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Meteor trail advection observed during the 1998 Leonid shower

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Abstract. Sodium resonance lidar observations of meteor trails are reported from the 1998 Leonid shower experiment at the Starfire Optical Range, Kirtland Air Force Base, NM (35.0° N, 106.5° W). The lidar was operating in a spatially scanning mode that allowed tracking for up to one half-hour. Three trails are presented here whose motion allowed inference of radial as well as vector wind components and apparent diffusivities. The winds are derived independently using the narrow linewidth sodium (Na) resonance Doppler lidar technique and are compared with the tracking results.

Introduction

It has been known for some time that meteor ablation is the source for the metallic layers observed in the mesosphere/lower thermosphere [*Slipher,* 1929; *Clemesha et al.,* 1978]. Initially, lidar data sets used to study freshly ablated trails [*Kane and Gardner,* 1993] were typically collected using integrations greater than 30 s. Such a configuration was sensitive to trails that either deposited a tremendous amount of metallic species or remained in the beam for a relatively long period of time, but it is likely that shorter duration trails (~1-5 seconds) were lost amidst the accumulating return from the background layer [*Höffner et al.,* 1999]. Data collection methods have since been improved by saving returns from every laser pulse. Such high temporal resolution data enables the detection of shorter duration trails (< 5 s) that may be lost in the former techniques as well as track meteor trails in multiple profiles as they pass through the lidar beam. As a demonstration of the improvements of this type of detection, *Höffner et al.* [1999] recorded seven potassium (K) meteors during the peak (0245-0445 UT) of the 1996 Leonid meteor shower. Although this improvement greatly reduces the possibility of losing trails in the accumulating background layer, the investigation is still limited to the short amount of time the trail remains in the fixed transmitted beam.

Grime et al. [1999] have recently reported resonance trail signatures recorded in two lidar beams separated spatially by ~ 15 km. The observed delay of ~ 5 minutes between trail onset in the two beams allowed estimation of horizontal winds (50 ± 10 m/s) as well as the apparent meteor trail diffusion coefficient (2.6 ± 0.5 m^2/s). Although observing over a longer period of time provided an additional asset to meteor trail investigations, the limited probability of detecting trails in two separate beams limits the utility of this type of study.

This letter discusses results from the 1998 Leonid meteor shower campaign at the Starfire Optical Range, Kirtland Air Force Base, New Mexico. Using the spatial steering capabilities of the site, it was possible to acquire and track meteor trails with a Doppler wind/temperature sodium (Na) resonance lidar. The spatial tracking provided an estimate of the region's neutral wind in comparison to the Doppler lidar as well as an inference of the local small-scale diffusivity.

Experiment

A variety of instruments were running during the 1998 Leonid shower, including a Na Doppler wind/temperature lidar, airglow imagers, intensified CCDs, and standard video recorders. A more complete description of the experiment can be found in *Drummond* [1999], but a foundation of the experiment was an observer relaying the coordinates of long-lived visual trails to the telescope operator, who then spatially scanned the beam in order to acquire return from the Na resonance lidar. Once lidar observations were established, the trails were spatially tracked using the Na lidar return signal. This proved beneficial since it allowed records to continue long after the visual trails had dissipated. Further details about the meteor tracking can be found in *Chu et al.* [1999].

The emphasis of this presentation is data collected by the University of Illinois' Na Doppler wind/temperature lidar that is interfaced with the site's 3.5 m diameter steerable telescope. This narrow linewidth lidar system probes the Na hyperfine structure to provide a measurement sensitive to both temperature as well as radial winds. Radial winds from 3 differing directions can be used to infer the vector winds. For the Leonids experiment, data sets were collected using a nominal collection time of 15 seconds per profile. This

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method of deriving temperatures and radial winds is discussed in detail in *Bills et al.* [1991], while *Chu et al.* [1999] discuss the system configuration specific to this campaign.

