USE OF THE MOON AS A CALIBRATION SOURCE

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Problem being addressed:
Long-term stability and absolute radiometric instrument response in flight.

A primary goal of EOS is long-term monitoring !

Procedure. Establish the Moon as a radiometric standard.

MAJOR PARTS:

Determine lunar radiometry (USGS & NAU Team)
- build dedicated facility
- observing program
- radiometric model

Instrument observes the moon (Instrument Teams)
- determine opportunities
- ? special maneuvers
- schedule observations, acquire them.

Produce radiometric images of that geometry (USGS & NAU Team)
- model the precise geometry of instrument observation
- if necessary, make small correction for spectral passband
- produce image(s) with higher resolution than instrument

Compare Instrument data with radiometric image (Instrument Teams)
- register instrument image to model
- resample to each pixel
- compare instrument level 1A data with radiometric model
- ratio is calibration discrepancy

Additional uses of lunar viewing.
- Almost black background
  - Bright stars are E-11 of sun
  - 4 K thermal level
- Quality of spatial response.
  - Estimate MTF by inversion of limb sharpness
  - Map near off-axis response with 1/2 deg source
  - band to band registration
  - transient response

\LUNAR\MODIS\CALTALK.T

RELEVANT PROPERTIES OF THE MOON

Radius 1738 km (max. deviation from sphere ~1 km)

Mean distance from Earth: 384,405 km, varies 356,400 to 406,700
Orbital eccentricity 0.055 Perigee precesses in 8.85 yr

Equivalent diameter at EOS (705 km) nadir, 6.37 km

Orbital period: siderial 27.32 days, synodic (month) 29.53

Orbital inclination to ecliptic 5.2°
Node precesses (retrograde) in 18.61 yr
Saros cycle of eclipses is 18.1 yr

Libration: Latitude +- 6.7 Longitude +- 7.6°
(physical libration order of .05°)

Inclination of equator to ecliptic 1.5°, to orbit 6.7°

RADIOMETRY

Full moon visible magnitude -12.70; sun is -26.78,
ratio is 4.3E5

Strong backscattering, opposition surge at small phase angles

Brightness varies about a factor of 2 over face of the moon.

Reflectivity increases with wavelength, with broad(~200nm), modest contrast(~5%) absorption bands.

Spectral reflectivity of returned lunar samples:

	.4μm	1.	2.5μm
mature mare soil	.06	.12	.26
mature highland soil	.11	.24	.43

Polarization: ~0 @ 0°, -1.2% @ 12°, ~0 @ 24°, +8% @ 90°
at visual wavelengths; decreases to longer wavelength.

Earthshine, as factor below to the sun:
1.E4 @ new moon, 4.4E4 @ quarter moon, 1.6E5 @ 50° from full moon

VG1

DETERMINE LUNAR RADIOMETRY

Build dedicated facility:
- Current site is at USGS in Flagstaff; similar to Lowell Observatory
  - Not as dark as best observatory sites,
    - But viewing only bright objects (-12 to +8 magnitude)
  - Seeing; moderate at best by modern astronomy standards
    - But expected to be adequate for 4.8 arcsec pixels
- Fully digital mounting.
- Small telescope for each wavelength region, all reflective, on-axis
  - Silicon CCD 0.35 to 1.0 um, 512 pixels square, 20 cm aperture
  - Infrared array (TBD) 0.9 to 2.5 um, 256 pixels square, ~ 20 cm
- Filters cover standard star system and several instrument passbands
  - Up to 34 in each telescope.
  - EOS instruments were encouraged to provide theirs.
- In-dome radiance standard; NIST traceable, but not 0.5 meter distance.

Status: Silicon CCD system in place.
- Have made initial manual observations
- Expect regular observations beginning next month
- Have begun specification for IR system
- Expected funding for operations "not there".

Observing Program
- Each photometric night (~100/year) during bright half of month
- Observe moon about every 1 deg of phase angle, more often near full
  - Image through ~ 20 filters
- Intersperse ~10 standard stars, use for extinction correction
  - Trail stars slightly, same set of filters, readout small area.
- Repeat all night.
- Archive raw data as spectral cubes of each filter cycle
- Radiance calibration of each cube
- Process stars to derive extinction as function of wavelength
- Correct moon images to exo-atmospheric (sky brightness removal)

Radiometric Model
- Resample every image onto standard lunar grid, "ALEX"
  - Mimimum distortion, but covers all surface ever visible from earth.
- Accumulate data as a function of phase angle and libration
  - The opposition effect, relatively rapid changes near full moon
  - Libration: 18 yrs for full cycle. 4.5 yrs for 1/4 cycle.
- Construct photometric model of each pixel in ALEX grid
  - Primary candidate; Hapke model, physical basis, 6 parameters
  - Work thus far fits observations within error.
- {Look for lunar surface types, use to reduce free parameters}
  - { albedo, spectra, photometric parameters}

INSTRUMENT OBSERVES THE MOON

Determine opportunities
  Lunar ephemeris is very well known
    Given instrument view angles, can forecast decades ahead
  Major issue is platform attitude
    When nadir oriented, Only MODIS can see moon (through spaceport)
      ~ 67 deg phase angle
      Available during two periods of year. 2 to 6 months
      Probability analysis report; March 1992
        With small rolls (10 deg), available ~ 8 months/yr
    Additional roll to allow limb-to-limb scan access 64° to Limb
      Geometry study needed. Probably only at large phase angles. -> 42°
  * With nadir view, available to all instruments
      { Planned by SeaWiFS. ?? Clementine, Landsat 7 ... }
      Halt continuous pitch; available at ~22 deg phase each month
      With additional ~20 deg yaw, available near full each month

Schedule Observations
  MODIS spaceport; ?? automatic, need to not treat as dark level!
  Additional roll. needs study
  * Nadir view; use residual pitch rate to scan at ~normal nadir angular rate

Do internal and solar calibration at ~ same time.

PRODUCE RADIOMETRIC IMAGE

Model precise geometry.
  Actual location of platform, and sun, at time of instrument observation
Wavelength correction (tentative method)
    Interpolate the spectral parameters of Hapke model
      single-scattering albedo, opposition surge, particle phase function
  Compute photometric model of each ALEX pixel
  Transform to point-perspective (as appears from Eos platform)
  Output image at resolution equivalent to 15m at nadir. Include solar variation if known.

COMPARE TO INSTRUMENT DATA

Produce Level-1B image (nominal radiometric correction) SeaWiFS study done
Register image to Lunar Model Image (LMI)
    Rotation and scale expected to be well known
    Do 2-axis rigid shift to best correlation
Co-add LMI pixels for each instrument pixel
    May wish to do areal convolution with point spread function
Ratio of LMI/L1-B is the discrepancy.
    Typically, will cover factor >2 dynamic range

If all detectors not covered:
- Use internal calibration consistency
- Use vicarious ground scenes for statistical calibration
- Schedule additional sweeps of view past the moon

POSSIBLE RADIOMETRY CONCERNS

Atypical instrument condition
- Thermal; roll involves unnormal insolation attitude
  - pitch hold maintains at-equator insolation attitude
- If not "nadir", optical path involves different part of scan mirror.

Size-of-source effect
- This knowledge is required in any event for radiometric calibration
- If instrument has appreciable off-axis response, this should be mapped in detail pre-launch.
- In pre-launch measurements, include simulated size of moon.

ATTITUDE MANEUVER CONCERNS

Loss of nadir science data:
- Twice/yr = 1 orbit of 2700

View of the sun
- Near full moon views have nadir nearly opposite sun.

