

Exploration of the Lower Atmosphere with Millimeter-Wave Radar

Mai T. Ngo*, George J. Linde, and WinJou J. Cheung
Naval Research Laboratory
Radar Division, Code 5306
4555 Overlook Ave, S.W.
Washington D.C. 20375

*Email address: ngo@radar.nrl.navy.mil. Phone: (202) 767-0253

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Abstract - With the high peak power and large antenna gain of the WARLOC W-band (94 GHz) radar, clear-air radar returns from the lower atmosphere, which have no visible underlying scattering mechanism, have been observed. Due to their close resemblance to classical sea spikes from the sea-surface scatter, the unknown phenomena are being referred to as “air spikes.” In this paper, a brief description of the high power WARLOC radar and preliminary observations of radar returns from air spikes are presented. Characteristics of air spikes in terms of height distribution, velocity response, volume density distribution, radar cross section, and spatial extent are discussed.

I. INTRODUCTION

High-power millimeter-wave instrumentation radars have a number of important uses ranging from radar applications to basic science studies [1, 2]. The Naval Research Laboratory (NRL) has recently developed a coherent, high-power, 94-GHz radar named WARLOC, with scanning capability. For the development of the WARLOC radar, a gyrokystron amplifier was developed by NRL’s Electronic Science and Technology Division as the final power amplifier. The amplifier is capable of producing 100 kW peak power and 10 kW average power, with an instantaneous bandwidth of more than 600 MHz. At the present time the NRL’s gyrokystron holds the world record of highest average power at this frequency. Other key advanced technologies that made WARLOC possible include low-loss, high-power, over-moded transmission lines developed by General Atomic and a high-power quasi-optical duplexer developed jointly by the MIT Lincoln Laboratory and NRL. Detailed design parameters of the WARLOC radar, applications that could benefit from the unprecedented sensitivity, and early-on experimental measurements are found in Refs. [3-5]. The WARLOC radar has been in operation since November 2001 at the NRL’s Chesapeake Bay Detachment (CBD) facility in Maryland. The WARLOC system is housed in two trailers as shown in Fig. 1. The bigger trailer (40ft x 8ft) houses the entire transmitter, including the gyrokystron tube, the driver tube (traveling wave tube), the high voltage modulator, the superconductor magnet, and the over-moded transmission line. As can be seen, the Cassegrain antenna is mounted on

top of the big trailer. The smaller trailer (20ft x 8ft) houses all the control and signal processing computers, the antenna controller, and part of the receiver and signal generation equipment.



Figure 1. WARLOC radar at NRL’s Chesapeake Beach, Maryland, facility.

Table I lists the WARLOC parameters under normal operating conditions. The WARLOC radar provides a sensitivity improvement of more than 3 orders of magnitude over previous 94-GHz weather radars. This unprecedented sensitivity and extremely high spatial and range resolution have opened up new research opportunities, one of which is the ability to detect much lower cloud returns at long range and the internal structure of clouds can be studied in greater detail [6].

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TABLE I

WARLOC Radar Parameters

Parameter	Value
Frequency	94 GHz
Bandwidth	600 MHz
Range resolution	0.3 m
Peak power	70 kW
Average power	7 kW
Antenna diameter	1.8 m
Antenna gain	62.5 dB
Beam width	0.1°
Transmit loss	3.5 dB
Receiver loss	3.0 dB
Noise figure	9.0 dB

