COST short term scientific mission report

Implementation of a method for retrieving lunar AOD in different European Skynet Radiometers (ESR) network sites

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Introduction

Sun/sky radiometers have been long used to retrieve the aerosol optical properties during day time, using the sun as a radiation source. However, aerosol properties could not be retrieved during night time. This creates gaps in the data series, specially, in polar regions. This also put a limitation on our understanding on daily variation of aerosols and its dynamics at night time.

The only solution to this limitation is taking measurement during night time. For example, Barreto et al (2013) proposed methods to perform calibration and to retrieve the aerosol optical properties using CIMEL CE318 sun/sky photometers. (Uchiyama et al., 2019) proposed other methods to calibrate and retrieve aerosol optical properties using PREDE POM radiometers. In both cases, the moon is used as a radiation source. Alternative methods use stars' brightness and their extinction in the atmosphere to derive the same optical properties.

Moon is not a strong source of light unlike the Sun. Although it is better to say, Sun is still our primary source of light. Moon is acting as a stable diffuser for solar irradiance (Barreto et al., 2013; Kieffer & Stone 2005.). Due to this, the reflectance of moon is a strong function of lunar phase angle its surface properties, which is filled with light coloured anorthosite (highlands) and dark coloured basaltic rocks (mare). This causes non-uniform reflectance. Apart from this, moon changes its phase during its cycle of 28 days where it goes from full moon to no moon to again full moon. Due to this the brightness of the moon changes continuously during this period (A. Barreto et al., 2013). This puts a challenge to get a correct calibration value. Since the phase of the moon changes every day, we cannot use the absolute Langley method as it is commonly used in solar radiometry (A. Barreto et al., 2013). In order to get the calibration value for the lunar sky radiometers, the Langley method is modified by including the data from the ROLO lunar model (Kieffer & Stone 2005).

Following the work done by (A. Barreto et al., 2013), AERONET is taking the measurement during night time using its Lunar photometers. The results are available on the website of AERONET (https://aeronet.gsfc.nasa.gov/cgi-bin/draw_map_display_aod_v3_lunar). However, the measurements are available only for few measurement sites and It is still in provisional phase. In order to understand the dynamics of aerosols during night time, it is important to get the night time measurements by other major sky radiometer networks. SKYNET is such a major network which is spread all around the world with more than 100 instruments. With recent work of (Uchiyama et al., 2019)), It is now possible to implement the network of lunar observation.

This report summarises the work done during the STSM at University of Sapienza, Rome to achieve its defined goal to 1) Implement the algorithm developed by (Uchiyama et al., 2019) to get the retrieval using data from Lunar PREDE on the server of CNR, 2) Learn to run the ILP method to get the calibration value.

Instrumentation

SKYNET uses two different type of radiometers which is POM-01 and POM-02. Both are filter wheel radiometers. Pom-01 works in seven wavelengths ranging from of 340-1020 nm while POM-02 works in eleven wavelength bands ranges from 315-2200 nm. Originally these two instruments are designed for solar measurements. Moon is a weak source of light and the signals on full moon day are 10^{-6} times smaller than the direct solar irradiance. In order to work with such small value of current, POM-02 is modified. Modified lunar photometer have meaningful current of the order of 10^{-13} A. Apart from this, all the hardware components like sensors and collimeter is same as used in Solar photometry, the field of view of the instrument remains same as that of used during daytime measurement.

ROLO

ROLO stands for Robotics Lunar Observatory is an empirical lunar model discussed in (Kieffer & Stone, 2005.). The main motivation behind the creation of this model was to calibrate the Earth orbiting satellites using the Moon as source of light.

Under the ROLO program, Kieffer and Stone, 2005 collected the lunar data for more than 6 years. they took more than 85,000 images in 32 wavelengths ranging from 350-2450 nm of the Lunar surface. Apart from this they also used 190 standard stars as a reference to determine the atmospheric extinction and instrument absolute response. An empirical relationship was derived between the Lunar reflectance and geometric variables.

$$lnA_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=0}^{3} b_{jk} \Phi^{2j-1} + c_1\theta + c_2\Phi + c_3\theta\Phi + c_4\Phi\phi + d_{1k}e^{-g/p1} + d_{2k}e^{-g/p2} + d_{3k}\cos[(g-p3)/p4] \quad -1$$

Where, A_k is the disk equivalence reflectance, g is the absolute phase angle, θ and ϕ are the selenographic latitude and longitude of the observer, Φ is the selenographic longitude of the sun.

