The Cross Calibration of SeaWiFS and MODIS Using On-Orbit Observations of the Moon

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ABSTRACT

Observations of the Moon provide one technique for the cross calibration of Earth remote sensing instruments. Monthly lunar observations are major components of the on-orbit calibration strategies of the SeaWiFS and MODIS instruments. SeaWiFS has collected more than 132 low phase angle and 59 high phase angle lunar observations over 12 years, while Terra MODIS has collected more than 82 scheduled and 297 unscheduled lunar observations over 9 years and Aqua MODIS has collected more than 61 scheduled and 171 unscheduled lunar observations over 7 years. The NASA Ocean Biology Processing Group's Calibration and Validation Team (OBPG CVT) and the NASA MODIS Characterization Support Team (MCST) use the U.S. Geological Survey's RObotic Lunar Observatory (ROLO) photometric model of the Moon to compare these time series of lunar observations. In addition, the Moon was observed simultaneously by SeaWiFS and Terra MODIS on 14 April 2003 as part of the Earth Observing System (EOS) Lunar Calibration Experiment, allowing a direct comparison of one set of lunar measurements. The OBPG CVT and MCST use residuals of the lunar observations from the ROLO model to cross calibrate SeaWiFS and the two MODIS instruments. The cross calibration results show that Terra MODIS and Aqua MODIS agree, band-to-band, at the 1-3% level, while SeaWiFS and either MODIS instrument agree at the 3-8% level. The main implication of these cross-calibration results is that the operations concepts for upcoming remote sensing instruments should be designed to maximize the number of lunar observations over the mission time frame, while minimizing the phase angle range of the observations.

Keywords: SeaWiFS, MODIS, Moon, reflective solar bands, lunar calibration, radiometric stability

1. INTRODUCTION

Observations of the Moon provide a unique way of cross calibrating two or more remote sensing satellite instruments on orbit. The best on-orbit calibrations derived for these instruments must be applied to the lunar data to correct for radiometric drifts in the instruments, thus allowing comparisons to be made with stable top-of-the-atmosphere (TOA) irradiances. A comparison of lunar data analysis methodologies developed by the OBPG CVT and MCST to provide these on-orbit calibrations for SeaWiFS and MODIS has been presented previously.[1] This paper presents the results of the cross calibration of SeaWiFS, Terra MODIS, and Aqua MODIS. The USGS ROLO photometric model of the Moon[2,3] is used to correct each instrument's lunar measurements for variations in the geometry of the observations, namely the changing Earth-Sun and Earth-Moon distances, and the phase and libration angles of the observations. The ROLO model also corrects for differences in the relative spectral responses of the instruments. Use of residuals of the lunar observations from the ROLO model allows the instrument cross calibrations to be made over different time periods and phase angle ranges.

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1.1 SeaWiFS Lunar Calibration

SeaWiFS observes the Moon on a monthly basis through its Earth View, which requires a spacecraft pitch maneuver. During a lunar calibration, the spacecraft is pitched across the Moon so that SeaWiFS views the Moon near nadir through the same optical path as it views the Earth. The individual lunar observations are then normalized by the ROLO model to a common viewing geometry for the radiometric stability analysis. The observations have also been normalized for variations in the oversampling of the lunar images (computed from the measured sizes of the lunar images in the along-track direction). The oversampling correction, which has an uncertainty of approximately 2% for each observation, is the largest systematic error source in the SeaWiFS lunar calibration time series.

The OBPG CVT has revised the prelaunch count-to-radiance conversion coefficients used in the SeaWiFS calibration, replacing the coefficients derived as part of the 1997 calibration of SeaWiFS by NIST[4] (during the integration of the instrument with the spacecraft by the spacecraft builder) with the coefficients derived as part of the 1993 calibration of SeaWiFS by Santa Barbara Remote Sensing[5] (during the instrument development). The 1997 coefficients had been used since the launch of the instrument through SeaWiFS global data Reprocessing 5, but trends in the lunar residuals as a function of wavelength and similar trends in the vicarious calibration coefficients for SeaWiFS[6] have led the CVT to adopt the 1993 coefficients for SeaWiFS Reprocessing 6. This change in coefficients does not impact the on-orbit radiometric calibration derived for SeaWiFS from the lunar data.

