CERES MEASUREMENTS OF THE LUNAR RADIATION BUDGET

by

R. B. Lee III*[a], G. L. Smith[b], D. P. Kratz[a], K. J. Priestley[a], Z. P. Szewczyk[c], S. Thomas[c], K. A. Bush[c], J. Paden[c], D. K. Pandey[c], R. S. Wilson[c], and A. Al-Hajjah[c]

[a]NASA Langley Research Center, MS 420, Hampton, VA, USA 23681-2199;
[b]National Institute for Aerospace, MS 420, Hampton, VA, USA 23681-2199;
[c]Science Applications International Corporation (SAIC), Hampton, VA, USA 23666-5854

SPIE PAPER 5151-37, SAN DIEGO, CA, AUG. 4-8, 2003

Measurements of filtered lunar radiances using the NASA Terra spacecraft/ the Clouds and Earth's Radiant Energy System (CERES) thermistor bolometer sensors during 2000 and 2001

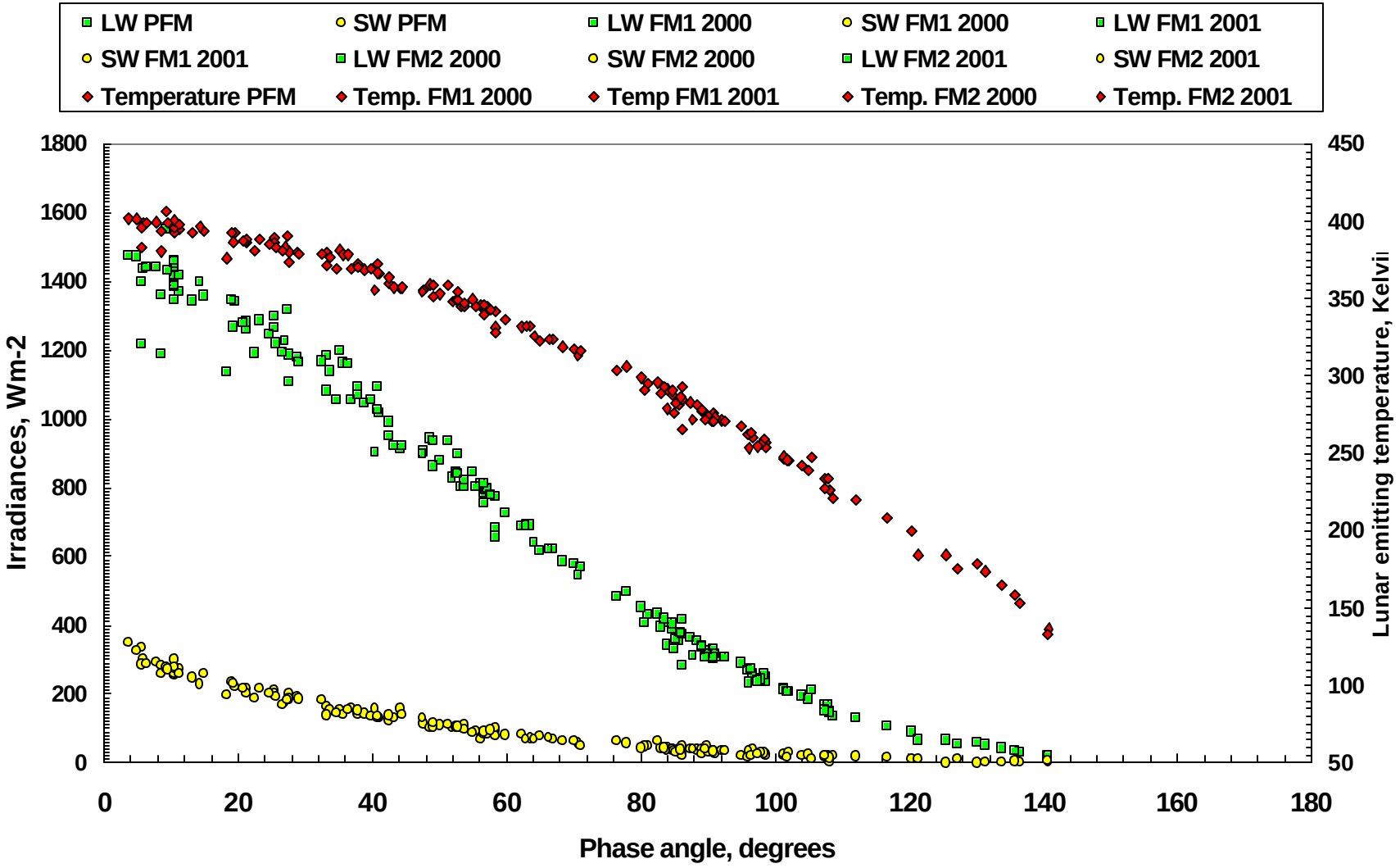
SUMMARY

0 Analyses of the Clouds and the Earth's Radiant Energy System (CERES) thermistor bolometer sensor observations of lunar radiances indicated that broadband shortwave and longwave lunar filtered radiances can be determined on a radiometric scale linked to ITS-90 at absolute levels approaching $\pm$ 0.2 $Wm^{-2}sr^{-1}$.

0 FIRST broadband lunar radiances/irradiances

0 For a lunar image of 31 arc minutes, an effective emitting whole-disc lunar temperature of approximately 400 Kelvin was estimated from the longwave radiances near 7-degree phase angle.

Figure 10. For a lunar image of 31 arc minutes, unfiltered shortwave and longwave radiances are presented for the PFM, FM1, and FM2 bolometers as well as lunar whole disc emitting temperatures.



Measurements of filtered lunar radiances using the NASA Terra spacecraft/CERES thermistor bolometer sensors during 2000 and 2001

OUTLINE

- OVERVIEW OF LUNAR MEASUREMENTS
- DATA REDUCTION EQUATIONS
- LUNAR MEASUREMENTS
- CHARACTERIZATIONS OF LUNAR RADIANCES
- RESULTS

OVERVIEW OF LUNAR MEASUREMENTS

CERES THERMISTOR BOLOMETER INSTRUMENT PACKAGE

0 Broadband Shortwave Bolometer
[0.3 to 5 micrometers];

0 Broadband Total
[0.3 to >100 micrometers];

0 Narrowband Water Vapor Window
[8 to 12 micrometers].

CERES THERMISTOR BOLOMETER INSTRUMENT PACKAGE

BOLOMETERS MAINTAINED LINK TO AN ABSOLUTE RADIOMETRIC SCALE BASED UPON THE INTERNATIONAL TEMPERATURE SCALE OF 1990 (ITS-90) BETWEEN VACUUM GROUND AND ON-ORBIT CALIBRATIONS AT LEVELS APPROACHING $\pm$ 0.2 $Wm^{-2}sr^{-1}$.

SUMMARY OF LUNAR MEASUREMENTS

- **IN 1998, 74 TROPICAL RAINFALL MEASURING MISSION (TRMM)/ CERES PROTO-FLIGHT MODEL (PFM) MEASUREMENTS**
- **IN 2000, 192 TERRA/CERES FLIGHT MODEL ONE (FM1) MEASUREMENTS**
- **IN 2000, 263 TERRA/CERES FLIGHT MODEL TWO (FM2) MEASUREMENTS**
- **IN 2001, 368 TERRA/CERES FLIGHT MODEL ONE (FM1) MEASUREMENTS**
- **IN 2001, 372 TERRA/CERES FLIGHT MODEL TWO (FM2) MEASUREMENTS**
- **JANUARY 9, 2001, TOTAL LUNAR ECLIPSE (28) PROFILES**
- **MAY 16, 2003, TOTAL LUNAR ECLIPSE (76) PROFILES**

