

Calibration with a lunar model: algorithm description

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Abstract

The design of a practical long-term lunar calibration system is described. The system is divided into modules for putting data into standard formats, one-time processing of instrument spectral characteristics, generation of photometric geometry for each observation, generating the Moon’s effective spectral reflectance, interpolating solar monitoring data to the observation time, and using the resulting spectral irradiance model to provide the instrument calibration ratio. The system is designed to accommodate any lunar disk reflectance model. Example details are based on the SLIM lunar spectral irradiance system, currently coded in IDL.

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2023 Mar 18: §1.3, Time, and §6.2 Use of SPICE in geometry
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1 Introduction

Lunar calibration involves an on-orbit instrument periodically observing the Moon and comparing the measured spectral irradiance to a model based on the spectral irradiance of the Sun and the global reflectance of the Moon. Although the Sun is slightly variable, it is frequently measured and known to about 1 part in 10,000. The Moons surface is effectively invariant (1 part in 10⁸ per annum) but the effective spectral reflectance of the Moon’s disk depends strongly on illumination and viewing geometry. Knowledge of the disk reflectance is an active area of research and has step-wise incremental improvements.

This work assumes that a lunar spectral irradiance model has already been generated and that definitions and coefficients for all its basis functions are available. This document does not address wavelengths outside the solar-reflectance range, which could be accomodated by the addition/modification of a few items in the two Tables.

The design here is based on several things, including current practice in the GSICS community, the concept of data permanence, the SLIMED lunar model as an example, and long-term foreseen calibration needs and improvements in lunar models. Approximations made in processing a lunar model should not involve loss of precision or accuracy of more than 0.01%, ideally 1 ppm.

The design is based on processing one-to-many observations at once. The design here uses the concept of three levels of permanence, and hence separate files; contents of these files could be combined in any useful way. In part it follows existing code.

Ref_1 herein describes the SLIM system and SLIMED model:
Hugh H. Kieffer, Multiple-instrument-based spectral irradiance of the Moon
Journal of Applied Remote Sensing (JARS). Vol. 16, Issue 3
<https://doi.org/10.1117/1.JRS.16.038502> Open Access

1.1 Basics

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

$$E_{\odot}(\lambda) = \underbrace{S_{\odot}(\lambda, t)}_{\text{Solar Module}} \bullet \frac{\Omega}{\pi D(t)} \bullet \underbrace{R_0(\lambda) \mathbf{L}(P, w) \mathbf{B}(P, w)}_{\text{Disk Equivalent Reflectance}} \quad (1)$$

Here $S_{\odot}(\lambda, t)$ is the solar spectral irradiance at 1 Astronomical Unit (AU); this may be treated as constant or variable. D is the 'distance factor' $d^2 U^2$ where d is the distance from the Moon (center) to the viewer normalized to a standard distance of 384,400 km, near the mean Earth: Moon separation; and U is the Sun: Moon distance in AU. Ω is the solid angle of the Moon, illuminated or not, at standard distance (6.41780e-5 steradian) The last 3 terms together constitute $R_{\odot}(\lambda, P)$, the model of lunar disk-equivalent-reflectance (DER) which is a function of 'wave' w and five photometric angles represented by P . w is the representation of wavelength; in SLIM it can be wavelength in micrometers, the inverse of this or the natural log of this. Subscript 0 represents reference conditions. $R_0(\lambda)$ is the high-resolution nominal lunar reflection spectrum, currently based on laboratory measurements of returned Apollo samples.

The distance factor D is not included in a lunar model; it is applied separately in calibration. It may be convenient to formulate application of the lunar model as

$$E_{\odot}(\lambda_j)_i = \underbrace{S_0(\lambda_j) R_0(P_0, \lambda_j)}_{\text{Ref. spectrum}} \frac{\Omega}{\pi} \underbrace{[1 + \mathcal{H}(\lambda_j, t_i)]}_{\text{Solar Variation}} \underbrace{\mathbf{L}(P_i, w_j) \mathbf{B}(P_i, w_j)}_{\text{Lunar Model}} \quad (2)$$

Lunar models should be continuous in all geometric parameters and in wavelength, as must be the Moon. Most Earth-observing bands are of modest normalized equivalent width, $\Delta\lambda/\lambda \sim 0.15$ or less. Panchromatic bands can be represented by a set of artificially created bands by dividing their RSR into a small number of sub-bands of similar weight. Each band or sub-band is represented by its effective wavelength (see Eq. 5) for Moon-light.

\mathbf{L} is an optional libration model (MapLib) based on the geographic distribution of reflectance over the lunar surface as determined by mapping with lunar orbiters.

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

$$B_{ij}(P_i, w_j) = \sum_{k=1}^K F_k(P_i) \underbrace{\sum_{m=1}^{M_k} c_{km} w_j^{m_k}}_{b_{jk}} \quad \text{and} \quad \mathbf{B}(P, w) = \exp B_{ij}(P_i, w_j) \quad (3)$$

where 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 a polynomial of low degree. M_k is the degree in wave for each of the k terms and c_{km} are the model coefficients. $F_k w^{m_k}$ make up the hybrid basis functions of the model.

\mathbf{L} has the same form as \mathbf{B} and they could be mathematically combined. However, note that in SLIM for historical reasons the scaling of viewer latitude and longitude are different in \mathbf{B} and \mathbf{L} . \mathbf{B} and \mathbf{L} are described in more detail in Ref.1 §2.1 and 2.2 .

1.2 Permanence

The instrument information needed to do lunar calibration varies in permanence and is divided into three categories.

Spectral: S The instrument team (Team) determines the system-level relative spectral response of each band, usually pre-launch. Band spectral response is commonly stable over the life of a mission. This category can also include **Stable** information about the spacecraft, instrument, institution and instrument team.

