Lidar Observations of Ship Spray Plumes

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ABSTRACT

As part of the Monterey Area Ship Track experiment, which was designed to study ship-generated cloud tracks, ship-based measurements were made by a gyroscopically stabilized scanning lidar system. This paper focuses on the spray plume observed by lidar behind the USS Truxtton, a nuclear-powered surface ship. Measurements are included from five passes at different speeds. Observed parameters include the speed of the plume meander, maximum speed of vertical mixing, and dispersion time.

1. Introduction

In June 1994, the Naval Research Laboratory (NRL) volume imaging lidar (VIL) (James and Hooper 1995b) participated in the Monterey Area Ship Track experiment. The purpose of this experiment was to study ship tracks observed in satellite images over ocean areas. The NRL lidar operated on board the research vessel (R/V Glorita) and provided a capability to sense "clear air" aerosol structures.

VIL systems are powerful tools for studying temporal and spatial changes in boundary layer structures. For example, the NRL system has been used to study dynamics in coastal areas (Hooper and James 1996). A shipboard lidar has advantages over land-based systems, since a shipboard system is not limited by ground obstructions such as trees and buildings and can be aimed almost horizontally, making low-level atmospheric aerosol features observable.

This paper focuses on the unique plume created by the USS Truxtton, a nuclear-powered, 172-m long, surface ship (Sharpe 1993). This plume is unlike those of conventional ships in that it contains only spray particles and does not contain any exhaust particles. Since a spray plume is composed of salt water particles and does not normally have elevated air temperatures or unusual chemicals, this plume is similar to the products of white caps and breaking waves and is not clearly identifiable using in situ techniques. However, the particles are in a size range that has a significant lidar backscatter cross section, and the scattering contrast between the plume and background is observable. Therefore, a lidar can characterize the plume’s width, length, and height.

2. Description of measurements

A number of in situ and remote measurements were made on the R/V Glorita and these are described in Porch et al. (1999). To make these measurements, the NRL lidar was placed on the top deck in the midsection of the R/V Glorita (Fig. 1). This location provided shelter from direct ocean spray and was an excellent location for scanning lidar measurements. Only in the Glorita’s forward sector were lidar measurements blocked by the ship’s superstructure. The lidar was housed in a modified shipping container that also contained data analysis and real-time display equipment.

The NRL lidar uses a laser that transmits short (2.4 m), infrared (1.06 μm) laser pulses into the atmosphere and a telescope that focuses the laser light scattered back from atmospheric aerosol particles onto a photodiode. The photodiode signal is amplified, digitized, and stored. A series of these corrected returns measured in different directions are combined to show variations of the backscatter coefficient in horizontal or vertical slices of the atmosphere. For this experiment, gyroscopes measured the attitude of the ship’s deck and allowed the scanning system to point the laser and telescope in a fixed direction independent of ship motion (James and Hooper 1995a). A detailed description of the lidar system and data processing can be found in James and Hooper (1995b).

Individual lidar returns are modeled by a modified form of the lidar equation (discussed in Measures 1984)

\[
P(r) = \frac{K\beta(r) \exp[-2\tau(r)]}{r^2},
\]

where
FIG. 1. This line drawing of the R/V Glorita shows the shelter containing the VIL in the middle of the ship. From this position, the lidar scanning mechanism could conduct a horizontal scan from one side across the stern to the other side. The system could also conduct a scan from the sea surface up to zenith in all directions except the forward direction, where Glorita’s superstructure blocks the laser beam below 45° elevation angles.

where $P$ is power returned, $r$ is range, $K$ includes system constants, $\beta$ is the volume backscatter coefficient, and $\tau$ is optical depth. Since the NRL lidar uses a logarithmic amplifier, the digitized, range-corrected signal is

$$S_{ij} = \ln(P_{ij} r^2) = \ln(K) + \ln(\beta_{ij}) - 2\tau_{ij},$$

(2)

where $i$ is the range bin and $j$ is the sequential number of the lidar return (in a series of returns). A convex hull (Sedgewick 1983) provides a minimum function

$$S_{i0} = \min[S_{ij}] = \ln(K) + \ln(\beta_{0}) - 2\bar{\tau},$$

(3)

where $\min$ denotes the convex hull operation, subscript $0$ denotes the minimum, and $\bar{\tau}$ is the “average” optical depth. For this analysis, the curve derived from convex hull operation is assumed to represent a range-independent, minimum backscatter return. Since $S_{ij}$ is measured and $S_{i0}$ can be determined, the normalized backscatter, which is backscatter divided by the minimum backscatter, can be calculated by

$$\frac{\beta_{ij}}{\beta_{0}} = \exp(S_{ij} - S_{i0}),$$

(4)

where the difference between the average and actual optical depth is neglected. This parameter was used in the data analysis and the false color images shown in the next two sections. Figure 2 shows a processed profile.

