

Use of radar wind profilers in operational networks

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ABSTRACT

Ground-based remote measurements of the vertical profile of the horizontal wind vector in the atmosphere by radar wind profiler (RWP) is a technique that has been significantly developed since the first demonstration with the Jicamarca radar by Woodman and Guillen in the early 1970s. Currently, there exist several operational networks of those instruments in the USA, Europe and Japan which provide continuous wind measurements in real-time and most of the data are successfully assimilated in numerical weather prediction models (NWPM). The main advantage of RWP's is their ability to provide vertical profiles of the horizontal wind at high temporal resolution under almost all weather conditions, that is in both the cloudy and the clear atmosphere. No other remote sensing instrument has this property. Comparisons have shown that the accuracy of the wind measurement of a well-operated and -maintained RWP is at least comparable to the accuracy of Radiosonde wind data. While this is already an obvious indication of maturity, further improvements of the instruments seem to be possible. After a short overview of physical and technical fundamentals, the paper will discuss a few important practical aspects of the operational application of RWP's.

1. Introduction

The current Global Observing System (GOS) for the atmosphere consists of a mix of ground and space based components, with a large part of them being remote sensing instruments. For ground based remote sensing systems, radar wind profilers (RWP) are among the most thoroughly developed and widely used sensors. As the name implies, they are special Doppler radars designed for measuring the vertical profile of the wind vector in the lowest 5 - 20 km of the atmosphere (depending on the operating frequency), on timescales ranging from seconds to years. RWP's are also able to provide additional information about the atmospheric state through the profiles of backscattered signal intensity and frequency spread (spectral width) of the echo signal. In contrast to the automated wind measurement, however, such data need still to be carefully analyzed by instrument experts due to the complexity of the measurement process. Comprehensive reviews of the technical and scientific aspects of RWP have been provided by Gage (1990); Röttger and Larsen (1990); Doviak and Zrnić (1993); Ackley et al. (1998); Muschinski (2004) and recently Fukao (2007). For a successful operational application of RWP's, a number of practical aspects need to be considered which are usually not discussed in the scientific literature. But at first it is useful to get a short overview of the fundamentals.

2. RWP fundamentals

2.1. Scattering mechanisms

A good starting point for reviewing the capabilities and potential problems of the RWP technology is provided by a consideration of both the physical fundamentals and the technical constraints. The unique characteristic of RWP is their use of longer wavelengths, in comparison with classical weather radars. The typical wavelength range is from about 20 cm (L-Band) to about 6 m (VHF). Electromagnetic waves in this range are scattered at fluctuations of the refractive index of particle-free 'clear air' which are almost omnipresent due to the turbulent state of the atmosphere. This effect is called *clear-air scattering*, it can be fully understood only on the basis of the theory of radio-wave propagation through the turbulent atmosphere. This theory, pioneered by V. Tatarskii, is a synthesis of Maxwell's classical Electrodynamics and Kolmogorov's statistical turbulence theory, see e.g. Tatarskii (1971); Muschinski (2004).

While this physical effect is the main reason for calling RWP's also clear-air radars, there are also other scattering processes, which need to be taken into account when dealing with RWP's in practice. The following scattering and echoing mechanisms are observed in reality:

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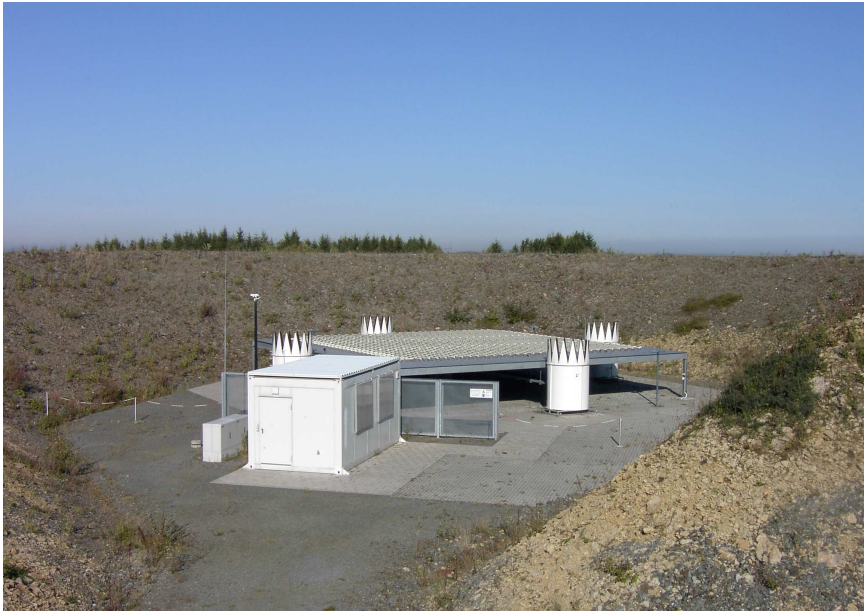


Figure 1. Photograph of the 482 MHz RWP installation at Bayreuth (Germany), showing the antenna array platform surrounded by four acoustic sources for RASS and the shelter containing the radar electronics.

- Scattering at refractive index inhomogeneities (clear air scattering)
- Scattering at particle ensembles (hydrometeors, like rain or snow)
- Scattering at plasma in lightning channels
- Echoes from airborne objects
- Echoes from the ground surrounding the RWP (through antenna sidelobes)

Most relevant for RWP is certainly clear-air or **Bragg scattering** at fluctuations of the refractive index, see e.g. Ottersten (1969a,b); Gossard et al. (1982); Gossard and Strauch (1983); Chadwick and Gossard (1984). The intensity of the scattered wave is usually very small and the power level of the received signal is often close to the sensitivity limit of the radar receiver, which is typically well below -150 dBm (10^{-18} Watt). Highly sensitive receivers and large antennas are therefore required for RWP's.

The second major scattering process for RWP is scattering at small particles, like droplets or ice crystals. Here, the Rayleigh approximation can be easily used for simplification, because the particle diameter is always much smaller than the wavelength. The whole process is then termed **Rayleigh scattering** (Gossard and Strauch, 1983; Oguchi, 1983; Kropfli, 1984; Doviak and Zrnić, 1993). Bragg and Rayleigh scattering are the main atmospheric scattering processes for RWP for most applications. Of course, the wavelength dependence of Rayleigh scattering leads to different relative contributions, i.e. particle scattering is much stronger at L-Band than at VHF.

If the RWP system is equipped with an additional Radio-Acoustic Sounding System (RASS) component, then measurements of the vertical profile of the virtual temperature are also possible through the generation of sound waves that act as an artificial radar target. RASS will not be discussed in this paper, more information can be found in Peters et al. (1993); Lataitis (1993); Görsdorf and Lehmann (2000).

