STRATEGIES FOR MITIGATING RANGE AND DOPPLER AMBIGUITIES IN THE WSR-88D

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EXECUTIVE SUMMARY

The WSR-88D system generates, displays and disseminates a large number of primary and secondary weather products. Most of them are generated automatically by using sophisticated computer software, and require data of high quality as inputs. The presence of range and velocity ambiguities, which is a fundamental weakness of pulsed radars, corrupts the data acquired by the radar and impairs the performance of the system.

In a pulsed radar, the range and Doppler velocity ambiguity problems are coupled such that trying to overcome one of them tends to aggravate the other. Special techniques are necessary to resolve both ambiguities to a level desirable for a high-performance system such as the WSR-88D. The WSR-88D system currently has a scheme for minimizing these ambiguities. Range ambiguities are resolved at the lowest elevation angles by using additional antenna scans with relatively long pulse repetition times (PRTs). At middle elevation angles, batches of long-PRT transmitted pulses are alternated with batches of shorter PRT. Doppler velocity ambiguities are detected and corrected by a special algorithm based on the continuity of Doppler velocities along radials relative to the radar.

The current mechanisms for ambiguity resolution in the WSR-88D serve their purpose in a number of applications, but a need has been felt for a higher level of performance in this regard. The present limitations on the unambiguous range for Doppler velocities, together with other system parameters, leave considerable areas of the displays without valid data. The Doppler velocity dealiasing software, while performing well most of the time, lacks reliability in certain critical situations.

To better mitigate the range and Doppler ambiguities in the WSR-88D, a systematic process of studies and development of software as well as hardware is necessary. This process is considered in this report in three different time scales.

The short term solutions to the ambiguity problem are those that can be implemented without requiring changes in the radar hardware or operating parameters, and should be achievable within two years. The best bet in this time frame is to refine the current Doppler velocity dealiasing algorithm to remove its weaknesses and enhance its robustness. However, to make this process systematic, certain studies are necessary. In

particular, an exhaustive failure analysis of the current algorithm on real data is recommended in order to identify its weak points and devise reinforcements. Specific improvements are also possible regarding performance in the presence of random noise, and determination of aliasing intervals of entire data fields and isolated storms. In the short term, it may not be possible to overcome the range ambiguity problem of the WSR-88D radar unless extra effort is devoted to expedite the scheme(s) now considered to be possible only in the medium term.

In the medium term, a solution to the range ambiguity problem is possible through enhancement of the PRT to provide a higher unambiguous range. However, this will impose a higher level of performance demand on the Doppler velocity dealiasing algorithm. A possible compromise may be achieved by introducing a triple PRT scheme which would mean the introduction of extra scans at low elevation angles and extra batches of pulses at middle elevation angles. Intricate multiparameter tradeoffs are necessary to be able to accommodate these additions, which must be studied carefully. There is also some promise of overlay separation through spectral decomposition of echo time series.

The long term solutions to the WSR-88D ambiguity problem are perceived to lie in the signal processing domain. Though they may take more time to implement, perhaps of the order of four years or more, their strength lies in their speed, robustness and saving of computational resources. There are three viable options in this category. One of these, with a random phase modulation of the transmitted signal and compatible signal processing, appears to hold the most promise. Two other methods, one with staggered PRT and the other with systematic phase modulation of the transmitted signal, need further study.

Given that there are multiple options for the WSR-88D ambiguity problem, and that the development and validation of these options involves considerable time and cost, a careful planning of the development strategy is necessary. There is a case for ultimately aiming for a signal processing solution to the problem, while using more immediate approaches to derive any available benefits in the shorter run. If, however, any of these intermediate solutions are able to solve the ambiguity problem to the desired extent before a signal processing method is perfected and implemented, it may be weighed against the signal processing approach at that time.

PART 1

BACKGROUND

1.1 GENERAL INTRODUCTION: THE AMBIGUITY PROBLEM

1.1.1 Range Ambiguity

In a pulsed radar, the distance from the radar to a scatterer of electromagnetic energy is found by measuring the time taken by the pulse to travel to the scatterer and back to the radar. If the distance of the scatterer is so much that one or more additional pulses are radiated by the transmitter before the echo of a given pulse reaches the receiver, then the radar would not be able to relate the echo with the transmitted pulse from which it originated. In the absence of other information, the receiver will assume the echo to be from the last pulse radiated before the instant that the echo is received. If, however, the echo is actually from the pulse before the last one, a range measurement error equal to

$$R_u = cT/2 \tag{1}$$

will occur, where c = speed of light, and T = pulse repetition time. The quantity R_u in eq. (1) is called the maximum unambiguous range (or just "unambiguous range"). In general, if the echo is the result of the m^{th} transmitted pulse before the last one, the error in range measurement will be mR_u, where m is a positive integer. Range ambiguity occurs when a scatterer, located at a true range R, is observed to be at an apparent range $R-mR_u$.

1.1.2 Velocity Ambiguity

Pulse Doppler radars such as the WSR-88D (Weather Surveillance Radar - 1988 Doppler) observe the radial velocity of scatterers by coherently processing echo signals to derive the Doppler frequency shift. However, since a pulsed radar samples the Doppler-shifted signal returned by the scatterer at discrete intervals, it can only measure frequencies lying within the limits of $\pm f_n$ (for a fully coherent radar such as the WSR-88D), where

$$f_n = 1/2T \tag{2}$$

is called the Nyquist frequency. A Doppler frequency f_d lying outside these limits will be seen by the processor as an apparent frequency f_{da} lying within the band, such that

$$|f_d - f_{da}| = 2nf_n \tag{3}$$

where n is a positive integer.

1.1.3 Relationship Between Range and Velocity Ambiguities

Equations (1) and (2) can be combined to yield

$$R_u \; f_n = c/4 \tag{4}$$

The Doppler shift f_d is related to the radial velocity V_r by the relation

$$f_d = 2V_r/\lambda \tag{5}$$

where λ is the wavelength of the transmitted radiation. Using eq. (5), eqs. (2), (3), and (4) can be rewritten respectively as

$$V_n = \lambda/4T \tag{6}$$

$$|V_r - V_{ra}| = 2nV_n \tag{7}$$

and

$$R_u \; V_n = c\lambda/8 \tag{8}$$

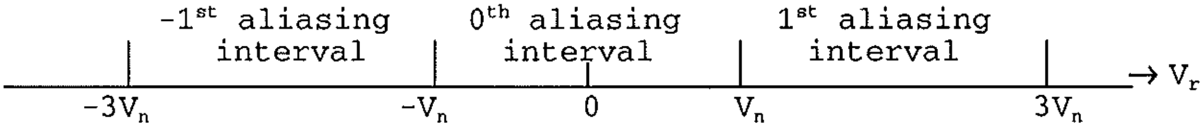
The observation of a radial velocity V_r as an apparent velocity V_{ra}, as in eq. (7), is called velocity aliasing.

Equation (8) is an important relation which shows that the unambiguous range and the Nyquist velocity cannot be varied independently for a pulsed radar with constant interpulse period. An increase in one of them causes a proportionate decrease in the other. Ambiguity problems in pulse Doppler weather radars have been discussed in some detail by Doviak and Zrnic' (1993).

1.1.4 Some Definitions

There is a lack of uniformity in the literature regarding some definitions relating to velocity ambiguity. The meanings of some terms used in this report are given below:

The *Nyquist velocity* V_n is defined by Eq. (6). The interval (in the Doppler velocity domain) lying within $\pm V_n$ is called the *unambiguous velocity interval*, or the *zeroth aliasing interval*. The *n^{th} aliasing interval* (n is a positive or negative integer) is equal to the zeroth aliasing interval, but shifted along the Doppler Velocity Axis by $2nV_n$. These intervals are shown in the figure below.



1.2 EFFECTS OF THE AMBIGUITY PROBLEM IN WSR-88D

WSR-88D is a long-range weather surveillance radar designed to provide accurate quantitative data on the reflectivity and Doppler velocity (both mean and spread) of each resolution cell within its scan volume. Ambiguity problems surface when severe phenomena involving large wind speeds are encountered. While simultaneously trying to observe long ranges and high velocities, the radar becomes subject to the limitations imposed by eq. (8), resulting in either range overlay(s), velocity aliasing, or both.

1.3 AMBIGUITY CONSIDERATIONS IN WSR-88D

The possibility of range overlay and velocity aliasing in the WSR-88D system has been recognized, and mechanisms have been provided to address these problems. The parameters of the WSR-88D system having a bearing on its ambiguity behavior are given below:

Transmitter Frequency (f_o) Band	2700-3000 MHz
Pulse Width (τ)	1.57-4.7 μs
PRF: Short Pulse	318-1304 s^{-1}
Long Pulse	318-452 s^{-1}

The existing features of the WSR-88D for alleviating ambiguity problems are summarized below.

1.3.1 Minimization of Range Overlays

The mechanisms provided in the WSR-88D for unambiguous mapping of reflectivities are different for different elevation angles, and are as follows (OFCMSSR, 1992):

Low Elevation Angles: At the lowest two elevation angles (usually 0.5° and 1.5°), the radar antenna scans azimuthally at each elevation twice. The first scan uses a "continuous surveillance waveform" (long PRT transmission) to generate an echo power array with 0.5 dB and 1 km resolution for each radial (spaced 1° apart). These are stored in the RDASC (Radar Data Acquisition Status Control) till the end of the scan. The second scan at the same elevation uses a "continuous Doppler waveform" (low PRT transmission). The data from this scan are combined with those stored from the previous scan, radial by radial, to generate a single record called "Doppler Data."

Middle Elevation Angles: Here a "batch mode" is employed. Surveillance (high PRT) and Doppler (low PRT) waveforms are interlaced to achieve the required range, while allowing the radar to simultaneously collect base reflectivity, mean radial velocity, and spectrum width data. Such a scheme is used at middle scan levels, but not the lower levels, because the requirement of clutter rejection is more stringent at lower levels, calling for a uniform PRT.

