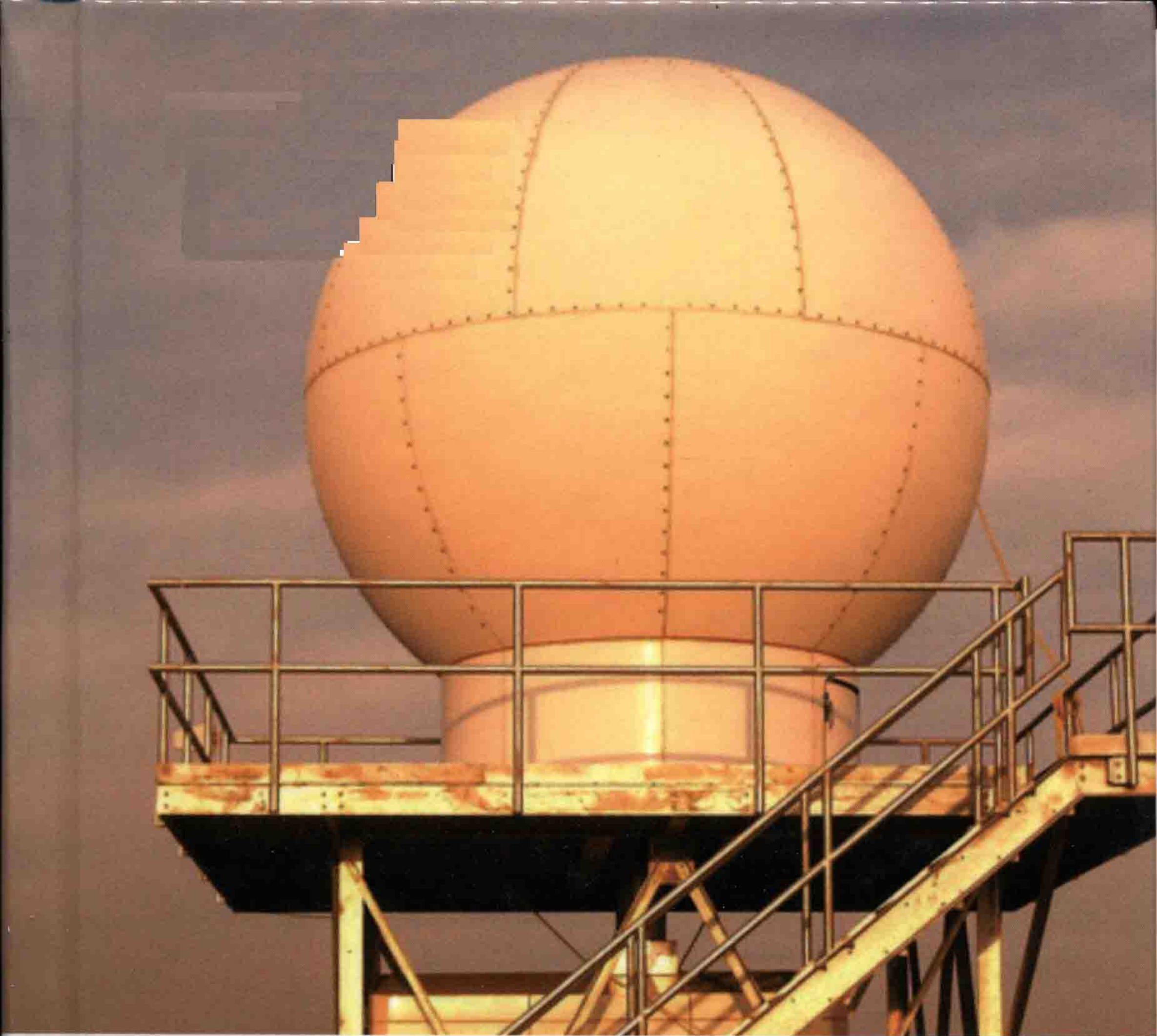

Handbook of Doppler Radar Observations

Henry Collier

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Edited by **Henry Collier**

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Preface

Doppler radar systems have been extremely helpful in enhancing our perception and monitoring capabilities of atmospheric phenomenon. Scientists and practitioners are using its methods and radio detecting and finding techniques, like wind profilers and others, frequently for analysis and operations. Some of the topics discussed in this book are - extreme weather supervision, wind and turbulence retrievals, estimation of precipitation and nowcasting, and the volcanological applications of Doppler radar. This book is appropriate for graduate students who are seeking an initiation in the area or for experts wanting to refresh their knowledge and information on the same.

