Evaluation of atmospheric anomalous propagation conditions: an application for weather radars

J. Bech[a,c], D. Bebbington[b], B. Codina[c], A. Sairouni[c], J. Lorente[c]

[a] Servei de Meteorologia de Catalunya, Dep. de Medi Ambient, Catalunya, Spain
[b] Wave Propagation Research Group, Dep. Mathematics, Essex University, UK
[c] Dep. d'Astronomia i Meteorologia, Universitat de Barcelona, Catalunya, Spain

ABSTRACT

Several meteorological conditions are known to cause anomalous propagation (AP) of microwave radiation. The effect of AP in weather radar measurements may be important as spurious echoes from distant ground targets may appear as precipitation leading to wrong rainfall estimations. AP may also affect dramatically the quality of clear air radar observations. In this study, more than one hundred radiosonde ascents are examined to evaluate the occurrence of AP at the coastal site of Barcelona (Spain). Temperature and humidity profiles are used to calculate refractivity gradients and to estimate the existence of ducting layers. Ducts represent the worst case of super refraction and within them microwaves travel trapped like in a waveguide. To detect thin AP features a vertical resolution higher than that given by standard operational radiosonde data is desirable. For this reason, radiosonde data recorded every 10 s have been used. Results are compared against standard operational radiosonde analysis revealing a significantly higher number of AP layers. The output of a mesoscale numerical weather prediction model is also used to derive refractivity gradients. The ability of the model to simulate the propagation conditions is overviewed in order to assess the feasibility of an operational diagnostic AP product.

Keywords: anomalous propagation, subrefraction, ducting, weather radar, atmospheric refractivity, radar rainfall estimation, radiosonde, numerical weather prediction

1. INTRODUCTION

The occurrence of anomalous propagation conditions, or anaprop (AP), affects weather radar systems performance and, more generally speaking, communication devices such as ground to ground or ground to satellite microwave links. Some

For further information -
J.B. (correspondence): wjbech@correu.gencat.es, Servei de Meteorologia de Catalunya, Av. Diagonal 523, Barcelona 08029, Catalunya, SPAIN.
D.B. - Wave Propagation Research Group, Dep. Mathematics, Essex University, UK
B.C., A.A., J.L. - Dep. d'Astronomia i Meteorologia, Universitat de Barcelona, Catalunya, Spain

Part of the EUROPTO Conference on Remote Sensing for Agriculture, Ecosystems, and Hydrology • Barcelona, SPAIN • September 1998
SPIE Vol. 3499 • 0277-786X/98/$10.00

meteorological situations are well known to cause AP. For instance, dry warm advections over relatively cold seas typically have anaprop effects. Non standard refraction has been described to affect dramatically the quality of weather radar observations in the Mediterranean area[1] or in the Baltic sea[2]. The impact in weather radar measurements may be tremendous as spurious echoes from distant ground targets may appear as precipitation leading to wrong rainfall detection. AP caused by ground clutter echoes usually produce high reflectivity values, comparable to thunderstorms, which are difficult to detect using automatic procedures.

Very small variations in the air refractive index (n) are responsible for anomalous propagation. Therefore the analysis of AP is usually done using refractivity (N), a magnitude defined as one millionth of n-1. Refractivity depends on atmospheric pressure, humidity and temperature. Using Debye theory, the dependence of refractivity with those magnitudes may be written as[3] :

$$N = (n-1)10^6 = \frac{77.6}{T}\left(p + \frac{4810e}{T}\right)$$

where N is refractivity (dimensionless), T is the air temperature (K), p atmospheric pressure (hPa) and e is the water vapor pressure (hPa). Valid range for radio frequencies is between 1 and 10 GHz. Other associated magnitudes, such as the modified refractivity, take into account the height of the layer where refractivity is considered.

Refractivity usually presents little horizontal inhomogeneities, though coastal areas are known exceptions because of high gradients of both temperature and moisture, sometimes with remarkable effects in microwave propagation[4,5]. For the same reason frontal boundaries between different air masses present high refractivity gradients as well[6]. Vertical gradients of N are traditionally used to classify anomalous propagation conditions as subrefractive (worse than normal) and superrefractive (better than normal). A subrefractive layer leads the radar beam to refract away from the earth surface. In superrefractive conditions the radar beam height increases at a lower rate than the assumed normal average propagation. In the worst case of AP, known as ducting, radar microwaves are trapped and may travel within duct layers just like in a waveguide. In extreme cases, this effect may extend the radar horizon even an order of magnitude.

