Combined Lidar and Radar Observations of Smoke Plumes from Prescribed Burns

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Abstract

Transport and dispersion of smoke plume from prescribed burns was studied using W-band radar (95 GHz) and a lidar ceilometer. The Microwave Remote Sensing Laboratory (MIRSL) at the University of Massachusetts observed prescribed burns conducted by the USDA Forest Service at Fort Benning Georgia during April 2008. The radar and lidar instruments, mounted on a single mobile platform, were located approximately 2 to 3 km downwind from the burn site. The lidar was a Vaisala CL31 ceilometer, operated with 10 m vertical resolution and 15 sec time averaging. The W-band radar operated with a range resolution of 30 m. The beamwidths of the radar and the lidar were both approximately 0.2 deg. Simultaneous data collections were obtained from the lidar, which was vertically pointed, and the radar which performed a mix of near-vertical observations, RHI, and PPI scans. These permitted observation of plume vertical extent, structure, and evolution. Results from two burns are highlighted. Observed reflectivities from the plumes are in the vicinity of -30 dBZ. Signal to noise ratio is sufficient to measure velocities and spectral widths from within the plume. Little or no lofted debris or large particulates were observed, and the smoke plume above the radar site was only faintly visible. It is hypothesized that for these 'moist' fires, the smoke particles serve as condensation nuclei permitting observation by the millimeter-wave radar.

Figure 1: UMass W-band mobile radar and lidar system observing smoke plume at Fort Benning on April 11, 2008

1. Introduction

As decades of efforts have been directed at supression of wildland fire, it is paradoxical that controlled fire is now

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Table 1: UMass W-Band Radar System Characteristics

Transmitter	Klystron
Center Freq.	95.04 GHz (3.3 mm)
Peak Power	1.2 kW
Pulse Width	200 ns - 1 us
PRF	13 kHz
Pulsing Scheme	HHHH,VVVV, HHVV, staggered
Max. unambiguous Range	12 km
Max. unambiguous velocity	± 40 m/s
Antenna	Cassegrain dish
Size	1.22 m/4ft
3dB Beamwidth	0.18°
Gain	59 dB
Receiver	Pentek 7631
Bandwidth	6.25 MHz
Intermediate Freq.	120 MHz
Sensitivity(single pulse)	-26.3 dBZ at 1km

Figure 2: A map of the prescribed burn zone(shadowed) and instrument location on April 15, 2008. UMass W-band system is oriented north-south at marker A, about 1.6km from the center of burn zone.

used extensively in the South to manage forests and to reduce the risk of catastrophic wildfire. Prescribed burns are used to consume fuel loads and understory debris to prevent wild fire. However, smoke from these prescribed fires contains a variety of air pollutants that are harmful to human health. Therefore, it is important to understand the characteristics of smoke and to predict its dispersion in order to maintain air quality standards and to minimize the impact on populated areas downwind.

A handful of observations and studies of smoke plumes have been conducted using remote sensing techniques such as lidar, weather radars, and wind profilers. Melnikov reported plume reflectivity around 5-10 dBZ as observed by a WSR-88D radar during a wild fire on March 12, 2008 (Melnikov et al. (2008)). Rogers and Brown observed a paint factory fire using multiple radars and detected rain-equivalent reflectivity exceeded 10 dBZ in the plume column (Rogers R.R. (1996)). Banta et al, 1992, reported observations of both prescribed and wild fires using radar and Doppler lidar (Banta et al. (1992)). Weather radars typically operate between S-band to X-band frequencies with sensitivities in the vicinity of 0-10 dBZ at typical ranges. As a result, reported observations of smoke plumes often rely on lofted debris as the primary source of scattering, and not the smoke or condensed water droplets.

2. Instruments and locations

Radar and Lidar

The UMass W-band radar and lidar system are shown in figure 1. The system consists of a commercial lidar, Vaisala CL31 ceilometer, and a millimeter-wavelength Doppler radar. The W-band radar operates at 95.04 GHz with a peak power of 1.2 kW. The single pulse sensitivity is -26 dBZe at 1km range. Both instruments have a beamwidth of approximately 0.2°. The spatial resolution of 30m in radial direction and 6 m in azimuthal direction at 2 km, provides very fine pixels in close range (≈ 5km) during the prescribed burn observations. The fine resolution reveals detailed smoke plume evolution and small-scale localized turbulence. The detailed specifications of the UMass W-band radar are listed in Table 1.