Temporary loss of attitude control
- Engineering assessment issue

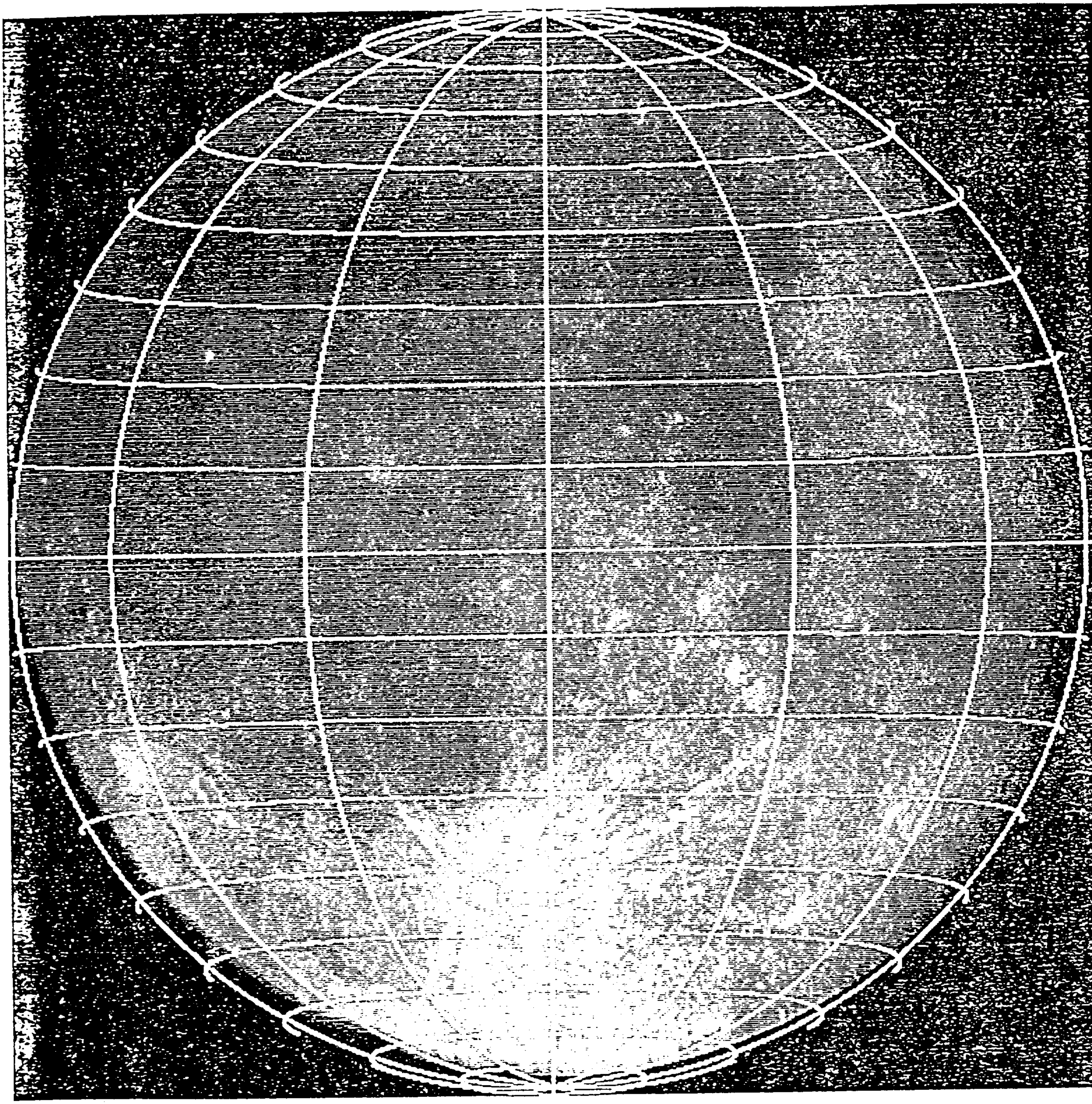
Loss of spacecraft
- Engineering assessment issue, plus management

TRADEOFFS

Stability of the moon (unmeasurable by many orders of magnitude)
Any later improved lunar radiometry is retroactively applicable
Cross-calibration to other spacecraft, or later similiar instrument

Launch and vacuum-stabilization offsets and Long-term drift of all on-board calibration systems.
Cost and complexity of calibrating earth scenes.
Risk of special maneuvers

A primary goal of EOS is long-term monitoring !



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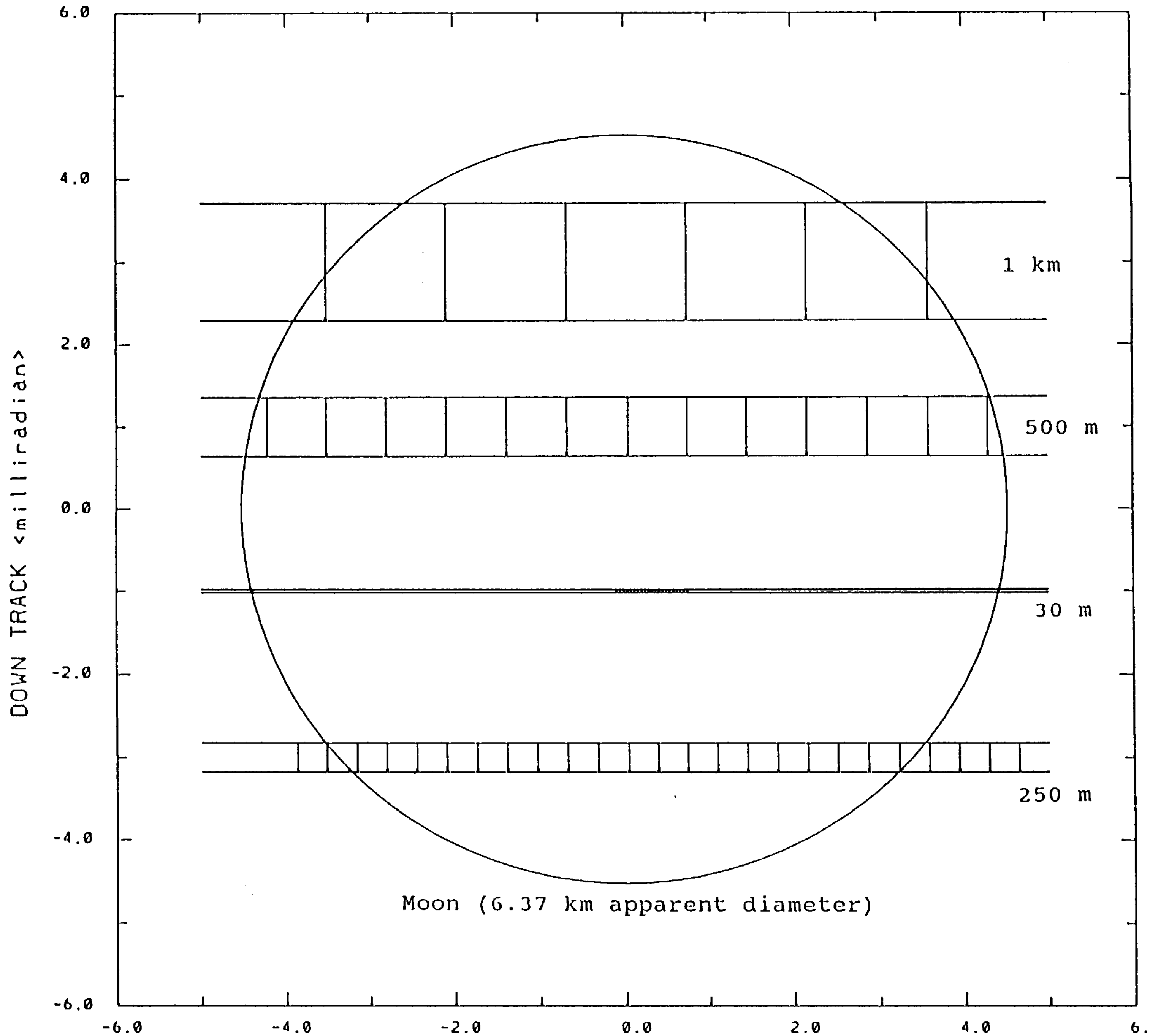
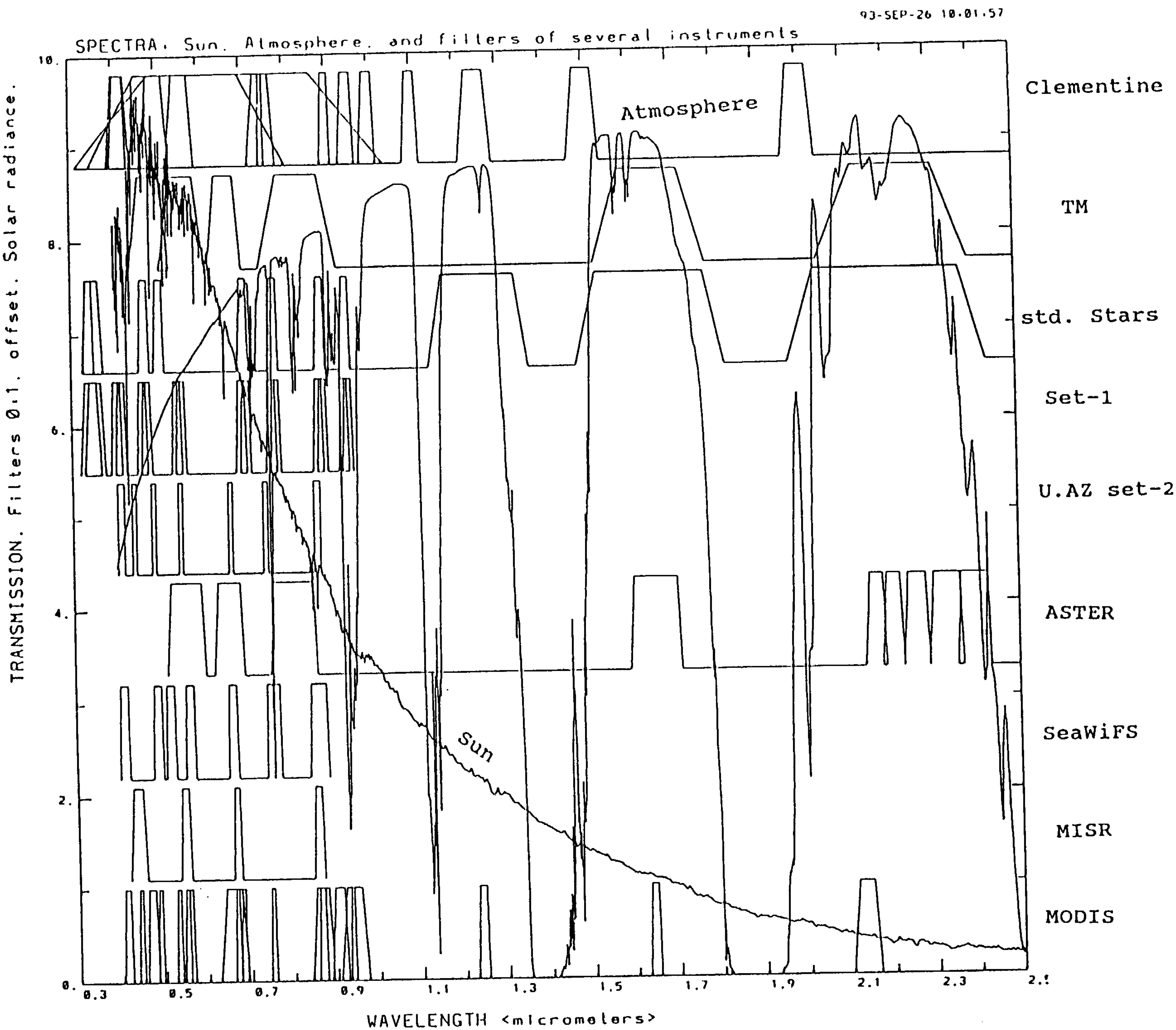
EOS instrument GIFOV on Moon, 30, 250, 500, 1000 m