High Elevation Angles: No special procedure to combat range overlay is considered necessary at high elevation angles. Since storm tops do not exceed heights of 70,000 feet, range overlay of velocity data is not expected at high altitudes. Also, the oblique radar beam pointing at high elevation angles tops (i.e. goes over) storm cells at relatively close ranges. As a result, all the weather echo is confined to close ranges and it is possible to employ a relatively high PRF at these elevation angles, which provides a larger aliasing interval.

1.3.2 Velocity Dealiasing

The WSR-88D system has built-in software for dealiasing velocity data. Although velocity dealiasing is part of preliminary processing, i.e. it is not a meteorological algorithm, it is performed in the WSR-88D's RPG (Radar Product Generator) computer, and not in the RDA (Radar Data Acquisition) unit (OFCMSSR, 1991).

The WSR-88D velocity dealiasing algorithm has been discussed in some detail in (OFCMSSR, 1991), and is based on the scheme proposed by Eilts and Smith (1989). The essential basis for the correction of aliases is the continuity of velocity along radials, and between adjoining radials at the same range.

When the data quality is good (adequate signal-to-noise ratio, no excessive "missing" data points, and no extreme wind shears), the algorithm detects sudden Doppler velocity changes (jumps) due to aliasing by examining data along only one radial (the current radial). For more difficult conditions, neighboring points from a previous radial are examined. Elaborate error checks are made at every stage of the algorithm to arrest the propagation of erroneous detection of aliasing. The algorithm is efficient, because it is adaptive, i.e. it uses simpler logic for well behaved data which occur relatively more frequently, and reserves more elaborate procedures for data that are difficult to dealias.

1.4 SOME ALTERNATIVE ROUTES TO AMBIGUITY RESOLUTION

The data processing strategy employed currently in the WSR-88D for ambiguity resolution is essentially one-dimensional, i.e. data from one radial is considered at a time to detect ambiguities. This is strictly true for the assignment of correct ranges to Doppler velocity data. For velocity dealiasing, data processing is done along one radial, with reference made only to the previous radial as required.

Ray and Ziegler (1977) have suggested a different one-dimensional (along a radial) technique for dealiasing that corrects Doppler velocities by multiples of the aliasing interval such that the corrected velocities are normally distributed about their mean value. This method is potentially more robust, but is difficult to apply in cases where severe aliasing causes a large spread of velocities and biases the sample mean.

Bargen and Brown (1980) have suggested another continuity-based single radial method of Doppler velocity dealiasing, which compares individual velocity values with an average of preceding values, and determines the proper aliasing interval by minimizing their difference. However, it requires operator intervention to handle velocity fields with difficult aliasing problems.

It is to be expected that simultaneous consideration of data from an entire scan (i.e. two-dimensional data) should provide a better basis for ambiguity resolution than one-dimensional processing, since the whole scan contains more information than one or two radials. Such attempts have been made, as summarized in this section.

Merritt (1984) proposed a two-dimensional processing approach consisting of three main steps. First, data from a complete azimuthal revolution of the radar antenna (at a constant elevation angle) is segmented into regions, each of which contains velocities that are close (within some percentage of the Nyquist velocity) to each other. In the second step, the aliasing interval of each region is adjusted so as to minimize shear (differential Doppler velocities) along the borders. The third step uses a wind model (an estimate of the ambient wind field) to determine the proper aliasing interval of large areas, which should already be internally consistent.

One problem intermittently found with Merritt's algorithm is the propagation of errors that might occur in the wind field model. To overcome this, Boren et al. (1986) added a wind field model monitor to Merritt's algorithm. They used a set of rules to determine if the wind field model is correct. If the model is found to be incorrect, it is abandoned and replaced with a preceding model that was considered valid, thus arresting the propagation of the model error.

The Merritt technique has also been enhanced by Bergen and Albers (1988) through the addition of a noise filter, a mechanism to deal with ground clutter, and the use of a sounding rather than a wind field model to estimate the aliasing of distant echo fields which do not have continuous velocity measurements out to their range.

Merritt's technique, and the family of algorithms that it spawned, have the common drawback of being highly computation-intensive. The basic methods themselves require high amounts of computation. In addition, the presence of strong shears causes problems in proper dealiasing which requires a second pass through the data to be resolved (in the Bergen and Albers algorithm, which is the most developed member of the family). This adds further to the computational load (Eilts and Smith, 1990). In their present form, apart from their algorithmic inadequacies (of which no studies based on WSR-88D type data are available), their computational load is difficult to accommodate on the WSR-88D computers in real time. Therefore, two-dimensional methods are not considered as candidates for implementation in the WSR-88D in this report. However, a watch should be kept on the developments in this direction, in particular with regard to the availability of computationally more efficient versions.

1.5 PERSPECTIVES ON AMBIGUITY RESOLUTION IN THE WSR-88D

In general, range and Doppler ambiguities in coherent radars can be resolved at two levels:

1. Signal Processing
2. Data Processing

In *signal processing,* one treats the radar echo(es) in such a way as to determine the true (unambiguous) Doppler velocity *before* a numerical value is associated with the velocity and stored as a data point. As a rule, signal processing aims to resolve the ambiguity at each individual resolution cell independently, without reference to other data points within the set. In *data processing,* on the other hand, the Doppler value of each resolution cell is first recorded as it is sensed, which may or may not be ambiguous. Then an attempt is made to resolve ambiguities at each data point by examining the point in relation to other points in the neighborhood, or even the entire data field.

It is, of course, possible to adopt a hybrid approach, combining the signal processing and data processing routes, to fight the ambiguity problem. In this approach, the signal processing route is used to resolve as much ambiguity as possible before data are recorded, and any residual ambiguity may be resolved by examining each data point in relation to others in the field.

It is clear that the algorithm currently employed by the WSR-88D for ambiguity resolution lies in the data processing domain. In many ways, resolving ambiguities via signal processing is superior to achieving the same goal via data processing. Some of the reasons are:

Speed: Signal processing methods are usually faster than data processing since there is less computation, less number of logical steps, and less need to access mass memories. Signal processing architectures are generally pipelined, with one-way, open loop signal paths.

Robustness: Since each point is treated independently in signal processing, the presence of noisy, spurious, contaminated or erroneous data at other points in the field do not affect the treatment of the point under consideration. Further, in the presence of extreme wind shears, when the velocity differential between neighboring (valid) data points is comparable to the aliasing interval, velocity aliasing may never be correctable by the data processing method (Eilts and Smith, 1989).

Resource Saving: The WSR-88D is a long range, high resolution radar, scanning at multiple levels, and recording multiple attributes of each resolution cell. Thus, keeping all the data in live memory requires a large capacity of random access memory (RAM) if on-line data processing is to be performed. The currently implemented range ambiguity correction procedure requires data from an entire circular scan to be stored, and velocity dealiasing requires data from two radials. Some of the more elaborate ambiguity resolution algorithms require reference to larger slices of data, including entire volume scans (consisting of 9 or 14 circular scans for the WSR-88D). These computer resources can be saved if ambiguities are resolved individually for each resolution cell, using signal processing methods.

Resolution of ambiguities is a critical preprocessing function which strongly influences the quality of the final weather products delivered by the WSR-88D system. Thus, a modern and reliable system such as the WSR-88D must resolve the range and Doppler ambiguities of its data with utmost reliability and efficiency, and should therefore aim to achieve a signal processing solution to the problem eventually. However, since certain signal processing methods may require hardware enhancements to the existing radar configuration, it is necessary to look for more immediate and medium-term solutions to the ambiguity problem in the WSR-88D context. These goals are addressed in this report.

The projected ambiguity resolution methods are divided into three categories. The immediate or *short-term* solutions are those that can be implemented without changing the hardware or the basic operating parameters of the radar. The *medium-term* solutions are possible through changes in the radar's operating parameters, and minor augmentation of the system hardware. The solutions that will require significant hardware enhancement are classified as the *long-term* solutions to the ambiguity problem, but are expected to enhance the system performance considerably.

PART 2

SHORT TERM SOLUTIONS TO THE AMBIGUITY PROBLEM

2.1 INTRODUCTION

The short-term solutions to the WSR-88D ambiguity problem would, of necessity, lie in the data processing domain. These solutions should not require any hardware changes in the radar, and should preferably not demand changes in the operating parameters of the system.

Since the WSR-88D already has an operational velocity dealiasing algorithm, the simplest and fastest way to improve the radar's ambiguity performance would be to refine the existing algorithm to remove its weaknesses and enhance its robustness. The refinement should not preclude changes to certain sections and modules if the existing ones are found to have reached (or come near) the limits of their performance and/or if large (or significant) performance gain are expected. The following sections discuss some possible developments on the existing algorithm in the order of increasing depth of change.

2.2 FAILURE ANALYSIS OF THE CURRENT ALGORITHM

The existing WSR-88D velocity dealiasing algorithm has been operating in the system for a significant length of time. Based on this usage, certain general impressions have been gained on the overall performance of the algorithm. One important observation is that the algorithm is basically sound and performs its intended functions over a vastly major part of the time. However, it has also been observed that the algorithm does fail in a certain percentage of weather situations (Zittel and O'Bannon, 1993). Very often these are the ones of significant interest, because they involve very high wind velocities and velocity gradients.

The algorithm, as used now, is fairly complex, and is not expected to be amenable to significant improvements through *ad hoc* changes or problem fixes. A systematic study of its failure modes must be made on real data before major improvements can be incorporated. Such a study is considered highly necessary in the WSR-88D context.

