Noise filtering for dual-PRF observed data from R/V Mirai shipborne Doppler radar

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Abstract The two post-processing procedures for the R/V Mirai Doppler radar data using dual-PRF technique are developed. One is to correct the Doppler velocity data which is falsely-unfolded by dual-PRF real-time unfolding. The correction amount is determined by comparing target data bin to neighbor data bins. Another is to reduce second-trip echo in the reflectivity data, by detecting characteristic alternate pattern in dual-PRF observation. The parameters for the procedures are tuned by statistical method using observed dataset for tropical cloud system. Both procedures demonstrate good performance on the observed dataset by using tuned parameters.

Keywords: R/V Mirai Doppler radar, dual-PRF, post-processing, second-trip echo, dual-PRF unfolding

1. Introduction

The precipitating clouds are the one of the most important factors in the climate system. For example, huge latent heat, which is released within the small cloud regions, affects largely on the ambient atmosphere. Therefore understanding the detailed internal structure of the precipitating clouds and their temporal evolution have been the principal goal of the many studies.

On the observational approach for these researches, the radar system is one of the important and fundamental tools to obtain various information of the precipitating clouds, and even ambient atmosphere and ocean. Among the huge variation of the radar system, the Doppler scanning precipitation radar is very common device not only in the field research experiment, but also in the operational observation.

Since 1998, JAMSTEC launched Research Vessel (R/V) Mirai for the field research experiments in widespread area in the western Pacific Ocean, the Indian Ocean, the Arctic Ocean, etc. The Doppler radar is the one of the most important and principal observational device of the vessel, to observe the oceanic precipitating clouds. The radar has been providing invaluable observational data to many researchers in the various fields.

However, the dataset of the Doppler radar on R/V Mirai have some uncertainty. Some of them are common problems to the ground-based radar systems, and others are the specific problems for the radar on R/V Mirai. The filtering and flagging for suspicious / erroneous part of the dataset are substantial for the observational research. As the first article of the series to describe the quality control of the dataset of the Doppler radar of the R/V Mirai, we report how to reduce noises from (1) false velocity unfolding, and (2) second-trip echo. The other problems will be presented in the subsequent articles.

2. Correction of false velocity unfolding

2.1 Problem

One of the characteristic features of the Doppler radar system on R/V Mirai is the “dual-PRF” observation, which uses two pulse repetition frequencies (PRFs) alternately for the rays. The dual-PRF observation enables to extend maximum detectable Doppler velocity \( V_{\text{max}} \), which is the one of the fundamental limitation on the Doppler radar observation.

In the single-PRF observation, The \( V_{\text{max}} \) (or Nyquist velocity) is defined by

\[
V_{\text{max}} = \frac{\text{PRF} \cdot \lambda}{4}
\]  

(1)

where \( \lambda \) is the wave length. The situation that the true Doppler velocity of the target exceeds \( V_{\text{max}} \) is called “folding”. The addition / subtraction of correct number of Nyquist velocity can correct the folded velocity. This correction procedure is called as “unfolding”.

Equation (1) indicates that the high PRF and long
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wave length is effective to expand $V_{\text{max}}$. However, the higher PRF accompanies shorter detectable range, and the long $\lambda$ accompanies the weak backscat ter from the relatively small scattering media. These are called as “Doppler-dilemma” (e.g., Rinehart 1997).

The dual-PRF unfolding method is the one of the approach to expand maximum detectable Doppler velocity in order to overcome the Doppler dilemma. When we suppose that the rays with two different PRFs observed same target volume, $V_{\text{max}}$ can be determined as

$$V_{\text{max}} = \frac{\lambda}{4(T_{\text{low}} - T_{\text{high}})}$$  \hspace{1cm} (2)

where $T_{\text{low}}$ and $T_{\text{high}}$ are the inverse of higher and lower PRFs. The observation in R/V Mirai, for example, usually adopted $T_{\text{low}}$ and $T_{\text{high}}$ as 5:4 ratio. Thus the detected velocity becomes five times larger than that of single-PRF observation at $T_{\text{low}}$. For the detailed description, see Sigmet (1996), Sigmet (2001), and / or Doviak and Zrnic (1993).