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SPECTRA, Sun, Atmosphere, and filters of several instruments
TRANSMISSION, Filters 0.1, offset. Solar radiance.
WAVELENGTH <micrometers>
Atmosphere
Sun
Clementine
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std. Stars
Set-1
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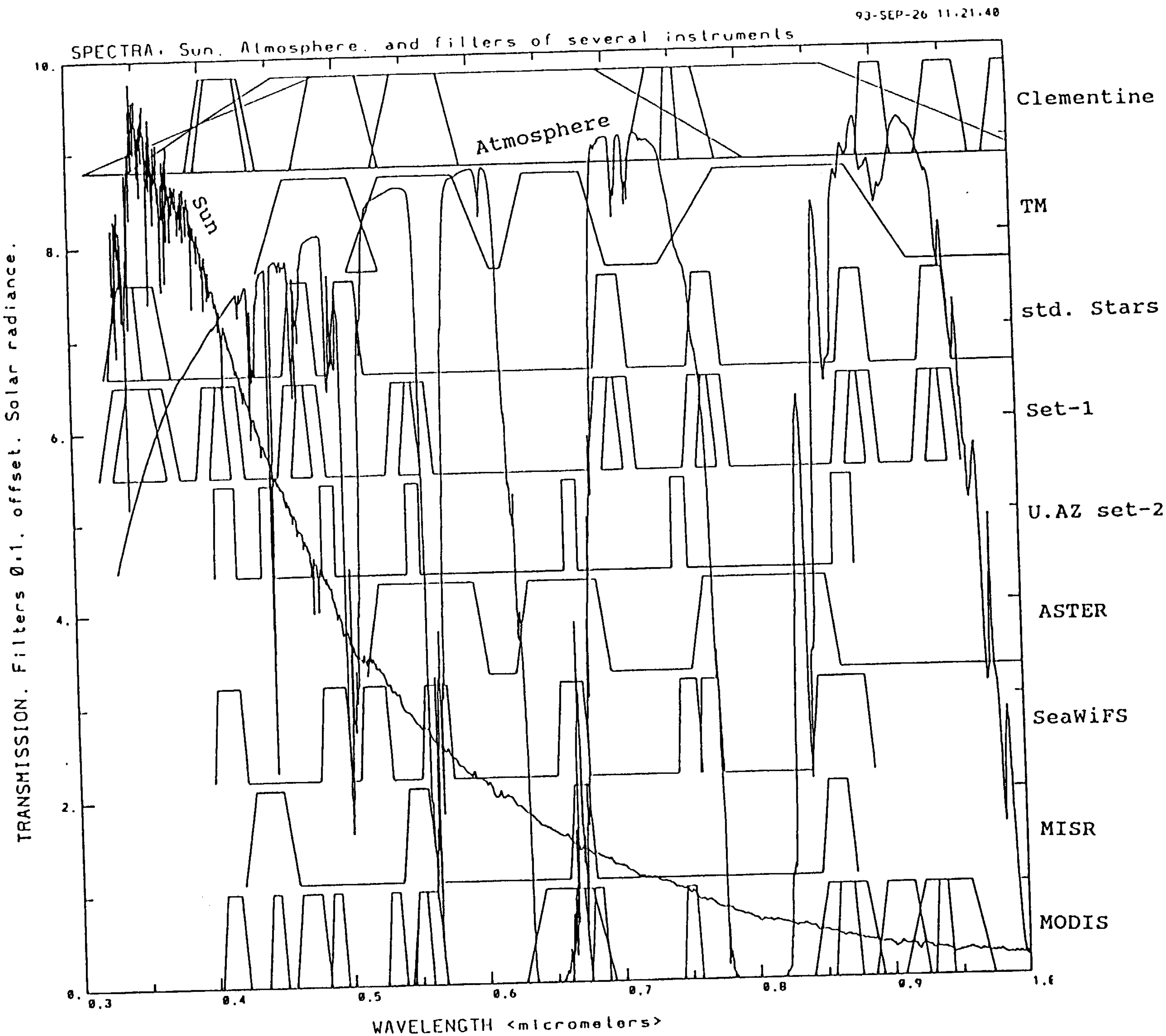
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SPECTRA, Sun, Atmosphere, and filters of several instruments
Clementine
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std. Stars
Set-1
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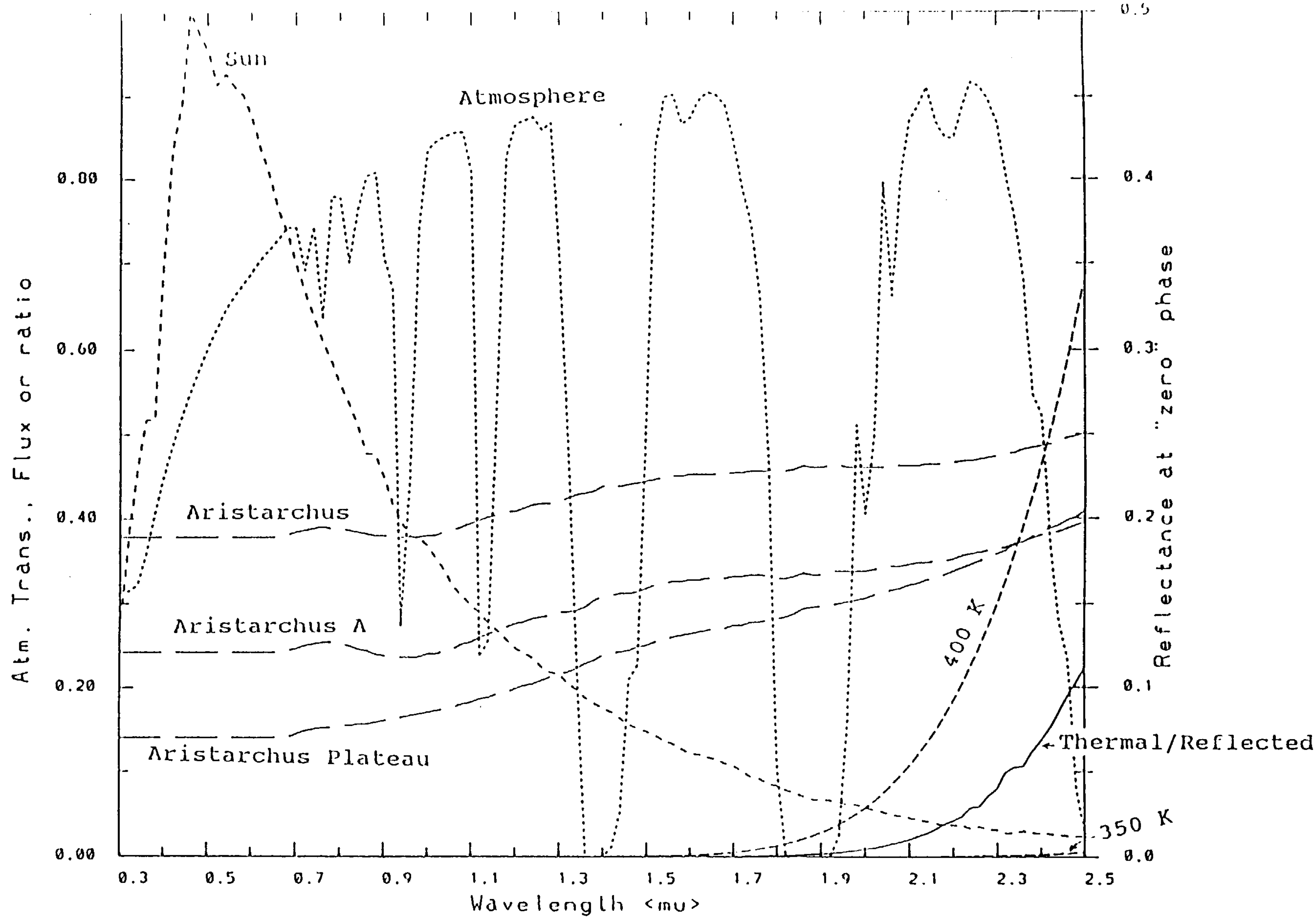