This book unites the global concepts and researches in an organized manner for a comprehensive understanding of the subject. It is a ripe text for all researchers, students, scientists or anyone else who is interested in acquiring a better knowledge of this dynamic field.

I extend my sincere thanks to the contributors for such eloquent research chapters. Finally, I thank my family for being a source of support and help.

Editor

Handbook of Doppler Radar Observations

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Part 1

Doppler Radar and Weather Surveillance

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Doppler Radar for USA Weather Surveillance

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1. Introduction

Weather radar had its beginnings at the end of Word War II when it was noticed that storms clutter radar displays meant to reveal enemy aircraft. Thus radar meteorology was born. Until the sixties only the return power from weather tracers was measured which offered the first glimpses into precipitation structure hidden inside clouds. Possibilities opened up to recognize hail storms, regions of tornadoes (i.e., hook echoes), the melting zone in stratiform precipitation, and even determine precipitation rates at the ground, albeit with considerable uncertainty.

Technology innovations and discoveries made in government laboratories and universities were quickly adopted by the National Weather Service (NWS). Thus in 1957 the Miami Hurricane Forecast Center commissioned the first modern weather radar (WSR-57) the type subsequently installed across the continental United States. The radar operated in the 10 cm band of wavelengths and had beamwidth of about 2^{o}. In 1974 more radars were added: the WSR-74S operating in the band of 10 cm wavelengths and WSR-74C in the 5 cm band.

Development of Doppler radars followed, providing impressive experience to remotely observe internal motions in convective storms and infer precipitation amounts. Thus scientists quickly discovered tell tale signatures of kinematic phenomena (rotation, storm outflows, divergence) in the fields of radial velocities.

After demonstrable successes with this technology the NWS commissioned a network of Doppler radars (WSR-88D=Weather Surveillance Radars, year 1988, Doppler), the last of which was installed in 1997. Much had happened since that time and the current status pertinent to Doppler measurements and future trends are discussed herein.

The nineties saw an accelerated development of information technology so much so that, upon installation of the last radar, computing and signal processing capabilities available to the public were about an order of magnitude superior to the ones on the radar. And scientific advancements were still coming in strong implying great improvements for operations if an upgrade in processing power were to be made. This is precisely what the NWS did by continuing infusion of the new technology into the system. Two significant upgrades have been made. The first involved replacement of the computer with distributed workstations (on the Ethernet in about 2002) for executing algorithms for precipitation estimation, tornado detection, storm tracking, and other. The second upgrade (in 2005) brought in fully programmable signal processor and replaced the analogue receiver with the digital receiver. In 2009 the NWS started the process of converting the radars to dual polarization which should be accomplished by mid 2013.

The number of radars used continuously for operations is 159 and there are two additional radars for other use. One is for supporting changes in the network brought by infusion of new science or caused by deficiencies in existing components (designated KCRI in Norman, OK). The evolution involves both hardware and software and the update in the former are typically made annually. The other (designated KOUN in Norman, OK, USA) is for research and development. Therefore its configuration is more flexible allowing experimental changes in both hardware and software.

Conference articles and presentation about the WSR-88D and its data abound and there are few descriptions of its basic hardware. Very recent improvements are summarized by Saxion & Ice (2011) and a look into the future is presented in Ice & Saxion (2011). Yet only few journal articles describing the system have been published. The one by Heiss et al. (1990) presents hardware details from the manufacturer's point of view. The paper by Crum et al. (1993) describes data and archiving and the one by Crum & Alberty (1993) contain valuable information about algorithms. The whole No. 2 issue of Weather and Forecasting (1998), Vol. 13 is devoted to applications of the WSR-88D with a good part discussing products that use Doppler information. A look at the network with the view into the future is summarized by Serafin & Wilson (2000).

