Adaptive clutter filtering using statistical radar data and atmospheric propagation conditions

Iñigo Hernáez, Mercedes Maruri, Javier López

1- Adasa Sistemas, Environmental Quality Division, José Agustín Goytisolo st, 30-32, PC:08908, L’Hospitalet de Llobregat, Spain, ihernaez@adasasistemas.com
2- Basque Meteorology Agency (EUSKALMET), Parque tecnológico de Álava, Albert Einstein av., 44, Bd. 6 Of. 303, PC: 01510, Miñano, Spain.
3- TECNALIA, Meteo Unit, Parque tecnológico de Álava, Albert Einstein av., 44, Bd. 6 Of. 303, PC: 01510, Miñano, Spain.

1. Introduction

The Basque Country is a region sited over a very complex terrain. It is a mountainous area with short river basins characterized by a fast response. In addition, the two most populated areas are close to the coast, crossed by some of these river basins. These characteristics define a lot of areas of potential flash flood risk.

Together with other observation instruments (mainly an AWS network, a wind profiler, a lightning detection network, and a radiosounding station) the Basque Meteorology Agency has a polarimetric doppler weather radar. Due to many reasons (Aranda et al.) the radar is sited on top of the Kapildui (Fig. 1) mountain (1162m height ASL), south-east of the region. To cover the necessities described in the previous paragraph the scan strategy was designed (Gaztelumendi et al.) with a high density of low elevations, some of them even negative. The topography causes a lot of blocked areas behind the main mountains.

The most important scan is a volumetric scan with a 100 km range and 15 elevations, especially because of its application to QPE algorithms. Vigilance tasks and different products make the 0.5º elevation crucial. The three lowest elevations (-0.5º, 0º and 0.5º) are affected by clutter. Beam propagation simulations show that elevations over 0.8º are completely clutter free. Despite the doppler filters, some clutter remains, which affects negatively the algorithms applied nowadays.

The aim of this study is to improve the clutter correction attempts with static clutter maps (Maruri et al.) considering the statistical behavior through the day and through the year and also the effect of the atmospheric conditions. Due to the system itself, unfiltered reflectivity data and differential reflectivity can’t be stored simultaneously, so the investigation is performed with filtered reflectivity data. Daily analysis of data showed some kind of statistical clutter pattern and a high dependence on atmospheric conditions, which lead to a deeper analysis of the historical data base, reflected in this paper. The final goal is to determine the pros and cons of both methods in order to develop a dynamic clutter map to use in combination with the filters.

2. Background

Two main areas of study are proposed in this investigation, statistical analysis of the clutter behavior and atmospheric conditions effect on radar beam propagation. In most studies (Bech et al.) the propagation of the electromagnetic wave is studied independently. However, it is difficult to correct some clutter based only on radiosonde data from a few stations, because the atmosphere can vary dramatically some tens of kilometers away. Therefore the combination with statistical tools improves the correction capabilities.
2.1 Statistical analysis background

Unfiltered topographic clutter, caused by non-steady vegetation or wind farms on top of mountains or hills, has a signature that appears to be constant throughout the year. That is useful for operators because the antenna positioning can be checked with the lowest elevations. However, statistical analysis of the evolution of this unfiltered clutter shows that the signature changes around the year. This evolution follows some patterns, which will be described later, through the day and through the year. That is what can be called “clutter climatology” and makes the statistical analysis critical.

To define a clutter climatology, two main characteristics of the received echoes are analyzed, the mean reflectivity and the clutter probability. The equations (Eq.1 and Eq.2) used are really simple, but they offer very important information to determine the behavior of the clutter:

\[
\bar{Z} = \frac{\sum_{i=0}^{m} Z_i}{m} \quad \text{(Eq.1)} \quad P(\%) = \frac{\sum_{i=0}^{m} e_i}{m} \cdot 100 \quad \text{(Eq.2)}
\]

Where \(Z_i\) means values of reflectivity (in mm\(^6/m^3\)) from every 10 minute period and bin, \(e_i\) means 1 if there is clutter over a defined threshold, and \(m\) is the discrete analysis period or number of samples considered.

2.2 Propagation analysis background

Radiosonde data provides information of the vertical structure of the atmosphere for a given point. This data can be used to determine (Eq.3 and Eq.4) the refractive index (ITU-R P.453-9):

\[
N = \frac{77.6}{T} \left( P + 4810 \frac{e}{T} \right) \quad \text{(Eq.3)} \quad n = 1 + N \cdot 10^{-6} \quad \text{(Eq.4)}
\]

Where \(T\) is the temperature (in K), \(P\) is the pressure (in hPa) and \(e\) is the water pressure (in hPa). This water pressure is obtained from the relative humidity of the air as follows:

\[
e = \frac{H}{100} a \exp\left( \frac{b t}{t + c} \right) \quad \text{(Eq.5)}
\]

Where \(H\) is the relative humidity (%), \(t\) is the temperature (in °C), and \(a, b\) and \(c\) are constants that depend on the state of water.