However, the dual-PRF unfolding algorithm needs the assumption that the adjacent data observed almost same volume so the observed Doppler velocity values are almost same. Therefore, erroneous correction may occur at the place where horizontal / vertical gradient of the Doppler velocity is large so the assumption is not valid. Because the shear line is the one of the most important factor to understand the convective clouds, it is crucial to remove this error.

If the dataset include the information of the raw (not corrected) detected velocity data, the processing could be done more precisely by post-processing. However, the radar system on the R/V Mirai is designed to record Doppler velocity data after dual-PRF unfolding process. Therefore, we try to recover the Doppler velocity by comparing the data in the target bin to that of the neighbor data-bins.

2.2 Algorithm Description

The velocity unfolding is done as

$$V_{\text{unfolded}} = V_{\text{obs}} + 2N \cdot V_n (\text{PRF})$$  \hspace{1cm} (3)

where $V_{\text{unfolded}}$ is the unfolded Doppler velocity data by using dual-PRF real-time unfolding process, $V_{\text{obs}}$ is the original observed Doppler velocity with PRF, $V_n$ is the Nyquist velocity depending on PRF, and N is the number of unfolding (positive or negative integer). The erroneous unfolding arises by erroneous determination of N.

Even the anomalous strong wind such as gust front occur, most of the phenomenon have the spatial scale larger than the range resolution of the radar beam. In other words, the similar wind should exist for certain expanse. Thus, the true unfolding number N in the equation (3) could be estimated from the data in the neighbor bins around the target bin, by assuming that (a) the neighbor data-bins have similar Doppler-velocity value and (b) the erroneous data are minority among the neighbor data-bins.

At first in the post-processing, we categorize the $V_{\text{obs}}$ for the neighbor data-bins. Each category has lowest and highest Doppler velocity values as

$$V_{\text{low}} (N) = (2N - 1) \cdot V_n (\text{PRF})$$

$$V_{\text{high}} (N) = (2N + 1) \cdot V_n (\text{PRF})$$

where $V_{\text{low}} (N)$ and $V_{\text{high}} (N)$ are the lowest and highest border values of the Doppler velocity for the N-th category. The Nyquist velocity $V_n (\text{PRF})$ is determined from PRF of the ray of target data-bin. Consequently, the category with maximum number of valid data-bins is adopted as the correct category with correct N for the target-bin. Using correct N and equation (3), the correct Doppler velocity could be re-calculated.

2.3 Results

The key issue for this algorithm is how to determine the suitable area as "neighbor" of target bin. If the area is too small, the assumption of “majority of the sampled data bins might be occupied by the correctly unfolded data-bin” may not be true, because the erroneous data-bins are usually gregarious like as the discontinuous line of the wind. If the area is too large, in contrast, the assumption “neighbor data-bin have similar Doppler-velocity value” may not be true, because (1) the real wind may spatially vary, and (2) azimuthal difference project same wind into different Doppler velocity.

For the suitable neighbor area, we first decide the number of rays to be used for azimuthal direction. We set the number of rays as five (the ray with target bin and two rays in both sides). This number is chosen with intent to minimize the effect of second-trip echo: With the dual-PRF observation, adjacent rays possibly include second-trip echoes from different target at the different range distance (see details for the description of second-trip echo in the next section). The azimuthal range is expanded to include two rays in both sides, to include rays with same PRF on the target bin.