As twenty years since deployment of the last WSR-88D is approaching there are concerns about future upgrades and replacements. High on the list is the Multifunction Phased Array Radar (MPAR). At its core is a phased array antenna wherein beam position and shape are electronically controlled allowing rapid and adaptable scans. Thus, observations of weather (Zrnic et al., 2007) and tracking/detecting aircraft for traffic management and security purposes is proposed (Weber et al., 2007). Another futuristic concept is exemplified in proposed networks for Cooperative Adaptive Sensing of the Atmosphere (CASA) consisting of low power 3 cm wavelength phased array radars (McLaughlin et al., 2009).

Very few books on weather radar have been written and most include Doppler measurements. Here I list some published within the last 20 years. The one by Doviak & Zrnic (2006) primarily concentrates on Doppler aspects and contains information about the WSR-88D. The book by Bringi & Chandrasekar (2001) emphasizes polarization diversity and has sections relevant to Doppler. Role of Doppler radar in aviation weather surveillance is emphasized in the book by Mahapatra (1999). The compendium of chapters written by specialists and edited by Meishner (2004) concentrates on precipitation measurements but has chapters on Doppler principles as well as application to severe weather detection. Radar for meteorologists (Rinehart, 2010) is equally suited for engineers, technicians, and students who will enjoy its easy writing style and informative content.

2. Basic radar

The surveillance range, time, and volumetric coverage are routed in practical considerations of basic radar capabilities and the size and lifetimes of meteorological phenomena the radar is supposed to observe. This is considered next.

2.1 Considerations and requirements for storm surveillance

Table 1 lists the radar parameters with which the surveillance mission is supported. Discussions of the reasons behind choices in volume coverage and other radar attributes of the WSR-88D network, with principal emphasis on Doppler measurements, follows.

Requirement	Values
Surveillance:	
Range	460 km
Time	< 5 min
Volumetric coverage	hemispherical
SNR	> 0 dB, for Z= - 8 dBZ at r=50 km (exceeded by ~5 dB)
Angular resolution	$\leq 1^{\circ}$
Range sampling interval:	
For reflectivity	$\Delta r \leq 1$ km; $0 < r \leq 230$ km; $\Delta r \leq 2$ km; $r \leq 460$ km
For velocity	$\Delta r = 250$ m
Estimate accuracy:	
Reflectivity	≤1 dB; SNR>10 dB; $\sigma_v = 4$ m s^{-1}
Velocity	≤1 m s^{-1}; SNR> 8 dB; $\sigma_v = 4$ m s^{-1}
Spectrum width	≤1 m s^{-1}; SNR>10 dB; $\sigma_v = 4$ m s^{-1}

Table 1. Requirements for weather radar observations.

2.1.1 Range

Surveillance range is limited to about 460 km because storms beyond this range are usually below the horizon. Without beam blockage, the horizon's altitude at 460 km is 12.5 km; thus only the tops of strong convective storms are intercepted. Quantitative measurements of precipitation are required for storms at ranges less than 230 km. Nevertheless, in the region beyond 230 km, storm cells can be identified and their tracks established. Even at the range of about 230 km, the lowest altitude that the radar can observe under normal propagation conditions is about 3 km. Extrapolation of rainfall measurements from this height to the ground is subject to large errors, especially if the beam is above the melting layer and is detecting scatter from snow or melting ice particles.

2.1.2 Time

Surveillance time is determined by the time of growth of hazardous phenomena as well as the need for timely warnings. Five minutes for a repeat time is sufficient for detecting and confirming features with lifetime of about 15 min or more. Typical mesocyclone life time is 90 minutes (Burgess et al., 1982). Ordinary storms last tens of minutes but microbursts from these storms can produce dangerous shear in but a few minutes. Similarly tornadoes can rapidly develop from mesocyclones. For such fast evolving hazards a revisit time of less than a minute is desirable but not achievable if the whole three dimensional volume has to be covered. The principal driver to decrease the surveillance time is prompt detection of the tornadoes so that timely warning of their presence can be issued. Presently, the lead time for tornado warnings (i.e., the time that a warning is issued to the time the tornado does damage) is about 12 minutes (see Section 5).