The remaining scattering or echoing mechanisms are considered as clutter, that is unwanted echoes. The high sensitivity of wind profilers makes them obviously vulnerable in that respect. Scattering at the plasma in lightning channels is sometimes observed with RWP (Petitdidier and Laroche, 2005), but it is no issue for practical wind profiling due to the

extremely short lifetime of the echoes, which mostly contribute to a higher noise level. Ground clutter echoes for RWP are more relevant, they are often observed due to ubiquitous sidelobes of finite aperture antennas and the high receiver sensitivity (Woodman and Guillen, 1974; Balsley et al., 1977; Farley et al., 1979; Ogura and Yoshida, 1981; Sato and Woodman, 1982; Woodman, 1985; Martner et al., 1993; May and Strauch, 1998). Also, scattering at larger flying objects like airplanes (Hogg et al., 1983; Strauch et al., 1984; Farley, 1985; Hocking, 1997) or birds (Barth et al., 1994; Wilczak et al., 1995; Engelbart et al., 1998) is sometimes observed and it can hardly be denied that such effects can become very relevant at times in operational applications. To avoid measurement errors due to misinterpretation of clutter echoes as atmospheric returns, all these effects need to be identified and filtered during an early stage of signal processing, if it is impossible to avoid them through hardware measures.

2.2. Radar hardware

Depending on their particular hardware architecture, RWP can be classified into three main groups (Muschinski et al., 2005). **Single signal systems** are the most frequently used wind profiler type (Law et al., 2002; Steinhagen et al., 1998; Engelbart et al., 1996; Carter et al., 1995; Ecklund et al., 1988; Strauch et al., 1984). They are monostatic pulse radars using one single carrier frequency with the hardware architecture resembling that of a typical Doppler radar system. The term single signal refers to the characteristics of the instruments sampling function, which can be regarded as an integral kernel function that maps a field describing the physical properties of the atmosphere relevant for the actual scattering process to the received radar (voltage or current) signal. For clear-air scattering, this is the scalar field of the refractive index (or permittivity) irregularities.

Two signal systems are extensions of the single signal architecture, where basically two different sampling functions are realized to improve the retrieval of atmospheric properties of interest. The two techniques that have been used are the frequency-domain interferometry (FDI) using a monostatic radar with two different carrier frequencies (Kudeki and Stitt, 1987; Chilson et al., 1997) and the spaced-antenna technique using one carrier frequency and multiple receiving antennas (Lataitis et al., 1995; Doviak et al., 1996).

Recently, **multi-signal systems** have been developed and tested. They either use a bistatic combination of a single transmit and a multitude of receiving antennas to perform digital beamforming (Mead et al., 1998; Pollard et al., 2000; Helal et al., 2001) or they transmit several carrier frequencies to achieve so-called range imaging (RIM) with a single (monostatic) antenna (Palmer et al., 1999; Luce et al., 2001; Smaïni et al., 2002; Chilson et al., 2003; Chilson, 2004). Much work remains to be done to further develop, understand and use this obviously most complex and demanding radar architecture.

In the following, the discussion will be restricted to single signal RWP systems, in particular to the 482 MHz instruments used in the operational network of the DWD (Lehmann et al., 2003). A photograph of a 482 MHz RWP/RASS system is shown in Fig. 1 and the technical parameters are given in Table 1.

The block diagram of the hardware is given in Fig. 4. The central unit is the radar controller, which uses a highly stable coherent oscillator as the single reference for all signals. It generates all control signals needed to operate the radar through Direct Digital Synthesis (DDS). The electromagnetic pulse to be transmitted is created by a waveform generator which acts essentially as an amplitude and phase modulator. After a frequency up-conversion and amplification (through a linear power amplifier), the transmit signal is delivered to the antenna and the resulting electromagnetic wave is radiated into free space. As the same antenna is also used for signal reception, a duplexer is necessary to protect the sensitive receiver electronics from the strong transmit signal. It is typically comprised of a ferrite circulator and additional receiver protecting limiters.

The antenna used in the 482 MHz profilers is a relatively simple passive phased array comprised of coaxial-collinear (CoCo) elements (Law et al., 2003; Balsley and Ecklund, 1972). A relay-switched true-time delay phase shifting unit generates the necessary phasing of the individual elements required to steer the beam in three fixed directions for each CoCo sub-array, as shown on the right hand side of Fig. 2. For the five-beam pointing configuration indicated in Fig. 6, two such CoCo sub-arrays are combined. Due to the finite extent of the antenna array, the beam can not be made infinitely narrow. This results in unwanted radiation through so-called sidelobes in other than the boresight direction and can be visualized through the antenna radiation pattern, which shows the distribution of the total radiated power P as a function of spherical antenna coordinates θ and ϕ . Fig. 3 shows the ideal radiation pattern for the DWD 482 MHz network wind profiler calculated with the method of Law et al. (1997). Note that the sidelobe level will be somewhat more irregular and

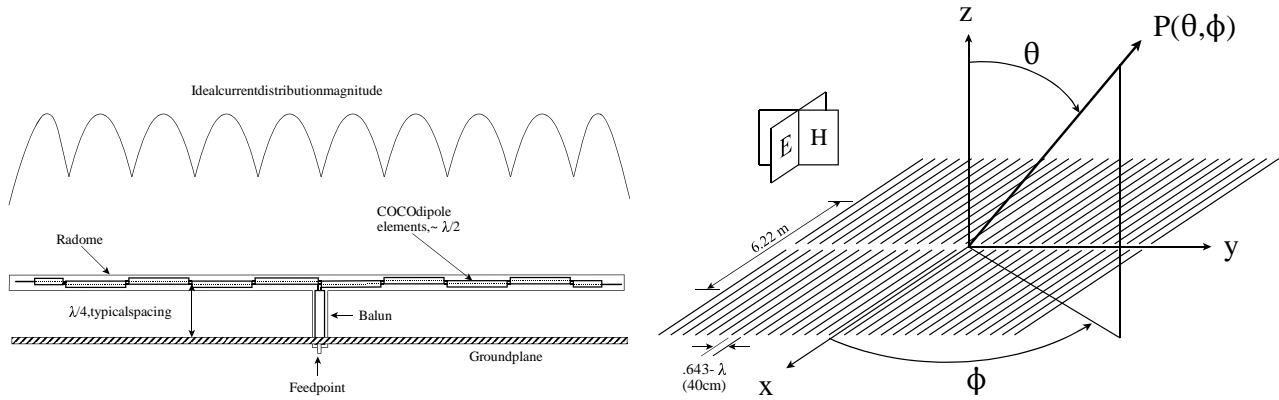


Figure 2. Single coaxial-collinear antennas with ideal current amplitude distribution (left) and array arrangement (right). A planar CoCo array generates a linear polarized electromagnetic wave, with the electric and magnetic field vector oscillating in the so-called E-plane or H-plane, respectively. The antenna beam is steerable in the H-plane through a different phasing of the CoCo lines. (Graphics courtesy of D.C. Law.)

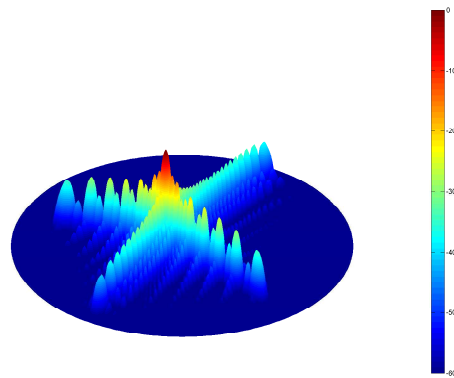


Figure 3. Surface plot of the ideal normalized antenna radiation pattern $|P(\theta, \phi)|^2/P_0$ in logarithmic scaling (dB) for an oblique beam of the 482 MHz RWP.

higher in reality because of stochastic excitation differences of array elements due to hardware imperfections (Mailloux, 1994).

