AERONET TECHNICAL DOCUMENT (DRAFT – 27 February 2019)

Lunar Aerosol Optical Depth Computation

Introduction.

New generation of Cimel automated sun photometers have many new features, and one of them is automatic nighttime direct moon measurements (Barreto et al., 2013, 2016; Li et al., 2016). A significant interest exists in using these measurements to obtain a nighttime Aerosol Optical Depth (AOD) (Berkoff et al., 2011). For that purpose, we need to have a direct moon calibration, top of the atmosphere lunar irradiance, and Lunar Zenith angle (LZA).

Direct Moon calibration can be obtained by three methods:

1. Lunar Langley on Mountain top.
2. Transfer of solar calibration.
3. Comparison with previously calibrated master instrument.

AERONET is currently at the beginning of lunar studies, so no master lunar calibration is yet available.

Lunar Langley method is the most work intensive, as we need to ship instruments to Mauna Loa, and perform a sequence of nighttime Langley measurements there.

Solar and lunar measurements are made using the same optical/electronic path: collimator, filter, and detector. The only difference is the sensitivity as the Sun is significantly brighter than the Moon. According to manufacturer, the sensitivity ratio between Moon and Sun is set to 2^{12} (4096). So in theory, we only need to take a solar calibration coefficient, divide it by 4096 and thus get lunar calibration coefficient. This so called “Transfer of solar calibration” method should become a method of choice if we can prove that it works.

At this stage the objectives of this study are:

1. Develop a lunar Langley algorithm within AERONET processing system (Version 3).
2. Compare results of Lunar Langley calibrations and solar Langley calibrations.
3. Retrieve nighttime AOD.

Method.

Obtaining lunar AOD (τ_a^l) and solar AOD (τ_a^s) are very similar.

For each wavelength, we need to measure irradiance at the ground level E_g and we need to know irradiance at the top of the atmosphere (E_0).

$$\tau_t = \frac{1}{m} ln \frac{E_0}{E_g} \qquad (1)$$

Where *m* is air mass and τ_t- is the total optical depth.

We need to know the gaseous optical depth τ_g to extract it from τ_t:

$$\tau_a = \tau_t - \tau_g \qquad (2)$$

So, lunar (*l*) and solar (*s*) equations are computed as:

$$\tau_a^l = \frac{1}{m^l} ln \frac{E_0^l}{E_g^l} - \tau_g \qquad (3.1)$$

$$\tau_a^s = \frac{1}{m^s} ln \frac{E_0^s}{E_g^s} - \tau_g \qquad (3.2)$$

τ_g is the same for Sun or Moon. Optical air mass is calculated similarly for Sun and Moon, since we need to know SZA (solar zenith angle) and LZA (Lunar zenith angle) respectively.

Ground level irradiances are measured directly by the ground-based radiometers,

$$E_g = V \cdot C \qquad (4)$$

Where V is instrument output, which is unitless, and C is calibration coefficient in $\mu W/m^2$ nm.

C is defined by instrument itself: Filter transmittance, detector sensitivity, electronics, etc.

C^l is the lunar calibration coefficient and C^s is the solar calibration coefficient are used to calculate ground irradiances.

Extraterrestrial solar E_0^s and lunar E_0^l irradiances are time dependent. Solar extraterrestrial irradiance changes between Aphelion and Perihelion by as much as 7%. Lunar extraterrestrial irradiance changes with the Moon phases, earth-moon and moon-sun distances.

We retrieve E_0^l from USGS ROLO model for each time and instrument coordinates combination (Kieffer and Stone 2005).

We calculate E_0^s using extraterrestrial spectrum data established jointly by the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP) and the Naval Research Laboratory (NRL) and adjusting it by Earth-Sun distance factor (Coddington et al., 2016).

For each wavelength, we convolve an actual filter function provided by manufacturer with both solar spectrum and ROLO spectra.