Data processing for velocity dealiasing by the current algorithm has five essential steps: (1) pre-filtering, (2) detection and estimation of Doppler velocity discontinuities, (3) the assignment of "correct" aliasing intervals and restoration of aliased velocities, (4) error checks, and (5) determination of absolute aliasing intervals of ensembles of data points. These are essentially sequential operations, and hence the failure probability of the overall algorithm would approximately be a sum of the failure probabilities of the individual operations (when the individual probabilities are small). A detailed study is necessary to determine the susceptibility of each of the major algorithm steps to malfunction. For this, a systematic analysis should be conducted by selecting potentially difficult data fields (those which contain high Doppler velocities, velocity gradients, isolated intense weather events, and relatively high percentage of noise and missing data points) and applying the dealiasing algorithm to these fields. It is not enough to judge only the final output(s) of the algorithm, but tracer outputs from individual subroutines within the program must be monitored for the nature and frequency of their failures. In this way, weak points within the program chain can be identified, which will help in devising steps for their reinforcement.

A significant difficulty expected in a systematic validation of the dealiasing algorithm is the absence of a standard (or validated) program against which this algorithm can be tested. But this is a common problem with much new software, and the solution would be a somewhat labor-intensive one, using the judgment of experienced radar meteorologists to validate the results of the algorithm. This calls for a careful program development and validation plan so as to minimize the cost and time involved.

Until such a study is conducted, it would not be possible to suggest major improvements to the current program with confidence. However, it is possible to identify certain areas where weakness may exist, and suggest remedial measures so that the developmental cycle may be shortened through parallel effort. In the following sections, a few such ideas are developed. They may serve as improvements over (or replacements for) individual subroutines within the current dealiasing algorithm.

2.3 A SMOOTHED DOPPLER VELOCITY JUMP DETECTION ALGORITHM

A major upsetting factor for any dealiasing algorithm utilizing Doppler velocity continuity is the presence of noise in the data. The presence of large-amplitude random errors (or system artifacts) flips the aliasing interval randomly, and each flip is carried over to the subsequent data points in the same run. Although subsequent error checks serve to detect many of these false switchovers, many of them remain undetected. This situation should improve if an intrinsically more noise-resistant algorithm is utilized for detecting sudden Doppler velocity changes.

Detecting a change by monitoring the difference between two noisy adjacent samples (as is currently done) increases the variance by a factor of two relative to the variance of the individual samples. This is the primary cause of the high noise susceptibility of the discontinuity detecting algorithm. To minimize noise variance, some form of data smoothing is necessary. However, ordinary block-averaging type of smoothing would also smooth out the true discontinuities in the data (which may be due to aliasing) while smoothing the noise. Even the present practice of comparing the current velocity with an average of past (radially inward) velocities may distort the level of discontinuity actually present in the data. Thus, special filtering methods such as median filtering (which preserves the jumps while removing spikes) are necessary to enhance the reliability of the discontinuity detection and estimation algorithm.

One potentially noise-resistant method, based on an adaptation of a curve-fitting algorithm, is given in some detail in Appendix A of this report. The method essentially breaks the radial run of data points into two parts, one backward (radially inward) of the current point, and the other forward (outward). A smoothing curve is fitted each way (backward and forward) from the break, and the discontinuity between the two curves at the current point is considered for the detection of jumps due to aliasing. Appendix A also provides details of the interpolation procedure and provision of redundancies for reducing errors in aliasing detection.

2.4 DETERMINATION OF THE ABSOLUTE ALIASING INTERVAL

Irrespective of the actual algorithm used for the detection of velocity discontinuities, a problem arises in certain situations in assigning the absolute aliasing interval to "locally dealiased" data. If the starting point of the dealiasing algorithm is, for some reason, assigned a wrong aliasing interval, all subsequent points in the same run which use the point as a reference will have their "dealiased" Doppler velocities wrong by the same amount. This is a very real possibility when the first valid point in a given data run has a high Doppler velocity which is aliased. The problem becomes quite serious when islands of relatively high reflectivity are separated by low-signal (no-data) spaces. This breaks the continuity between data runs, requiring the program to be reinitialized repeatedly, without the benefit of prior information on the absolute Doppler velocity of the reference point(s).

A few different solutions to the absolute aliasing interval determination problem may be pursued:

(1) Reduction of Noise Threshold: The current SNR threshold of the WSR-88D (3 to 5 dB) is such that clear air returns from a major part of the radar's field of view is precluded when observing severe weather. This aggravates the discontinuity problem. Important information is lost because clear air areas surrounding severe weather can provide an indication of environmental winds which can serve as the basis for fixing the true Doppler velocities in storm areas. Attempts should be made to lower the SNR threshold to as small a value as possible without disrupting other functions of the WSR-88D system. Of course, the Doppler velocity (and spectrum width) estimates within these low-SNR areas will be relatively more erroneous, but these could be better than the total absence of data over significant patches of the data field.

2. Incorporation of Environmental Winds: After the implementation of the current WSR-88D dealiasing algorithm, originally developed at the National Severe Storms Laboratory (NSSL) (Eilts and Smith, 1990), further refinements have been made at NSSL in estimating environmental winds and incorporating them into the dealiasing program for the estimation of the absolute aliasing interval. This procedure should be perfected, and a well-tested module for environmental wind determination should be incorporated into the WSR-88D algorithm. Since the development at NSSL is an increment over the algorithm adopted for WSR-88D, it is generically compatible with the current WSR-88D algorithm.

3. Incorporation of Additional Logic: It is possible to build in further logic into the process of determining the absolute aliasing interval. The reasoning given in some detail in Appendix B may be incorporated in stages, subject to validation by actual data, into the current or enhanced (by

NSSL) version of the WSR-88D dealiasing program. This logic may be helpful in cases where the environmental wind data are unavailable, incomplete, or unreliable.

4. Disposal of Doubtful Data: This is not a solution to the absolute ambiguity determination problem, but a default option for data that cannot be properly dealiased. If it is detected that certain data points have been wrongly dealiased, but it is not possible to determine their true Doppler velocity, it is better in many applications to restore the original ("raw") data in its place rather than either leaving the wrongly dealiased data or dropping the data altogether and declaring the points as void. This aspect should be studied further to determine whether and under what conditions these "difficult" data should be removed.

PART 3

MEDIUM TERM SOLUTIONS TO THE AMBIGUITY PROBLEM

3.1 INTRODUCTION

The solutions to the ambiguity problem in the medium term are those that may be achieved with some changes in the operating parameters of the WSR-88D radar, but would not require any significant changes in the radar hardware.

Because the currently permitted unambiguous range values in the WSR-88D are all less than its maximum range requirements, the range overlay problem is always potentially present. Regions where overlaid signals cannot be assigned the proper unambiguous range interval are painted purple on the WSR-88D displays. Under a large variety of conditions, this "purple haze" covers significant portions of the displays, reducing both the visual impact as well as the utility of data fields. In particular, residual ground clutter close to the radar is overlaid on an annular area immediately outside the unambiguous range circle, obliterating large tracts of data in that region in a significant fraction of data fields.

As mentioned before, the range and velocity ambiguity problems are intimately connected. Thus, the solution of one of them usually causes problems in resolving the other. Some of the medium-term solutions to the ambiguity problem, keeping this fact in view, are discussed in this part of the report.

3.2 OVERLAY MINIMIZATION THROUGH PRF REDUCTION

The single most important radar parameter that affects a radar's ambiguity behavior strongly and simultaneously in both range and Doppler dimensions is the PRF (Pulse Repetition Frequency) or, inversely, the PRT (Pulse Repetition Time). This parameter must be chosen optimally to derive the best ambiguity performance.

Adaptive PRF selection has already been tried in the

Terminal Doppler Weather Radar (TDWR) (Crocker, 1989). The WSR-88D currently has an automatic PRT selection algorithm operational. However, it is only a limited optimization scheme in the sense that the optimum PRF is selected out of only four discrete values within given limits. The "best" PRF is selected as the one yielding the least obscuration due to overlaid echoes over the entire scan circle at the lowest elevation. This PRF is maintained during the rest of the volume scan up to an elevation of 7°, above which ambiguity problems are not operationally significant.

The present limits of PRF (or PRT) for the WSR-88D are such that the maximum unambiguous range lies between 115 and 145 km. The upper limit is determined by the memory capacity available to store the scan data. From eq. (8), the Nyquist velocities for these limits are 32.60 m s^{-1} and 25.86 m s^{-1} respectively, assuming the transmitted frequency to be 3,000 MHz, which is the worst as far as ambiguity is concerned (the WSR-88D has a transmitter frequency band of 2,700-3,000 MHz (OFCMSSR, 1992)).

From the point of view of radar transmitter and receiver hardware, there need be no lower limit on the PRF i.e. no upper limit on the unambiguous range. Since the limit now comes from memory/data organization in the computer, appropriate reorganization of data storage/handling procedures should permit higher unambiguous ranges to be achieved. Good progress has been made on this approach at the WSR-88D Operational Support Facility (OSF). It appears possible to increase the unambiguous range to 180 or 200 km, or even the full 230 km range required to be covered by the WSR-88D for Doppler velocity mapping.

The only catch in increasing the unambiguous range to 230 km is that the Nyquist velocity V_n goes as low as 16.3 m s^{-1}. At such low Nyquist velocities, the currently used dealiasing algorithm, as well as the alternative algorithms available, would not function properly (Zittel and O'Bannon, 1993), especially under conditions of high shear. Unfortunately, high shear very often accompanies the severe weather phenomena that are of most interest in many applications of radar meteorology.

Thus, as expected, the success of attempts to increase the unambiguous range to 230 km would not only depend on the ability to reorganize the data handling process within the WSR-88D computers so as to accommodate the enhanced number of range cells in each radial, but also on devising more robust velocity dealiasing schemes that function at relatively low Nyquist velocities. However, this is an option worth pursuing, because it provides Doppler data fields with no range obscuration due to ground clutter overlay. This is perceived as a medium term solution and not a short term solution because of the complexity involved in the twin problems of range extension and Doppler velocity dealiasing with a low Nyquist velocity.