Figure 1. CERES field stop and field-of-view (FOV) for lunar measurements

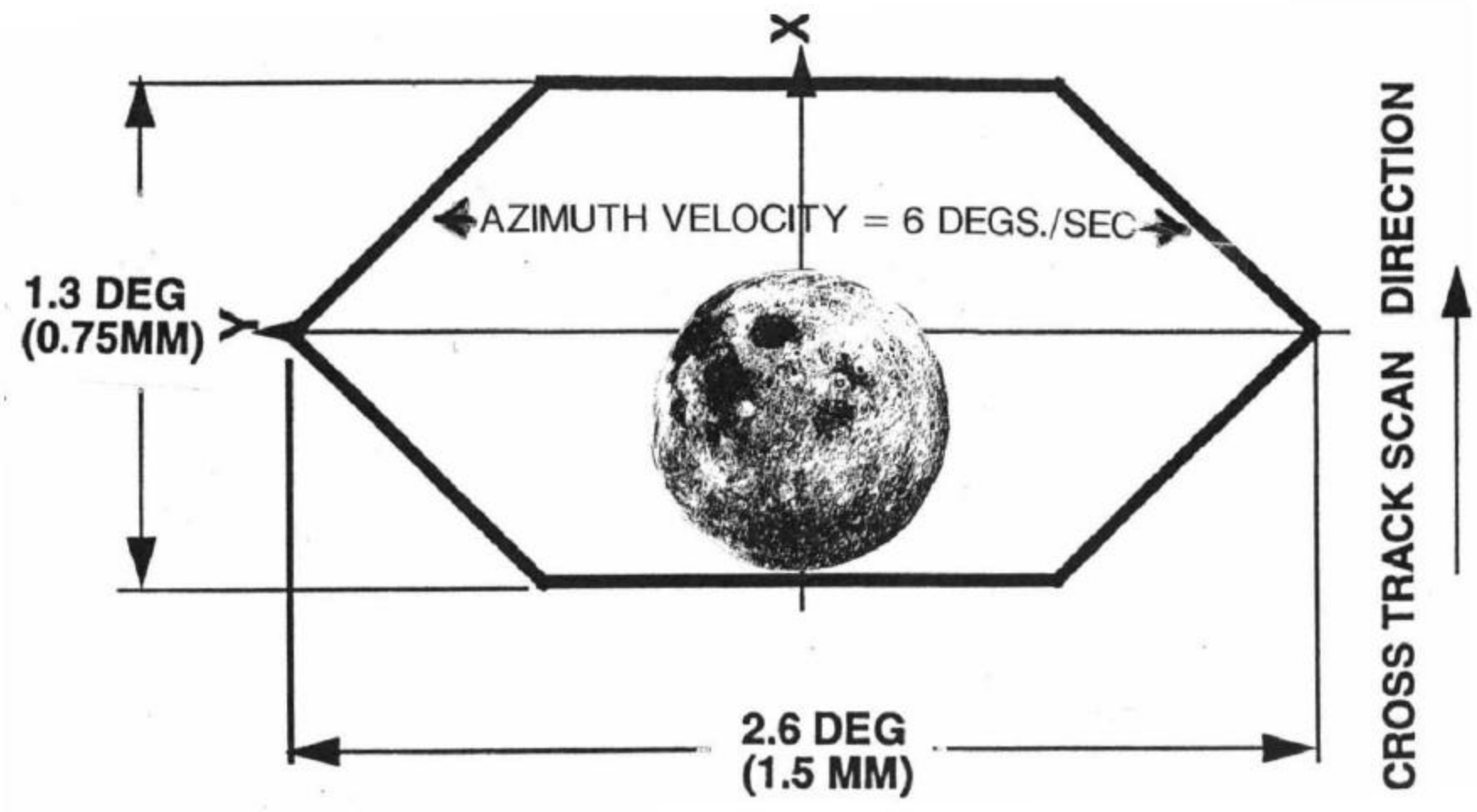


Figure 2. June 10, 1998, TRMM/CERES PFM lunar filtered measurements: 7 hour; 1 minute; 47 seconds; Universal Time

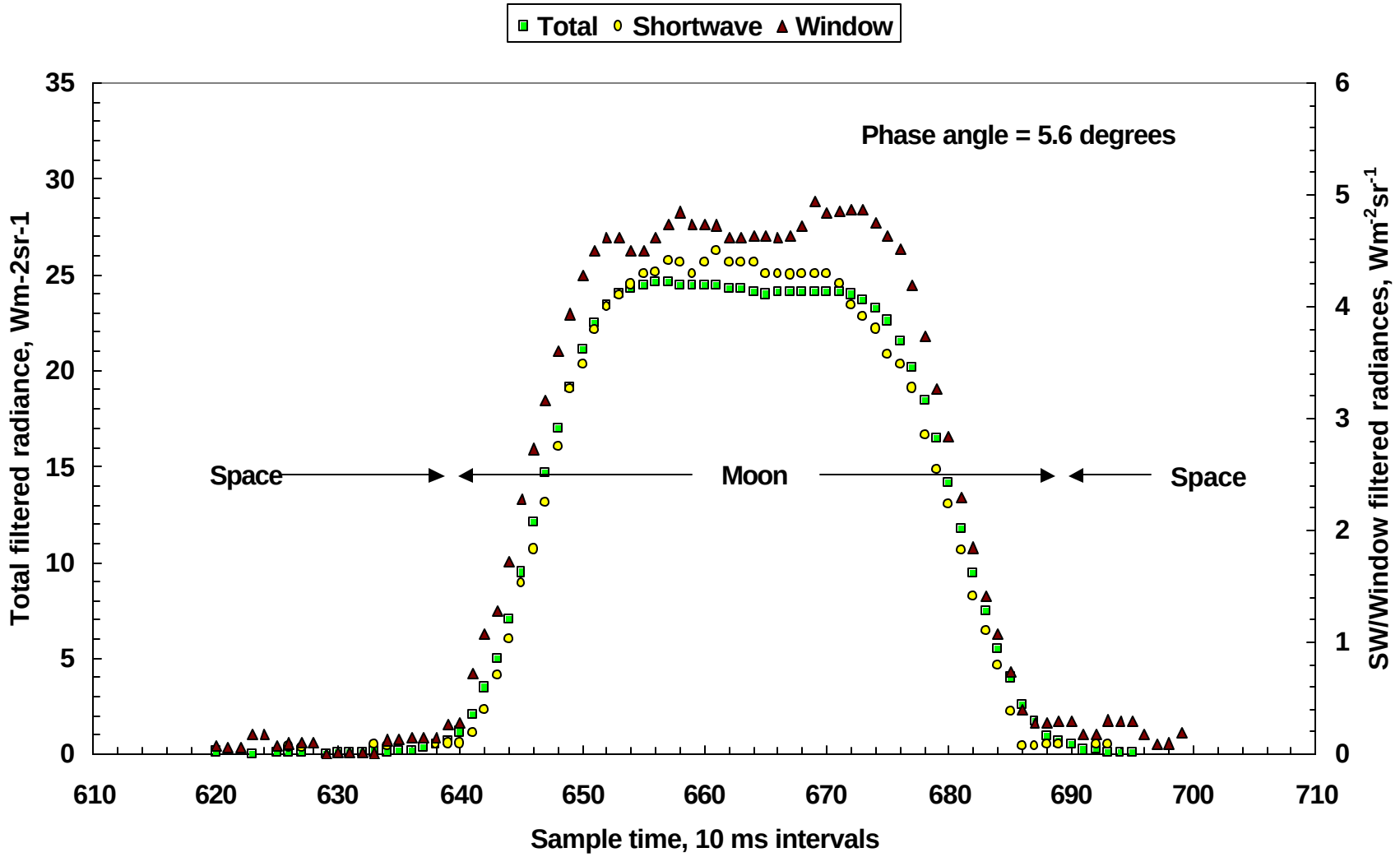


Figure 3. September 14, 2000, Terra/CERES FM1 lunar filtered measurements: 1 hour; 29 minutes; 18 seconds; Universal Time

