Interaction Between Beam Blockage and Vertical Reflectivity Gradients

Norman Donaldson
Environment Canada, King City, ON, Canada, norman.donaldson@ec.gc.ca

1. Introduction

In cold climates, winter precipitation systems are often shallow, so weather radars may need to scan at low elevation angles to avoid overshooting the precipitation. At the same time, low angles increase the probability that the radar beam may be partially blocked by terrain or obstructions such as trees and buildings. Given that winter precipitation can have strong vertical reflectivity gradients, consideration must be given to the interaction between obscuration and reflectivity gradients within the beam.

This work originates from efforts to develop obscuration maps for Environment Canada’s C-band weather radar network. Two approaches were adopted. The first approach is calculation of the fraction of the beam blocked by terrain based on a digital terrain map (LEM) and a radio propagation model, for example as in Bech et al. (2007). The second approach is statistical analysis of long term echo patterns, looking for azimuth patterns of signal loss. The LEM approach seems reliable when the source of blockage is more than some tens of kilometres from the radar and results show reasonable approximation to observations. At closer ranges, objects such as trees and buildings and inaccuracies in the LEM force dependence on statistics. Despite the reasonable accuracy of the LEM approach, results vary from case to case. The statistical approach is more difficult because one must estimate the hypothetical values in the absence of blockage. Our approach was to collect data during widespread precipitation cases, with the hope that the underlying precipitation statistics would be spatially uniform. Unfortunately we find that the blockage estimated from statistics also varied between analysis periods. It seems that at least some of this variation is due to interaction with the vertical profile of reflectivity (VPR).

For quantitative precipitation estimation by radar in mid-latitudes it is well known that one should adjust for the vertical profile of reflectivity, both to extrapolate measurements aloft down to the surface and to compensate for non-uniform beam filling, for example Kitchen et al (1994), Germann et al (2006), and Bern et al (2004). Typically the vertical profile correction is implemented as a multiplicative correction to measurements as a function of range once the VPR is determined. Corrections for partial obscuration are also usually implemented as multiplicative corrections as a function of azimuth. If reflectivity gradients are weak, the two factors may be combined multiplicatively, but in the presence of strong gradients they cannot.

Fig. 1 A 30 day accumulation showing blockage of Holyrood Radar in Newfoundland, Canada. On left, a geographical presentation. On right, polar coordinate (“B-scan”) presentation focused on the southern blockage.

2. Observations of partial blockage

Partial blockage of a radar in eastern Canada is illustrated by the 30 day accumulation map shown in Fig 1. A set of communication towers near the site produce narrow and straight blockage lines. To the south of the radar a hill a few kilometres from the radar produces wider partial blockage of the beam. For this area the edges of the blockage are not
straight. It might seem possible that this lack of obviously radial patterns is merely an artifact of the colour pattern chosen and spatial variation of reflectivity, but the pattern is seen to vary over time. This became especially clear when echo statistics were used to produce quantitative blockage maps for use in quantitative precipitation estimation (QPE) algorithms. The blockage maps are created using a combination of computer analysis with human refinement but varied noticeably between analysis periods. The results here and at other radars also indicated that the fractional losses change with range, even though the blockage is restricted within 10km of the radar. It has been concluded that a large portion of this variability is in fact meteorological in origin and is driven by changes in the apparent profile of reflectivity over time and range.

3. Conceptual Models and Simulations

3.1 Partial blockage correction

The simplest view of blockage correction is that at some range a particular fraction of the power in the beam has been blocked by terrain, trees, towers, etc. This geometrical fraction may vary as meteorological conditions change the propagation path of the beam. In principle, if the unblocked fraction, F, can be estimated then one can adjust the observed echo powers by the fraction to recover a good estimate of reflectivity.

$$Z_{\text{adjusted}} = Z_{\text{observed}} / F_{\text{blockage}} \quad (1)$$

Fig 2a shows the ideal case of this, where the beam is uniformly filled and the reduction of returned power is directly related to fractional blockage. The concept will fall apart in the other examples in Fig 2 because the geometrical fraction of the beam does not correspond to the power-weighted fraction.

