

# Off-axis detection and characterization of laser beams in the maritime atmosphere

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# Previous work

- A 10×10 detector array was used and the scattered intensity was found to be roughly consistent with the prediction based on Mie scattering from a generic continental aerosol distribution. Aerosol concentrations can vary widely depending on regional and local weather conditions. Aerosol concentrations can vary widely depending on regional and local weather conditions. *J. P. Cariou, “Off-axis detection of pulsed laser beams: simulation and measurements in the lower atmosphere,” Proc. SPIE 5086, 129–138 (2003).*
- Increased humidity leads to larger aerosols and generally enhances the scattering. In typical conditions, even at low altitude, the scattering is extremely weak and can be difficult to detect in the presence of background light.

# Introduction

- Theory of the remote detection of scattered light and comparisons with Monte Carlo calculations to understand the effect of multiple scattering on the received intensity.
- Temporal data from a high-speed 30-channel angle resolved receiver is presented and compared with the analytic theory.
- Volume scattering is estimated by using a range of modeled aerosol distributions representative of the observed weather conditions.
- Assuming a volume scattering function, the laser power and distance as well as the direction of the beam all affect the scattered intensity at the receiver and these parameters cannot be readily distinguished from intensity data alone.
- Accurate timing information of the received scattered light can be used to estimate beam direction and subsequently laser power.

# Off-Axis Scattering Theory

The scattering is characterized by a **volume scattering function**  $\beta(\psi + \theta)$

Assumption:  $\beta$  is spatially uniform

Laser power is extinguished along the beam line as  $P_0 \exp(-\alpha z)$  where  $\alpha$  is the beam extinction coefficient due to absorption  $a$ , and total scattering along the path  $b$ .

$$b = 2\pi \int_0^\pi \sin(\theta) \beta(\theta) d\theta$$

Neglect multiple scattering, which is a good approximation if the mean free path  $1/b$  is large compared with the spatial scale of the experiments.

The light collected by the receiver to be only due to volume scattering from aerosols in the path of the beam.

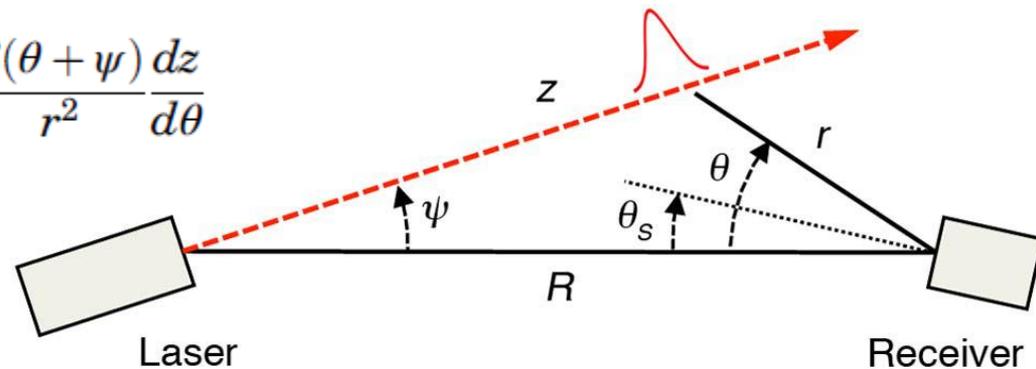
Assume a uniform homogeneous medium, the angle and time-dependent scattered **irradiance** at the receiver from a laser pulse with an initial power  $P_0$  can be written in terms of the beam extinction coefficient  $\alpha$  and the volume scattering function  $\beta$ .

$$\frac{dI(\theta, t)}{d\theta} = P_0 [t_{SR}(\theta) - t] \exp[-\alpha(z + r)] \frac{\beta(\theta + \psi)}{r^2} \frac{dz}{d\theta}$$

$$z(\theta) = R \sin(\theta) / \sin(\theta + \psi)$$

$$r(\theta) = R \sin(\psi) / \sin(\theta + \psi)$$

$$t_{SR}(\theta) = (z + r) / c :$$



Angle from the direction of the source to a reference direction on the receiver is given by  $\theta_s$

## Off-Axis Scattering Theory

If a detector collects scattered light over a limited one-dimensional angular range  $\Delta\theta$  in the scattering plane, the total intensity  $I(\theta; t)$  centered at  $\theta$  in the middle of the range  $\Delta\theta$  will be a convolution of the time-dependent pulse with the scattering along the path subtended by  $\Delta\theta$ .

$$I(\theta, t) = \int_{\theta-\Delta\theta/2}^{\theta+\Delta\theta/2} P_0[t_{SR}(\theta') - t] \times \exp[-\alpha(z + r)] \frac{\beta(\theta' + \psi)}{R \sin(\psi)} d\theta'.$$

To find peak intensity at the receiver determine the time  $t$  that maximizes  $I(\theta; t)$ . The integration could be replaced by an analytic summation over discrete angles within  $\Delta\theta$ , and the sum was maximized with respect to  $t$  as a parameter.