2.1.3 Volumetric coverage

The volume scan patterns currently available on the WSR-88D have maximum elevations up to 20° and many are accomplished in about 5 minutes. Meteorologists have expressed a desire to extend the coverage to higher elevations to reduce the cone of silence. It is fair to state that the 30° elevation might be a practical upper limit for the WSR-88D. Top elevations higher than 20° have not been justified by strong meteorological reasons.

2.1.4 Signal to noise ratio

The SNR listed in Table 1 provides the specified accuracy of velocity and spectrum width measurements to the range of 230 km for both rain and snowfall rates of about 0.3 mm of liquid water depth per hour. That is, at a range of 230 km the SNR is larger than 10 dB thus the accuracy of Doppler measurements to shorter ranges is independent of noise and solely a function of number of samples and Doppler spectrum width.

2.1.5 Spatial resolution

The angular resolution is principally determined by the need to resolve meteorological phenomena such as tornados and mesocyclones to ranges of about 230 km, and the practical limitations imposed by antenna size at wavelength of 0.1 m. Even though beamwidth of 1° provides relatively high resolution, the spatial resolution at 230 km is 4 km. Because the beam of the WSR-88D is scanning azimuthally, the effective angular resolution in the azimuthal direction is somewhat larger (Doviak & Zrnic, 2006, Section 7.8); typically, about 40% at the 3 RPM scan rates of the WSR-88D. This exceeds many mesocyclone diameters, and thus these important weather phenomena, precursors of many tornadoes, can be missed. Tornadoes have even smaller diameters and therefore can not be resolved at the 230 km range.

The range resolution is indirectly influenced by the angular resolution; there is marginal gain in having range resolution finer than the angular one. For example better range resolution can provide additional shear segments and therefore improve detection of vortices at larger distance. The range resolution for reflectivity is coarser for two reasons: (1) reflectivity is principally used to measure rainfall rates over watersheds which are much larger than mesocyclones and (2) reflectivity samples at a resolution of 250 m are averaged in range (Doviak & Zrnic, 2006, Section 6.3.2) to achieve the required accuracy of 1 dB.

2.1.6 Precision of measurements

The specified 1 dB precision of reflectivity measurements (Table 1) provides about a 15% relative error of stratiform rain rate (Doviak & Zrnic, 2006, eq 8.22a). This has been accepted by the meteorological community. The specified precisions of velocity and spectrum width estimates are those derived from observations of mesocyclones with research radars. The 8 dB SNR is roughly that level beyond which the precision of velocity and spectrum width estimates do not improve significantly (Doviak & Zrnic, 2006, Sections 6.4, 6.5). But, it is possible that lower precisions can be tolerated and benefits can be derived therefrom. For example, it has been proposed (Wood et al., 2001) that velocity estimates be made with less samples (e.g., by a factor of two) in order to improve the azimuthal resolution. Although this increases the error of the Doppler velocity estimates by the square root of two, the improved angular resolution can increase the range, by about 50% (Brown et al., 2002 and 2005), to which mesocyclones and violent tornadoes can be detected. Therefore in the recently introduced scanning patterns, the data (i.e., spectral moments) are provided at 0.5° increments in azimuth (Section 3.5).

2.2 Radar operation

The essence of the hardware (Fig. 1) is what radar operators see on the console. To the left of the data link (R,V,W,D) is the radar data acquisition (RDA) part consisting of the transmitter, antenna, microwave circuits, receiver, and signal processor. These components are located at radar site and data is transmitted to the local forecast office (LFO) where Radar Product Generation (RPG, Fig. 1) takes place. Operators at the LFO control (the block Control in Fig. 1) the radar and observe/analyze displays of data fields. At a glance of a console they can see the operating status of the radar and data flow. In the RPG the data is transformed into meteorologically meaningful information (Products in Fig. 1) by algorithms executed on Ethernet cluster of workstation.