Observations

Tracking meteor trails with a steerable lidar system provided the opportunity to investigate their evolution over an extended period of time, since the Na signature endured considerably longer than the visual glow. For example, the meteor observation from 17 November 1998 labeled *Rope* for its visual ablation trail characteristics ablated with a visual magnitude of –1 at 11:35:52 UT and the lidar recorded data until 12:06:00, making the half-hour observations the longest of the experiment. Using a simple diffusion estimate as presented in *Grime et al.* [1999] and assuming an initial trail radius ~ 1m [*Ceplecha et al.*, 1998], the trail's full-width-half-max (FWHM) of 370 ± 70 m at 1600 seconds yields an apparent diffusivity of 8 ± 3 m^2/s. This is roughly the same value one would expect for molecular diffusivity at this altitude [*Banks and Kockarts*, 1973]. This result, as well as values for two other trails, are presented in Table 1 along with actual temperatures measured by the lidar. These are referred to as apparent diffusivities since tracking ambiguities, such as the trail not being orthogonal to the probe beam or the beam being offset from trail center, influence the error bounds on the derived values. Also, if electrodynamic/chemical effects are present, these reported numbers may not truly represent diffusivity of the neutral background [*Kelley et al.*, 1998]. Regardless, in the cases of these observations the question that naturally arises is "why do the trails last so long? " To address this we investigated the response of the Na chemistry of this region to simulated meteoric input. A sudden influx of Na was assumed over a small altitude range and the time constant for absorption into the background was calculated using a 1-D time resolved model [*Plane et al.*, 1999, and references therein]. Above 90 km, this time constant was on the order of hours but rapidly fell off below, so that at 85 km any added Na is observable for only a few seconds, due largely to the increased atomic oxygen as well as neutral density. This result is supported by the fact that, of the 15 trails observed during this experiment, only two were below 90 km (and they were near 89 km). The trend of this increased observation probability for higher altitudes has been previously discussed and is important to consider when transferring characteristics of observed meteor observations to general metal layer characteristics [*Kane and Gardner*, 1993; *Höffner et al.*, 1999].

Active tracking provided the opportunity to investigate meteor trail advection. The measurements serve as a comparison to the Doppler processed radial winds and allow mapping into meridional, zonal, and vertical components. The meteor is tracked by following the trail's peak photon count (greatest Na density) as it drifts across the night sky. This tracking is in terms of radial range, azimuth and elevation angles; that is, spherical coordinates. The radial wind is inferred from the time variation of the peak's range, while the vector components are found from the time variations of trail location in Cartesian coordinates. Perhaps the largest challenge in interpreting such "winds" is knowing which section of the meteor trail the lidar is actually probing. With this in mind, we present here three of the best-tracked trails (of twelve total). The trails are categorized by names derived from visual characteristics of the meteor ablation. For each event, some details of the meteor tracking method are mentioned to explain the variety of attempts used to properly follow the advecting trails. These events all occurred on 17 November 1998 and are reported in Universal Time.

Rope:

The first trail presented is the *Rope* event previously discussed. In this particular observation, the telescope/beam was continually steering to maximize the Na trail's return. We will see that this is in contrast to the night's previous meteor tracking efforts presented in the following discussion (*Sailboat, Diamond Ring*). Figure 1a shows the time

Table 1. Summary of selected meteor events during the 1998 Leonid Meteor Shower

Event/ Tracking Time/ Altitudes	Doppler radial, zonal(i), meridional, & vertical winds	Tracking radial, zonal, meridional, & vertical winds	Temperature/ Apparent Diffusivity (see text)	Tracking Method
Rope	24 ± 2 m/s	15 ± 4(iii) m/s	172 ± 2 K	Initially acquire meteor trail, actively track trail by preventing photon counts from significantly decreasing.
11.64-12.1 UT	33 ± 5	31 ± 8		
96 to 98 km	34 ± 10 / 8(ii) ± 4	22 ± 6 / 3 ± 1	8 ± 3 m^2/s	
	2.0 ± 0.7	1.0 ± 0.2		
Sailboat	9 ± 2 m/s	3 ± 1 m/s	205 ± 2 K	Initially acquire meteor trail, collect data until trail entirely drifts from lidar FOV, adjust lidar to reacquire the trail.
11.1-11.43 UT	-16± 3	-3 ± 1		
88 to 89 km	-4 ± 3	-4 ± 1	5 ± 2 m^2/s	
	0.3 ± 0.7	-0.3 ± 0.1		
Diamond Ring	4 ± 2 m/s	2 ± 1 m/s	176 ± 2 K	Initially acquire meteor trail, collect data until lidar photon counts significantly decrease, adjust lidar to increase counts.
9.64-9.85 UT	5 ± 7	6 ± 2		
97.5 to 98.5 km	4 ± 6	6 ± 1	10 ± 5 m^2/s	
	0.6 ± 1	1.4 ± 0.4		

(i) The Doppler wind vector components cannot be calculated while tracking the meteor trail. Shown are data from ~ 12.2 UT for *Rope*, ~ 10.7 UT for *Sailboat*, and ~10.4 UT for *Diamond Ring*.

(ii) Two meridional wind values were calculated for this case, from 96-97 km altitude and 97-98 km (see Fig. 2).

