Improvements of the French operational triple-PRT Doppler scheme

C. Augros[1] and P. Tabary[2]

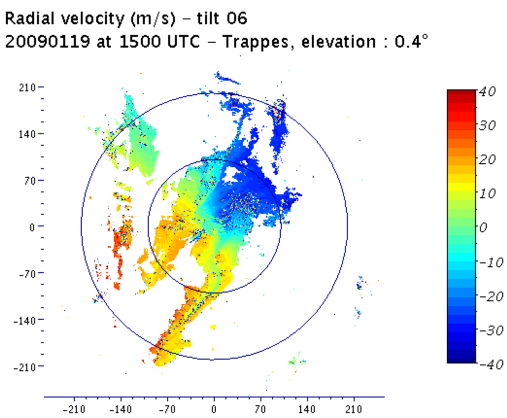
[1] Centre de Météorologie Radar, Direction des Systèmes d'Observation, Météo France, Trappes, France
[2] Centre de Météorologie Radar, Direction des Systèmes d'Observation, Météo France, Toulouse, France

1 Introduction

Staggered pulse repetition time (PRT) schemes are known for their ability to solve the long-lasting range–velocity dilemma (Zrnić 1977; Zrnić and Mahapatra 1985; Sachidananda and Zrnić 2002; Torres et al. 2004; Tabary et al. 2005). In 2005, a triple-PRT (Pulse Repetition Time) Doppler scheme was introduced in the French operational network (Tabary et al. 2006) with the objective to provide de-aliased radial velocities (up to 60 m s^{-1}) up to long range (250 km) and the constraint to keep the mean PRT at the same initial level (1/333 Hz for C-band radars). To evaluate the quality of this new triple-PRT scheme, we estimated the Dealiasing Success Rate (DSR). This value is the percentage of pixels that are correctly dealiased on a radial velocity image. It is calculated as follows:

- First a median filter (5 by 5 km) is applied to the radial velocity image
- Then, a pixel of the original radial velocity map is qualified as an "error" if the absolute difference between its value and the corresponding filtered velocity value is higher than the Nyquist velocity associated to the maximum PRF (V_{N1}).
- The DSR is equal to : (number of pixels – number of errors)/number of pixels.

The Cartesian 1 km² radial velocity PPIs produced with the triple PRT Doppler scheme have a Dealiasing Success Rate (DSR) of about 90% in the mean but 4 years of operations have shown that the DSR can be much less (60%) in clear-air or convective situations (cases of low-SNR and / or large spectrum widths), as illustrated in Figure 1.



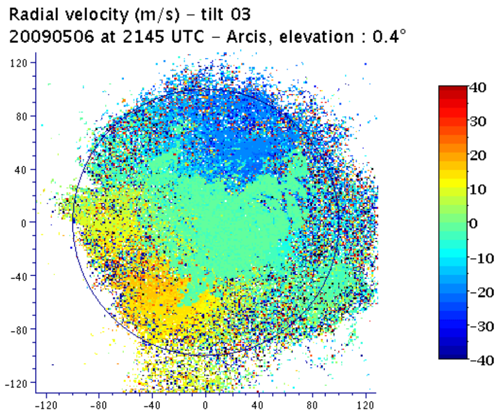


Figure 1 : Radial velocity images. Top : 512*512 km, Trappes radar on 19/01/2009 at 1500 UTC (elevation 0.4°) on a convective situation: DSR=84.2%. The circles are at 100 and 200 km from the radar. Bottom : 256*256 km, Arcis radar on 06/05/2009 at 21h45 UTC (elevation 0.4°) on a clear air situation: DSR=56%. The circle is at 100 km from the radar.

Therefore, the recommendation to the users has been so far to apply a 5x5 km² running filter on the raw PPIs. To improve the quality of these raw radial velocity PPIs, different solutions are tested.
The first one is to increase the PRFs : several radars have been upgraded since 2005 and can now support higher PRFs. Another way to improve the quality of the radial velocity is to lower the extended Nyquist velocity (V_{NE}). But a method has then to be used to dealiase the velocities beyond this limit velocity.
In this report, we first present results of simulations "à la Zrnić" (Zrnic, 1975) to emphasize the theoretical improvement of radial velocity thanks to the increase of the PRFs and to the decrease of the Nyquist velocity. Then, the results of data acquisition experiments adapted to different kinds of radars are described and finally, an algorithm using the advection field for velocity dealiasing is introduced.