The OBPG CVT has optimized the long-term radiometric correction for SeaWiFS over its mission by fitting the lunar time series with a single function of time.[7] The current fitting function is a simultaneous decaying exponential with a 400-day time constant and a linear function of time., which has the form:

$$f(\lambda, t) \;=\; A_0(\lambda) \;-\; A_1(\lambda)\left[1 \;-\; e^{-C_1(\lambda)(t-t_0)}\right] \;-\; A_2(\lambda)(t-t_0) \tag{1}$$

where:

A_i ≡ fitted values of the function
C_1 ≡ time constant of the exponential function
t ≡ time of the observation
t_0 ≡ reference time for the time series
λ ≡ SeaWiFS band.

Since these fits model the instrument radiometric response over time, the inverses of these fits constitute the radiometric gain corrections that are applied to the Earth data during calibration. The OBPG CVT has achieved a long-term RMS error in the radiometric stability of the SeaWiFS TOA radiances of better than 0.1% per band using this approach.[1,7]

1.2 MODIS Lunar Calibration

The MODIS Reflective Solar Bands (RSB) are calibrated primarily by its on-board calibrators, the Solar Diffuser (SD) and the Solar Diffuser Stability Monitor (SDSM). For each band (B), detector (D), and mirror side (M), a calibration coefficient $m_1(B, D, M)$ is derived from every SD/SDSM calibration. These coefficients track the degradation of the MODIS system response at the Angle of Incidence (AOI) of the SD, which is 50.25°. MODIS is also scheduled to view the Moon approximately monthly through its Space View (SV) Port to track the degradation of the MODIS response at the AOI of the SV, which is 11.4°. The MODIS scheduled lunar observations usually require a spacecraft roll maneuver in order to keep the lunar phase angle in a small range. The difference in the degradation at the two AOIs represents the on-orbit change of the Response Versus Scan angle (RVS) of the MODIS scan mirror.

The response degradation at the AOI of the SV is tracked by the lunar coefficient, calculated as:[8]

$$m_1^{moon}(B, M) \;=\; \frac{f_{vg,B}\; f_{os,B}}{\sum_D m_1^0(B, D, M)\; dn'_{moon}(B, D)} \tag{2}$$

where:

Table 1. **Instrument Bands.** The bands are listed as a function of wavelength. The MODIS bands shown are those with wavelengths shorter than 900 nm which do not saturate on the Moon.

SeaWiFS	λ **(nm)**	**Bandwidth**	**MODIS**	λ **(nm)**	**Bandwidth**
Band 1	412	402–422	**Band 8**	412	405–420
Band 2	443	433–453	**Band 9**	442	438–448
			Band 3	468	459–479
Band 3	490	480–500	**Band 10**	487	483–493
Band 4	510	500-520	**Band 11**	530	526-536
Band 5	555	545–565	**Band 12**	547	546–556
			Band 4	554	545–565
Band 6	670	660–680	**Band 1**	647	620–670
Band 7	765	745-785			
Band 8	865	845–885	**Band 2**	857	841–876

$f_{vg,B}$ $\equiv$ viewing geometry correction
$f_{os,B}$ $\equiv$ oversampling correction
m_1^0 $\equiv$ initial on-orbit calibration coefficient
dn'_{moon} $\equiv$ digital response corrected for background signal and instrument temperature effects
B $\equiv$ MODIS band
D $\equiv$ MODIS detector
M $\equiv$ mirror side.

The viewing geometry correction is provided by the ROLO model and the oversampling correction is computed analytically from the geometry of the lunar observation through the Space View Port.

1.3 Cross Calibration

The cross calibration presented here uses all eight SeaWiFS bands and the MODIS reflective solar bands with wavelengths shorter than 900 nm that do not saturate on the Moon (bands 1-4 and 8-12). The SeaWiFS and MODIS bands being compared are shown in Table 1. A summary of the lunar observations obtained by the three instruments over their missions is shown in Table 2.

