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A Look to Different Approaches for the Detection and Correction of Anomalous Propagation in Meteorological Radars for Its Application in Colombia

Julián R. Camargo L.[1], Ernesto Gómez Vargas[2] and César A. Perdomo Ch.[3]

[1,2,3] *Engineering Faculty, Universidad Distrital Francisco José de Caldas, Bogotá D.C., Colombia*

Abstract

Currently the use of weather radars, which are designed to monitor continuously (in time and space) cloud formation and in general the formation of precipitation, allows a complete and reliable meteorological measurement and management of data generated for these. Knowing this is essential for the aviation industry operates properly and without risks to passengers, crew and aircraft, it is also important to anticipate and/or avoid if possible climatic disasters generated by events related to rainfall.

Keywords: Anomalous propagation, metereological radar, polarimetric variable, reflectivity.

INTRODUCTION

Radars have an important role in the field of meteorology. These devices send and receive signals that provide valuable information about the location and intensity of rainfall. Doppler radar technology goes far beyond the simple detection of reflectivity allowing obtaining high resolution data and estimated speed data, which is vital for short-term weather forecasting and weather prediction in severe conditions. [1]

In equatorial zones with presence of humid climate the rains are frequent for long periods of time and unlike other areas of the planet the presence of snow is not a normal type of precipitation (given this by the non-existence of stations). In Colombia, civil aeronautics has acquired in recent years some meteorological radars whose use is very limited since their full potential is not exploited, which would allow for multiple benefits associated with early warning systems and climate prediction.

The uses of these equipment are not limited to aeronautical purposes and climate prediction, they are also used as a complement with meteorological stations that allow the management of reservoirs, irrigation channels and water sources by agencies responsible for the care and prevention of natural disasters in specific critical areas.

CONCEPTUALIZATION

The radar

The radar is an electronic system that allows detecting objects out of sight and determine the distance where they are projecting radio waves on them. The word radar corresponds to the initials of *"radio detection and ranging."* [2]

The capacity of meteorological radars to detect rain was already known in the 40s, its initial development took place during the Second World War after the invention of the resonance magnetron, with which it was possible to emit a considerable amount of power at a few lengths wave of several centimeters. One of the unintended consequences was that the rain and snow became clearly visible. This new ability to detect rain remotely, observe its pattern in space and its evolution over time was the driving force in the development of meteorological radars.

Basic functioning

The operating principle of the weather radar is to emit, through an antenna, a pulse of electromagnetic energy of duration *t* (of the order of ms) and a wavelength *l* (of the order of centimeters, since the desired target is raindrops) [3].

This energy is concentrated in a beam that when emitted to the outside and by effect of diffraction takes a conical shape. Inside that cone the energy is not distributed uniformly but in the form of a lobe: it is much larger in the center and decreases rapidly as it moves away from it. Because it is impossible to confine all the energy in said cone part of it escapes out of it. As a result, the energy emitted is distributed in the form of a central lobe (which is the one that contains most of the energy) and a series of secondary lobes of lower energy.

When that energy is intercepted by a 'target' (for example, a drop of water) it is scattered in all directions (see Figure 1), so that a fraction is returned in the direction of the radar and picked up by the receiver (located in the same antenna). The distance to the 'target' is determined by recording the time elapsed between the emission and reception of the energy and knowing that this energy is transmitted at the speed of light [3].

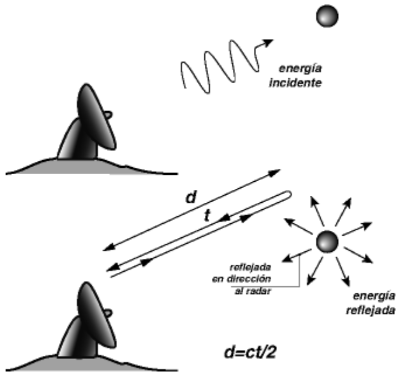

Figure 1. Scheme of the energy captured and reflected by a drop [3]

Types of meteorological radar

There are several types of meteorological radars used for detection in different ranges of distances, Table 1 shows a summary of them:

Table 1. Types of meteorological radars

Band	Freq.	Wavelength	Operation interval	Advantages	Disadvantages
S	2-4 GHz	8-15 cm	< 240km	They are not affected by attenuation	They need a large disk, as well as all the machinery. High price.
C	4-8 GHz	4-8 cm	< 120 km	Small disk size: portability Price	Affected by the attenuation
X	8-12 GHz	2,5-4 cm	< 60 km	Very sensitive to small particles. Useful for the study of cloud development. Small disk size: portability Price.	Very affected by the attenuation

Equation of the radar

Actually what the radar records is the energy returned in its direction by the water droplets located inside a certain V_{res} volume (see Figure 2).