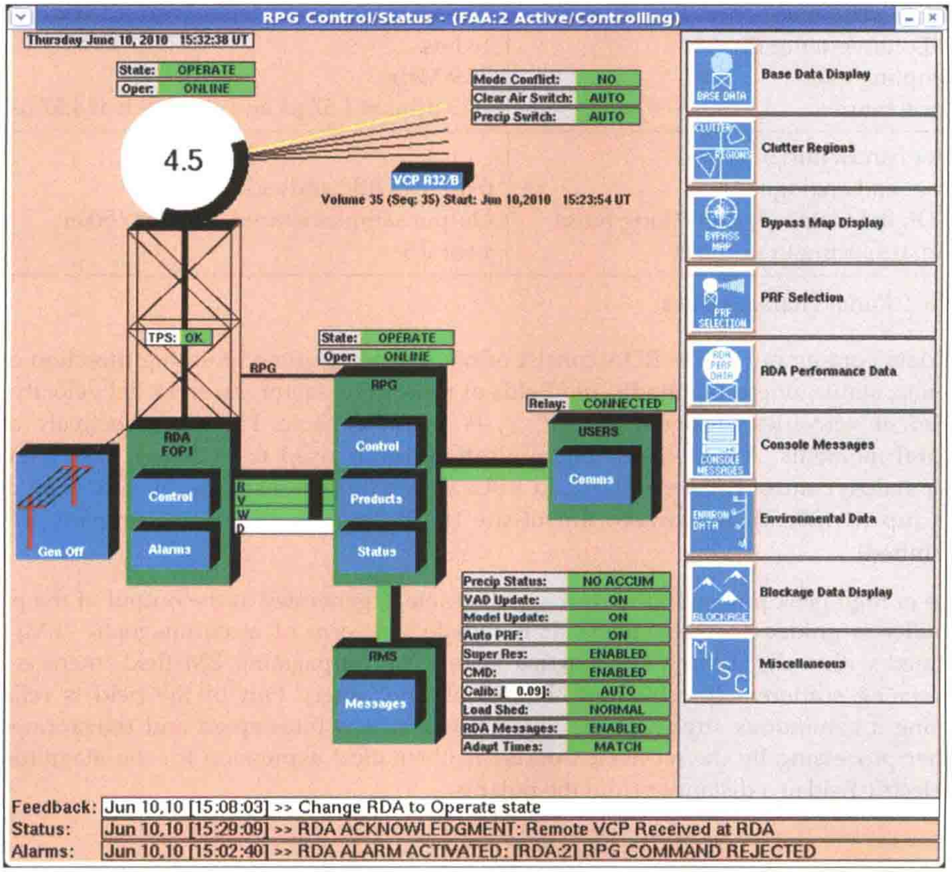

Fig. 1. Block diagram of the WSR-88D seen on the console of operators.

The radar is fully coherent pulsed Doppler and pertinent parameters are listed in Table 2 (see also Doviak & Zrnic, 2006 page 47). Each radar is assigned a fixed frequency in the band (Table 2), hence some values like the beamwidth and unambiguous velocities (not listed) depend on the exact frequency.

Frequency	2.7 to 3 GHz
Beamwidth	1°
Antenna gain	44.5 to 45.5 dB
Transmitter:	
Pulse power	750 kW
Pulse width	1.57 μs and 4.57 μs
Rf duty cycle	0.002
PRFs (Hz, 5 sets of 8, variation ~3%)	322, 446, 644, 857, 1014, 1095, 1181, 1282
Unambiguous range (km)	466, 336, 233, 175, 148, 137, 127, 117
Receiver linear:	
Dynamic range	94 dB at 1.57 μs pulse and 99 dB at 4.57 μs
Intermediate frequency (IF)	57.6 MHz
A/D converter at IF	14 bits
Sampling rate	71.9 MHz
Noise figure	-113 dBm at 1.57 μs and -118 dBm at 4.57 μs
Filter bandwidth or type:	
Front end analogue	6 MHz (3 dB bandwidth)
IF Digital matched, short/long pulse	Output samples spaced at 250 m/500m
Radial spacing in azimuth	1° or 0.5°

Table 2. Radar characteristics.