SeaWiFS has made 132 monthly lunar observations at a nominal phase angle of 7°, distributed before and after full phase; these observations are the primary radiometric monitor of the instrument response for SeaWiFS on orbit. It has also made the EOS cross calibration observation on 14 April 2003 at a phase angle of $-27°$. To extend the phase angle range of the lunar observations, SeaWiFS has made 59 lunar observations distributed over nominal phase angles of $-45°, -40°, -28°, +28°, +45°$, and $+55°$.

Terra MODIS has made 82 scheduled monthly lunar observations by rolling the spacecraft to at a nominal phase angle of of $+55°$, while Aqua MODIS has made 61 scheduled monthly observations by rolling the spacecraft to a nominal phase angle of $-55°$; these observations are the primary radiometric monitor of the instrument response for MODIS on orbit at the AOI of the Space View. There are also about thirty unscheduled lunar observations every year for both MODIS instruments, where the Moon is fully visible in the space view port one or more orbits before or after the scheduled lunar observations.[9] A range of phase angles arises from these unscheduled observations because the spacecraft is not rolled to control the phase angle of the observations. Terra MODIS has obtained 297 observations over a phase angles of $+55°$ to $+82°$, while Aqua MODIS has obtained 171 observations at phase angles of $-54°$ to $-80°$. In addition, Terra MODIS observed the 14 April 2003 EOS cross calibration observation at a phase of $-27°$.

Table 2. **Lunar Observations.** Summary of observations for each instrument. *The primary radiometric stability monitor observations.

Instrument	Type	Phase Angle	Number	Time Range
SeaWiFS	Low Phase*	-6.0 to -8.0	83	Nov 97 – Apr 09
		+5.0 to +10.0	49	
	Cross Cal	-27.1	1	14 Apr 03
				22:34:21 UT
	High Phase	-27.0 to -49.0	26	Jul 04 – Dec 07
		+27.0 to +65.0	32	
Terra MODIS	Scheduled*	+52.0 to +62.0	82	Mar 00 – Feb 09
	Cross Cal	-27.7	1	14 Apr 03
				22:09:35 UT
	Unscheduled	+55.0 to +82.0	297	Jul 00 – Dec 08
Aqua MODIS	Scheduled*	-51.0 to -58.0	61	Jun 02 – Apr 09
	Unscheduled	-54.0 to -80.0	171	Dec 02 – Dec 08

Table 3. **Terra MODIS / Aqua MODIS Biases.** The relative biases between Terra MODIS and Aqua MODIS.

	Band 8	**Band 9**	**Band 3**	**Band 10**	**Band 11**
λ (nm)	412	442	468	487	530
Bias (%)	0.7 ± 1.1	1.3 ± 0.8	2.8 ± 0.6	1.6 ± 0.6	2.7 ± 0.5
	Band 12	**Band 4**	**Band 1**	**Band 2**	
λ (nm)	547	554	647	853	
Bias (%)	1.8 ± 0.5	2.8 ± 0.5	0.7 ± 0.5	0.7 ± 0.6	

2. MISSION-LONG COMPARISON

The mission-long comparison of the lunar observations for these instruments is made using the primary lunar calibration data set for each instrument: the low phase angle observations for SeaWiFS ($\pm 7°$) and the scheduled observations for Terra MODIS ($+55°$) and Aqua MODIS ($-55°$). Each instrument has had the best current on-orbit calibration applied to the lunar data, providing stable TOA irradiances for the Moon. This comparison is made using the mission-averaged ROLO residuals for each instrument and band, as shown in Fig. 1. For all three instruments, the residuals of the lunar observations from the ROLO model are essentially spectrally flat. The primary source of the biases between all three instruments arises from differences in the prelaunch calibration of the instruments, since the on-orbit calibration of the instruments should correct any changes in the biases over time. The relative biases between Terra and Aqua MODIS are 1-3%, as is shown in Table 3. The relative biases between SeaWiFS and either MODIS instrument are 3-8%, as is shown in Table 4. The biases between the two MODIS instruments or between SeaWiFS and either MODIS instrument are within the combined absolute calibration uncertainties for the given pair of instruments.