As for the radial length of the neighbor area, on the other hand, various range distances were examined to select appropriate value. In the test, the number of the data-bins is counted for the categories with 10 m/s coverage for the simplification. The 96 PPIs (hourly data of four different days in the tropical observation, with the
elevation of 0.5 degree) with widespread echo areas, including erroneously-unfolded data bins, are tested for 11 different setting of the range distances “RangeD” from 100 m to 20000 m. Figure 1 shows the ratio of the number of the data-bins with the Doppler velocity larger than 20 m/s or smaller than -20 m/s, to the number of the all valid data-bins. Because the tropical low-level wind usually does not exceed 20 m/s, the number of bins with large Doppler velocity could be recognized as the alias of the number of erroneously-unfolded bins. The result shows obviously that the bins with large Doppler velocity decreases when the sampling range distance increases. However, the larger range distance is not suitable because: (1) The “almost uniform” assumption is ambiguous in larger “neighbor area”. In some cases, the number of bins with large Doppler velocity even “increase” for larger range distance, as shown in Table 1. (2) Larger area needs large computation resources, while the ratio in Fig. 1 decreases insensitive-ly with the increase of the range distance. These results suggest that the value 3000 m of the range distance is appropriate. An example of the result with the range dis-

tance of 3000 m (Fig. 2) shows that the natural smooth field of the Doppler velocity is retrieved by correcting noisy velocity data.

![Figure 1: The ratios of, number of data-bins with Doppler velocity over 20 m/s, to that of all data-bins with valid Doppler velocity. The abscissa is for the range (radial) distance “RangeD” of the sampled volume. The allow shows 3000 m of RangeD, which is applied for the result in Fig. 2.](image)

![Figure 2: The close-up images for Doppler velocity on PPI obtained at 0801UTC on Jun. 21, 2000. The elevation is 3.0 degree. (a) is the original data, while (b) is the result of correction of false velocity unfolding, using 3000m as RangeD. The horizontal extent of the area is 60-km by 60-km. The black arc indicates 60-km range distance from radar.](image)

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Table 1: Number of the data-bins with certain velocity ranges, by using various RangeD on the algorithm to correct falsely-unfolded Doppler velocity. The top row indicates value of RangeD, while first column indiciates velocity range. See text for detail.
3. Reduction of the second-trip echo

3.1 Problem

When the reflecting target located beyond the unambiguous range distance $R_u$, which is determined by $R_u = c / 2PRF$ where $c$ is the speed of electromagnetic wave, the return signal of the previous transmit mixed into the present receiving process. Consequently this pseudo radar echo appeared at the distance $D_{pseudo} = D_{true} - R_u$ where $D_{pseudo}$ and $D_{true}$ is the distance from the radar to pseudo echo, and to real reflecting target, respectively. This pseudo echo is called "second-trip echo (STE)".

From the observation cruise MR01-K05 in November 2001, the new signal processor RVP-7 is at work on R/V Mirai. The RVP-7 has the function to remove the second-trip echoes by "random-phase technique" in which the return signal is flagged by the coherency between the transmitted and returned signal (Sigmet, 2001). This technique realized the real time hardware processing to remove STE, while it is impossible to reprocess the data obtained before introduction of RVP-7 to R/V Mirai (before October 2001). For such old dataset, the post-processing to remove STE is desired. In addition, even with the random-phase technique, the setting of the observation parameters is sensitive so the STE might be remained. Therefore, the post-processing to remove STE is also useful for the recent dataset.

3.2 Algorithm Description

In the dual-PRF observation, $R_u$ differs from the adjacent rays. As a result, the second trip echo appeared at different range distance alternately for ray-by-ray. The present technique to remove second-trip echo uses this characteristic.

If the target bin include only first-trip echo, it is natural that the echo extends both in azimuthal and range directions. In contrast, the second-trip echo extends only in the target ray because it does not appear in the adjacent rays with different PRF. Thus, we examined whether the target bin includes second-trip echo by using following two steps. (1) If the reflectivity of target bin is stronger than that of both azimuthally adjacent bins, and the differences on the both side are larger than threshold value $T_x(r)$, the bin is flagged as "potentially STE bin". The value $T_x(r)$ is determined from the given constant threshold value "Hgrad", which is the allowed maximum horizontal gradient for natural echo, and range distance "$r$", which could be converted to the distance between centers of the target bin and azimuthal adjacent bin. (2) Count the number of "potentially STE bins" within given range distance "RangeD" from target bin, and calculate ratio of this number to all number of bins within range distance RangeD from target bin. If the ratio exceeds given threshold value "STEratio", the target bin is flagged as the "second trip echo bin".