In terms of vertical of the refractivity gradient, $\partial N/\partial z$, subrefractive layers are characterized by values greater than 0 km^{-1} . Ducting occurs when $\partial N/\partial z$ is equal or less than – 157 km^{-1}. The refractivity gradient for normal refraction conditions ranges between 0 and –78.7 km^{-1}. It should be noted that these threshold values are deduced from geometrical considerations of propagation models such as the effective Earth's radius model or the modified effective Earth's radius model[7]. Therefore, different assumptions in each formulation may explain the small discrepancies found in the literature for these thresholds (except for subrefractive layers), being the most relevant those discriminating superrefractive and ducting layers.

In this study, radiosonde data are used to evaluate the occurrence of AP at the particular coastal site of Barcelona (Spain). Pressure, temperature and humidity profiles are used to calculate refractivity gradients and, in particular, to estimate the existence of ducting layers. Following previous research[8] intended for ground based microwave communication purposes, refractivity calculations have been done up to 1000 m above sea level. Results from this study provide useful information for microwave system design and in particular could improve the knowledge of extreme orographical blockage cases for the Vallirana Doppler radar[9]. A second objective of this work, developed in sections 3 and 4, is to present a first overview of the performance of anaprop diagnosis from operational sources: radiosounding observations and NWP mesoscale model data.

2. RADIOSONDE OBSERVATIONS

The vertical resolution of standard radiosonde observations launched daily worldwide is given by the so-called standard levels, mandatory significant levels and additional levels, following WMO regulations. Standard pressure levels are 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa. Significant levels relevant for this study (restricted to heights up to 1000 m) include the surface level and any level with certain strong gradients of temperature, humidity or wind. They do not necessarily include strong refractivity gradients so, in order to detect thin ducts or other anaprop features[10], a vertical resolution greater than that given by standard radiosonde measurements is required. For this reason, radiosonde data recorded every 10 s have been used. Up to 1000 m, they contain some 20 levels (50 m aprox. of vertical resolution) in front of 3 to 6, typically, in standard TEMP data. To distinguish both types of data, standard TEMP data will be referred as RAOB1, and higher resolution data as RAOB2.

Radiosonde data used in this study were obtained between September 1997 and July 1998 employing a Vaisala RS-80 radiosonde station. The radiosonde was launched at 12 UTC from the Dep. of Astronomy and Meteorology of the University of Barcelona (41.38 º N, 2.12 º E , 94 m ASL). It should be taken into account that use of 00 UTC data would show a high increase in superrefraction occurrence due to the effect of nocturnal inversion layers.

For a general preliminary description of the propagation environment, 148 ascents sampled at 10 s intervals (RAOB2) have been used. They contained 3125 different levels (2977 layers). From them, 330 (11%) were classified as subrefractive, 2193 (74%) standard propagation, 270 (9%) superrefractive and 184 (6%) as ducting layers. Only two days of the whole set had complete standard propagation (no anaprop). Defining a duct day as a day with at least a ducting layer (and in the same way subrefractive day, super refractive day, etc.) it was found that the number of subrefractive days was 119, normal propagation days 148, superrefractive days 114 and finally the number of duct days was 109. Extreme observed refractivity gradients were –1155 and 261.

Most ducts (85%) were surface ducts (based at ground level), while the rest of them had their base aloft (note that this analysis is restricted at the first 1000m; there could be elevated ducts with higher bases). Mean duct height was 412 m while the median duct height was 173 m and the mode 144 m.

3. COMPARISON BETWEEN RAOB1 AND RAOB2 AP DIAGNOSIS

A preliminary comparison between RAOB1 and RAOB2 data is shown below for heights up to 1 km (Table 1). In this comparison 135 radiosoundings were used. RAOB1 data provided an analysis, considered here a forecast, and was verified against the RAOB2 diagnosis, considered as the observed truth. The forecast consisted in stating categorically if a particular anaprop feature was present or not for a given sounding. Several indexes used commonly in weather forecasting analysis were calculated: POD (probability of detection), PC (percent correct) and CSI (critical success index) (see for example [11]):

Anaprop Feature	POD	PC	CSI
Subrefractive layer	32.71	45.93	32.41
Superrefractive layer	44.34	51.11	41.59
Ducting layer	83.00	75.56	83.00

Table 1. Verification of anaprop diagnostics using RAOB1 (standard TEMP radiosonde data) vs. RAOB2 (10 s resolution radiosonde data).