2 Simulation results

2.1 Description of the simulation tool

Simulations were performed as the one proposed by Zrnic (1975) :

- The signal is defined from its frequency spectrum, converted to a gaussian velocity spectrum, centered on a mean velocity V_0 and having a spectrum width σ_V.
- Noise in phase and amplitude is added to the signal, which is then converted to I and Q time series by FFT^{-1}.
- The simulation of the resampling of the signal in a triple PRT way is done as explained in Tabary et al. (2006).
- A maximum PRF (PRF1) is chosen. Then, different couples of ratios PRF2/PRF1 and

PRF3/PRF1 are tested. The tested couples are chosen so that the corresponding extended Nyquist velocity remains between 40 and 65 m/s.

- The simulation is carried out with 500 velocities included in the [-10, +10 m/s] interval for each ratio couple. The dealiased velocity is calculated from V1, V2 and V3 using the algorithm presented in Tabary et al. (2006).

The dealiasing process is considered as a success if the absolute error is lower than the Nyquist velocity associated to PRF1 (V_{N1}).
The simulation was carried out for different parameters :

- Spectrum width of 1, 3 or 5 m/s
- SNR of 1, 3 or 20 dB
- A number of points used to represent the spectrum set to 4096, 2048 or 1024, which correspond to radar distances of respectively 35, 70 and 140 km, in the case of a Cartesian projection with a 1km^2 resolution and with an antenna rotation rate of 7.5 °/s.

2.2 Simulation results for different radar types

The radars of the French network ARAMIS have different constraints in terms of maximum PRF. In this section, we present the simulation results obtained for (i) old C-band radars, (ii) recent C-band radars and (iii) S-band radars. For each kind of radars the classification of the ratio couples (PRF2/PRF1 ; PRF3/PRF1) functions of the mean dealiasing success rate is exposed. The (n/n+1) ratios were only selected because the dealiasing algorithm used operationally only works with this kind of ratios.

2.2.1 Simulation results for C-band radars

First, we can see on Figure 2 the classification of the ratio couples for C-Band radars with the current maximum PRF used in the Aramis network (PRF1=379 Hz).

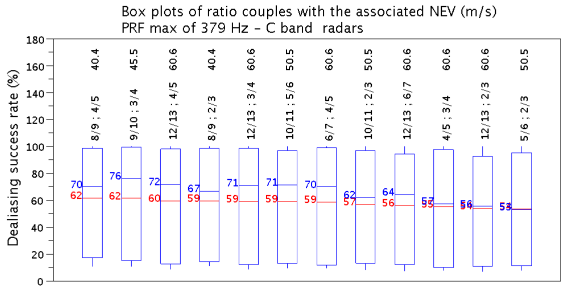


Figure 2 : Global classification of the ratio couples as a function of their mean dealiasing success rate. The ratio couples are sorted by decreasing order of the mean dealiasing success rate (red line) among all the simulations. The Nyquist extended velocity (V_{NE}) associated to each couple of ratios is indicated next to the couple of ratios above the box plot. This classification is done for C-band radars with a maximum PRF of 379 Hz. A box plot for each couple combines the dealiasing success rates for all sets of parameters (on SNR, spectrum width and number of points). The lower and upper limits of the box respectively represent the first and third quartiles of the different dealiasing success rates. The blue and red lines inside the box represent the median and mean success rates. The observations that are above the first quartile from at least 1.5 IQR (Inter Quartile Range : third – first quartile) or below the third quartile from more than 1.5 IQR are linked to the box by a vertical line. "Extreme" outliers, or those that are more than three times the IQR lower and above from the first and third quartiles respectively, are indicated by stars (here not visible because there are no outliers in these data).

For an extended Nyquist velocity (V_{NE}) of 60.6 m/s, the best ratio couple is (12/13 ; 4/5) with a mean dealiasing success rate of 60%. The ratio couple currently used in the french network is (6/7 ; 4/5). Its success rate is very close to the previous one (59%). If we accept to lower the extended Nyquist velocity to 40.4 m/s, the best ratio couple (8/9 ;4/5) has a mean success rate of 62%. This improvement is not very significant but a better success rate could be achieved by increasing the maximum PRF, as it is presented hereafter.

For our **old C-band radars**, the maximum PRF is 400 Hz. Simulation results for this maximum PRF are shown on Figure 3. For an extended velocity of 64 m/s, the best ratio couples are (12/13 ; 3/4), (6/7 ; 4/5) and (12/13 ; 4/5), with a mean dealiasing success rate of 62%. If we accept to lower the extended Nyquist velocity to 42.7 m/s, the best ratio couple, (8/9 ;4/5) has a mean success rate of 65% (6% more than the current ratio). These simulation results led us to decide to carry out a data acquisition experiment on one of the old C-band radars to test the (6/7 ; 4/5) and (8/9 ;4/5) ratios couples (for 64 and 42.7 m/s extended velocities) with a PRF1 of 400 Hz, in comparison to the current PRFs configuration (see section 3.2).

