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PERFORMANCE OF S-BAND FMCW RADAR FOR BOUNDARY LAYER OBSERVATION

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Abstract—**Over the past 30 years, S-band FMCW radars have seen repeated use in atmospheric boundary layer observations. FMCW radars provide tremendous sensitivity and spatial resolution compared to their pulsed counterparts and are therefore attractive for clear-air applications. These instruments are not without limitations, however. Range (height) mislocation errors due to non-zero Doppler velocities and finite coherence of the clear-air echo have implications on both spatial resolution of FMCW radars and on Doppler estimation. Mislocations of O(m) can occur for relatively small velocities using standard signal processing techniques, so some care must be exercised when interpreting echoes from thin interfacial layers. Operating principles of FMCW radar are reviewed and measurement limitations for atmospheric targets are presented. Data collected by the University of Massachusetts' high-resolution S-band FMCW radar is used to illustrate typical performance.**

I. INTRODUCTION

Over the past 30 years or so, a number of FMCW radars have been developed for atmospheric probing, e.g. [Richter, 1969], [Chadwick et al., 1976], [Eaton et al., 1995], [Hirsch, 1996], [Ince et al., 1998]. While S-band FM-CW radars have been designed with the capability to obtain height and time resolutions of 1 m and 1 s, respectively, the degree to which these resolution limits are obtained in practice depends upon the properties of the atmospheric echo itself. Such measurement limitations, which can impact the interpretation of echoes from extremely thin interfacial layers, has received scant attention in the literature. In this paper we review of the theory of operation of FM-CW radar with respect to range-Doppler ambiguity, and we illustrate system performance with data collected during recent field experiments by the University of Massachusetts' S-band FMCW radar.

II. RANGE VS. DOPPLER IN FMCW RADARS

FMCW radars are a form of pulse-compression radar that provide exceptional range resolution when compared to pulsed radars. They operate by transmitting a long, coded waveform of duration, T, and bandwidth, B. The improvement factor they gain over pulsed radars of equivalent range resolution is given by the time-bandwidth product of the waveform, BT, or the compression gain. This gain can be very large, exceeding 60 dB. While several types of frequency coding may be used to yield the bandwidth B, linear frequency modulation is most commonly used in atmospheric FMCW radars.

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As discussed by [Strauch et al., 1976], Doppler information can be retrieved on a sweep-to-sweep basis by analysing the sequence of complex echoes from a particular range. In this case, the sampling frequency is the reciprocal of the sweep time T, the Nyquist Doppler frequency is 1/2T, and the unambiguous velocity interval is given by

$$|u_{max}| \leq \frac{\lambda}{4T} \tag{1}$$

where λ is the electromagnetic wavelength. This simple analysis assumes that misregistration in range due to Doppler can be ignored. The sensitivity of linear FM waveforms to Doppler is treated in several radar texts (e.g. [Rihaczek, 1985]). It can be shown that the response of the FMCW radar to a point target at range, R_0, moving at radial velocity, u_r, can be expressed

$$y(R) = \frac{\sin\left[\pi\left(f_D T + (R - R_0)\right)/\Delta R\right)]}{\pi\left(f_D T + (R - R_0)/\Delta R\right)} \tag{2}$$

where $f_D = 2u_r/\lambda$ is the Doppler frequency, and $\Delta R = c/2B$ is the range resolution. The presence of both range and Doppler terms in the argument of the sinc function illustrates the effect of target motion on the radar's ability to locate. By rearranging the terms in the argument in (2), the apparent range of the target can be expressed

$$R_{app} = R_0 - f_D T \Delta R \tag{3}$$

where it is easy to see that misregistration by one resolution cell occurs when the product, $f_D T$, equals unity, or when

$$u_r = \pm\frac{\lambda}{2T}. \tag{4}$$

The right hand side of this equation also corresponds to the Nyquist velocity interval for an FMCW Doppler radar. Thus, targets with unambiguously measured velocities are misregistered by no more than one half a resolution cell.