Geometry: G Time and location of lunar observations. These data are usually static soon after each observation.

Irradiance: I The total irradiance of the Moon as derived using the same calibration coefficients as for science products. These may be computed multiple times as those coefficients evolve or/and image processing procedures improve.

1.3 Time systems

Definitions: largely excerpts from SPICE time.req

UTC Coordinated Universal Time, clock time in the Greenwich (or Zulu) time zone. Expressed as year, month, day, hour, minute, second in some order.

TAI International Atomic Time. The physical realization of TDT, it is the "count of atomic seconds that have occurred since the astronomically determined instant of midnight January 1, 1958 00:00:00 at the Royal Observatory in Greenwich, England."

TDT or TT Terrestrial Time, "used when describing motions of objects near the earth ... TT and TAI change at the same rate." At the zero point of TAI, TT has a value of 32.184 seconds.

Some lunar observations are labeled as 'Seconds from 1970 ...', and here are labeled 'T7S', which may be the same as TT

TDB or ET Barycentric Dynamical Time or Ephemeris time. Now, two names for the same thing. Used for the motions of the planets, Sun and Moon. The unit of time is the TAI second, and TDB is zero at UTC 2000-01-01T11:58:55.816, or 64.184 second before noon.

TDB and TDT run at slightly different rates through a year, the difference is never more than 0.002 seconds, which is ignored in SLIMED

GPS Global Position System Time. Clocks on GPS satellites, as observed by those on Earth, run 38 microseconds faster per day than those on the Earth; the design of GPS corrects for this. GPS is synchronized to TAI, with a constant offset: $\text{TAI} - \text{GPS} = 19$ seconds.

GPS time is theoretically accurate to about 14 nanoseconds, due to the clock drift relative to TAI that the atomic clocks in GPS transmitters experience. Most receivers lose some accuracy in their interpretation of the signals and are only accurate to about 100 nanoseconds.

JD Julian date. Days from noon on Jan 1, 4713 BC. Used in astronomy and other physical sciences. In double precision, good to about a microsecond in the current era. JD 2451545.0 is noon Jan 1, 2000

MJD Modified Julian Date. Two variants. Used extensively by the US Naval Observatory as $\text{MJD} = \text{JD} - 2400000.5$. Used in development of ROLO as $\text{MJD} = \text{JD} - 2451545d0$ (2000-01-01T12:00:00).

The human-recognizable form of time, UTC as year, month (integer or character, day of month, hour (24/day), minute, second in some order, cannot be used in calculations. Some numeric form strictly linear with the passage of time as used in ephemerides is required. Use of the SI unit of time, seconds, yields numbers virtually meaningless for human recognition. Similarly, the time commonly used for astronomical observations, Julian date, days from 4713 BC, is not easily mentally recognized. Julian days increment at noon and are the normal unit for input to the FORTRAN version of the JPL ephemeris. For lunar calibration discussion and display, the unit of days (86400 SI seconds) is useful, lunations being roughly 30 apart.

ROLO development used days (of 86400 seconds) from 2000 Jan 01 noon UTC as the time system, and the SLIM system also used this initially; these were stored as integral days and fraction of a day in two single-precision numbers. When the NetCDF version of SLIMED began, string representations of UTC (ISO 8601) were

adopted as the format for input into the SLIM system. After the JPL NAIF SPICE system was adopted for geometry calculations, 2023 March, the SPICE ephemeris time in seconds (ET), or its conversion to days, is used for calculations.

Observations are often labeled with a UTC string, but the “native” time recorded with an observation is usually (always?) one of the uniform and continuous time systems.

ET is generated from UTC with the SPICE routine call

`cspice.utc2et, utc_string, etsec`

after the SPICE leap-second kernel is loaded.

For communication and display, time units of days and years are convenient; generally used UTC or ET. To avoid half-day offsets or improper handling of leap-seconds, conversion between time systems should be done in ET.

Constants:

`utmet = 0.49925713d0 = 0.499257` UTC minus ETday at 2000.

`daysec = 86400.d0` SI seconds per day

`dayyear = 365.25` days per year

Transforms:

`etday = etsec / daysec`

`etyear = etday / dayyear`

`utcdday = etday + utmet` Error is the change in the number of leap-seconds from 2000.0

`utcyear = utcdday / dayyear` Could be considered misleading by up to 0.00137 year (1/2 day)

UTC in character form can be recovered from ETsec with SPICE routines:

`cspice.et2utc, ETsec, 'ISOC', 3, UTC_string`

Conversion between UTC and other time systems requires a leap-second table.

SLIMED uses several formats for observation time:

Early .bin files: 'MJD' is days from 2000 Jan 01 noon UTC. OBSOLETE

Input, _tv file: UTCc as string, precision unlimited

Geometry, _pg file: ET seconds in double precision, 1.1E-16 proportion, or 0.1 microsec in 50 years

Model output, _mc file: UTC in days, labeled 'utcd', single precision, 6.e-08 proportion.

Ignores leapsecond differences from 2000. Otherwise, accuracy linear with time from 2000 Jan 01, grows to 1.6 minutes by 2050. Easily adequate for tracking and trending.

The basis for trend analysis is commonly days after launch.

1.3.1 seconds from 1970

The time “seconds from 1970” has been encountered in exchange of spacecraft data. Here, this will be called 'T7S'. If this is used, it must be accompanied by a precise definition of the UTC or TDB time of T7S=0, and how leap-seconds are handled.

Beware that 'UNIX time', which starts at UTC 1970-01-01T00:00:00 and is sometimes called 'seconds from 1970', is discontinuous at leap-seconds and should not be used.