They used this empirical equation to fit the ROLO observations. The average residual in the fitting was less than 1%.

SPICE

In order to use the ROLO irradiance model, the algorithm developed by (Uchiyama et al., 2019) (TEST003_ROLO_MRI_byAU_new.for) is used. The algorithm uses the SPICE toolkit to access the ROLO model. SPICE is a toolkit developed by NASA. It is used to obtain the astronomical parameters.

The toolkit needs to be downloaded, extracted and compiled in the suitable folder. It is freely available on the NASA's NAIF (The National Ancillary information Facility) (https://naif.jpl.nasa.gov/naif/toolkit.html).

In present work, SPICE toolkit for the FORTRAN, PC, Linux, Intel FORTRAN (IFORT), 64bit was downloaded and extracted on the server of CNR. Following the commands from the readme file, the spice toolkit was compiled.

Apart from this, kernels are also required to be downloaded to run the script (TEST003_ROLO_MRI_byAU_new.for).

The kernels are downloaded from (https://naif.jpl.nasa.gov/naif/data_generic.html). A met kernel file (metakernel.tm) was created to load the required kernels. The example file is shown below which contains required kernel.

```
“\begindata

KERNELS_TO_LOAD = (
 '/home/gaurav/Lunar/moon/generic_kernels/naif0011.tls.pc',
 '/home/gaurav/Lunar/moon/generic_kernels/pck00010.tpc',
 '/home/gaurav/Lunar/moon/generic_kernels/earth_fixed.tf',
 '/home/gaurav/Lunar/moon/generic_kernels/earth_070425_370426_predict.bpc',
 '/home/gaurav/Lunar/moon/generic_kernels/moon_assoc_me.tf',
 '/home/gaurav/Lunar/moon/generic_kernels/moon_assoc_pa.tf',
 '/home/gaurav/Lunar/moon/generic_kernels/moon_080317.tf',
 '/home/gaurav/Lunar/moon/generic_kernels/moon_pa_de421_1900-2050.bpc',
 '/home/gaurav/Lunar/moon/generic_kernels/de430.bsp' )
```

\begintext”

Lunar disk reflectance

“TEST003_ROLO_MRI_byAU_new.for” is a FORTRAN script used to get the ROLO reflectance file. This script is provided by Dr Uchiyama. It provides the ROLO reflectance for every minute. It can provide the ROLO reflectance data for maximum of one month. Input data required to run this script are date, time, location (latitude, longitude and Altitude) and time difference. Earlier these data are written directly into the script. To run the script daily, we had to make changes in the script daily. In order to avoid the problem, Modifications are made in the script. In the modified script, now the location is taken from dsform.par which is an input file for Sunrad.

Calibration

Calibration is the first and most important step towards determining the columnar property. Standard Langley and Improved Langley method is used to determine the calibration value in AERONET and SKYNET. In case of lunar observation, It is difficult to make the Lunar Langley because Moon changes its phase every day and the frequency of observation is less. To overcome this problem, (Uchiyama et al., 2019) sent his instrument to Mauna loa observatory and made Lunar Langley using 3 month of dataset to find moon calibration (V_m). They fitted the ratio (V_m/V_s) of moon and sun calibration with phase angle of the moon. They found a parabolic relation given as: -

$$V_m = V_s(A_c.g^2 + B_c) \qquad -2$$

$$C = \frac{V_m}{V_s} \qquad -3$$

Since the ratio of moon and sun calibration depends on the phase angle of the moon, It is independent of the instrument. It means it can be applied for any Sky radiometer given that it uses the same sensor to observe sun and the moon. This relation was used to get the calibration value of the lunar sky radiometer.

Dsform module

Dsform module is the part of Sunrad which is used to process the direct solar irradiance and get columnar aerosol properties. The main function of the dtform module is to create the triplets of the measurements within one minute. Before making the triplets, few modifications are done in the algorithms which are as follows.

Subroutine DTINPUT_ROLO is added to read the ROLO reflectance, phase angle, distance between the sun and the moon, distance between the moon and the observer, optical airmass.