The data coming out of the RDA consist of housekeeping (time, pointing direction of the antenna, status, operating mode, and fields of reflectivity factor, mean radial velocity, and spread of velocities (designated as R, V, W in the console, Fig. 1), collectively called spectral moments. A wideband communication link is used to exchange base data and radar status/control between RDA and RPG. Depending on distance this link is by direct wire (up to 120 m), microwave line-of-site (to 38 km), or telephone company T1 line (unlimited).

Pulse of high peak power and narrow width (Table 2) generated at the output of the power amplifier is guided to the antenna. It is radiated in form of electromagnetic (EM) field confined within the narrow (1°) antenna beam. The propagating EM field interacts with intervening scatterers (precipitation, biological, and other). Part of the field is reflected forming a continuous stream at the antenna where it is intercepted and transformed for further processing by the receiver. Concise mathematical expression for the magnitude of the electric field at a distance r from the radar is

$$E=\left[\frac{P_a\eta}{\pi}\right]^{1/2}\frac{f(\theta,\phi)}{2r}\cos\left[2\pi f\left(t-\frac{r}{c}\right)+\psi_t\right]U(t-r/c), \quad (1)$$

where P_a is the power radiated by the antenna, r is the distance, $f(\theta,\phi)$ is the antenna pattern function (one way voltage), η is the free space impedance ($120\pi\ \Omega$), c speed of light, f radar frequency, and ψ_t arbitrary phase at the antenna. $U(t-r/c)$ designates the pulse function such that it is 1 if its argument is between 0 and τ (the pulse width).

2.2.1 Radar signal and Doppler shift

The effective beam cross section and pulse width define the intrinsic radar resolution volume but processing by the receiver increases it in range. Scatterers (hydrometeors such as rain, hail, snow and also insects, birds etc.,) within the resolution volume contribute to the backscattered electric field which upon reception by the antenna is transformed into a microwave signal. The signal is converted to an intermediate frequency f_{if} then passed through anti-alias filter (nominal passband ~ 14 MHz), digitized (as per Table 2), and down converted to audio frequencies (base band) for further processing.

At intermediate frequency the signal coming from a continuum of scatterers can be represented as $A(t)\cos(\omega_{if}t+\omega_d t)$ where the amplitude $A(t)$ fluctuates due to contribution by scatterers and ω_d is the instantaneous Doppler shift caused by their motions toward (positive shift) and/or away (negative shift) from the radar. To determine the mean sense of motion (sign of Doppler shift) the intermediate frequency is removed and the signal is decomposed into its sinusoidal and cosinusoidal components, the inphase I and quadrature phase Q parts. These carry information about the number and sizes of scatterers as well as their motion. Samples of I and Q components are taken at consecutive delays with respect to the transmitted pulse. The delays are proportional to the range within the cloud from which the transmitted pulse is reflected. Samples from the same range locations (delays) are combined to obtain estimates of the spectral moments: reflectivity factor Z, mean Doppler velocity v, and spectrum width σ_v (Doviak & Zrnic, 2006). The Doppler velocity v is related to the frequency shift f_d and wavelength λ via the Doppler equation

$$f_d = 2v/\lambda, \tag{2}$$

and so is the spectrum width.

Radars display (and store) equivalent reflectivity factor (often denoted with Z_e) which is computed from the power and other parameters in the radar equation (Doviak & Zrnic 2006) assuming the scatterers have refractive index of liquid water. For small (compared to wavelength) spherical scatterers, Z_e expressed as function of the distribution of sizes $N(D)$, equals

$$Z_e = \int_0^{D_{max}} N(D)D^6 dD. \tag{3}$$

2.2.2 Processing path from signals to algorithms

Top left part in Fig 2 illustrates the continuum of returns (either I or Q), after each transmitted pulse from 1,...to M. Thus M samples at a fixed range delay (double vertical line) are operated on in various ways to produce estimates. There are as many estimates along range time as there are samples. That is, sample spacing is typically equal to pulse duration and therefore consecutive samples are almost independent. Closer sampling (i.e., oversampling) has some advantages (Section 4.2).