3.3 AMBIGUITY RESOLUTION THROUGH TRIPLE PRF RADAR SCANS

Doppler velocity aliasing is a result of undersampling of the relatively high Doppler frequencies by the radar pulses. Since the true Doppler velocity and the apparent or aliased velocity are related by the Nyquist velocity of the radar system, it is logical to expect that observation of a particular Doppler velocity at two (or more) different PRFs (sampling rates) should yield information that could be used to resolve the velocity ambiguity.

One method of varying the PRF is to alternate them between two values in quick succession, even from pulse to pulse. However, there are difficulties with this scheme, for which such a possibility is considered in this report as a long-term prospect, and discussed in a latter section. Here a simpler scheme for Doppler observation at two different PRFs is proposed.

In the proposed method, each radar scan in which combined range-Doppler ambiguity is a problem is scanned three times, each time at a different PRF. In the context of WSR-88D, these are the lowest two scans of the volume scan cycle. Currently, each of these two scan levels is scanned twice -- once with a long PRT (the "continuous surveillance waveform", with an unambiguous range of 460 km) for range-unambiguous reflectivity data, and a second time with a shorter PRT (the "continuous Doppler waveform") for Doppler velocity data (OFCMSSR, 1992). The introduction of the triple PRF scheme means that each of these two levels is scanned three times -- once for unambiguous reflectivity data (as is currently done), a second time at a certain higher PRF (again, as currently done), and a third time at a different PRF. Thus, two more scans would be introduced into the volume scan cycle, as compared to the current scheme. At the maximum antenna rotational rate of 5 rpm (OFCMSSR, 1992), this would add a further 24 seconds to the volume scan cycle. At normal rotational speeds, the additional time would be 30-40 seconds. For the tasks assigned to the WSR-88D, this order of additional scan time should be affordable.

If the current volume coverage pattern (VCP) times (5 min for VCP11 and 6 min for VCP21) are to be maintained without any stretching, then speeding up the antenna by the order of 10% would be necessary. Without any other system changes, this would reduce the number of samples available for processing by the same fraction, about 10%, resulting in a corresponding loss of accuracy of the Doppler moment estimates. This loss can be readily estimated in the case of the WSR-88D.

Some details of a triple-PRF scan scheme and some possible parameter values for the scheme are given in Appendix C.

The triple PRF scheme can also be applied to mid-elevation-angle scans of the WSR-88D. Currently, for these elevation angles, an interlaced batch PRT scheme is employed in which a batch of constant-PRT pulses alternates with another batch at a different but constant PRT. Extension of this scheme to a 3-PRT batch scheme would involve cyclically transmitting 3 bursts of pulses, each at a different but constant PRT. The PRT values can be chosen by the same logic as used for the 3-PRT scan scheme (Appendix C). Switchover to a 3-PRT scheme would not, by itself, add to the volume scan time, since that depends only on the antenna rotational speed and the total number of scans in the VCP. However, If a third batch of pulses is merely appended to the two existing batches, the cycle time of PRT change would increase, leading to additional spatial decorrelation between the echoes from the three PRTs. To maintain the decorrelation at the current levels, the three PRT batches should be accommodated within the same time slot as the current two batches, leading to a 33% decrease in the number of samples in each batch. This would correspondingly increase the errors in Doppler parameter estimation, as well as the clutter residues.

If it is desired to maintain the number of samples per batch at their current value, and yet have three cyclic PRTs without introducing any additional (spatial) decorrelation, then the antenna scan rate would have to be brought down to 2/3 of its current value. This would increase the time for the mid-elevation portion of the volume scan time by 50%, or somewhat more than a minute in absolute terms. The overall volume scan time will increase by the order of two minutes if the additional time for the extra scans at the two lower elevation angles is also taken into account.

Thus, the introduction of a triple-PRF scheme, like that of any other scheme requiring changes in radar parameters, would involve an intricate process of multiparameter tradeoffs. Fortunately, most of the effects of such tradeoffs on the primary products of the radar can be estimated analytically. Such a study should be undertaken for the WSR-88D for arriving at the best tradeoff as far as the ambiguity problem is concerned.

The triple-PRF scheme, in addition to helping determine Doppler velocities unambiguously, can also minimize Doppler data loss due to range overlay. Currently, if the range-overlaid signals differ from each other in power by a certain threshold ratio (default value 10 dB, but operator-selectable down to 5 dB) or more, the velocity and spectrum width estimates are assumed to correspond to the stronger signal, and are assigned the range cell where the stronger signal occurs (as determined by the long-pulse or "surveillance" scan). However, if the overlapping data have comparable power levels, (differing by a ratio less than the threshold) then both overlapped range cells are declared to have erroneous data (or no data). In operation, especially under conditions of widespread heavy weather in the radar field, this results in the loss of data from a significant number of resolution cells. This problem can be mitigated to a considerable extent by the triple-PRF scheme. If a certain cell C_1 is overlaid on another cell C_2 at a given PRT T_1, and the power ratio in the two cells is less than the threshold, the data processor can now look at the overlay of C_1 with a third cell C_3 at a second PRT T_2. Since the probability of the power in C_1 being within the threshold ratio of the powers in both C_2 and C_3 is much less than the probability of being within that ratio of the power in C_2 alone, a significant fraction of Doppler data that would have been lost due to range overlaying in a 2-PRT scheme (one long, one short) would be recoverable in a 3-PRT (one long, two short) scheme.

If the triple-PRF scheme is not implemented, its advantages can be realized to a certain extent by deriving Doppler information from the long-PRT scan of the present 2-PRT scheme. Currently, that scan is being used only to provide reflectivity data; Doppler velocities are derived only from the short-PRT scan of the 2-PRT scheme. It is true that the Doppler velocity derived from the long-PRT pulses would be highly ambiguous

(Nyquist velocity of the order of 8 m s^{-1}), and would be of little use by itself. But if a radial discontinuity is detected in the Doppler velocity data (derived from the short-PRT scan) using the current dealiasing algorithm, and it is not possible to decide whether it is due to aliasing or high shear, the local continuity of radial velocity obtained from the high-PRT scan can be used to make the decision. This scheme will be aided by choosing the two PRTs of the 2-PRT scheme such that integer multiples of their respective Nyquist velocities do not coincide.

3.4 OVERLAY SEPARATION THROUGH SPECTRAL DECOMPOSITION

The problem of Doppler data loss due to range overlay, discussed in the penultimate paragraph of the last section, may be mitigated through an alternative approach based on spectral analysis. In general, the spectra of Doppler velocities obtained from single resolution cells can be quite well approximated by a Gaussian function. Also, in general, overlaid resolution cells, because they are separated by one or more unambiguous range intervals, would have different average radial velocities. Thus, when their signals are superimposed, a Fourier analysis of the composite signal would often show bimodal spectra. By making a Gaussian fit on each of the modes, it should not only be possible to estimate the individual Doppler velocities, but even the echo power levels of the returns from each of the range cells which have been overlaid (Waldteufel, 1976). The only situations where it may not be possible to separate the signals from the two or more overlapped range cells are those where the Doppler velocities are so close that the modes cannot be separated, but this would constitute only a small fraction of the overlaid cases, and these residual data points can be handled the way they are being done currently.

If both power and Doppler velocities of overlaid range cells can be separated by using the spectral decomposition method, then relatively high PRFs can be used, which would increase the Nyquist velocity. However, if more than two range cells overlap, it would become progressively difficult to separate the constituent individual spectra, and the method would become less reliable. Thus by using the spectral decomposition method, the unambiguous range cannot be reduced below half of the maximum range, i.e. below 115 km for the WSR-88D. (Even then out-of-range echoes may produce more than two peaks.) This would leave the Nyquist velocities in the neighborhood of 30 m s^{-1}, and thus the velocity aliasing problem would not disappear completely. However, many of the dealiasing algorithms would work much better for such orders of Nyquist velocities than for velocities less than the 20 m s^{-1} which corresponds to an unambiguous range of 230 km.

A major drawback of the spectral decomposition method is its relative complexity. Time series data from each resolution cell must be processed through the FFT algorithm, and then subjected to mode separation, which will be a recognition algorithm of some complexity. Further, when the spectra of returns from one or more of the overlapping resolution volumes depart significantly from the Gaussian shape (in some cases, e.g. tornadic storms, the individual spectra may even be bimodal), their separation will be even more difficult. Because of the large number of resolution cells in a scan, and the need for real-time processing, the spectral separation procedure would impose considerable additional computational burden compared to the current pulse-pair processing in WSR-88D. For this reason, and to develop the necessary software *ab initio*, the spectral decomposition solution is considered as a medium term solution to the ambiguity problem. In fact, pulse-pair processing is so fundamental to all the spectral estimation algorithms in the WSR-88D that a changeover to Fourier methods may even be regarded as a long-term possibility.

PART 4

LONG TERM SOLUTIONS TO THE AMBIGUITY PROBLEM

4.1 INTRODUCTION

As mentioned in the general introduction to this report (Sec. 1.1), the most radical solution to the ambiguity problem in the WSR-88D would be to resolve the ambiguities even before they appear in the data, rather than trying to remove them after the data have been affected. Several schemes have been proposed in the past for ambiguity resolution via suitable radar signal design and processing. These include staggered and batch PRTs, and the use of phase diversity, among others. A few of these methods are discussed below in the context of the WSR-88D system.

4.2 STAGGERING OF PRT TO INCREASE UNAMBIGUOUS VELOCITY

In the staggered PRT method (Zrnic' and Mahapatra, 1985, Sirmans et al. 1976), the PRT is varied sequentially from pulse to pulse to effectively obtain a large unambiguous velocity. In its simplest and most common form, a dual PRT is used, with two constant values of PRT alternating from pulse to pulse.