Lunar and solar Aerosol Optical depth equations are:

$$\tau_a^l = \frac{1}{m^l(t)} ln \frac{E_0^l(t)}{V^l(t) \cdot C^l} - \tau_g \qquad (5.1)$$

$$\tau_a^s = \frac{1}{m^s(t)} ln \frac{E_0^s(t)}{V^s(t) \cdot C^s} - \tau_g \qquad (5.2)$$

In the Langley calibration method, we assume the optical depth to be constant during the calibration sequence.

$$\tau_a + \tau_g = T_{const} \qquad (6)$$

Equations (5.1) and (5.2) can now be modified:

$$ln \frac{V^l(t)}{E_0^l(t)} = -T_{const} \cdot m^l(t) - lnC^l \qquad (7.1)$$

$$ln \frac{V^s(t)}{E_0^s(t)} = -T_{const} \cdot m^s(t) - lnC^s \qquad (7.2)$$

These equations are used to make Moon Langley calibration (7.1) and Sun Langley calibration (7.2) and then to compare the results.

After the measurement sequence is complete, we have a set of (t), instrument readings for a set of time moments for each wavelength.

In case of Lunar sequence for each time (t), we retrieve the spectral irradiance $E(\lambda)$ and LZA from USGS ROLO model (Kieffer and Stone 2005). These parameters are calculated on the USGS web site and then transferred and archived on AERONET server.

In case of Solar sequence, we calculate SZA using site coordinates and time (t), and scale extraterrestrial spectral irradiance $E(\lambda)$ by Earth-Sun distance factor. Both parameters are computed on AERONET server.

We calculate optical air mass m(t) from either SZA or LZA.

Using the spectral irradiance, we convolve $E_0(t)$ for each wavelength:

$$E_0(\lambda) = \frac{\int R(\lambda)\, E(\lambda) d\lambda}{\int R(\lambda) d\lambda} \qquad (8)$$

Where $R(\lambda)$ is a filter transmittance function provided by filter manufacturer.

We present equations (7.1) and (7.2) as a common linear expression: y = Ax + B, and create a numerical sequence of $y(t) = \ ln\frac{V(t)}{E_0(t)}$, $x(t) = m(t)$. Numerically, solve them by a Least Squares method, thus finding slope (A) and Intercept (B),

where A = -T_{const} , B = -lnC.

Finally, we can find:

$$C = e^{-B}.$$

Once we have C^l and C^s, we can compare them directly. In theory, we should have:

$$\frac{C^s}{C^l} = 4096, \qquad (9)$$

which is the sensitivity ratio between Moon and Sun according to the manufacturer.

Results.

During 2015-2017, we had 7 instruments on the Mauna Loa that could perform Lunar measurements.

We automatically retrieved both Sun and Moon Langley plots for these deployments.

For Sun, only morning Langley plot are used because afternoon Mauna Loa sky is usually contaminated. For Moon, only pre-dawn Langley are counted for similar reason.

For the Langley plots, we used optical air mass range between 2.5 and 4.5. We required at least 15 measurements for single Sun Langley plot and 40 measurements for Moon Langley plot. The correlation coefficient for a single Langley plot had to be 0.99 or more.

Sun : $N \geq 15,\ 2.5 < m < 4.5,\ CC > 0.99$ (10.1)

Moon: $N \geq 40,\ 2.5 < m < 4.5,\ CC > 0.99$ (10.2)

Where m is an optical air mass, N is a number of measurements within specified optical air mass interval in the sequence, and CC is the Correlation coefficient of the regressions in equations (7.1) and (7.2).

In Table 1, we can see the statistics or checking conditions (10.1) and (10.2) for considered Mauna Loa deployments.

Table 1.

Deployments of Lunar instruments on Mauna Loa.

Instrument	Days	Sun Langleys	Nights	Moon Langleys
1027	64	45	29	9
814	122	76	50	12
818	254	122	85	23
837	753	494	298	61
839	258	89	32	7
864	336	239	186	49
867	146	106	46	13

For each of wavelength (if available) we averaged Solar calibration coefficients and Lunar calibration coefficients and found their ratios.

The following wavelengths are presented in Tables 2.1–2.7:

1020 nm, 1640 nm, 870 nm, 675 nm, 440 nm, 500 nm, 1020 nm InGaAs

Table 2.1

Average calibrations of channel 1020 nm.