The Vaisala CL31 operates at a wavelength of 0.9 μm and is thus sensitive to the fine particulates of the smoke plume. The lidar pulses at a 10 kHz rate and accumulates pulses over a 1.6 s averaging period, reporting a profile at most every 2 seconds. During the experiment, it operated exclusively in a vertically pointing configuration. Various scanning strategies were used during the experiment including stationary nearly-vertical scans, range height indicator (RHI) scans, and plan position indicator(PPI) scans. Nearly-vertical scans are presented with lidar measurement for plume verification whereas RHI scans provide insights of smoke column vertical transportation and PPI scans show plume nonvertical dispersion.

Deployment Setup

Depending on the fire weather forcast every morning, the USDA fire crew select a target burn zone according to local temperature, humidity, wind speed and mixing heights. UMass team estimated the plume trajectory according to USDA projection model and situated the instruments about 1 to 2 km downwind from the burn site. The lidar recorded vertical backscatter at the ignition and continued until plume died down. The radar, depending on the deployment location and meteorological condition, performed different type of scans. Figure 2 demonstrates one of the deployment plans. The shadowed area indicates the burn zone, the projected dispersion boundaries are outlined in red. The radar and lidar system was located about 1.6 km downwind, at marker A.

3. Observations

A measurement was performed on April 15, 2008. Forestry weather and fire menagement forecasted relative humidity 25% to 28% with northerly surface winds. The UMass system was situated 1.6 km south of burn site as illustrated in Figure 2. Mechanical constraints limited the maximum elevation angle of the radar to 75°. As the smoke plume drifted south, it was first illuminated by the radar, then by the lidar. The average time delay between radar and lidar observations of an advecting volume is 1-2 minutes. As a result, only the gross plume features can be compared.

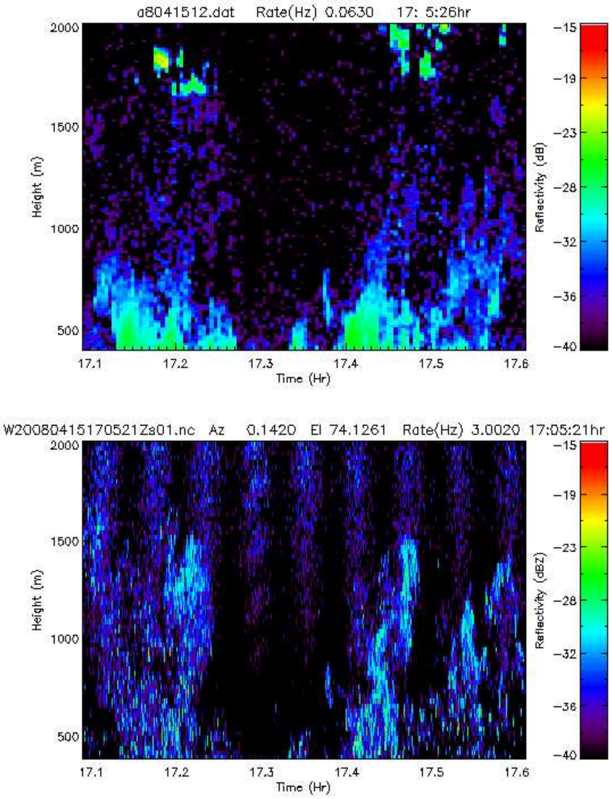

Figure 3: A 40-minute time-height plot of radar reflectivity (bottom) and lidar attenuated backscatter (top). Lidar echo is attenuated through the plume. Note: Ranges within the radar's near field are omitted.

