P9.7 AUTOMATIC QUALITY CONTROL OF AIRBORNE DOPPLER RADAR DATA

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1. INTRODUCTION

Doppler radars mounted on aircraft platforms have proven useful for studying a variety of weather phenomena including tropical cyclones, convective initiation, tornadic thunderstorms, and mesoscale convective systems. In order to do a multi-Doppler synthesis with data from these platforms the data must be heavily edited to remove non-weather echoes such as second trip, sidelobe, ground, and low signal to noise returns. Some of these echoes can be removed automatically, but others require manual editing of individual sweeps and are time consuming to remove.

This paper will introduce methods that can be used to automatically flag spurious echoes for removal in ELDORA data. A concurrent effort is also underway to apply aircraft navigation corrections in real time. By combining these two applications the radar observations collected by ELDORA have the potential to be used for tactical decision making during the aircraft mission and can be assimilated into numerical models to improve short term forecasts of the phenomena being studied. Having these data available has been shown to lead to smarter and more efficient resource allocation during field programs (Kessinger and Lee 1991).

2. BACKGROUND

Automatic quality control (QC) of radar data is not a new idea. A variety of algorithms exist for removal of clutter and non-meteorological targets (Steiner and Smith 2002, Kessinger et al. 2003, Zhang et al. 2004, Dixon et al. 2006, Lakshmanan et al. 2007). Some of these tools are inappropriate for airborne platforms that are moving. For example, a clutter map can be made for a ground-based radar that shows areas where stationary targets such as trees, terrain, or manmade structures exist that contaminate the observations. This is impossible for aircraft-mounted radars that are constantly in motion. However, some of the tools developed for ground-based radars, such as standard deviations and textures fields, can be applied to airborne radar data.

Researchers at the Hurricane Research Division (HRD) have developed an algorithm for automatic quality control of radar data collected by the National Oceanic and Atmospheric Association (NOAA) Tail-Doppler Radar (TDR; Gamache 2005, Gamache et al. 2008). While both the TDR and ELDORA can be used to observe the same phenomena there are enough differences between them that each algorithm is designed specifically for that radar. One of the measurements from ELDORA is the normalized coherent power (NCP), which is the ratio of the power calculated at lag one to the total received power. This field will be an important part of the ELDORA automatic QC algorithm, but is not currently recorded by the TDR. Velocity folding is also a concern for the TDR because of its relatively small Nyquist velocity (often 12 m s^{-1}) and must be properly addressed. Folding is much less common in ELDORA (Nyquist velocity of 60 m s^{-1}) because of its dual PRF mode and will only be present in very strong winds such as a Category 4 or 5 hurricane, a tornadic storm, or bow echo. It will be addressed in the ELDORA algorithm but not as rigorously as in the TDR algorithm.

The two algorithms also differ in their approach. The TDR algorithm uses a set of complex rules to perform the quality control. For example, side lobe reflections are removed when low reflectivity is observed in a thin ring near the radius equal to the altitude of the aircraft above a sea surface (Gamache et al. 2008). The ELDORA algorithm uses fuzzy logic to determine how likely a particular echo is to be a meteorological target. Interest maps are created based on fields derived from the radar observations. They are then combined to calculate a probability of weather that an individual user can tune to his or her specifications.

3. CASE DESCRIPTION

In order to test the automatic QC algorithm for the ELDORA cases have been chosen that represent a wide variety of weather phenomena and situations with a goal of choosing cases from nearly all of the field programs to which ELDORA

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has been deployed. Radar meteorologists have also manually edited each case to give a benchmark to which the results of the algorithm can easily be compared.

ELDORA has mainly been used to study different types of convection, so the QC algorithm needs to work well for each type and their various phases. Continental convection has been observed in three different projects: Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX), the International H2O Project (IHOP), and the Bow Echo and MCV Experiment (BAMEX). IHOP will provide a case with convective initiation along a dryline that will contain a large amount of clutter and noise, which will be difficult to remove automatically. The case from VORTEX is a tornadic supercell and contains large gradients in reflectivity and velocity over a short distance. A squall line from BAMEX may also be studied in order to test the algorithm on larger scale convection.

Oceanic convection cases will come from the Thorpex Pacific Area Regional Campaign (T-PARC) Tropical Cyclone Structure (TCS-08) field campaign and the Hurricane Rainband and Intensity Change Experiment (RAINEX). Part of T-PARC TCS-08 was focused on the development of tropical cyclones and observations from early phases of Typhoon Hagupit give a fine example of organizing oceanic convection. The RAINEX case that will be used for testing is from Hurricane Rita and contains strong, heavily banded convection.

