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[1] Bistatic radar measurement of clear-air winds in the atmospheric boundary layer is considered. The context is three-dimensional wind field measurement using dense networks of short-range radars configured to operate in bistatic geometries. Such networks exploit a combination of Rayleigh scattering from insects and Bragg scattering from refractive index turbulence, the latter exhibiting enhanced scattering intensity in forward scatter geometries compared to the monostatic case. Bistatic radar fundamentals are reviewed, and beam-limited scattering volumes are considered. Measurements with sufficient precision ($<1 \text{ m s}^{-1}$) are achievable with relatively low average powers (100 W) with reasonably short dwell times (1 s) for transmitters and receivers separated by as much as 15 km. For a fixed antenna aperture size, frequency dependence of sensitivity for the Bragg component of the composite scattered signal is weak ($\lambda^{2/3}$), provided that the Bragg-resonant wave number for the forward scattering geometry lies within the inertial subrange of refractive index turbulence. In contrast, the strong (λ^4) frequency-dependent Rayleigh insect echo dominates the scattered signal for short wavelengths (i.e., X band and higher frequencies) under many conditions except for small forward scatter angles. Owing to this dominance and to the tendency for refractive index turbulence and insects to occur together in the atmospheric boundary layer, reliance on the bistatic Bragg scattering mechanism is not warranted for short-range, short-wavelength radar networks.

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1. Introduction

[2] Knowledge of the atmospheric boundary layer (ABL) wind field is of considerable value for applications in numerical weather forecasting, aviation, transport and dispersion modeling and prediction, and nowcasting. However, comprehensive measurement of ABL winds over extended areas during nonprecipitating conditions remains elusive because of geometric limitations of current technology as well as the relative weakness of the clear-air radar echo compared to that from precipitation. During warm season months, meteorological radar such as the WSR-88D (NEXRAD) operating at S band (10 cm wavelength) observes clear-air scattering arising from a combination of Bragg scattering from refractive index turbulence and Rayleigh scattering from insects. *Wilson et al.* [1994] observed that such clear-air echo is measurable in the vicinity of such systems and appears to be dominated by insect scattering. Such observations, which are confirmed by other studies [*Achtemeier*, 1991; *Zrnic and Ryzhkov*, 1998; *Kusunoki*, 2002] are operationally limited to maximum ranges of 50–100 km. Beyond this range the radar beam elevation exceeds the ABL height owing to the curvature of the earth, and clear-air observations are therefore limited to a relatively small fraction of total volume mapped out by long-range (230 km) meteorological surveillance radars.

[3] Bragg scattering from refractive index turbulence is known to be the primary source of backscatter at lower microwave frequencies (e.g., L band and below). For example, vertically pointed radar wind profilers operating at VHF and UHF frequencies rely on this mechanism to provide 3D wind vector estimates versus height above the radar [*Ecklund et al.*, 1988]. This technology has

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matured to the point where radar wind profilers are now commercially available from a variety of vendors.

[4] The availability of very low-cost microwave and digital integrated circuits as well as the ubiquity of wired and wireless networks has motivated consideration of dense networks of short-range Doppler radars for use in storm tracking, precipitation estimation, and comprehensive boundary layer wind mapping [Smith *et al.*, 2002; Serafin *et al.*, 2003]. Limiting the operating range of a radar to a few tens of km enables its design on the basis of low-cost, low-power technologies, and networks configured from such radars do not suffer the earth curvature-induced height limitation of their higher-power, longer-range counterparts. The definition, fundamental understanding, development, and validation of the technologies needed to realize short-range radar networks are all active topics of current research inquiry [e.g., McLaughlin *et al.*, 2005; Chandrasekar *et al.*, 2004]. Size, cost, and weight are among the considerations that motivate the use of short microwave wavelengths (X band, 3 cm) in the design of these networks as a means to achieve fine spatial resolution (~ 500 m) using small antennas. An example of a system being developed to observe severe storms and precipitation is given by McLaughlin *et al.* [2005].

[5] Rayleigh scattering from insects will be an important component of the echo when short range radar networks are used during clear-air conditions. However, short-wavelength (3 cm) networks will be insensitive to Bragg scattering from refractive index turbulence. For bistatic radar geometries a significant, though little exploited, enhancement exists for Bragg scatter that substantially favors forward scatter geometries and potentially offers improved sensitivity over the monostatic case. This so-called “bistatic enhancement” was recognized by Atlas *et al.* [1968] and later demonstrated by Doviak *et al.* [1972] through observation of elevated atmospheric layers by a bistatic radar system operated between Wallops Island, VA and Valley Forge, PA. This enhancement (discussed in detail in the following section) yields both an increasing volume reflectivity with forward scatter angle and an increasing upper bound of radio frequency sensitivity compared to the monostatic case. That is, it is possible for short wavelength radar networks that are normally insensitive to Bragg scatter to become sensitive to it when operated as part of a bistatic or multistatic network.