The receiver is of the classical superheterodyne type (Tsui, 1989). A rather broadband low-noise amplifier with an excellent noise-figure is necessary to raise the signal level of the weak atmospheric return for further processing. After frequency down-conversion to an intermediate frequency (IF), the signal is bandpass-filtered, demodulated and A/D converted for further digital processing in the radar processor. To maximize the per-pulse signal-to-noise ratio (SNR) for optimal signal detection, the bandwidth of the bandpass filter is matched to the transmitted pulse (Zrnić and Doviak, 1978). Actual technical implementations differ, for example the received signal can be digitized either at IF (so called digital IF receivers) or at base-band, after further analog down-conversion by a quadrature detector (analog receiver).

2.3. Signal processing

The purpose of RWP signal processing is to convert the measured electrical signal to meteorological parameters - this most concise definition is due to Zrnić (1990). Key aspects are to extract as much information as possible, with the specific purpose of obtaining accurate, unbiased estimates of the characteristics of the desired atmospheric echoes, to estimate

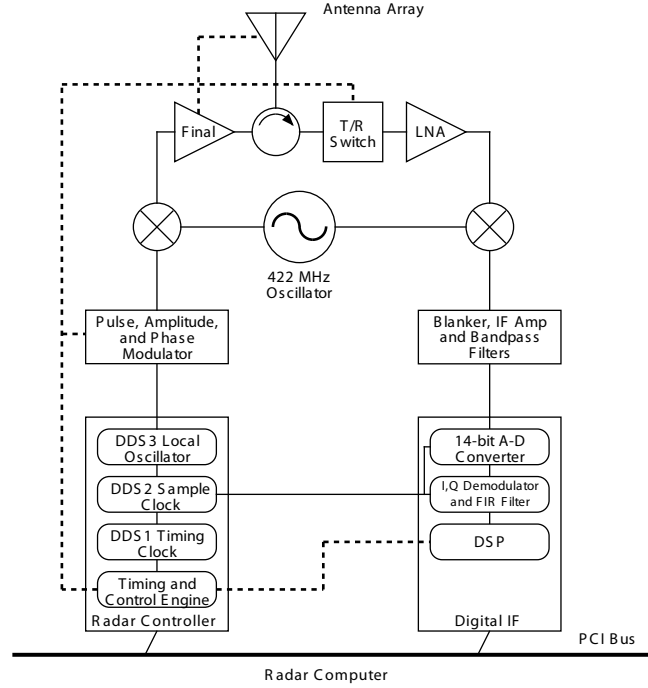


Figure 4. Simplified block diagram of the DWD 482 MHz radar wind profiler. (Graphics courtesy of J.W. Neuschaefer.)

the confidence/accuracy of the measurement and to mitigate effects of clutter or interfering signals (Keeler and Passarelli, 1990; Fabry and Keeler, 2003).

The quality of signal processing largely determines the accuracy and precision of the final data. The receiver signal at the antenna output port of a pulsed single-frequency RWP can be regarded as a continuous real-valued (Gaussian random) narrowband voltage signal with a potentially large dynamic range (Lehmann and Teschke, 2008), so the generic processing steps are therefore:

- Demodulation, range gating and A/D conversion
- Digital pre-filtering
- Estimation of the Doppler spectrum
- Signal detection, classification and moment estimation
- Computation of the wind

The majority of RWP's today uses the same standard signal processing, which is briefly summarized in the following. Details can be found in Woodman (1985); Tsuda (1989); Röttger and Larsen (1990). After demodulation and range gating, the receiver signal \mathbf{S} at one particular range gate forms a discrete complex time series for $k = 0, \dots, N_{ci} \cdot N_p \cdot N_s - 1$ (The length of the time series is written as a product of three integers for later convenience, $i = \sqrt{-1}$):

$$S[k] = S_I[k] + iS_Q[k]. \quad (1)$$

The sampling time ΔT depends on the inter-pulse period. Considering only one range gate, the next step is a simple preprocessing method called coherent integration:

Table 1. Technical parameters of the DWD 482 MHz RWP

Center frequency	482.0078 MHz
Peak (Average) RF envelope power (PEP)	16 (2.4) kW
Pulse modulation	Amplitude (B/W) Phase (pulse compression)
Pulse widths (vert. resolution)	1.0 μ s (150 m) 1.7 μ s (250 m) 2.2 μ s (330 m) 3.3 μ s (500 m)
Antenna type	Phased array of 180 CoCo antennas
Antenna aperture (area)	142 m ² (12.4 \times 11.5 m)
On-axis gain above isotropic	\geq 34 dBi
One-way half power (3 dB) beamwidth	\leq 3°
Oblique beam zenith distance	15.2°
RX type	Heterodyne (IF 60 MHz), Digital IF
LNA noise figure	\leq 0.6 dB
A/D conversion	14 bit (@ max 66 MHz)
Pulse compression	Bi-phase, complementary, max 32 bit
System sensitivity	\leq -154 dBm
Vertical measuring range	16 km (wind), 4 km (virt. temp.)

$$S^{ci}[m] = \frac{1}{N_{ci}} \sum_{n=0}^{N_{ci}-1} S[m \cdot N_{ci} + n]. \quad (2)$$

This is a digital filter with decimation (Farley, 1985), whereby the sampling interval is increased to $N_{ci}\Delta T$. Its frequency response is referred to as comb-filtering (Schmidt et al., 1979). To estimate the Doppler spectrum, the nonparametric FFT-based Periodogram method using a simple window sequence \mathbf{w} (e.g. Hanning) is used. Additionally, spectral or incoherent averaging is applied (Strauch et al., 1984; Tsuda, 1989) to reduce the variance of the estimate. This is *Welch's overlapped segment averaging (WOSA) estimator* (Welch, 1967; Percival and Walden, 1993). For N_s segments of length N_p without overlapping of the blocks, N_s single spectrum estimates are obtained as

$$P[l, k] = \frac{1}{N_p} \left| \sum_{m=0}^{N_p-1} w[m] S^{ci}[l \cdot N_p + m] e^{-i \frac{2\pi k m}{N_p}} \right|^2 \quad (3)$$

$$P[k] = \frac{1}{N_s} \sum_{l=0}^{N_s-1} P[l, k] \quad (4)$$

The dwell time for the estimation of a Doppler spectrum is $T_d = N_s \cdot N_p \cdot N_{ci}\Delta T$. To discriminate between electronic noise and echo signals, a mean noise level P_N is objectively estimated using the method of Hildebrand and Sekhon (1974). Next, the signal peak caused by the atmospheric return is selected. A simple but well-established method is to select the maximum energy peak (Strauch et al., 1984; May and Strauch, 1989), this is called a single peak algorithm. For multiple peak spectra more complicated methods have been proposed (Riddle and Angevine, 1991; Griesser, 1998; Cornman et al., 1998; Morse et al., 2002; Weber et al., 2004).

An example of a coherently averaged time series and its corresponding Doppler spectrum is shown in Fig. 5.