For the **most recent C-band radars,** the maximum PRF is 550 Hz. Simulation results for this maximum PRF are presented on Figure 4. For an extended velocity of 58.7 m/s, the best ratio couple is (8/9 ; 4/5), with a mean dealiasing success rate of 86%. If we accept to lower the extended Nyquist velocity to 44 m/s, the best ratio couple, (6/7 ; 3/4) has a mean success rate of 88% (29% more than the current ratio). It was therefore decided to carry out a data acquisition experiment on one of the recent C-band radars to test the (8/9 ;4/5) and (6/7 ; 3/4) ratio couples (for 58.7 and 44 m/s extended Nyquist velocities) with a PRF1 of 550 Hz, in comparison to the current PRFs configuration (see section 3.1).

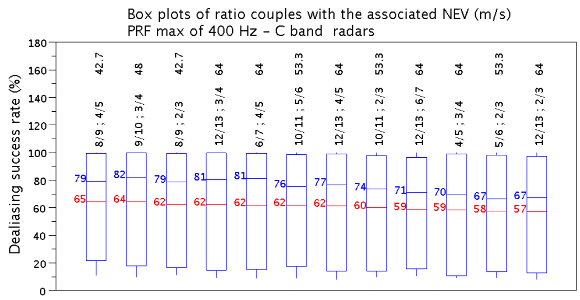


Figure 3 : Similar to Figure 2, but for C-band radars with a maximum PRF of 400 Hz.

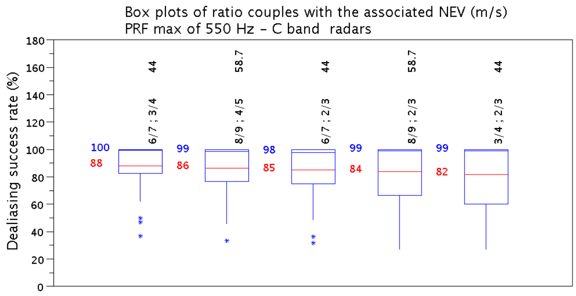


Figure 4 : Similar to Figure 2, but for C-band radars with a maximum PRF of 550 Hz.

2.2.2 Simulation results for S-band radars

On Figure 5, we present the classification of the ratio couples for S-Band radars. The maximum PRF is fixed to 290 Hz as the one currently used in the Aramis network.

The best ratios couple is here (6/7 ; 3/4) with a V_{NE} of 43.5 m/s. The ratio couple used currently with the S-band radars is (8/9 ; 4/5) with V_{NE} of 58 m/s and a mean dealiasing success rate of 88%.

When the maximum PRF is increased to 500 Hz, the only ratio couple with a (n/n+1) shape having a V_{NE} ranging from 40 to 65 m/s is (4/5 ; 2/3). It is associated to a Nyquist extended velocity of 50 m/s and has a 100% dealiasing success rate! Therefore, this ratio couple was chosen to be tested on one S-band radar of the Aramis network (with a maximum PRF of 500 Hz) in comparison to the current couple (see the results in section 3.3).

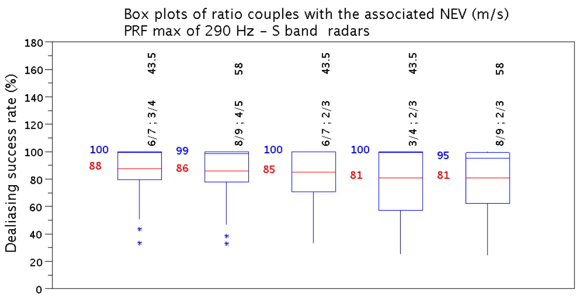


Figure 5 : Similar to Figure 2, but for S-band radars with a maximum PRF of 290 Hz.

3 Results from data acquisition experiments

3.1 Test on "recent" C-band radars

A first test on the Trappes radar was carried out on 19 January 2009 from 09 to 17 UTC with the scanning strategy exposed on Table 1. The tilts 6 and 18 (with a 0.4° elevation) were compared, in order to measur e the impact of the increase of the PRFs and the decrease of the extended Nyquist velocity on the tilt 18.