Figure 3. Spectra of the sun (normalized), nominal earths atmosphere transmission (one pass to sea level), and 3 lunar areas which represent nearly the full range of lunar albedo in the visual region. Normalized lunar spectra obtained by Paul Lucey have be scaled to approximate absolute values based on adjusting their shortest wavelength (0.7 μm) to calibrated photoelectric photometry in the visible. Also shown are blackbody emission curves for 350K and 400K (near the maximum lunar surface temperature). The ratio of emitted (400K) to reflected radiation is shown as the solid curve in the

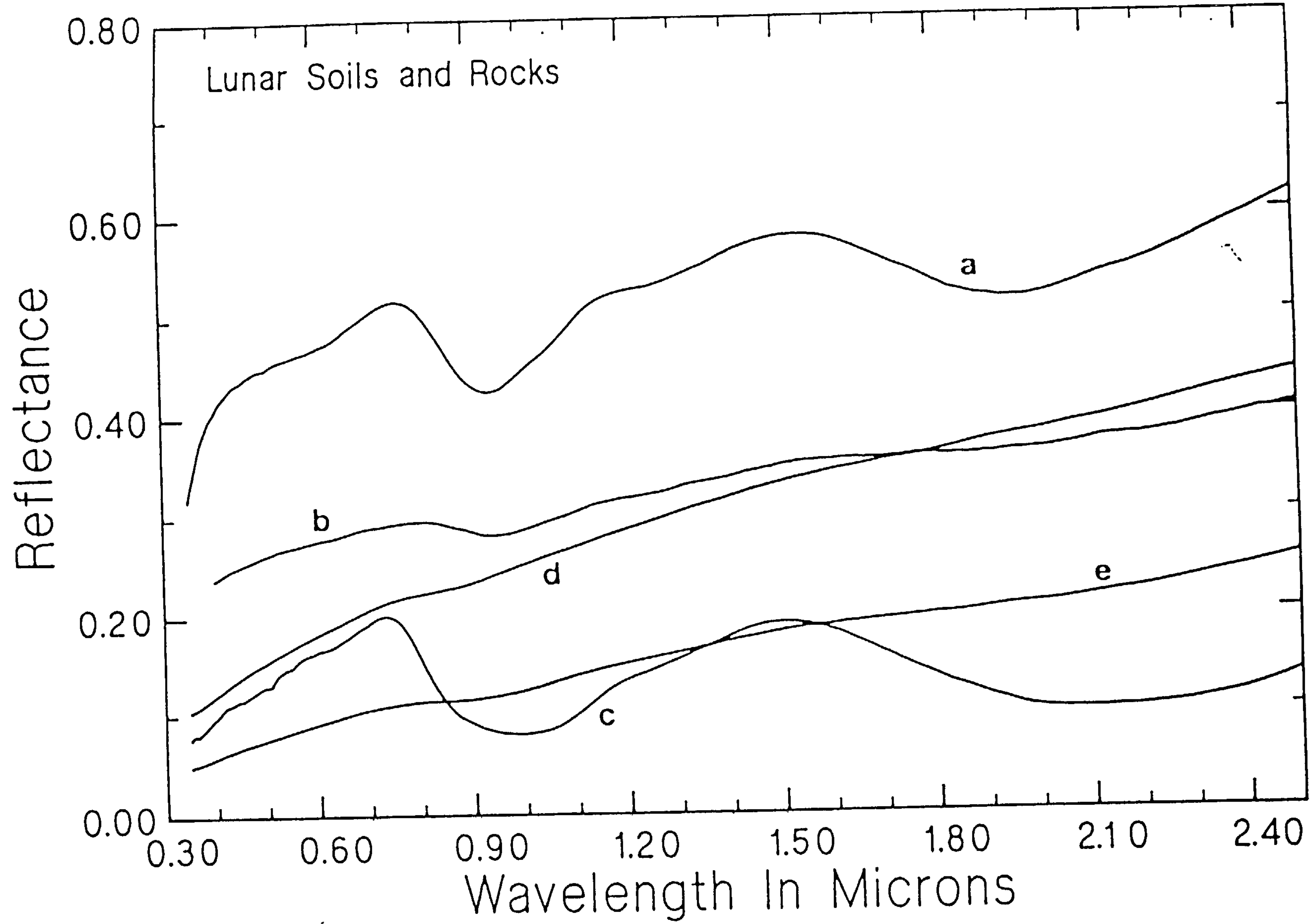

FIGURE 4. Laboratory reflectance spectra of lunar rocks and soils: a) feldspathic highland breccia (67455); b) highland regolith breccia (lunar meteorite Y791197); c) lunar mare basalt (15555); d) mature lunar highland soil (62231); e) mature lunar mare soil (12070). [Spectra a–c are bidirectional reflectance; soil spectra e and d were obtained as directional-hemispheric (diffuse) reflectance by J. B. Adams.]