The vertical structure of the refractive index describes the propagation of an electromagnetic signal through the atmosphere. For an easier calculation, the earth radius, \(a\), is modified using the \(k\) factor to create the modified earth radius \(ka\). This factor can be obtained from the vertical gradient of the refractive index:

\[
k = \frac{1}{1 + a \left( \frac{dn}{dh} \right)} \quad \text{(Eq.6)}
\]

Some models have been proposed (Doviak et al., Hossain et al.) to calculate the radar beam propagation with this information. Here we will see that temperature gradients associated to anticyclonic episodes and their heights are two very important points to determine the probability of anomalous propagation and clutter incidence.

3. Statistical behavior of clutter

From the previous point one can understand that the propagation of the radar beam, as an electromagnetic wave, depends on the atmospheric conditions. Considering a synoptic scale, the evolution of weather through the different seasons provides different behaviors of clutter. On a shorter time scale, the differences between day and night also affect clutter behavior under similar conditions. Thus, there are two time scales to define clutter effects, here called annual and daily time scale.

For the annual evolution, the best statistic is the percentage of clutter probability. The most important observation is that in the hot season there are more echoes in clear air days, whereas this number decreases in the cold season (Fig. 2). For this
reason, more strict clutter corrections must be applied during the hot season.

Fig. 2 Percentage of clutter echoes for the cold season (a) -0.5° and b) 0.5°) and for the hot season (c) -0.5° and d) 0.5°). In this example 13/01/2012 and 31/07/2011 are the case study days.

These percentages have to be considered carefully, because during summer more echoes can appear from other types of clutter, such as biological clutter, especially on the areas surrounding the radar site. For this reason, one must take also into account the mean reflectivity of each bin, because this is usually much lower than that coming from mountainous areas. Combining both statistics the evolution of a certain type of clutter can be studied, thresholding reflectivity and percentage of appearance. In this study a mean reflectivity threshold of 10dBZ and a clutter percentage threshold of 50% are considered (Fig. 3), because they define correctly the static clutter of the region. In this plots, the annual behavior of clutter is also well defined.

Fig. 3 Number of bins exceeding the 10dBZ threshold of mean reflectivity and 50% clutter probability stacked for different elevations of the scan. In this example 10/02/2012 (cold season) and 31/07/2011 (hot season) are the study days.

The daily evolution of clutter is more associated to the effects of temperature on the propagation. The cooling of surface air during night creates important inversions that tend to increase clutter during the first hours of the day.

4. Atmospheric effects on propagation

As seen on section 2.2, many studies have been done to analyze how the atmosphere affects the propagation of the EM signal. The main dependence is the vertical profile of refractivity or the k factor, which can be calculated with equations 3 to 6. The most reliable data for this point is that taken from radiosondes (Table 1). Using equations (Eq.7) proposed by Doviak et al. the propagation of the radar beam can be approximated. The most challenging part of this simulation is the case of ducting, where the simplified model can’t be applied because the k-factor becomes negative. In this case, Snell’s law is used for ducting layers.

<table>
<thead>
<tr>
<th>Rasioonde</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Altitude (m)</th>
<th>Distance (km)</th>
<th>Azimuth (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santander</td>
<td>43.48</td>
<td>-3.8</td>
<td>59.0</td>
<td>129</td>
<td>308</td>
</tr>
<tr>
<td>Zaragoza</td>
<td>41.66</td>
<td>-1.01</td>
<td>258.0</td>
<td>176</td>
<td>134</td>
</tr>
<tr>
<td>Arteaga*</td>
<td>43.35</td>
<td>-2.66</td>
<td>13.0</td>
<td>65.27</td>
<td>351.5</td>
</tr>
</tbody>
</table>

Table 1 Summary of radiosondes considered in this study (*Available only since 04/2012, thus only used for some tests).
In addition, in order to test the behavior of the simulation equation itself, complete multi-layer ray-tracing using Snell’s law was performed. In general, the results show that this model is more restrictive and tends to bend more the ray towards Earth’s surface. Thus the number of bins marked as clutter area increases.

In most cases, situations of increasing clutter have been related with the presence of anticyclones, especially in coastal regions, where this can produce large vertical gradients of temperature and temperature inversions. These layers tend to cause anomalous propagation due to ducting and superrefraction. The height of this special propagation area in comparison with the radar height is the most important parameter to consider. The other variables that affect propagation (pressure and humidity) are less meaningful. In this case, with the radar located at about 1221.2 meters, inversion layers between 500 and 2000 meters have to be considered as clutter increasing for the case study elevations. Other inversion layers are also important, but they affect high elevations and are only important for strict echo location.