The first three moments of the Doppler spectrum are: Echo power M_0 , Doppler frequency M_1 and spectral variance M_2 , they are calculated for frequency bins where $P[i] > P_N$, that is between lower and upper signal bounds k_1 and k_2 :

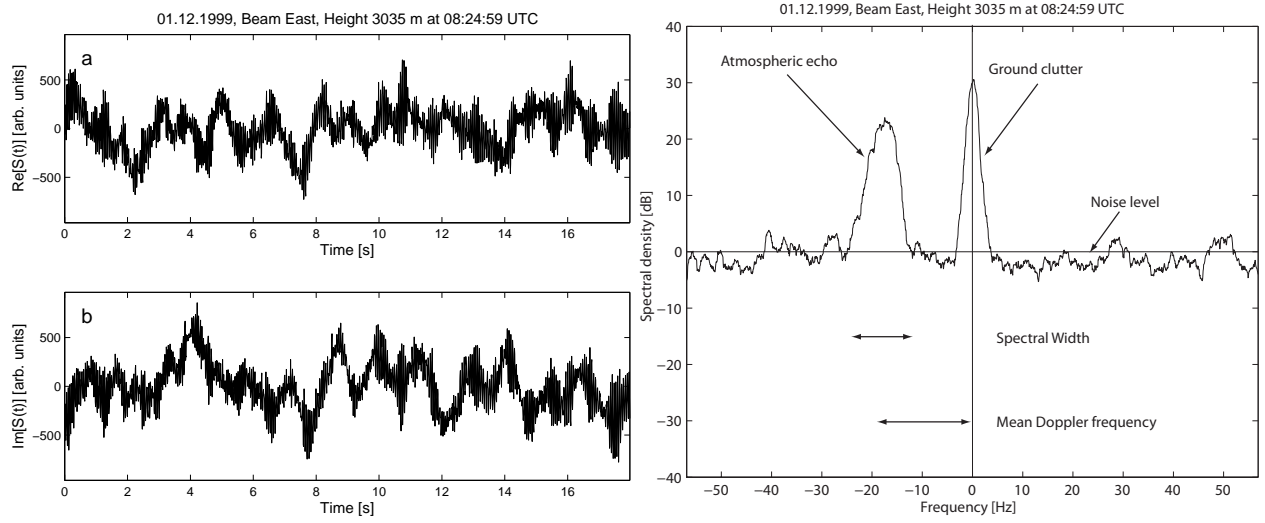


Figure 5. Coherently average I/Q time-series (left) and estimated Doppler spectrum (right) of a 482 MHz radar wind profiler (adapted from Muschinski et al. (2005).)

$$M_0 = \sum_{k=k_1}^{k_2} (P[k] - P_N) \quad (5)$$

$$M_1 = \frac{1}{M_0} \sum_{k=k_1}^{k_2} k(P[k] - P_N) \quad (6)$$

$$M_2 = \frac{1}{M_0} \sum_{k=k_1}^{k_2} (k - M_1)^2 (P[k] - P_N) . \quad (7)$$

Note that there are differences in the definitions of the spectral width. Often, the convention of Carter et al. (1995) is used, where spectral width is defined as $\sigma_v = 2\sqrt{M_2}$.

Due to clutter echoes, the receiver signal may become multi-component and non-stationary, which requires additional processing steps to filter the unwanted contributions and retrieve the atmospheric signal:

Any non-stationary character of clutter signals, as for example caused by bird or airplane echoes, make it obvious that a sole spectral representation of the signal is inadequate to efficiently describe the clutter component. Methods of non-stationary signal analysis therefore need to be used to find a decent (hopefully sparse) representation for such signals, which may then allow efficient filtering strategies with the purpose of removing the intermittent clutter component (Jordan et al., 1997; Boisse et al., 1999; Lehmann and Teschke, 2001, 2008).

Stationary clutter components will give rise to a Doppler spectrum with additional signal peaks. Such a situation is not accounted for in standard processing, and a variety of so-called multi-peak algorithms have therefore been proposed. Among them are simple methods, like the ground clutter algorithm by Riddle and Angevine (1991) which is in widespread use, as well as other, more complex techniques (Griesser, 1998; Cornman et al., 1998; Wilfong et al., 1999; Morse et al., 2002). The number of existing algorithms is symptomatic for the many different approaches to tackle the multiple peak problem. Unfortunately, there are only few validation attempts (Cohn et al., 2001; Gaffard et al., 2006; Hooper et al., 2008) and operational experience is still indicative of problems with these methods. The most important issue is the excessive use of weakly justified a-priori assumptions, like vertical continuity constraints, for peak selection. More work is needed to refine multi-peak processing.