The propagation time increases with both  $\psi$  and  $\theta$

$$\frac{dt_{SR}}{d\theta} = \frac{R}{2c} \sin(\psi) / \cos[(\theta + \psi)/2]^2.$$

## Experiment

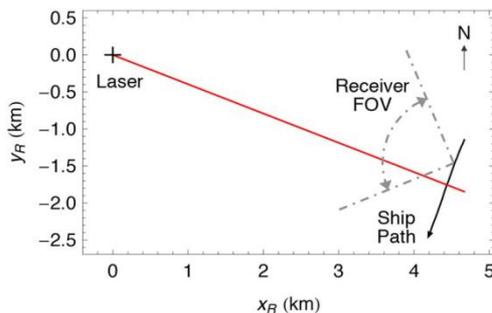
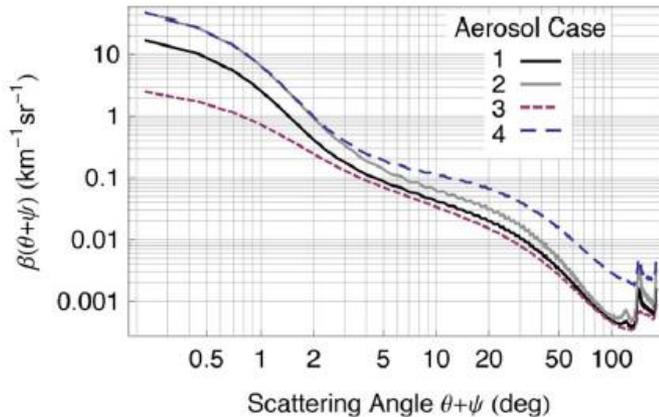
- $\lambda = 1.06 \mu\text{m}$
- Arrival time and intensity over a horizontal field of view (FOV) from  $-45^\circ$  to  $+45^\circ$ .
- Two 15-element linear detector arrays with separate collection optics that covered the range, in receiver coordinates  $\theta$ - $\theta_s$ .
- Each of the 30 angular channels had a narrow asymmetric FOV,  $\Delta\theta = 3^\circ$  in the horizontal plane  $-15^\circ < \theta_v < 15^\circ$  in the vertical plane.
- Each channel digitized the signal and recorded the crossing time over nine threshold values.
- Full daylight conditions in the presence of significant background irradiance.
- Detectors were AC-coupled and the constant background had little effect.
- Pulse width  $\tau = 20$  ns full width at half maximum source was located on the beach about 1–2m above sea level and the beam was collimated and directed at a stationary target boat offshore.

# EXPERIMENT

Table 1. ANAM Environmental Parameters Used to Generate the Four Aerosol Distributions and the Total Scattering Coefficient  $b$  and Absorption Coefficient  $a$  Calculated from the MIE Code

Aerosol Case	Wind Speed $w$ (m/s)	amp	Height $h$ (m)	$b$ ( $\text{km}^{-1}$ )	$a$ ( $\text{km}^{-1}$ )
1	2	3	2	0.0474	0.00023
2	8	3	2	0.0828	0.00058
3	8	3	300	0.0316	0.00006
4	8	8	2	0.1563	0.00219

In all cases, the relative humidity was 90% and the 24 h average wind speed was 3 m/s. amp air-mass parameter



- Atmospheric aerosols in the beam path are the source of off-axis laser scatter.
- An estimate of the source angle  $\theta_{SE}$  was obtained from the intensity data by taking the angle of the channel with the largest signal.
- ANAM describes the generation and distribution of aerosols in maritime environments based on environmental conditions.
- ANAM model includes wavelength-dependent absorption and refractive indices for the spherical aerosols.
- ANAM used to estimate angle-dependent volume scattering function appropriate for detection of scattered light from a source polarized perpendicular to the scattering plane,
 
$$\beta = (\lambda/2\pi)^2 (S_{11} - S_{12})$$
 where  $S_{ij}$  are Mueller matrix elements.
- **Mueller calculus** is a matrix method for manipulating Stokes vectors.

The laser source is located just on shore at Cowley Beach, Queensland, Australia, and the path of the receiver was nearly parallel to shore and perpendicular to the beam (red). The horizontal receiver FOV, shown schematically at one point on the path, was centered directly to starboard.

