Nighttime Aerosol Optical Depth Measurements in the Arctic; Development of a Lunar Photometer for use in Barrow, Alaska

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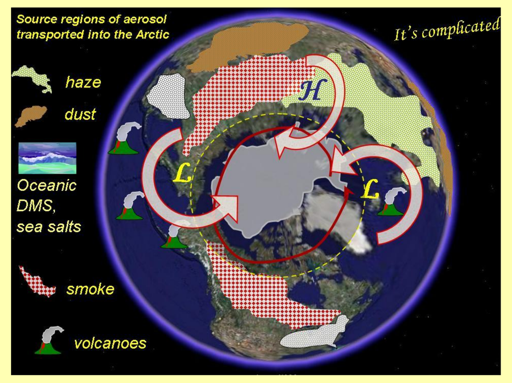
Introduction

The Arctic climate is influenced by incursions of aerosols from lower latitudes (*right*). Arctic aerosols are highly variable over space and time [*Stone et al*., 2013]. Sun photometers have been used to derive values of spectral aerosol optical depth *AOD(λ)* in order to characterize atmospheric composition and assess climate impacts.

A cost-effective means to measure AOD during Arctic winter is needed to better characterize the aerosol and quantify their impact on the surface radiation budget.



(*above*) Long-range transport of pollutants and natural aerosols influence the Arctic climate.

(*below*) Aerosols commonly observed in the Arctic.

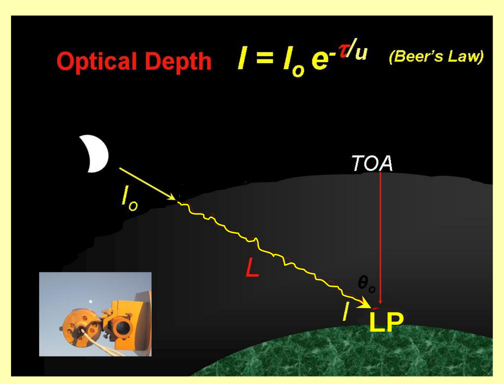
Objective

To develop a lunar photometer for Arctic deployment and show the feasibility of monitoring AOD during periods of darkness.

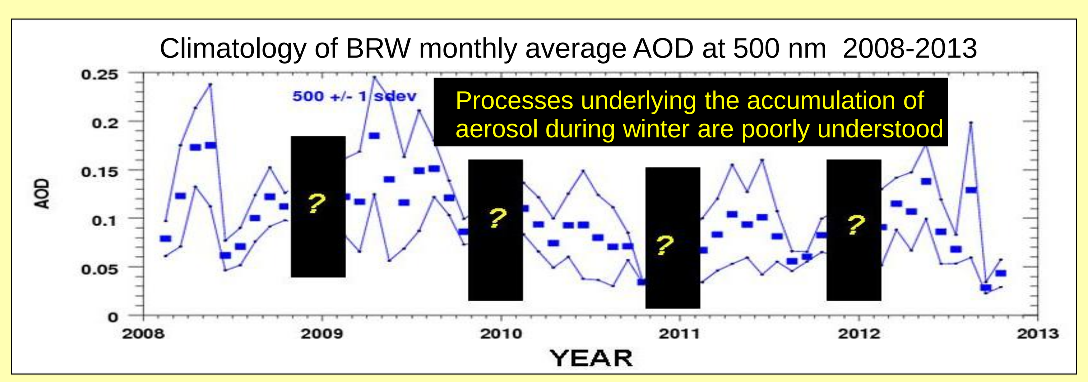
Aerosol Optical Depth (AOD)

AOD quantifies the attenuation of light passing through the atmosphere. Spectral measurements are used to identify different types of aerosol (*right*).

AOD is derived from moonlight in the same way as for sunlight, by inverting Beer's Law.



Moonlight of intensity *Io* is attenuated along the path *L*, measured as *I* by the lunar photometer LP.



The climatology of AOD at high latitudes is incomplete, illustrated above for BRW (at 500 nm). Using lunar observations, gaps in the time series will be filled and transport and climate impacts can be better understood.