[6] Bistatic configurations have been proposed and demonstrated for obtaining two-dimensional vector winds in the presence of precipitation. Wurman *et al.* [1994] implemented a system using standard, high-power meteorological radars as transmitters augmented with separate low-gain receivers. Two components of wind are then retrievable: one from the high-power meteorological radar and the other from the bistatic configuration. A number of studies have been carried out with this approach [Protat and Zawadzki, 1999; Elia and Zawadzki, 2001; Takaya

and Nakazato, 2002; Satoh and Wurman, 2003; Friedrich and Hagen, 2004].

[7] Dense networks of short-range bistatic radars having higher-gain antennas are more complex to implement owing to the need to synchronize transmitter and receiver antenna beam positions in space. This can be accomplished at a cost of increased design complexity provided this increase is warranted by benefits such as increased scattering sensitivity. In this paper, we explore the feasibility and suitability of bistatic geometries as a means to comprehensively map atmospheric boundary layer winds in the absence of precipitation using dense radar networks. To properly conduct this analysis, it is necessary to consider the two dominant sources of clear-air scattering: Bragg scattering from refractive index turbulence and Rayleigh scattering from nonhydrometeor sources such as insects. It is important to consider both Bragg and Rayleigh scattering because the conditions that favor the presence of insects and significant levels of refractive index turbulence are similar. Both are prevalent in warm season months for temperatures exceeding about 10°C . Both sources of scattering have a well-defined diurnal cycle modulated by the structure of daytime and nocturnal boundary layers [Wilson *et al.*, 1994; Kusunoki, 2002]. In wintertime conditions insects are generally absent, and the low humidity associated with colder air yields generally lower levels of refractive index turbulence.

[8] We note that within the radar community, many authors associate the term clear-air scattering exclusively with Bragg scattering, while in the meteorological community, it is common to also include Rayleigh scattering from insects as source of clear-air echo. In this paper we refer to both sources of scattering by their respective mechanisms, Bragg or Rayleigh.

[9] The paper begins with a review of bistatic radar and terminology and the relevant scattering mechanisms. In section 3 we illustrate the relative impacts of frequency and scatter angle on both Bragg and Rayleigh scatterers, and we consider the properties of hypothetical measurement systems operating at S band (“long” wavelength) and at X band (“short” wavelength). We will show that the bistatic enhancement indeed offers improved sensitivity to Bragg scatter at both long and short wavelengths, but because of Rayleigh scatter’s strong dependence on wavelength (λ^{-4}), it will tend to dominate the scattering at short wavelengths for most forward scatter angles geometries. Owing to this dominance, we conclude that bistatic geometries are not a requirement for clear-air wind mapping using short wavelength radars, as discussed in the last section of this paper.

2. Theory

[10] A bistatic radar system consists of a transmitter, and one or more receivers located physically distant from

Figure 1. Bistatic radar system geometry: The transmitter (T) and receiver (R) are separated by baseline (B) along the x axis. S denotes the scattering location which lies on the ellipse defined by constant $R_1 + R_2$ in the plane defined by the triangle RST.

the transmitter (Figure 1). The transmitter, T, and receiver, R, constitute the foci of an ellipsoid, which defines the natural coordinate system for measurements made by the bistatic radar. Ignoring multiple scattering, all targets lying on the ellipsoid share a common range ($R_1 + R_2$). The radar range equation for bistatic radar is expressed as

$$P_r = \frac{P_t G_t A_{er} \sigma_b}{(4\pi)^2 R_1^2 R_2^2}, \quad (1)$$

where P_r is the power at the receiving antenna, P_t is the transmitted power, G_t is the gain of the transmitting antenna, A_{er} is the effective aperture area of the receiver, σ_b is the bistatic radar cross section of the target, and $R_1 + R_2$ is the path between transmitter, sampling volume, and receiver. This equation reduces to the monostatic form if transmitter and receiver are colocated. For atmospheric targets, σ_b is represented by the product $\eta_b V$ which is the product of the bistatic volume reflectivity and the scattering volume. Both η_b and V vary with position along a given ellipsoid.