Comparisons between standard propagation and real propagation based on radiosonde data show that ray bending towards earth has an important effect. If vertical beam blocking is shown against mean clutter, high correlation appears (Fig.4). Blocking percentage is higher in areas where mean reflectivity falls. However, this correlation fails in some areas, especially on those closer to the radar site. Another source of differences is that filtered reflectivity is considered for the calculation of the mean values. Nevertheless, simulations appear very similar whereas real clutter changes dramatically.

Most of the studied cases do not have the 0º elevation, which was included in the operation on February 2012, so the different correlations were only tested for -0.5º and 0.5º. For all the simulations the nominal 0.7º half-power beam width was considered. One important observation is that the simulated propagation correlates better with lower elevations because the inversions cause a stronger bending; in this case there is better correlation for -0.5º than for 0.5º.

Finally, wind is also an important atmospheric influence on the remaining clutter. If wind speed is high under anomalous propagation conditions, the movement of vegetation and wind mills increases, thus leading to more unfiltered clutter. In case of an anticyclonic influence with strong pressure gradients the worst cases are observed.

5. Clutter correction

The results of this investigation show that both statistical and propagation approaches are good way to study the behavior of clutter. Statistics show a good correlation with mean values over a relatively long period of time, from days to months, and one can also check the roughly evolution of clutter over a day. On the other hand, atmospheric propagation simulations allow a better adaptation to the actual situation, taking into account short time anomalies. However these are based on models and on vertical data from a few points, this is, there is a high uncertainty due to approximations. In addition, simulations show that the propagation multi-layer equation doesn’t take into account the anomalies as much as desired, thus it is better to
consider the height of the ducting layers as an indication of possible anomalies.

Combining both strategies is the way to get the best results. The way proposed to combine them (Fig.5) consists of creating clutter maps based on statistics which will depend basically on the part of the year (more generally on the clutter climatology season) and add special clutter bins based on propagation conditions. These special bins can be extracted from simulations with radiosonde data and statistically defined bins that show to be typically cluttered under those specific situations. If there is no precipitation, the clutter map to be applied must be compared with the last clear air data in order to identify anomalous propagation areas which must be also included.

![Basic decision tree of the combining method for a clutter climatology with two seasons. Under clear-air conditions, extra areas can be applied from the comparison with last data.](image)

One of the most important decisions is to define correctly the season changes because the main correction comes from the mean clear air values taken in the correct period (Fig.6). This is also a site dependant condition. In case of the Basque Country, statistics show that clutter tends to increase from May to September, in coincidence with spring and summer. Thus, the hot season is defined for that period, whereas the cold season lasts during the rest of the year.

![Correction case study 2011/05/30 (hot season) using flagging algorithm. Left: Original scan data. Center: Correction with a cold season map. Right: Correction with a hot season map. Hot season map shows best results in a day where the Azores anticyclone caused atmospheric instability and anomalous propagation.](image)

In case of a strong anticyclonic situation with strong gradients in the risk zone (about ± 1000 meters around the radar site height), mountainous areas where statistics show clutter incidence under anomalous propagation conditions should be included.

### 6. Conclusions and future work

Most of the results taken from this study show that two common strategies used for clutter identification and correction
have their benefits depending on the situation. Their deficiencies have also been remarked, especially those from the propagation simulation. In this point, a new approach has been defined. Clutter conditions show a statistical evolution that can be used for a general correction. More specific situations can be derived from vertical profiles and weather models, thus more robust correction can be used under severe clutter conditions.

A division of the year into clutter seasons has been proposed. In general hot and cold seasons show different clutter patterns. Also a day-night division can be considered taking into account surface cooling and heating process. Finally, if anticyclonic influence is detected from models, anomalous propagation can be derived from radiosonde data, where the height of the main inversion and ducting layer can be checked.

To improve the method, different ideas should be considered:

- Take into account different time scales for the statistical analysis. This will allow a better correlation in shorter time scales and special events.
- Consider other variables in the statistical analysis. Some preliminary results with differential reflectivity show that very constant patterns can be used for clutter identification. Also wind data shows high correlation with clutter, because the stronger the wind, the stronger the unfiltered clutter.
- Extend the atmospheric variations to the horizontal axis. A 3D ray tracing based on outputs from models or on Kolmogorov’s approach introduces a more reliable propagation model.
- Correct the propagation equation. This equation shows good correlation with real data, but in some situations such as inversion and ducting, areas close to the radar site are not well simulated.

It is worth remarking that the statistical study has been done with filtered data due to the system itself. Studies with raw reflectivity could show better correlations, because clutter signature is more constant. Under current strategy this could not be tested.

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**References**


Doviak R.J., Zrnić D.S., 1984: Doppler radar and weather observations. *Academic Press (USA)*


Committee to assess NEXRAD Flash Flood Forecasting Capabilities at Sulphur Mountain California, 2005: Flash Flood Forecasting Over Complex Terrain: With an Assessment of the Sulphur Mountain NEXRAD in Southern California. *National Research Council flash, National Academies Press (USA)*