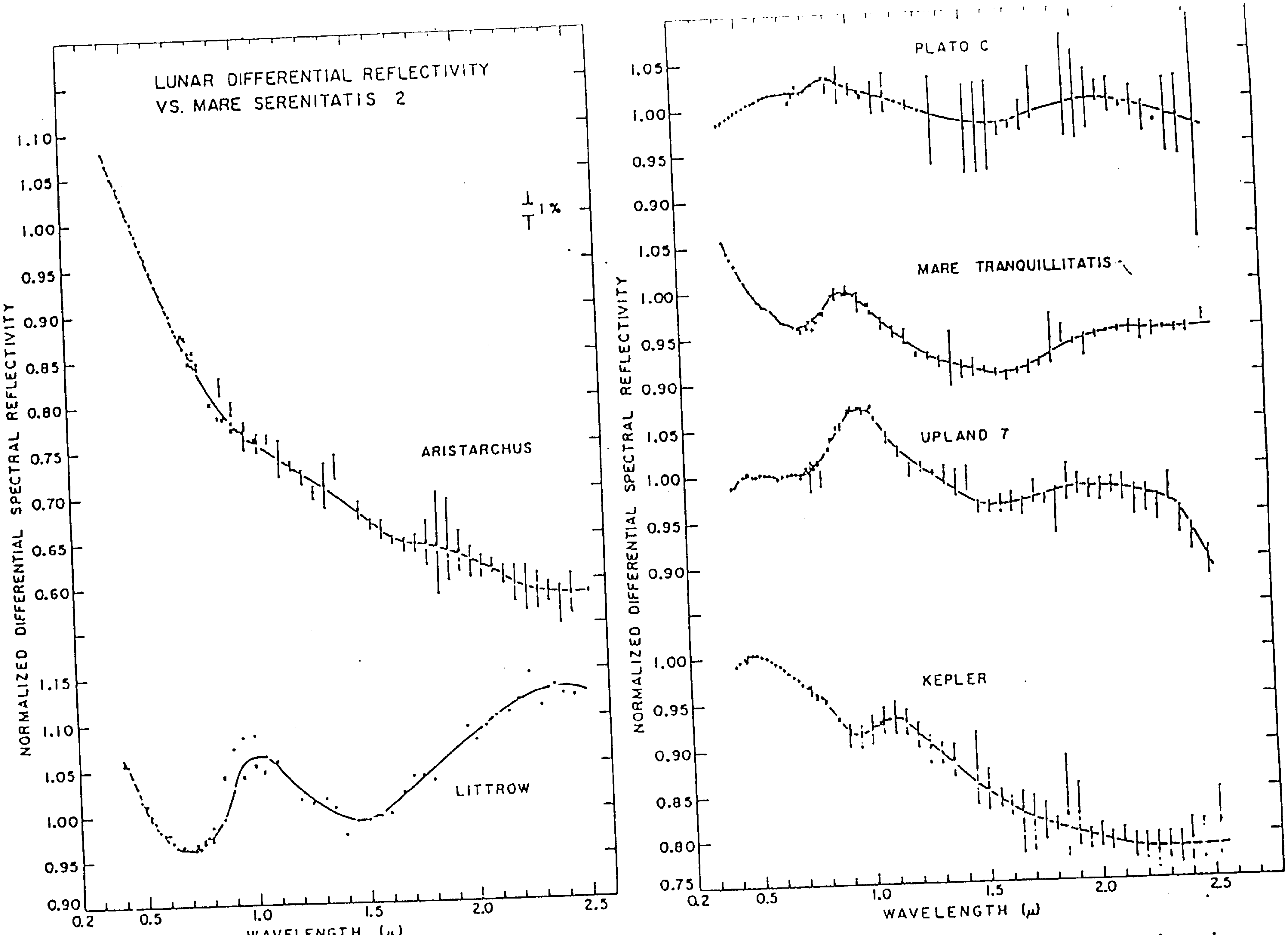

Fig. 2. Lunar spectral reflectance for six small lunar areas treated by *McCord and Johnson* [1970] is shown plotted as relative spectral reflectance, i.e., as the ratio of the reflectance at each lunar area divided by that at one "standard" lunar area [illegible] and for the first time showed the presence

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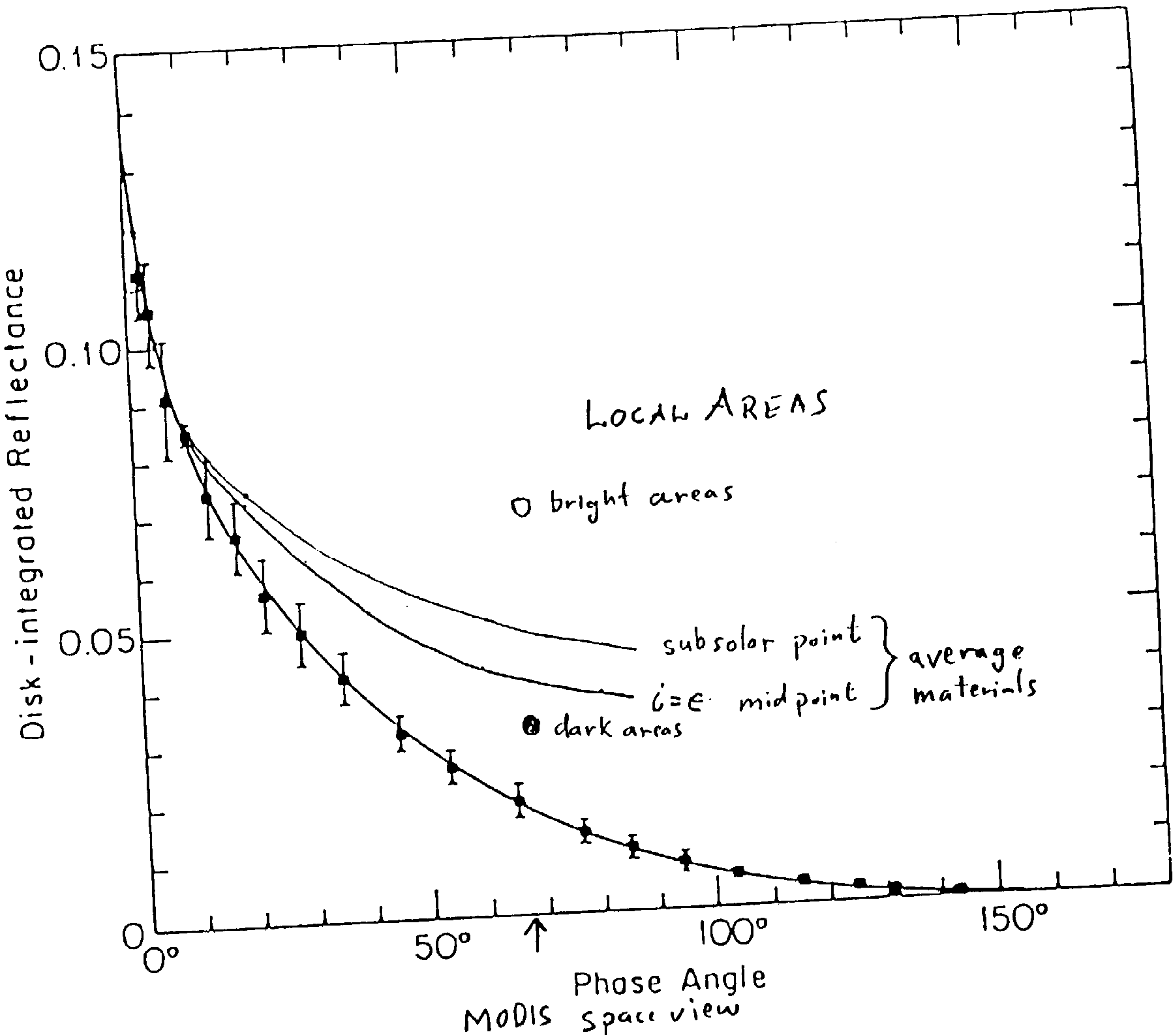

FIG. 2. Fit of Hapke's equation to disk-integrated lunar lightcurve (continuous curve). Brightness at zero phase is the geometric albedo. Plotted data points are normalized to be consistent with Lane and Irvine (1973) and averaged as described in text. Error bars ... standard deviation.

