Precipitation Bragg Scatter in Radar Observations at Nadir

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ABSTRACT

As precipitation sediments and interacts with turbulence, spatial structures appear as the familiar “streamers” of precipitation sweeping across the road during a thunderstorm or like those so obvious in snow that is backlit. Some of these are at scales that resonate with the radar wavelength, and as a consequence they produce coherent backscatter (precipitation Bragg scatter). Recently, and in contrast to incoherent scattering, it was found that the power-normalized cross-correlation functions of backscattered complex amplitudes in neighboring range bins \( r_{12} \) averaged over time exist. Moreover, they are identical to the fractional contributions \( F \) made by radar coherent backscatter in the radial direction to the total backscattered power in rain and snow. This coherent power can significantly affect some radar techniques for measuring precipitation intensity because it depends upon the square of the particle concentrations rather than the linear dependence in the case of incoherent backscatter. All of these observations were made by radars looking tangentially to the ground, however. Yet for many purposes, including the global measurements of precipitation from space, radar observations in precipitation are at or near nadir to the surface of the earth. A natural question, then, is: Can coherent backscattered power be found in observations at nadir as well? Here, radar observations collected at nadir in a convective shower and snow are analyzed. It is found that \( r_{12} \) and, hence, precipitation Bragg scatter exist in these nadir observations. Moreover, the intensity of the Bragg scatter is independent of the size of sample volume. Reasons for these findings and some implications are discussed.

1. Introduction

Recent results (Jameson and Kostinski 2010a, b) show that precipitation can produce radar coherent backscatter (Bragg scatter) when the streamers of precipitation are spaced on scales that resonate with the radar wavelength. These structures can apparently act as diffraction gratings with velocity components along as well as orthogonal to the direction of the axis of the radar beam.

That is, the classical autocorrelation functions of complex amplitudes in time are always taken at each range bin independent of the other range bins. Indeed, from the classical perspective the complex amplitudes at each range bin should, in time, be statistically independent of those in neighboring bins when the scatter is incoherent and when there is no spatial correlation on any scale among the scatterers. By contrast, statistically meaningful real values of time-averaged cross correlations between complex amplitudes in neighboring range bins can exist when there are spatial structures of the precipitation on scales of the radar wavelength, however. Along the beam axis, then, Jameson and Kostinski (2010b) show that the average cross-correlation function \( r_{12} \) between simultaneous backscattered complex amplitudes in neighboring range bins normalized by the geometric mean of the powers in the two bins is equal to the mean fractional coherent contribution to the total backscattered power, where \( Z_1 \) and \( Z_2 \) are the mean backscattered powers (i.e., mean square amplitudes of the backscattered waves) in the first and second range bin, respectively.

Perpendicular to the beam (i.e., the azimuthal direction), Jameson and Kostinski (2010a) argue that the motion of the coherent grids of particles can induce fluctuations in \( Z \) in excess of those generated by radial velocity variability associated with incoherent scatter. That is, for our purposes, a coherent target is the spatial-temporal arrangement of a collection of scatterers that enables electromagnetic waves to maintain temporally and spatially constant interference. In principle this can be a collection of separate objects like raindrops. Moreover, when this interference is constructive, Bragg scatter can occur. With respect to clouds and precipitation, in previous research it has been shown that the particles are not perfectly random as an ideal gas but rather do

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possess spatial correlations between particle positions. The work of Jameson and Kostinski (2010a) then argues that spatially periodic (albeit fleeting) elements are present in precipitation and are capable of backscattering in spatially coherent diffraction-like patterns having a velocity component perpendicular to the beam axis. The motion of these gratings subsequently induces power spectral fluctuations in excess of those usually expected solely by differential velocities among the scatterers.