	PRF1	PRF2	PRF3	mean PRF	V_{NE}	Ratios
Mode 1 : (tilts 1 to 6)	379 Hz	325 Hz	303 Hz	333 Hz	60.6 m/s	6/7 ; 4/5
Mode 2 : (tilts 7 to 12)	472 Hz	413 Hz	367 Hz	413 Hz	44.1 m/s	7/8 ; 7/9
Mode 3 : (tilts 13 to 18)	550 Hz	471 Hz	412 Hz	471 Hz	44 m/s	6/7 ; 3/4

Table 1 : Scanning strategy of the C-band Trappes radar during the data acquisition experiment on 19/01/2009. Test of the increase of the PRFs and the decrease extended of the Nyquist velocity.

Figure 6 shows that the radial velocity calculated with the high PRFs (tilt 18) contains significatively less errors (calculated from the method described in the in section 1) than with the current low PRFs (tilt 06). On tilt 06 at 1500 UTC, there are 6024 errors (15.8 %) whereas the tilt 18 associated to the higher PRFs and lower extended Nyquist velocity only contains 1615 errors (4.2 %): the percentage of errors is nearly divided by 3.

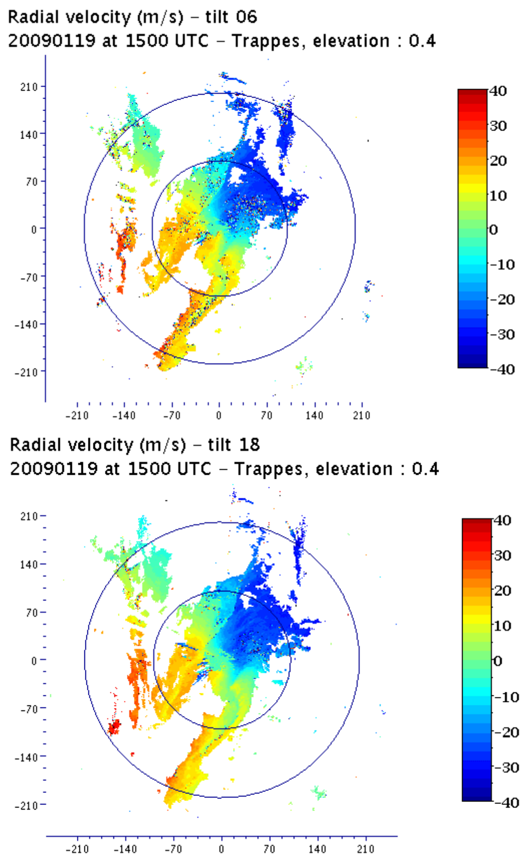


Figure 6 : Radial velocity images with two different PRFs modes. Top : low PRFs (mode 1 of Table 1). Bottom : high PRFs (mode 3 of Table 1). Trappes radar at 0.4°. 20090119 at 1500 UTC. The circles are at 100 and 200 km from the radar.

Figure 7 presents the histogram of the errors on the radial velocity for the low PRFs mode (black curve) and the high PRFs mode (blue curve) for the duration of the test (from 10 to 16 UTC on 20090119). Both curves clearly peak to a maximum centered on zero, which means that the majority of the radial velocities are properly dealiased. However, there is a series of secondary peaks distributed quite regularly and symmetrically on either side of the main lobe, as evidenced by Tabary et al. (2006). These secondary peaks are interpreted as dealiasing errors, and are located at (around) +/-2kVn1, k=1,…,6 for the low PRFs mode and k=1,..3 for the high PRFs mode. The amplitude of the error peaks is significantly lower for the high PRFs mode than for the low PRFs mode. Moreover, the mean percentage of errors calculated over the period from 10 to 16 UTC for this convective rain case, is 17.8% for the low PRFs mode against 5.2 % for the high PRFs mode. The increase of the PRFs and the reduction of the extended Nyquist velocity from 60.6 to 44 m/s clearly improve the quality of the radial velocity.

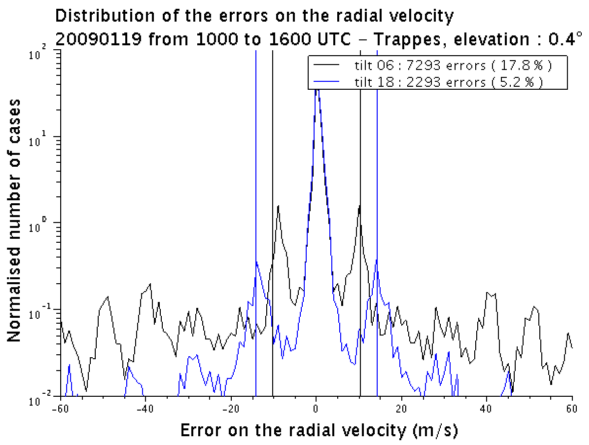


Figure 7 : Distribution of the errors on the radial velocity for the low PRFs (mode 1 : tilt 06, black curve) and high PRFs (mode 3 : tilt 18, blue curve). Data from 1000 to 1600 UTC 20090119, elevation of 0.4°. The vertical lines indicate the value of the Nyquist velocities (positive and negative) associated to the PRF1 of each mode. The vertical axis is logarithmic.

