ABSTRACT

Physical Sciences Inc. is developing an advanced, compact lidar capable of continuous mapping of atmospheric extinction to provide environmental situational awareness for high energy laser weapon operations by the Navy. The lidar uses a MicroPulse Lidar architecture and combines a solid state Nd:YLF laser operating at 1 micron with photon counting detectors and advanced aerosol retrieval algorithms. We report on the design of the engineering prototype and provide a summary of the system performance demonstrated during the Comprehensive Atmospheric Boundary Layer Extinction / Turbulence Refinement eXperiment conducted at the Shuttle Landing Facility at Kennedy Space Center in June, 2017.

Keywords: lidar, aerosol, environmental situational awareness

1. INTRODUCTION

Operation of a ship-borne laser weapon system effectively requires environmental situational awareness. Atmospheric conditions can affect high-energy laser beam propagation via extinction and turbulence. To support the concept of operations of a LWS, atmospheric extinction data as a function of range to the horizon (~12-13 km) are needed to support weapons selection against surface or airborne targets. Lessons learned during the deployment of the Laser Weapon System (LaWS) led to a recommendation that the Navy should…”Develop a compact, single-ended device to provide approximate values of extinction and turbulence”. Thus the Navy seeks new capability to dynamically characterize the maritime atmosphere in order to predict laser weapon effectiveness. Atmospheric attenuation data at the wavelength of the weapon can be used to generate a “Laser Effectiveness Range” so a ship’s tactical team can determine whether the LWS is an appropriate weapon choice for a given threat. Systems that can characterize the atmosphere continuously, providing data for a hemisphere centered on the vessel, and that also can operate on-demand, will provide the greatest flexibility.

We are developing an advanced, highly compact lidar capable of continuous, automated mapping of atmospheric extinction. Lidar is a well-developed and successful remote sensing technique for monitoring aerosols in the lower atmosphere. Systems have been developed using both elastic and Raman scattering. Raman lidar returns directly measure the aerosol extinction coefficient. However, the Raman backscattering cross section is generally 3 orders of magnitude smaller than elastic backscattering cross-sections. Thus, Raman lidars typically are large systems using 10s-100s mJ pulse energies and large aperture receivers. Much more compact elastic backscatter lidars have been developed. Our general strategy adapts the so-called MicroPulseLidar (MPL) architecture to the current need. The MPL design relies on transmission of low energy pulses at relatively high repetition rates (in contrast to transmission of high energy pulses at low repetition rates). Systems using 10s-100s µJ pulse energies, single photon counting detection, and small aperture receivers have been developed. Elastic lidar returns can, with specific assumptions, be used to infer the aerosol extinction coefficient. This approach allows us to create the required measurement capability within the desired SWaP.

Our Shipboard Atmospheric Extinction Lidar (SAEL) uses the MicroPulse Lidar (MPL) architecture to help meet the SWaP and environmental requirements. In the MPL architecture, the lidar transmits low energy pulses (µJ) at high repetition rates (kHz). This works to minimize the SWaP of the system by decreasing the size of both the transmit laser and the receiver telescope. A consequence is that useable signals are acquired after sufficient signal averaging, as opposed to via a single or a few shots. There are two other consequences of the design. The first is that the system requires a narrow FOV in order to minimize the detected diffusely scattered solar background radiation. A very narrow bandpass filter, sized to accommodate the transmitter spectral bandwidth, aids with this task. A second consequence is the mechanical stability under environmental stress that is required to maintain the alignment of the narrow receiver.

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FOV and the transmitter divergence cone. Many MPL systems use a monostatic design (common transmit and receive optical path) to maximize alignment stability. The common path ensures the transmitter and receiver axes share the same environment. Thus, each axis may drift under thermal stress, but the relative drift (and therefore alignment) is expected to be minimized. This strategy maximizes performance and also importantly for automated systems, minimizes maintenance. MPL systems have been shown to work well for atmospheric vertical sounding for which periods of 10-15 minutes are used for signal averaging. NASA operates a network of compact MPL systems (operating at 532 nm) (MPLnet) to monitor aerosol profiles, boundary layer height, and cloud base heights. For all these reasons, the MPL architecture was chosen for the SAEL development.