The observations of $\mathcal{F}$ estimated using this “excess fluctuation” approach are not necessarily identical to those observed using $p_{12}$. This is because the cross-correlation approach only “sees” those spatial structures in resonance and in common to the two nearest neighbor range bins. In contrast, the fluctuation approach sees resonant precipitation structures contained within just one sample volume. While not necessarily mutually exclusive, the detected radial structures in range are most likely generally only a small subset of all the resonant structures within a sample volume so that it is expected that the excess fluctuation approach will yield $\mathcal{F}$ that are, in general, equal to or larger than those found using $p_{12}$.

Regardless of which is larger, however, it is clear that precipitation Bragg scatter (pBs) is seen by radars looking tangentially to the ground. In the limited number of observations thus far, the average $\mathcal{F}$ in rain and snow are 34% and 72%, respectively. An obvious question, then, is: Can pBs also occur when a radar looks vertically? In this brief paper, it is shown that the answer is yes.

I then also discuss some of the potential implications that pBs may have on observations using nadir-pointing radars whether on the ground, from an aircraft, or aboard spacecraft. Some observations are presented first.

2. Some observations

In this section two examples are considered, one looking vertically in a Colorado convective shower producing rain at the ground and the other in a snow storm. Although ice processes control the formation of precipitation in both cases, rain produced by convective summer showers in Colorado comes largely from melting graupel formed from heavily rimmed ice crystals and small hail, whereas the snowflakes come from the aggregation of pristine ice crystals as they descend. Hence, the two sets of data represent different kinds of hydrometeors.

The radar data in both the convective shower and the snow were collected using the National Science Foundation Colorado State University–University of Chicago–Illinois State Water Survey (CSU–CHILL) Radar Facility at Greeley, Colorado, that is operated by Colorado State University. This radar has a 1.1° beamwidth. It operates at a frequency of 2.725 GHz corresponding to a nominal wavelength of 11.01 cm. Pointing the antenna vertically, time series observations of the complex backscattered amplitudes ($I, Q$ pairs) were collected 1024 times per second at vertical polarization. The convective shower observations were collected using 150-m-sized range bins over a distance up to 22.5 km, well above the top of the storm at about 8 km. The minimum range of data collection for the convective shower was 2.85 km. This is about 0.7 km below the height of the melting level. For a common drop size of 2-mm diameter beginning as high-density ice, say, this distance is not quite sufficient for the complete melting of the ice—in particular, in conditions of low relative humidity common in the high plains (see Johnson and Jameson 1982). For lower-density ice, however, any remaining solid is likely enveloped in a significant coating of liquid that would look like a raindrop to a radar. Hence, the lowest few observations in the convective shower may well be quite similar to rain, whereas those above approximately 3.5 km are almost certainly in small hail and graupel. These observations, therefore, are over a wide variety of types of precipitation.

In Fig. 1 are plotted the vertical profiles that are calculated every second and then averaged over the 57 s of observations. The first point to note is that $\mathcal{F}$ is significantly greater than zero throughout the profile. For statistically

![Fig. 1](http://example.com/fig1.png)
stationary conditions, the statistics (see Jameson 2011) indicate that the standard deviation of these measurements derived using \( \rho_{12} \) is less than 0.004 so that the mean of around 0.27 is very significant statistically, lying more than 67 standard deviations from the null. Second, it is noted that these \( \bar{\gamma} \) are, on average, close to the minimum expected when \( \bar{\gamma} \) is estimated using the excess fluctuation approach [for a detailed discussion of this topic see Jameson and Kostinski (2010a, 1943–1945)]. Note also that \( \bar{\gamma} \) derived using the excess fluctuation approach is always larger than the values calculated using \( \rho_{12} \), perhaps for the reasons discussed earlier.

It is also worth noting that, even though the size of the sampling volume has increased by fivefold from the lowest to the highest altitude, \( \bar{\gamma} \) has remained essentially constant. That is, for statistically homogeneous conditions, one would expect \( \bar{\gamma} \) to decrease linearly with increasing \( V \) [see Jameson and Kostinski 2010b, Eq. (7), p. 3002]. In statistically heterogeneous conditions, however, this need not be the case. One might then expect the sources of the pBs to be distributed randomly throughout the domain. As a consequence, as \( V \) increases the number of sources of pBs would also tend to increase. If this increase is linear with \( V \), \( \bar{\gamma} \) would remain approximately constant as observed. Of course, other factors may enter in as well.