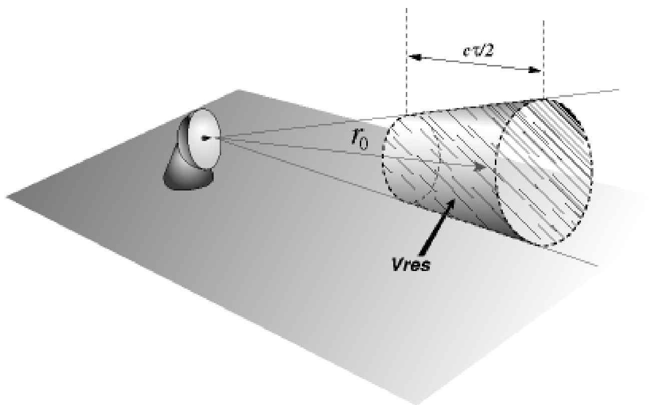

Figure 2. Radial size volume c t/2 that corresponds to the energy measured at a given time and associated to a given distance [3]

That energy, that is measured in the form of power, can be expressed as:

$$\overline{P}(r_0) = \frac{C}{L^2(r_0)r_0^2} Z(r_0) \tag{1}$$

Where P is the average power returned by the drops located inside the V_{res} located at a distance r0 from the radar. The power is expressed as average because the radar usually emits a train of n pulses; thus, for a volume located at a distance r_0, n power values are measured and then averaged.

The reason for taking measurements of a volume is that in this way the final measurement is more robust (since the power varies in time due to the movement of the drops inside the volume). On the other hand, the constant C groups a whole series of characteristics related to the radar, this is what is known as the radar constant. Finally, the reflectivity Z is the variable related to the drops that can be derived once the P power is measured.

The reflectivity Z is defined as the sum of the diameters to the sixth power of the drops contained within a volume, that is:

$$Z = \int_0^\infty N(D)D^6\, dD \tag{2}$$

Where N(D) is a function of distribution of water droplets [3].

On the other hand, the intensity of rainfall can be expressed as the flow of water through a surface, and it can also be formulated as a function of N(D) as:

$$R = \frac{\pi}{6}\int_0^\infty V(D)N(D)D^3 dD \tag{3}$$

From experimental data of Z and R it has been verified that the relationship between both variables tends to respond to a potential function of type [3]:

$$Z = aR^b, \text{como } Z = 200R^{1.6} \tag{4}$$

Images made with a meteorological radar

From the information recorded by the radar at different elevations, two types of images are usually generated:

PPI (*Plan Position Indicator*):

Corresponding to the reflectivity recorded in each of the elevations and that is projected on the horizontal plane (Figure 3), which only produces a two-dimensional image of the radar return. It must be remembered that the data (returns) come from different distances to the radar, at different heights above the ground [3].

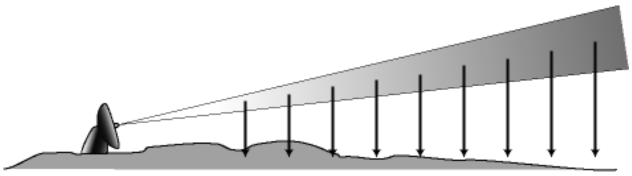

Figure 3. Projection of the PPI on the horizontal [3]

CAPPI (*Constant Altitude Plan Position Indicator*):

This second type of image tries to represent the reflectivity recorded on a plane at a constant height. To generate this second type of image, those fragments of information of the different elevations that are closer to the height for which the CAPPI is to be generated are used (see Figure 4).

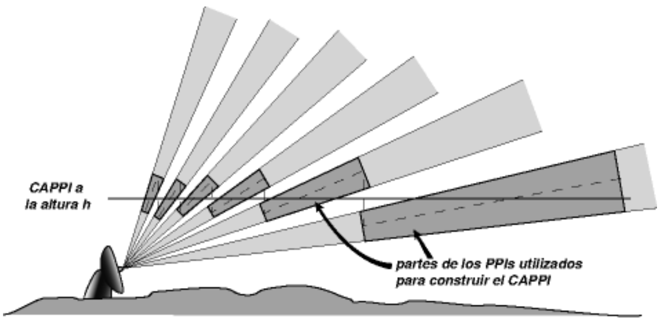

Figure 4. Schematization of the elevation fragments used to generate a CAPPI image [3].