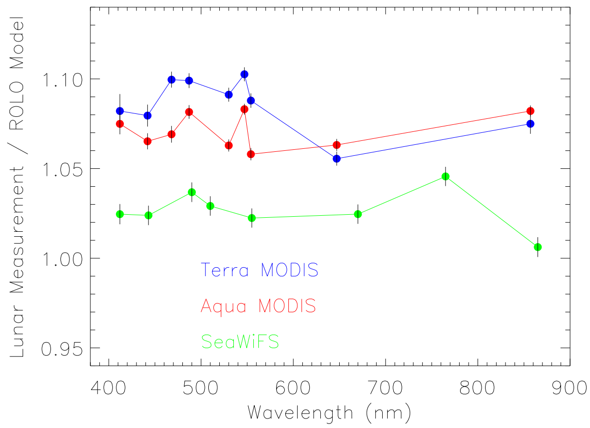

Figure 1. **SeaWiFS and MODIS Lunar Calibration Comparison.** The SeaWiFS mission-average low phase angle observations are compared with the MODIS mission-average scheduled observations. The error bars are the standard deviations of the mean.

Table 4. **SeaWiFS / MODIS Biases.** The relative biases between Terra MODIS and SeaWiFS and between Aqua MODIS and SeaWiFS, are shown for comparable bands. The final column shows the results of the single-point cross calibration.

SeaWiFS	MODIS	Band Centers (nm)	Terra Bias (%)	Aqua Bias (%)	Terra Cross (%)
Band 1	**Band 8**	412 , 412	5.6 ± 1.1	4.9 ± 0.8	1.5
Band 2	**Band 9**	443 , 442	5.4 ± 0.8	4.0 ± 0.7	2.0
Band 3	**Band 10**	490 , 487	6.0 ± 0.7	4.3 ± 0.7	4.0
Band 4	**Band 11**	510 , 530	6.0 ± 0.7	3.3 ± 0.6	2.1
Band 5	**Band 12**	555 , 547	7.8 ± 0.7	5.9 ± 0.6	3.6
Band 5	**Band 4**	555 , 554	6.4 ± 0.7	4.9 ± 0.6	1.5
Band 6	**Band 1**	670 , 647	3.0 ± 0.7	3.8 ± 0.6	0.4
Band 8	**Band 2**	865 , 857	6.8 ± 0.8	7.5 ± 0.6	5.0

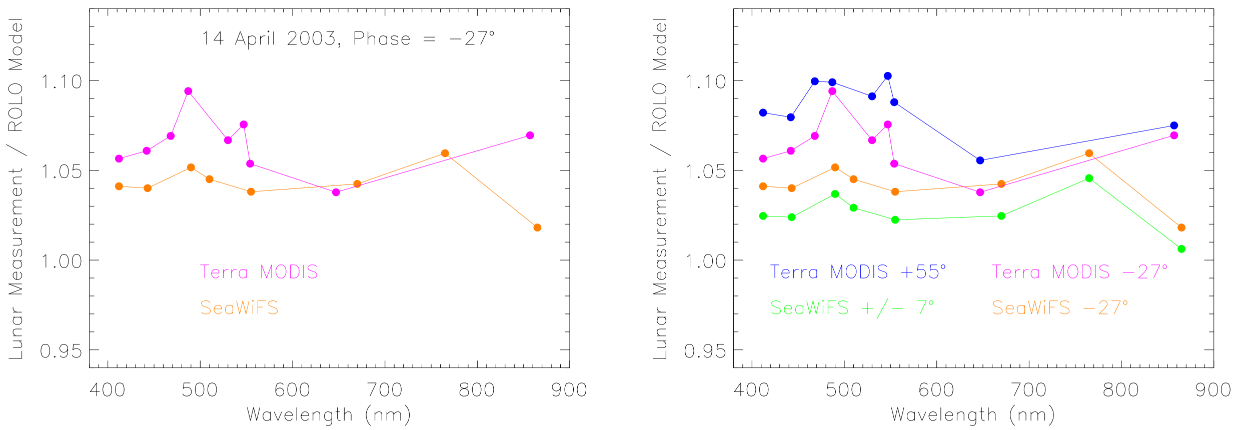

Figure 2. **SeaWiFS and MODIS Lunar Cross Calibration.** The plot on the right shows the mission-average residuals in addition to the cross calibration residuals.

