1 Anomalous Propagation (AP)

To properly describe problems associated with AP, knowledge of normal and anomalous radar beam propagation is required. This section summarizes and illustrates radar beam refraction provided by Michelson (2003).

Propagation of electromagnetic waves is comprehensively covered by Kerr (1951) and presented in a weather radar context by Watson (1996), among others. Electromagnetic waves would travel in straight lines if the atmosphere were homogeneous. Since the permittivity of the atmosphere (ε) is stratified, electromagnetic wave propagation is not straight. The atmosphere's refractive index (n) is related to the relative permittivity such that $n^2 = \varepsilon_r$, where $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$ and ε_0 is the permittivity of free space. The radio refractive index

$$N = (n - 1) \times 10^6 \tag{1}$$

is often used instead of n since small changes in n, caused by different atmospheric water vapour contents, can cause large changes in electromagnetic wave propagation.

Given the height of a ray above the Earth's surface (h), the radius of the ray curvature (r), and the vertical refractive index gradient (dn/dh), the horizontal angle of the path (θ) to a given point may be expressed as

$$\frac{1}{r} = \frac{1}{n}\frac{dn}{dh}\cos\theta. \tag{2}$$

The term r may be related to the relative Earth radius (R_e) in terms of the refractive index gradient, according to Brussaard and Watson (1995), by

$$\frac{r}{R_e} = k_e \approx \frac{1}{1 + R_e(dn/dh)} \tag{3}$$

where k_e is the effective Earth radius factor. If the Earth radius is assumed to be $k_e R_e$ then rays can be modelled as propagating in straight lines. Given an Earth radius of 6370 km, k_e may be expressed in terms of N as

$$k_e \approx \frac{1}{1 + (dN/dh)/157}. \tag{4}$$

The radio refractive index gradient (dN/dh) near the Earth's surface is around $-39\ N$/km which gives an effective Earth radius factor of $k_e = \frac{4}{3}$. This has given rise to the assumed phenomenon "$\frac{4}{3}$ Earth radius radar beam refraction" or "standard refraction".

Regions where $k_e < 0$ are referred to as containing ducts, where rays remain at heights proximate to the Earth's surface. Regions where $0 \leq k_e \leq \frac{4}{3}$ are said to be regions of super-refraction, meaning that rays propagate abnormally towards the Earth's surface. Regions where $k_e > \frac{4}{3}$ are said to be regions of sub-refraction, meaning that rays propagate abnormally away from the Earth's surface.

For any radar the radius of ray curvature is given as

$$r' = H_r + \frac{1}{(1/R_e + dN/dh)} \tag{5}$$

where H_r is the height of the radar's antenna (m a s l).

Then, each range bin's height is

$$H = \sqrt{A^2 + B^2} - r' \tag{6}$$

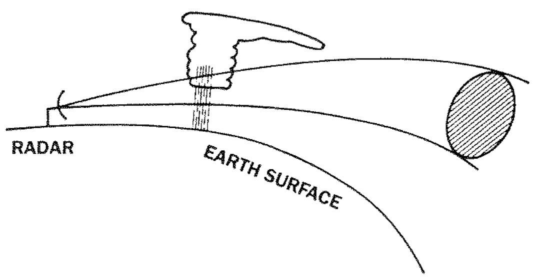
where

$$A = 0.001 + r' + S \times \sin\phi \tag{7}$$

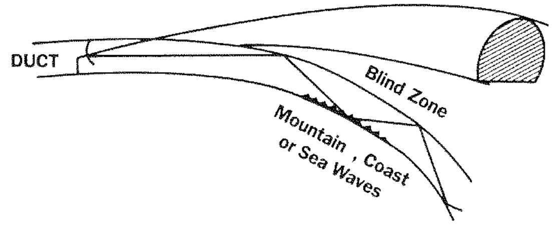
where S is the slant range (m) and ϕ is the elevation angle for the given scan (radians), and

