High vertical Resolution Measurements of Backscatter, Depolarization, and Extinction Near the Ocean Surface

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Abstract: A High Spectral Resolution lidar has been deployed to measure optical properties and atmospheric structure near the ocean surface. The use of angle scanning allows high altitude resolution with good signal to noise ratio very close to the surface.

1. Introduction

One of the University of Wisconsin High Spectral Lidars (HSRL) [1] is currently operating at Ragged Point on the East shore of Barbados. This deployment is part of the MAGPIE experiment to study the exchange processes of heat and moisture, African dust, and sea spray over the Subtropical Atlantic Ocean.

The HSRL is collecting optical property and turbulent structure measurements from the ocean surface layer up through the Saharan dust layer. Measurements began in August of 2023 and are expected to continue through the summer of 2025.

Eye safe lidars operating at visible wavelengths are forced to use small field-of-view receivers to minimize the solar background signal. As a result, the minimum range to full overlap is large. The required near-range geometric correction is large making measurements sensitive to mechanical alignment and turbulence beam spreading. The HSRL backscatter cross-section measurement is not sensitive to errors in the geometric correction because it is derived from a ratio of signals that are affected equally. However, the extinction cross-section is sensitive because it is derived from a derivative of the molecular signal alone.

The HSRL in Barbados is executing elevation angle scans to make measurements close to the surface while using data at ranges where the overlap corrections are small. Figure 1 depicts the scan geometry. The near-horizontal pointing angles allow averaging over range while maintaining high vertical resolution in the profiles. For example, using a horizontal averaging interval of 1 km, these scans with ¼ degree steps near the surface and ½ degree steps above, can provide vertical profiles from the surface to 2.7 km. The vertical resolution ranges from ~4 m at the surface to ~300m at 2.7 km.

A series of profiles can be generated from these short segments at ranges between ~5km and ~12 km from the lidar.

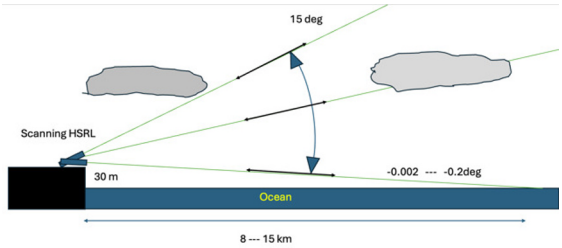

Figure 1. HSRL elevation scanning

Background counts are removed from the data and results are averaged over a period of 1 to 3 hours. The HSRL inversion is then performed to separate aerosol and molecular returns.

2. Optical Property Profiles

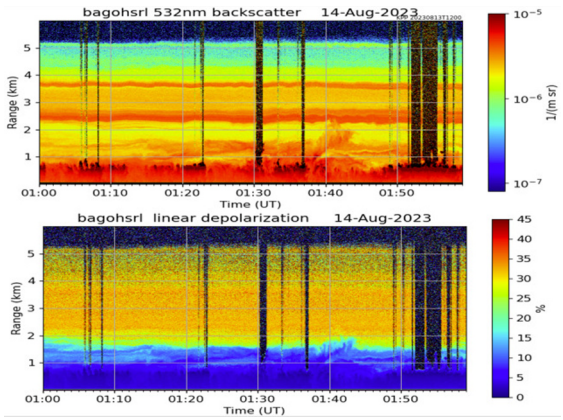

Figure 2. Vertical pointing HSRL measured backscatter cross-section and depolarization in the hour before starting an elevation scan sequence shown in the following plots.

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Savitzky-Golay fitting is applied to each range segment and the segment midpoint values are used to compute backscatter, depolarization, and extinction.

Figure 2 shows backscatter and depolarization measurements just prior to a sequence of elevation scans on August 14, 2023. Saharan dust fills the altitude layer between 2 and 5 km while water haze occupies the boundary layer below 1.5 km. A scattered layer of small cumulus exists near 600 m.

Figure 3 shows backscatter cross-section profiles averaged over the 3-hour period immediately after the image data shown in Figure 2. Profiles derived at 6, 8, 10 and 12 km are shown. This measurement approach allows high fidelity measurements of tenuous aerosol layers (at 1.75 km the scattering ratio is ~1).

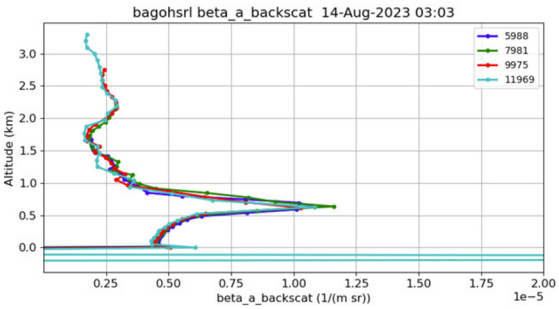

Figure 3. Aerosol backscatter cross-section profiles at ranges of 6, 8, 10 and 12 km from the HSRL.