Instrument	**864**
N of Sun Langleys	16
Solar CC µWatt/m^2/nm	1.340423
Solar CC uncertanty %	0.49
N of Moon Langleys	4
Lunar CC µWatt/m^2/nm	0.000312
Lunar CC uncertanty %	0.47
Ccsun/Ccmoon	4297.929
Deviation from 4096 (%)	4.93

Table 2.2

Average calibrations of channel 1640 nm.

Instrument	**818**	**837**	**839**	**864**	**867**
N of Sun Langleys	89	409	58	207	95
Solar CC µWatt/m^2/nm	0.2313	0.1983	0.1991	0.2053	0.2020
Solar CC uncertanty %	10.75	4.96	0.25	0.86	1.21
N of Moon Langleys	6	26	4	35	8
Lunar CC µWatt/m^2/nm	0.000055	0.000046	0.000045	0.000048	0.000046
Lunar CC uncertanty %	2.05	2.25	1.99	2.9	2.76
Ccsun/Ccmoon	4231.11	4266.22	4377.42	4321.00	4363.22
Deviation from 4096 (%)	3.3	4.16	6.87	5.49	6.52

Table 2.3

Average calibrations of channel 870 nm.

Instrument	818	837	864	867
N of Sun Langleys	100	401	214	100
Solar CC ϻWatt/m^2/nm	1.1781	1.1368	1.1570	1.0354
Solar CC uncertanty %	10.13	5.04	0.81	1.02
N of Moon Langleys	4	10	21	4
Lunar CC ϻWatt/m^2/nm	0.000268	0.000256	0.000258	0.000234
Lunar CC uncertanty %	0.84	0.6	0.81	0.29
Ccsun/Ccmoon	4396.47	4448.06	4475.93	4429.86
Deviation from 4096 (%)	7.34	8.6	9.28	8.15

Table 2.4

Average calibrations of channel 675 nm.

Instrument	1027	814	818	837	839	864	867
N of Sun Langleys	45	72	110	448	74	226	101
Solar CC ϻWatt/m^2/nm	1.3518	1.4245	1.4754	1.4222	1.4864	1.4719	1.4488
Solar CC uncertanty %	0.57	0.51	9.64	4.79	0.5	0.82	0.95
N of Moon Langleys	6	8	17	45	4	44	10
Lunar CC ϻWatt/m^2/nm	0.000309	0.000321	0.000335	0.000322	0.000335	0.000332	0.000328
Lunar CC uncertanty %	1.87	0.33	0.8	0.77	0.64	0.9	0.41
Ccsun/Ccmoon	4378.24	4435.80	4402.49	4422.14	4443.05	4437.65	4411.53
Deviation from 4096 (%)	6.89	8.3	7.48	7.96	8.47	8.34	7.7

Table 2.5

Average calibrations of channel 500 nm.

Instrument	**1027**	**814**	**818**	**837**	**839**	**864**	**867**
N of Sun Langleys	45	75	117	478	88	232	104
Solar CC μWatt/m^2/nm	1.8809	2.0099	2.0041	1.9178	1.9743	1.9546	1.9574
Solar CC uncertanty %	0.71	0.6	9.47	4.73	0.94	1.13	1.25
N of Moon Langleys	9	11	22	58	7	47	13
Lunar CC μWatt/m^2/nm	0.000437	0.000454	0.000457	0.000435	0.000452	0.000443	0.000447
Lunar CC uncertanty %	2.84	2.21	1.36	1.28	3.61	1.35	1.08
Ccsun/Ccmoon	4305.40	4431.28	4390.19	4406.46	4368.43	4408.43	4383.66
Deviation from 4096 (%)	5.11	8.19	7.18	7.58	6.65	7.63	7.02

Table 2.6

Average calibrations of channel 440 nm.