Polarimetric Variables

As the main difficulty in the measurements with radars is basically related to the diameter of the drops, the polarimetric radars are used. These have the ability to emit microwaves with double polarization, which incorporates new measurement variables, in addition to Z (reflectivity), called polarimetric variables, the specific phase difference (KDP) and differential reflectivity (ZDR). The first of these variables, KDP, gives an estimate of the specific phase difference between the received signals.

This is achieved when the drops are large and are deformed generating a difference of optical paths between the radiation with horizontal and vertical polarization. On the other hand, ZDR is defined as the quotient between the horizontal reflectivity Zh and the vertical Zv that the radar receives providing an estimate of the shape of the hydrometeors. This measurement shows that the larger the value of ZDR is the larger and more deformed the drops will be; and the closer these values are to one, the smaller and more spherical they will be [4].

Anomalous Propagations (AP)

The first assumption is that the radar beam moves through the air, which cools at a certain rate with the height. The position of the echoes depends completely on this hypothesis, however, the actual atmosphere can vary greatly from the norm.

Super refraction

When the deviation of the radar waves downwards is greater than normal causes a super refraction. this occur when the temperature increases with the altitude, i.e when there is a thermal inversion. Super refraction may allow the detection of local targets at greater distances than when there are normal conditions.

Sub refraction

In many occasions radar waves do not deviate below the way they normally should, and under particular and extreme conditions they deviate upwards, this condition is called sub refraction, which is less common than super refraction.

DIFFERENT APPROACHES TO TREAT WITH THE DETECTION AND THE CORRECTION OF ANOMAL PROPAGATIONS IN METEOROLOGICAL RADARS

There are several approaches to dealing with the detection and correction of anomalous propagation in meteorological radars, however, as it will be presented below, each of these approaches does not combine the use of polarimetric and non-polarimetric parameters, in addition to the variability of space temporary rainfall, these approaches have been worked in areas where the seasons prevail.

Non Parametric approaches

Many researchers have used the spatial and temporal information of anomalous propagations as a threshold or in a probabilistic way to identify these problems [5] - [19]. In reference [18], the spatial variability of the reflectivity field and the vertical gradient of the reflectivity calculated in polar coordinates are combined with the vertical extent of radar echoes to identify anomalous propagations using a decision tree. In the references [20, 21] a fuzzy logic approach was adopted that included the texture of the reflectivity, the average radial velocity, the broad spectrum of the median and the standard deviation of the radial velocity. In [12] a neural network was applied based on the local characteristics of reflectivity and velocity fields.

The anomalous propagation belongs to one of representative non-precipitation echoes that have significant influences on the weather forecast process [22]. This happens due to the super refraction or the phenomenon of ducts of the trajectory of the meteorological radar beam, generated by the temperature or the distribution of the humidity. In order to classify the echoes of anomalous propagations in the radar data, an automated procedure based on a classification scheme of artificial neural networks is suggested. After applying the spatial grouping in corrected reflectivity data and extracting coordinate information for the Doppler velocity data, the artificial neural network classification method is applied because it has flexible characteristics in the modeling of real-world complex relationships. By using the artificial neural network method, it is possible to establish a powerful detection system with characteristics extracted from the Doppler speed. The experimental result with the case of the actual appearance of the anomalous propagation echo describes that the proposed system with the artificial neural network shows a good performance in the classification process.

In reference [23] a method is developed to detect anomalous propagations based on radar echo characteristics, this approach is similar to that found in [20, 21]. However, the membership functions for the fuzzy logic are derived from the statistics of the observed echo characteristics (the absolute value of the radial velocity, the standard deviation of the reflectivity, and the vertical reflectivity gradient) as a function of the adequate reflectivity and weights for these membership functions, are also obtained from these statistics to optimize the elimination of anomalous propagations. The data used comes from a S-band radar that transmits a polarized beam linearly at 45° and receives horizontal and vertical components simultaneously. Scan at the speed of 6 rotations per minute (rpm) or 36° s^{-1} (equivalent to 24 elevation angles for the full 5-minute cycle). To validate the model, they perform two tests: an examination of the resulting precipitation accumulation maps and by comparison with the polarimetric identification of anomalous propagations and earth echoes in all the PPIs. As a conclusion of the mentioned work, the proposed fuzzy logic method is more objective and can easily be adapted to other geographical conditions analyzed.