The Mesoscale Alpine Program (MAP) will also provide a test case. All of the other test cases occurred either over the ocean or the central plains in the U.S., both of which are quite flat so that the ground is relatively easy to find. MAP, as its name implies, took place in a mountainous area. The complex terrain over which the data were collected makes it difficult to locate and remove the ground automatically and accurately.

4. METHODOLOGY

Many different ingredients to the algorithm have been investigated, each with their own pros and cons. The goal is to find the best combination of them. This section will describe those methods that have the greatest potential for removing non-meteorological echoes in ELDORA data. The algorithm is attempting to flag three main sources of bad data: noise (including sidelobes, ring, and second trip echoes), ground, and speckles. Every gate will be assigned a probability of the occurrence of each of these. Those probabilities will be summed and subtracted from 1 to give the probability of weather.

Interest maps will be used for most fields to avoid using thresholds. This will also allow the users to have some say in how strict they want the QC algorithm to be. For some applications such as modeling or in a real time situation (e.g. inside the aircraft during the flight) very strict rules may be applied so that it is all but guaranteed that any echoes left are truly meteorological in nature. Conversely, other applications such as processing volumes for post-analysis may require less strict rules so that details can be kept in that may be vital to getting an accurate answer. A good example is boundary layer winds, which are usually difficult to extract due to surface clutter. In a dual-Doppler analysis they are critical for deriving accurate vertical motions, which may be important in research topics but not as much in a real time setting. By using interest maps this algorithm can be tuned to the user's desires.

4.1 Normalized Coherent Power

The NCP field is very efficient at removing noise. The lower (higher) the NCP value the more (less) likely that a given radar return is noise. Generally, a simple NCP threshold is applied to the reflectivity and velocity fields, meaning that any data with an NCP value below a defined threshold are deleted. In the QC algorithm, instead of deleting data below a threshold we assign a lower probability of weather to it, based on an interest map. In this mapping function any echo with an NCP value less than 0.2 has an interest value of 0. The map value increases linearly with NCP until it reaches 1 (maximum interest) at an NCP value of 0.4. Anything with an NCP above 0.4 has a high probability of being a weather echo.

NCP cannot be the sole ingredient in this algorithm, though, as demonstrated in Fig. 1. Figure 1a shows a raw reflectivity field from ELDORA with no quality control applied and a combination of weather, clear air, and non-meteorological targets including second trip echo, ground, and sidelobes. Due to the sensitivity of the ELDORA receiver there is some sort of return from nearly every part of the image, even the clear air. If a threshold of 0.2 is applied (Fig. 1b) then a large portion of the clear air echoes are removed, though there are still some speckles. The second trip echo that extends out from the center of the images to the left is also still mostly intact. Figure 1c shows radar reflectivity when a threshold of 0.4 is applied. This strict treatment results in the removal of almost all of the clear air speckles and a large part of the second trip echo. However, it also removes more of the weather echo on the right side of the images and may cause some details to be missed. This illustrates why the endpoints of 0.2 and 0.4 were chosen for this interest map; they strike a balance between leaving and taking out too much echo. Note that the ground (line of high reflectivity near the bottom of the images), echoes from below the ground, the ring (circle of echo at the center with a radius equal to the aircraft altitude), and sidelobes (lower left side of the ring) are still considered to be weather echoes, even at the higher threshold. The NCP values of those artifacts (Figure 1d) are just as high as those of the weather echoes, making them difficult to remove. They will require further processing.