Instrument	**1027**	**814**	**818**	**837**	**839**	**864**	**867**
N of Sun Langleys	45	76	122	494	89	239	106
Solar CC μWatt/m^2/nm	2.4118	2.3062	2.3840	2.3687	2.3799	2.3630	2.3459
Solar CC uncertanty %	0.79	0.84	9.35	4.85	1.13	1.65	1.17
N of Moon Langleys	8	10	19	56	6	48	12
Lunar CC μWatt/m^2/nm	0.00056	0.000509	0.000539	0.000536	0.000546	0.000533	0.000533
Lunar CC uncertanty %	2.54	5.39	1.93	2.18	3.83	1.84	0.97
Ccsun/Ccmoon	4307.35	4532.61	4424.73	4416.62	4358.40	4431.96	4404.75
Deviation from 4096 (%)	5.16	10.66	8.03	7.83	6.41	8.2	7.54

Table 2.7

Average calibrations of channel 1020 nm InGaAs

Instrument	**837**	**864**
N of Sun Langleys	403	204
Solar CC ɱWatt/m^2/nm	1.0568	1.0719
Solar CC uncertanty %	5	0.82
N of Moon Langleys	5	8
Lunar CC ɱWatt/m^2/nm	0.000242	0.000246
Lunar CC uncertanty %	0.94	0.56
Ccsun/Ccmoon	4373.88	4357.27
Deviation from 4096 (%)	6.78	6.38

The Solar/Lunar calibration ratios in average deviate from the theoretical value of 4096 by several percent. The deviation is around 7% to 8% for shorter wavelengths (<900 nm) and 5 to 6 % for longer wavelengths (1020nm and 1640m). These parameters have their own uncertainties of 1% to 2% for each instrument, which may depend on changing instrument conditions during the years of observations, and also vary from instrument to instrument.

At the moment, we think that the best comparisons are obtained from matching pairs of Sun-Moon Langley sequences.

The sky is normally clear during mornings on Mauna Loa and we would only like to use these Langley sequences. The natural match for them will be pre-dawn Lunar Langley, as the sky clears up at the end of night. The same strict conditions (10.1) and (10.2) were used to select Morning Sun Langley sequences and pre-dawn Moon Langley sequences. We then paired them for each instrument with the requirement that the pre-dawn Moon Langley sequence was immediately followed by Sun morning sequence within 4 hours. The number of these matching pairs is smaller than the total number of all sequences. For each pair, we calculate the ratios CCsun/CCmoon and then averaged only the ratios. Thus, we could eliminate the influence of temporal variations of instrument conditions.

The following wavelength are presented in Tables 3.1 to 3.6:

1640 nm, 870 nm, 675 nm, 440 nm, 500 nm, 1020 InGaAs (we could not get enough matching pairs for 1020 nm Si that satisfies conditions (10.1) and (10.2)).

Table 3.1.

Average ratios of calibrations of 1640 nm for matching pre-dawn Moon Langley and morning Sun Langley.

Instrument	**818**	**837**	**864**	**867**
N of matching Langleys	5	15	18	3
Average Ratio	4288.401	4269.92	4269.008	4308.444
Uncertainty of Ratio(%)	1.61	1.72	2.23	1.78
Deviation from 4096 (%)	4.7	4.25	4.22	5.19

Table 3.2.

Average ratios of calibrations of 870 nm for matching pre-dawn Moon Langley and morning Sun Langley.

Instrument	**818**	**837**	**864**
N of matching Langleys	4	6	12
Average Ratio	4458.14	4455.063	4458.892
Uncertainty of Ratio(%)	0.19	0.36	0.63
Deviation from 4096 (%)	8.84	8.77	8.86

Table 3.3.

Average ratios of calibrations of 675 nm for matching pre-dawn Moon Langley and morning Sun Langley.

Instrument	**1027**	**814**	**818**	**837**	**864**	**867**
N of matching Langleys	5	4	11	23	24	4
Average Ratio	4385.777	4416.649	4449.675	4439.387	4440.252	4437.436
Uncertainty of Ratio(%)	1.9	0.6	0.51	0.75	0.82	0.22
Deviation from 4096 (%)	7.07	7.83	8.63	8.38	8.4	8.34

Table 3.4.

Average ratios of calibrations of 500 nm for matching pre-dawn Moon Langley and morning Sun Langley.

Instrument	**1027**	**814**	**818**	**837**	**864**	**867**
N of matching Langleys	5	5	12	32	28	4
Average Ratio	4337.591	4412.569	4422.246	4417.758	4405.988	4402.215
Uncertainty of Ratio(%)	2.68	1.51	0.62	1.53	1.69	0.43
Deviation from 4096 (%)	5.9	7.73	7.96	7.86	7.57	7.48

Table 3.5.