The NOAA/CIRES prototype lunar photometer

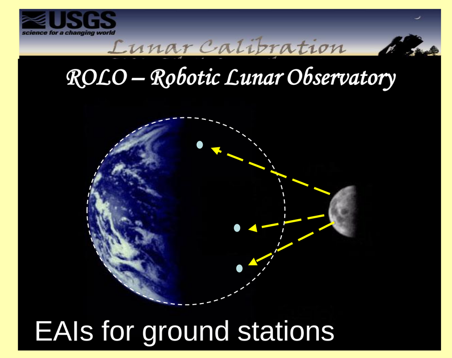
- modified Carter-Scott SP02 Sun photometer
- 4 wavelengths at 425, 500, 675 and 862 nm
- thermally stabilized and insulated
- re-programmed solar tracker to track Moon
- paired with a webcam to capture lunar images
- one-minute data is logged using a Campbell CR10X
- fabricated and tested at NOAA/GMD - Boulder, CO
- calibrated at Mauna Loa Observatory (MLO), HI
- re deployed to Barrow, AK; November 2012
- cost-effective and easily deployed in the network

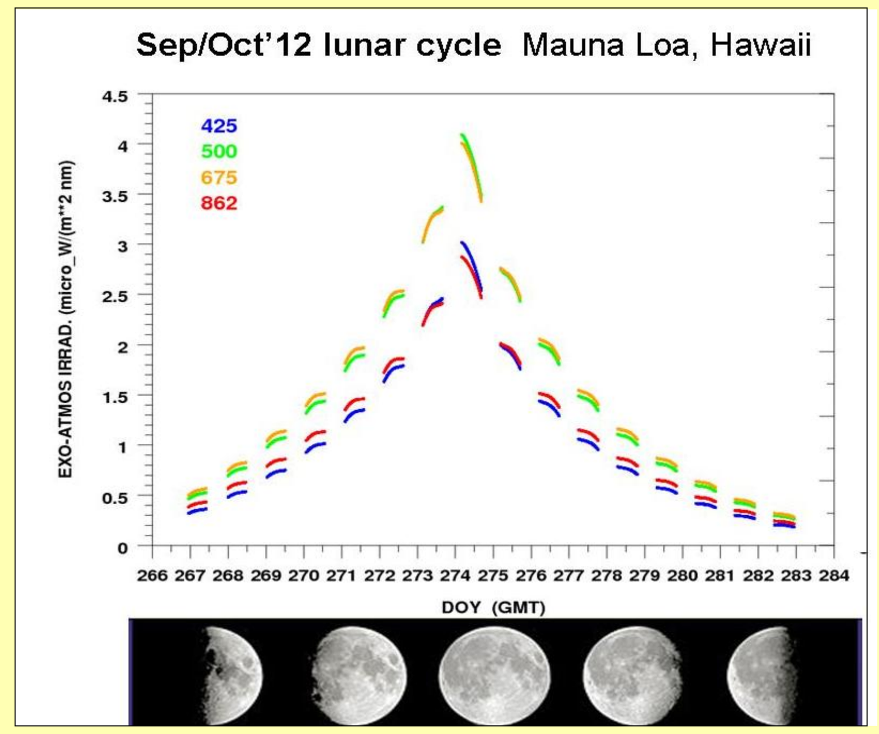
Expectations

- fill gaps in the BRW AOD climatology; characterize aerosols during winter
- provide nighttime data to validate satellite and Lidar retrievals of AOD
- verify climate model simulations of aerosol transport and radiative forcing

Advances in Lunar Photometry

Previously, researchers abandoned lunar measurements in favor of Star photometry because of the uncertainty in determining exo-atmospheric lunar irradiance (EAI) [*Herber et al*. 2002]. Today, high-precision EAIs are available through the USGS ROLO project (*right*) [*Keiffer and Stone*, 2005]. EAIs are essential for determining equivalent, top-of-atmosphere photometer voltages V_o (*example below*).





ROLO output for the Sep/Oct 2012 lunar cycle at MLO showing nightly EAIs for the four channels of the NOAA/CIRES prototype lunar photometer.

Approach; data analysis

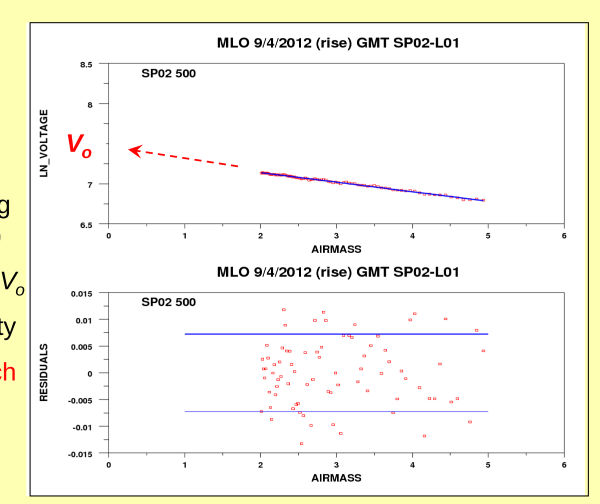
- convolve raw photometric data with corresponding ROLO output
- calibrate, using a modified Langley Plot Method (*see below*)
- apply calibrations to scale raw data and invert Beer's Law
- compute AOD, correcting for varying airmass, Rayleigh scattering and gaseous absorption
- analyze time series; conduct climate studies, validations ….