(13)

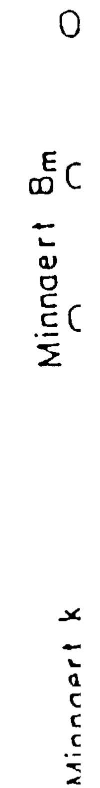

TABLE I

SUMMARY OF PHOTOMETRIC PARAMETERS

Symbol	Description
	Hapke's parameters
w	Single scattering albedo which characterizes th efficiency of an average particle to scatter and absorb light
h	Characterizes the width of opposition surge in terms of soil structure (porosity, particle-siz distribution, and rate of compaction with depth)
$S(0)$	Opposition surge amplitude term which characterizes the contribution of light scattered from near the front surface of individual particles at zero phase
b, c	Coefficients in the Legendre polynomial mode particle phase function, $P(\alpha) = 1 + b \cos \alpha + c(1.5 \cos^2\alpha - 0.5)$
$\bar{\theta}$	Average topographic slope angle of surface roughness at subresolution scale
	Other related quantities
B_0	Total amplitude of the opposition surge $B_0 = S(0)/w\{1 + b + c\}$
g	Asymmetry factor of the particle phase function. $g = \langle \cos \theta \rangle = -b/3$, where $\theta = \pi - \alpha$ is the scattering angle

pke

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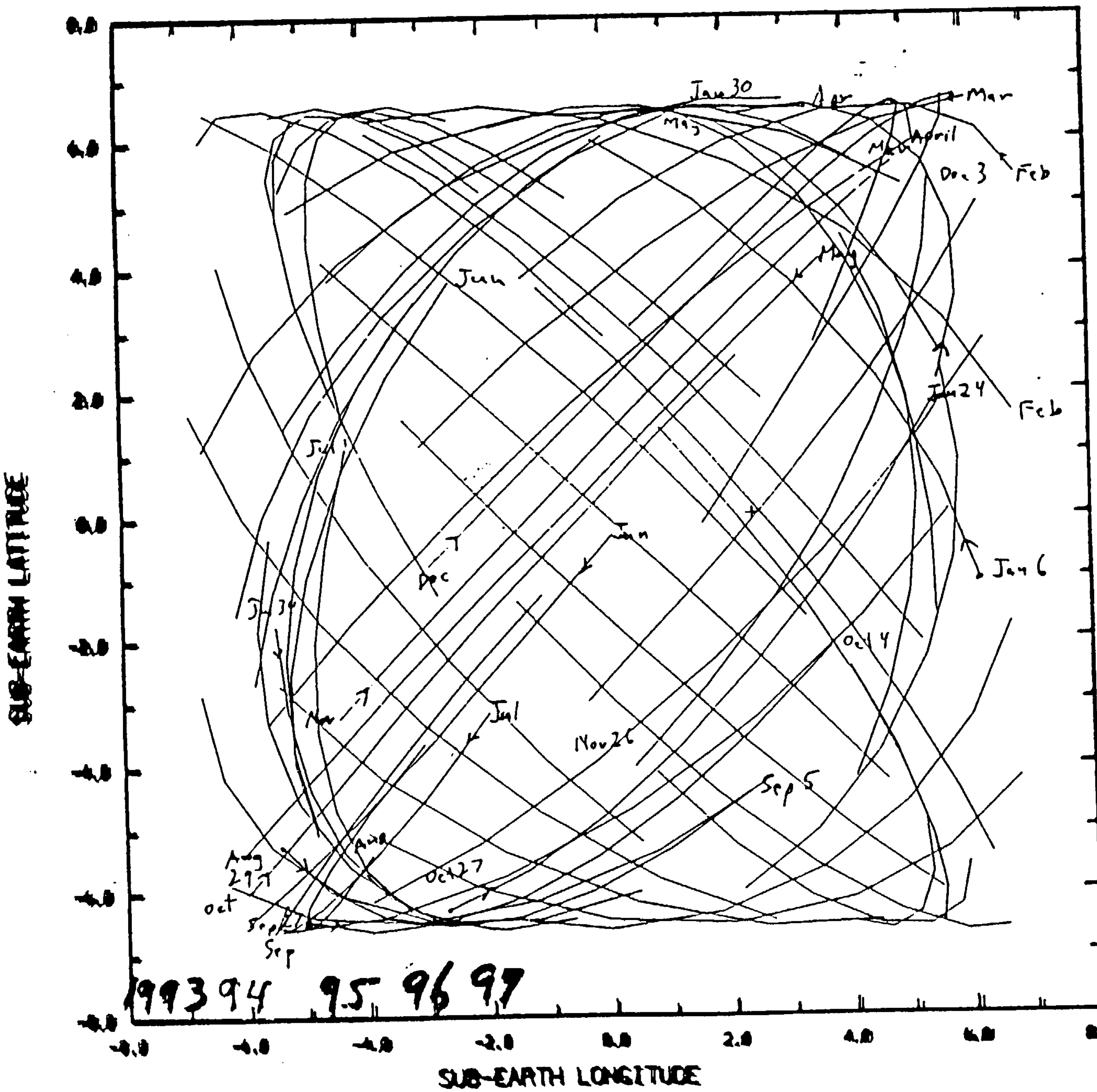
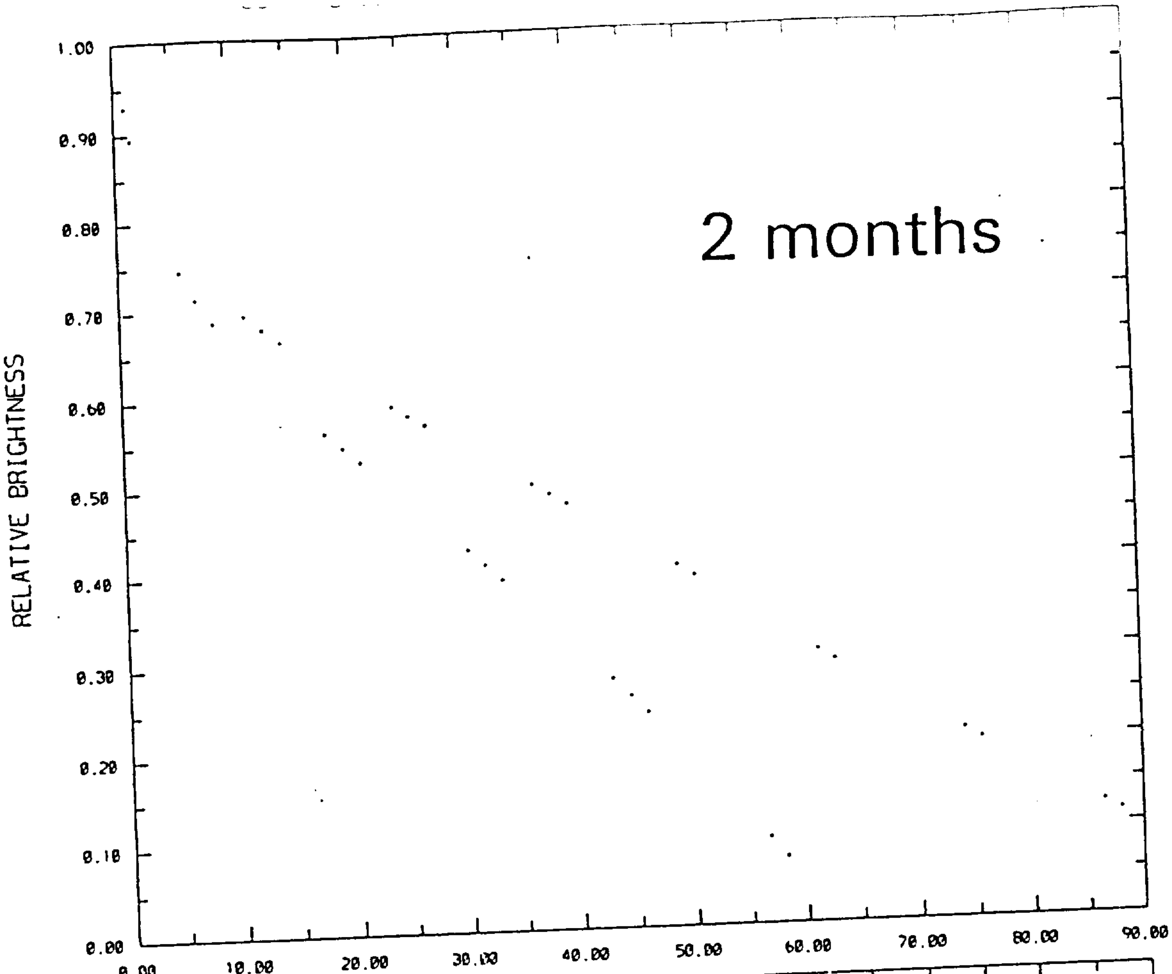
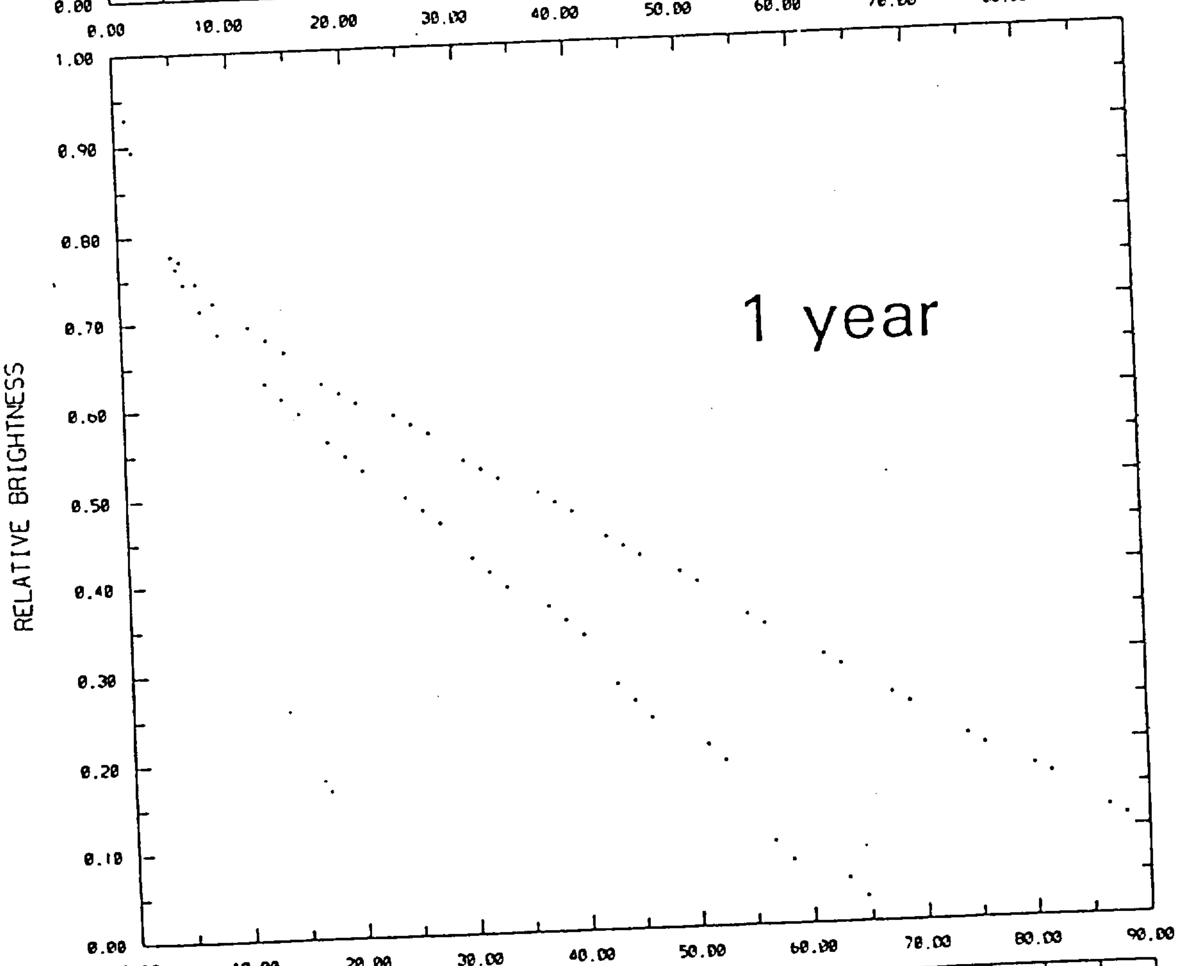
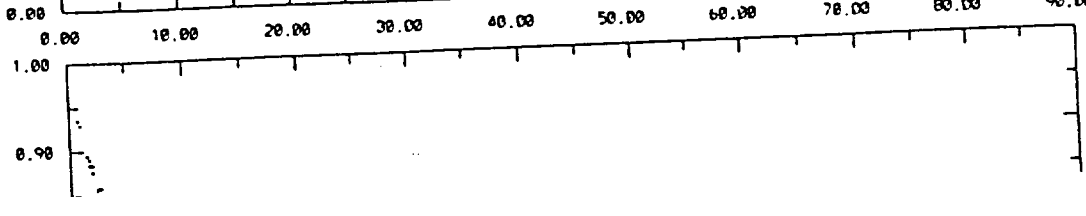
LUNAR LIBRATION. PHASE<45 ICE 1-day interval 1994