A dramatic example of the misregistration issue can be seen in Fig 1 which shows the radar signatures birds traversing the radar beam. The overall signatures usually display

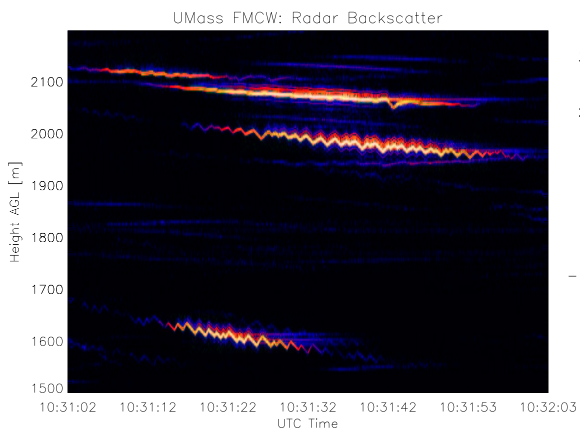

Fig. 1. FMCW radar signature of birds traversing the radar beam. Undulations in the radar echo are a consequence of Doppler-induced misregistration due to the flapping of the wings.

Fig. 2. UMass S-Band FMCW Radar Antennas

a parabolic shape indicative of the time-varying slant range, while the undulations of O(10 m) are indicative of the time varying Doppler shift induced by the flapping of the bird's wings. Interestingly, the time averaging is critical to identifying this signature. The vertical profiles of Fig 1 are not averaged, (20 profiles/s). The details of this signature are lost, however, if averaging exceeds even 1 s. While it is true that atmospheric echoes will rarely display the kinds of vertical velocities observed here, it is a noteworthy effect.

Of perhaps greater concern for resolution considerations is the coherence of the atmospheric target during the sweep interval. Implicit in the discussion of FMCW radar resolution is the assumption that the target produces a constant-frequency sinusoidal echo during the sweep interval T. For complex moving targets and for volume scattering, the coherence time (or the reciprocal of the Doppler spectral width) of the echo will limit resolution. A distribution of Doppler velocities observed over an integration time, T, will yield a distribution of apparent ranges. The resultant spreading in range is dictated by the transformation of the Doppler spectrum using (3), and the rms spread in range is given by

$$\sigma_R = (\sigma_f T)\Delta R, \quad (5)$$

where σ_f is the Doppler spectral width of the echo. From this relation, it is apparent that range resolution and sensitivity are optimized by matching the sweep time, T, to the reciprocal of the Doppler bandwidth of the echo. When this is done the range spreading is equal to the range resolution, and the entire Doppler spectrum is confined, more or less, to one range bin. No improvement in sensitivity or in resolution is achieved by increasing T beyond this value, as the result is the echo simply spreading to adjacent range bins.

To maximize sensitivity, it is desirable to make T as large as possible. T is, however, constrained by the coherence time of the atmospheric echo. In addition, since the ouput of the radar receiver's matched filter is the result of a coherent integration (usually an FFT of the echo waveform), it often has poor statistical merit. Several independent sweeps must be averaged to increase the fidelity of the power estimate, so several coherence times of dwell are usually necessary to obtain independent samples.

III. Atmospheric Observations

The UMass FMCW radar (Figure 2) consists of a pair of 8' parabolic dish antennas, a 250 W transmitter operating at 2.9 GHz with a bandwidth of 60 MHz and a sweep time of 50 ms. The first incarnation of this system employed a 24-bit direct digital synthesizer derived from a 150 MHz clock. Acquired data was processed in real-time using a TMS3020C40 Digital Signal Processor and transferred to a personal computer. The radar has recently been upgraded with a 32-bit DDS operating from a 300 MHz clock, and data acquisition and signal processing are now performed directly on the personal computer CPU. This is made possible using a real-time variant of the Linux (Unix) operating system, and greatly eases the development of software.

Figure3 shows one hour of convective boundary layer observations obtained on 26 Oct 1999 during the CASES'99 experiment in eastern Kansas. The three panels of the figure show respectively reflectivity, Doppler (vertical) velocity, and the correlation coefficient of successive echoes. The latter two products are the result of the pulse-pair processing (e.g. Doviak and Zrnic, 1993) averaged over 100 pulses (approx. 5 s averaging).