A data acquisition test on another recent C-band radar (Cherves) with the same high and low PRFs modes was performed. For this experiment, the tilt 06 was set to a high PRFs mode (as mode 3 of Table 1). It was compared to tilt 11 (low PRFs mode, same as mode 1 of Table 1). The test was carried out from 26 August 2009 to 14 September 2009.

An example of the radial velocities calculated for both modes on a stratiform situation is shown on Figure 8. The percentages of errors on this case are 36.9% for the low PRFs mode (tilt 11 on the top picture) against 16.8% for the high PRFs mode (tilt 06 on the bottom picture). For the stratiform period from 1300 to 2345 UTC the percentages of errors are 32.4% and 11.9%.

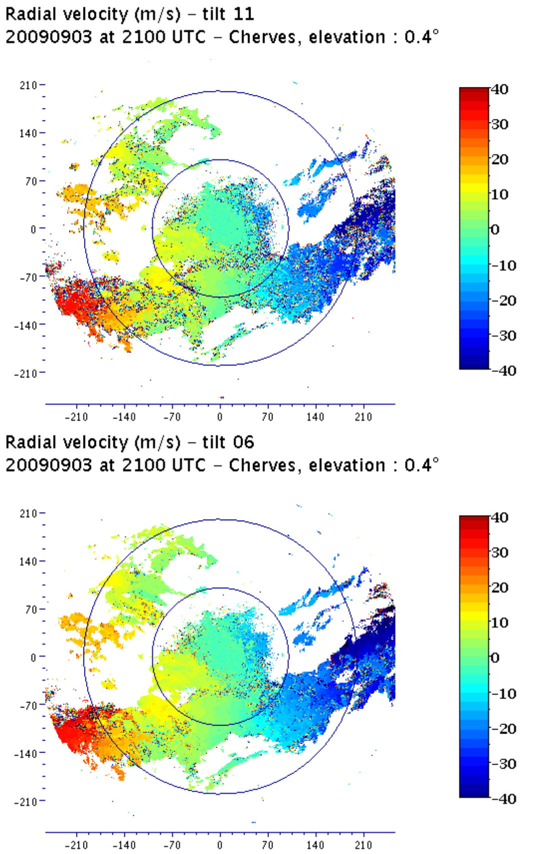
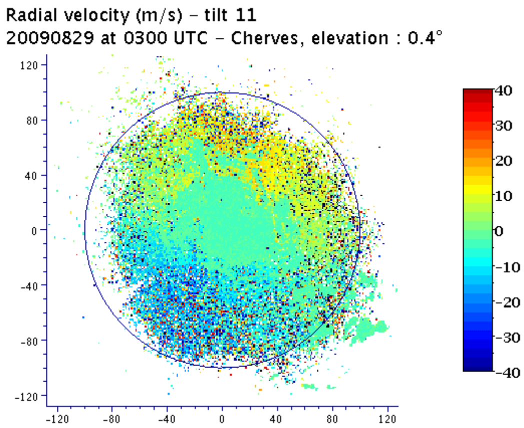


Figure 8 : Radial velocity images with two different PRFs modes. Top : low PRFs (mode 1 of Table 1). Bottom : high PRFs (mode 3 of Table 1). Cherves radar at 0.4°. 20090903 at 2100 UTC.

An example of the radial velocities calculated for both modes on a clear air case is shown on Figure 8. The percentages of errors on this case are 44% for the low PRFs mode (tilt 11 on the top picture) against 25% for the high PRFs mode (tilt 06 on the bottom picture). For the clear air period from 0000 to 0445 UTC the percentages of errors are 31.5% and 22.2%.



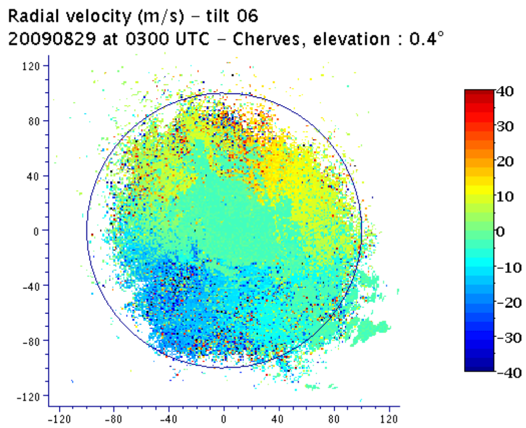


Figure 9 : Similar to Figure 8, but for a clear air case : 20090829 at 0300 UTC and zoomed (the circle is at 100 km from the radar).