2.1. Bragg Scattering

[11] A primary source of clear-air scattering in the atmospheric boundary layer and lower free troposphere is Bragg scattering from refractive index turbulence. In the Bragg-scattering theory derived by *Tatarskii* [1961], the dominant source of scatter comes from spatial variations in the refractive index field which are of an appropriate scale to interact resonantly with the probing electromagnetic signal. The radar volume reflectivity for such scattering can be expressed as [Doviak and Zrnic, 1984]

$$\eta = 8\pi^2 k_0^4 \Phi_n(\mathbf{k}_B) \sin^2 \chi, \quad (2)$$

where $k_0 = 2\pi/\lambda$ is the radar wave number, $\Phi_n(\mathbf{k}_B)$ is the average spectral density of refractive index fluctuations

evaluated at the Bragg-resonant wave vector, $\mathbf{k}_B$, and χ is a polarization term to be discussed shortly.

[12] If the turbulence is statistically homogeneous and isotropic, then the spectral density of refractive index turbulence becomes independent of direction and $\Phi_n(k)$ is described by a power law,

$$\Phi_n(k) \approx 0.033 C_n^2 k^{-11/3}, \quad (3)$$

where C_n^2 is the refractive index structure parameter in $\text{m}^{-2/3}$. The Bragg-resonant wave vector is given by

$$\mathbf{k}_B = \hat{\mathbf{m}} 2k_0 \sin(\theta_s/2), \quad (4)$$

which describes the spatial scale of the inertial subrange turbulence that is responsible for the microwave scatter. Here, θ_s is the forward scatter angle defined as the angle between the forward propagation direction and the scattered direction (0 for forward scatter, π for backscatter), and $\hat{\mathbf{m}}$ is a unit vector which bisects the incident and scattered directions. When (2) and (3) are combined, one obtains

$$\eta = 0.38 C_n^2 \lambda^{-1/3} \sin^{-11/3}(\theta_s/2) \sin^2 \chi. \quad (5)$$

[13] This equation's strong dependence on θ_s reveals a substantial amplification for forward scatter geometries. This enhancement is a consequence of shift in the Bragg-resonant scale to lower wave numbers where the spectral density, $\Phi_n(k)$, is substantially larger. For example, forward scatter angles of 60° and 30° result in enhancements of 11 dB and 21 dB respectively over backscatter. In the context of electromagnetic propagation, this forward scatter is termed troposcatter, a mechanism included in modern electromagnetic propagation models [Hitney, 1993; Wyngaard et al., 2001]. In the case of backscatter, (5) reduces to the familiar monostatic expression commonly attributed to *Ottersten* [1969].

[14] The validity of (5) hinges on the existence of an inertial subrange containing the wave number, k_B . The inertial subrange is bounded at small scales by the Kolmogorov microscale, or inner scale, which is of the order 1–10 mm depending upon environmental conditions. Measurements are reliable at Bragg resonant scales a few times this limiting scale.

[15] At low wave numbers, the assumption of isotropy of the turbulence sets the bound. A spatial scale of the order of meters is a reasonably safe limit to this assumption in most cases. The scale may be much larger in highly convective conditions, or lower in stably stratified conditions. As a consequence of (5), the spatial scale of turbulence influencing the radar echo varies substantially forward scatter angle, and hence with position in a bistatic radar geometry. At scales where turbulence becomes anisotropic, the spectral density, $\Phi_n(\mathbf{k})$ becomes direction dependent and the entire concept of C_n^2 breaks

down. Such cases are beyond the scope of this paper, however.

2.2. Rayleigh Scattering

[16] The other primary source of clear-air scattering is Rayleigh scattering from biota such as insects. It is usually described in terms of the radar reflectivity factor used to describe scattering from precipitation,

$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 Z \sin^2 \chi, \quad (6)$$

where K depends upon the complex dielectric constant of the scattering particles. For rain at low to moderate microwave frequencies, $|K|^2 \approx 0.9$. Z is the reflectivity factor, defined as the 6th moment of the size distribution of the scatterers, and the final term is the same polarization term as in (2).

[17] The angle, χ , is that between the incident electric field vector and the scattered propagation direction (depicted in Figure 1 for vertical polarization). This polarization term describes the radiation pattern of the scattering, which behaves like that of an electric dipole. As a result, vertically polarized incident radiation scatters preferentially in the horizontal plane (where $\sin^2 \chi = 1$), whereas horizontally polarized incident radiation scatters preferentially in the vertical plane. For mapping horizontal winds in a nearly horizontal plane, vertical polarization is the preferred mode of transmission and reception.