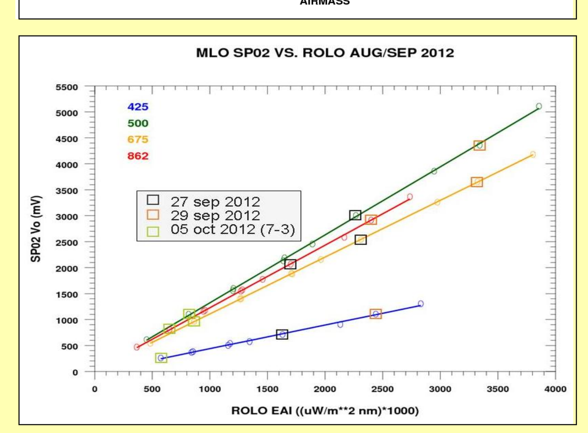
Calibration procedure

The key to successful photometry lies in routine calibration. Here, a modified Langley Plot Method is employed. The prototype was calibrated at MLO (*elev.* 3397 m) during two successive lunar cycles, Aug.- Oct. 2012.

Modified Langley Plot Method (*right*)

- one-min raw photometer voltages (*V*) are recorded
- voltages are normalized to account for the varying EAI of the Moon using ROLO output (*above*)
- *ln(V)*, plotted as a function of airmass, is fitted using linear regression typically in the range 5-2 (*blue line*)
- the fit is extrapolated to zero airmass to determine V_o
- evaluation of residuals are used to determine quality
- **NOTE**; each night's V_o will vary with phase and each cycle from the previous one (*illustrated below, right*)

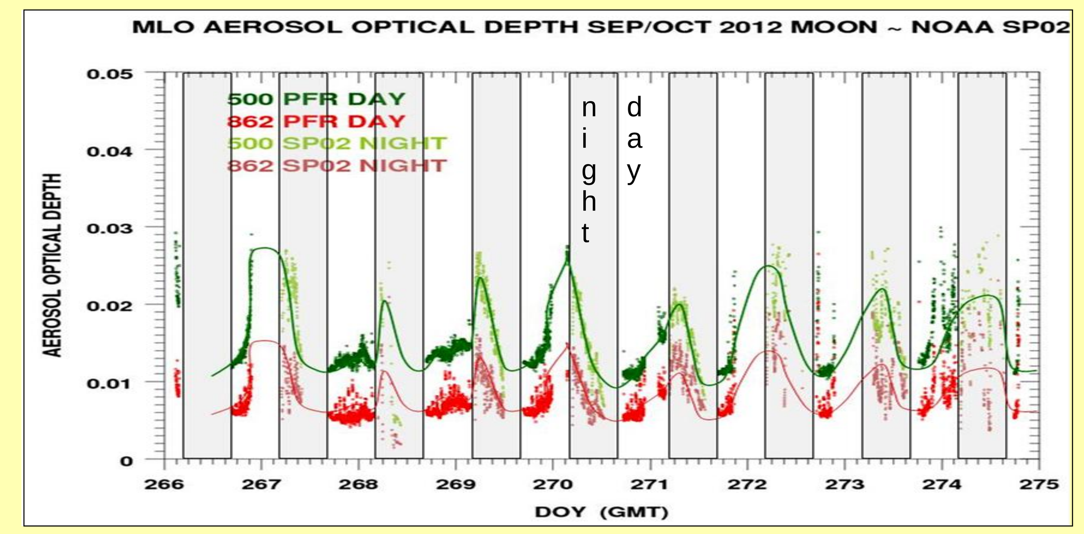




(*right*) Langley analyses at MLO show the stability of the photometer over two lunar cycles. Empirical relationships are then used to compute AOD(λ) by inverting Beer's Law.