These values are then interpolated for the observation time using subroutine using DLHOKAN.

Both DLHOKAN and DTINPUT_ROLO are provided by Dr Uchiyama.

In the original Sunrad, the raw observation data is grouped into triplet without performing any operation on the raw dataset. In case of modified Sunrad, there are few operations done before creating the triplets. The operations are described below.

Observed raw signal $V(\lambda_0)$ can be written as (Uchiyama et al., 2019)

$$V(\lambda_0) = \frac{\mathrm{C}A_{ROLO}}{\pi} \Omega_M \frac{V_{S0}(\lambda_0)}{R_S^2} \frac{1}{R_m^2}$$

$$\exp(-m(\theta)\tau(\lambda_0)) T_{gas}(\lambda_0, \theta) \qquad -4$$

where $F_C.C' = C$

A_{ROLO} is ROLO reflectance

C' is the constant of proportionality for error in ROLO model (Á. Barreto et al., 2016) and F_c is the smoothing constant for ROLO reflectance.

R_s is distance between sun and moon in astronomical units,

R_m is the distance between moon and the observer (normalized by 384400 km),

$V_{S0}(\lambda_0)$ is the calibration value obtained from direct sun measurements,

T_{gas} is the transmittance due to gas absorption.

m is the air mass

τ is the aerosol optical depth.

Since, Sunrad is used for the processing the lunar data, It is better to do minimum modification in the existing algorithm to avoid errors. To avoid modification in the dsproc module which is used after running dsform module, Equation 3 is manipulated to resemble the equation used in case of solar irradiance.

$$V(\lambda_0) = \frac{V_{S0}(\lambda_0)}{R_S^2} \exp(-m(\theta)\tau(\lambda_0)) T_{gas}(\lambda_0, \theta) \qquad -5$$

Equation 4 is used for calculations in case of solar irradiance.

Comparing equation 3 and 4, $\frac{CA_{ROLO}}{\pi} \Omega_M \frac{1}{R_m^2}$ is the extra term

Replacing C from equation3 and manipulating equation 5, we get,

$$\frac{V(\lambda\_0)\pi R_S^2 R_m^2}{\Omega_M \mathrm{C}A_{ROLO}} = V_{S0}(\lambda_0) \exp(-m(\theta)\tau(\lambda_0)) T_{gas}(\lambda_0, \theta) \qquad -6$$

Further equation 6 can be rewritten as

$$V'(\lambda_0) = V_{S0}(\lambda_0) \exp(-m(\theta)\tau(\lambda_0)) T_{gas}(\lambda_0, \theta) \qquad -7$$

$$V'(\lambda_0) = \frac{V(\lambda_0)\pi R_S^2 R_m^2}{\Omega_M C A_{ROLO}} \qquad -8$$

Equation 7 resembles equation 5 except R_S^2 but R_S^2 is used to take care of variation of distance between the Sun and the Earth. It is already taken care in equation 7.

Modified raw signal $V'(\lambda_0)$ from equation 7 is used to create triplet using modified dsform.

On compiling and running the modified dsform we get output file which contains triplet of lunar observation and optical airmass. Further, these triplets are used to do cloud screening in the dsproc module following the cloud screening criteria given by (Smirnov et al., 2000).

Dsproc module

Dsproc module is used to calculate the columnar properties of aerosol such as AOD and angstrom exponent. It uses the output file of dsform module as an input file and uses triplet to calculate the columnar properties and uses triplets to do cloud screening. The dsproc module remains almost unchanged. Two modifications are done in the dsproc modul

1. Reading the optical airmass values from the input file (output from dsform module).
2. Two outputs are obtained after compiling and running the dsproc module. First output is cloud screened data and other output is the non-cloud screened data.

Other modifications

Upon visual inspection of the raw lunar data from the sky radiometer, It was found that the file near the full moon missed header lines. It caused error in the algorithm. To avoid the error, a script was made to read the raw data files before running dsform and rewrite the header lines in the data files.

Once everything started to run without any error, a shell script was made to compile and run all the algorithm at once. Finally, using cron the shell script was scheduled and put on the ESR server to run every day.