From all these results, we can conclude that for this type of radar:

- the best improvement of the quality of the radial velocity thanks to the increase of the PRFs and to the decrease of the Nyquist velocity are obtained during convective or stratiform events (the number of dealiasing errors is divided by 3 at least).
- For clear air cases, the improvement is also important but the number of errors remains significant (around 20%).

3.2 Test on an “old” C-band radar

The ratio couples chosen in section 2.2.1 for the “old” C-band radars with a maximum PRF of 400 Hz were tested on the Arcis radar, with the scanning strategy exposed in Table 2.

	PRF 1	PRF 2	PRF 3	mean PRF	V_{NE}	Ratios
Mode 1 : (tilts 1 to 3)	380 Hz	326 Hz	304 Hz	334 Hz	60.9 m/s	6/7 ; 4/5
Mode 2 : (tilts 4 to 6)	399 Hz	342 Hz	319 Hz	350 Hz	63.8 m/s	6/7 ; 4/5
Mode 3 : (tilts 7 to 9)	399 Hz	355 Hz	319 Hz	355 Hz	42.6 m/s	8/9 ; 4/5

Table 2 : Scanning strategy of the C-band Arcis radar during the data acquisition experiment from 5 Mai to 24 August 2009. Test of the increase of the PRFs and the decrease of the extended Nyquist velocity.

Examples of radial velocity images with each mode are shown on Figure 10. For the period from 00 to 08 UTC, the percentages of errors were calculated for modes 1 to 3 : 15.9%, 14.8%, 13.7%. For a clear air situation (from 00 to 0345 UTC 20090506) the percentages of errors for modes 1 to 3 were 38%, 35.2% and 32%. And for a convective situation (from 12 to 20 UTC 20090513) the following percentages of errors were calculated for modes 1 to 3 : 27%, 24.9% and 23.2%.
In these three different situations, the dealiasing success rates are very close from each other for the three modes. This is because the PRF1 was only increased by 20%. Mode 3 is the best one thanks to the decrease of the extended Nyquist velocity, which is consistent with the simulation results.

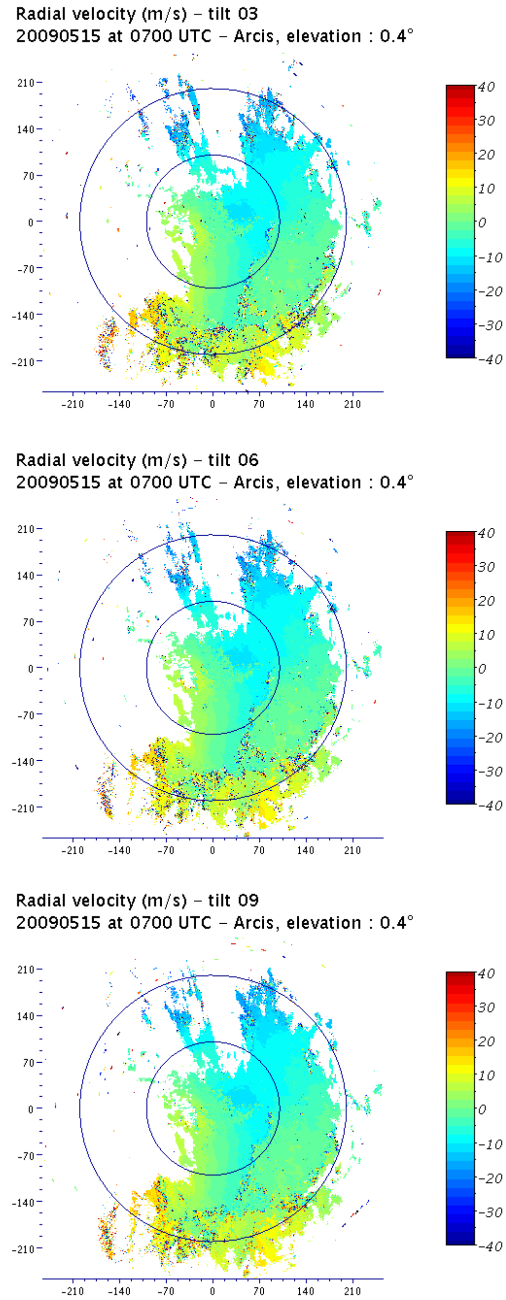


Figure 10 : Radial velocity images with 3 different PRFs modes. Top : low PRFs (mode 1 of Table 2). Middle : increased PRFs but about the same NEV (mode 2 of Table 2). Below : Increased PRFs and reduced NEV (mode 3 of Table 2). Arcis radar at 0700 UTC 20090515. Elevation : 0.4°.