First Results; nighttime AOD time series at MLO

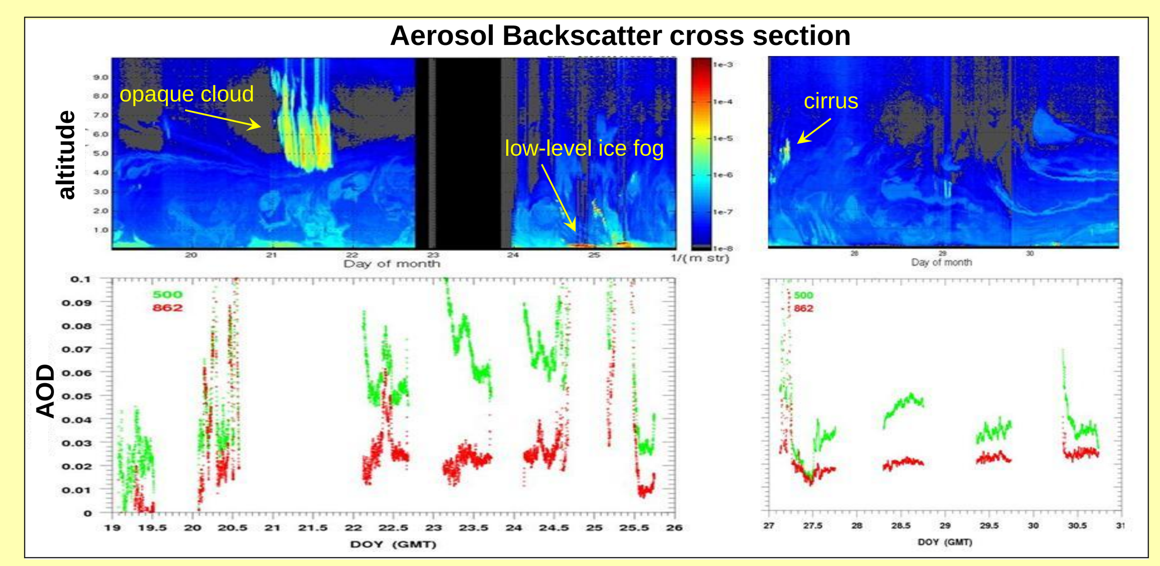
The lunar photometer calibrations compared well with those derived from three other systems operating during the MLO campaign, for which corresponding Langley slopes agreed to within 0.001 OD units (*not shown*). Night-day AOD time series were generated by merging results from a precision filter radiometer (PFR) (*below*).



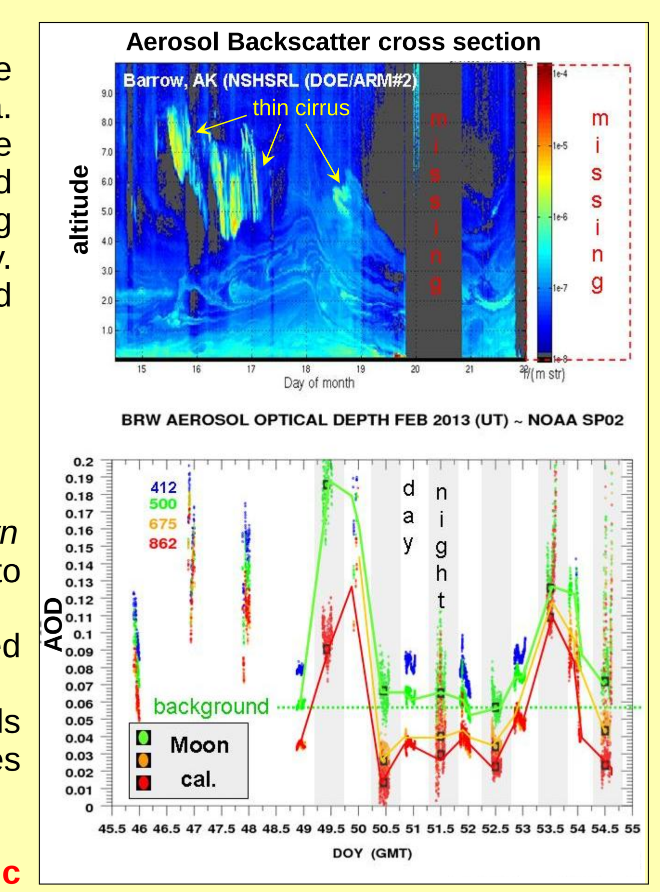
Time series of AOD at 500 and 862 nm obtained at MLO, 22-30 September, 2012. Note the diurnal cycle, wherein AOD increases evenings due to upslope flow that lofts aerosol from the boundary layer. Data are sampled each minute when clear.

Results during winter at Barrow, AK

During winter 2012/2013 the lunar prototype was operated at BRW, during which time a high spectral resolution Lidar operated nearby. The DoE NSHSRL resolves layers of aerosol and thin cloud by measuring backscattered light; *combined time series are shown below*.



At BRW, Langley calibrations were applied to each night's raw data. Shown *above* and to the *right* are time series of coincident spectral AOD and Lidar cross-sections for periods during Jan. and Feb. 2013, respectively. Daytime data in late Feb. are derived from the BRW SP02 Sun photometer.