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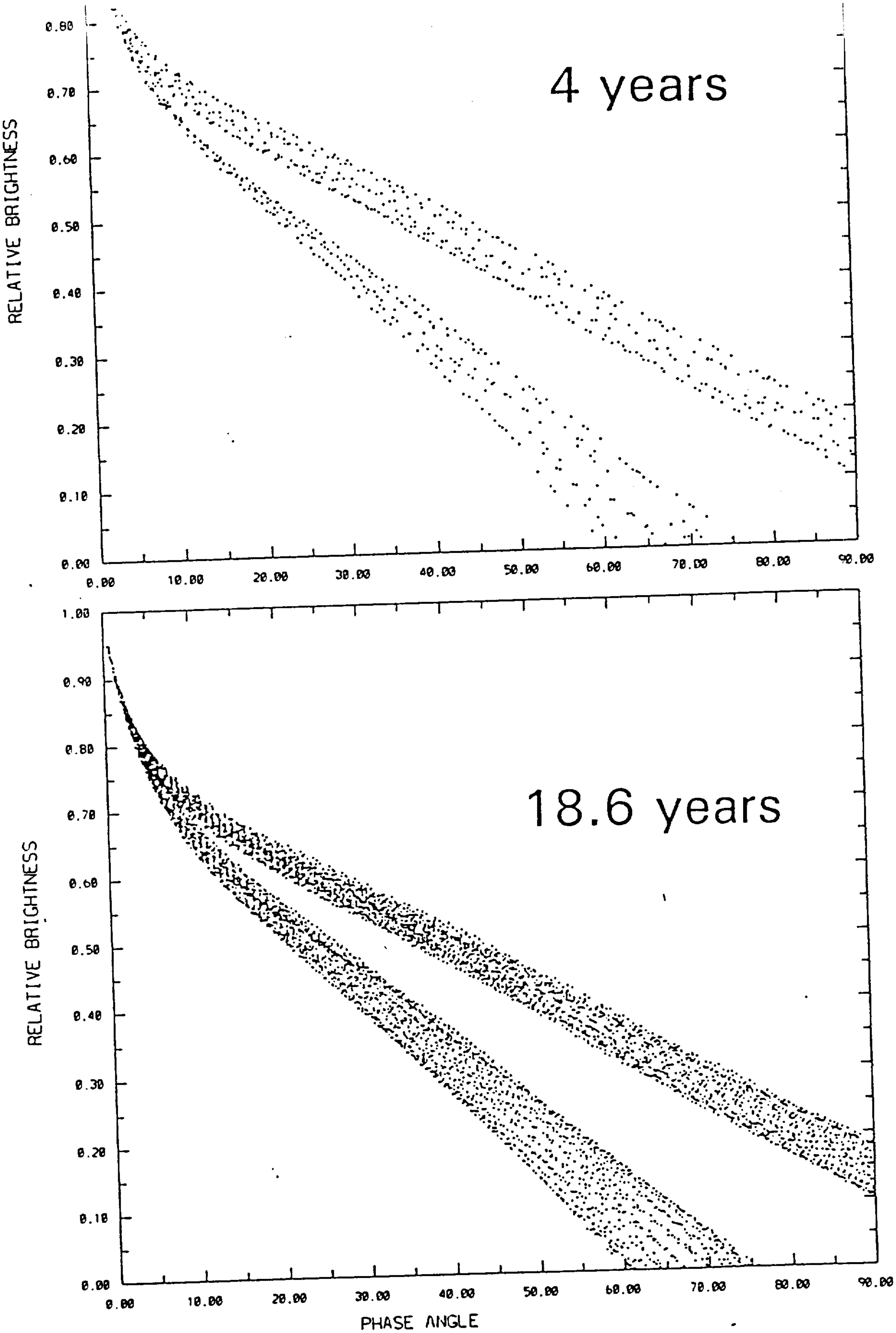
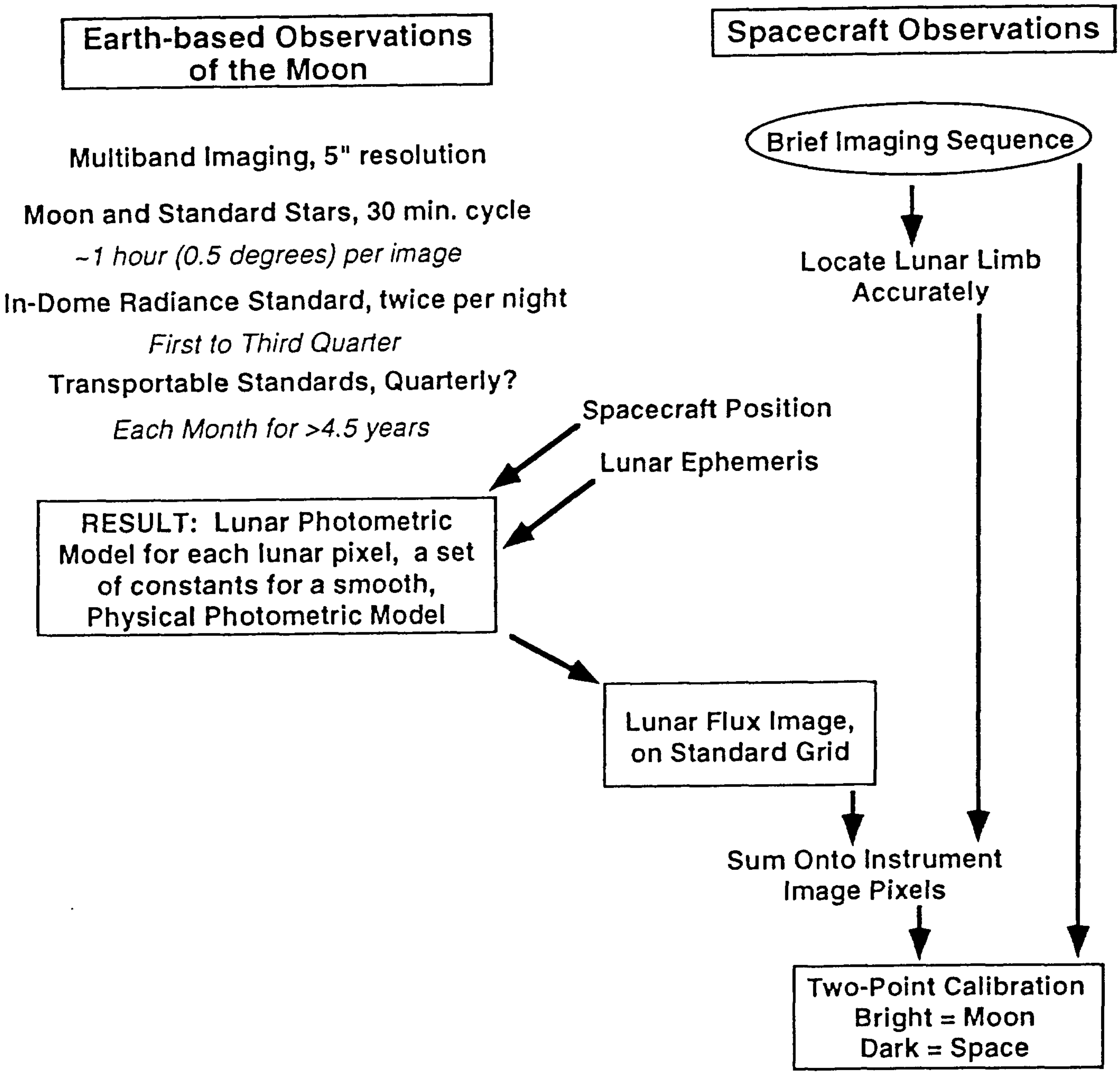