1.3.2 Obsolete styles

Because single-precision (32 bits, 23-bit fraction) has a precision 6.e-8 (0.06 ppm), or resolution of 0.005 arc-second at 360 degrees, it is easily adequate for lunar calibration for everything except time. Real arrays in ROLO and early SLIM files are largely single-precision, and time is stored as days of 86400 seconds as integer and fraction, both as real single precision. Full resolution is easily recovered by

`time= double(integer_part) + double(fractional_part) ;`

this scheme is accurate to 0.005 seconds.

1.4 Polarization

Moonlight is known to be polarized, up to several percent for common lunar calibration geometries (see Ref.1, §1.1 and references therein). Although at present lunar models rarely treat polarization, the place and requirements for inclusion of polarization are noted here.

What must be added to the calibration system to handle polarization: (.xx files are defined in Table 1 and 2)

to .wt: for each band: the degree of polarization sensitivity and the angle of polarization around the +Z axis (conventionally aligned with the central pointing direction of the instrument) relative to the instrument X-axis (conventionally aligned close to the direction of orbital motion for on-orbit instruments)

to .tv: The orientation of the instrument relative to the International Celestial Reference Frame (ICRF); 3 angles or a quaterion.

to .pg: The twist of the instrument X-axis relative to the Sun-from-Moon vector (degenerate at zero phase), the bright limb position angle (measured anticlockwise around the disk from the north point of the hour circle through the center of the Moon).

to .cl: For each band: for the model, replace the irradiance with 3 items; the maximum irradiance, the orientation of the maximum irradiance, and the percent polarization. The calibration ratio for each band now must consider the instrument polarization sensitivity and the relative polarization angle.

1.5 A word about uncertainties

The uncertainty of a lunar irradiance observation is not necessary for a lunar calibration but is essential if data are to be used in generating a lunar model. Historically, uncertainties have rarely been provided by teams. Here it is included in the files as 'obs_unc' and 'obs_qual'.

The uncertainty of a lunar model is difficult to determine, largely due to the absence of any “ground truth” about the reflectance of undisturbed lunar surface. Several planned investigations aimed at measuring lunar spectral irradiance may improve this situation. The method of propagating the uncertainty of basis function coefficients in a lunar model to uncertainty of model irradiance is mathematically straight-forward but currently a small part of the total uncertainty. It is computed during SLIMED model generation, but not currently included in SLIMED model application.

2 Files

Tables 1 and 2 list the proposed minimum contents of lunar calibration files. The “standard ID set” listed in the first file is based on GIRO. The content and terminology of each file should be discussed by the lunar calibration community to reach consensus.

Here, files are indicated only by their type as '.xx', where xx is the type. Full file names would include the instrument, the number of times or the time-range covered, the processing version, the file type and, as an extension, the file format. Something like SeaWiFS57b.xx.nc .

2.0.1 Abbreviations in the file tables

Word type: Arrays are followed by an indication of dimensionality.

S: string

I: integer, generic. I1 is byte, I2 is 16-bit, I4 is 32-bit

R: real, generic. R1 is 32-bit (single precision), R2 is 64-bit (double)

Category: in order of decreasing strictness: **C** in tables below

e: essential. Required for calibration to run

c: compulsory. Required for complete identification

m: model. Good practice, but required only if data are to be used in lunar model generation

w: which. Only if needed to distinguish between similar entities

d: descriptive. Will be forwarded to calibration output if present.

o: optional. May be included, but are not forwarded to the calibration stage

2.1 Table 1 and 2 Notes

The following attributes MUST agree between packets: 'platform', 'instrument', 'acronym' and 'serial'.

For convenience, the first items, from 'title' to 'oversamp_stat' are kept in a string array. 'Vardesc' is usually much larger, and is different for each file, but is meant to be included in the *ditto* line for each file.

date Lunar observations are commonly initially labeled in UTC, preferably in ISO 8601 format and this time is stored in the `_tv` files. The GIRO standard for date has been seconds after 1970 Jan 1 00:00, Terrestrial Time, here labeled T7S. In the photometric geometry file, `_pg`, time is stored as ET. See §1.3.

history Human-readable history of processing, with a set of 4+ items in order appended for each process. Inclusion of none or all of the item identifiers within brackets below is TBD.

- 1) Entry separator, " [=> ". Omitted before the first entry.
- 2) [now~] Date of running the process as `yyyymonddThh:mm`
- 3) [proc~] Process name + '_' + version date as `yyyymondd`
- 4) [mail~] Institutional email address of the person who is responsible for this processing. May include additional contact information
- 5) [src~] Name of primary input file, if any
- 6) [url~] Optional: URL of a document describing this process.
- 7) [note~] Optional: Notes: any additional description or comments.

Example: [=> 2023Apr17T12:43 pro slim2pg'2023apr14 mail HHKieffer@gmail.com src /work2/slimnet/S/AerN.-tv.nc

This growing attribute replaces 6 GIRO individual fields: 'date_created', 'date_modified', 'creator_name', 'creator_email', 'creator_url', and 'history', which could loose the record of prior processing.

'history' may [should?] be restarted when 'data_source' is fresh.

irr_obs For irradiance, the SLIM system uses micro-Watt $\text{m}^{-2} \text{nm}^{-1}$, as does ROLO; values are on the order of 1. Values in GIRO units of $\text{W m}^{-2} \mu\text{m}^{-1}$ are smaller by a factor of 1000.

modes To accomodate different operational modes. E.g., different gains, space-port versus nadir port, GEO scan mode, ...

oversamp_fa, oversamp_stat Determination of any oversample-factor ('oversamp_fa', OSF) is done by the instrument team. It is commonly the same for all bands, but might be 2-D:[N,M]. 'oversamp_stat' (OSS) records the OSF status: 'none' if there is none. If OSF is applied before reporting 'irr_obs', then 'oversamp_stat' should be 'team'; else it should be 'calib' and the OSF will be applied in the calibration stage. The value 'Yang' may occur for historic observations accompanied by the apparent size of the Moon; these are converted to oversampling factor. 'oversamp_fa' may be repeated in `_pg` file for convenience in calibration processing.

sat_pos If `tele_loc` absent, must have N points of Cartesian Earth-Centered Inertial position; e.g., Earth-centered ICRF in km. (as used in the JPL ephemeris) or some other ECI system different by less than 0.4 km (1 ppm of lunar distance).