II. MEASUREMENTS

A. Observations of Air Spikes

With the high power and high range resolution (30 cm) of WARLOC, unexplained radar returns have been detected from the lower atmosphere. These echoes appear to travel with the wind, have low radar cross section, and appear at short range with characteristics similar to sea spikes. Since these returns occur during clear-air conditions, they are being referred to as air spikes. Figure 2 shows a temporal profile of radar returns for duration of more than 35 seconds on October 10, 2003, from a short-pulse waveform (100-ns pulse width, 70-kW peak power, and 250-Hz pulse repetition frequency). The antenna was held fixed at 40° azimuth and 50° elevation during the recording period, and air spikes appeared to be transported across the radar beam by the wind. The figure also shows that air-spike cross sections range from 10^{-8}m^2 to 10^{-5}m^2 . On-site weather measurements showed an air temperature of 56°F, a dew point of 39°F, and a relative humidity of 56%, and visibility was relatively high. No visible targets could be detected with the 2 video cameras (near-sight and wide-field on bore sight) mounted on the antenna platform while air spikes were observed. As can be seen from the figure, air spikes are more concentrated at ranges of 1 km or less. At an antenna elevation of 50°, this corresponds to an altitude of 766 m. A few air spikes are scattered above this height.

B. Height Distribution of Air Spikes

To study the height distribution of air spikes, the antenna was set up to scan in elevation, keeping the azimuth stationary.

Figure 3 shows the height versus range of air-spike returns from April 29, 2004, as the antenna scans in elevation from 5° to 80° at a rate of 2° per second, with the azimuth held fixed at 50°. Similar to Fig. 2, air spikes are much denser at lower altitudes (<1km); however, in this figure, another thin layer is observed right above it, and not much is observed above 2 km.

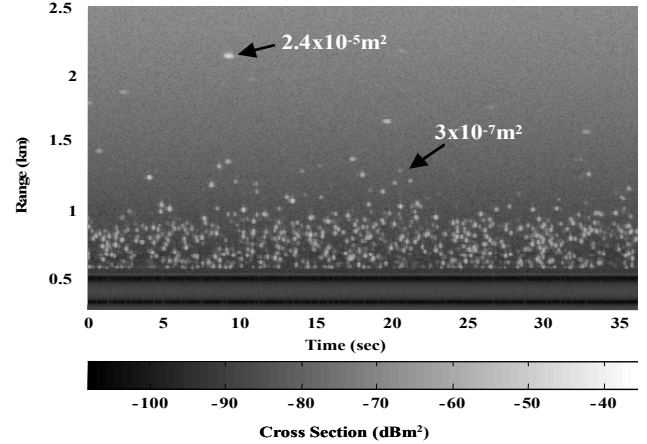


Figure 2. Temporal profile of air spikes on October 10, 2003.

Another example of elevation scanning from 5° to 80° was recorded on 13 May, 2004, with the azimuth fixed at 120° (Fig. 4). In this image, it is interesting to note that a visible cloud-like structure is clearly seen near from a range of 1 km to 2.5 km and a height of around 1.5 km. However, this structure was neither observed with the naked eye nor with video cameras. Again, not much activity is detected above 2 km.

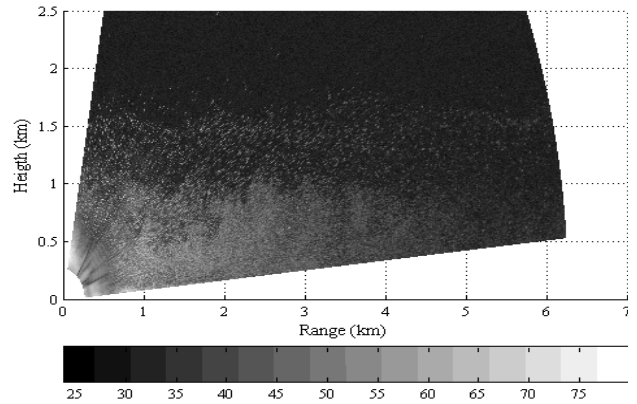


Figure 3. Height vs. Range of air spikes. Elevation Scan of air spikes at 2° per second, Az = 50°.