# ANAM Advanced Navy Aerosol Model

- Aerosols are considered to be uniform spherical particles with radius  $r$  and refractive index  $n$ .
- Five distinct types of aerosol particles, each characterized by a log-normal distribution peaked at a humidity-dependent modal radius

width parameter  $\sigma_4 = 1/2$   

$$\sigma_i = 1/2^{1/2} \quad (i = 0, 3)$$

$$\frac{dN}{dr} = \sum_{i=0}^4 \frac{N_i}{\sqrt{2\pi}\sigma_i \exp(\sigma_i^2/2)} \exp\left\{-\frac{[\ln(r/\rho_{si})]^2}{2\sigma_i^2}\right\}$$

- Particle 0 is a nonhygroscopic dust particle originating over land with modal radius  $\rho_s = \rho_0$ . For all other particles, the modal radii increase with the fractional relative humidity  $s$  (0 to 1) according to  $\rho_s = g(s)\rho_0$  with

$$g(s) = [(A - s)/B(1 - s)]^{1/3}$$

- Complex refractive indices for particles 1–4 are volume-weighted averages.

$$n = n_W + (n_0 - n_W)g^3(0)/g^3(s)$$

- where  $n_0$  is the index of the dry particle material and  $n_W$  is the index of water at  $\lambda = 1.06 \mu\text{m}$

**Hygroscopy** is the ability of a substance to attract and hold water molecules from the surrounding environment

Table 2. ANAM Parameters for Each of the Five Particle Types

Particle	$\rho_0$ ( $\mu\text{m}$ )	$n_0$ ( $\lambda = 1.06 \mu\text{m}$ )	A	B
0	0.03	$1.52 + i0.008$	-	-
1	0.03	$1.392 + i0.000153$	1.17	1.87
2	0.24	$1.47 + i0.0002$	1.83	5.13
3	2.0	$1.47 + i0.0002$	1.97	5.83
4	8.0	$1.47 + i0.0002$	1.97	5.83

- Total number density  $N_i$  ( $\text{cm}^{-3}$ ) of each particle type depends on the amp, wind speed  $w$  (m/s), 24 h average wind speed  $W$  (m/s), and height  $h$  (m) above the sea surface.

$$\left\{ \begin{array}{l} N_0 = 0 \\ N_1 = 136.55 \text{ amp}^2 \end{array} \right\} \quad \text{amp} \leq 5,$$

$$\left\{ \begin{array}{l} N_0 = 0.3 \times 136.55 \text{ amp}^2 \\ N_1 = 0.7 \times 136.55 \text{ amp}^2 \end{array} \right\} \quad \text{amp} > 5,$$

$$N_2 = 0.5462 \text{Max}[5.866(W - 2.2), 0.5],$$

$$N_3 = 0.007214 \times 10^{0.06w},$$

$$N_4 = 0.01 \times 10^{0.07w - 0.04h}.$$

# RESULTS

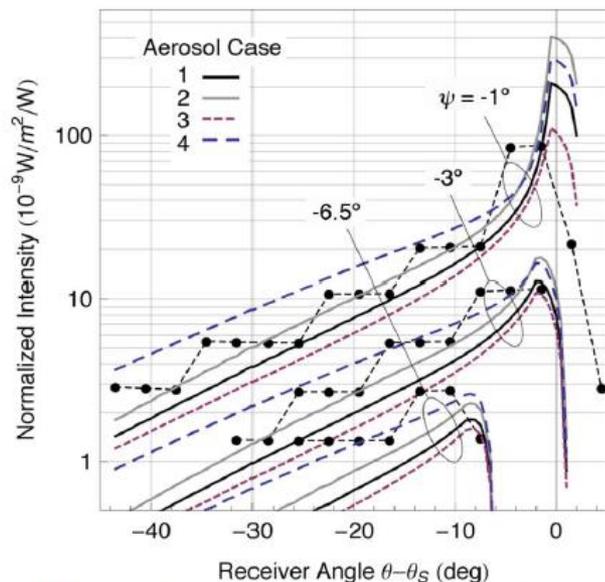


Fig. 5. (Color online) Normalized scattered intensity at the receiver for three selected points along the ship path prior to crossing the beam line. The model predictions are calculated on a  $0.5^\circ$  grid with  $\Delta\theta = 3.0^\circ$ , for the four aerosol cases of Table 1. The receiver orientations relative to the source  $\theta_S$  and the beam angles  $\psi$  were taken from GPS tracking data.