3. SINGLE-POINT CROSS CALIBRATION

On 14 April 2003, Terra MODIS and SeaWiFS made near-simultaneous observations of the Moon as part of the EOS Lunar Calibration Experiment. A nominal lunar phase angle of −28° was chosen by the EOS Project to facilitate the simultaneous observations. SeaWiFS performed a standard lunar calibration at the cross calibration time, while the Terra spacecraft performed a deep space maneuver so MODIS viewed the Moon through the Earth-View aperture. The actual time and phase angles of the lunar observations are shown in Table 2, while the instrument comparison is shown in Fig. 2. The cross calibration shows relative biases between SeaWiFS and Terra MODIS of 1-5%, as is shown in Tabel 4. The second plot, comparing the residuals at −27° phase with the residuals at the standard phase angles, shows a reduced bias between the two instruments compared to the bias for the standar observations. The bias reduction is greater than the errors in the means for standard observations show in Fig. 1. Since these SeaWiFS and Terra MODIS lunar measurements here were made at essentially the same phase angle, the ROLO model was not required to normalize measurements made at significantly different phase angles as is the usual case when SeaWiFS and MODIS lunar observations are being compared. The reduced biases between SeaWiFS and Terra MODIS for these observations raise the question of whether the ROLO model has any residual phase dependence. To try to answer this question, the OBPG CVT and MCST have examined the full set of lunar observations for all three instruments.

4. COMPARISON WITH PHASE ANGLE

The OBPG CVT and MCST have undertaken a comparison of the full set of SeaWiFS and MODIS lunar calibration residuals over their respective missions as a function of phase angle. The primary goal of this analysis is to determine if the SeaWiFS low-phase (±7°) lunar observations can be compared directly with the MODIS scheduled lunar observations (±55° phase). While the comparisons were made for all of the bands shown in Table 1, we present the results of the comparison for three wavelengths:

412 nm: SeaWiFS Band 1 / MODIS Band 8, shown in 8 in Fig. 3, the shortest wavelength of the cross calibration.

555 nm: SeaWiFS Band 5 / MODIS Band 12, shown in in Fig. 4, the wavelength with the smallest errors (from Fig. 1) for all three instruments.

865 nm: SeaWiFS Band 8 / MODIS Band 2, shown in in Fig. 5, the longest wavelength of the cross calibration.

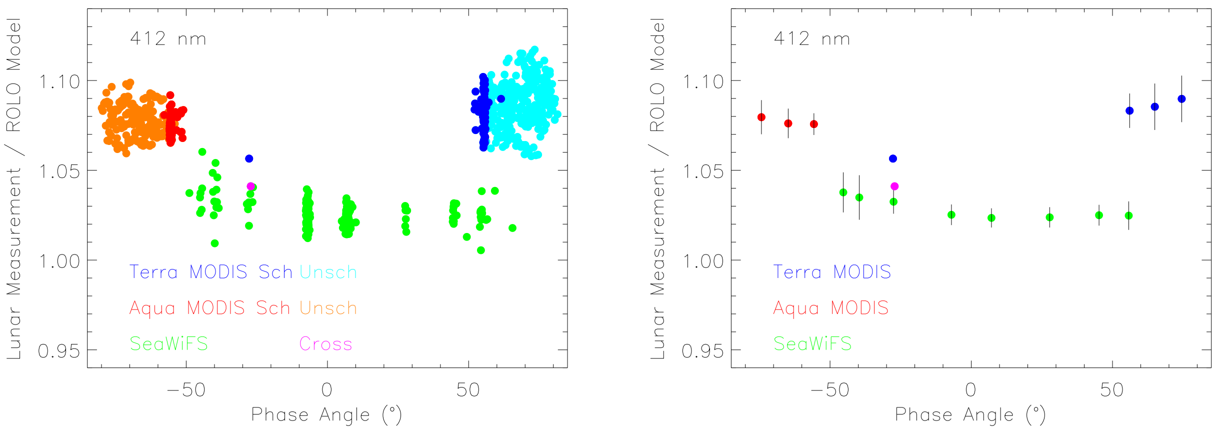

Figure 3. **SeaWiFS Band 1 / MODIS Band 8 Comparison with Phase Angle.** The plot on the right shows the mean residuals for the phase angle ranges.