It may be observed that POD is high for ducts and gets lower with super and specially with subrefractive layers, implying that RAOB1 are unable to find a significant proportion of such anaprop features. PC also shows better performance for duct detection than for other types of anaprop. CSI makes clear that only duct forecasts are reliable in this analysis. This comparison must be regarded only as preliminary and should be completed, but already shows that some of the information contained in TEMP messages could be profitable in certain circumstances for anaprop analysis, in particular for duct detection.

4. NWP MESOSCALE MODEL

The analysis of a mesoscale numerical weather prediction (NWP) model can also be used to retrieve microwave propagation conditions. This approach has the great advantage of providing 2-D information, so some horizontal inhomogeneities should be detected (though this depends very much on the model resolution and the physics included in the model). Another very attractive feature is that, obviously, NWP mesoscale models provide not only analysis but also forecasts, so anaprop could be eventually forecasted 1 or 2 days in advance. The main concern here is that operational NWP mesoscale models have still limited (both vertical and horizontal) resolution compared to typical anaprop features.

An updated version of the MASS model[12, 13], as implemented in the Meteo’96[14] and Meteo’2000 projects has been used to derive refractivity gradients for the first 1000 m above sea level. The grid spacing used by the model for running the simulations is about 55 km. Better performance should be achieved using a nested run of the same model. Currently the nested grid spacing is 15 km.

As a case study, a strong superrefractive day has been chosen, the 18th of September of 1997. For that day, three different simulations have provided a 36, 24 and 12-hour forecast respectively for the refractivity profile. The forecasts are compared with three different analyses: one performed by the model initialized with observations of that moment (including the Barcelona radiosonde), another with RAOB1 data and the last with RAOB2 data.

Table 2 shows the number of layers used in each case and the type of propagation of each layer. It is clear that the model foresaw correctly the existence of superrefractive and ducting layers in advance (note that the threshold between superrefractive and ducting layer may not be very relevant in this case). The three different analyses agree reasonably well, showing the existence of ducting layers in every case. RAOB1 even reveals a subrefractive layer, though ducting is clearly the anaprop prevailing feature.

	Layers used	*Sub. layers*	*Std. layers*	*Sup. layers*	*Ducting layers*
36 H M. FOR.	7	0	4	0	2
24 H. M. FOR.	7	0	4	0	2
12 H. M . FOR	7	0	5	0	1
M. ANA.	7	0	4	1	1
RAOB1 ANA.	7	0	2	2	2
RAOB2 ANA.	20	1	10	2	6

Table 2. Propagation analysis for 12 UTC 18th September 1997 performed by forecasts derived from the MASS model and 3 different analysis: the MASS analysis, RAOB1 analysis (standard TEMP data) and RAOB2 analysis (10 s resolution radiosonde data).

5. RESULTS AND DISCUSSION

Interest in identifying anomalous propagation radar echoes has driven a large number of studies with the final goal of correcting radar observations operationally. Despite the improvements obtained using Doppler clutter cancellation[15] with respect to older non-Doppler systems, several operational procedures [2, 16, 17] have been developed to identify and correct anaprop echoes through the analysis of radar data. These procedures are especially necessary for quantitative use of the radar observations.

Other sources of radar propagation information operationally available have been explored here: TEMP radiosonde data and mesoscale NWP model forecasts. In both cases a diagnostic AP product would be easy to implement and could provide a flag for severe anaprop cases useful as a stand-alone product or as a contribution in a more complex weather radar quality checking procedure. The comparison of both diagnostic methods with fine-scale radiosonde data still deserves a more in depth analysis. However preliminary results shown here seem promising and may well contribute to improve an operational anaprop detection technique.