If `tele_loc` supplied, these cartesian positions are optional. In either case, additional columns may be used to record other observation conditions, which must be described in 'spade' (Sat_Pos-Additional-DEscriptions)

serial Instrument serial number. If not null, will be appended to the acronym name for identification in file names.

rsr Concatonation of wavelength and system-level relative response within each band. Bands must be in the same order as in 'band_id' and 'nom_wav'.

tele_loc Ground-fixed instrument location in WGS-84: degrees E (longitude) and N (latitude), and altitude in meters. Required if 'sat_pos' not supplied. If 'sat_pos' is also present, can choose which to use.

Table 1: Instrument team Lunar Observation file contents. **M** is the number of bands, **N** is the number of dates. Leading brackets in the description column contain name used in GIRO, if different than in SLIM. See §1.4 for changes to include polarization.

NAME	C	TYPE	Attributes	Packet S: Spectral and Source	File _wt
title	d	S	Brief name for what is in this file; e.g.,		
summary	d	S	Summary of file, identifying major contents		
institution	c	S	Name of organization generating this file		
insti_url	d	S	url of the institution		
license	d	S	Any legal limits or disclaimers		
platform	c	S	Name of spacecraft or observatory		
instrument	e	S	Name of instrument. Should not repeat 'platform'		
serial	w	S	Serial number within virtually identical instruments. May be null. See note		
acronym	c	S	Short word for platform+instrument that is unique within GSICS. Registered upon first submission		
data_source	d	S	Source of the data, and any version number or date. Comments allowed.		
history	d	S	Processing history: [separator], date, software and version, email, purpose ... See note		
id	d	S	File names(s) that institution would normally associate with these data. Commonly ridgedly formatted and long.		
model	c	S	Lunar spectral irradiance system being used		
reference	d	S	List of materials describing the instrument, observations or processing		
oversamp_stat	c	S	Status of over-sample factor. Valid values are: 'none', 'team', 'calib'. See note		
---	-	-	--- End of standard ID set --- See note.		
vardesc	c	S	Description of all the variables in this file.		
num_band	e	I	[chan] Number of bands (or channels) in the VIS/NIR.		
---	-	---	Variables		
band_id	c	S(M)	[channel_name] Name normally associated with the band, each unique		
nom_wav	e	I2(M)	[effective_wavelength] Nominal wavelength in nm, each unique		
rsr	e	R1(x,2)	[srf] System-level Relative Spectral Response, bands concatenated. [*,0] is Wavelength in nm. [*,1] is the System-level relative spectral response. See note		
nin_band	e	I2(M)	Number of points in each band in 'rsr'		
NAME	C	TYPE	Attributes	Packet G: Geometry	File _tv
<i>ditto</i>	"	"	The standard set in Packet S. 'oversamp_stat' is controlling		
date_type	e	S	Normally 'UTC'. See § 1.3		
num_date	e	I2	[date] Number of observation times.		
launch	d	S	Launch date, UTC		
vardesc	c	S	Brief description of the variables		
---	-	---	Variables		
date	e	S(N)	Observation time of center of the Moons disk, UTC. See note.		
sat_pos	e	R1(N,3)	Viewer location (satellite_position). XYZ of Earth-Centered Inertial position. Required unless 'tele.loc' supplied.		
tele_loc	e	R1(3)	Telescope location as Longitude E, latitude, elevation. Only if observatory.		
obs_qual	m	R1(N)	Relative uncertainty of the irradiance determination of each observation. Median value of 1.		
oversamp_fa	d	R1[N]	Optional. Oversample-factor. Use depends upon 'oversamp_stat'		
conditions	o	R1(N,C)	Optional. Any number of columns of condition at each observation time		
condes	o	S(C)	Requires if 'conditions' present. Explanation for each columns of 'conditions'		
NAME	C	TYPE	Attributes	Packet I: Irradiance	File _ir
<i>ditto</i>	"	"	The standard set in Packet S		
vardesc	c	S	Brief description of the variables		
---	-	---	Variables		
band_id	c	S(M)	[channel_name] Duplicate of that in _wt file for insurance.		
irr_obs	e	R1(N,M)	Measured lunar spectral irradiance. Units: micro-Watt m ⁻² nm ⁻¹ . See note		
obs_unc	m	R1(N,M)	One-sigma uncertainty of the measurement, same units. Independent of 'obs_qual'		
modes	w	S[k]	Optional, Names of different modes		
nummod	w	I1[k]	Number of observations in each mode, aligned with 'modes'		

2.2 Lunar calibration output files

Table 2: Lunar Calibration output files contents. 'dup4conv' means: duplicate of an earlier file, for convenience. See §1.4 for changes to include polarization.