(iii) These 'error bounds' are simply estimates acknowledging data uncertainties as well as human error in tracking.

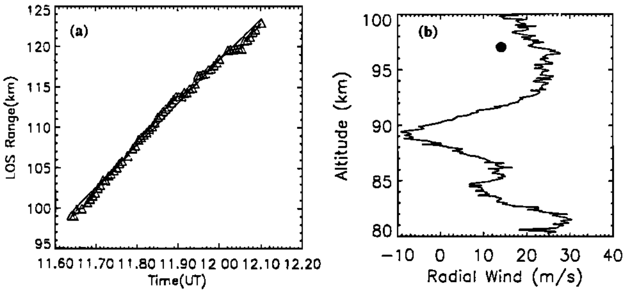

Figure 1. The *Rope* meteor trail's (a) Line-of-Site range vs. time is used to infer a radial wind of 15 ± 4 m/s near 97 km altitude which can be compared to (b) radial winds vs. altitude determined by the Doppler wind technique.

progression of *Rope's* line of sight (LOS) range. The figure shows a general trend which has been used to develop an estimate for radial winds; the inferred radial wind is 15 ± 4 m/s (note that this is averaged from 11.64 to 12.1 UT and hence over a range of Az-El too). This value is represented by a dot in figure 1b, which also shows Doppler radial winds vs. altitude. The Doppler radial wind, averaged over the same time period as well as the 96 to 98 km height range traced out by the trail, is 24 ± 2 m/s. Figure 2a-c show the mapping of the LOS range into East/West (zonal), North/South (meridional), and vertical components respectively. Note that for all the tracking data presented in this paper (except *Rope's* meridional component) a simple linear fit suffices for estimating velocities. In the case of the meridional wind during *Rope*, it can be broken down into a large wind during the first half of the observation (corresponding to 96 to 97 km altitude) and a smaller wind term in the second half (corresponding to 97 to 98 km altitude). Vector wind components were also measured by the Doppler Lidar; however, they were not common volume with the meteor trail (the Lidar has to be scanned North, East and vertically to retrieve these components), nor could they be taken while tracking the trail, though they were typically acquired within a half hour. All these results are summarized in Table 1.

Sailboat:

The *Sailboat* ablated at 11:07:00 with a visual magnitude of −2. The event left a long-lived visual trail which observers recorded until 11:13:30. Although the lidar collected returns from the trail for twenty minutes, the tracking of the trail was not optimal. Figure 3a displays the LOS range and shows the significant difference (compared to the *Rope* tracking, Figure 3a) of simply allowing the trail to drift out of the lidar beam followed by a lidar adjustment to reacquire the trail. The radial wind is estimated from Figure 3a to be 3 ± 1 m/s (from 11.1 – 11.43 UT). The radial wind determined using the Doppler technique at the trail's altitude is 9 ± 2 m/s (Figure 3b). The inferred as well as Doppler zonal, meridional, and vertical winds for this event are also given in Table 1.

Diamond Ring:

A spectacular ablation trail of visual magnitude −1.5 was observed at 09:27:50. The trail was visible until 09:33:00 and during this time, it developed the appearance of a diamond ring (see *Kelley et al.* [1999] for photometrics CCD image). For this event, the trail was first recorded in lidar returns at 09:28, but it took a few profiles to properly acquire the trail. Figure 3c shows the LOS range after the trail was acquired (~09:39). The radial wind is determined using this LOS range to be 2 ± 1 m/s (from 9.64 – 9.85 UT) and the mapped wind components are listed in Table 1. The Doppler radial winds are shown in Figure 3d and are 4 ± 2 m/s over the observation altitudes.

Discussion

It has been shown that tracking long-lived meteor trails provides a comparison for radial winds measured using the Doppler lidar technique. Although there are limitations due to the difficulty in properly tracking the (admittedly rare) meteor trails, it is of great benefit to have a distinct tracer within the Na layer that is moved due to the region's neutral winds. With proper tracking, the meteor trails can also provide common volume estimates of zonal, meridional, and vertical wind components. From Table 1, what becomes apparent is that for the 3 trails analyzed, the Doppler winds are always slightly larger in magnitude than the tracked winds. Though perhaps coincidental, this bias warrants further experimentation to clarify the situation.