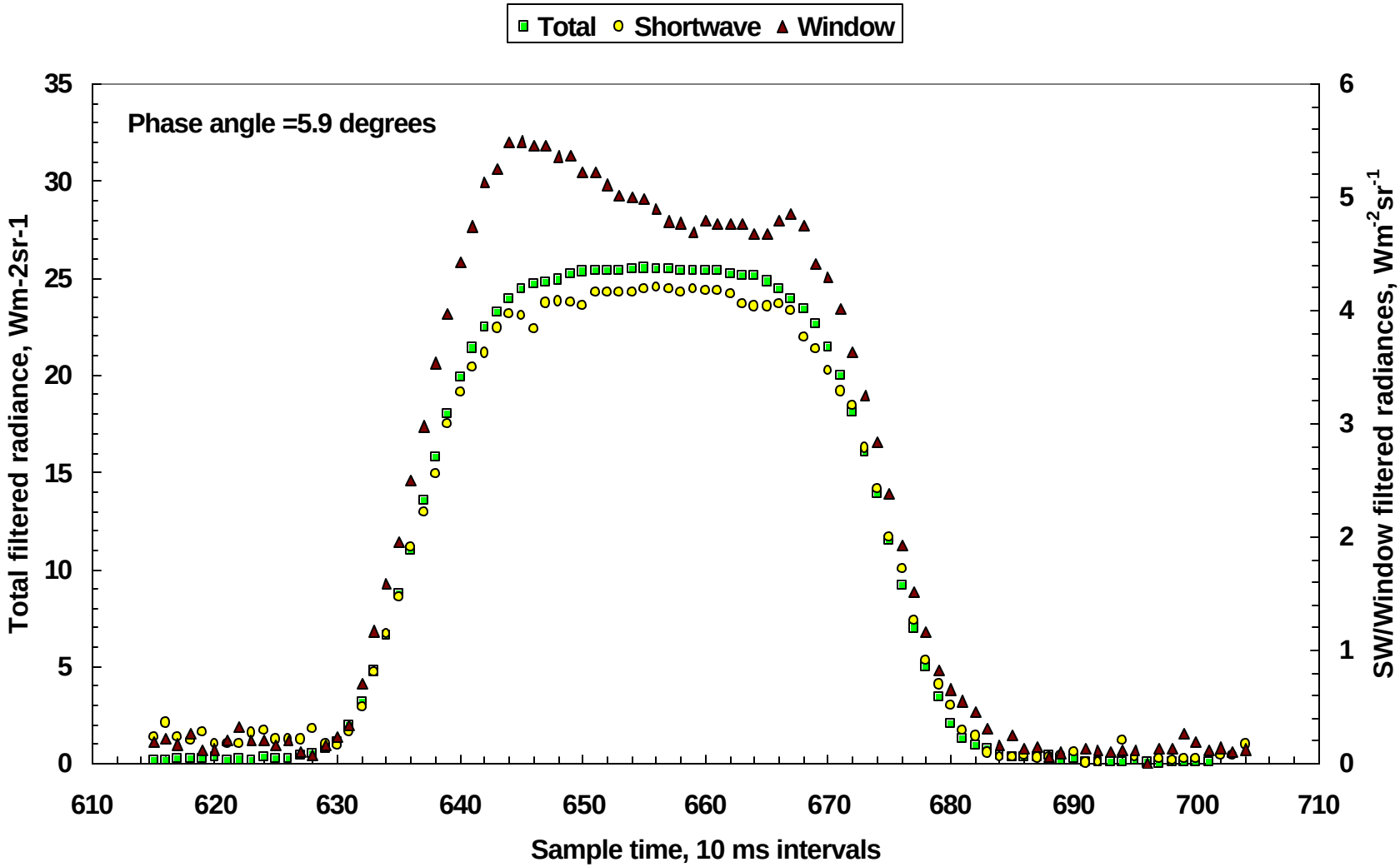


Figure 4. December 10, 2000, Terra/CERES FM2 lunar filtered measurements: 17 hours; 10 minutes; 29 seconds; Universal Time.

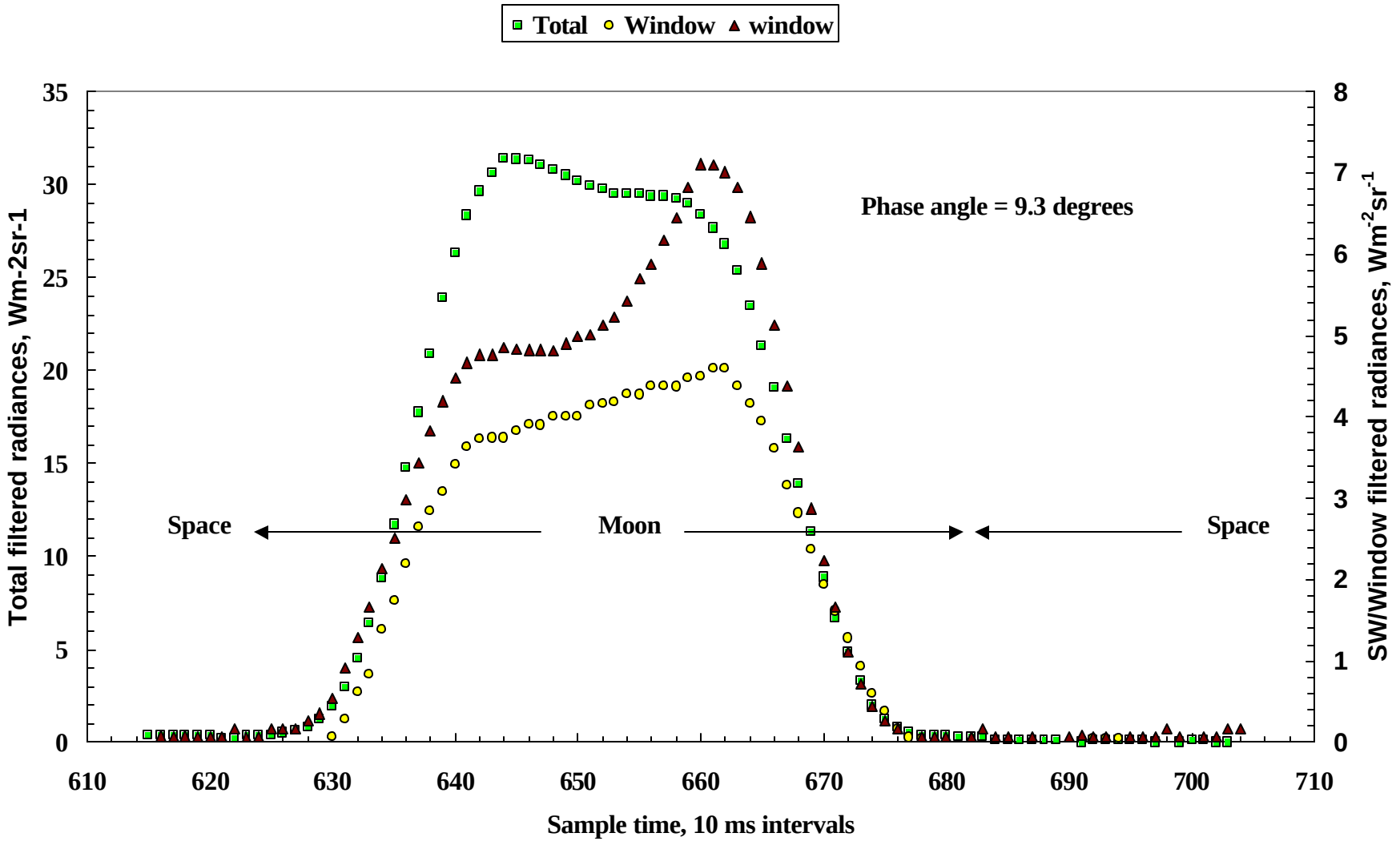
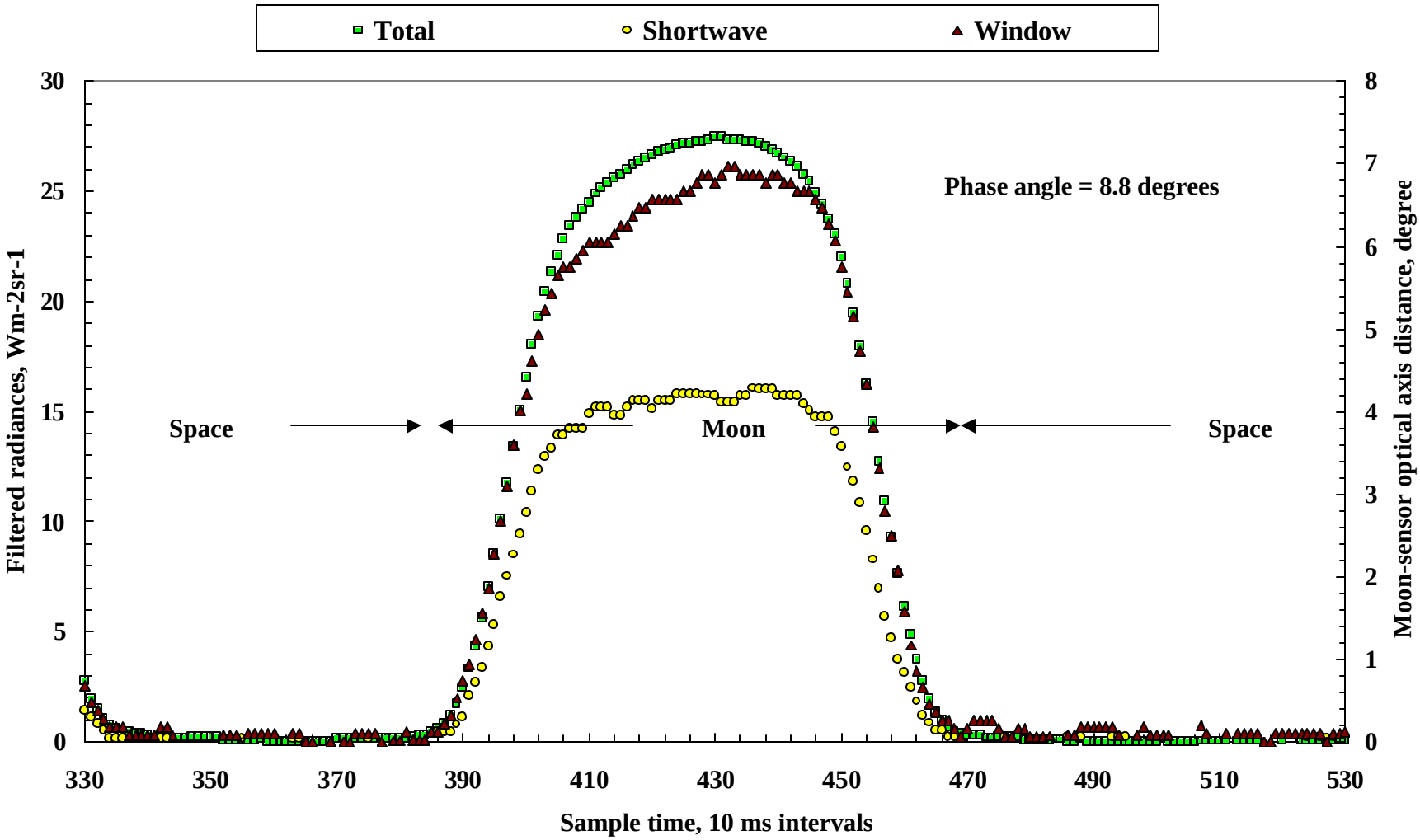