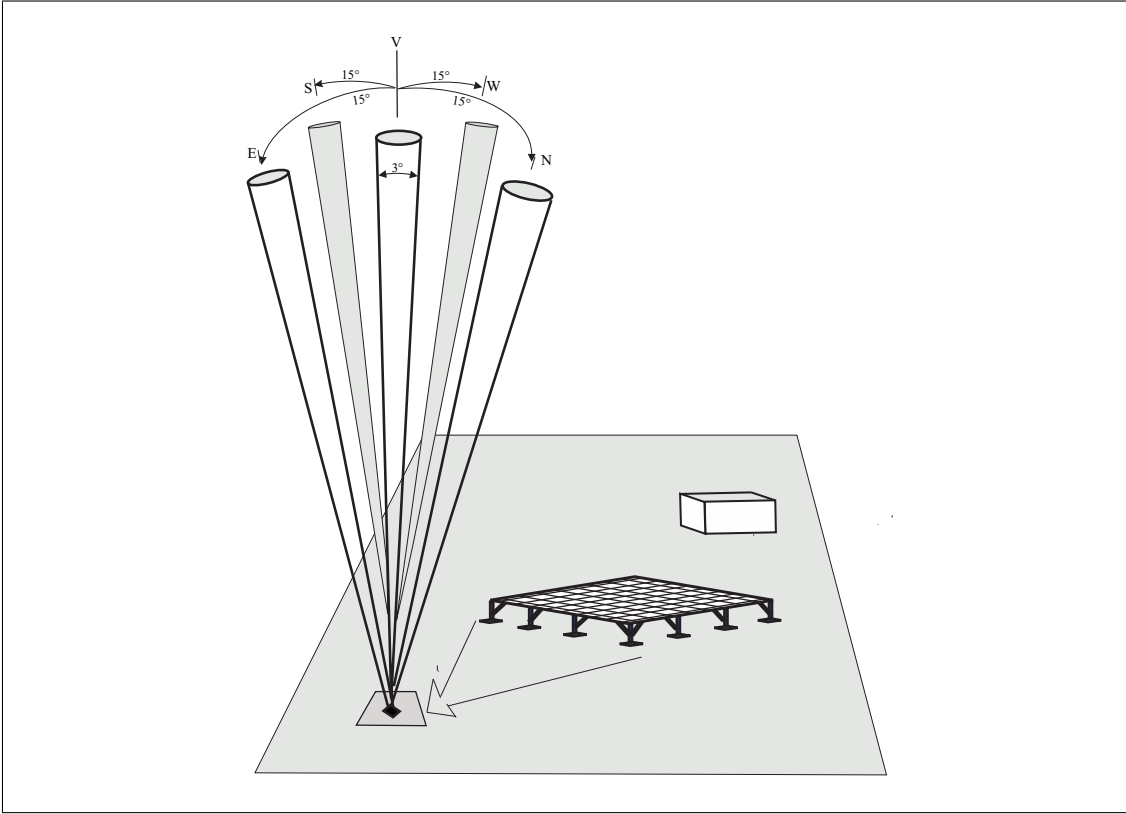


Figure 6. Beam pointing configuration of a five-beam DBS radar wind profiler

2.4. Wind determination - Doppler Beam Swinging

Single signal RWP use the simple method of Doppler beam swinging (DBS) to determine the wind vector. At least three linear independent beam directions and some assumptions concerning the wind field are required to transform the measured 'line-of-sight' radial velocities into the wind vector. Comparisons of RWP winds with data from a meteorological tower (Adachi et al., 2005) and balloon soundings (Rao et al., 2008) have shown, that a four-beam based DBS sampling configuration is superior over a three-beam configuration in terms of data quality. Therefore, a sampling configuration using four oblique beams is employed in the DWD profilers. More generally, Cheong et al. (2008) have found that the RMS error of RWP measurements can be significantly reduced by increasing the number of off-vertical beams in DBS beyond four. At present, such a configuration can only be used by a few RWP's systems because of restrictions imposed by the simple phased array constructions that are mostly used.

For a five beam system, the sampling configuration is illustrated in Fig. 6. Under the assumption that the wind field \mathbf{v} is horizontally homogeneous in the area that is spanned by the oblique beams, the relation between the cartesian wind field components (u, v, w) and the radial velocities measured by the profiler can be expressed through a system of linear equations:

$$\begin{pmatrix} \sin(\alpha_1)\sin(\epsilon_1) & \cos(\alpha_1)\sin(\epsilon_1) & \cos(\epsilon_1) \\ \sin(\alpha_2)\sin(\epsilon_2) & \cos(\alpha_2)\sin(\epsilon_2) & \cos(\epsilon_2) \\ \sin(\alpha_3)\sin(\epsilon_3) & \cos(\alpha_3)\sin(\epsilon_3) & \cos(\epsilon_3) \\ \sin(\alpha_4)\sin(\epsilon_4) & \cos(\alpha_4)\sin(\epsilon_4) & \cos(\epsilon_4) \\ \sin(\alpha_5)\sin(\epsilon_5) & \cos(\alpha_5)\sin(\epsilon_5) & \cos(\epsilon_5) \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} v_{r1} \\ v_{r2} \\ v_{r3} \\ v_{r4} \\ v_{r5} \end{pmatrix}$$

where α_i and ϵ_i denote azimuth and elevation angles of beam i . In compact matrix notation, this can be written as

$$\mathbf{A}\mathbf{v} = \mathbf{v}_r .$$

This over-determined system can be solved in a least-squares sense

$$\|\mathbf{A}\mathbf{v} - \mathbf{v}_r\|^2 \rightarrow \text{Min.}$$

so that the wind vector components can be obtained from the measured radial velocities through a pseudo-inverse as (the matrix superscripts T and 1 denote transposition and inverse, respectively):

$$\mathbf{v} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{v}_r$$

The homogeneity condition is of course not always fulfilled, in particular not in a convective boundary layer or in patchy precipitation (Adachi et al., 2005). A discussion of the DBS method can be found in Koscielny et al. (1984); Weber et al. (1992); Goodrich et al. (2002). The problem and the resulting measurement errors have recently been investigated by Scipion et al. (2008, 2009), they are even noticeable in NWP data assimilation (Cardinali, 2009). However, the assumption is usually correct for mean winds averaged over a longer time interval. Cheong et al. (2008) have used data obtained with a volume-imaging multi-signal wind profiler in a convective boundary layer to show that for this particular case the assumptions inherent in the DBS method were valid for a wind field averaged over 10 minutes. This is the main reason why DBS RWP wind measurements are typically averages over 10-60 minutes. More work is required to obtain reliable quantitative estimates of this error under a variety of atmospheric conditions.

3. Operational use

3.1. Historical development

After the first successful demonstration of clear-air wind measurements by Woodman and Guillen (1974), the potential capabilities of this technique for meteorological applications became suddenly apparent (Larsen and Röttger, 1982) and dedicated meteorological profiler systems were suggested (Hogg et al., 1983). It took not long until the installation of a small experimental wind profiler network in Colorado (Strauch et al., 1984). A brief historical overview of wind-profiling radars is given by Van Zandt (2000).

The first truly operational network, called the Wind Profiler Demonstration Network (WPDN), was completed in May 1992, later it became known as the NOAA National Profiler Network (Weber et al., 1990; Barth et al., 1994; Schlatter and (Editors), 1994). While the first systems used mostly operating frequencies in the VHF or lower UHF range, higher frequency (so-called boundary layer) profilers were also developed and later commercialized by a technology transfer to the private sector (Ecklund et al., 1988; Carter et al., 1995). In Europe, a first demonstration of wind profiler networking was organized during the COST-76 action in early 1997 as the CWINDE (COST WIND initiative for a network demonstration in Europe)-97 project (Nash and Oakley, 2001). This has been rephrased as the Co-ordinated WIND profiler network in Europe, which is currently managed by the E-WINPROF Programme of EUMETNET. Right now, CWINDE is comprised of 26 systems in 9 countries. Most radars are Boundary layer profiler (915, 1280 or 1290 MHz), but there are also four full tropospheric 482 Mhz systems in Germany and five VHF systems (45 - 64 MHz) in France, the UK and Sweden. In Asia, the Japanese Meteorological Administration is operating a network of 31 L-band wind profilers (Ishihara et al., 2006), and the Korean Meteorological Administration has installed five L-band wind profiler since 2002 (Park and Lee, 2009).

3.2. Accuracy of the wind measurements

A large number of publications have discussed the accuracy and precision of RWP data based on comparisons with independent measurements (meteorological towers, tethered balloon sounding systems, Radiosondes, aircraft measurements and Doppler wind lidar), see e.g. Larsen (1983); Strauch et al. (1987); Wuertz et al. (1988); Weber et al. (1990); Martner et al. (1993); Angevine et al. (1998); Daniel et al. (1999); Luce et al. (2001); Cohn and Goodrich (2002); Adachi et al. (2005).

Meanwhile, NWPM data are increasingly used in lieu of independent upper-air wind measurements to estimate the quality of a wind profiler (Steinhagen et al., 1994; Panagi et al., 2001; Hooper et al., 2008). This is especially important for operational quality monitoring, as will be discussed later.

A long-term statistical intercomparison of data measured with the 482 MHz profiler at Lindenberg in 1997 with more than 1000 independent profiles measured with a collocated Radiosonde has shown, that the wind speed bias was usually less than 0.5 m/s, except for the tropopause region where it was about 0.7 m/s. Wind speed standard deviation was less than 1.5 m/s below 8 km and less than 2.2 m/s for all heights. With the exception of the lowest levels, the wind direction bias was determined as about 1 degree, with a standard deviation of less than 20 degrees in general and below 10 degrees above 4500 m height. The results are published in Dibbern et al. (2001).