NAME	C	TYPE	Attributes ——— File _ew: Effective wave; Static
<i>ditto</i>	"	"	The standard set in Packet S.
vardesc	c	S	Brief description of the 2nd dimension of 'eff_wave'
num_band	e	I	[chan] Number of bands (or channels) in the VIS/NIR.
——	—	——	Variables ———
eff_wave	e	R1(M,8)	Effective wavelength array [band,item]
NAME	C	TYPE	Attributes ——— File _pg: Photometric Geometry
<i>ditto</i>	"	"	The standard set in Packet S. 'oversamp_stat' is controlling.
vardesc	c	S	Brief description of the variables, esp. the 2nd dimension of 'pgeom'
num_date	e	I2	[date] Number of observation times. dup4conv
——	—	——	Variables ———
etsec	e	R2(N)	Observation time of center of the Moon's disk, ephemeris time in seconds. See note.
pgeom	e	R1(N,11)	Photometric geometry, distances and celestial angles
oversamp_fa	d	R1(N)	Optional oversample-factor. See note. dup4conv
NAME	C	TYPE	Attributes ——— File _mc: Model and Calibration
<i>ditto</i>	"	"	The standard set in Packet S
reference_model	e	S	Name of the reference model and its version
vardesc	c	S	Brief description of variables
num_date	e	I2	[date] Number of observation times.
num_band	e	I	[chan] Number of bands (or channels) in the VIS/NIR.
——	—	——	Variables ———
band_id	c	S(M)	Name normally associated with the band. dup4conv
eff_wave	e	R1(M,8)	Effective wavelength array [band,item]. dup4conv
utcd	e	R1(N)	Observation time, center of the Moon's disk, as days from 2000 Jan 01 00:00 UTC
irr_mod	e	R1(N,M)	Model spectral irradiance; micro-Watt m ⁻² nm ⁻¹ .
calib_ratio	e	R1(N,M)	Calibration ratio: Observed / model irradiance [date,band]. [7,7] is invalid placeholder
modes	w	S[k]	Optional, Names of different modes. See note.
nummod	w	I1[k]	Number of observations in each mode, aligned with 'modes'

3 Design modules: Overview

All files will need names, presumably something like: Instrument + unique + type, where 'unique' might be the null or the date created or the number of observation contained. Here, for brevity and convenience, file types are named '_xx' using the two letters of the SLIM file type. The symbol \Rightarrow *fileName* indicates an output file.

The contents of each file are listed in Tables 1 and 2. In implementation, files within each Table could be combined but loses consideration of permanence.

Ingest Get all needed information into standard input format.

Reference: Sun and Moon spectra, Solar variation. \Rightarrow *SlimRefSpec.nc*

Instrument: Band information (RSRs), observation time and location, image irradiance.

\Rightarrow *_wt, _tv, _ir*

Spectral (band) Process reference spectra information into form needed by the Model module. Process instrument spectral information into form needed by the Model module.

\Rightarrow *_ew*

Geometry Process geometric information into photometric geometry in the form needed by the Lunar module.

\Rightarrow *_pg*

Lunar Process the photometric geometry for each observation and the effective wavelength for each band into the lunar disk model (time,band).

\Rightarrow *_lu* of $\mathbf{L}(P_i, w_j)\mathbf{B}(P_i, w_j)$ (time,band).

Solar Interpolate the solar tables to the time and wavelength of each observation.

\Rightarrow *_hv* of $[1 + \mathcal{H}(\lambda_j, t_i)]$ (time,band).

Calibration Use products of the earlier modules to yield the model spectral irradiance and the calibration ratio; (observed / model) spectral irradiance (time,band).

\Rightarrow *_mc*

Note, in the IDL version of the SLIM system the Lunar, Solar and Calibration modules are all in the single Model routine **slim2mc.pro** and do not generate the *_lu* and *_hv* files.

4 Ingest module

This module ensures that the instrument data are in proper units and format for further processing. It is divided into three parts based on permanence. Files submitted by a team may already be in standard units and format, in which case little is needed beyond linking with the proper file name.

4.1 Spectral: S

Requires the system-level relative spectral response (RSR) for each band. E.g., a set of pairs for the wavelength or wave-number in well-defined units and RSR (dimensionless, consistent scale) for each band. Uncertainties for each point are encouraged but optional. Each band should have a name and a unique nominal wavelength. The order of the bands submitted by the team will be preserved throughout all processing.

Construct a band-concatenated array of point pairs ($\sum_m L, 2$): wavelength in nanometers and RSR values. Define an integer array of the number of points L in each band. Transfer the band names and nominal wavelengths. \Rightarrow *_wt*.

4.2 Geometry: G

Requires the time of the imaging the center of the Moon in an unambiguous and well defined system, with resolution of about 1 second. E.g. UTC as a string: '2017-Nov-06T12:34:56' Convert the observation time to UTC in ISO 8601 format.

Requires the location of the instrument (“viewer”) in Earth-centered-Inertial (ECI) Cartesian coordinates, ICRF preferred. This location, a Cartesian vector, is called VE for “Viewer-from-Earth”

If the viewer was fixed to the ground, then only that location is needed. Recommend WGS-84, east longitude and latitude in decimal degrees and altitude in meters.

If an over-sample factor is known, and was already applied, it is optional. If it has not been applied to the irradiance, it is mandatory.

⇒ *_tv*

4.3 Irradiance: I

Requires the lunar spectral irradiance at each date in each band in well-defined units.

Convert to standard spectral irradiance units. SLIM uses: micro-Watts nm⁻¹ m⁻² as values are then near 1. Could use SI: Watts m⁻³. This is the observed irradiance, which may involve an un-applied over-sampling factor.

⇒ *_ir*

5 Spectral module

The system-level relative spectral response (RSR, $T(\lambda)$) of each instrument band j is put on the UPRS and then combined with the solar and lunar reference spectra to determine the band effective wavelength for the Moon, the equivalent width, and the mean in-band lunar irradiance at standard distances.

Effective wavelengths for an instrument band are the wavelengths weighted by the band RSR and the nominal source flux.