[18] Strictly speaking, an appropriate value of K should be used for insects, whose dielectric constant differs from water, though this is rarely, if ever, done. Similarly, for short wavelengths, scattering from larger insects may enter the Mie regime, in which case Z is replaced by Z_e , the equivalent reflectivity factor, which simply acknowledges the likely presence of Mie scattering. Though highly variable, a typical value of reflectivity factor due to insects in warm season conditions is approximately -5 dBZ [Wilson *et al.*, 1994]. Reflectivities as high as 10 dBZ can occur in convergence zones where insect densities are high. Finally, the complex shape of insects leads to polarization signatures that differ noticeably from both precipitation and refractive index turbulence [Zrnic and Ryzhkov, 1998].

[19] To summarize we find the following conclusions. For Bragg scattering, as long as k_B lies within the inertial subrange, the scattering is weakly dependent on wavelength and, for vertical polarization, is strongly dependent on forward scatter angle. Rayleigh scattering is strongly dependent on wavelength and independent of forward scatter angle. Both types of scattering radiate like electric dipoles.

2.3. Scattering Volume

[20] In (1), V is the scattering or resolution volume. Under the assumption that scattering sources are distrib-

uted homogeneously in space, this may be limited by the intersection of the radar beams (beam limited) or by their intersection and the pulse length (pulse limited).

[21] For beam-limited scattering volumes, Ishimaru [1978] gives the following approximate expression for narrow Gaussian shaped beams,

$$V = \frac{\pi(\beta_t R_1)^2}{4 \ln 2} \frac{\beta_r R_2}{\sqrt{\ln 2} \sin(\theta_s)}, \quad (7)$$

where β_t and β_r are the transmit and receive 3 dB beam widths. This expression approximates the volume as a slanted cylinder with diameter $\beta_t R_1$ and height $\beta_r R_2 / \sin(\theta_s)$. In this case, it is assumed that $\beta_t R_1 < \beta_r R_2$. An exchange of terms satisfies the case where $\beta_t R_1 > \beta_r R_2$.

[22] The pulse-limited volume adds another range dimension to the beam-limited expression. In general, the scattering volume is the intersection of the two cones defined by the transmit and receive beam solid angles and of the ellipsoidal shell defined by the range interval. The range interval, ΔR , defined as the normal distance between concentric ellipsoidal shells, can be expressed as

$$\Delta R = \frac{c\tau}{2 \sin(\theta_s/2)}, \quad (8)$$

where τ is the pulse length and θ_s is the forward scattering angle (Figure 1). Note that the internal (or bistatic) angle, γ_s , between R_1 and R_2 is $\pi - \theta_s$. The range interval is minimum for R_1 and R_2 lying along the baseline defined by the transmitter and receiver, where $\theta_s = \pi$ and where ΔR reduces to the monostatic expression, $c\tau/2$. It is maximum for $R_1 = R_2$ where the forward scatter angle is minimum.

[23] Most bistatic demonstrations to date have employed a low-gain receiving antenna in combination with a high-gain transmitter [Wurman *et al.*, 1994; Elia and Zawadzki, 2001; Friedrich and Hagen, 2004]. In such a case, the scattering volume is defined essentially by the transmitter beam and the pulse interval,

$$V = \frac{\pi(\beta_t R_1)^2}{4 \ln 2} \Delta R. \quad (9)$$

2.4. Doppler Velocity

[24] The ultimate objective is to measure winds via the Doppler shift of the radar scattering. The Doppler shift is determined by the time rate of change of scatterer range, $d(R_1 + R_2)/dt$. Because the ellipsoid defines the locus of points of constant range, only velocities normal to the ellipsoid are detectable by a bistatic radar. Denoting this normal component of velocity, V_n , we have

$$f_D = \frac{2V_n}{\lambda} \sin(\theta_s/2) = \frac{2V_a}{\lambda}, \quad (10)$$

Figure 2. Velocity uncertainty versus dwell time for fixed forward scatter angle of 30° : (left) S band and (right) X band.

where f_D is Doppler frequency and the forward scattering angle has again been used. V_a is defined as the apparent Doppler velocity, as would be interpreted by a monostatic radar yielding $V_a = V_n \sin(\theta_s/2)$ [Protat and Zawadzki, 1999]. The direction of V_n is also along the bisector of the bistatic angle, $\gamma_s/2$. The expression for f_D reduces to the monostatic form for R_1 and R_2 lying along the transmitter-receiver axis. The Doppler frequency is minimally sensitive to V_n where $R_1 = R_2$ which is also where θ_s is smallest. We note this reduction in velocity sensitivity occurs in contrast to the increase in volume reflectivity for Bragg scattering.