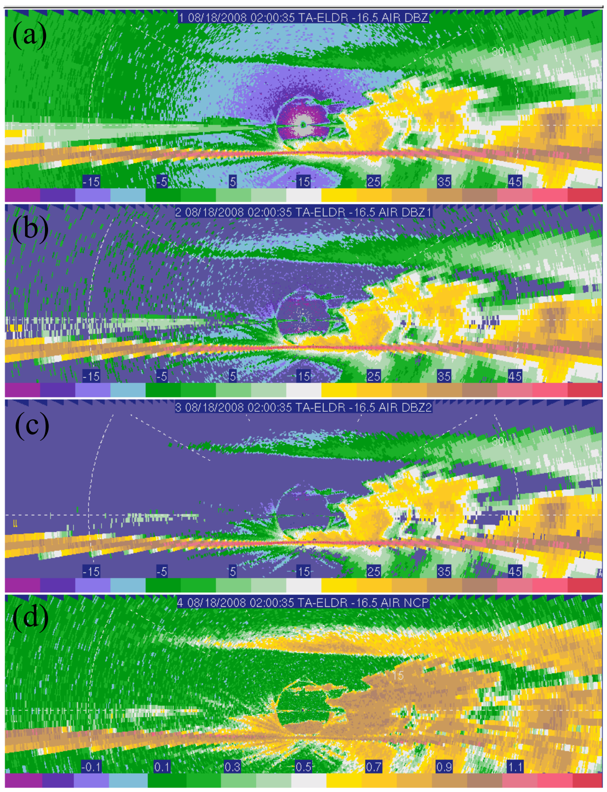

Figure 1. (a) Raw reflectivity from the ELDORA aft radar. The reflectivity field after NCP thresholds of 0.2 (b) and 0.4 (c) have been applied. (d) The NCP field.

4.2 Spectral Width

The spectral width (SW) field can be used to remove some of the noise that the NCP field misses. Noise generally has a high spectral width so thresholds are sometimes applied so that anything too high can be removed. Turbulent motions can also have a high spectral width and thresholding may remove good weather echo in cases where strong turbulence is likely such as thunderstorms, mesoscale convective systems, and tropical systems. To avoid this, noise removal techniques generally delete data where the spectral width is above a certain threshold and the reflectivity is low. These areas are more likely to be noise or bad data.

Because the ELDORA QC algorithm is interested in determining the probability of weather a slightly different approach is taken. The algorithm calculates a ratio between the spectral width and reflectivity for each point and maps that value to an interest that can be combined with other noise-finding procedures. The higher the ratio the more likely an echo is noise.

First, the reflectivity is converted from a log scale to a linear scale (Z). Then, the spectral width is divided by this value. This becomes the ratio, which is capped at ten so that the probability of noise is given by:

$$P_{noise} = R / 10 \text{ where } R = SW / Z \quad \textbf{(1)}$$

For high reflectivity values high spectral width is required to result in a large noise probability while lower spectral width values would be required for low reflectivity areas. For example, an area with reflectivity of 50 dBZ and a spectral width of 15 would result in a noise probability of essentially 0. Decreasing the reflectivity to 5 dBZ increases that probability to 0.47.

Figure 2 shows the reflectivity and spectral width along with the ratio calculated by Eqn. 1. It is similar to the NCP field in that it produces low values for second trip echo and is unable to distinguish ground from weather. This field adds value by flagging some of the sidelobes as bad data, something that the other methods struggle with. Note the low probabilities around the sidelobe to the lower left of the aircraft in Fig. 2c. This is substantially more than the amount identified by NCP alone. Though it still leaves quite a bit of bad echo this field appears to be a useful discriminator, especially if NCP is not available (e.g. NOAA TDR data). Identification and removal of sidelobes in an automated algorithm remains a difficult problem and more fields will need to be explored to arrive at a solution.

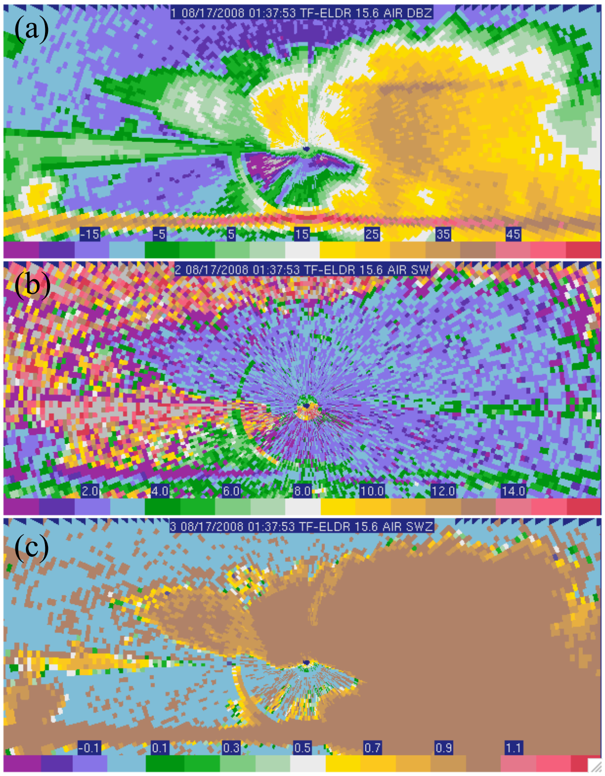

Figure 2. (a) Raw reflectivity and (b) spectral width from the ELDORA. (c) The spectral width to reflectivity ratio. Lower values are more likely to be noise or spurious echo.