Results

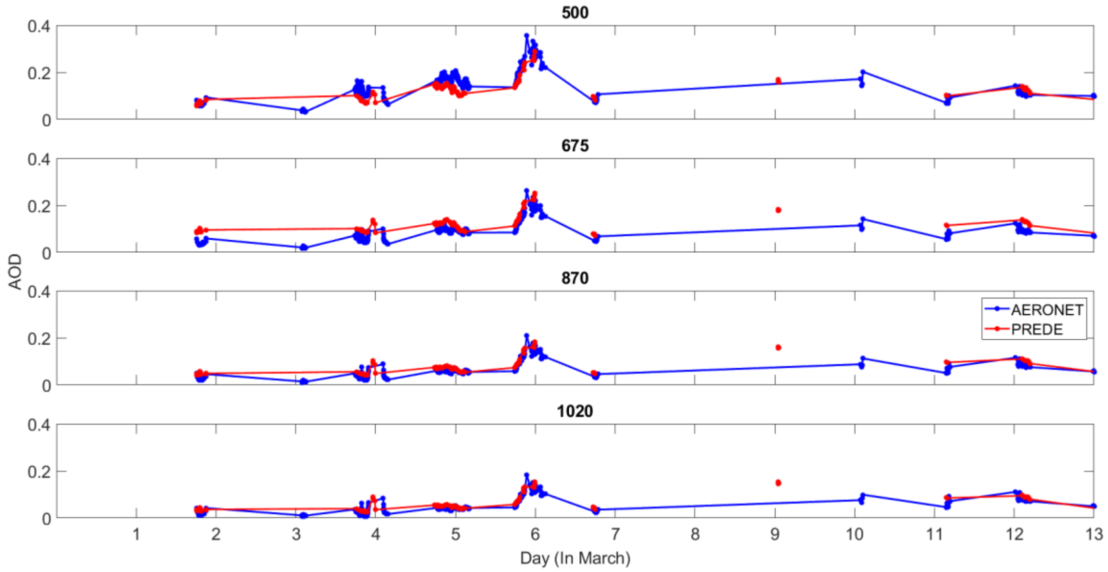

Figure 1 Comparison of Lunar measurements between PREDE (at Sapienza) and AERONET (at Tor Vergata)

AERONET data for Tor Vergata site was downloaded from the AERONET website for March 2023. It was then compared with the PREDE data obtained by running modified Sunrad for Sapienza. Although Tor Vergata is ~20 km away from Sapienza but both instruments were not collocated at one place. Since 20 km is not a large distance and there should not be much difference between the columnar AOD at two sites.

Figure 1 shows the comparison of cloud screened lunar AERONET with cloud screened PREDE data obtained using modified Sunrad. From figure 1 we can see that the comparison is very good and It validates that the modified Sunrad along with other scripts are working properly.

ILP

Improved Langley plot is an alternative method to calculate the calibration value using sky radiometer. It uses the radiance data with scattering angle less than 30 degrees ands greater than 3 degrees. Unlike Standard Langley which requires pristine environment in high altitude, Improved Langley can be done at any site given that scattering angles remains in the range of [3,30] (in degrees).

The scattering angle is chosen because there is no significant dependence of ground albedo and refractive index on radiance. For scattering angle > 30 degree, Radiance data is highly dependent on refractive index and surface albedo (Campanelli et al., 2004).

In the present report, I learnt how to run the scripts in order to get the ILP calibration.

Following steps are followed in order to successfully run the ILP and get calibration value.

1. Dtform and sproc modules are compiled and run to get the output which consist of AOD, airmass and error.
2. Data is screened for the condition of AOD<0.4, ERROR<0.07, AIRMASS<0.3
3. Screened points are used to get a linear fit.

4.

   a. Chouvent criteria at 5 points is applied considering standard deviation<=2.0
   b. 3 point moving average is performed
   c. Monthly average of remaining point is done to get monthly mean values of calibration.

Below is the table of ILP monthly mean calibration value obtained for Valencia site from October 2022 to May 2023.