One of the main benefits of this technique may be in studying characteristics of the trails other than just their drifts. For example, *Kelley et al.* [1999] proposes a Na catalyzed ozone reaction as a possible source for long-lived visible light emissions. Also, the various optical instruments (CCD cameras, video recorders, etc.) have been used to observe the visual transformations in the trails [*Drummond,* 1999]. Comparison winds for these measurements can aid in developing an understanding of the various processes involved. The observations also provide the opportunity to determine estimates of the region's diffusivity, which were

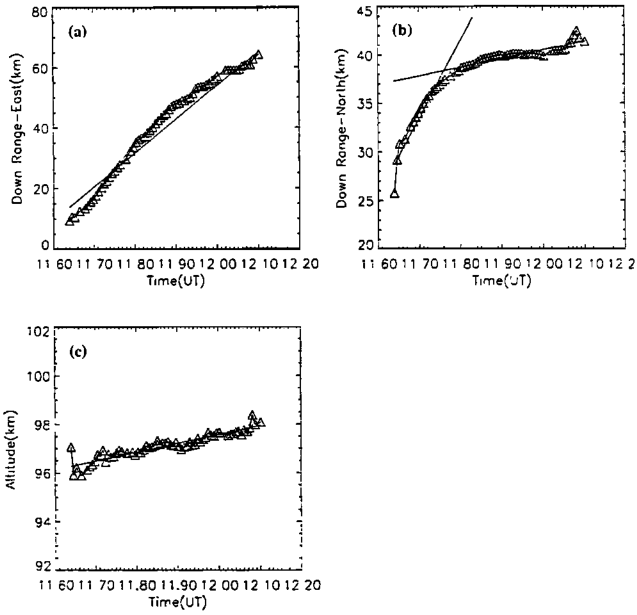

Figure 2. *Rope's* (a) zonal, (b) meridional, and (c) vertical trail motion as determined from the range and azimuth/elevation look angles. Wind components inferred from linear fits to these data are given in Table 1.

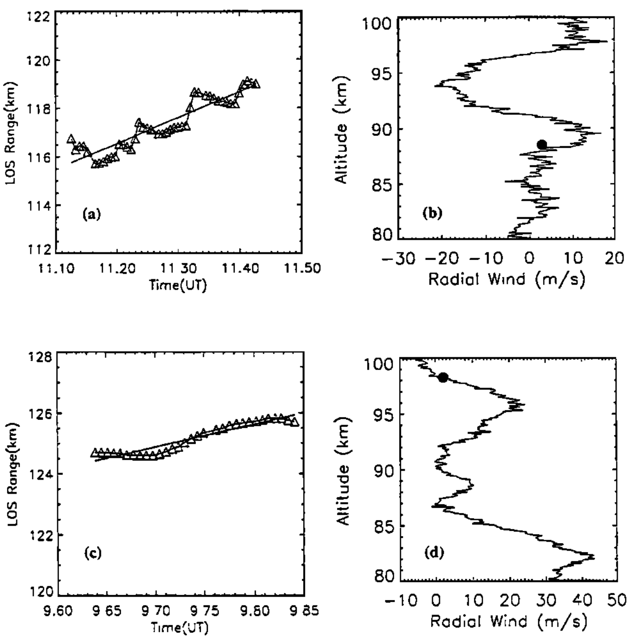

Figure 3. The *Sailboat* meteor trail's (a) Line-of-Site (LOS) range vs. time is used to infer a radial wind of 3 ± 1 m/s near 88.5 km which can be compared to (b) radial winds vs. altitude determined by the Doppler wind technique. The *Diamond Ring* trail's (c) LOS range vs. time is used to infer a radial wind of 2 ± 1 m/s which can be compared to (d) radial winds determined by the Doppler wind technique. The range values for both trails are mapped to determine the meridional, zonal, and vertical components presented in Table 1.

found here to be comparable to molecular. Understanding diffusion on a small scale is important for investigating the turbulence and dispersive nature of this atmospheric region [*Lübken,* 1997; *Hocking,* 1985]. Also, the lifetimes and inferred diffusivities will aid in understanding Na (as well as other metal) chemistry [*Plane et al.,* 1999]. Further understanding of heterogeneous chemistry of the region could also be gleaned by occasionally detuning off Na resonance to look for scattering from meteoric "dust" while tracking a trail.

Another suggestion for future measurements is use of a triangulation photography system as reported in *Larsen et al.* [1998]. These experiments use the triangulated photos of sounding rocket released TMA trails to determine wind as a function of altitude. The visual long-lived meteor observations occurring during the Leonid 1998 meteor storm would provide a natural tracer for determining the winds in the same fashion. An interesting investigation would be to compare the winds inferred from the Doppler lidar, meteor tracking, and triangulation techniques. Since the Leonid meteoroids themselves are moving rapidly, they should ablate at higher altitudes. Future experiments could even actively search for trails between 100 and 110 km, where the traditional Doppler Lidar method cannot measure wind.

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