Let T_1 and T_2 be the two alternating PRTs with $T_2 > T_1$, and let $T = T_1 + T_2$. The Doppler velocity estimate for such a pulse train may be obtained from the difference of the arguments of the two autocovariance functions, each calculated from those alternate pairs of pulses that are at a constant PRT (Zrnic' and Mahapatra, 1985). The unambiguous velocity for this scheme is inversely proportional to the difference $(T_2 - T_1)$, and can be increased by choosing T_1 and T_2 closer together. However, there is a limit to how close they can be brought together, because the velocity estimates also become less accurate (i.e. the variance of the velocity estimates increases) as $(T_2 - T_1)$ decreases. The principle of deciding the values for T_1 and T_2 is to choose the lowest value of $(T_2 - T_1)$ that provides the necessary unambiguous Doppler velocity, and to check whether that value is consistent with the necessary velocity estimation accuracy.

For the WSR-88D, with 10 cm wavelength and 60 m s^{-1} unambiguous Doppler velocity, (T_2 - T_1) would be 0.41 ms. If (T_1 + T_2) is taken so as to clear the range interval of 230 km, then $T = T_1 + T_2 = 1.53$ ms. Thus, $T_1 = 0.56$ ms and $T_2 = 0.97$ ms. With these values, it may be shown that the specified velocity estimation accuracies may be met at an SNR of 20 dB, but not a lower value like 5 dB, which is often used to threshold data in WSR-88D.

Apart from the difficulty about estimation accuracies, the staggered PRT scheme has certain other major drawbacks. The first is that the measurement of reflectivity and the assignment of correct ranges to overlaid reflectivity values follows a somewhat complex logic (Zrnic' and Mahapatra, 1985) which has not been tried on real data. The second difficulty with the staggered PRT scheme is that the realization of clutter filtering is difficult, and, in general, larger clutter residues are left over than in the case of uniform PRTs. Since the presence of clutter residues, because of their overlaying on the zone outside the first unambiguous range ring, is a major cause of obscuration in the WSR-88D currently, the implementation of a staggered PRT scheme in this system will require considerable and careful study as well as development.

A staggered PRT scheme may, however, be readily adapted for restricted use in the WSR-88D by drawing upon a related development. The scheme was quite fully developed, almost to the point of field trials, for a derivative of the NEXRAD (the developmental name of the WSR-88D system) called the Interim Terminal Weather Radar (ITWR) which was devised to test certain concepts relating to the Terminal Doppler Weather Radar (TDWR), especially in connection with the detection of wind shear at airports. The microcodes for staggered PRT operation on the

ITWR were ready, and should be adaptable on the WSR-88D. This would make the implementation possible in the near term. However, the operation of the scheme in high-clutter situations (e.g. at low antenna elevation angles) has not been established, and hence it is reasonable to hope that the scheme may be usable in the WSR-88D only for the scans above the elevation angle of 2.5°.

4.3 USE OF RANDOM PHASE TRANSMISSION TO RESOLVE AMBIGUITY

Echoes from different pulse intervals can be "recognized" by coding the transmitted pulses in suitable ways. One of the simplest methods is to use uniformly spaced rectangular monotone transmitted pulses (as is currently being done for the WSR-88D), but provide a random phase shift from pulse to pulse. This would cause echoes to be coherent only with the transmitted pulses which cause them, but incoherent with other pulses (Zrnic' and Mahapatra, 1985). By storing the known phases of the individual transmitted pulses digitally, it is possible to "recohere" separately the echoes from each unambiguous range interval. The overlaid echoes from other range intervals would then appear as white noise (Laird, 1981). The recohered echoes can be adaptively filtered, and a subsequent recohering of the residues will enhance the ratio between the in-trip signal and the overlaid signal (Siggia, 1983).

Some details of the random phase method of ambiguity resolution and the considerations for its adaptation to the WSR-88D system are given in Appendix D.

4.4 SYSTEMATIC DISCRETE PHASE CODING FOR AMBIGUITY REDUCTION

Sachidananda and Zrnic' (1986) have proposed a method for recovering spectral moments from overlaid echoes in a Doppler weather radar. The method essentially imparts a periodic sequence of discrete phase shifts such as $0, \pi/4, 0, \pi/4, \ldots$, or

$0,0,\pi/2,\pi/2,0,0,\pi/2,\pi/2, \ldots,$ or $0,0,0,\pi,0,0,0,\pi, \ldots,$ etc. to the transmitted pulses. This has the effect of splitting the spectrum of second trip echoes (and possible echoes from farther trips) such that it does not bias the first trip echo mean velocity estimates. By repeating the same procedure for the second trip, the biasing effect of the first trip echo on the second can be eliminated. Thus the signal from both the trips can be independently recovered even when the desired trip signal power is as low as 15 dB (theoretical and simulated estimation) below that of the overlapping signal. Like the random phase method, the systematic phase coding method, in effect, enhances the unambiguous range by a factor of 2 without sacrificing the unambiguous velocity.

The discrete-coded pulse method is a potentially powerful method that should be studied in some detail in the WSR-88D context. However, it has some known features (Sachidananda and Zrnic', 1986) for which it cannot be readily recommended for use in that system. Among them are the following:

1. The accuracy of some of the spectral moment estimates, especially the spectrum width, is highly sensitive to the relative location of the overlaid spectra. For overlapping or closely spaced spectral peaks, the estimate is highly erroneous. In fact, the applicable pulse-pair expression for spectrum width yields a value that depends more on the power ratio of the overlaid spectra than on the true spectral width.

2. For comparable powers of the two overlapping spectra, the estimation of the mean velocity of each has a high variance. To keep this within reasonable limits, a large number of samples would have to be used for autocovariance estimation, which may not be compatible with the normal scan rates of the WSR-88D.

3. The method is realizable quite neatly for resolution of echoes from two trips. But the presence of third (and higher) trip echoes makes the logic very complex, and would introduce large errors into the spectral moment estimates.

4. To be able to preserve the power ratios over which spectra can be estimated with acceptable accuracy, a combination of spectral processing and autocovariance processing must be used, which is not only highly computation-intensive, but cannot be readily implemented for minimizing the effect of third and higher trip echoes.

For these reasons, additional studies are required, including tests on real data, before the discrete-coded pulse method can be used in the WSR-88D system.

4.5 AMBIGUITY RESOLUTION BY SINGLE-PULSE DOPPLER ESTIMATES

It is worth recalling that the primary reason for velocity aliasing in Doppler radars is the sampled nature of the radar signal. If the Doppler velocities were estimated from non-sampled signals, aliasing problems would not arise. An example is the laser Doppler radar, in which velocities are usually estimated from echoes of single transmitted pulses. Since Doppler shifts at laser frequencies is high, a significant number of cycles of this signal would be contained within one transmitted pulse, permitting straightforward measurement. However, in the case of the microwave radar, the problem is more difficult because of the relatively low Doppler frequencies.

The aim in microwave Doppler radars should therefore not be to get the final and accurate estimate of the velocity from a single pulse. A crude mean velocity estimation accuracy of the order of the aliasing interval, which would serve to resolve the velocity ambiguity, would be a very valuable output of single-pulse processing. If this is not possible, at least an indication of the sign of the Doppler shift would serve to reduce the number of aliasing intervals over which the search for the true velocity is to be conducted. These possibilities are examined here.

In the WSR-88D system (at λ=10 cm), mean Doppler velocities of 20 and 30 m s^{-1} (which are representative Nyquist velocities for different unambiguous ranges) would produce Doppler frequencies of 400 and 600 Hz respectively. Within the short pulse width of 1.57 μs, these Doppler frequencies would cause phase changes of about 0.23° and 0.35°. To be able to resolve Doppler velocity ambiguities due to aliasing, therefore, phase changes of the order of 0.2-0.3° during the pulse period would have to be reliably detected. It must be further remembered that samples within the pulse width are well correlated only during the first half of the pulse width (Doviak and Zrnic', 1993), during which only a half of these values of phase change would occur.

Detection of such small phase changes is considered difficult on a pulse-to-pulse basis in the presence of phase changes due to equipment drifts and instabilities, propagation anomalies, and multipath effects. However, the problem is significantly different in the case of phase changes within a single pulse because of the very short time period over which the phase change occurs. Over such short time scales (1.57 μs), most other relatively slow drifts would have insignificant effects, and the phase change due to Doppler shift should stand out more clearly in a relative sense (of course, broad-band white noise would still be present). It would be a great advantage if Doppler phase changes could be measured with enough accuracy to resolve velocity ambiguities. The advantage may be worth the cost of the necessary additional circuitry. However, this is a relatively revolutionary idea in the microwave radar context, and will have to be studied further before any possibility of implementation.

PART 5

PRIORITIES FOR
WSR-88D AMBIGUITY REDUCTION

Given the diversity of options as outlined in the earlier sections, a clear plan of action is necessary to solve the WSR-88D ambiguity problem in an optimal way. The possibilities outlined in this report have been organized as short-term, medium-term, and long-term ones. Short-term solutions are those that can be implemented within a period of one or two years, medium-term solutions may take up to four years, and the long-term solutions are expected to take over four years. These estimates assume that studies and implementation of the methods are initiated simultaneously.

It is possible that one of the short term or medium term solutions suggested here may solve the ambiguity problem in the WSR-88D to an acceptable degree. In such a case, further development toward long term solutions will be optional, depending on the status of development of these methods, and the extra benefits expected from their implementation. However, at the present time, a safe strategy is to consider and compare all the three types of options with an open mind.

To ameliorate the WSR-88D ambiguity situation in the shortest possible time, attention should be given right away to improvements in velocity dealiasing algorithms to dealias Doppler velocities correctly with greater reliability. The first step in this process should be a systematic failure mode analysis of the current algorithm with extensive and diversified real data sets. The next step should be the augmentation of specific subroutines within the program. *A priori* there appears to be scope for improvements on two major fronts. The first is to improve the noise resistance of the velocity discontinuity estimation algorithm, and the second is the assignment of the proper absolute aliasing interval to entire data fields or isolated patches. Some specific suggestions are given in this report in these two areas (Appendices A and B) which may be explored. In addition, attempts should be made to lower the SNR threshold above which data are now considered valid. The resulting de-blanking of data will provide more continuity within the data field, which will improve the performance of the current and future dealiasing algorithms.