Figure 5. May 16, 2003, Terra/CERES FM4 lunar filtered measurements: 18 hours; 20 minutes; 17 seconds; Universal Time.



DATA REDUCTION APPROACHES

0 MEASUREMENT PROFILES WITH SPACE BEFORE AND AFTER LUNAR RADIANCE MEASUREMENTS.

0 PROFILES WHERE MOON PASSED WITHIN 0.25 DEGREE OF BOLOMETER OPTICAL AXIS.

0 NORMALIZED MEASUREMENTS TO MEAN SUN-MOON DISTANCE OF 1 AU (±3.3%).

0 NORMALIZED MEASUREMENTS TO MEAN MOON-SPACECRAFT DISTANCE OF 384,400 KILOMETERS (±13.7%).

Data reduction equation for Filtered Radiances

$$L_{nf} = L_f \times (D_{s\text{-}m})^2 \times (D_{m\text{-}sp})^2$$

where L_f represents the CERES sensor averaged filtered radiances;

$D_{s\text{-}m}$ represents the sun-moon distance variation, and is the ratio of the moon-earth distance to 384,400 kilometers;

and $D_{m\text{-}sp}$ represents the moon-spacecraft distance variation, in astronomical units (AU).

Figure 6. 2000 Terra/CERES FM1 lunar filtered radiances are presented as a function of phase angle.

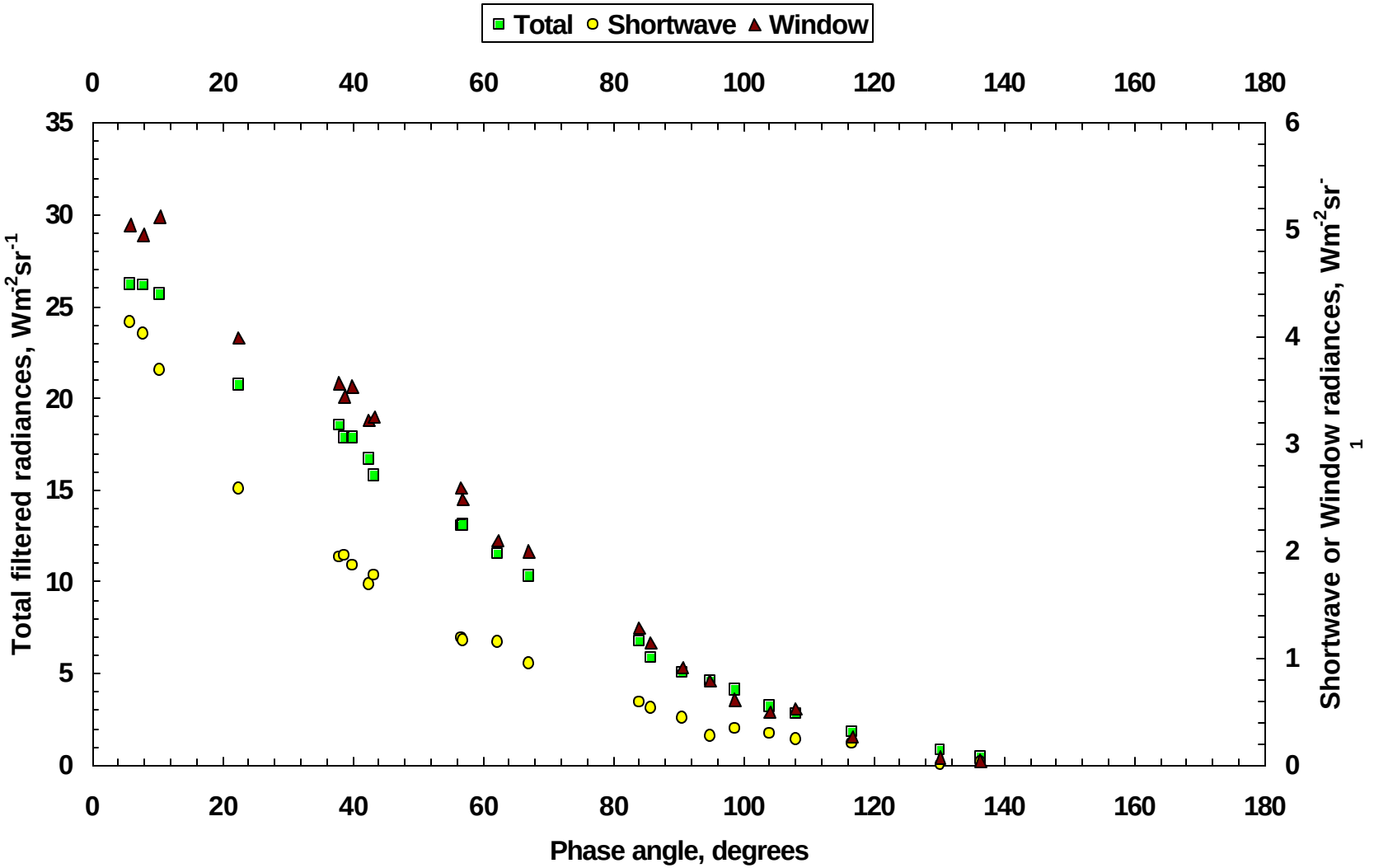


Figure 7. 2001 Terra/CERES FM1 lunar filtered radiances are presented as a function of phase angle.

