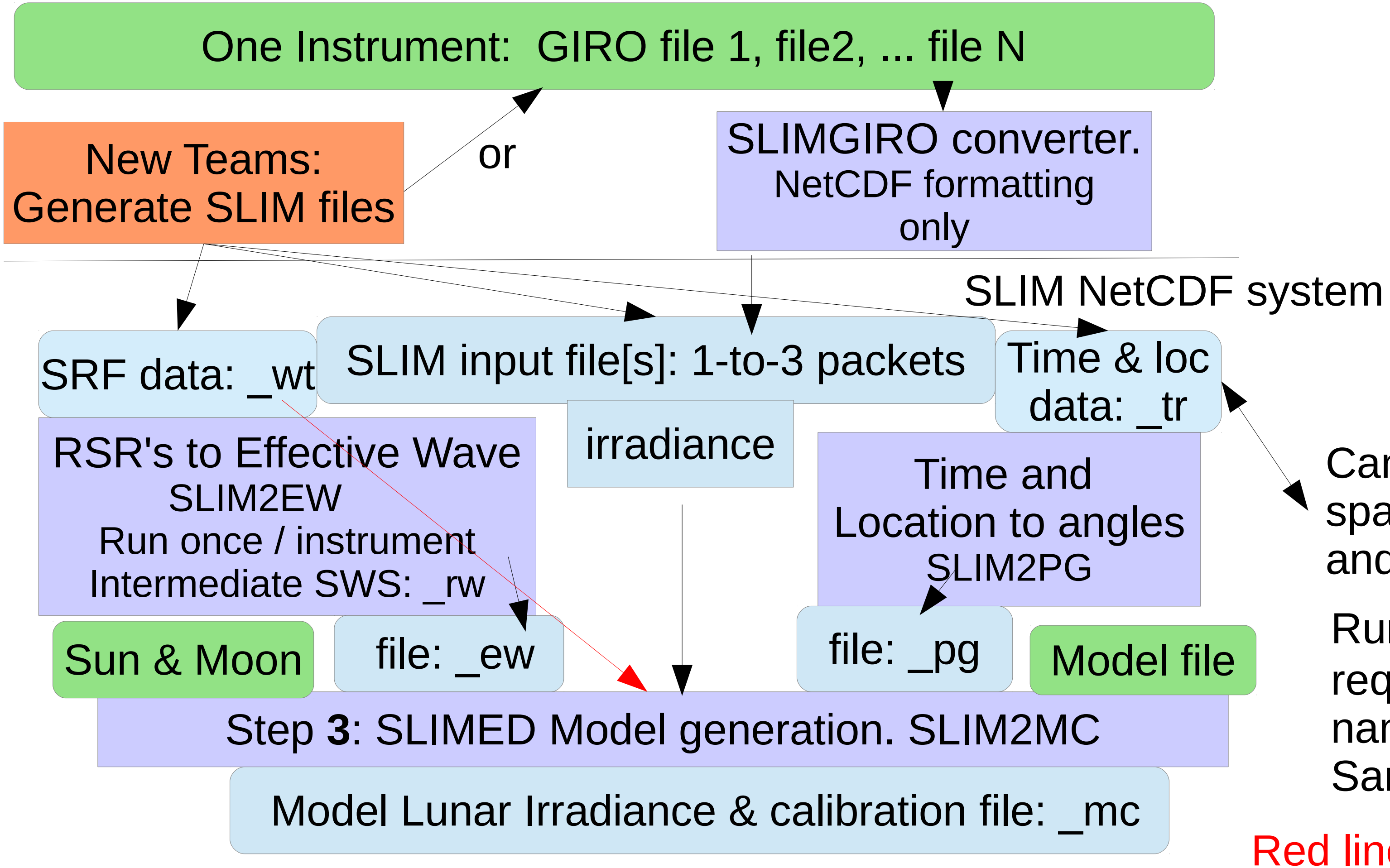
$R_0(\lambda)$ is the reference Moon, a high-resolution nominal surface reflection spectrum.
$\mathbf{L}$ is an optional independent libration model derived from Lunar orbiter data.
$\mathbf{B}$ represents the primary variation of lunar brightness with geometry and wavelength,

w = "wave" can be any of: wavelength λ [in μm] or 1/λ or ln λ

B does not have to address the high spectral-resolution features of lunar irradiance.