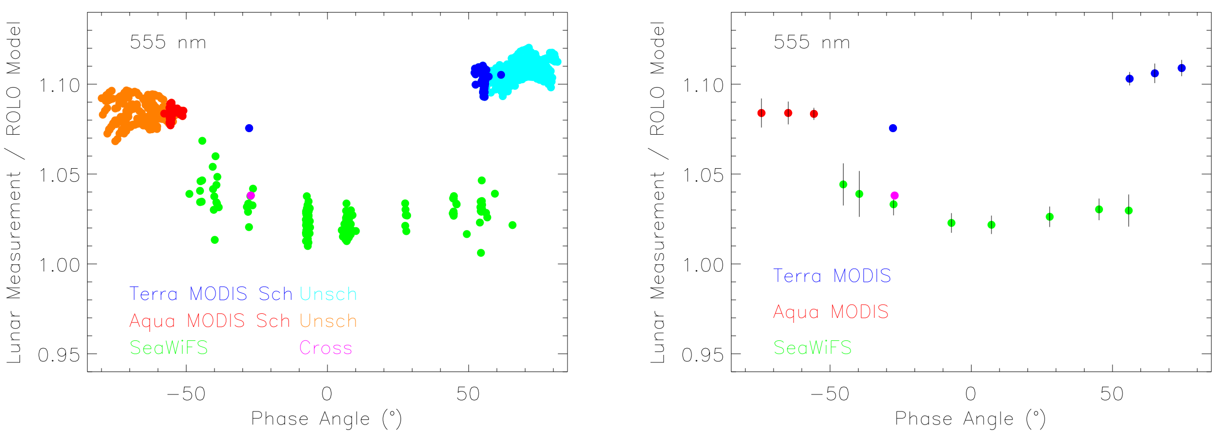

Figure 4. **SeaWiFS Band 5 / MODIS Band 12 Comparison with Phase Angle.** The plot on the right shows the mean residuals for the phase angle ranges.

For each of the figures showing this comparison, the first plot in the pair of plots shows the full set of lunar observations for each instrument. The second plot in the pair of plots shows the mean values of the ROLO residuals at the nominal phase angles over the full range of phase. For SeaWiFS, the mean residuals are computed at the nominal phase angles of $-45°, -40°, -28°, -7°, +7°, +28°, +45°$, and $+55°$. For the two MODIS instruments, the mean residuals are computed for the scheduled observations ($\pm 55°$ phase) and over phase angle ranges of $60°$ to $70°$ (plotted at $\pm 65°$) and of phase angles $> 70°$ plotted at ($\pm 75°$). The cross calibration residuals are plotted at $-27°$ phase without any error bars. For each wavelength, the cross calibration data points are within the envelope of residuals for scheduled observations (Terra MODIS) and for the low phase observations (SeaWiFS), though at the upper end of the range for SeaWiFS. The residuals for SeaWiFS before full phase increase with phase angle, but the uncertainties in the oversampling correction also increase with phase, which is a source of error in addition to the standard deviation of the mean shown in the plots. The residuals for the unscheduled lunar observations by both MODIS instruments are larger than the residuals of the scheduled observations. The conclusion that can be drawn from this analysis is that there is no statistically significant residual phase dependence in the ROLO model. These comparisons also show that the uncertainties in the lunar time series can be minimized if the phase-angle range of the observations is minimized.