Practically, all spectra must be re-sampled onto a common set of wavelengths, then spectral operations are simple. For the SLIM system, a set with uniform resolution $\lambda/\Delta\lambda = 1000$ and starting at 300 nm was chosen, the Uniform Proportional Resolution Set, UPRS. The number of points need only cover the longest wavelength in any RSR. SLIM uses 2115 points with the last wavelength at 2481.8 nm. E.g., the reference solar spectrum $S_0(\lambda)$ (25281 points) and the Lunar Albedo Reference Spectrum $R_0(\lambda)$ (221 points) are put on this 2115 point system.

Reference spectra: each treated as a single band

Sun Solar spectral irradiance at 1 Astronomical Unit. Resolution comparable to or better than used for measuring RSR’s

Moon Reflectance factor for the nominal Moon near-side. Ideally the geometric albedo, but this is impractical because of the opposition effect. The scale does not matter as long as the same reference spectrum is used in model generation and application. Practically, to date, the reflectance of returned Apollo samples measured in the lab at some practical geometry has been used.

Instrument bands:

Re-sample each band RSR separately.

Compute the effective wavelength for each band.

$$\lambda_{e_j} = \frac{\int_{\lambda_1}^{\lambda_2} \lambda \cdot S_0(\lambda) R_0(\lambda) T_j(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S_0(\lambda) R_0(\lambda) T_j(\lambda) d\lambda} \quad (4)$$

where S_0 is the nominal solar irradiance spectrum, R_0 is the lunar reference spectrum and T is the RSR (transmission).

The wavelengths limits are in theory zero and infinity but realistically are the wavelengths over which the RSR is measured. In practice, summations are used and the summation is done over the full point set of the UPRS as T_i is zero outside the RSR range of a band j .

$$\lambda_{e_j} = \frac{\sum_i \lambda \cdot S_{0i} R_{0i} T_{ji} \Delta\lambda_i}{\sum_i S_{0i} R_{0i} T_{ji} \Delta\lambda_i} \quad (5)$$

Compute the equivalent width:

$$W_{\Delta j} = \sum_i T_{ij} \Delta \lambda_i \quad (6)$$

Where T must be normalized to a maximum of unity for each band.

Compute the mean in-band reference lunar spectral irradiance for each band:

$$E_j = \frac{\sum_i S_{0i} R_{0i} T_{ji} \Delta \lambda}{\sum_i T_{ji} \Delta \lambda} \quad (7)$$

Combine the nominal wavelength, the effective wavelength, the equivalent width and the in-band lunar irradiance into an array (band,item) and \Rightarrow `_ew.nc`

In SLIM these summations and others are done by the routine **slim2ew.pro**

5.1 Rigorous resampling

Simple interpolation is inappropriate when the input spectrum point density may be much higher or lower than the output. A method that works nicely for all relative densities is to construct the cumulative sum array

$$S_I = \sum_{i=1}^I Y_i \delta \lambda_i$$

over the input points, where Y_i are input spectral values and $\delta \lambda_i$ is the spectral width (between the 2 adjacent midpoints) associated with each point i . Then do simple linear interpolation of S at the midpoints between the output points, take the ΔS and divide by the output $\delta \lambda$ between these midpoints. Outside the set of input points, Y can be assumed to be either zero (for RSR's) or constant at the end-point value (physical spectra). If the input point spacing is at least twice the output spacing, then simple interpolation of the input is adequate. In SLIM, this is all implemented in the routine **dinterp.pro**.

6 Geometry module

6.1 Geometry notation

Define five locations, 'center' for large bodies means center of gravity:

- B: barycenter of the solar system
- H: center of the Sun (Helios)
- E: center of the Earth
- M: center of the Moon
- G: (Gravitational) Barycenter of the Earth: Moon system
- V: 'Viewer', an instrument or point-location observer

Symbols:

- \cdot is the dot-product
- \times is the cross-product
- \sharp indicates matrix multiplication
- \overrightarrow{QV} is the vector to Q from V
- \overline{QV} is the magnitude (distance) between Q and V
- \widetilde{DA} is the **rotation matrix** taking vectors from the A to the D system

Five angles, p, x, y, z and h with 4 independencies, comprise P , the "Lunar Observation Angle Set" (LAOS)

- p signed phase angle
- h or 'Hlon': the sub-solar selenographic longitude
- z or 'Hlat': the sub-solar selenographic latitude
- x or 'Vlon': the sub-viewer selenographic longitude
- y or 'Vlat': the sub-viewer selenographic latitude

Also used will be:

- $g \equiv |p|$: the absolute value the phase angle
- $q \equiv 1/g$: the inverse of the absolute phase angle
- w or 'wave': the effective wavelength in micrometers, or its inverse or its log.

For increased numerical stability of the fit, the independent variables may be scaled to the order of 1

6.2 Derivation

Alert: This section describes using direct calls to the ephemeris ala the older routine moongeom.pro. As of 2023 April, geometry calculations are done using the NAIF SPICE system in the newer routine spicemoon.pro. Tests indicate agreement to about 3.e-5 degrees or better.

Convert the observation time to Julian date TDB for calls to an ephemeris.

The ephemeris is assumed to be the JPL double-precision ephemeris; DE430 or 440 suggested. Set the ephemeris to return solar-system barycenter positions in kilometers; the native system of the JPL ephemeris.

Access the ephemeris at each ET for the position: of the Sun \overleftarrow{HB} , of the Earth-Moon barycenter \overleftarrow{GB} , the geocentric position of the Moon \overleftarrow{ME} and the orientation of the Moon Υ . All of these are in the ICRF.