4.3 Ground

The concept of ground removal is quite simple. Since the altitude of the aircraft is known then the gates that intersect the ground can be easily determined using trigonometric functions when the surface is flat. However, a variety of factors come into play that make finding the actual ground location much more difficult.

First, the radar beam widens the further it gets from the aircraft. This may cause return from the ground to appear before the center of the beam actually reaches it and is especially noticeable further from the aircraft where the angle between the radar beam and the ground is more oblique. To handle this the ELDORA QC algorithm finds the first gate in each ray that is likely to be contaminated by the surface based on the ray number, aircraft altitude, and effective beamwidth. Once that gate is found everything beyond it is assigned a maximum probability of being affected by the ground.

The algorithm then considers gates leading up to the calculated gate as these may be contaminated as well. Errors in aircraft altitude or radar beamwidth may cause the initial ground gate to be incorrect. More importantly, the propagation of the beam is a function of the atmospheric conditions and the distance from the aircraft. The longer the range the more that the beam may be refracted, causing ground contamination well before the first calculated ground gate. More research needs to be done on the amount of likely contamination based on range and weather conditions, but the algorithm will consider some number of gates leading up to the first calculated ground gate. Each will be assigned a ground probability that decreases with distance from that gate. It can be thought of as an interest map where the maximum interest is found at the likely first ground gate and the minimum is reached x gates prior to it, where x is a function of range, with no ground probability for any gates closer to the aircraft.

In Fig. 1a the ground is thicker near the edges and also appears to be bending upwards slightly. This is due to beam spreading and is easy to see where precipitation is not reaching the surface on the left side. A sudden along-beam increase in radar reflectivity in gates near the surface can be used to boost the likelihood of ground contamination.

If precipitation is falling, especially if it is heavy, then the gradient in reflectivity becomes less useful because it is difficult to identify the transition (Fig. 1a, far right edge). However, if the aircraft motion has been removed from the velocity data then the velocity gradient can be used. Over land, the ground will have a velocity of zero and the weather echo will usually be non-zero. Over the ocean, where the surface may be in motion, finding the surface in heavy precipitation is more difficult to do but a combination of the three fields described above should do quite well in most circumstances.

Perhaps the most difficult place to find the surface is in regions of complex terrain. Calculating the first likely ground gate is not possible unless a high-resolution topography dataset is ingested, which is difficult in real time. The gradients must be relied on heavily in this case. Because the ground will be stationary the velocity gradient is likely to be the most useful when precipitation is falling in these situations.

4.4 Speckles

Speckles are isolated gates of noise outside of the main echo. They can be made up of one isolated gate or even a group of gates. Determining the number of consecutive gates that can be considered speckles before removal of good echo occurs is a difficult problem. The ELDORA algorithm will calculate the probability that a gate or group of gates is speckle by applying a gate number threshold that is based on the likelihood of that number of gates being noise. For a single gate with echo surrounded by empty gates the probability of speckle will be 100%. That probability will decrease as concurrent gates with echo are added so that once the number of gates reaches eight the probability of speckle is 0%.

Flagging of speckles can be done in either the radial or azimuthal direction by applying the thresholds. Eight gates in the radial direction is equal to 1.2 km, meaning that at the highest threshold echoes less than that size will be flagged for possible removal. In the azimuthal direction the scale of eight gates will vary because of the beam spreading out with distance from the aircraft. Both rings (radial) and second trip echoes (azimuthal) are made up of thin reflectivity bands in their respective directions and are usually able to be identified with a relatively low threshold.

5. SUMMARY & FUTURE WORK

Early tests have shown that these methods can be used to flag a large portion of bad echoes with decreased probability of weather. Some artifacts, such as sidelobes, still need more work to be distinguished from weather returns. Other fields to be tested include standard deviations and derivatives of velocity and reflectivity along with additional methods that have proven useful for ground-based radars and are applicable for airborne platforms.

This paper presents an overview of the automatic QC algorithm that will be applied to ELDORA data. The concepts described here will continue to be tested and combined with other derived fields in order to come up with the best set of interest maps for removing non-meteorological targets from airborne radar data. This algorithm will be combined with an automatic navigation correction algorithm with the goal of providing real time display of flight-level wind vectors overlaid on reflectivity at the science workstation on the ELDORA aircraft by 2012.

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