6. ACKNOWLEDGMENTS

This study has been done within the frame of the EU funded project Development of Advanced Weather Radar Techniques for its Application to Hydrometeorology (DARTH), contract number ENV4-CT96-0261. We thank valuable comments provided by Tage Andersson, member of the Swedish Meteorological Institute and coordinator of the anaprop work in the DARTH project and from Sandro Nanni and his team at Servizio Meteorologico Regionale - ARPA, Italy. In this study radiosonde data was provided by the Servei de Meteorologia de Catalunya and mesoscale NWP data from the Meteo 2000 project sponsored by the Servei de Meteorologia de Catalunya and the Catalan Science Foundation.

6. REFERENCES

1. L. Battan, *Radar observations of the atmosphere*. University of Chicago Press, Chicago, p.26, 1973.
2. T. Andersson, P.P. Alberoni, P. Mezzasalma, D. B. Michelson, S. Nanni, "Anomalous propagation: identification from terrain and sea waves using vertical reflectivity profile analysis", *28th Conf. Rad. Met., Am. Met. Soc.,* pp. 93-94, 1997.

3. B. Bean, E. Dutton, *Radio Meteorology,* p.19, Dover Publications, Inc., 1968.

4. Shen X.D., Vilar E., "Anomalous Transhorizon Propagation and Meteorological Processes of a Multilink Path", Rad. Sci., **30**, Iss. 5, pp 1467-1479, 1995.

5. S. H. Abdul-Jauwad, P. Z. Khan, T. O. Halawani, "Prediction of radar coverage under anomalous propagation condition for a typical coastal site: a case study", Rad. Sci., **26**, Iss. 4, p.909-919, 1991.

6. E.E. Gossard, R.G. Strauch, *Radar observations of clear air and clouds*, p.41, Elsevier, 1983.

7. B. Bean, E. Dutton, *Radio Meteorology,* chapter 3, Dover Publications, Inc., 1968.

8. J. Lorente, S. Alonso, "First results of estimation of the air refractivity index in Barcelona", *Proc. of the V Spanish National Geophysics Assembly*, Madrid, pp. 805-808 (in Spanish), 1987.

9. J. Bech, J. Lorente, O. Puig, "Preliminary observations obtained with the Vallirana weather radar", *Proc. of the I Spanish-Portuguese Geophysics Assembly*, Almeria, p. 334 (in Spanish), 1998.

10. S. M. Babin, "Surface height duct distributions for Wallops Island", Virginia, J. Appl. Met., **35**, Iss. 1, pp. 86-93, 1996.

11. C. Marzban, G. J. Stumpf, "A Neural Network for Damaging Wind Prediction", Weath. and Forecast. , **13**, No. 1, pp. 151–163, 1998.

12. M. L. Kaplan, J. W. Zack, V. C. Wong, J. J. Tuccillo, "Initial results from a mesoscale atmospheric simulation system and comparisons with an AVE-SESAME I data set", Mon. Wea. Rev., **110**, 1564-1590, 1982.

13. S. E. Koch , W. C. Skillman, P. J. Kocin, P. J. Wetzel, K. F. Brill, D. A. Keyser, M. C. McCumber, "Synoptic scale forecast skill and systematic errors in the MASS 2.0 model", Mon. Wea. Rev., **113**, 1714-1737, 1985.

14. B. Codina, A. Sairouni, J. Bech, A. Redaño, "Operational Application of a nested mesoscale numerical model in Catalonia (Meteo'96 Project)", *INM/WMO International Symposium of Cyclones and Hazardous Weather in the Mediterranean*, ISBN 84-7632-329-8, p. 657-667, 1997.

15. J. Koistinnen, "Clutter cancellation and the capabilities of modern Doppler radars", Proc. *COST-75 Workshop on Doppler Weather Radar*, Cervignano di Friuli, Italy, October 1996, European Commission, Luxembourg pp. 7-11, 1996.

16. J. Joss, R. Lee, "The application of Radar-Gauge Comparisons to Operational Precipitation Profile Corrections", J. Appl. Meteor., **34**, Iss. 12, 2612-2630, 1995.

17. J. A. Pamment, B. J. Conway, "Objective Identification of Echoes Due to Anomalous Propagation in Weather Radar Data", J. Atm. Oc. Tech., **15**, Iss. 1, pp 98-113, 1998.