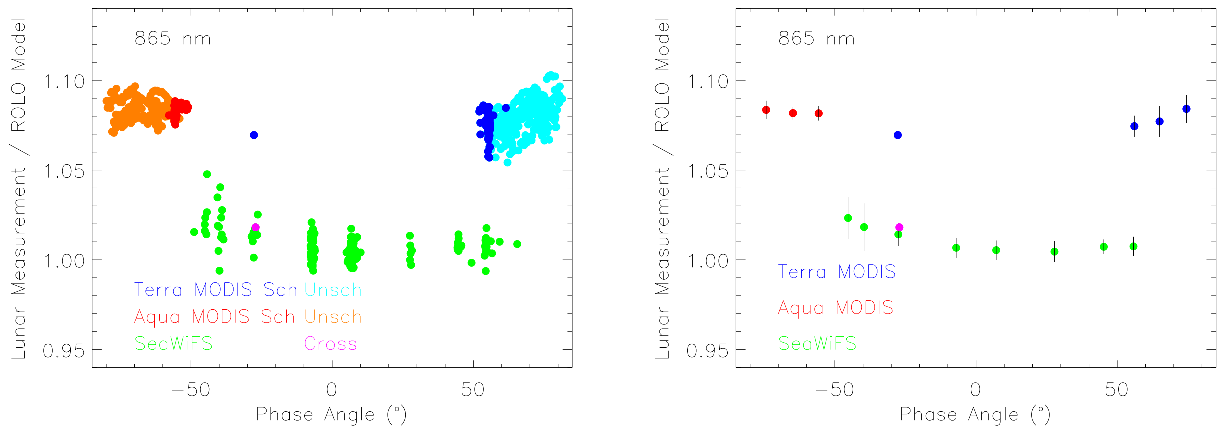

Figure 5. **SeaWiFS Band 8 / MODIS Band 2 Comparison with Phase Angle.** The plot on the right shows the mean residuals for the phase angle ranges.

5. APPLICABILITY AND IMPLICATIONS OF CROSS CALIBRATION RESULTS

The primary motivation for the on-orbit cross calibration of remote sensing satellite instruments is to facilitate the merger of geophysical products from these instruments. A robust estimate of the relative biases in the on-orbit calibration of these instruments is necessary for the data merger to occur. Observations of the Moon, facilitated by the ROLO model, provide one mechanism for the evaluation of these biases at the top of the atmosphere, where complications of atmospheric correction algorithms can be avoided. The shortcoming in using this approach to cross calibration are instrument bands that saturate on the Moon. The cross calibration results show that Terra MODIS and Aqua MODIS agree, band-to-band, at the 1-3% level, while SeaWiFS and either MODIS instrument agree at the 3-8% level. The primary sources of these biases are the prelaunch calibrations of the instruments, since the on-orbit calibration of the instruments should correct any changes in the biases over time. For ocean color products from SeaWiFS and MODIS, the on-orbit vicarious calibration of the instruments mitigates the calibration biases for ocean color bands, except at the 865 nm atmospheric correction band.[10, 11]

For SeaWiFS or MODIS, a single lunar calibration has an uncertainty of 0.5% or more, while the long-term lunar calibration time series can achieve an RMS error of 0.1% per band.[1, 7] The OPBG CVT and MCST have developed and maintained long-term time series of lunar observations for the SeaWiFS and MODIS instruments in order to reduce the overall uncertainties in the on-orbt calibrations of these instruments.

The results of this cross calibration study have implications for upcoming remote sensing instruments, such as VIIRS on the NPOESS Preparatory Project and NPOESS satellites. They also have implications for instruments currently being designed for the NASA Decadal Survey missions. For the first implication, this cross calibration of SeaWiFS, Terra MODIS, and Aqua MODIS demonstrates the importance of the USGS ROLO photometric model of the Moon to the on-orbit calibration of remote sensing satellite instruments. The second implication is that future instruments should be designed on-orbit calibration using the Moon with bands that do not saturate on the Moon. A final implication, which builds on the previous two, is that the operations concepts for upcoming instruments should be designed to maximize the number of lunar observations over the mission time frame, while minimizing the phase angle range of the observations. MODIS views the Moon during most of the year without roll maneuvers, though over a range of phase angles. One of the issues with VIIRS is that the space view is narrower for VIIRS (48 samples, or $\sim 0.85°$) than for MODIS (50 samples, or $\sim 4.1°$). This means that, without roll maneuvers, only part of the Moon will be viewed by VIIRS for most months.[12] Small rolls of the spacecraft are required for VIIRS to view the complete lunar disk at every available opportunity, and larger rolls are required to view the Moon at a constant phase angle. These three design considerations would allow the optimum calibration of future instruments to be derived on orbit.