Reference [24] presents an algorithm for the automatic elimination of non-precipitation echoes related to anomalous propagation (AP) at the lower elevations of the meteorological radar volume scans. The objective of the developed algorithm is to minimize the human interaction with the data obtained by the radar. The algorithm uses both the textural information and the intensity obtained from the two lower elevation reflectivity maps. The texture of the reflectivity maps is analyzed with the help of multifractals. Four multifractual exponents are calculated for each pixel of the reflectivity maps and compared with "strict" and "soft" thresholds. Pixels with multifractal exponents larger than the strict threshold are marked as "no rain," and pixels with exponents less than the soft threshold are marked "rain." The pixels with the other values of the exponent are examined using the intensity of the information. The algorithm is evaluated by comparing it with the quality control algorithm developed by the Tropical Rainfall Measurement Mission (TRMM). The comparisons are based on a series of selected cases in which rainfall and a variety of rainfall events are present, as a result of the effective of both algorithms in the elimination of ecosystems related to precipitation, while maintaining rain pixels. The main advantage of the algorithm is that it is automated; therefore, provide the requirements for quality control analysis and carry out the process of data reduction by eliminating the need for human interaction in the software.

The purpose of the anomalous propagation mitigation scheme presented in [25] is to improve the precipitation estimates derived from the WSR-88D radar by improving the quality of the data through the identification and elimination of certain pollutants, specifically ground echoes. The elimination of ground echoes is needed, as it causes erroneous rainfall estimates within the WSR-88D precipitation processing subsystem [26], as well as errors in other algorithms and errors in interpretation. The classifier echo determines where the earth echoes are located that are contaminating the radar's base data and where precipitation is occurring to facilitate automatic detection and elimination of the problem.

Polarimetric approach

In reference [27] polarimetric meteorological radars provide additional measures that allow a better characterization of the target medium. Because echoes have different polarimetric characteristics of time echoes, dual polarization measurements can be used to distinguish one from the other. Earth and time echo signals also have different statistical properties that can be used to distinguish one from the other. A test statistic, obtained from the generalized likelihood ratio test (PRVG), and a Bayesian classifier, with contributions from the mean and the covariance of the received signals, are developed to detect these anomalies. It has been found that the test statistic produces false detections caused by narrow band signals whereas the Bayesian classifier can effectively neutralize them. With this work, ground echoes are detected based solely on the data of each resolution volume. The performances of the test statistic and the Bayesian classifier are shown by their application to the data collected with the polarimetric radar of the University of Oklahoma for Innovation in Meteorology and Engineering.

In [28] an algorithm is used to correct by attenuation (absorption and "scattering") the horizontal reflectivity factor Zh using the polarimetric radar data. The correction is made taking into account atmospheric gases, cloud particles and precipitation. The calculation method is based on the recovery of the parameters that define the distribution of droplet sizes in a cloud given by (Λ, μ, N0). For this purpose, the empirical relationships Λ - μ and μ - N0 given by Zhang et al. (2001). The results obtained shows corrections, for regions of high reflectivity factor Zh> 50 dB, of approximately ~ 6 dB. Corrections of this style, in these regions increase the precipitation rate in an appreciable factor with respect to the empirical method Z-R proposed for INTA Castelar.

In a different work [29] a study designed to classify anomalous propagations in meteorological radars obtained from a double-polarized meteorological radar system on land is presented. The unwanted signals are due to echoes of earth, sea noises and the echoes of anomalous propagations, which represent sources of error in the quantitative estimation of radar precipitation. Fuzzy logic and Bayesian classifiers are evaluated as an alternative approach to traditional methods. Both systems were trained and validated by C-band dual polarization radar measurements, and a new technique for calculating the texture function is proposed to mitigate edge effects at the boundaries of the precipitation regions. A methodology is presented to extract membership functions and conditional probability density functions to train the classifiers. The critical success rate indicates that the Bayesian classifier has, on average, a slightly better performance than the fuzzy classifiers. However, when the optimal weight is applied, the fuzzy classifier gave better results. The classifiers are robust enough to be used when measurements are made on single polarization radars.