3.3 Test on a S-band radar

The ratio couple chosen in section 3 for the S-band radars with a maximum PRF of 500 Hz (4/5; 2/3) was tested on Nimes radar. This ratio couple is associated with an extended Nyquist velocity of 50 m/s. The high PRF mode was set up on Tilt 07 (elevation : 2.4°), and compared to the current PRFs mode (PRF1=290 Hz, NEV=58 m/s) on tilt 9. For this kind of radar, we choose to show the distribution of errors for a convective case from 00 to 0445 UTC 20090715 (Figure 11). With this Nyquist extended velocity of 50

m/s and the maximum PRF of 500 Hz (black curve, tilt 07), there are only 3 modes in the distribution of errors.
The percentages of errors for this case are 13.4% and 4.2% for the low and high PRFs modes : the quality of the radial velocity is clearly improved with the high PRFs mode.

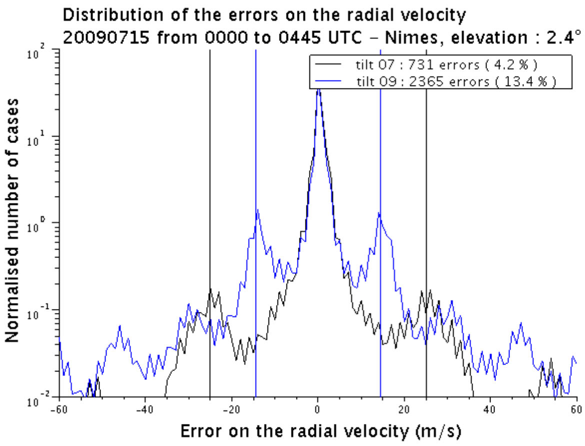


Figure 11 Distribution of the errors on the radial velocity for the low PRFs (tilt 09, blue curve) and high PRFs (tilt 07, black curve). Data from 00 to 0445 UTC 20090715, elevation of 2.4°.

4 Test of a velocity dealiasing algorithm using the advection field

4.1 Description of the algorithm

As shown in section 3 the decrease of the extended radial velocity leads to a great improvement of the quality of the radial velocity by reducting the number of dealiasing errors. In our triple PRT schemes, it was decided to decrease the extended Nyquist velocity from 60 to about 40 m/s. An additionnal specific algorithm is therefore necessary to dealiase the velocities exceeding this value.
Many algorithm have been proposed (Tabary and Petitdidier, 2002; Hiroshi Y., and O. Suzuki, 2007; Ming et al., 2009). We propose here a very simple algorithm using the advection field.

- First we admit that the velocities exceeding V_{NE} are systematically aliased in the Nyquist interval in the following way :

$V_{measured} = V_{real} + 2kV_{NE}$, k = -1 or 1
so $| V_{measured} - V_{real} | = 2V_{NE}$

- Then, we calculate a radial velocity (V_{adv}), from the advection field that has previously been filtered with a 5 by 5 pixels median filter (the pixels have a resolution of 32 km^2).
- Then, the algorithm tests the validity of the following condition :

$| V_{measured} – V_{adv} | < V_{NE}$
If the condition is not verified, the velocity is dealiased by adding or retrieving 2 V_{NE}.

4.2 Results

The algorithm was tested on different situations. It was first tested on a storm case that affected the South of France on 24 January 2009 as illustrated in Figure 12. As at this time, the Nyquist extended velocity of the triple-PRT scheme of Toulouse radar was 60.6 m/s, we first aliased the real velocity as if the extended Nyquist velocity was of 40 m/s (Velocity_aliased, below left on Figure 12). Then, the algorithm was applied. It perfectly corrected the velocity to restore a dealiased velocity very close to the original velocity. This algorithm was tested on many other cases and it always enabled to restore the real velocity.