REFERENCES

[1] J. Sun, R.E. Eplee, Jr., X. Xiong, T. Stone, G. Meister, and C.R. McClain, "MODIS and SeaWiFS on-orbit lunar calibration," in *Earth Observing Systems XIII*, J.J. Butler and J. Xiong, eds., *Proc. SPIE* **7081**, 70810Y, 2008.

[2] H.H. Kieffer and T.C. Stone, "The spectral irradiance of the Moon," *Astron. J.* **129**, 2887–2901, 2005.

[3] T.C. Stone, "Radiometric calibration stability and inter-calibration of solar-band instruments in orbit using the Moon," in *Earth Observing Systems XIII*, J.J. Butler and J. Xiong, eds., *Proc. SPIE* **7081**, 70810X, 2008.

[4] B.C. Johnson, E.A. Early, R.E. Eplee, Jr., R.A. Barnes, and R.T. Caffrey, *The 1997 Prelaunch Radiometric Calibration of SeaWiFS*, NASA Tech. Memo. 1999–206892 **4**, S.B. Hooker and E.R. Firestone, eds., (NASA Goddard Space Flight Center, Greenbelt, Maryland), 1999.

[5] R.A. Barnes, A.W. Holmes, W.L. Barnes, W.E. Esaias, C.R. McClain and T. Svitek, *SeaWiFS Prelaunch Radiometric Calibration and Spectral Characterization*, NASA Tech. Memo. 104566 **23**, S.B. Hooker, E.R. Firestone, and J.G. Acker, eds., (NASA Goddard Space Flight Center, Greenbelt, Maryland), 1994.

[6] R.E. Eplee, Jr., S.W. Bailey, R.A. Barnes, H.H. Kieffer, and C.R. McClain, "Comparison of the SeaWiFS on-orbit lunar and vicarious calibrations," in *Earth Observing Systems XI*, J.J. Butler and J. Xiong, eds., *Proc. SPIE* **6296**, 629610, 2006.

[7] R.E. Eplee, Jr., R.A. Barnes, F.S. Patt, G. Meister, and C.R. McClain, "SeaWiFS lunar calibration methodology after six years on orbit," in *Earth Observing Systems IX*, W.L. Barnes and J.J. Butler, eds., *Proc. SPIE* **5542**, 1–13, 2004.

[8] J. Sun, X. Xiong, W.L. Barnes, and B. Guenther, "MODIS reflective solar bands on-orbit lunar calibration," *IEEE Trans. Geosci. Remote Sens.* **45**, 2383–2393, 2007.

[9] J. Sun, X. Xiong, and W. Barnes, "MODIS reflective solar bands unscheduled lunar observations," in *Earth Observing Systems XII*, J.J. Butler and J. Xiong, eds., *Proc. SPIE* **6677**, 66771K, 2007.

[10] R.E. Eplee, Jr., W.D. Robinson, S.W. Bailey, D.K. Clark, P.W. Werdell, M. Wang, R.A. Barnes, and C.R. McClain, "Calibration of SeaWiFS. II. Vicarious techniques," *Appl. Opt.* **40**, 6701–6718,2001.

[11] B.A. Franz, S.W. Bailey, P.J. Werdell, and C.R. McClain, "Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry," *Appl. Opt.* bf 46, 5068–5082, 2007.

[12] F.S. Patt, R.E. Eplee, R.A. Barnes, G. Meister, and J.J. Butler, "Use of the Moon as a calibration reference for NPP VIIRS," in *Earth Observing Systems X*, J.J. Butler, ed., *Proc. SPIE* **5882**, 588215, 2005.