3. Data analysis

On 28 June 1994, a series of measurements were made using the R/V Glorita, which carried the lidar, and the USS Truxton, which generated the spray plume. During these measurements, the Glorita moved in a northwesterly direction at approximately 2.5 m s$^{-1}$ (Fig. 3) and the Truxton made loops around the Glorita. During each pass, the Truxton would pass approximately 1
nmi off the *Glorita* starboard side. After the *Truxton* passed approximately 1 nmi ahead of the *Glorita*, the laser was turned on. Lidar measurements were made until the *Truxton* executed a turn to return back around the *Glorita*.

The *Truxton* made five passes by the *Glorita* (Table 1). On the first three passes, the elevation of the lidar stepped through a series of angles to determine the vertical, horizontal, and temporal extent of the plume. On the last two passes, the lidar system did not scan, but instead was aimed nearly horizontal. These data provide more detail on the horizontal and temporal extent of the plume but provide no vertical detail.

Global positioning system (GPS) data were used to determine the relative position of the ships. For the *Glorita*, positions were available every 2 s and provided excellent spatial and temporal resolution. However, the GPS positions of the *Truxton* were only recorded every 15 min, and these positions had to be supplemented by visual observations made from the *Glorita* of the relative azimuth of the *Truxton* and its approximate range. Since the estimated positions of the *Truxton* on pass 4 are inaccurate, the data from this pass are not used in this paper.

Figure 4 shows a false color image of the lidar data taken on pass 5 where the spray plume can be seen in the vertical band of stronger scattering. If a uniform surface wind is assumed, the range of the *Truxton* plume can be calculated as a function of time and compared with the observed plume. Figure 5 shows the observed and estimated ranges for peak plume return.

Since the lidar was aimed horizontally in pass 5, the

![Image](image_url)

**Fig. 3.** On this plot of the *Glorita*’s position on 28 Jun 1994 during the measurement session with the USS *Truxton*, the crosses indicate the hourly position (starting at 1400 PDT and ending at 1900 PDT), while the boxes indicate the *Glorita*’s position at the start of each pass.

**Fig. 4.** This false color image of the lidar data from pass 5 is an example of a range-time indicator (or RTI). Each horizontal line represents one lidar return. The horizontal axis shows the range in kilometers from the lidar. The vertical axis shows elapsed time where zero is the earliest return. The lidar was aimed horizontally and all the data are within 20 m of the surface. The plume from the *Truxton* starts at 1.8 km, gradually moves closer in range, and at 600 s ends at 1.6 km. The white areas outside the *Truxton*’s plume are return from naturally occurring aerosol structures. The color scale on the right side of the figure shows the value of the normalized backscatter, where yellow represents the strongest return, and the strength of the return is shown in descending order by yellow, red, white, and blue.

### Table 1. Times and speeds of *Truxton* passes.

<table>
<thead>
<tr>
<th>Pass no.</th>
<th>Time (PDT)</th>
<th><em>Glorita</em> Speed (m s$^{-1}$)</th>
<th><em>Glorita</em> Direction (deg)</th>
<th><em>Truxton</em> Speed (kt)</th>
<th><em>Truxton</em> Direction (deg)</th>
<th>Lidar scan type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14:33</td>
<td>2.8</td>
<td>45</td>
<td>11.8</td>
<td>39</td>
<td>RHI</td>
</tr>
<tr>
<td>2</td>
<td>15:05</td>
<td>2.5</td>
<td>41</td>
<td>8.7</td>
<td>38</td>
<td>RHI</td>
</tr>
<tr>
<td>3</td>
<td>16:32</td>
<td>2.4</td>
<td>35</td>
<td>5.1</td>
<td>40</td>
<td>RHI</td>
</tr>
<tr>
<td>4</td>
<td>17:39</td>
<td>2.4</td>
<td>32</td>
<td>11.8</td>
<td>36</td>
<td>RTI</td>
</tr>
<tr>
<td>5</td>
<td>18:34</td>
<td>2.2</td>
<td>41</td>
<td>8.7</td>
<td>37</td>
<td>RTI</td>
</tr>
</tbody>
</table>
surface structures in both the background aerosol structures and the Truxton’s plume can be seen in Fig. 4. Lidar measurements of continental boundary layers (Kunkel et al. 1977) have shown that the regions with stronger returns can be associated with updrafts that can carry aerosol from the surface into the boundary layer. A similar process probably occurred on this day with white-capped waves generating aerosol particles that were carried by convection up into the marine boundary layer (MBL). These regions of stronger return, which will be called background structures, appear interconnected and often surround regions of weaker return, which will be called surface cells. Using false color images, the following conclusions can be drawn concerning the size of the various features.

1) The Truxton’s plume width (full width at half maximum) varies from 10 to 200 m and has an average width of 84 m (Fig. 6).
2) The width of the background structures has the same functional dependence as the Truxton’s plume.
3) The diameter of the surface cells ranges between 50 and 500 m and averages 276 m (Fig. 7).