The results in snow are different in some respects (Fig. 2). These observations were gathered at a resolution of 30 m over 152 range bins over a distance of about 2.3–6.4 km above the radar. As before, these profiles are computed every second and then averaged over 1 min. The behavior of the radar reflectivity factor \( Z \) with altitude is consistent with the aggregation of pristine snow crystals resulting in increasing \( Z \) at the lower levels. Yet, despite this transformation from pristine crystals to aggregates, \( \bar{\gamma} \) calculated using \( \rho_{12} \) fluctuates around a mean of 0.42 at all altitudes. The fluctuations are larger than those in Fig. 1 because the time to decorrelation is over 20 times as large so that the standard deviation of \( \bar{\gamma} \) is on the order of 0.02.

This profile of \( \bar{\gamma} \) calculated using the excess fluctuation method is also similar. The latter values are all approximately a factor-of-2 greater than those calculated directly in range, however. This difference appears to be real because it remains even after assigning all of the observed 1/\( e \) time to decorrelation to incoherent velocity fluctuations as was done here. [Calculations using the standard deviation of the velocity and the assumption of Gaussian incoherent fluctuations show an average contribution of only 16 ms to the time to decorrelation from incoherent velocity fluctuations whereas the average of the observed times to decorrelation was 45 ms. The reasons for this are discussed in Jameson and Kostinski (2010b). Hence, assigning all of the increased time to decorrelation to incoherent scattering is likely overly generous, leading to an underestimation of the actual \( \bar{\gamma} \).] The results are also insensitive to different coherent spectral power thresholds. Hence, the differences are believed to be real, and it is concluded that nonradial contributions to \( \bar{\gamma} \) are as significant as those in range. That is, the structures responsible for the coherent scatter occur not only in radar range but also azimuthally as the precipitation structures move laterally as they fall. Note also that \( \bar{\gamma} \) appears to be indifferent to the structure in altitude of the radar reflectivity \( Z \) profile.

As in Fig. 1, the volume from the lowest (\( \sim 1 \times 10^5 \) m\(^3\)) to the greatest altitude (\( \sim 5 \times 10^5 \) m\(^3\)) increases by a factor of 5. Yet this does not affect the observed \( \bar{\gamma} \). It is reasonable, then, to speculate that this insensitivity to the size of the sample volume may be valid over even larger sample volumes. If so, then pBs may be important to radar measurements even from space depending upon the radar frequency. This conjecture, however, remains to be verified experimentally.

3. Concluding comments

The observations using \( \rho_{12} \) show that significant pBs occurs in radar observations at nadir apparently regardless
of the type of precipitation. This requires spatial structures on the order of multiples of half wavelengths in the vertical direction. One possible source of these might be the introduction of tilt of horizontally spaced vertical steamers by wind shear.

Like observations in the tangential direction, it appears that the grids of particles responsible for coherent scatter are moving at angles with respect to the axis of the radar beam, producing resonances in both the radial and azimuthal directions. Of course, in some cases, turbulence may produce some of these structures, or they may simply appear as a natural consequence of hydrodynamics of sedimentation as some research suggests for different problems (e.g., Crowley 1971).

The occurrence of pBs in observations of precipitation at nadir will likely impact the quantitative interpretation of such measurements, particularly in snow. Perhaps their most profound effect could be the apparent independence of pBs with respect to the size of the sample volume, however. If valid over very large domains, pBs could then affect attempts to use radar observations from space to achieve global estimates of rain and particularly snow even when using more sophisticated dual-frequency techniques because the response of each frequency to pBs may differ. This should be of concern to some National Aeronautics and Space Administration program managers who oversee projects that attempt to measure precipitation from space using observations at nadir.

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