- A beam of 20 ns laser pulses from a fixed laser source was propagated above the sea surface and its scattering from atmospheric aerosols was detected by a multichannel receiver on a ship that traveled across the beam line.
- Extensive measurements of off-axis scattering observed at ranges up to  $\sim 5\text{km}$  with a high-speed multichannel receiver.
- The high angular resolution of the receiver allowed the direction of the source to be tracked during the experiment.
- Representative aerosol distributions were calculated with the ANAM for the range of observed weather conditions, and Mie theory was used to predict intensity at the receiver.
- The laser beam scattering was predominately in the forward direction and receiver intensity depended critically on the beam angle relative to the baseline between the source and receiver.
- The scattering model gave reasonably good agreement with experiment, within the uncertainty of the aerosol conditions, up to beam angles  $|\psi| < \sim 6.5^\circ$  where the scattering was sufficiently strong for the SBLAS receiver.
- The receiver also recorded the relative arrival times of the scattered light for each of the angular channels.
- The change in arrival time with angle, along with information about the source position, was used to calculate the beam angle  $\psi$ .

# Calculation of the power

The beam angle  $\psi$  can be determined from

$$\frac{dt_{SR}}{d\theta} = \frac{R}{2c} \sin(\psi) / \cos[(\theta + \psi)/2]^2.$$

if the source angle  $\theta_S$  and range  $R$  are known.  $\psi$  was calculated by substituting  $dt/d\theta_i$  and solving for  $\psi$  using the estimated source angle  $\theta_{SE}$  and known range  $R$  (from GPS data).

Over the range from  $-6^\circ$  to  $+6^\circ$  the rms error is  $0.22^\circ$ .

The laser power can then be calculated from

$$I(\theta, t) = \int_{\theta - \Delta\theta/2}^{\theta + \Delta\theta/2} P_0 [t_{SR}(\theta') - t] \times \exp[-\alpha(z + r)] \frac{\beta(\theta' + \psi)}{R \sin(\psi)} d\theta'.$$

based on an estimate of the beam extinction.

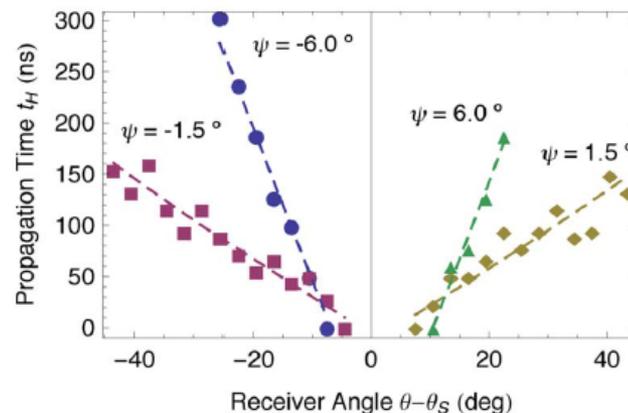


Fig. 8. (Color online) The relative propagation time from the laser to the receiver determined by the crossing time of the highest threshold level for single measurements at beam angles  $\psi = -6.0^\circ$  ( $\circ$ ),  $-1.5^\circ$  ( $\square$ ),  $1.5^\circ$  ( $\diamond$ ), and  $6.0^\circ$  ( $\triangle$ ). Timing curves calculated from  $(z + r)/c$  using the known geometry and offset to give the best fit are shown as dashed lines.

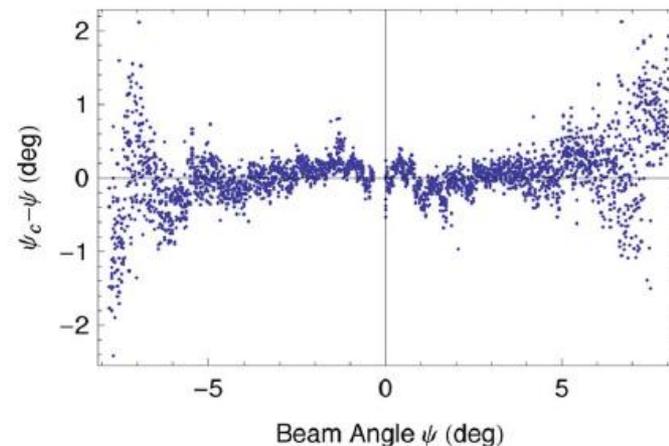


Fig. 9. (Color online) Difference of beam angle  $\psi_c$  (blue) calculated from Eq. (3) using the estimated source angle  $\theta_{SE}$  and timing data  $\langle dt_H/d\theta \rangle$  from SBLAS and the beam angle obtained from GPS data.