[25] The velocity uncertainty is directly tied to uncertainty in the Doppler frequency. Doviak and Zrnic [1984] give the following expression for velocity uncertainty assuming spectral (FFT-based) processing with monostatic radar,

$$\sigma_{\hat{V}} = \frac{\lambda}{2\sqrt{MT_s}} \left[\frac{\sigma_{V_{norm}}}{4\sqrt{\pi}} + \frac{2\sigma_{V_n}^2}{SNR} + \frac{1}{12SNR^2} \right]^{1/2}, \quad (11)$$

where $\hat{V}$ is the estimated mean Doppler velocity, M is the number of samples used in the estimate (FFT size), T_s is the sample interval, and $\sigma_{V_{norm}}$ is the RMS velocity of the observed scatterers normalized by the Nyquist velocity range, $\lambda/2T_s$. That is, it is the normalized spectrum width.

[26] For bistatic geometries, we can modify (11) by replacing V with V_a , the apparent Doppler velocity. Then we can relate the uncertainty in the estimate of V_a to that of V_n using

$$\sigma_{\hat{V}_n} = \frac{\sigma_{\hat{V}_a}}{\sin(\theta_s/2)}. \quad (12)$$

Thus uncertainties in apparent velocity are amplified for forward scatter angles.

[27] The first term within the brackets in (11) implicitly assumes the RMS velocity of the scatterers is isotropic, though it may, in fact, be direction dependent. Such will be the case if the scattering volume is comparable to or exceeds the outer scale of turbulence, which is likely in many instances. Nonetheless, we will proceed with an assumption that RMS velocities are about 1 m/s, which is a typical value for summertime clear-air observations.

2.5. Signal-to-Noise Ratio

[28] The bistatic radar signal-to-noise ratio (SNR) is calculated as for the monostatic case,

$$SNR = \frac{P_r}{k(T_{rec} + T_{ant})B}, \quad (13)$$

where P_r is obtained from (1), k is Boltzman's constant, T_{rec} and T_{ant} are respectively the receiver equivalent noise temperature (including all front-end losses) and the radiometric noise temperature collected by the receiving antenna, also called the antenna temperature. The latter will depend on pointing angle and atmospheric conditions, but for low elevation angles (e.g., 5° and lower), it is not unreasonable to assume an opaque atmosphere of 290 K. Resulting SNR estimates will be, if anything, slightly pessimistic. B is the receiver bandwidth, which for pulsed systems is approximately the reciprocal of the pulse width.

[29] In the case of beam-limited operation, the transmitter may radiate a continuous wave (CW) signal in which case B need only be large enough to accommodate the range of expected Doppler frequencies. Such a receiver bandwidth is much narrower than for the pulsed

Figure 3. Velocity uncertainty versus bistatic angle for fixed dwell time of 0.1 s: (left) S band and (right) X band.

case, resulting in substantially greater receiver sensitivity and permitting substantially reduced peak transmitter power. The practical issue in realizing such operation is adequate rejection of the signal propagating directly along the baseline from transmitter to receiver. If transmitter and receiver are within line of sight, then sidelobes in this direction must be quite low, and may require use of nulling techniques at the receiver.

3. Sensitivity

[30] Using (11) and (12) we plot Figures 2 and 3, which show the dwell time and scatter angle depend-

ences on velocity uncertainty for bistatic systems. Figure 2 shows velocity uncertainty as a function of dwell time for a constant forward scatter angle of $\theta_s = 30^\circ$ for SNRs of -5 dB, 0 dB and 10 dB. Dwell time is expressed as

$$T_d = MT_s, \quad (14)$$

where M is the number of samples, and T_s is the sampling interval chosen to permit a maximum apparent velocity of $V_a = 10$ m/s. The left plot is plotted for S band, where $T_s = 1.25$ ms and the right plot is for X band, where $T_s = 0.375$ ms. We observe that for a fixed velocity uncertainty, the dwell time required is around three times

Figure 4. Map of required transmit power to obtain 0 dB SNR from refractive index turbulence with $C_n^2 = 10^{-16} \text{ m}^{-2/3}$: (left) S band and (right) X band.

Figure 5. Map of required dwell time to obtain velocity measurement uncertainty of 1 m/s: (left) S band and (right) X band.

more for S band than X band as a consequence of the differing wavelength.

[31] Figure 3 shows uncertainty in velocity versus bistatic angle θ_b for a fixed dwell time of 0.1 s. Again, the left plot is plotted for S band and the right is for X band for SNRs of -5 , 0 and 10 dBs. For S band the measurement error is greater than that of X band because of the equal dwell times. Both plots show dramatic increase in uncertainty for small forward scatter angles as a result of the dilution of velocity precision given by (12).