An internal investigation of the data quality of the Lindenberg profiler by the data assimilation group at DWD has found, that the profiler wind data was of high quality. In particular, the 'observation minus model' statistics below 400 hPa was better for the RWP data, than for the Radiosonde data (Buchhold, 2001).

3.3. Data use and impact

RWP's are widely used in operational meteorology and atmospheric research, for reviews see Fukao (2007) and Gage and Gossard (2003). Nowadays, major meteorological field experiments make regular use of RWP as observation system, e.g. METCRAX (Whiteman et al., 2008), T-REX (Grubisic et al., 2008), NAME (Higgins et al., 2006), IHOP (Weckwerth et al., 2004), BAMEX (Davis et al., 2004), CASES (Poulos et al., 2002) and MCETEX (Keenan et al., 2000).

In a more operational setting, RWP measurements have been used either directly in subjective weather forecasting and case studies (Dunn, 1986; Kitzmiller and McGovern, 1990; Beckman, 1990; Edwards et al., 2002; Crook and Sun, 2004; Bond et al., 2006; Wagner et al., 2008), or automated in data assimilation for numerical weather prediction (Monna and Chadwick, 1998; Guo et al., 2000; De Pondeca and Zou, 2001; Bouttier, 2001; Andersson and Garcia-Mendez, 2002; Benjamin et al., 2004; St-James and Laroche, 2005; Ishihara et al., 2006). Their particular advantages are a high temporal resolution and the capability to provide unambiguous profiles independently of the used assimilation system, the latter being in contrast to most passive remote sensing systems. Furthermore, measurements can be made under almost all weather conditions.

Due to the potential of RWP's to provide high-resolution observations, they are especially well suited to describe the atmospheric state at the mesoscale (Browning, 1989; Park and Zupanski, 2003; Browning, 2005), where the current observation coverage is still quite incomplete in space, time and also state variables of the models. It is very unlikely, that the models can always generate the correct mesoscale atmospheric state without proper initial data. The current experience with high-resolution models has shown that even a 12-24 hour deterministic prediction of some intense convective precipitation systems can drastically fail. For example, Gallus et al. (2005) reported about an intense derecho event accompanied by a well-organized band of heavy rainfall that they were not able to simulate although a range of different models, different parameterizations and initial conditions was used. The authors conclude:

Evidence suggests inadequacies in the initial and boundary conditions probably harmed the simulations.(..) It thus appears that useful forecasts of systems such as this one may require a much better observation network than what now exists.

Mesoscale data assimilation suffers especially from a penury of high-quality profile data, including wind (Roberts, 2007; Carbone et al., 2009; Fabry and Sun, 2009), so RWP networks will continue to play an important role for the provision of initial data. However, this is not the only use for this high resolution data type: Nielsen-Gammon et al. (2010); Hu et al. (2010) were recently able to improve a NWP planetary boundary layer parametrization by calibrating its parameters through an Ensemble Kalman Filter (EnKF) based data assimilation of continuously available RWP/RASS data.

While both the numerical models and the global observation system are constantly evolving, impact studies are regularly performed to assess the usefulness of RWP and other observations in various NWPM's. This task is obviously quite challenging and the results depend on the number of observations available, their quality, as well as on the particular meteorological situation. For example, Armstrup (2008) has used DMI-HIRLAM to assess the impact of various terrestrial observing systems in 2005. While it was found that *the impact from the very few wind profilers used is generally negligible,*

there was also a case identified where the assimilation of only three RWP in Alaska *showed a very positive impact...in an extreme weather situation near the Faeroe islands*. Experiences gained with a high resolution (COSMO-2 model, grid spacing 2.2 km) by MeteoSwiss indicate that RWP data are especially beneficial for short range forecasts at smaller scales. It was found that the assimilation of three ground based remote sensing stations (equipped with a 1290 MHz low tropospheric wind profiler and microwave radiometer) substantially improved the quality of COSMO-2 forecasts (Ruffieux et al., 2009).

Apparently, the usefulness of RWP data is variable in time and, in specific meteorological situations, also in height. Cardinali (2009) has identified a situation where high wind variability on small spatial and temporal scales had an impact on the measurements of the North American RWP, which lead subsequently to a degradation of the forecast in the ECMWF model. This problem was associated with a rather large height and strong activity of the continental convective boundary layer at the profiler sites.

Recently, Benjamin et al. (2010) have used the RUC model of NCEP to assess the short-range forecast impact of a number of data types, including RWP's, in an observation system experiment OSE and concluded:

This OSE study included vertically stratified results for the data-rich Midwest verification domain. Even here, nearly all observation types contributed positive impact, with clear, positive and complementary effects from profiler and aircraft data, indicating that this region is not oversampled by observations.

4. Practical aspects of operational RWP use

There can be no doubt that high-quality wind observations of RWP are beneficial for NWPM. The challenge of operational networks is then to provide this high quality data on a 24/7 basis. A necessary prerequisite for a positive impact of RWP's is that the instruments are able to provide such high-quality measurements in an operational, fully automated fashion. This seemingly trivial requirement requires a constant endeavor in the operational practice. In the following, a few important practical aspects of the operational use of RWP are discussed.

4.1. Frequency management

The high sensitivity of the RWP's make them vulnerable to any external radio-frequency interference of sufficient strength that is in-band. Frequency management is therefore an essential issue for operational networks. As more and more technical applications are using electromagnetic waves, the frequency spectrum has become a scarce resource. Effective management of allocated frequency bands is paramount to maintaining and enhancing the quality of radar wind profilers and therefore an important task.

Wind profiler frequency allocations were on the agenda of the World Radiocommunication Conference 1997 (WRC-97), where the resolutions COM5-5, and Footnotes S5.162A and S.5.291A were accepted. In these documents, RWP frequency allocations are assigned for the bands 50 MHz, 400 MHz and 1000 MHz, depending on the ITU Region. Since then, the allocations have been constantly under pressure from other intended usage of these bands. For example, the European Radio Navigation Satellite Service GALILEO is going to use an L-band frequency range assigned to boundary-layer wind profilers. Compatibility studies* were therefore necessary to ensure the best possible protection.

The sharing of profiler frequency bands with other services is obviously inescapable, but coexistence is often possible. Of advantage is here the nearly vertical direction of the profiler beams, which naturally enhances the protection against horizontally propagating waves. The 482 MHz RWP in Germany are operated in a frequency band that is primarily assigned to digital terrestrial television broadcasting (DVB-T) in UHF channel 22. With the exception of short-lived tropospheric ducting events, when TV signals can propagate over long distances up to 1000 km or more, the emissions of TV stations are no issue for the three 482 MHz wind profilers at Ziegendorf, Bayreuth and Lindenberg. However, RWP signal processing and quality control procedures needs to be developed further to eliminate all spurious data in such cases.

A convincing, but rather extreme example is the RFI that is constantly observed with the 482 MHz RWP at Nordholz, Germany. This profiler operates at a distance of only 30 km away from a powerful (10 kW ERP) DVB-T transmitter as a result of a frequency management mistake. Although the television signal is always clearly detectable in the Doppler spectrum, see Fig. 7 as an example, the valid profiler data have a good quality and are routinely assimilated by ECMWF. However, the vertical data availability of this system is inevitably reduced due to the RFI.