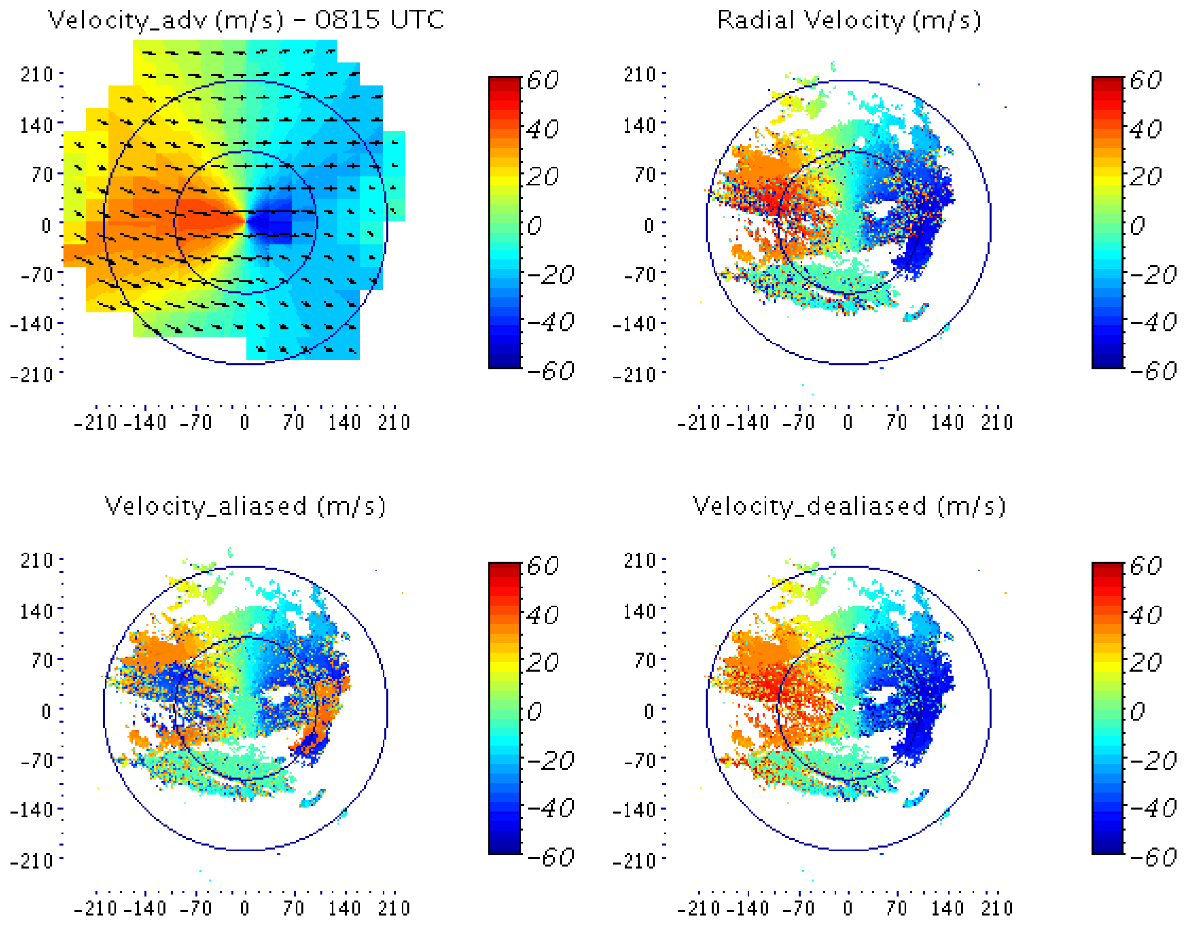


Figure 12 : Top left : radial velocity restored from the advection field. Top right : real radial velocity. Below left : radial velocity aliased in the interval [-40, 40 m/s]. Below right : dealiased radial velocity thanks to the algorithm using the advection field. Toulouse radar at 0815 UTC 24 January 2009, elevation of 0.4°.

5 Conclusions

As the quality of the radial velocity measured by Doppler radars in the French network was not satisfactory, we decided to test the increase of the PRFs and the decrease of the extended Nyquist velocity to try to reduce the number of dealiasing errors. First, simulations “à la Zrnic” have been performed and enabled to choose new optimum PRFs triplets adapted to each kind of radar of the Aramis network. Then, data acquisition tests with the new PRF triplets were done. All of them show an improvement with the increase of the PRFs and the decrease of the Nyquist extended velocity. The best improvements can be achieved for the most recent radars and particularly for S-band radars (with a DSR of about 95% in convective situations). An algorithm using the advection field was tested to dealiase the velocities that exceed 40 m/s. It worked perfectly on all the situations tested.
Given the results of these tests, we are soon going to increase the PRFs of our operational Doppler radars, and reduce the Nyquist extended velocity. The algorithm using the advection field will also need to be implemented to dealiase the high velocities.

Thanks to this new improved quality of the Doppler network, we will be able to test new products based on radial velocity cappies, like wind shear indicators.

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