For the study carried out in reference [30] the effect of the interaction between anomalous propagation (AP) and the blades of wind turbines that are very far from the radar is important for the rainfall type estimates generated by the radar. Interference from wind turbines in radar observations can result in significant errors in rainfall estimates since wind turbines are often grouped to form wind farms. This study propose a new approach based on the polarimetric capacity of radars WSR-88D NEXRAD, which identifies and eliminates the problem produced by the wind turbine, together with the effect generated by earth echoes. The main objective of the work is to design a fully automated method using polarimetric variables, which handles the characteristics of the anomalies, which are difficult to detect using single-channel reflectivity data. To solve this problem, we explore the use of polarimetric variables such as: reflectivity differential (ZDR), co-polar correlation (RHO), and differential phase (PHIDP). Thus, they developed three new approaches using polarimetric variables, which are combined with an anomalous propagation detection algorithm that uses a three-dimensional structure of reflectivity. The new algorithms are evaluated in terms of removing non-meteorological radar echoes, thus preserving the actual rainfall returns. The proposed algorithm, which uses RHO conditioned to horizontal reflectivity values and also the variation of ZDR or PHIDP, shows good performance.

RADARS IN COLOMBIA

In equatorial areas (where the phenomenon of the seasons does not occur) and specifically in Colombia, studies related to this type of anomalies have not been carried out, except for a few isolated cases, so that the use of the few existing radars in the country, located in Corozal (Sucre), El Tablazo (Cundinamarca) and San Andres Island, all recently acquired with new technology in the country, so there is still no clarity on how to give adequate use to the data obtained by these.

Given the great spatial and temporal variability of rainfall, the models and studies carried out in other areas of the world are not fully applicable for tropical zones and specifically for Colombia, as explained in reference [31]:

"The complexity of Colombian hydrology is due in large part to the number of factors that intervene in the spatial and temporal distribution of precipitation." The spatial distribution of rainfall in the Colombian territory is mainly determined by its tropical dynamics, the displacement of the ZCIT throughout the year, the moisture sources of the Amazon basin and those from the Pacific and Atlantic Oceans and its physiography that has as main component the Andes mountain range, with oceanic and inter-Andean valleys, the latter presenting special characteristics associated with the generation of local circulations inside them. The variability of the processes of surface hydrology, such as contrasts in soil moisture and evapotranspiration are also of great importance for the understanding of the spatial variability of precipitation.

The temporal variability of precipitation in Colombia is determined by several factors that operate at different scales such as climate change, the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO), the Quasi - Biennial Oscillation, the ENSO, the ITCZ, the jet of Chocó, the dynamics of Mesoscale Convective Systems, the oscillation of Madden - Julian, the tropical dynamics and the physiographic characteristics of the country.

The role of relief in the country's climatology is of great importance due to the direct consequences of altitude on temperature and humidity, due to the obstacle role played by the mountainous mass in front of air flows laden with moisture, differentiating itself in this way climates of Windward and Leeward, known as shelter effects on Colombia to which are added a fundamental characteristic of its climate as are local circulations. The separation of humid air sources and the orientation of the valleys and slopes are also causes of great rainfall variability "[31].

HOW ALL THESE STUDIES CAN BY APPLIED FOR COLOMBIA?

In Colombia, Aerocivil has three C-band polarimetric radars located in Corozal (Sucre), El Tablazo (Cundinamarca) and San Andres Island, all recently acquired with new technology in the country, which have included in their operating software the Park´s algorithm, that was designed for climatic conditions of zones governed by stations, so the degree of accuracy of the classification decreases considerably for equatorial zones. These radars generate their readings in formats that offer the possibility of decoding them and if it is necessary to improve them, for this case this improvement is necessary since as mentioned the algorithm included in the radar does not apply to equatorial zones, so a new model is required, a model that allow the detection correction of anomalous propagation. By having an algorithm that allows the detection correction of anomalous propagations presented during a precipitation it is possible to improve the estimate of the amount of said precipitation presented during a given event.

Thus, it is possible to propose, by means of the exploration and analysis of existing models used for the detection of anomalous propagations generated in a meteorological radar, a model that allows the detection and correction of errors in said radars located in equatorial zones, produced by anomalous propagations. This model would try to solve some problems that have not been covered so far in this area.

CONCLUSION

Studies shows that polarimetric variables are sensitive to the shapes, sizes, and other microphysical properties of hydrometeors, however, there are still some gaps in the knowledge of polarimetric signatures that make room for improvement in classification methods, detection and correction.

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