Average ratios of calibrations of 440 nm for matching pre-dawn Moon Langley and morning Sun Langley.

Instrument	**1027**	**814**	**818**	**837**	**864**	**867**
N of matching Langleys	5	5	12	32	28	4
Average Ratio	4334.613	4425.657	4454.537	4399.137	4409.678	4410.872
Uncertainty of Ratio(%)	2.5	0.93	0.45	2.06	1.84	0.29
Deviation from 4096 (%)	5.83	8.05	8.75	7.4	7.66	7.69

Table 3.6.

Average ratios of calibrations of 1020nm InGaAs for matching pre-dawn Moon Langley and morning Sun Langley.

Instrument	**864**
N of matching Langleys	7
Average Ratio	4363.768
Uncertainty of Ratio(%)	0.58
Deviation from 4096 (%)	6.54

We can see that the averaged ratios derived from matching Langleys have better agreements from instrument to instrument and also smaller uncertainties. We can even call these ratios "Instrument independent".

Out of 7 instruments, 864 appears to be most productive as it appears to be listed in all tables.

In the Table 4.0, we put together results of matching Langleys of only instrument 864 for all its channels:

Table 4.0

Average ratios of calibrations of all channels of instrument 864 for matching pre-dawn Moon Langley and morning Sun Langley.

Channel	**1640nm**	**870nm**	**675nm**	**440nm**	**500nm**	**1020nm InGaAs**
N of matching Langleys	18	12	24	28	28	7
Average Ratio	4269.0077	4458.892	4440.252	4409.678	4405.988	4363.768368
Uncertainty of Ratio(%)	2.23	0.63	0.82	1.84	1.69	0.58
Deviation from 4096 (%)	4.22	8.86	8.4	7.66	7.57	6.54

1020nm channel is not available in that comparison. It is available only if we compare average calibrations without requirement time correlation. In Table 4.1 we put together results of comparison of average results from instrument 864 for all channels.

Table 4.1.

Average calibrations of all channels of instrument 864

Channel	**1020nm**	**1640nm**	**870nm**	**675nm**	**440nm**	**500nm**	**1020nm**
N of Sun Langleys	16	207	214	226	239	232	20
Solar CC μWatt/m^2/nm	1.3404	0.2053	1.1570	1.4719	2.3630	1.9546	1.07
Solar CC uncertanty %	0.49	0.86	0.81	0.82	1.65	1.13	0.8
N of Moon Langleys	4	35	21	44	48	47	8
Lunar CC μWatt/m^2/nm	0.000312	0.000048	0.000258	0.000332	0.000533	0.000443	0.000
Lunar CC uncertanty %	0.47	2.9	0.81	0.9	1.84	1.35	0.5
Ccsun/Ccmoon	4297.93	4321.00	4475.93	4437.65	4431.96	4408.43	4357
Deviation from 4096 (%)	4.93	5.49	9.28	8.34	8.2	7.63	6.3

In the following table 4.2 we averaged all 7 instrument results for matching Langleys.

Table 4.2

Average ratios of calibrations of all channels of all instrument for matching pre-dawn Moon Langley and morning Sun Langley on Mauna Loa.

Channel	1640	870	675	440	500	1020In
N of matching Langleys	42	26	71	86	86	11
Average Ratio	4276	4457	4436	4409	4409	4368
Uncertainty of Ratio(%)	1.9	0.5	0.9	1.8	1.6	0.6
Deviation from 4096 (%)	4.4	8.8	8.3	7.6	7.6	6.6

We tried to apply the same technique to the measurements in Izana, using conditions (10.1) and (10.2). Instruments 790, 914, 915 and 933 were making Lunar measurements on Izana during 2015–2017 years.

Table 4.3

Average ratios of calibrations of all channels of all instruments for matching pre-dawn Moon Langley and morning Sun Langley on Izana.

Channel	1020	1640	870	675	440	500	1020In
N of matching Langleys	11	18	18	23	24	24	6
Average Ratio	4299	4292	4458	4448	4437	4431	4397
Uncertainty of Ratio(%)	0.9	2.3	0.6	1.1	2.0	1.8	0.5
Deviation from 4096 (%)	5.0	4.8	8.8	8.6	8.3	8.2	7.3

Then results are very similar. Izana also give us 1020 Si channel.