The medium term solutions should aim to increase the unambiguous range of the WSR-88D system beyond the current 145 km, possibly all the way to 230 km. Exploratory work towards this goal has already been carried out at the OSF. This effort, which is based on the reorganization of the data acquisition and storage functions in the WSR-88D RDA, should be further developed and formalized in the WSR-88D operational framework, with the necessary changes in the radar operating parameters (such as the PRT) incorporated.

In parallel with such extension of the current unambiguous range, development toward the relatively new scheme with triple PRF radar scans and batches (Sec. 3.3) should be carried out. That scheme appears to have a better potential for restoring aliased velocities to their true values, as well as minimizing range overlay of Doppler data than continuity-based methods. However, the scheme involves a complex tradeoff between system parameters, which should be first systematically analyzed to arrive at an optimum set of parameters.

It is recognized that a truly robust and permanent solution to the ambiguity problem must come from a signal-processing approach which can enhance unambiguous ranges while providing Doppler velocity estimates that are inherently unambiguous. The operation of this class of methods is data-independent, which is a very desirable feature.

From the present perspective, it appears that the random phase transmission method (Sec. 4.3) is the most promising one for the WSR-88D system, and should be pursued seriously. The additional hardware requirements are minimal, consisting of a low-power phase shifter in the transmitter chain, with a measuring device for the actual phase shift introduced. The rest of the changes are algorithmic at the signal processor level.

There is need for some supporting studies for the random phase method which should be initiated at the earliest. These consist of the validation of the method by simulation with real time series data taken from a radar similar to the WSR-88D, e.g. the NSSL Cimarron radar. Although the original data from the Cimarron radar are taken with constant-phase constant-PRF transmitted signals, two time series can be phase shifted, each by its own (pseudo-)random sequence, and then combined to simulate the signal due to overlaid echoes. Such studies will help refine the signal processing algorithm, and help estimate the effects of out-of-range echoes.

The systematic phase coding method (Sec. 4.4) requiring about the same hardware enhancement as the random phase method, is also a very promising one for the WSR-88D. However, its relative complexity and certain known drawbacks will mean a larger development time. This may, therefore be considered only as a later option, if a need arises to utilize its strong points (e.g. separation of echoes with greater power ratios).

Finally, single-pulse Doppler measurement is a more novel and involved solution in terms of radar hardware, and its behavior has not been studied either with real data, or even from an analytical viewpoint. This method, as also the methods based on staggered PRT and spectral decomposition, should therefore first be subjected to a level of academic study before their utility for the WSR-88D can be considered.

CONCLUDING REMARKS

The problem of overcoming range and velocity ambiguity problems in the WSR-88D radar system is discussed in this report. A holistic view is taken, discussing possible solutions that may be implemented through various routes and in different time frames.

The ambiguity problem in a sophisticated system like the WSR-88D is quite ramified, and a wide diversity of solutions are possible in a conceptual plane, each with its advantages and drawbacks. Only those solutions that hold some promise for realization are discussed in the report. Where specific studies are needed for implementation of particular ideas, such requirements are brought out.

This study is restricted to the use of the values of a single parameter, i.e. the Doppler velocity, for dealiasing Doppler velocities through the data processing route. It is recognized that there may be information in other observed parameters that may help resolve the ambiguities with greater reliability. For example, the values of the Doppler spectrum width in the vicinity of a point under consideration might contain important clues in determining whether a certain Doppler velocity jump is due to aliasing or the presence of intense shear. However, considering the constraints of the current study as well as implementation on WSR-88D, such a broad scope of research has not been covered in this report.

ACKNOWLEDGMENTS

The authors would like to thank Don Burgess, Steve Smith, Tim O'Bannon, Dave Zittel and Dale Sirmans for illuminating discussions which have helped generate a clear insight into the WSR-88D ambiguity problem, constraints and solutions. Critical comments and useful suggestions by Dick Doviak are appreciated. The support of Dr. Robert A. Maddox, Director, National Severe Storms Laboratory, is acknowledged for sponsoring this study as an internal project of NSSL.

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APPENDIX A

A SMOOTHED DOPPLER VELOCITY JUMP DETECTION ALGORITHM

A procedure for reducing noise effects on the detection of Doppler discontinuities is suggested here as an alternative to (or refinement over) the corresponding part of the current algorithm.

It is desired to estimate the discontinuity between the data points N and N+1 along a given radial, and to judge which of these discontinuities (for various values of N) may be due to aliasing. To do this, the steps given below may be followed:

Step #1: Pre-filter the data as in the current algorithm, i.e. give a "missing" flag to velocity data if the corresponding spectrum width is too high (greater than two-thirds of the Nyquist velocity) or if the SNR is too low (less than 0 dB). The remaining data points are considered valid, though ambiguities may still exist.

Step #2: Consider the valid data points N, N-1, N-2, ... , and fit a curve through their Doppler values V_N, V_{N-1}, V_{N-2}, ... The order of the curve and the method of fitting will be discussed later in this appendix. Let the value of this curve at the point N be V'_N. Similarly, fit a curve through V_{N+1}, V_{N+2}, ... , and let its value at N+1 be V'_{N+1}. The Doppler velocity jump between the points N and N+1 is defined as

$$\Delta V_N = V'_{N+1} - V'_N \tag{A1}$$

Note that the curve fitting is only an operation for estimating the local velocity discontinuities with reduced noise interference. The original Doppler values are not discarded or modified in favor of the smoothed values, but are retained in the data set during and after the estimation of discontinuities.

Step #3: Locate the local maxima in the Doppler velocity jump ΔV_N as computation proceeds along the radial, and store the values of N and ΔV_N at these points. These are the candidate discontinuities due to aliasing.

Step #4: Compare each local maximum of ΔV_N with a threshold Th1, which may be of the order of the Nyquist velocity V_N. If ΔV_N < Th1, then assume that the change is not due to aliasing. Otherwise, it is due to aliasing, and correct it by $\pm 2V_N$ (by choosing a proper value of n) such that ΔV_N falls below Th1.

Step #5: A jump cannot have a magnitude more than $2V_N$+Th1. If it is found to be so, then that point is discarded, and the ΔV at the next radial point is considered as the candidate for checking for aliasing jump.

Step #6: Once an aliasing jump has been detected in a given sense (i.e $+2V_N$ or $-2V_N$), the next jump along the same radial has a low probability of being in the same direction. If such an occurrence is observed, special care must be taken. To gain further confidence that the two jumps are of natural origin, the aliasing jumps of the previous radial must be examined. The previous radial must have an aliasing jump between the two aliasing jump points of the current radial, or within a few range gates on either side of this interval.

Step #7: In general, the sense of the aliasing jumps (i.e. +1 for an increase in the order of the aliasing interval, and -1 for decrease) along a radial should add up to a small integer, typically 0 or ±1, rarely ±2. A value of ±2 should lead to the radial being flagged as suspect (with more careful data checks performed), and a magnitude higher than 2 should invalidate the data along the radial. Such a radial should not be used as a reference for the next radial.

These steps constitute only a skeletal procedure subject to further detailed flowcharting and development. The following discussion points are important for the understanding and development of the algorithm.

1. *Redundancy in Continuity Test*

Although radial continuity check is a simple method of determining jumps due to aliasing, a more reliable test for such jumps would be provided by a crosswise check, i.e. checking for an aliasing jump at a point both along radial and azimuthal directions. However, this will require a number of radials (perhaps 11 or, better, 21) to be stored. Also, the "current" radial being dealiased would be a few (5 to 10) radials behind the currently observed radial.

2. *Interpolating Curve and Fitting Algorithm*

It is necessary to discuss the nature of the curve used to interpolate data on either side of the jump being estimated, and the fitting procedure. *A priori*, it appears that a polynomial curve of second order should be adequate under most situations, but this may require modification as experience is gained. Further, the fitting should be on a least-mean-square-error (LMSE) basis, and be such that points closer to the current point get a higher weight, and farther points are progressively de-emphasized. Thus, the curve for point N should minimize the weighted square sum

$$\sum_{i=N}^{1} \{V_i - (a_0+a_1x_i+a_2x_i^2)\}^2 \exp(-kx_i) \qquad \text{(A2)}$$

where $x_i = (N-i)\Delta R$, ΔR being the range resolution.

Similarly, the curve for the point N+1 should minimize the weighted square sum

$$\sum_{i=N+1}^{N_{max}} \{V_i - (b_0+b_1x_i+b_2x_i^2)\}^2 \exp(-kx_i) \tag{A3}$$

where $x_i = \{i-(N+1)\}\Delta R$, and N_{max} is the number of resolution cells in the radial.

If an azimuthal continuity check is also done, then 5 to 10 radials on either side of the current radial may be considered, and a uniform weighting applied to all the azimuthal points at the same range.

The "fading factor" k determines how much the current point is weighted in preference to the farther points. To start with, k may be so chosen that $\exp(-5k\Delta R) = 0.5$, which means that the squared error of a point five range cells away from the current one is weighted half as much as the error at the current point. However, this fading factor would have to be optimized based on experience with actual data.

3. *Special Procedure Near the Ends of Data Runs*

Some discussion is also in order regarding the procedure to be adopted at the beginning and the end of radial data blocks, where there may not be sufficient backward (or forward) data points for polynomial fit. A second order polynomial requires a minimum of 3 points to be determinate, and five or more points to do any significant noise filtering. Thus, a clear starting procedure must be defined to deal with the first few (or last few) points along each radial. The procedure is as follows:

N=1 A polynomial fit is done only for the points N+1 onwards. ΔV_N is defined as $V'_{N+1} - V_N$.