Get the Earth/Moon mass ratio: emrat=81.300569074190619 in DE430

Compute the position of the Moon relative to the solar-system Barycenter

$$\overleftarrow{MB} = \overleftarrow{GB} + \overleftarrow{ME}/(1 + \text{emrat})$$

Compute the Sun-from-Moon vector in AU (astronomical units: 149597870.7 km in DE430)

$$\overleftarrow{HM} = (\overleftarrow{HB} - \overleftarrow{MB})/\text{AU}$$

Compute the Viewer-from-Moon vector: $\overleftarrow{VM} = \overleftarrow{VE} - \overleftarrow{ME}$

Rotate \overleftarrow{HM} and \overleftarrow{VM} vectors into the selenographic system using Υ to generate \overleftarrow{HM}_m and \overleftarrow{VM}_m vectors

Convert the Cartesian coordinates to spherical coordinates of co-latitude (ϑ), longitude (ϕ) and radius (r)

Construct the lunar photometric angles

$$h = \overleftarrow{HM}_{m\phi}$$

$$z = 90 - \overleftarrow{HM}_{m\vartheta}$$

$$x = \overleftarrow{VM}_{m\phi}$$

$$y = 90 - \overleftarrow{VM}_{m\vartheta}$$

$$g = 180/\pi \arccos(\overleftarrow{HM}/\overline{HM} \cdot \overleftarrow{VM}/\overline{VM}) ; \text{ dot-product of unit-length vectors}$$

p : magnitude same as g , sign same as $x - h$

Construct the distance factor: $\text{distFac} = (\overline{HM}/\text{AU})^2 (\overline{VM}/384.4e3)^2$

Construct celestial angles:

Right ascension (R.A.), Declination: Convert \overleftarrow{MV} to spherical angles

R.A. is the longitude and Dec. is the latitude

Position angles:

Construct the $\widetilde{\mathbf{MA}}$ rotation matrix, to Lunar from astronomic.

Define a C='Camera' coordinate system with the +Z axis along \overleftarrow{MV} and celestial North in XZ plane.

Construct the $\widetilde{\mathbf{CA}}$ rotation matrix

Axis position angle:

Extract the Moon +Z axis in the astronomic system: $\overleftarrow{ZM}_a = \text{row 3 of } \widetilde{\mathbf{CA}}$.

Rotate the Moon +Z into the C system: $\overleftarrow{Z}_{ac} = \widetilde{\mathbf{CA}}^\# \overleftarrow{ZM}_a$

Convert \overleftarrow{Z}_{ac} to spherical angles, axis position angle is the longitude.

Bright limb position angle:

Rotate \overleftarrow{HM} into the C system: $\overleftarrow{HM}_c = \widetilde{\mathbf{CA}}^\# \overleftarrow{HM}$

Convert \overleftarrow{HM}_c to spherical angles, bright limb position angle is the longitude.

7 Lunar Module

The required inputs are:

The photometric angles at each observation time

The effective wavelength (Eq. 5) and the mean in-band lunar irradiance (Eq. 7) for each band

The list of one-character names of each photometric angle

The term symbols representing each of the hybrid basis functions of the model

The coefficients of each of those terms.

Implement calculation of $B_{ij}(P_i, w_j)$ in Eq. 3 for SLIM or its equivalent for some model other than SLIM. The derivation of model terms and coefficients for SLIM is described in Ref_1

Read the model file, extract symbols for each term and the coefficient values C_k . Example: symbols corresponding to Table 5 of Ref.1 are:

c cw cw2 g g2 g3 gw gw2 g2w q q2 qw qw2 q2w h h3 h5 hw hw2 h3w z zw x y x2 y2 xw yw hx hy h2x2 h2y2 hxw hyw .

Generate the LOAS basis functions plus those for g and q with the same scale as used in the model (e.g., p in radians), the “angle Basis Functions” (aBF’s). Each is a vector of length N , the number of observation times.

Because of the mix of pure geometric and wavelength terms, the summations of Equation 3 may be done several ways. For example:

Generate the $K \sim 35$ hybrid basis functions (hBFs) including the wave component for each term by multiplying the aBFs to the appropriate power as indicated in the symbols for each term. For the published SLIMED model, $K=34$. E.g., ‘hw2’ is the h aBF times the w hBF (constant over time) squared.

Accumulate the aBFs into a $\mathcal{M}(N,K)$ matrix

Matrix-multiply $C_k \mathcal{M}$ to get B_{ij}

The SLIM IDL routine **sid3bij.pro** does this messy task with a modest amount of code. However, it is repetitious in computing the pure geometric parts.

If a separate libration model was used, implement calculation of $L_{ij}(P_i, w_j)$ in the same manner. See Ref.1 §2.2 .

Then add L_{ij} to B_{ij}

Take the exponent of B_{ij} to get $\mathbf{B} \times \mathbf{L}$

8 Solar module

The required inputs are:

Time of each observation (in UTC days)

Effective wavelength of each band

Variation of both total and spectral solar irradiance are small but well known. Total solar irradiance (TSI) S has been measured with a precision of about 1/10,000 over the period of lunar calibration.

As the TSI varies, the variation of spectral irradiance increases toward shorter wavelengths, represented here by a quadratic fit in log/log space over 290:2412 nm to the ratio f of solar spectral irradiance (SSA) variation (high-pass filtered) to TSI variation; see Ref.1 §2.3 .

$$f(\lambda) = \exp(-0.338752 - 0.785894 \ln \lambda + 0.202152 \ln^2 \lambda) \quad (8)$$

where λ is in micrometers.

Solar variation is implemented in SLIM as

$$S_{\odot}(t, \lambda) = S_0(\lambda) \left[1 + \underbrace{f(\lambda) \left(\frac{H(t)}{H_0} - 1 \right)}_{\mathcal{H}} \right] \quad (9)$$

where $S_{\odot}(t, \lambda)$ is the solar spectral irradiance and $H(t)$ the total solar irradiance; with subscript 0 being the long-term average. $\mathcal{H}(t, \lambda)$ is the solar variation model. It is applied to the irradiances going into a model fit and/or a calibration, normally both.