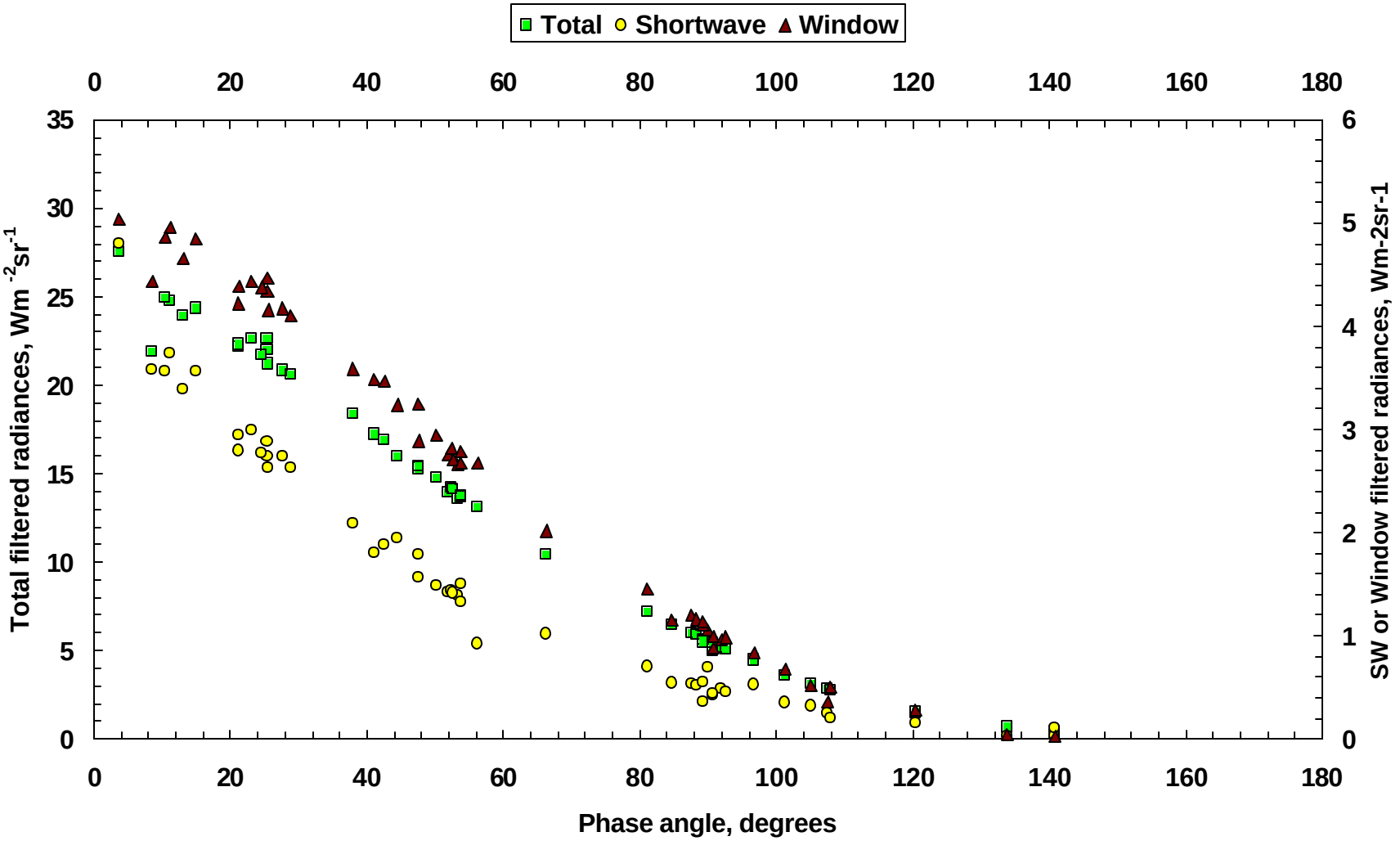


Figure 8. 2000 Terra/CERES FM2 lunar filtered radiances

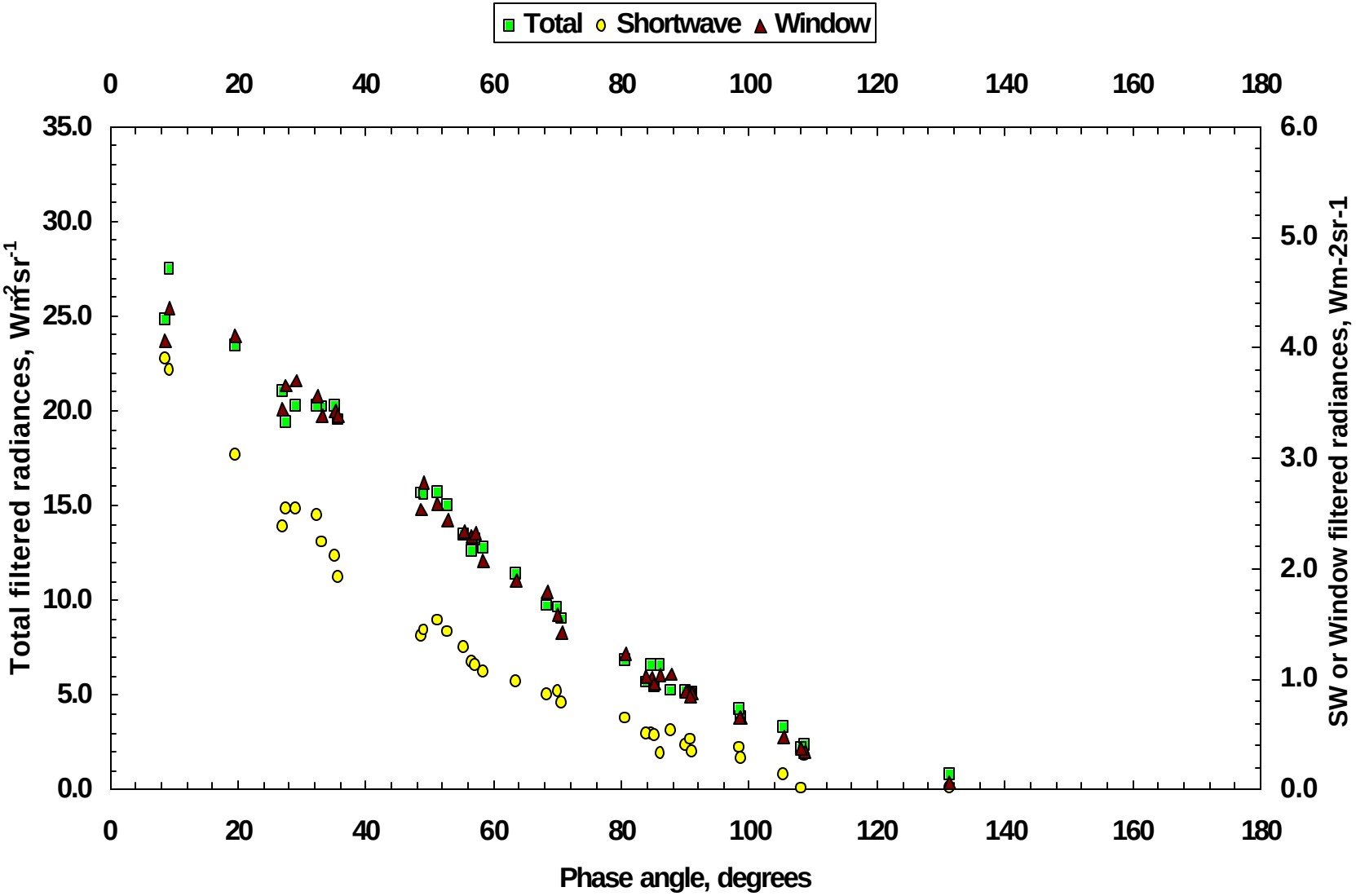


Table 1. CERES filtered lunar radiance measurements of phase PHASE ANGLE IN THE 3-25 DEGREE RANGE

Spacecraft /CERES Sensors	Year	Day of Year	Hours	Minutes	Seconds	Phase Angle Degrees	FOV Angle Degree	Filtered Radiance Total $Wm^{-2}sr^{-1}$	Shortwave $Wm^{-2}sr^{-1}$	Window $Wm^{-2}sr^{-1}$
TRMM/PFM	1998	161	7	1	47.332	5.6	0.02	24.02	4.63	4.81
Terra/FM1	2000	110	16	23	51.82	22.4	0.22	20.73	2.58	4.00
Terra/FM1	2000	258	1	29	18	5.9	0.206	26.22	4.14	5.05
Terra/FM1	2000	286	16	45	7	10.4	0.228	25.66	3.69	5.12
Terra/FM1	2001	41	1	51	20	25.4	0.029	22.64	2.88	4.47
Terra/FM1	2001	68	17	58	40	3.7	0.21	27.54	4.80	5.04
Terra/FM1	2001	70	10	5	15	23.1	0.089	22.60	2.99	4.43
Terra/FM1	2001	70	12	46	37	25.4	0.059	22.01	2.73	4.34
Terra/FM1	2001	99	6	15	20	14.9	0.164	24.35	3.57	4.85
Terra/FM1	2001	216	22	19	21	8.6	0.248	21.86	3.58	4.43
Terra/FM1	2001	218	3	59	55	21.3	0.142	22.18	2.95	4.39
Terra/FM1	2001	218	4	37	6	21.2	0.041	22.31	2.79	4.22
Terra/FM1	2001	218	14	29	53	25.6	0.122	21.19	2.63	4.16
Terra/FM1	2001	244	19	26	50	13.1	0.268	23.93	3.39	4.66
Terra/FM1	2001	244	21	45	46	11.2	0.214	24.74	3.74	4.95
Terra/FM1	2001	246	17	37	5	10.5	0.222	24.97	3.56	4.86
Terra/FM1	2001	248	3	13	9	24.6	0.033	21.74	2.77	4.38
Terra/FM2	2000	168	6	26	0	8.6	0.106	24.79	3.90	4.06
Terra/FM2	2000	318	8	36	33	19.5	0.05	23.46	3.02	4.11
Terra/FM2	2000	345	17	10	29	9.3	0.21	27.49	3.80	4.36
Terra/FM2	2001	97	9	10	43.012	10.5	0.094	25.41	4.11	5.71
Terra/FM2	2001	97	9	10	43.012	10.5	0.01	26.14	3.81	5.42
Terra/FM2	2001	126	20	8	28.062	9.6	0.191	25.60	3.72	4.86
Terra/FM2	2001	157	13	24	18.912	5.7	0.18	25.34	3.92	4.60
Terra/FM2	2001	187	21	9	49.083	14.3	0.122	24.45	3.13	4.61