Radials of spectral moments are transmitted to the RPG (a radial of velocities is in the top right part of Fig. 2). Spectral moments are displayed at Weather Forecast Offices, are recorded, and are also processed by algorithms to automatically identify hazardous weather features, estimate amounts of precipitation, and to be used in numerical models among other applications. Example displayed in Fig. 2 (right bottom) is the field of Doppler velocities obtained by the WSR-88D in Dove, North Carolina during the Hurricane Irene on Aug 28th, 2011 at 2:29 UTC. The end range on the display is 230 km which is also the range up to which quantitative measurements are currently being made. Extension to 300 km is planned.

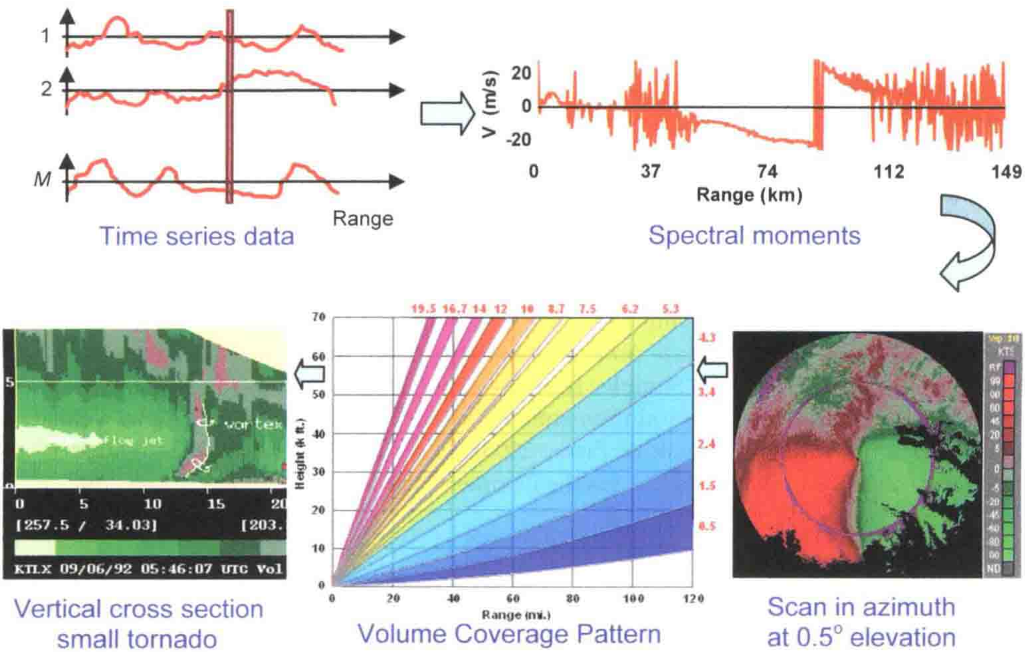

Fig. 2. Information path from time series to output of algorithms.

The radar is sufficiently sensitive to detect precipitation at much larger ranges where the beamwidth and observations high above ground mar quantitative interpretation of impending weather on the ground. At the elevation of 0.5°, the radar makes two scans: one with the longest PRT (3.1 ms) for estimating reflectivities unambiguously up to 465 km in range, the other with one of the short PRTs to estimate unambiguously velocity over a sufficiently large span. The ambiguities in range and velocity are inherent to pulsed Doppler radars. Reflections from scatterers spaced by the unambiguous range ($r_a = cT_s/2$ where T_s is pulse repetition time) appear at the same delay with respect to the reference time (determined by the last of two transmitted pulse). Obvious increase in range can be made by increasing T_s. And this is fine for measurements of reflectivity but would harm measurements of velocity. At the 10 cm wavelength Doppler velocities are