The reflectivity panel shows both clear-air echo from refractive index fluctuations and insect echoes within and above the boundary layer. The velocity image which is derived from the phase of the single-lag covariance shows structure for some, but not all of the clear-air echo. Discontinuities in the smoother portions of the velocity image are indicative of velocity aliasing – and hence some misreg-

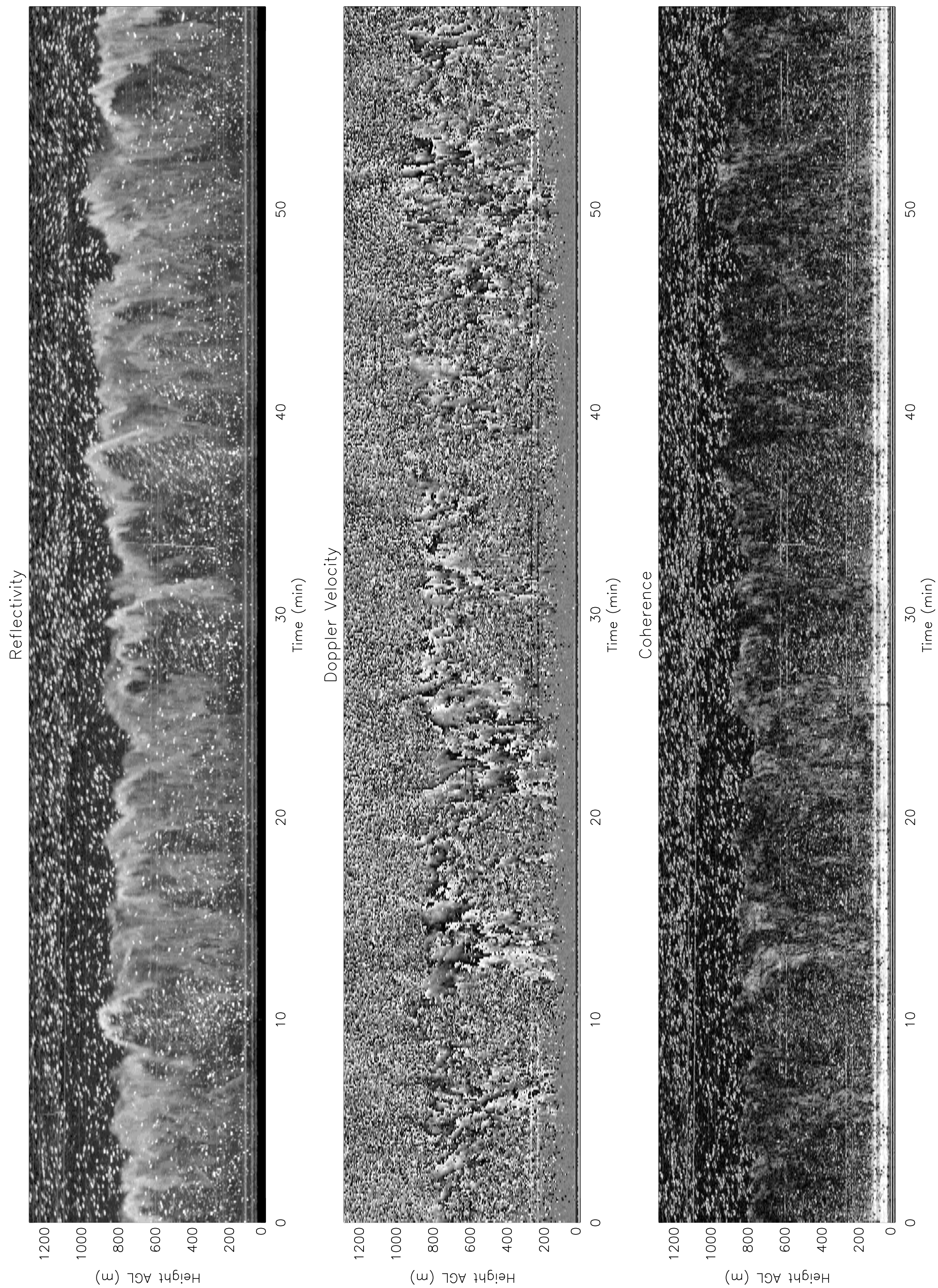

Fig. 3. One hour of CBL echo obtained during CASES'99 experiment 26 Oct 1999. Reflectivity (top), velocity (middle), and single-lag correlation coefficient, ρ (bottom).