N=2,3 The average of the two values V_N and V_{N-1} is defined as V'_N, and $\Delta V_N = V'_{N+1} - V'_N$. This is a zero-order fit for V_N and V_{N-1}.

N=4 A linear fit (first order fit) is made with the points N, N-1, N-2 and N-3, and discontinuity is defined by eq. (A1).

N>4 The normal procedure as outlined earlier is carried out.

The starting procedure is carried out in reverse at the end of the radial series of data.

APPENDIX B

DETERMINATION OF THE ABSOLUTE ALIASING INTERVAL

It is also necessary to comment on the determination of the absolute aliasing interval. A local Doppler velocity continuity check will resolve velocity ambiguities only in a relative sense, i.e. it will relate the "true" Doppler velocity after the discontinuity to that before the discontinuity in terms of a multiple of $2V_n$. However, if the assignment of the ambiguity interval to the Doppler velocity at the starting point in a given radial data run is incorrect by a certain number of aliasing intervals, then the entire run of contiguous data would be raised or lowered by the same number of intervals.

This generalized shift can be corrected in some situations by using the estimates of the environmental winds, as currently done. However, these estimates may not always be available, and even when they are available, the program may still not assign the correct ambiguity to starting points. Additional help for determining the absolute aliasing intervals of data fields or patches may be obtained by examining the global properties of sets of data points.

The simplest set of data points to examine are those along an entire radial. In a vast majority of all realistic weather fields, it may be assumed that the mean of the Doppler velocities over an entire radial of connected data extending up to the maximum range of WSR-88D would lie in the zeroth aliasing interval. Thus, after a radial has been locally (i.e. relatively) dealiased, the Doppler data along the entire radial are averaged, and if the average value is not located in the zeroth aliasing interval, then it is shifted by an appropriate number of aliasing intervals until it is located in the zeroth interval. All the Doppler values along that radial are then shifted up or down by the same amount as the mean value.

There may be situations where this procedure for absolute ambiguity determination is not adequate. This may happen when the true Doppler velocities along a radial are such that their mean does not actually fall within the zeroth aliasing interval. Such a situation can arise, for example, while looking tangentially into a large-scale high velocity phenomenon like a hurricane. The absolute velocities in this case can be determined by reference to the mean values of the previous radials. It is expected that the Doppler velocity mean values of successive radials would move gradually (with some noise) from one aliasing interval to the next. So in most situations, the mean Doppler velocity of a given radial would lie in the same aliasing interval as that of its previous radial. When the two do not lie in the same interval, they must be separated by a value close to $2V_n$. So a continuity/jump test similar to that in the radial direction can also be conducted in the azimuthal direction on the mean values of the radial Doppler velocities. Such a check should be relatively simple and robust, since the mean value of Doppler along a radial, being the average of a large number of data points, will be far less noisy than individual Doppler data. For this reason, a continuity check on radial mean values may not require a curve fitting procedure, but may be based on straight comparison of individual mean values.

Finally, the relative aliasing interval determination among adjacent radials would leave open the problem of fixing the absolute aliasing interval of the first radial. This can be solved by placing the mean Doppler velocity of the entire scan in the zeroth aliasing interval, if it is already not there. It must be cautioned that such a procedure will be reliable only in situations where the data points or patches in the radar scan are effectively contiguous.

A more difficult situation for absolute velocity dealiasing arises in cases of isolated storm patches separated by regions of no data (low SNR or range-overlaid data). In such cases, individual radials will be broken into runs of contiguous data points, each of which may be dealiased on the basis of a different aliasing interval than the other runs. For these cases, each run is treated like a separate radial and its absolute aliasing interval is decided on its average value being continuous with the corresponding run on the previous radial. However, it is not easy to fix the absolute aliasing interval of entire isolated patches through automatic means (without human intervention). A robust solution to this problem has not been found, and would require considerable study and computer program development. In particular, a systematic study is necessary to obtain the statistical behavior of the mean Doppler velocities of weather patches (as defined by SNR thresholding) of different sizes both in an absolute sense, and in relation to wind soundings with varying spatial and temporal separations relative to the radar scan under consideration.

APPENDIX C

PARAMETERS OF A TRIPLE PRF SCHEME FOR AMBIGUITY RESOLUTION

In a triple PRF scan scheme the first of the three scans would be used for generating reflectivity data with a large unambiguous range, and the last two, at two different PRFs, would be used to estimate the absolute (or unaliased) Doppler velocity values. It is necessary to suggest a logic for the selection of the two PRFs for optimal resolution of the velocity ambiguities.

The logic by which a two-PRF velocity dealiasing algorithm works is as follows. Let a certain true Doppler velocity V_t be observed as V_1 at a PRF f_1 and as V_2 at a PRF f_2. Let the two PRFs correspond to Nyquist velocities V_{n1} and V_{n2} respectively. Then

$$V_t = V_1 \pm 2n_1V_{n1}, \quad n_1 \text{ is a positive integer and } -V_{n1}<V_1\leq V_{n1} \qquad \text{(C1)}$$

and

$$V_t = V_2 \pm 2n_2V_{n2}, \quad n_2 \text{ is a positive integer and } -V_{n2}<V_2\leq V_{n2} \qquad \text{(C2)}$$

The dealiasing algorithm would work by trying to find out the values of n_1 and n_2 for which the equality

$$V_1 \pm 2n_1V_{n1} = V_2 \pm 2n_2V_{n2} \qquad \text{(C3)}$$

is satisfied. Since Doppler velocities in severe storms span values between ±60 m s^{-1} (Doviak and Zrnic', 1993), n_1 and n_2 are small integers, between 0 and 2 for Nyquist velocities of the order of 30 m s^{-1} and between 0 and 3 for Nyquist velocities in the neighborhood of 20 m s^{-1}, n_1 and n_2 can readily be determined by the computer through direct search (trial and error).

Under ideal conditions, it is possible to choose V_{n1} and V_{n2} such that n_1 and n_2 would be unique for any given V_t. This is done by ensuring that the least common multiple of V_{n1} and V_{n2} is higher than the highest magnitude of the Doppler velocity expected to be encountered.

In practice, however, the situation is more complicated by the presence of noise in the measurement of V_1 and V_2, which necessitates the equality to hold within a band, i.e.

$$|(V_1 \pm 2n_1V_{n1}) - (V_2 \pm 2n_2V_{n2})| < V_{th} \qquad \text{(C4)}$$

where V_{th} is the Doppler velocity error threshold, and is related to the uncertainty in the Doppler velocity estimate. This raises the possibility that n_1 and n_2 may not be unique. The probability of this happening increases with increase in V_{th}. On the other hand, a smaller V_{th} increases the chances that no small values of n_1 and n_2 may satisfy the inequality (C4). Each of these probabilities, for any given V_{th}, depends on the choice of V_{n1} and V_{n2} (i.e. PRFs f_1 and f_2), which must be carefully done.

A rigorous and formal procedure for the optimum choice of V_{n1} and V_{n2} is possible, but its solution will have to be numerical. To understand the process better, a heuristic approach is taken here for the choice of the two PRFs.

The main criteria for the choice of V_{n1} and V_{n2} are: (i) their least common multiple should be more than the expected maximum magnitude of the true Doppler velocity, and (ii) no integer multiple of V_{n1} should come close to any integer multiple of V_{n2} within the Doppler band of interest. For the parameters of WSR-88D, the two PRFs corresponding to the Nyquist velocities of 30 and 20 m s^{-1} (or close to them) would appear to be a good choice. This pair of frequencies would dealias Doppler velocities up to 60 m s^{-1}. If an even higher limit for dealiasing is desired, Nyquist velocities of 30 and 22.5 m s^{-1} may be chosen, which will dealias Doppler velocities up to 90 m s^{-1}. However, within this band this pair of velocities will make the algorithm more susceptible to noise effects than the (30,20 m s^{-1}) pair. For a maximum Doppler velocity of 48 m s $^{-1}$, which may be adequate for a majority of applications, the Nyquist velocity pair (24,16 m s^{-1}) would be a good combination. The very few high Doppler velocities that may be aliased with the unambiguous velocity of 48 m s^{-1} may be readily dealiased by using the continuity algorithm.