*<http://www.erodocdb.dk/Docs/doc98/official/pdf/ECCREP090.PDF>

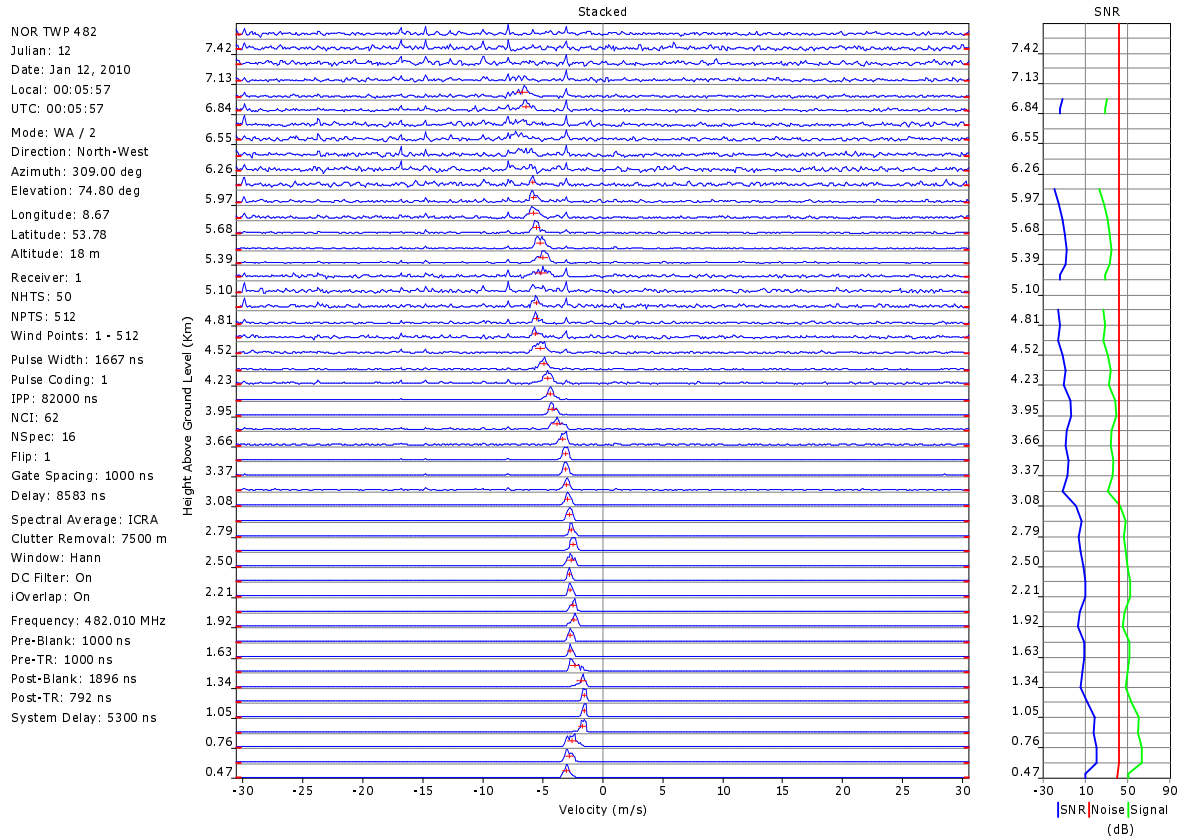


Figure 7. Stacked Doppler spectra obtained with the 482 MHz RWP at Nordholz, Germany, on January 12, 2010 at 00:05:57 UTC. External Radio Frequency Interference due to an external digital television signal is visible in the upper gates.

4.2. System setup: Sampling and processing

Wind profilers were developed for research and it is therefore no surprise, that sampling and processing can be set-up in a variable way. After the first commercial radars were available, most research users were asking for further enhancements in flexibility. This has, among other things, lead to the development of modular and highly configurable RWP operating software.

However, this extensive flexibility, which is most welcomed by developers and researchers, can be quite intimidating and dangerous in an operational setting, where users usually only want a fully-automatic 'turn-key' meteorological instrument for mean wind profiling. Depending on the particular system, there is a great potential for suboptimal settings of both the profiler sampling and processing, which can easily lead to bad data quality. To avoid potential pitfalls, some basic knowledge about signal processing issues is essential.

In terms of the sampling settings (pulse repetition frequency, time increment in the I/Q raw data) it is of utmost importance to make sure that range and frequency aliasing (Gaffard et al., 2008; Gangoiti et al., 2002; Miller et al., 1994) effects are ruled out, because they can lead to large errors. Also important is a sufficient number of beam cycles to assure the validity of the DBS assumptions.

In some systems, also the chain of signal processing algorithms can be fully configured. That is, the user not only can make a selection for several parameters of an algorithm (and thereby determining important parameters like the dwell length, the time that is used to estimate a Doppler spectrum), but different processing algorithms can be daisy-chained in various ways. This option has clear advantages for addressing site-specific clutter issues, but deriving a good set-up is no trivial exercise. Sophisticated algorithms should only be used after they were properly tested and validated. As a rule of thumb, the simplest possible processing should be preferred over complex and widely 'tunable' algorithms.

4.3. Maintenance

RWP are complex technical instruments and regular maintenance is necessary to guarantee a high level of data quality. While the systems are typically specified to operate over a time period of 10-20 years without major technical upgrades, the MTBF of several system components is much less and both preventive and corrective maintenance becomes a clear necessity. A comprehensive discussion of various aspects of RWP maintenance can be found in Dibbern et al. (2001).

Of particular importance is the preventive maintenance of systems components that can degrade or partly fail unnoticeable, but with consequences for the data quality. A prominent candidate is the usually employed phased array antenna. As an outdoor element, the antenna is exposed to humidity, precipitation and radiation and it needs to withstand temperature changes over 50 K during the course of the year. On the other hand, the failure of single antennas in a phased array is quite difficult to detect. Although the overall array performance degrades, this typically remains hidden due to the high variability of the atmospheric scattering processes. The 482 MHz RWP of DWD use a simple but proven and economical coaxial-collinear passive phased array design, which is comprised of a total of 180 antenna elements arranged in two sub-arrays. The elements are similar to those used in the first generation 404/449 MHz RWP network of NOAA. A failure of a single element does not significantly reduce the return loss of the whole array, so it often remains undetected in real-time VSWR[†] monitoring. To identify such faulty elements, DWD employs an antenna probing technique originally developed at NOAA (Law et al., 1997). A test signal generated with a vector network analyzer is inserted into the feeding network in the array and a small loop probe is used to measure the complex current at the individual antenna elements, see Fig. 8. This diagnostic method allows to identify bad antenna elements as well as problems within the feeding network and the phase shifter. Furthermore, the complex current distribution obtained from a probing of the complete array allows the calculation of an estimate of the far-field radiation pattern of the whole antenna, as shown in Fig. 3. Such data is otherwise very difficult to obtain (Law et al., 2003).

4.4. Data handling

The RWP measurements are disseminated using the FM-94 BUFR format. A special BUFR code table for wind profiler has been defined in COST-76, and is used in the European CWINDE network. After several years of application, it appears to be necessary to clarify some of the definitions used. For example, the meaning of the descriptor 0 025 001 ('range-gate length') is not very well defined and therefore used in different ways (either as 3 dB range resolution determined by the pulse width or as the vertical difference between adjacent range gates). It would be useful to further harmonize the BUFR format, so that data from all operational RWP are encoded in the same way.