Figure 3 shows a 40-minute time-height cross sec-

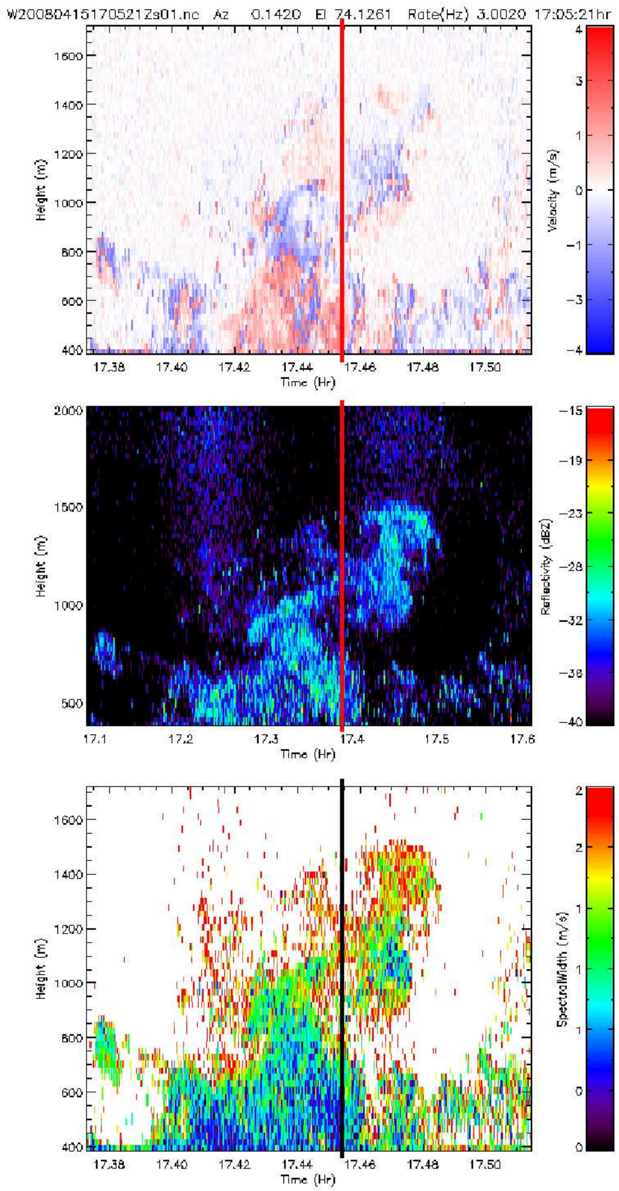

Figure 4: Zoomed detail of the plume signature between 17.4 and 17.5 hour. (a) Nearly-vertical velocity. (b)reflectivity. (c)spectral width

Figure 5: Corresponding video documentation of 17.54 hour, April 15, 2008

tion of both radar and lidar observations of the advecting smoke plume. The radar data has been corrected in height to correspond to lidar measurement. Lower heights are omitted as they were beneath the minimum range of the radar. We note very similar plume morphology exists in both measurements. The lidar backscatter is strongly attenuated above 1,000 m. The radar echo, on the other hand, extends further and also shows more detailed vertical structure. On average, the plume reflectivity is in the vicinity of -30 dBZ.

To reveal more detail plume turbulence and transportation from radar echoes, figure 4 shows a zoomed detail of the plume signature between time 17.4 and 17.5 hour. Vertical velocity, reflectivity and spectral width are shown in figure 4(a),(b) and (c) respectively. From velocity plot, a spot of updraft(colored red) surrounded by colder downdraft (colored blue) was observed around 17.40 hour. Started around 17.42 hour, a larger up-lifting plume came into the radar beam. Velocity is around 0.5 to 1 m/s in low elevation (400 m-800 m). It rapidly increased its velocity to 4 m/s as it moved upwards. The reflectivity plot shows several brighter spots, around -25 dBZ, in the plume. Stronger echoes may be reflections of larger particles or ash. The velocities and spectral widths observed are typical of a daytime convective boundary