4. Measurement results

Plumes are dispersed by variations in the wind and vertical mixing. Horizontal wind variations cause the plume to move away from the centerline of the plume. For a plume generated at the surface, vertical mixing initially transports the plume up into the MBL. The mixing processes cause the plume scattering to decrease over time. This section discusses the magnitude of these mixing processes and models the decrease of plume scattering with time.
The size of the plume meander is defined in this paper as the difference between the plume location derived for a constant advection velocity and the actual observed lidar location. The meander speed is this distance divided by the elapsed time between the lidar observation and the passage of the *Truxton*. The plume takes on the shape of the background structures with the stronger returns, and the plume curves around the surface cells with weaker returns. The lateral movement of the plume (or plume meander) may be caused by the secondary circulation in convective cells that pull the plume away from the ship track and into regions of updrafts. The meander speed provides a lower bound to the rate at which plume material is drawn away from the plume centerline into the updraft regions. The number of occurrences for the different meander speeds was counted and formed into a histogram (Fig. 8). The rms variation of the meander speeds is 0.23 m s\(^{-1}\), as shown by the Gaussian fit to the histogram. Since surface structures, which can be seen by the lidar, have a scale size of 300 m, the plume material takes approximately 600 s to move from the center of the cells into the regions of stronger return.

A series of vertical scans (also called range–height indicator or RHI in radar terminology) was taken on the first three passes of the *Truxton*. In Fig. 9, a false color image from an RHI scan, the top of the plume can clearly be seen. By examining all the RHI scans, the height of the plume top as a function of time can be determined (Fig. 10). Even though the *Truxton’s* speed was different on each pass, the rise rate of the plume top is constant, suggesting that the vertical speed is determined by natural convection rates and not influenced by the turbulence created by air flow past the *Truxton’s* superstructure. Since this measurement shows the maximum height of the plume material, the speed (0.5 m s\(^{-1}\)), which can be estimated from Fig. 10, is the maximum vertical transport speed, and most of the plume material...
moves slower. However, cloud base has a height of 180 m above the water surface, and the spray plume material will begin reaching cloud base 360 s after being generated at the surface.

During a pass, the Truxtun introduces spray particles into the lowest 20 meters. Figure 11 shows the peak value of the normalized backscatter as a function of time. The strength decreases with time as the larger particles fall back to the surface and the smaller particles move slower. However, cloud base has a height of 180 m above the water surface, and the spray plume material will begin reaching cloud base 360 s after being generated at the surface.

During a pass, the Truxtun introduces spray particles into the lowest 20 meters. Figure 11 shows the peak value of the normalized backscatter as a function of time. The strength decreases with time as the larger particles fall back to the surface and the smaller particles are drawn into updrafts. Typically particles larger than approximately 10 μm are removed by deposition, although the exact removal rate depends on atmospheric conditions (Giorgi 1986). The plume’s normalized backscatter can be modeled by the exponential function

$$\frac{\beta_m}{\beta_0} = a + be^{-t/\sigma}$$

(5)

where the subscript $m$ denotes the maximum plume backscatter, $a$ is the maximum normalized backscatter in the background structures, $b$ is the initial strength of the Truxtun’s plume, $t$ is the elapsed time of the observation, and $\sigma$ is the dissipation time of the surface plume structure. When Eq. (6) was fit to the data from pass 5, the constants were determined to be (i) 1.5 for the normalized backscatter, (ii) 3.9 for the initial plume strength, and (iii) 223 s for the dissipation time ($\sigma$).

5. Conclusions

During this experiment, a nuclear ship created a spray plume providing a unique lidar measurement opportunity. The NRL lidar observations show a spray plume that was initially scaled by the ship size (approximately 20 m). However, after a few minutes, the ship plume was drawn into regions with stronger lidar return (probably updraft regions) and was transported up into the overlying cloud structures. The plume size became similar to the size of the background aerosol structures. There is no evidence in the lidar data that ship-generated turbulence influences either the vertical movement of the spray particles or the final shape of the spray plume.

At a range of 1.5 km, the lidar almost instantaneously observed aerosol backscattering from a cylindrical volume that was 7.5 m long and almost 1 m wide. By recording one profile per second, the lidar provided plume sampling statistics that allowed the spray plume movement to be clearly observed. When the ship passed under an updraft region, the spray material moved up into the cloud in about 360 s. However, when the spray particles were created in the center of the surface cells, the particles had to be transported across the surface into updraft regions, and this movement could take up to 600 seconds.

The movement of the particles in the Truxtun’s spray plume should be useful in understanding the movement of exhaust particles from other ships. When the exhaust plume is buoyant, the timescales for spray plumes, which are not strongly buoyant, represent the maximum time required for the exhaust particles to reach the cloud base. When strong turbulent mixing takes places and the exhaust plume quickly loses its buoyancy, the movement of exhaust and spray particles should be the same.

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