[32] We now consider two hypothetical bistatic radar networks in which the radars (and hence the transmitter-to-receiver bistatic baseline) are separated by 15 km. One system operates at S band ($\lambda = 10$ cm) and the other operates at and X band ($\lambda = 3$ cm). For both systems the transmit and receive antennas have fixed aperture area of 4.5 m^2 (2 m diameter), resulting in antenna gains of 35 dB and 45 dB at S and X band respectively. These correspond to 3 dB beam widths of 3° and 0.9° at S and X bands respectively. We assume receiver noise figures of 3 dB and receiver bandwidths of 1 kHz. (The specific values of radar spacing, antenna size, noise figure, and bandwidth described here are representative of a range of deployment scenarios over which any individual number might differ by a factor of 2 or more without changing the substance of the results that follow.)

[33] Figure 4 shows a map of required transmitter power necessary to obtain 0 dB SNR assuming $C_n^2 = 10^{-16} \text{ m}^{-2/3}$, a value representative of weak refractive index turbulence. The x axis represents the transmitter-receiver baseline and the y axis represents the off-axis baseline. The gridding of the 2D space represents the intersections of 3 dB beam widths of the transmitting and receiving antennas located at either end of the x axis. In Figure 4, an off-axis distance of 3700 m midway along

the x axis corresponds to $\theta_s = 30^\circ$. As a consequence of the fixed aperture size, the X band system yields a finer sampling grid than does S band. Also, power requirements are similar, as the overall dependence of (1) for fixed aperture is $\lambda^{2/3}$. Thus X band requires about 3 dB more power than does S band for equal sensitivity.

[34] Figure 5 shows a map of required dwell time to obtain a velocity uncertainty of 1 m/s assuming equal transmit powers of 100 W. We note the presence of a contour of minimum required dwell time. For scatter angles larger than this optimum value, dwell time increases because of reduced SNR, while for scatter

Figure 6. Time-height cross section of clear-air echo observed with an S band FMCW radar. Dots indicate insect echoes, while distributed backscatter is from refractive index turbulence.

Figure 7. Separated echoes of Figure 6: (left) Bragg echoes and (right) Rayleigh echoes.

angles smaller than this optimum value, dwell time increases because of the geometrical dilution of precision for small forward scatter angles.

4. Influence of Bragg and Rayleigh Scattering

[35] In this section, we simulate bistatic observations of clear-air scattering using data collected with a high-resolution, monostatic, S band frequency-modulated continuous wave (FMCW) radar [Ince *et al.*, 2003]. This radar operates with a 3° beam width and 2.5 m range resolution and routinely resolves individual insects in addition to refractive index turbulence. Figure 6 shows a time versus height cross section of the atmospheric

boundary layer obtained with the FMCW radar. The radar was pointed vertically in this case. Distributed echo is that from refractive index turbulence, while dot echoes are from insects. The Atmospheric Boundary Layer occupies the lower 1 km of Figure 6, with three elevated and insect-laden layers above the capping inversion. The volume reflectivity scale here is from -165 dB m^{-1} to -115 dB m^{-1} .

[36] Through fairly simple image processing, it is possible to separate, approximately, the Rayleigh and Bragg scattering sources. By median filtering and thresholding, we isolate discrete scatterers from distributed sources thereby effecting a separation of reflectivities by scattering source. Figure 7 illustrates this separation where the left plot shows the reflectivity of Bragg echoes

Figure 8. Same as Figure 7 but with forward scatter angle of 30° : (left) Bragg echoes, 21.5 dB bistatic enhancement, and (right) Rayleigh echoes.

Figure 9. Same as Figure 8 but operating at X band: (left) Bragg echoes, 22 dB increase, and (right) Rayleigh echoes, 21 dB increase.

and the right plot shows the same for Rayleigh echoes. Note that the reflectivity scale is same as Figure 6. The Rayleigh echoes are obtained by subtracting from the original image a 7×7 window median filtered image. Only positive excursions from the median filtered image are retained as Rayleigh echoes, so negative values in the difference image are set to zero, and the result is the Rayleigh-scattering component. This is subtracted from the original image to obtain the Bragg-scattering component. While by no means a perfect separation, it is adequate to illustrate the separate impacts of bistatic operation on two different scattering mechanisms.