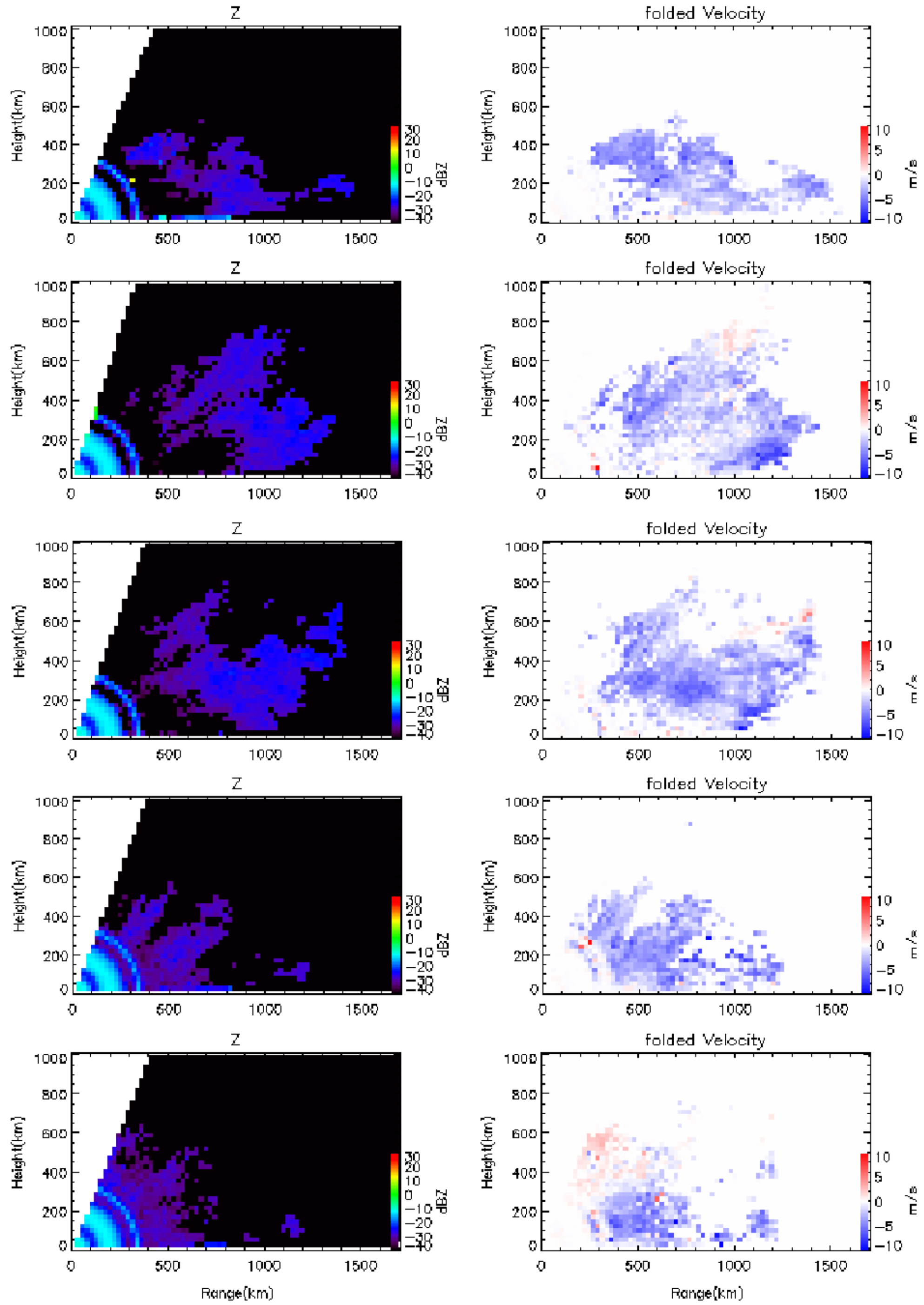

Figure 6: Vertical plume structure from RHI scans on April 11, 2008.

layer. Given the distance from the source, the smoke plume serves as the tracer of the boundary layer flow.

Visual documentation of this vertical obersvation is shown in figure 5. The video camera was pointed directly against sunlight. In the image, the crosshair indicated the location of the radar beam. A thin layer of white smoke can be distinguished from the background. The GPS time stamp on top of the image provides a mean for aligning video information with radar data. The radar image corresponds to the video snapshot is marked in figure 4.

Vertical structures

Vertical structure, plume velocities and evolution were observed on April 11, 2008. UMass W-band radar and lidar were located 3 km north of the burn zone for southly wind. Figure 6 shows a series of RHI scans along the plume axis. Each scan was taken from 0° to 68° elevation and separated in time by 2 minutes. The majority of the plume, shown in blue, approached the radar with average speed between 2.3 m/s to 3 m/s. Evident in the images is the rapid evolution of the plume as it adcents and disperses. However, some plume, shown in red, moved in the opposite direction was observed the scans. This suggests some form of localized turbulance occurred and is well documented by the radar.

4. Discussion

For the cases shown here, the mean reflectivity of the smoke plumes appears to be about -25 dBZe. These would be unobservable by standard weather radars, but are observable by a cloud radar due to its greater sensitivity. The exact source of the scattering the radar sees remains somewhat unclear. The size distribution of smoke particulates lie in the ranges of <1 μm up to approximately 10 μm. These particle distributions alone would result in reflectivities well below the sensitivity of the W-band radar. Thus, we find it unlikely that the radar is seeing the bulk of the smoke particluate, however, it may be possible that there exist sufficient very large particulates in the upper tails of the distribution to give rise to a detectable signature. Large lofted debris (e.g. ash, pine needles, etc.) were not visually evident, and continuity of the observed reflectivity suggests that another source is responsible. These fires were not characterized by particularly vigorous combustion that would loft large quantities of debris. The most likely possibility is that the radar sees the result of condensation of water onto smoke particulates resulting in droplets that are large enough to detect. Thus the radar sees the faint cloud produced by condensed water.

5. Conclusions

These observations demonstrate that millimeter-wave cloud radar can be used to observe smoke plumes from biomass burning at ranges of a few km. The signal to noise ratio is sufficient to deduce the plume extent. Future polarimetric measurements would aid in time specific identification of scattering sources.

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