Figure 2. A model of the brightness of one point on the moon as a function of phase angle. This point is 22 degrees in latitude and longitude from selenographic origin. This build up of coverage is shown for observations covering: 2 months, 1 year, 4 years, and 18.6 years.

Calibration of Spaceborne Imaging Instruments Through Use of the Moon



LERROR.WK1 Uncertainty of lunar calibration

Preliminary assignments	1-sigma			92feb01 93sep20
	percent			Notes
	min.	expect.	max.	(expect. level)
Long-term precision				full well = 311000e-
CCD read error	0.00	0.01	0.10	7 e-, of 100000
Atm. Extinction	0.20	0.50	1.00	Note 1.
Lunar polarization	0.00	0.05	0.40	if telescope were 5%
Photon noise	0.18	0.32	0.58	311,100,30 ke-
Std. Star System	0.20	0.50	1.50	Note 2
Root_sum_square	0.34	0.78	1.94	
[", With many pixels]	0.28	0.71	1.85	
Absolute radiance				
Detector drift	0.10	0.30	0.60	
local standard lamp	0.09	0.30	1.91	Note 3
& Diffuser	0.20	0.40	1.00	
or				
Color-magnitude transf	0.10	0.50	1.00	
Root_sum_square (of larger of above)	0.41	0.97	2.96	
Spacecraft observation				
Geometric error	0.20	0.40	0.70	(0.2 Pixel)
Phase angle interp.	0.10	0.30	0.50	
Root_sum_square (of all above)	0.47	1.09	3.08	

Note 1.
Strongly wavelength dependant.
Note 2.
Stars that are bright at 2 mu are typically poorly known
Note 3.
Accuracy of transfer from NIST with conventional sources is the biggest single error.
This can be improved by round-robin calibrated radiometers

Errors listed in NIST Pub 250-20 (page 35) are: (3-sigma)

	mu	%	1-sig
Silicon CCD range	0.25	0.57	0.19
	0.35	0.33	0.11
	0.655	0.28	0.09
	0.9	0.88	0.29
IR camera range	1.3	0.9	0.30
	1.6	1.48	0.49
	2	2.61	0.87
	2.4	5.74	1.91

MODIS ~~HIRIS~~ Calibration methods 1990 jul 15

	Pre-Flight	Sun	Moon	Internal: ~~Wave-D~~ Spectral	Internal: AutoC. Reticle	Natural: Char.	Natural: Non.	Atm Gas	AVIRIS	Cross Inst.	Stars & Planets
	0	P	L	I-1	I-2	C	N	G	A	X	U
Radiometric											
Absolute scale	C	A	A	B		B			C	B	D
DN-to-radiance curve	C	B	B	C		B			B	B	
DN sizes	A		C			B	A				
Random noise	C	B	C	C			A				C
Quasi-stationary noise	D	B	C	C	B	D	B				C
Drift	C	C	C	~~C~~ B			B				
Vignetting	A					~~B~~				~~B~~	
~~IMC relative gains~~	~~B~~					~~B~~	~~B~~			~~B~~	
Dynamic											
Hysterisis	B		A		?	C	B				
Bright-target recovery	B				B?		B				
Spectral											
Effective wavelength	C			A				~~A~~ B		C	
Band width	B			B				B			
Out-of-band response	B			?							
Spatial											
Effective IFOV	C				~~B~~ A	B			C		
MTF	C		~~A~~ B		B	C					C
Off-axis response	C		A		C		C				
Inter-band alignment	C		B	C	~~C~~ B	B	A				C
Jitter	D		~~D~~ ?		C	B					B
Pointing	C		~~C~~ ?		~~C~~	B	B				C
Polarization	B									~~C~~	
	0	P	L	I-1	I-2	C	N	G	A	X	U

A = direct ,substantial
B = secondary
C = partial contribution
D = minor contribution

Typed entries were for HIRIS

MODIS Cal. team encouraged to modify entries for MODIS