[37] Figure 8 shows the same scattering sources as they would appear to a hypothetical bistatic radar system

operating at S band with a forward scatter angle of 30° . Note the significant enhancement of the Bragg echo relative to the Rayleigh echo as a result of the $\sin^{-11/3}(\theta_s/2)$ term. For $\theta_s = 30^\circ$, the reflectivity increases by 21.5 dB. Figure 9 shows the effect of the same forward scattering geometry as viewed by a hypothetical X band bistatic radar. Compared to the S band bistatic case of Figure 8, there is only a modest increase in Bragg reflectivity arising from the $\lambda^{-1/3}$ dependence while there is a strong increase (λ^{-4}) in Rayleigh reflectivity.

[38] Finally, Figure 10 illustrates the recombination of the scattering sources at S band (left plot) and X band (right plot). In this case the reflectivity appears to be dominated by Bragg echoes at S band which have

Figure 10. Same as Figure 6 but as perceived by a hypothetical bistatic radar operating at (left) S band, 21.5 dB increase by Bragg echoes, and (right) X band, 22 dB.

Figure 11. Fraction of reflectivity due to Bragg scattering versus forward scatter angle at frequencies of 1, 3, and 10 GHz for $C_n^2 = 10^{-14} \text{ m}^{-2/3}$ and Rayleigh reflectivity of -10 dBZ .

increased by 21.5 dB while the Rayleigh echoes remain essentially constant. At X band, the Bragg echo has been enhanced by 22 dB over the monostatic S band case, however it is still strongly influenced by Rayleigh echo because of the 21 dB increase in reflectivity from the λ^{-4} dependence.

5. Discussion

[39] This comparison, while necessarily anecdotal, is representative of typical boundary layer echoes often observed during the daytime. It illustrates that under warm season clear-air conditions the presence of Rayleigh scattering from insects will dominate the bistatic Bragg scattering at short (X band) wavelengths except for the cases of small forward scattering angles. Indeed, one can estimate, crudely, the fraction of received power attributable to Bragg scattering by comparing volume reflectivities. This assumes that both sources of scattering are volume filling. Figure 11 plots the fractional scattering due to Bragg mechanism, f_B , as a function of forward scatter angle for frequencies of 1, 3, and 10 GHz. Here we have plotted

$$f_B = \frac{1}{1 + \eta_R/\eta_B}, \quad (15)$$

where f_B is the fractional echo due to Bragg scattering, η_R is the Rayleigh volume reflectivity corresponding to a weak reflectivity factor of -10 dBZ , and η_B is the Bragg reflectivity corresponding to $C_n^2 = 10^{-14} \text{ m}^{-2/3}$ corresponding to moderate refractive index turbulence. For these particular conditions, Bragg scatter is always dominant for frequencies below 1 GHz, but is only

dominant for forward scatter angles below 45° at 3 GHz, and below 15° at 10 GHz. However, we note that these small forward scatter angles are also those where the geometrical dilution of velocity precision given by (12) is significant. Were Figure 11 to be recalculated for stronger, more typical Rayleigh reflectivity values or for weaker turbulence values, the Bragg fraction would be even weaker than that shown. Thus, while the bistatic geometry does indeed enhance the scattering from refractive index turbulence, the composite echo is substantially dominated by insect echo. This has important implications for system design: since the insect echo exhibits similar cross section in monostatic and bistatic geometry (assuming vertical polarization) overall sensitivity advantage is not achieved by exploiting bistatic enhancement of Bragg scattering at short (X band) wavelengths. This indicates that monostatic operation exploiting Rayleigh scattering from insects is sufficient, and is the preferred clear-air operating mode for dense X band radar networks during warm seasons.

[40] A potentially important caveat is that the reliability of insects as tracers of the winds needs to be further investigated. At lower frequencies (S band and below), the bistatic enhancement can significantly exceed the insect scatter, and as truly passive tracers, bistatic echoes from clear-air turbulence are more reliable indicators of wind. However, we note that other challenges arise at these lower frequencies. Large antennas are required to obtain significant directivity, and ground clutter will be more prevalent if low-directivity antennas are employed. Such may be mitigated through signal processing techniques provided they do not saturate the radar receiver.

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References

- Achtemeier, G. (1991), The use of insects as tracers for “clear-air” boundary-layer studies by Doppler radar, *J. Atmos. Oceanic Technol.*, 8, 746–765.
- Atlas, D., K. Naito, and R. E. Carbone (1968), Bistatic microwave probing of a refractively perturbed clear atmosphere, *J. Atmos. Sci.*, 25, 257–268.
- Chandrasekar, V., S. Lim, N. Bharadwaj, D. McLaughlin, V N. Bringi, and E. Gorgucci (2004), Networked radar operation at attenuating frequencies: Principles and applications, paper presented at 3rd European Conference on Radar Meteorology and Hydrology, Copernicus Ges., Visby, Sweden, 5–8 Sept.