$$B = S \times \cos\phi. \tag{8}$$

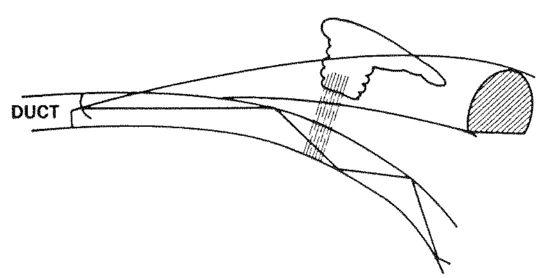
Figure 1 illustrates normal propagation and ducts giving rise to echoes from the Earth's surface. This entrapment and propagation of a small amount of radiation offset from the main beam axis in such ducts, and even in less severe super-refractive conditions, is referred to as anomalous (AP or ANAPROP) and the echoes are referred to as AP echoes. Such echoes are strong and highly variable on small spatial scales over land (Alberoni et al. 2001). Over sea, where they are referred to as sea clutter (Collier 1998), they are more homogeneous and generally weaker in strength. All types of non-precipitation echoes are referred to as being spurious.



(a) Normal propagation conditions with precipitation.



(b) Anomalous propagation (super-refraction) conditions.



(c) Anomalous propagation conditions with precipitation.

Figure 1: Normal propagation conditions with precipitation and anomalous (super-refraction) propagation conditions giving rise to radar echoes from the Earth's surface with and without precipitation. From Alberoni et al. (2001).

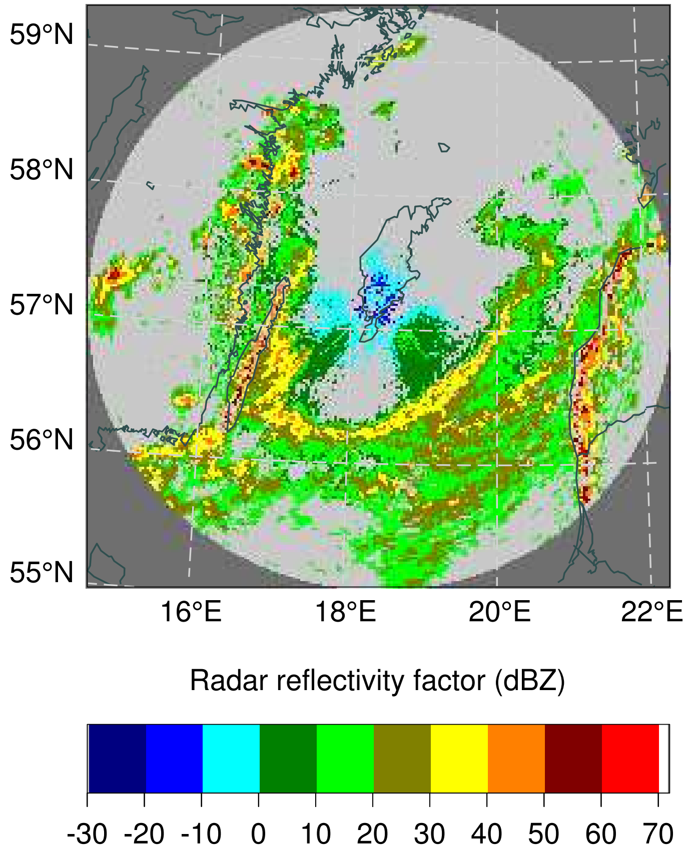


Figure 2: Severe AP conditions as seen from Hemse on August 25, 1997 at 14:09 UTC. A line of convective cells stretches from west to north over the Swedish mainland. Strong AP echoes from land are seen covering the Swedish island of Öland and the Latvian and Lithuanian coasts. Severe sea clutter is organized as more-or-less concentric half-rings at different ranges, with the closest ring being the most discernible.