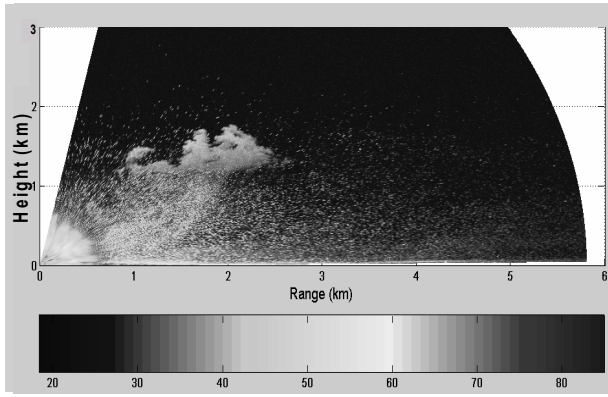


Figure 4. Elevation Scan of air spikes at 2° per second and $Az = 120^\circ$. Data collected on 29 May 2004.

C. Velocity Response of Air Spikes

Correlations of air spikes with wind speed and direction were studied to investigate the velocity response of air spikes. For this measurement, knowing the wind speed and direction, the antenna was set up to do a 1° sector scan at 0.5° per second in the azimuth direction with and against the wind, keeping the elevation fixed at about 10° . Top of Fig. 5 shows the azimuth position of the antenna, while bottom of Fig. 5 shows the air-spike returns as the antenna was scanning with and against the wind. As can be seen, there is a marked difference between going with the wind and going against the wind. When the antenna was moving with the wind, the RF beam followed the air spikes, as if it were tracking these returns. The air spikes appear much longer in duration; some last as long as 3 seconds. In contrast, when the antenna was moving against the wind, these returns are much shorter. From this measurement, it is concluded that air spikes seem to travel with the wind.

D. Air Spike Cross Sections

Air-spike cross sections were calculated for data collected from September 2003 to September 2004. For each day that the data were collected, a maximum cross section was calculated. Figure 6 shows the maximum air-spike cross section as a function of air temperature. The air temperature was taken at the radar site. As can be seen, the maximum air-spike cross sections ranged from 10^{-8}m^2 in the winter time, when the air temperature dropped well below 30°F , to 10^{-5}m^2 when the temperature increased to 80°F in the summer. Although not shown, air-spike cross sections as small as 10^{-10}m^2 have been observed in the cold weather. The fact that these air spikes have been observed in the cold weather, where temperatures at nightfall dropped below 10°F and the surface of the Chesapeake Bay was covered with ice, strongly rules out insects as the only source for these returns. In addition, the strong temperature dependence of the cross sections of these air spikes suggests that the observed returns may be caused by some kind of atmospheric phenomenon,

such as clear-air turbulence, turbulence bursts [7], or water droplets.

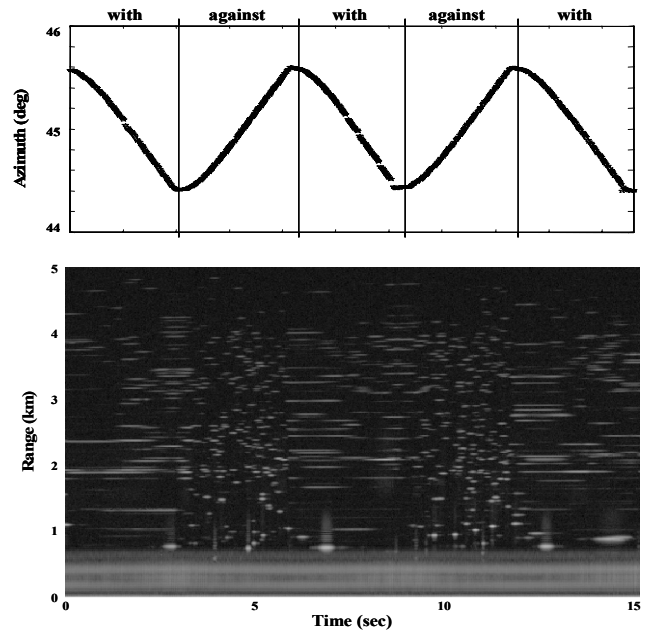


Figure 5. Correlation of air spikes with wind speed and direction at a 10.4° elevation: azimuth position of antenna (top); air-spike returns (bottom).