- Doviak, R. J., and D. S. Zrnic (1984), *Doppler Radar and Weather Observations*, pp. 374–384, Elsevier, New York.
- Doviak, R. J., J. Goldhirsch, and A. R. Miller (1972), Bistatic radar detection of high altitude clear-air atmospheric targets, *Radio Sci.*, 7, 993–1003.
- Ecklund, W. L., D. A. Carter, and B. B. Balsley (1988), A UHF wind profiler for the boundary layer: Brief description and initial results, *J. Atmos. Oceanic Technol.*, 5, 432–441.
- Elia, R. D., and I. Zawadzki (2001), Optimal layout of a bistatic radar network, *J. Atmos. Oceanic Technol.*, 18, 1184–1194.
- Friedrich, K., and M. Hagen (2004), On the use of advanced Doppler radar techniques to determine horizontal wind fields for operational weather surveillance, *Meteorol. Appl.*, 11, 155–171, doi:10.1017/S1350482704001240.
- Hitney, H. V. (1993), A practical troposcatter model using the parabolic equation, *IEEE Trans. Antennas Propag.*, 41, 905–909.
- İnce, T., S. J. Frasier, A. Muschinski, and A. Pazmany (2003), An S-band frequency-modulated continuous-wave boundary layer profiler: Description and initial results, *Radio Sci.*, 38(4), 1072, doi:10.1029/2002RS002753.
- Ishimaru, A. (1978), *Wave Propagation and Scattering in Random Media*, vol. 1, chap. 4, pp. 74–77, Elsevier, New York.
- Kusonoki, K. (2002), A preliminary survey of clear-air echo appearances over the Kanto plain in Japan from July to December 1997, *J. Atmos. Oceanic Technol.*, 19, 1063–1072.
- McLaughlin, D. J., V. Chandrasekar, K. Droegemeier, S. Frasier, J. Kurose, F. Junyent, B. Philips, S. Cruz-Pol, and J. Colom (2005), Distributed collaborative adaptive sensing (DCAS) for improved detection, understanding, and prediction of atmospheric hazards, paper presented at 9th Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface, Am. Meteorol. Soc., San Diego, Calif., 9–13 Jan.
- Ottersten, H. (1969), Atmospheric structure and radar backscattering in clear air, *Radio Sci.*, 4, 1179–1193.
- Protat, A., and I. Zawadzki (1999), A variational method for real-time retrieval of three dimensional wind fields from multiple Doppler bistatic radar network data, *J. Atmos. Oceanic Technol.*, 16, 432–449.
- Satoh, S., and J. Wurman (2003), Accuracy of wind fields observed by a bistatic Doppler radar network, *J. Atmos. Oceanic Technol.*, 20, 1077–1091.
- Serafin, R. J., et al. (2003), *Tracking and Predicting the Atmospheric Dispersion of Hazardous Material Releases: Implications for Homeland Security*, Natl. Acad. Press, Washington, D. C.
- Smith, P. L., et al. (2002), *Weather Radar Technology Beyond NEXRAD*, Natl. Acad. Press, Washington, D. C.
- Takaya, Y., and M. Nakazato (2002), Error estimation of the synthesized two-dimensional horizontal velocity in a bistatic Doppler radar system, *J. Atmos. Oceanic Technol.*, 19, 74–79.
- Tatarskii, V. I. (1961), *Wave Propagation in a Turbulent Medium*, McGraw-Hill, New York.
- Wilson, J. W., T. M. Weckwerth, J. Vivekanandan, R. M. Wakimoto, and R. W. Russell (1994), Boundary layer clear-air radar echoes: Origin of echoes and accuracy of derived winds, *J. Atmos. Oceanic Technol.*, 11, 1184–1206.
- Wurman, J. W., M. Randall, C. L. Frush, E. Loew, and C. L. Holloway (1994), Design of bistatic dual-Doppler radar for retrieving vector winds using one transmitter and a remote low-gain passive receiver, *Proc. IEEE*, 82, 1861–1872.
- Wyngaard, J. C., N. Seaman, S. J. Kimmel, M. Otte, X. Di, and K. E. Gilbert (2001), Concepts, observations, and simulation of refractive index turbulence in the lower atmosphere, *Radio Sci.*, 36, 643–669.
- Zrnic, D. S., and A. V. Ryzhkov (1998), Observations of insects and birds with a polarimetric radar, *IEEE Trans. Geosci. Remote Sens.*, 36(2), 661–668.

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