Aerosol swelling causes the backscatter to increase with altitude in the sub-cloud layer. The peak at 0.6 km is caused by the scattered cumulus layer.

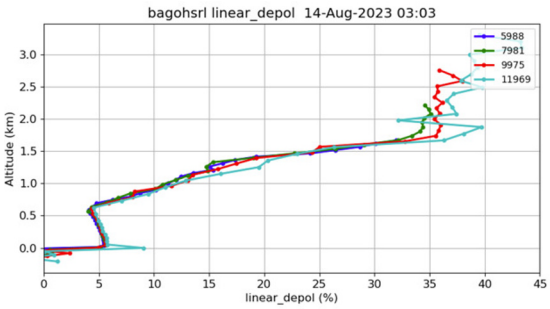

Figure 4: Aerosol depolarization profiles at ranges of 6, 8, 10 and 12 km from the HSRL.

The aerosol depolarization decreases with altitude below the peak of the scattered cloud layer. This occurs due to the increasing influence of scattering from spherical particles as the aerosol size grows in response to increased relative humidity. Depolarization increases in the transition layer between the top of the clouds and the pure aerosol layer starting at 1.7 km. Depolarization in the dust layer is ~35%.

Figure 5. shows the extinction cross-section as a function of altitude. Notice the high vertical resolution and low noise achieved by the combination of scanning and averaging. The peak at 0.6 km is the result of averaging between cloud and cloud-free parcels.

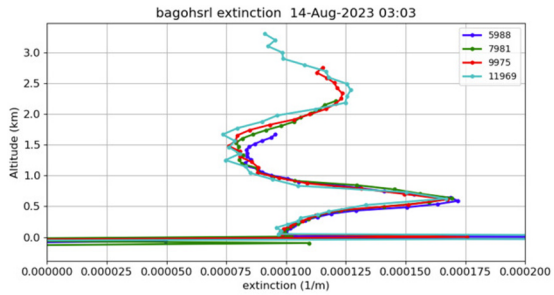

Figure 5: Extinction profile at ranges of 6, 8, 10, and 12 km from the lidar.

The lidar ratio profile shown in figure 6 exhibits the expected value near 20 [1] for small cloud droplets in the cloud layer and in the humid sub-cloud layer. In the Saharan dust layer, the lidar ratio is near 50.

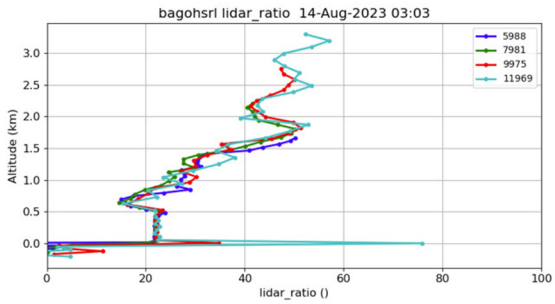

Figure 6: Lidar ratio profiles at ranges of 6, 8, 10, and 12 km from the HSRL.

3. Surface Layer Structure

The HSRL has also been used to observe aerosol structure in the surface layer. For these observations the lidar is operated at a fixed elevation angle selected such that the lidar beam impacts the surface. This provides information on the aerosol distribution in the layer between the 30 m altitude of the HSRL and the ocean surface. When the wind direction is not aligned with the lidar beam, images depicting the surface layer structure can be generated.

Figure 7 shows the vertical structure in the aerosol backscatter and depolarization observed

between 1:00 and 2:00 on August 13, 2023. Aerosol swelling is seen in plumes beneath scattered cu with bases at -600m.

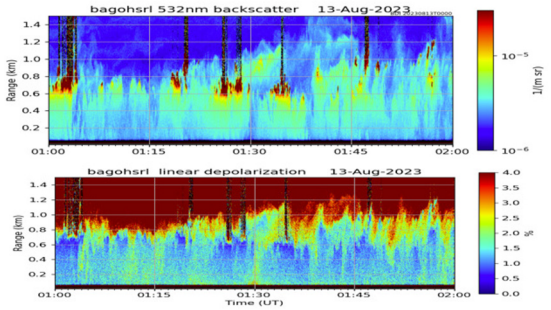

Figure 7: Aerosol backscatter and depolarization measured just prior to surface layer observations.

Range-vs-time plots of the aerosol backscatter and depolarization are shown in Figure 8. The wind measured at the HSRL was ~10 m/s from ~80 degrees. The lidar was pointed at an azimuth angle ~60 degrees with an elevation slightly below horizontal so that the beam hit the ocean surface at a range of ~11km.