A classic example of AP echoes can be seen in Figure 2. Many different methods have been formulated over the years to identify and remove AP echoes. Radar-based methods using non-coherent radars have been developed based on combined signal processing of raw pulse data and image processing techniques which appear to perform well, one example of which is reported by Wessels and Beekhuis (1992). Image processing based quality control methods, many examples of which are referred to by Steiner and Smith (2002), and elaborate quality control systems such as those developed in Switzerland (Joss and Lee 1995), the UK (Harrison et al. 2000), and the USA (Fulton et al. 1998) all demonstrate the difficulties in identifying and suppressing AP echoes while retaining echoes from true precipitation, especially where AP echoes are embedded in precipitation areas. Where Doppler signal processing is available, it has been demonstrated as being an effective means of removing AP echoes which are static in space, i.e. from land (Koistinen 1997). Sea clutter is much more difficult to remove using traditional Doppler techniques because the echoes are generated from sea waves which have true velocities and are therefore indistinguishable from precipitation. Recently, with improved computer performance, filtering methods employing original polar volume data have been tested, both in Europe (Alberoni et al. 2001) and in the USA (Steiner and Smith 2002), which point towards similar limitations to those experienced with 2-D cartesian data, i.e. that image/volume analysis techniques are often extremely sensitive to individual cases and must be fine-tuned in order to gain maximum performance. Multisource methods, e.g. Michelson and Sunhede (2004), combine data from different sources in an attempt to identify areas void of potentially precipitating clouds; radar echoes in these areas can be then either flagged and/or removed. Such methods can be very robust but, like every other method, they can remove a small amount of true precipitation along with a significant amount of non-precipitation echoes.

2 References

Alberoni, P. P., Andersson, T., Mezzasalma, P., Michelson, D. B., and Nanni, S., 2001. Use of the vertical reflectivity profile for identification of anomalous propagation. *Meteorol. Appl. 8*(3), 257–266.

Brussaard, G. and Watson, P. A., 1995. *Atmospheric modelling and millimetre wave propagation*. Chapman and Hall.

Collier, C. G., 1998. Observations of sea clutter using an S-band weather radar. *Meteorol. Appl. 5*, 263–270.

Fulton, R. A., Breidenbach, J. P., Seo, D.-J., and Miller, D. A., 1998. The WSR-88D Rainfall Algorithm. *Weather and Forecasting 13*, 337–395.

Harrison, D. L., Driscoll, S. J., and Kitchen, M., 2000. Improving precipitation estimates from weather radar using quality control and correction techniques. *Meteorol. Appl. 7*, 135–144.

Joss, J. and Lee, R., 1995. The Application of Radar-Gauge Comparisons to Operational Precipitation Profile Corrections. *J. Appl. Meteor. 34*, 2612–2630.

Kerr, D. E. (Ed.), 1951. *Propagation of Short Radio Waves*. New York: Dover Publications. 728 pp.

Koistinen, J., 1997. Clutter cancellation and the capabilities of modern Doppler radars. Proc. COST 75 Workshop on Doppler Weather Radar. European Commission, Luxembourg. pp. 7-11.

Michelson, D. B., 2003. *Quality Control of Weather Radar Data for Quantitative Application*. Ph. D. thesis, Telford Institute of Environmental Systems, School of Environment and Life Sciences, University of Salford. 281 pp.

Michelson, D. B. and Sunhede, D., 2004. Spurious weather radar echo identification and removal using multisource temperature information. *Meteorol. Appl. 11*(1), 1–14.

Steiner, M. and Smith, J. A., 2002. Use of Three-Dimensional Reflectivity Structure for Automated Detection and Removal of Nonprecipitating Echoes in Radar Data. *J. Atmos. Oceanic Technol. 19*, 673–686.

Watson, R. J., 1996. *Data Comparisons for Spatially Separated Meteorological Radars*. Ph. D. thesis, Dept. Electronic Systems Engineering, University of Essex, UK. 284 pp.

Wessels, H. R. A. and Beekhuis, J. H., 1992. Automatic suppression of anomalous propagation clutter for noncoherent weather radars. Scientific reports; WR 92-06. KNMI, PO Box 201, 3730 AE De Bilt, The Netherlands. 11 pp.