In SLIM, TSI is represented by a list of TSI minus a base value of 1360 W/m² at 1 day resolution covering 1978 Nov. 17 to 2021 Feb. 16 .

the Solar reference spectrum is specified in Ref.1 §2.3

The resolution of TSI is one day

The spectral coefficients are in Ref.1 Eq. 7

The Sun and Moon spectra on the UPRS ready for use are in `-/slimnet/refer/SlimRefSpec.nc`

Algorithm:

Read the TSI versus time table.

Read the relative spectral variation coefficients.

For each band, evaluate $f(\lambda)$ using Eq. 8.

Do interpolation of TSI for each observation time. Linear interpolation is probably adequate.

If time is outside table range, use the long-term average and accumulate a count.

When done, if any times were outside of table, print an alert.

For each date, compute the solar variation model given by Eq. 9, $[1 + \mathcal{H}(\lambda, t)]$ (time,band).

9 Calibration Module

The required inputs are:

The observed irradiance.

The model mean in-band reference lunar irradiance for each band E_j

The distance factor $D(t)$.

Optionally, the oversample factor.

From Lunar module: BL (time,band)

From Solar module: $1 + \mathcal{H}(\lambda, t)$ (time,band)

Algorithm: implement Eq. 2.

Start with the mean in-band lunar irradiance for the Reference Spectrum for each band, multiplied by the constant $\frac{\Omega}{\pi}$, yields array(band)

Multiply these by the BL (time,band) to yield an array (time,band).

If using solar variation, multiply this array by the solar variation array $[1 + \mathcal{H}(t, \lambda)]$

This yields the model lunar spectral irradiance (time,band) at standard distance $E_{\odot}(\lambda_j)_i$.

Based on the value of 'oversamp_stat', if there is any un-applied over-sampling factor 'oversamp_fa'(time), divide the distance factor (time) D by it.

Multiply the observed irradiance (time,band) by the [modified] distance factor (time) to get the corrected irradiance (time,band) E_{ij}

Divide the corrected irradiance (time,band) by the model result (time,band) to yield the calibration ratio (time,band).

Output the model and the calibration ratio, along with instrument band information and observation times for convenience. \implies *_mc*

A Acronyms

aBF	angle Basis Function
AU	Astronomical Unit
DER	Disk Equivalent Reflectance
ECI	Earth-Centered Inertial
hBF	hybrid Basis Function
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IDL	Interactive Data Language
ISO	International Standards Organization
GIRO	GSICS Implimentation of the ROLO model
GSICS	Global Space-based Inter-Calibration System
JPL	Jet Propulsion Laboratory
LOAS	Lunar Observation Angle Set
MapLib	Map-based Libration model
OSF	over-sample factor
OSS	over-sample status
ROLO	RObotic Lunar Observatory
RSR	Relative Spectral Response
SLIM	Spectral Lunar Irradiance Model
SLIMED	Spectral Lunar Irradiance Model, Effective wavelength methoDology
TDB	Barycentric Dynamical Time (in French)
TSI	Total solar irradiance
TT70	Terrestrial Time, seconds from 1970 jan 01
UPRS	Uniform Proportional Resolution Set
UTC	Coordinated Universal Time
WGS	World Geodetic System

B How oversample factor is handled in SLIM

The key item is the attribute 'oversamp_stat' (OSS), index[16] in the Standard ID set of attributes in all files. See Table 1 Packet S.

SLIMGIRO Defined by input argument matt[1].

SLIM2TV In the `_tv` file, OSS is set to 'none' unless an array of oversample-factors is supplied, in which case OSS is set to either 'team' or 'calib'; 'calib' indicates that the factor should be applied in the calibration module. For historic reasons (e.g., Landsat imagers, including Landsat-9 OLI), an alternate 'Yang' is allowed to indicate the along-scan apparent angular diameter of the Moon (in milliradians) which can be used to later compute the oversample factor.

SLIM2EW Does not modify anything related to oversample factor

SLIM2PG SLIM2PG looks for the 'oversamp_fa' array in the `_tv` file. If it is there and has the same number of dates as the `_ir` file, then it sets a flag `doos` to do oversampling and checks the OSS. If OSS is 'Yang' the 'oversamp_fa' array is converted from Y-angle to oversample factor and it asks if the oversample factor should be applied. If yes, then OSS is set to 'calib'; otherwise it sets the OSS to 'team', indicating the oversample factor has already been applied.

SLIM2MC If the OSS is 'calib' it first checks if the 'oversamp_fa' array size agrees with the number of observation times; if not, processing will stop with an error message. If the size is correct, 'oversamp_fa' is applied as a divisor to the distance factor.

C How attributes are handled in SLIM

The routine `slimsatt.pro` contains a firm-code array of attribute names and values. The first $N=13$ are the 'standard' set (`stdset`), and are included in all files. These are followed by a few pairs that are a convenient place to hold information about the people doing the processing. This firm-code should be edited by each institution.

This routine can be called to return only the `stdset`, or all in the firm-code or just the first N ; or just a set specified by a list of attribute names. Or, it will return all attributes in the current open NetCDF file.

When reading from a file, the `stdset` are expected; these are always returned in the order specified in the firm-code. `read_nc.pro` calls `slimsatt.pro` to fetch and return attributes with the same options.

Attributes are written to a file in the same high-level routine (`SLIM2xx`) that opens a file. Additional attributes to be written can be transferred into some of these routines with the keyword '`atv`'.