In adapting the MPL architecture to the Navy’s application, our design combines a highly compact solid state laser with single photon counting detectors to create a system that is on the order of a few cubic feet in volume, i.e. small enough to be easily deployed on a Navy vessel. The lidar operates at a wavelength of 1.05 micron, near the wavelength of the LWS, so that no extrapolation of results to the weapon wavelength is required. In addition, the lidar operates at a transmit power consistent with eye safety. It will operate autonomously and continuously, scanning the atmosphere to monitor atmospheric extinction (Figure 1). The sensor output will be a map of atmospheric attenuation with an “Indicated Laser Effectiveness Range.”

Figure 1. Lidar continuous hemispherical scan operational schematic.

2. LIDAR DESIGN

SAEL is an elastic backscatter lidar with similar architecture to MicroPulse Lidar (MPL). It transmits pulses in the (50) µJ regime at relatively high pulse repetition rate (1-3 kHz) and achieves usable SNR with adequate time averaging. It is characterized by a very narrow field-of-view. This, in combination with a narrow bandpass filter, allows signal recovery over the scattered solar background. Detection is accomplished using single photon counting with Si gAPDs. There are two detection channels; one receives 90% of the return light (FF) and the other receives 10% of the return light (NF). They have the same FOV. The lidar operates at a wavelength of 1 µm, close to the operating wavelength of current Navy laser weapon systems. The transmit aperture is 150 mm diameter. The lidar is Class 1M at the aperture. The optical design features shared transmitter-receiver axes to minimize thermal-mechanical drifts in alignment. A beam director provides elevation/azimuth pointing. SAEL is housed in an environmentally controlled cabinet measuring 2 x 2 x 3 ft.

A general schematic diagram of the optical system is presented in Figure 2. After leaving the laser, the beam enters a beam expander followed by a pair of axicons. The beam exits these two component pairs with an annulus profile that is collimated in the near field. The beam is then directed into a polarizing beam splitter cube and then through a quarter wave plate. A focusing lens then injects the beam into the telescope past a field stop. Backscattered light retraces the optical path through the telescope and proceeds through the wave plate and polarizing beam splitter, as it has orthogonal polarization to the outgoing beam. The light passes through a narrow bandpass filter and then is split by a 90/10 beamsplitter and each beam is refocused onto a fiber pickup and directed onto the detector.

The lidar is packaged in a NEMA 4 rated enclosure. The internal environment is stabilized to ±2 degrees with an integrated HVAC system. The cabinet is 12 ft³ in size, weighs 410 lbs, and requires 1200 W at maximum HVAC.
3. FIELD CAMPAIGN RESULTS

3.1 Background

SAEL was deployed at the Shuttle Landing Facility at KSC for the CABLE-TRAX mission from 20 to 28 June, 2017. It was part of a lidar constellation that included the GTRI Integrated Atmospheric Characterization System (IACS) and Maritime Atmospheric Characterization System (MACS) lidars, and an NRL MPL. The lidar was operational from 20th June on, and recorded 36.5 hours of raw data. It achieved ~83% availability. The lidar operated under an LCH manual deconfliction protocol. Times recorded were UTC based on an 18 sec shift of recorded GPS times. Temporal averaging was 6 seconds. Spatial resolution (bin width) was 7.5 m. Data collection continued during LCH “no transmit” windows during which the laser was shuttered closed. SAEL raw data is post processed to correct for: detector saturation, background, and overlap function. We have begun intercomparison with the other lidars and are continuing to do so as the various data sets from the other investigators are received.

3.2 Horizontal Scan Data

Data from horizontal scans can be used to determine the lidar constant and overlap function assuming the aerosol loading is constant in space and time during data collection and that other data measuring the aerosol loading is available. We obtained horizontal data on the morning of Monday, 6/26/2017. A range-time-intensity plot of the raw data is presented in Figure 3. For this data, elevation = 2°, azimuth = 330°. The white streak at early times is an echo from the CONEX box at 1.6 km from the test site that was used as a beam stop/target for the GTRI lidars.