Table 2. CERES filtered lunar measurements at phase angle near 7 degrees

Spacecraft	TRMM	Terra	Terra	Terra	Terra
Instrument	PFM	FM1	FM1	FM2	FM2
Year	1998	2000	2001	2000	2001
Sensor	$Wm^{-2}sr^{-1}$	$Wm^{-2}sr^{-1}$	$Wm^{-2}sr^{-1}$	$Wm^{-2}sr^{-1}$	$Wm^{-2}sr^{-1}$
Total	23.93	26.15	26.29	26.4	26.43
Shortwave	3.99	4.03	4.2	4.11	4.14
Window	4.78	4.96	4.95	5.27	5.08

CHARACTERIZATIONS OF LUNAR RADIANCES

CHARACTERIZATIONS OF LUNAR RADIANCES

SHORTWAVE RADIANCES

$$L_{swf}(\lambda) = [2 \times W_M \times P(\psi) / (3 \times W_T)] \times \{\Sigma A_m(\lambda_m) \times S(\lambda_m) \times R(\lambda_m) \times \Delta\lambda_m\}$$

where $A_m(\lambda_m)$ represents the full-disc albedos of the moon as a function of wavelength, λ_m;

W_M is the solid angle of the moon (6.4236×10^{-5} steradian);

W_T is the solid angle of the CERES telescopes, (7.722×10^{-4} steradian);

ψ is the phase angle, formed at the moon between directions to the sun, and to the earth;

$S(\lambda_m)$ is the spectral isotropic emittance of the sun at the mean sun-moon distance;

$P(\psi)$ represents a phase function such as the Russell phase function for a diffusely reflecting or emitting spherical moon;

$R(\lambda_m)$ is the spectral responsivity of a CERES sensor;

and $\Delta\lambda_m$ is the wavelength interval of the λ_m.

Figure 9. Terra/CERES FM1 estimated spectral lunar shortwave radiances calculated using the FM1 sensors spectral responses, Apollo 16 site soil surface, and the solar spectral radiances. The Apollo 16 lunar reflectances are presented.

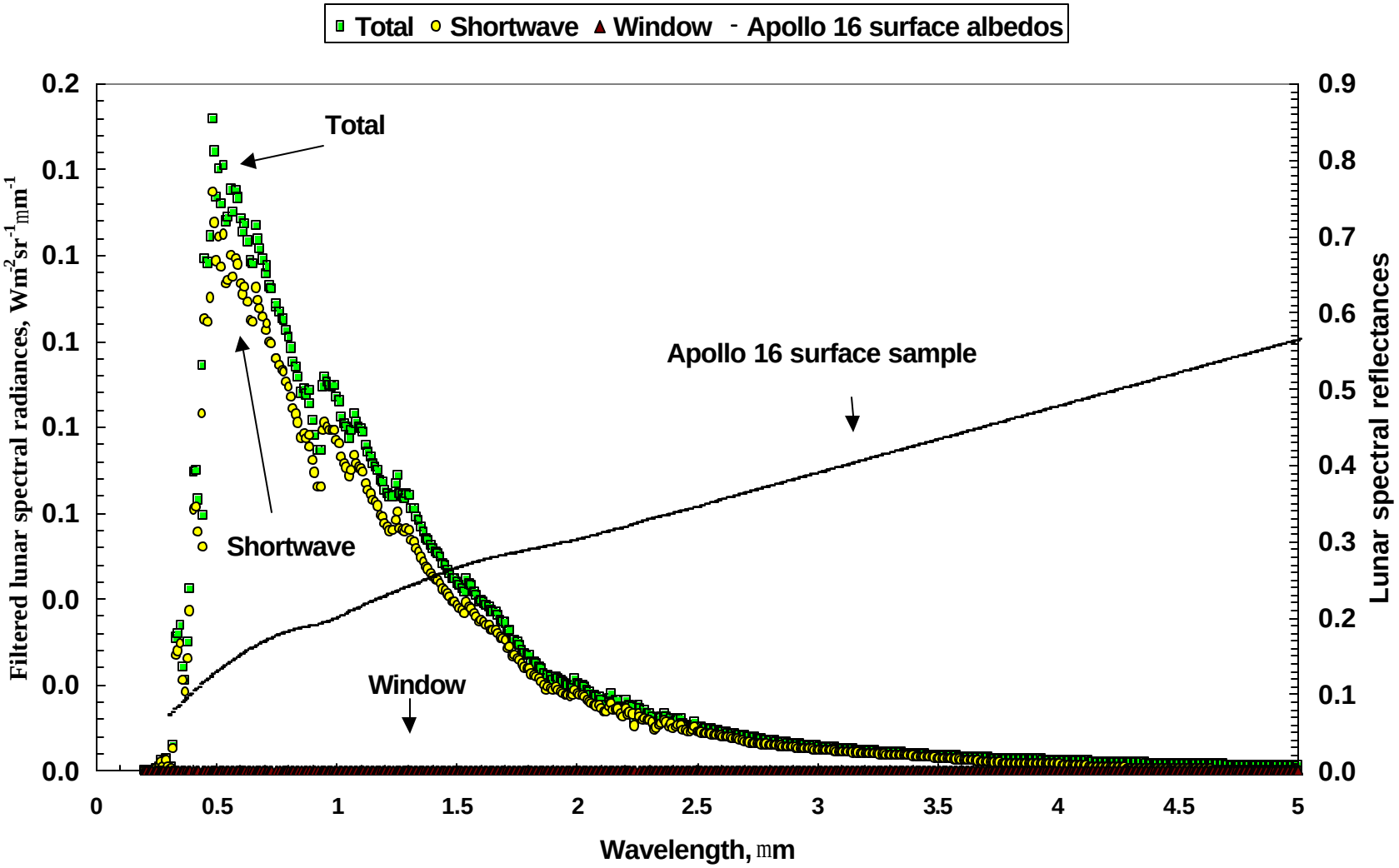


Table 3. Calculated CERES shortwave filtered radiances near a phase angle of 7 degrees

Spacecraft	TRMM	Terra	Terra	Aqua	Aqua
Instrument	PFM	FM1	FM2	FM3	FM4
	$Wm^{-2}sr^{-1}$	$Wm^{-2}sr^{-1}$	$Wm^{-2}sr^{-1}$	$Wm^{-2}sr^{-1}$	$Wm^{-2}sr^{-1}$
Filtered Total	3.95	4.00	3.99	3.66	3.70
Filtered Shortwave (SW)	3.43	3.43	3.43	3.21	3.24
Filtered Window	0.00	0.00	0.00	0.00	0.00
Unfiltered SW Lunar	4.41	4.41	4.41	4.41	4.41
SW-T conversion Factor	1.15	1.17	1.17	1.14	1.14
SW unfiltering Factor	1.29	1.29	1.29	1.37	1.36

CERES filtered LONGWAVE lunar measurements at phase angle near 7 degrees

LONGWAVE RADIANCES

$$L_{lwf}(\lambda, T_y) = [2 \times \omega_M \times P(\psi) / (3 \times \omega_T)] \times \{\Sigma E_m(\lambda_m, T_y) \times R(\lambda_m) \times \Delta\lambda_m\}$$

where $E_m(\lambda_m, T_y)$ is the lunar blackbody spectral emittance as defined by Planck's relation, assuming that the moon emits like a perfect blackbody;

ω_M is the solid angle of the moon (6.4236×10^{-5} steradian);

ω_T is the solid angle of the CERES telescopes, (7.722×10^{-4} steradian);

ψ is the phase angle, formed at the moon between directions to the sun, and to the earth;

$P(\psi)$ represents a phase function such as the Russell phase function for a diffusely reflecting or emitting spherical moon;

$R(\lambda_m)$ is the spectral responsivity of a CERES sensor;

$\Delta\lambda_m$ is the wavelength interval of the λ_m;

and T_y represents the lunar disc-emitting temperature as a function of phase angle.