In the following table we combined the results from Izana and Mauna Loa.

Table 4.4

Average ratios of calibrations of all channels of all instruments for matching pre-dawn Moon Langley and morning Sun Langley on Izana and Mauna Loa.

Channel	1020	1640	870	675	440	500	1020In
N of matching Langleys	11	60	44	94	110	110	17
Average Ratio	4299	4281	4457	4439	4415	4414	4378
Uncertainty of Ratio(%)	0.9	2.0	0.5	0.9	1.9	1.6	0.6
Deviation from 4096 (%)	5.0	4.5	8.8	8.4	7.8	7.8	6.9

Conclusion

A consistent bias is determined between Langley plot calibration results from Solar and Lunar measurements.

The cause of the bias is not known at the moment of this writing.

The observed bias is consistent on two mountain top sites , 11 different instruments, and 3 years of observations.

Such consistency makes possible using method (2) of lunar calibration: transfer of solar calibration.

From expression (9) and the Table 4.4 the following can be derived:

$$C^l = \frac{C^s}{4096 \cdot (1+\delta)} \qquad (11)$$

Where δ is a bias from Table 4.4:

Table 5.

Bias used in the Solar – Lunar calibration transfer.

Channel	δ
1020Si	0.049
1640	0.055
870	0.093
675	0.083
440	0.082
500	0.076
1020In	0.064

The method is currently implemented in the AERONET Version 3. nighttime AOD are being retrieved and are planned to be part of the upcoming Version 3 release (Giles et al., 2019).

References:

Barreto, A., Cuevas, E., Damiri, B., Guirado, C., Berkoff, T.,Berjón, A. J., Hernández, Y., Almansa, F., and Gil, M.: Anew method for nocturnal aerosol measurements with a lunar photometer prototype, Atmos. Meas. Tech., 6, 585–598,https://doi.org/10.5194/amt-6-585-2013, 2013.

Barreto, Á., Cuevas, E., Granados-Muñoz, M.-J., Alados-Arboledas, L., Romero, P. M.,Gröbner, J., Kouremeti, N., Almansa, A. F., Stone, T., Toledano, C., Román, R., Sorokin, M.,Holben, B., Canini, M., and Yela, M.: The new sun-sky-lunar Cimel CE318-T multiband photometer – a comprehensive performance evaluation, Atmos. Meas. Tech., 9, 631-654, https://doi.org/10.5194/amt-9-631-2016, 2016.

Berkoff, T.A., Sorokin, M., Stone, T., Eck, T.F., Hoff, R., Welton, E., and Holben, B.: NocturnalAerosol Optical Depth Measurements with a Small-Aperture Automated Photometer Using the Moon as a Light Source. J. Atmos. Ocean. Tech., 28, 1297–1306, https://doi.org/10.1175/JTECH-D-10-05036.1, 2011.

Coddington, O., Lean, O. J., Pilewskie, P., Snow, M., and Lind-holm, D.: A solar irradiance climate data record, B. Am. Mete-orol. Soc., 97, 1265–1282, https://doi.org/10.1175/BAMS-D-14-00265.1, 2016.

Giles, D. M., Sinyuk, A., Sorokin, M. G., Schafer, J. S., Smirnov, A., Slutsker, I., Eck, T. F.,Holben, B. N., Lewis, J. R., Campbell, J. R., Welton, E. J., Korkin, S. V., and Lyapustin, A. I.: Advancements in the Aerosol Robotic Network (AERONET) Version 3 database – automated near-real-time quality control algorithm with improved cloud screening for Sun photometer aerosol optical depth (AOD) measurements, Atmos. Meas. Tech., 12, 169-209, https://doi.org/10.5194/amt-12-169-2019, 2019.

Kieffer, H. H. and Stone, T. C.: The spectral irradiance of the moon,Astron. J., 129, 2887–2901, 2005.

Zhengqiang Li, Kaitao Li, Donghui Li, Jiuchun Yang, Hua Xu, Philippe Goloub, Simple transfer calibration method for a Cimel Sun-Moon photometer: calculating lunar calibration coefficients from Sun calibration constants. Appl.Opt. 55, 7624-7630 (2016).