3.2 Vertical profile correction

Vertical profile correction is more difficult and many variations on the method exist, but essentially all assume some estimated shape, S, for the vertical profile of reflectivity, V. If this shape is known, together with the approximate gain pattern, G, of the antenna, then convolution can estimate the ratio of the measured reflectivity to the near surface reflectivity.

$$Z_{\text{estimated}} = Z_{\text{observed}} \times S_{\text{surface}} / S_{\text{convolved}} = Z_{\text{observed}} / F_{\text{vpr}} \quad (2)$$

3.3 Observed reflectivity from partially blocked VPR

The ideas in the previous sections can be combined to a more general framework that explicitly includes vertical variation within the beam. In the presence of partial blockage, the lower limits of the convolution of the beam gain with the reflectivity are set by the lowest unblocked elevation, $E(a,r)$, as a function of azimuth, $a$, and range r. If the antenna axis is pointed at azimuth $a_0$ and elevation $e_0$, the observed (“apparent”) reflectivity is given by

$$Z_{\text{observed}}(a_0, e_0, r) = \int_{0}^{2\pi} \int_{E(a,r)}^{\pi} G^2(a-a_0, e-e_0) V(e) d\phi d\theta \quad (3)$$

where $G^2$ has been normalized to integrate to unity over the entire domain, and V is expressed as reflectivity $Z$. (In this approach the radar constant divides away.) $V(e)$ is implicitly a function of range due to the connection between height, range and elevation. Further, if V is expressed as the surface value of $Z$ scaled in height by a shape function S, $V(e) = Z_{\text{sfc}} \times S(e)$, as in say Andrieu and Creutin (1995), then the “measurement ratio”, L, can be defined as the ratio of the observed value to the surface value:

$$L(a_0, e_0, r) = Z_{\text{observed}}(a_0, e_0, r) / Z_{\text{sfc}} = \int_{0}^{2\pi} \int_{E(a,r)}^{\pi} G^2(a-a_0, e) S(e) d\phi d\theta \quad (4)$$

Note that for low elevation angles of the antenna axis the lower integration limit $E(a,r)$ could be determined by the curvature of the Earth’s surface, in addition to any specific obscuration like hills, trees, etc. The measurement ratio could be used to replace the product of the classic blockage fraction and VPR corrections in estimates of surface $Z$:

$$Z_{\text{estimated}} = Z_{\text{observed}} / L \quad (5)$$

Unfortunately L is computationally expensive to calculate and varies throughout the domain. Usually L will be less than one, but the presence of a bright band in the beam would produce enhanced reflectivities and L can considerably exceed one. In this paper simulations will be done for an obstruction at the centre of the azimuthal domain, at a fixed range from the radar. In order to illustrate the impact of the blockage, we calculate ratios of potentially blocked $Z$ to the unblocked value of $Z$

$$R(a,e,r) = Z(a,e,r) / Z(a_0,e_0) \quad (6)$$

R provides the fractional impact of blockage on top of any vertical profile effect. For example if half of the beam were blocked and the beam were uniformly full, then R=0.5, or if the beam were half blocked but the echo tops were below the blockage then R=0.0.

3.4 Qualitative examples

Fig 2b shows four qualitative examples of the interaction of the reflectivity profile and beam blockage. Fig 2a is the ideal case with a uniform profile that fills the beam. In this case the only effect is blockage and correction is straight forward. Fig 2b shows a case where the VPR is uniform up to a sharp cut off. In this case the VPR factor is 0.9 due to incomplete beam filling and the blockage factor remains at 0.5, however since the blockage has disproportionately affected the lower half of
the returned echoes, the product of the two fractions gives a result that is too low (75%). If we think in terms of a power-weighted beam centre, then it is lower than geometric centre in this case and blockage is commensurately larger. On the other extreme, Fig 2d shows a case with a bright band in the top half of the beam. In this case the contribution from the upper, unblocked half is very much greater than from lower blocked half and the product of the two fractions gives a result that is too high.