Table 4. Calculated CERES FM1 longwave filtered radiances near a phase angle of 7 degrees

TOTAL UNFILTERING Unfiltered LW/Filtered T	SHORTWAVE UNFILTERING Unfiltered LW/Filtered SW	WINDOW UNFILTERING Unfiltered LW/Filtered W	EMITTING TEMPERATURE KELVIN DEGS.	UNFILTERED LONGWAVE Wm-2sr-1	TOTAL FILTERED Wm-2sr-1	SHORTWAVE FILTERED Wm-2sr-1	WINDOW FILTERED Wm-2sr-1
1.16	46.41	5.04	**390.16**	418.20	20.04	0.50	4.61
1.17	187.42	5.61	**298.16**	142.63	6.79	0.04	1.41
1.17	247.55	7.21	**248.50**	68.82	3.26	0.02	0.53
1.18	232.24	8.05	**235.00**	55.04	2.60	0.01	0.38
1.18	223.47	8.44	**230.00**	50.50	2.38	0.01	0.33
1.18	215.13	8.89	**225.00**	46.25	2.18	0.01	0.29
1.18	205.23	9.39	**220.00**	42.28	1.99	0.01	0.25
1.18	194.76	9.97	**215.00**	38.56	1.81	0.01	0.21
1.19	144.29	14.52	**190.00**	23.52	1.09	0.01	0.09
1.23	57.55	86.33	**130.16**	5.18	0.23	0.01	0.00
1.26	40.54	214.44	**113.16**	2.96	0.13	0.00	0.00

RADIANCE UNFILTERING

SHORTWAVE (SW)

UNFITERED RADIANCE = SHORTWAVE BOLOMETER FILTERED RADIANCE x UNFILTERING FACTOR x [3 x W_T / 2 x W_M]

LONGWAVE (LW)

UNFILTERED RADIANCE = [FILTERED LW PORTION OF TOTAL BOLOMETER RADIANCE] x UNFILTERING FACTOR x [3 x W_T / 2 x W_M]

LW PORTION OF TOTAL BOLOMETER RADIANCE =

{TOTAL FILTERED RADIANCE – [SW UNFILTERED RADIANCE/ LW UNFILTERING FACTOR]}

TEMPERATURE = {3.14 x UNFILTERED RADIANCE/(5.6697 X 10^-8)}^0.25

EARLIER LUNAR TEMPERATURE MEASUREMENTS

LUNAR NOON SUBSOLAR

360 – 390 K [1927, 1939, 1953 PRE-TOTAL LUNAR ECLIPSES]

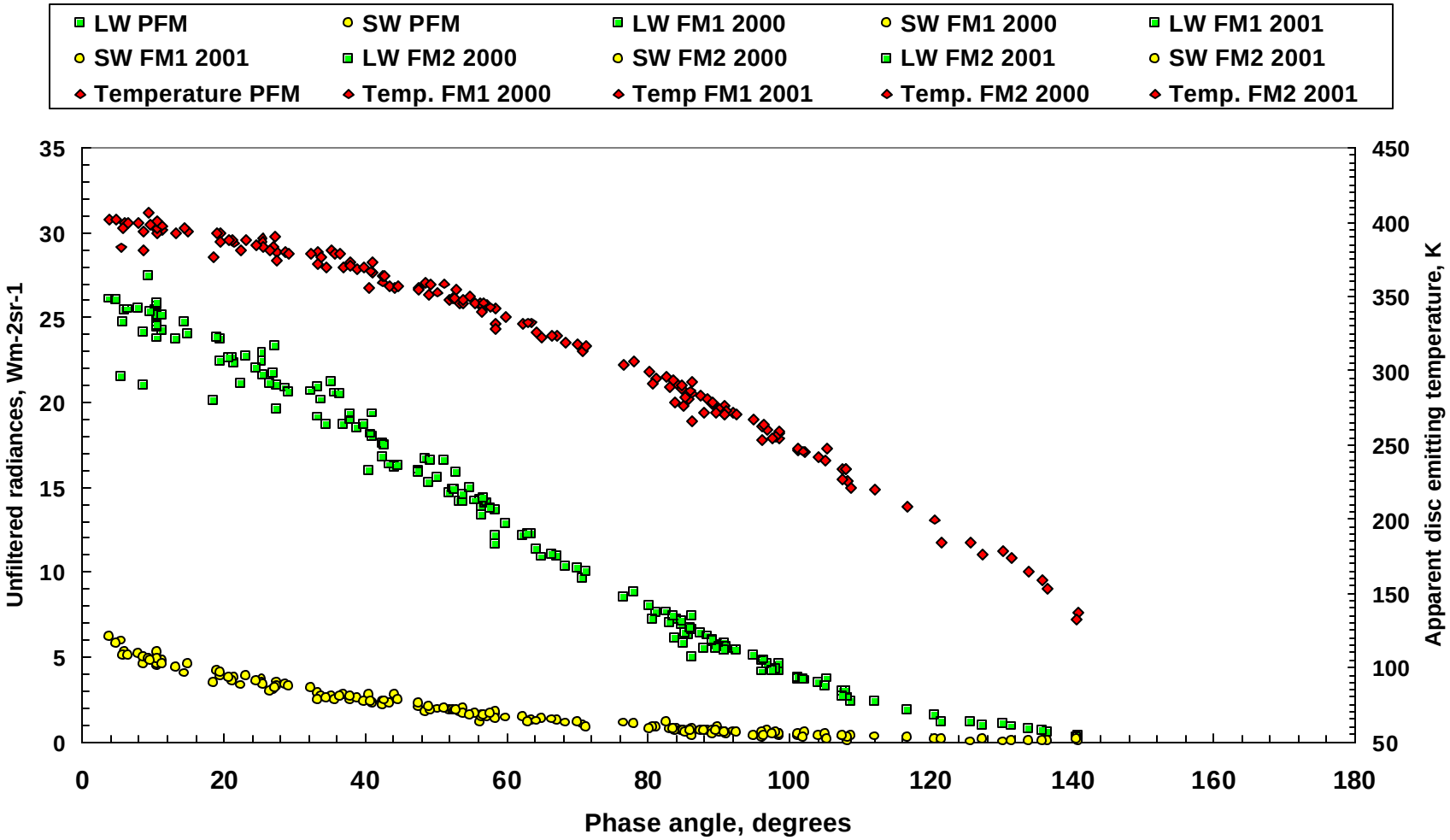
LUNAR LIMB

30 K COOLER THAN NOON SUBSOLAR [PRE- TOTAL LUNAR ECLIPSES]

LUNAR NIGHT

105-125 K

Figure 10. For a lunar image of 31 arc minutes, unfiltered shortwave and longwave radiances are presented for the PFM, FM1, and FM2 bolometers as well as lunar whole disc emitting temperatures.



SIMPLE PLANETARY HEAT BALANCE RELATIONSHIP

$$e\,s\,T^4 = [(1-ALBEDO) \times \text{Total Solar Irradiance}]/[4 \times D_{s-m})^2];$$

Implies T ~ 263 K assuming albedo ~ 0.2, and $e = 1$

Figure 11. For a lunar image of 48 arc minutes, unfiltered shortwave and longwave radiances are presented for the PFM, FM1, and FM2 bolometers as well as lunar whole disc emitting temperatures.