After the data was corrected, the slope method was used to recover the extinction coefficient. The natural log of the range-corrected data is given as:

$$\ln \left( \frac{P_{ret} \times r^2}{P_o} \right) = \ln \left( C \beta O(r^2) \right) - 2 \int_0^r \alpha \, dr'$$

where $P_{ret}$ is the return power, $r$ the range, $P_o$ is the transmit power, $C$ is a collection of lidar system constants, $\beta$ is the aerosol backscatter coefficient, $O(r)$ is the overlap function, and $\alpha$ is the extinction coefficient. The slope method resulted in an extinction coefficient = 0.07 km$^{-1}$ with $R^2 = 98.6\%$, as shown in Figure 4. The GTRI MACS lidar had horizontal data from 21 June, 1:11 to 1:43 PM EST. Conditions were not as homogeneous and stable in the afternoon as they were during our data collection in the morning. Analysis of a 10 minute moving average of the extinction coefficient resulted in a value that varies between 0.08 - 0.09 km$^{-1}$. The NRL/Monterey MPL lidar only probed to zenith. Figure 5 (left) shows data from 22 June, 10:00 local time and Figure 5 (right) shows data from 27 June, 10:00 local time.
For the 22nd, the extinction coefficient from the lowest range bin = 0.25 km\(^{-1}\). The NRL MPL operates at a wavelength of 532 nm while the SAEL and GTRI lidars operate a 1 \(\mu\)m. For boundary layer maritime aerosol, the extinction coefficient can vary appreciably with wavelength depending on the relative humidity. Kaloshin and Grishin have developed a Marine Aerosol Extinction Profiles model that parameterizes the amplitudes and widths for modes of the aerosol size distribution as functions of fetch and wind speed.\(^4\)\(^5\) The shape of the aerosol size distribution and its dependence on meteorological parameters, height above sea level (H), fetch (X), wind speed (U) and relative humidity (RH), were investigated and used to predict aerosol extinction as a function of wavelength and the other variables. Their data, along with some experimental data, is shown in Figure 6. For the high RH values (~90%) experienced in the mornings at CABLE-TRAX, the ratio of the coefficients can be high, i.e. \(\alpha(532)/\alpha(1064) \sim 2.5\). Thus the NRL MPL data extrapolates to 0.08 km\(^{-1}\) at 1 \(\mu\)m. For the 27th, the extinction coefficient from the lowest range bin = 0.17 km\(^{-1}\), which extrapolates to 0.06 km\(^{-1}\) at 1 \(\mu\)m. There is reasonable agreement between the lidars, given the separation in time of the datasets.

![Figure 3. Range-time-intensity plot of raw data for 6/26 FF channel. Elevation 2°, azimuth 330°. White streak at early times is echo from CONEX box at 1.6 km from test site used as beam stop/target for GTRI lidars.](image)

![Figure 4. Natural log of range corrected data vs range showing slope retrieved by the slope method. The slope is twice the extinction coefficient.](image)
Figure 5. NRL/Monterey MPL lidar vertical profiles of extinction coefficient. (left) 22 June (right) 27 June. Temperature profiles are from collocated radiosondes.

Figure 6. Modeled spectra of aerosol extinction, $\sigma(\lambda)$, at $H = 4$ m for $X = 30$ km, $U = 3.3$ m/s and for different RH values. Observational results are from Institute of Atmospheric Optics of the Siberian Branch of the Russian Academy of Sciences (IAO SBRAS). From Reference 4.

3.3 Vertical Profiling Data

As with horizontal data, there were very few times when all three lidars were operating vertically simultaneously. MACS was unable to profile vertically. Figure 7 shows a vertical profile of aerosol extinction from 10:00 LT 26 June. General agreement with the maritime aerosol model (MODTRAN) is very good. Figure 8 provides an intercomparison with MPL data for 6/27 at 10:00 LT, provided by Dr. James Campbell. The MPL data is from the next day, but at the same time of day. Also shown is 1 point at ground level from the morning horizontal data. The agreement is very satisfactory. Figure 9 provides another intercomparison with MPL data for 6/22 at 15:00 LT. The agreement is remarkable, showing much of the same vertical structure.
Figure 7. Aerosol extinction vertical profiles: SAEL data from 6/26 at 10:00 LT and maritime model.

Figure 8. Aerosol extinction vertical profiles: SAEL data from 6/26 at 10:00 LT and MPL data for 6/27 at 10:00 LT.

Figure 9. Aerosol extinction vertical profiles: SAEL data from 6/22 at 15:00 LT and MPL data for 6/22 at 15:00 LT.
4. SUMMARY AND CONCLUSIONS

We have designed, fabricated, characterized, and field demonstrated a compact elastic backscatter lidar, having a micropulse lidar architecture, for the retrieval of aerosol extinction. Intercomparison between the lidars that participated in the CABLE-TRAX mission is ongoing. The SAEL lidar is planned to be deployed in Summer of 2018 for another field mission.

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REFERENCES