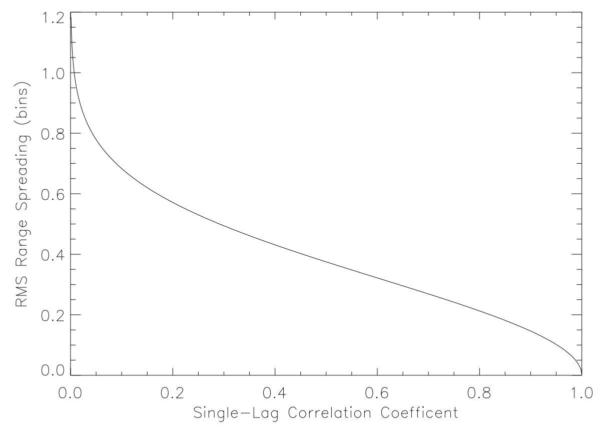

Fig. 4. RMS range spreading as a function of sweep-to-sweep correlation coefficient, ρ (assumes SNR $>> 1$).

istration as discussed earlier (the Nyquist velocity range is ± 50 cm/s). Ground clutter produces near zero velocity at heights below 100 m. Elsewhere, velocities appear random. The lower panel shows extremely high correlations for the insect scattering which is not suprising since they are simple point targets. Even though their mean velocities may be aliased, their spectral width is narrow. This suggests a relatively simple thresholding operation is possible for insect detection. The correlation coefficient for the clear-air echo is much lower on average, indicating some spreading in range of the echo which may obscure the finer details.

For reference, Figure 4 shows the expected spreading in range as a function of the measured correlation coefficient of successive pulses (or, more correctly, sweeps in the case of FMCW radar). The correlation coefficient is typically used as a measure of spectral width when the spectrum is Gaussian and when it is necessarily narrower than the Nyquist Doppler frequency interval. Thus, this plot is only valid for unambigously estimated spectral widths. As one is unable to estimate the width of a spectrum wider than the Nyquist interval, the expression in (5) should be used in general.

IV. Summary

In this paper we have illustrated the well known effect of Doppler velocities and spectral widths on the FMCW radar signatures of atmospheric targets detectable at S-band frequencies. Misregistration occurs when velocities are aliased, and smearing in range occurs for spectral withs exceeding the reciprocal of the sweep time. Care should be taken when configuring an FMCW radar for a particular anticipated resolution and when attempting to interpret fine-scale detail.

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References

[Chadwick et al., 1976] Chadwick, R., Moran, K., Strauch, R., Morrison, G., and Campbell, W. (1976). Microwave radar wind measurements in the clear air. *Radio Sci.*, 11:795–802.

[Eaton et al., 1995] Eaton, F., McLaughlin, S., and Hines, J. (1995). A new frequency-modulated continuous wave radar for studying planetary boundary layer morphology. *Radio Sci.*, 30:75–88.

[Hirsch, 1996] Hirsch, L. (1996). Spaced-antenna-drift measurements of the horizontal wind speed using a FMCW-radar-RASS. *Contr. Atmos. Phys.*, 69:113–117.

[Ince et al., 1998] Ince, T., Pazmany, A., Frasier, S., and McIntosh, R. (1998). A high resolution fm-cw s-band radar for boundary layer profiling and cloud applications. In *Proceedings of 1998 Battlespace Atmospherics & Cloud Impacts on Military Operations Conference*, pages 432–439, Hanscom AFB, MA.

[Richter, 1969] Richter, J. (1969). High-resolution tropospheric radar sounding. *Radio Sci.*, 4:1261–1268.

[Rihaczek, 1985] Rihaczek, A. (1985). *Principles of High-Resolution Radar*. Peninsula Publishing, Los Altos, California.

[Strauch et al., 1976] Strauch, R., Campbell, W., Chadwick, R., and Moran, K. (1976). Microwave FM-CW Doppler radar for boundary layer probing. *Geophys. Res. Lett.*, 3:193–196.