E. Spatial Extent of Air Spikes

A high-resolution, $20\text{-}\mu\text{s}$, 300-MHz linear chirp waveform with stretch processing was used to determine the spatial extent of the air spikes. Figure 7 shows an image of air spikes for duration of 1.05 s. With the high range resolution (50 cm) of this waveform, individual air spikes can be observed. From this image, it can be seen that the spatial extent of the radar returns from the air spikes are as much as 10 m , which is more evidence suggesting that insects are not the only possible source for these radar returns.

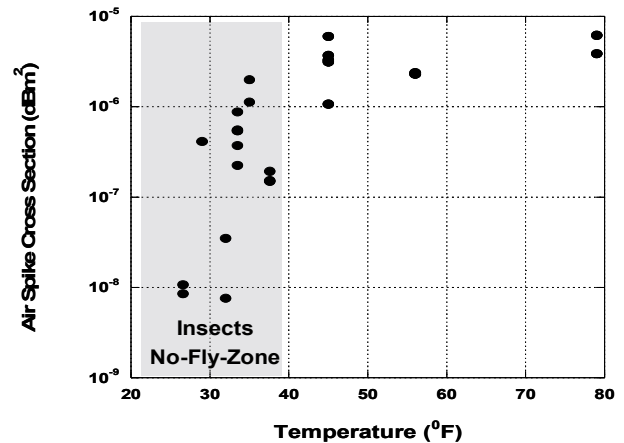


Figure 6. Maximum air-spike cross section from September 2003 to September 2004.

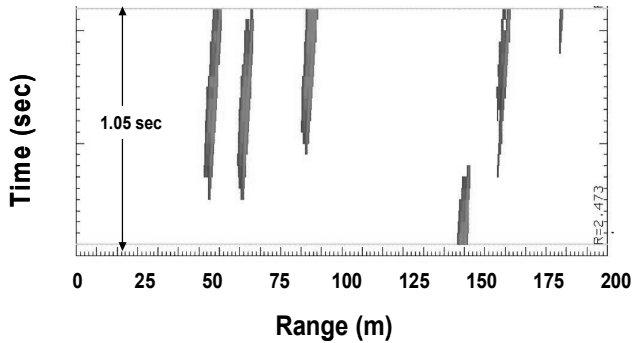


Figure 7. High-resolution image of air spikes.

III. SUMMARY AND CONCLUSIONS

With the high resolution and high power provided by the WARLOC radar, an unexplained atmospheric phenomenon (air spikes) has been observed. From the preliminary experimental measurement air spikes have the following characteristics: radar cross sections are in the range from 10^{-7}m^2 to 10^{-5}m^2 in warm weather and decreased to 10^{-9}m^2 to 10^{-7}m^2 in the winter. Most of the data so far indicate that air spikes seem to travel with the wind, and volume density of air spike is higher at low altitude. Using high resolution waveform, range extent of these air spikes have been measured to be in the range of few meters to up to 10 meters.

From the preliminary data collected thus far, it is established that insects are not the only sources of air spikes. Other atmospheric-related phenomena must be responsible for these air spikes. Possible sources that could cause these clear-air returns including non-homogeneities in refractive index caused by homogeneous turbulence in the atmosphere [8] or turbulent bursts generated in high shear regions [9].

Although radar has been widely used to detect clear-air echoes caused by atmospheric turbulence, little or no research on detecting atmospheric turbulence at millimeter wavelengths, especially at 94 GHz has been conducted to date. Since the WARLOC radar has more than 3 orders of magnitude greater sensitivity than standard atmospheric millimeter-wave radars, it becomes possible to detect clear-air turbulence in the lower atmosphere where other smaller radars have failed.

Based on these preliminary WARLOC observations of unexplained radar detections from the clear-air atmosphere, a collaborative research effort between the Remote Sensing and the Radar Divisions of NRL is underway to extend the research of atmospheric phenomena to millimeter-wave frequencies.

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