3.4 Quantitative simulations

To assess the impact of interactions between partial blockage and vertical gradients, simulations were done based on Equation 4. The set-up is shown schematically in Fig 3. The antenna gain, G, was modeled as a Gaussian, with a half power beam width of 0.7 degrees, which approximates the C band radars in the Environment Canada network. The antenna was assumed to be on 12m tower. A triangular obstruction 30m high was added to an otherwise featureless globe between 4 km and 6km from the radar. The obstruction’s azimuthal extent was 2 deg. A number of shapes, S, for the VPR were used, of the types shown in Fig 2. Since the domain is symmetric, calculations were done by scanning the modeled beam azimuth from 0 to 5 degrees and only half of the domain presented. Blockage is established by calculating the maximum elevation E(a,r) of any obstruction closer to the radar, based on the standard 4/3 propagation model, although in the real world one would ideal allow for variations in propagation as discussed by Bech et al. (2007). For practical reasons, the domain of numerical integration of Equation 4 is terminated at a maximum of 3 beam widths away from the beam axis.

Results are presented in polar coordinates (range, azimuth) for specific elevation angles of the antenna. Fig 4 shows results for a simulated bright band based at 1.0km (see Fig 2d) for an elevation of 0.4 degrees.

Near the radar, within about 60km range, the echoes are entirely from the rain portion of the profile, and the beam is uniformly filled. Looking at the reduction ratio, L, values drop approximately linearly from the minimum near 0 to their unblocked value. The ratio of blocked to unblocked, R, is constant with range at fixed azimuth, as is consistent with a simple blockage representation.

From about 60km to 120km of Fig 4 the bright band dominates the returns. L increases well above 1 with somewhat lower values in the partially blocked area. Note that the ratio R at 0 azimuth increases relative to values closer to the radar. The
azimuthal pattern of blockage is distinctly different in the bright band area compared to the uniformly filled area closer to the radar. Above the bright band the reflectivity Z drops off exponentially in a snow profile, as in Fig 1c. In this area, the portion of the reflectivity blocked by terrain is considerably more important than that from the unblocked portion. The azimuthal variation of L shows a much deeper loss near 0 azimuth than for either the rain or bright band regions. This results in ratios R of greater than -10db; although the fractional blockage of the beam is only about 30%, the decrease in measured values relative to those from a VPR correction is over 10 times.

4. Conclusions and discussion

This work shows that interactions between blockage and vertical variations in the profile of reflectivity are more complex than one might anticipate. In comparison to the uniform beam filling case, partial blockage can result in proportionally more or less impact depending on the structure of echoes within the beam. In effect the power weighted beam centre can be either lower or higher than the geometric beam axis, resulting in blockage that is more or less than the simple geometric calculation suggest.

Unfortunately, the multiplicative corrections for simple blockage and the VPR cannot be themselves multiplied in the presence of both blockage and strong vertical gradients within the beam. In this case the geometrical fraction of the beam is not the same as the power weighted fraction. At low, partially blocked elevations, the implicit vertical integration of the profile behind VPR corrections has a lower limit that can vary as a function of both range and azimuth, forcing a recalculation wherever partial blockage is an issue.

The implications of the interaction between partial blockage and vertical gradients in dual polarization techniques are unclear. Some polarimetric estimates of rain rates are less sensitive to blockage itself, but the biases due to non-uniform partial beam filling will still present a challenge.

Since the interaction of the vertical profile of reflectivity is a function of meteorological conditions, considerations of this effect must be combined with meteorological changes to blockage caused by changes in the vertical structure of the index of
refraction such as discussed in Bech et al (2007). At a minimum this work suggests that in locations where the VPR has significant variation through the year, separate blockage maps may be required for each season.

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References