System Evaluation

- night 425 nm data too noisy; *not shown*
- thermal control needs improvement to stabilize 'zero-offsets' (dark signals)
- good accuracy (± 0.005) is achieved when applying nightly calibrations
- continuity of day/night AOD retrievals was attained, consistent with features seen in the Lidar cross-sections

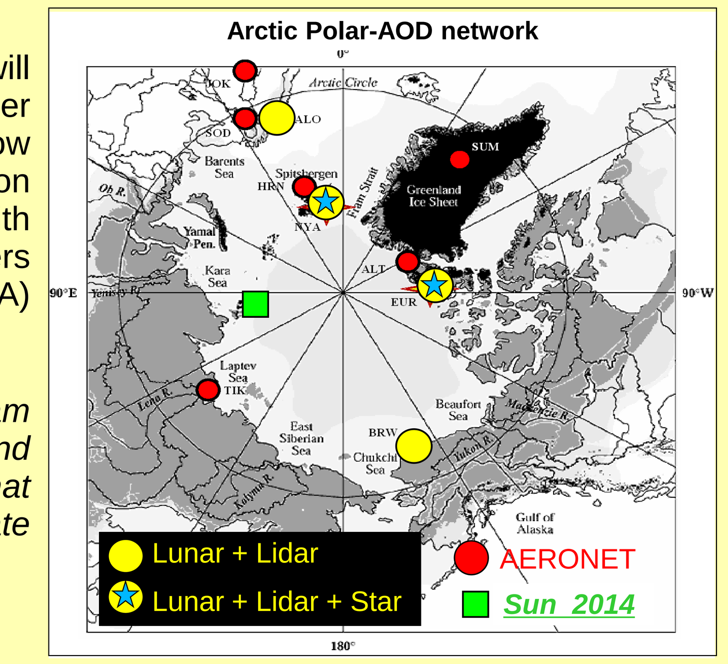
➢ **AOD retrievals during the Arctic night are limited to ≤ 40% of the time**

Berkoff et al. (2011) and *Barreto et al*. (2013) demonstrated similar success in retrieving AOD at night at lower latitudes using modified Cimel Sun photometers.

The way forward

In the near future, lunar photometers will be operated during the winter at other Polar-AOD+ network sites (*right*). Yellow circles indicate stations where Moon observations will be made coincident with Lidar measurements. Star photometers are also operated at Ny-Alesund (NYA) and at Eureka (EUR).

+*The objectives of the Polar-AOD Program are to characterize aerosol properties and gain an understanding of factors that control their distribution and climate impacts*



Research Opportunities

There are many uses of nighttime AOD retrievals related to Arctic research:

- fill gaps in AOD climatologies
- characterize spectral signatures of winter aerosols; resolve type and size
- improve understanding of aerosol transport during winter
- identify links between aerosol burden and deposition of black carbon
- evaluate longwave radiative forcing by aerosols
- improve understanding of cloud-aerosol interactions during winter
- validate and improve AOD retrievals from satellite and Lidar measurements
- verify regional climate models' treatment of aerosol transport/forcing

Summary & Conclusions

- Sun photometers are being modified to enable nighttime measurements of AOD using reflected moonlight; Beer's Law applies
- retrievals rely on the availability of site- and instrument-specific exo-atmospheric lunar irradiance data; e.g., ROLO output
- retrievals are currently possible only during the bright half of the lunar cycle
- results from the 2012/2013 BRW campaign demonstrated the feasibility of monitoring AOD during the Arctic winter
- other groups are developing lunar photometers for Arctic deployment to further the goals of the Polar-AOD Community
- re deployment of the (improved) NOAA/CIRES lunar photometer this winter will complement the existing Sun photometer program there

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References

Barreto, et al. (2013), A new method for nocturnal aerosol measurements with a lunar photometer prototype, *Atmos. Meas. Tech.* , 6, 585-598, doi:10.5194/amt-6-585.

Berkoff, et al. (2011), Nocturnal Aerosol Optical Depth Measurements with a Small-Aperture Automated Photometer Using the Moon as a Light Source. *J. Atmos. Oceanic Technol*., 28, 1297–1306.

Herber,et al. (2002), Continuous day and night aerosol optical depth observations in the Arctic between 1991 and 1999, *J. Geophys. Res*., 107: 4097.

Kieffer and Stone (2005), The spectral irradiance of the Moon, *Astron. Jour., 129,* 2887-2901.

Stone, et al. (2013), A characterization of Arctic aerosols and their forcing of the surface radiation budget, *ELEMENTA* (*under review*).

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