Year	Month	340	400	500	675	870	1020
2022	10	1.162E-06	7.610E-05	2.565E-04	3.841E-04	2.287E-04	1.081E-04
2022	11	1.231E-06	7.800E-05	-9.990E+02	3.873E-04	2.320E-04	1.081E-04
2023	1	1.239E-06	8.019E-05	2.633E-04	3.875E-04	2.321E-04	1.060E-04
2023	2	1.187E-06	7.791E-05	2.588E-04	3.853E-04	2.307E-04	1.069E-04
2023	3	1.157E-06	7.622E-05	2.552E-04	3.807E-04	2.282E-04	1.065E-04
2023	4	1.148E-06	7.661E-05	2.570E-04	3.837E-04	2.282E-04	1.065E-04
2023	5	1.118E-06	7.565E-05	2.556E-04	3.822E-04	2.274E-04	1.071E-04

Conclusion

The goal of the STSM was to implement the algorithm on the server of CNR and learn the ILP method to get the calibration value.

During the STSM both the goals are completed as promised in the workplan. The algorithm is successfully implemented on the server of CNR. We run the algorithm for March 2023 and compared it with the AERONET retrieval at Tor vergata. Although PREDE was installed at Sapienza university while CIMEL was installed at Tor vergata but there was no other site with both instruments installed together. Since the distance between two places is not more than 20 km, the difference in AOD at both the site should not be significant. From our preliminary analysis of the data, the results were very good and promising.

The cloud screening was found to be over safe and deleted many points. However, it was working correctly.

Second objective of the STSM was also completed. It was knowledge transfer to learn the ILP method and successfully calculate the calibration value. After understanding the script, I was able to run the ILP script successfully. I run the ILP for Valencia site from October 2022 to May 2023. I was able to calculate the calibration values successfully.

Future work

- Updating the cloud screening algorithm- Currently the same cloud screening algorithm is used which is used in the Sunrad to perform cloud screening in the direct sun data product. Although it is working well, It seems to be over safe. It removed a lot of points. More research work is required to optimize the cloud screening algorithm.

- Validation of calibration values- The current calibration values are good and gives correct AOD values (as compared to AERONET). However, the coefficients used to calculate values are taken from uchiyama et al 2019. The coefficients seem to be independent from the instrument but its validation is required by making Lunar Langley from our own instrument. In future, a campaign is required to send the instrument at high altitude site (preferably Izana) to accomplish this work.
- Currently, the products obtained from the algorithm is provisional and a comprehensive research is require including validation of calibration value and comparison of aerosol products across various network and publish a research paper to make it a standard product and use it for other research purposes.
- Currently, ILP method is using Skyrad 4.2. It needs to be updated to Skyrad 5/MRI. Apart from this some sensitivity tests are also required to conduct in order to understand the problem with underestimation of ILP calibration values as compared to standard Langley.

References

Barreto, A., Cuevas, E., Damiri, B., Guirado, C., Berkoff, T., Berjón, A. J., Hernández, Y., Almansa, F., & Gil, M. (2013). A new method for nocturnal aerosol measurements with a lunar photometer prototype. *Atmospheric Measurement Techniques*, *6*(3), 585–598. https://doi.org/10.5194/amt-6-585-2013

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., & Yela, M. (2016). The new sun-sky-lunar Cimel CE318-T multiband photometer – A comprehensive performance evaluation. *Atmospheric Measurement Techniques*, *9*(2), 631–654. https://doi.org/10.5194/amt-9-631-2016

Campanelli, M., Nakajima, T., & Olivieri, B. (2004). Determination of the solar calibration constant for a sun-sky radiometer: proposal of an in-situ procedure. *Appl. Opt.*, *43*(3), 651–659. https://doi.org/10.1364/AO.43.000651

Kieffer, H. H., & Stone, T. C. (n.d.). *THE SPECTRAL IRRADIANCE OF THE MOON*. http://aa.usno.navy.mil

Smirnov, A., Holben, B. N., Eck, T. F., Dubovik, O., & Slutsker, I. (2000). Cloud-Screening and Quality Control Algorithms for the AERONET Database. *Remote Sensing of Environment*, *73*(3), 337–349. https://doi.org/https://doi.org/10.1016/S0034-4257(00)00109-7

Uchiyama, A., Shiobara, M., Kobayashi, H., Matsunaga, T., Yamazaki, A., Inei, K., Kawai, K., & Watanabe, Y. (2019). Nocturnal aerosol optical depth measurements with modified sky radiometer POM-02 using the moon as a light source. *Atmospheric Measurement Techniques*, *12*(12), 6465–6488. https://doi.org/10.5194/amt-12-6465-2019