This is key to the SLIM method

Flow: SLIMED in NetCDF



Existing files

New or modified code

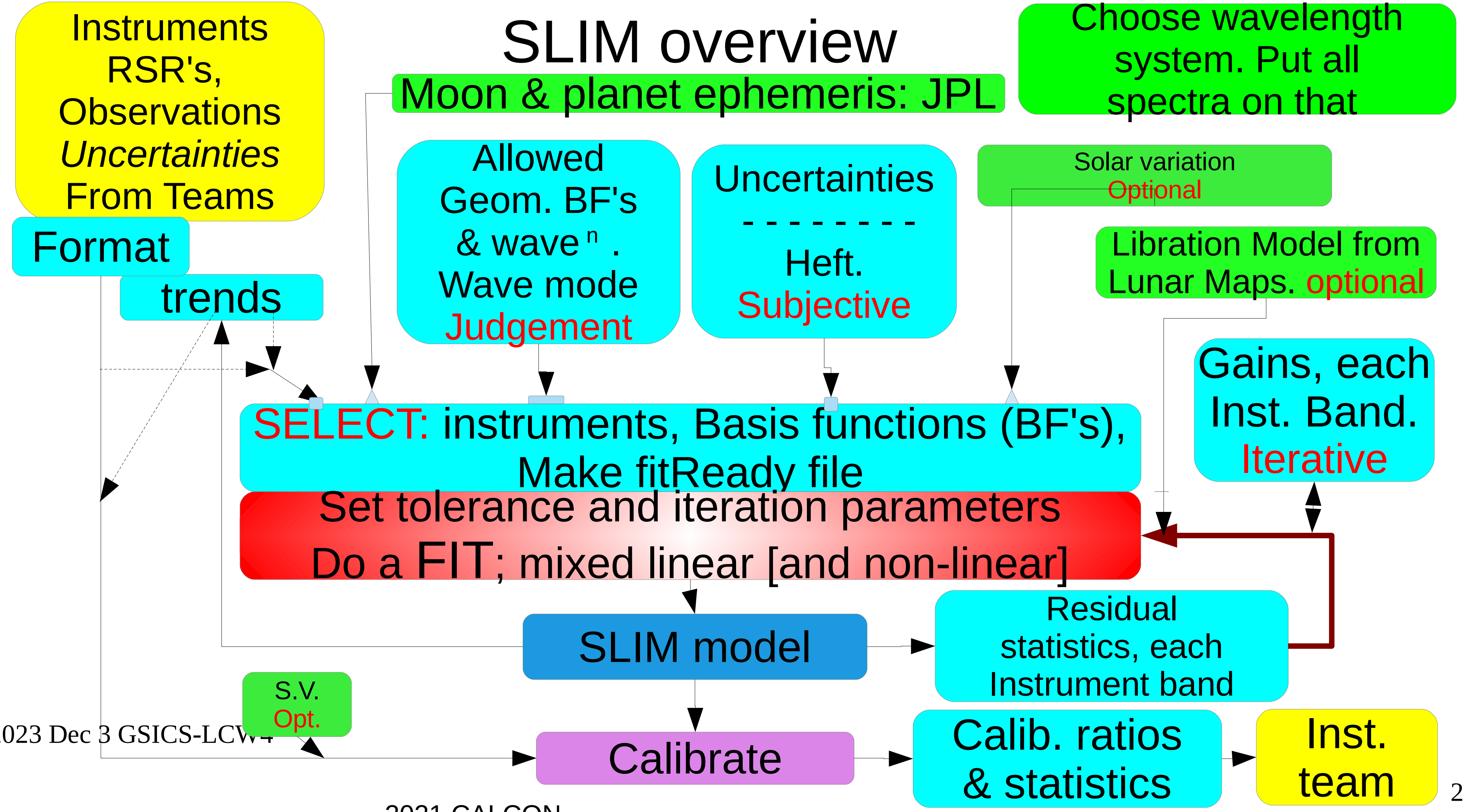
New files

Can handle spacecraft, aircraft and observatories

Running any procedure requires a string array of file name parts.
Same array for all steps.

Red line: if no use of _ew file.

SLIM overview



2023 Dec 3 GSICS-LCW4

2021 CALCON

SLIM fit Double iteration loops