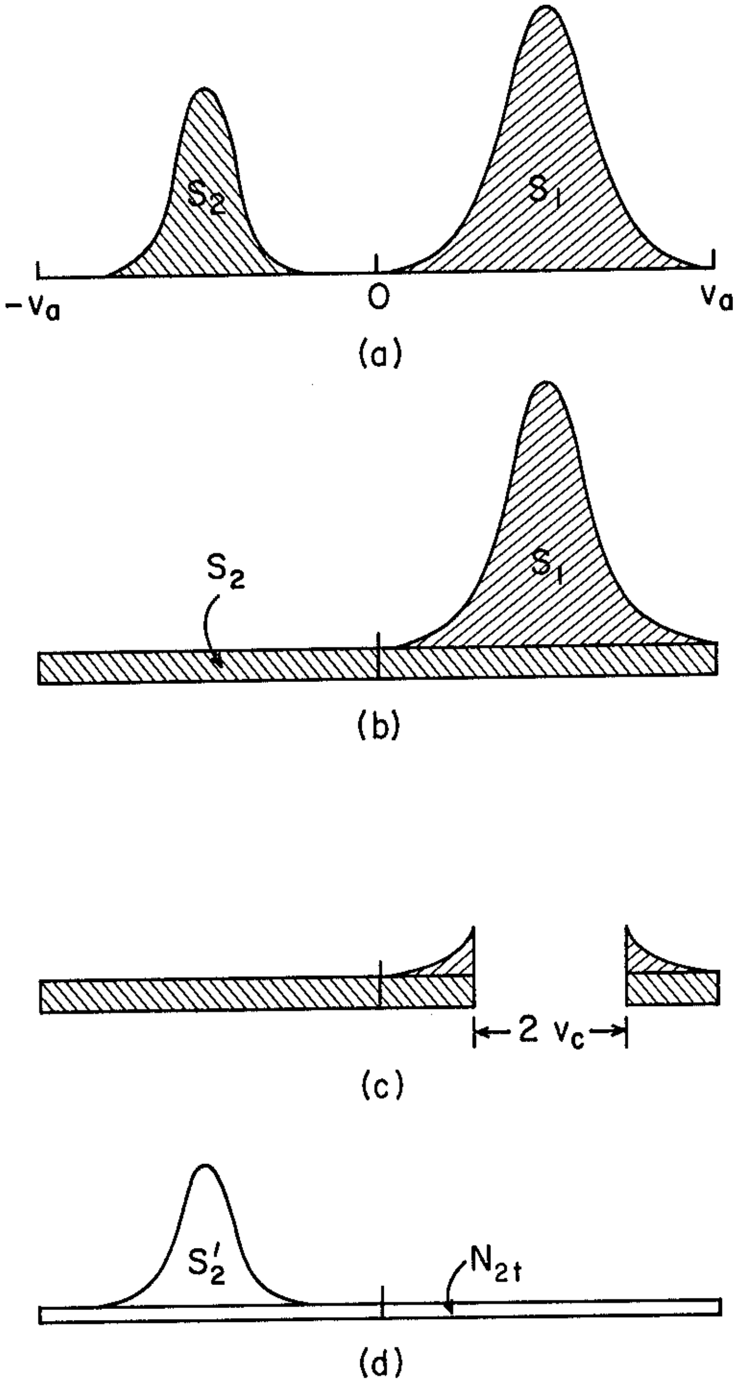
APPENDIX D

RANDOM PHASE TRANSMISSION TO RESOLVE AMBIGUITY

Details of signal processing in the random phase method are given in (Zrnic' and Mahapatra, 1985). Because of the importance of the method, the relevant paragraph of that paper is adapted and reproduced below.

It is first assumed that the total power in the signal that is coherent in the first trip is S_1, and the one coherent in the second trip is S_2 (see figure). For visual clarity, the spectra in the figure do not overlap, but this is not a requirement for the method to work. When the sequence is coherently processed for the first trip, the echoes from the second trip appear as white noise. Suppose that a band-rejection filter with a variable notch width $2V_c$ is centered on the spectrum of S_1. Then, after rejection, there will remain a noiselike residue of the signal S_1 denoted by N_{1r}, and a part of the desired signal S_2 will be filtered out. It can be shown that the effect of the filtering on S_2 is to attenuate it to a value S_2', and to generate (by random phase and amplitude modulation) a self-noise power N_2. So the added incoherent noise N_{2t}, after reconstruction of S_2', is the sum of self-noise and noise from the residue of S_1, i.e. $N_{2t} = N_{1r} + N_2$. The ratio of the signal (S_2') to the added noise (N_{2t}) can be obtained in closed form if the signal S_1 has a gaussian signal shape with a narrow width compared to the aliasing interval $2V_n$.

For a given spectrum width of each trip's echo signals (S_1 or S_2), and the power ratio S_1/S_2, there is a normalized notch width that will produce a maximum SNR for each recohered signal. This optimum notch width must be estimated from the signal parameters. A formal way of obtaining the optimum would be to set the derivative of the SNR with respect to the notch width equal to zero, substitute the estimated spectrum width of each



Rejection of overlaid echoes with random phase method. (a) Power spectra for overlaid first- and second-trip echoes of a fully coherent receiver, (b) Spectra of echoes for a receiver that is coherent for the first trip, (c) Spectra of (b) after bandpass filtering, and (d) Spectra of (c) after recohering second trip echoes.signal and their power ratio S_1/S_2, and solve for the filter notch width. However, such an elaborate procedure would impose considerable computational load, especially when implemented in real time for each of the numerous resolution cells in each scan. Further, the result may not be optimum when the spectra depart significantly from a Gaussian shape in the presence of noise. To make the problem tractable, it is necessary to find a heuristic way of determining the notch widths of the adaptive filters.

The adaptive filters can be derived from the FFT coefficients of the echo time series. The incoherent out-of-trip returns will appear in the spectral domain as a uniform (in the mean) noise added to the ambient and system noise level. The in-trip signal, when present with adequate SNR, will be superposed on this summed noise level, typically as a unimodal hump. The location of the signal spectrum can be assumed to coincide with the largest magnitude of the Fourier coefficient.

The simplest way to handle the filter notch width problem is to assume it to have a fixed width about the spectrum mean. The "adaptive" filter in this case would only have an adaptive center frequency, but fixed width. One candidate value for the fixed filter width could be 4 m s^{-1}, which is the median value of the Doppler spectral widths in severe storms (Doviak and Zrnic', 1993). However, in a majority of cases, especially in non-storm situations, the filter would cut out an unnecessarily large fraction of the randomized out-of-trip echo signal which, when recohered, will be correspondingly attenuated and possibly distorted.

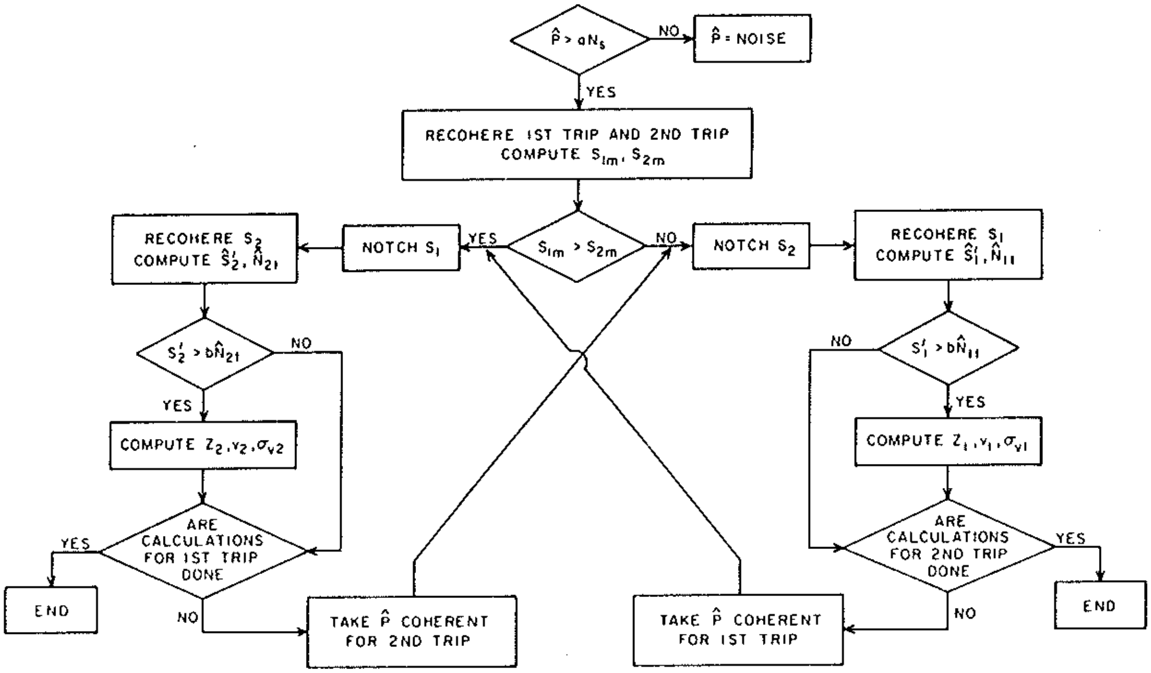
To obviate this difficulty, a scheme for signal-adaptive filter width, however simple, is recommended for the WSR-88D. The width can be obtained from the height of the signal spectrum, which may be assumed to be equal to the height of the largest Fourier coefficient minus the average noise pedestal.

The noise pedestal may be estimated by averaging all the Fourier coefficients falling outside a band of ±5 m s^{-1} from the largest coefficient. This band of 10 m s^{-1} is 2.5 times the median storm spectral width of 4 m s^{-1}. Once the spectrum height is estimated, a threshold is set relative to the peak. The contiguous set of Fourier coefficients that stay above the threshold determine the filter width. The value of the threshold relative to the spectral peak is a matter of conjecture at the present time. It appears that a threshold between 6 and 12 dB down from the peak should be close to the optimum. However, some further studies on real data need to be conducted to fine-tune the threshold value.

It is now necessary to fix the broad parameters of the random phase scheme, such as the PRT and the number of overlaid echoes to be separated. The most appropriate PRT for the WSR-88D would be the one that corresponds to an unambiguous range of 115 km. With such a PRT, the processing of 2 range intervals would cover the entire Doppler velocity range specification of 230 km for the system. The unambiguous range of 115 km would correspond to a Nyquist velocity of 32.6 m s^{-1} (at a transmitter frequency of 3,000 MHz) which is sufficiently large for a good velocity dealiasing algorithm to work reliably.

The WSR-88D, however, has a requirement to observe out to a range of 460 km for reflectivities alone. In principle, this entire range can be covered by the random phase transmission method with a basic unambiguous range of 115 km by processing echoes from four consecutive trips. However, the processing for four intervals would be quite complicated, and randomization of echo power from three trips would reduce the SNR for the coherent trip signal even more than the two-trip processing. Thus, it is recommended that the present WSR-88D scheme of devoting one full long-PRT scan at each of the two lower levels for reflectivity estimates be continued, and random phase transmission and processing be used only during the Doppler data scans.

The long-PRT scan can also be used to assign spectral moments to their appropriate range intervals. However, for those range locations where the long PRT indicates the presence of overlaid echoes in the first two trips, correct range association of moments can still be done using the echoes from the random-phase transmitted signal via the algorithm outlined in the accompanying flowchart (Zrnic′ and Mahapatra, 1985).



Flow diagram of procedure to estimate spectral moments. For simplicity, only data from first and second ambiguous trips are processed.