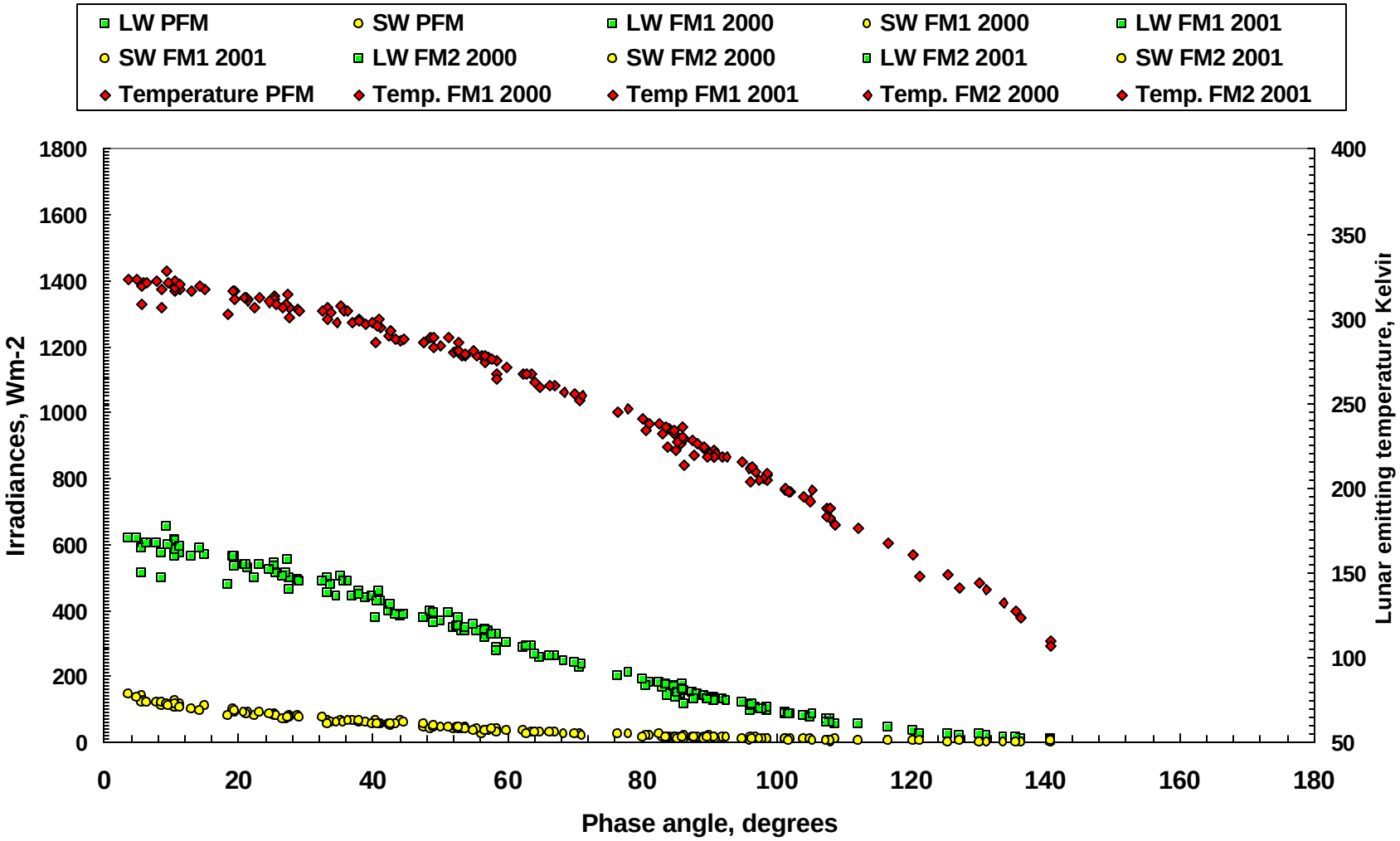


Table 5. FM2 January 9, 2001, Total Lunar Eclipse Measurements.

Day of Year	Time Hours	Minutes	Seconds	Phase Angle Degrees	FOV Angle Degree	Total $Wm^{-2}sr^{-1}$	Shortwave $Wm^{-2}sr^{-1}$	Window $Wm^{-2}sr^{-1}$
9	16	43	39.468	2.3	0.12		5.40	
9	17	23	22.038	2.4	0.08	29.01	5.45	5.01
9	**17**	**44**	**Moon entered earth shadow penumbra, beginning of lunar eclipse.**					
9	18	22	32.796	1.4	0.12		4.89	4.86
9	**18**	**43**	**Moon entered earth shadow umbra.**					
9	19	2	8.766	1.7	0.12	8.48	1.32	1.28
9	19	2	15.366	1.7	0.26	8.19	1.26	1.28
9	**19**	**50**	**Moon located completely in umbra and beginning of totality.**					
9	20	1	26.123	0.8	0.19		0.14	0.26
9	20	1	32.723	0.8	0.23		0.15	0.23
9	**20**	**21**	**Moon located at center of umbra.**					
9	**20**	**52**	**Moon located on edge of umbra, end of totality**					
9	21	40	19.449	1	0.23		1.39	1.03
9	21	40	26.049	1	0.19		1.27	1.05
9	**22**	**0**	**Moon left umbra.**					
9	22	19	48.819	1.8	0.08	24.39	4.68	4.20
9	**22**	**58**	**Moon left penumbra, end of lunar eclispe.**					
9	23	19	19.376	1.8	0.15		5.60	5.44
9	23	58	35.546	2.4	0.23	29.06	5.20	5.10
9	23	58	42.146	2.4	0.15	28.53	5.26	4.88

Table 6. FM2 May 16, 2003 Total Lunar Eclipse Measurements.

Day of Year	Time Hours	Time Minutes	Time Seconds	Phase Angle Degrees	FOV Angle Degree	Total $Wm^{-2}sr^{-1}$	Shortwave $Wm^{-2}sr^{-1}$	Window $Wm^{-2}sr^{-1}$
135	23	42	16.07	1.8	0.13	22.82	5.08	4.66
135	23	42	22.607	1.8	0.25	24.58	5.21	4.73
135	23	43	41.806	1.8	0.12	28.57	5.24	5.75
136	**1**	**6**		**Moon entered earth shadow penumbra, beginning of lunar eclipse.**				
136	**2**	**3**		**Moon entered earth shadow umbra.**				
136	**3**	**14**		**Moon located completely in umbra and beginning of totality.**				
136	**3**	**40**		**Moon located at center of umbra.**				
136	3	42	23.634	1.4	0.11	0.82	0.10	0.08
136	3	43	49.433	1.4	0.04	0.91	0.00	0.10
136	3	45	15.232	1.5	0.03	0.74	0.00	0.00
136	**4**	**7**		**Moon located on edge of umbra, end of totality**				
136	**5**	**18**		**Moon left umbra.**				
136	**6**	**15**		**Moon left penumbra, end of lunar eclipse.**				
136	6	59	43.893	1.8	0.09	27.57	5.22	5.5
136	7	1	16.292	1.8	0.18	27.95	5.12	5.5
136	18	30	31.396	8.1	0.04	25.82	4.01	5.37
136	18	32	3.795	8.2	0.01	25.88	3.96	5.44
136	18	33	36.194	8.2	0.08	21.53	3.92	4.51

Table 7. FM4 May 16, 2003, total lunar eclipse measurements.

Day of Year	Time Hours	Time Minutes	Time Seconds	Phase Angle Degrees	FOV Angle Degree	Total Wm-2sr-1	Shortwave Wm-2sr-1	Window Wm-2sr-1
136	0	15	2.395	2	0.04	20.94	4.78	4.78
136	**1**	**6**		**Moon entered earth shadow penumbra, beginning of lunar eclipse.**				
136	**2**	**3**		**Moon entered earth shadow umbra.**				
136	**3**	**14**		**Moon located completely in umbra and beginning of totality.**				
136	3	29	50.903	0.6	0.21	0.79	0.03	0.07
136	3	29	57.503	0.6	0.06	0.87	0.03	0.10
136	3	31	23.302	0.7	0.06	0.82	0.02	0.05
136	3	32	49.101	0.7	0.17	0.68	-0.01	0.02
136	3	32	55.701	0.7	0.21	0.66	0.02	0.03
136	**3**	**40**		**Moon located at center of umbra.**				
136	**4**	**7**		**Moon located on edge of umbra, end of totality**				
136	**5**	**18**		**Moon left umbra.**				
136	**6**	**15**		**Moon left penumbra, end of lunar eclispe.**				
136	6	47	44.209	2.1	0.25	23.83	4.60	5.37
136	6	47	50.809	2.1	0.14	24.65	4.78	5.88
136	6	49	16.608	2.1	0.09	24.75	4.77	5.95
136	6	50	42.408	8.8	0.03	20.90	4.73	4.69
136	18	20	17.459	8.8	0.03	23.08	3.60	5.74
136	18	21	36.659	8.8	0.26	22.51	3.51	5.32
136	18	21	43.259	8.8	0.15	22.77	3.60	5.74
136	18	23	2.458	8.8	0.16	20.10	3.53	4.57
136	18	23	9.058	8.8	0.24	18.10	3.54	4.37

Measurements of filtered lunar radiances using the NASA Terra spacecraft/CERES thermistor bolometer sensors during 2000 and 2001

RESULTS

0 Analyses of the Clouds and the Earth's Radiant Energy System (CERES) thermistor bolometer sensor observations of lunar radiances indicated that broadband shortwave and longwave lunar filtered radiances can be determined on a radiometric scale linked to ITS-90 at absolute levels approaching ± 0.2 $Wm^{-2}sr^{-1}$.

0 FIRST broadband lunar radiances/irradiances

0 For a lunar image of 31 arc minutes, an effective emitting whole-disc lunar temperature of approximately 400 Kelvin was estimated from the longwave radiances near 7-degree phase angle.