After the flagging, the reflectivity is corrected as the following procedure. When the one of, or both the azimuthally adjacent bins, has invalid data (e.g. below the noise level, flagged as shadow), the reflectivity of the target bin is replaced by the certain low reflectivity value. On the other hand, if both the adjacent bins have valid reflectivity data, the reflectivity of target bin is interpolated by using the values in the azimuthally adjacent bins. This interpolation will avoid unnatural missing of the data in the center of the echo mass.

3.3 Results

This algorithm needs three given threshold; RangeD, STEratio, and Hgrad. To adjust these three parameters to appropriate values, we use the PPI reflectivity field obtained with low PRF (260 pps) as the "reference". This low PRF value results the unambiguous range distance as more than 500 km. In such distance, the beam center at the elevation of 0.5 degree almost reaches tropopause (e.g. Doviak and Zrnic 1993; Rinehart 1997) so the STE is hard to be appeared. We selected the pair of "reference PPI" and "filtered PPI" (dual-PRF PPI to be processed) with the following three criteria: (1) Time difference is less than 60 seconds, to exclude the effect of moving of both platform (vessel) and target. (2) Difference of heading of the platform is less than 0.5 degree, to avoid difference in the position of shadow by ship structures. (3) The STE appear so largely. The two cases are selected; one is the case at 2000UTC, on Dec. 4, 2000, with RVP-6 signal processor (without random-phase technique), and another is at 0400UTC on Mar. 10, 2004, with RVP-7 signal processor (using random-phase technique). Both "reference" and "filtered" PPIs are interpolated to the Cartesian horizontal plane with 1-km interval. Then, the reflectivity values are compared statistically.

The results show that it is less sensitive to Hgrad varying from 2.0 dB/km to 8.0 dB/km. Thus we shows in this article only the tested results with Hgrad = 2.0 dB/km in Fig. 3 for two cases. The skill score is calculated by determining grids with 15 dBZ or larger reflectivity as "echo exist", while other grids as "no echo". Thus, the skill score is the ratio of, number of grids where both reference and filtered result are "echo exist" or both are "no echo", to number of all grids. This value indicates how the second-trip echoes over no-echo area are removed accurately. On the other hand, the correlation coefficient between reference and filtered reflectivity values is calculated using the grids with
reflectivity over 15dBZ in both reference and filtered result. This value indicates the accuracy of interpolation over second-trip echoes using first-trip echo in adjacent data-bins.

The result shown in Fig. 3 indicates that the correlation coefficient between reference and filtered results is better on the higher STEratio value, but the dependency on STEratio seems not varied in the larger RangeD (larger than 4km). The tendency is same in (d). On the other hand, the better skill score appear with STEratio of 0.4 to 0.6 in (c), while larger RangeD make score worse. Considering that the second-trip echoes are significant in the data without using random-phase technique, and the saving of the computing cost by set RangeD smaller, the appropriate parameters are estimated as 4 km in RangeD and 0.5 in STEratio for these cases.

Figure 4 shows the results of the filtering on another case using 4 km of RangeD, 0.5 of STEratio, and 2.0 dB/km in Hgrad. The result shows that the most of the STE are removed, and first-trip echoes with STE contamination are also recovered naturally.

4. Concluding Remarks

This study proposes one of the possible ways to reduce noisy or uncertain data with dual-PRF observation. The “correction of the false unfolded velocity data” is the measures for the negative face of the dual-PRF observation, while the “remove of second-trip echo” is one of the smart utilization of the dual-PRF data. The algorithms in this study could be applicable to the all radar dataset obtained with dual-PRF observation, not only by R/V Mirai, by adjusting the parameters for individual observation.

On the other hand, the algorithms in the present study are not perfect because these techniques are post-processing using pattern recognition. For more complete filtering, the combination of these post-processing techniques with new parameters related to the signal quality, and / or real-time processing are more effective.

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