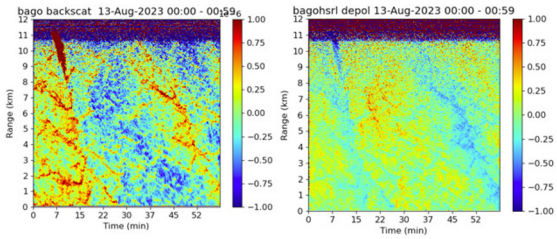

Figure 8: Nearly horizontal pointing backscatter and depolarization images showing deviation from the mean. Backscatter in units of 1.0e-6 1/(m sr) and depolarization in units of %.

The backscatter and depolarization patterns are inversely related. High backscatter and low depolarization occur in areas of surface convergence. Moist surface air is swept together in these areas and the resulting aerosol growth enhances the backscatter. Meanwhile, the depolarization is larger in the downdraft induced divergent area; aerosol from aloft increases the depolarization here.

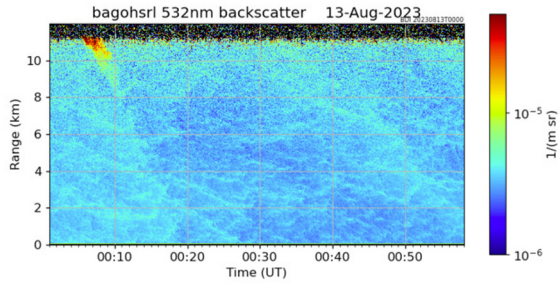

Figure 9: Full hour view of Aug 13 backscatter showing an isolated aerosol plume—possibly a wave breaking event.

Figure 9 shows the backscatter cross section instead of deviation from the mean. A strong backscatter plume with low depolarization rises from the water surface at about 7 min after beginning of the hour. This may be the aerosol wake of a motorboat injecting spray into the surface layer. Other cases show small surface plumes that may be the result of wave breaking.

The power spectrum of the backscatter cross-section computed from the data shown in figures 8 and 9 is shown in figure 10. As expected, these show a -5/3 dependence at the highest frequencies.

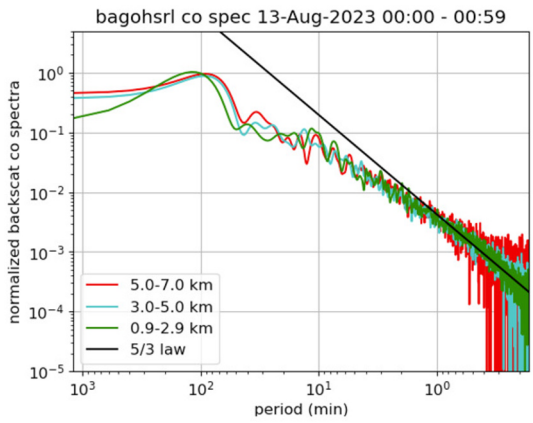

Figure 10: Power spectrum of aerosol backscatter in range bands of 0.9-2.9, 3.0-5.0 and 5.0-7.0 km.

Spatial-temporal patterns of backscatter and depolarization seen in these near-horizontal cross-sections vary from day to day and with changes in the wind direction relative to the lidar pointing direction. Example of this variation is seen in figure 11.

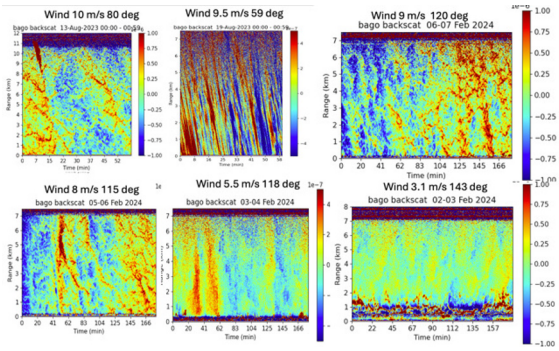

Figure 11: Aerosol backscatter patterns on different days and wind directions.

4. Discussion

We are still early in the expected 2-year observation period. Detailed analysis has just begun. The HSRL measurements will be integrated with the larger MAGPIE collected dataset. This includes: aerosol and turbulence observations from a Twin Otter aircraft flown along the lidar beam, Saildrone autonomous sailing vessel atmospheric and ocean observations, NASA DC-8 regional flights with a large array of airborne instrumentation, tower based atmospheric and aerosol instrumentation located next to the HSRL, scintillometer optical turbulence measurements on overwater path near the HSRL, Motorboat based optical and turbulence measurements along the lidar pointing direction.

All HSRL observations are available for viewing and download on the web site: http://hsrl.ssec.wisc.edu.

5. Acknowledgements

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6. References

[1] Eloranta, Edwin, “High Spectral Resolution Lidar” in Weitkamp, Claus. "Range-resolved optical remote sensing of the Atmosphere." *Springer-Verlag New York*102 (2005): 143-163.

[2] O'Connor, Ewan J., Anthony J. Illingworth, and Robin J. Hogan. "A technique for autocalibration of cloud lidar." *Journal of Atmospheric and Oceanic Technology* 21.5 (2004): 777-786.