Besides the final wind profile data, RWP's generate and save a number of raw data during different stages of the processing. This includes the time series of the demodulated receiver voltage, the Doppler spectra and the estimated moments. For diagnostic purposes it is useful to archive some of these data. For the DWD 482 MHz RWP, the time series data are temporarily saved at the site for about a week, to allow detailed investigations if this becomes necessary (e.g. for failure investigation). All spectral and moments data are transferred once a day to the Observatory Lindenberg, where they are archived on optical discs. This way, the essential raw- and metadata remain available for later analysis.

To transfer these larger files through the network, a DWD software called Automatic File Distributor (AFD) is used. The AFD provides a framework for very flexible, non-stop, log and debug-able delivery of an arbitrary amount of files to multiple recipients as expressed in Uniform Resource Locators (URL). AFD is made available by DWD under a GNU-GPL license and can be downloaded from <http://www.dwd.de/AFD/>.

4.5. Data monitoring

Most important is a continuous data quality evaluation. As the systems are unattended, there is no operator at the site for intervention in case of technical malfunctions. The problems are almost always associated with cases where the system does not fail completely, but continues to (automatically) send data which are degraded due to the failure. This requires a combination of human data evaluation, starting from the final wind estimate and, if necessary, continues down to the raw data (Doppler moments, Doppler spectra and even the I/Q time series of the demodulated receiver voltage). A specialist is usually able to narrow down the technical problem(s), which makes it easier to plan and execute the corrective action. An example is given for illustration: Figure 9 shows a quite unusual stacked plot of Doppler spectra, which could not be explained by any scattering or echoing mechanism. A hardware issue was therefore suspected and evidence pointed toward

[†]Voltage Standing Wave Ratio

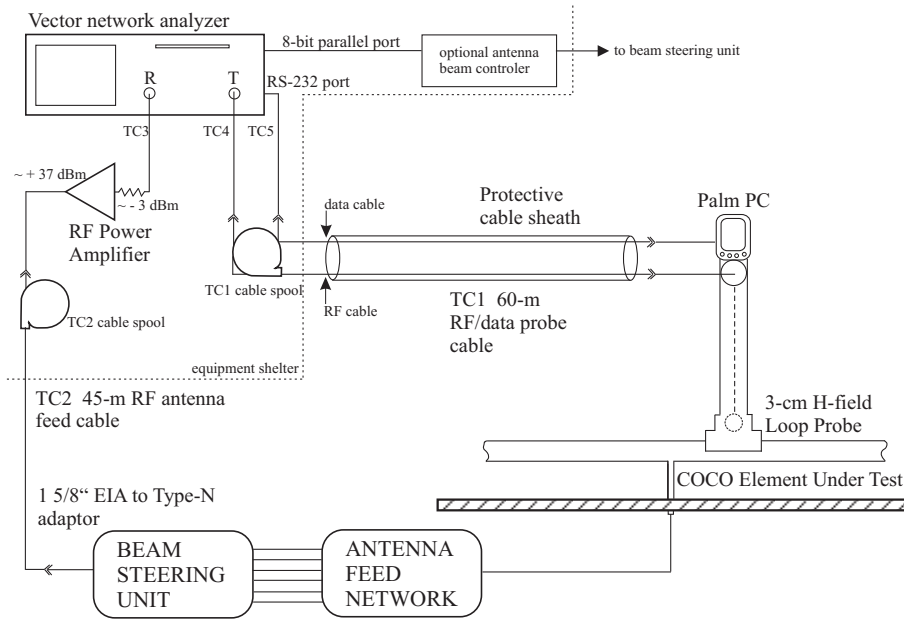


Figure 8. The top schematics contains the measurement set-up for antenna probing, the lower photograph shows a DWD engineer during a routine antenna check at the RWP in Nordholz.

a failure in the beam steering unit of the profiler. Consequently, a site visit was initiated, which indeed confirmed this conjecture.

Such rather obvious hardware failures can quite easily and quickly be detected by regular data monitoring. The principle is simple, but requires some experience in data interpretation: Any measurement that can not be explained as being caused by atmospheric scattering mechanisms needs to be analyzed in depth. If clutter or RF interference issues can be ruled out, such suspicious data very often lead to the identification of hardware problems.

There are, however, other hardware issues which can not be identified that easy without some independent reference

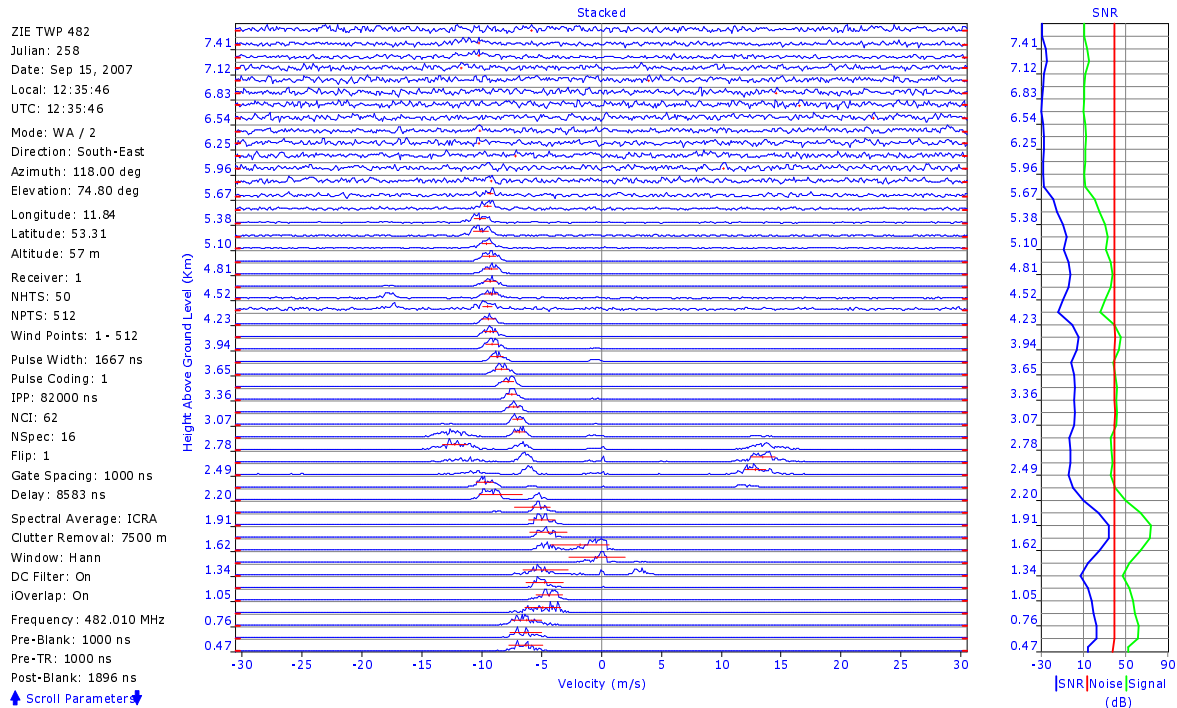
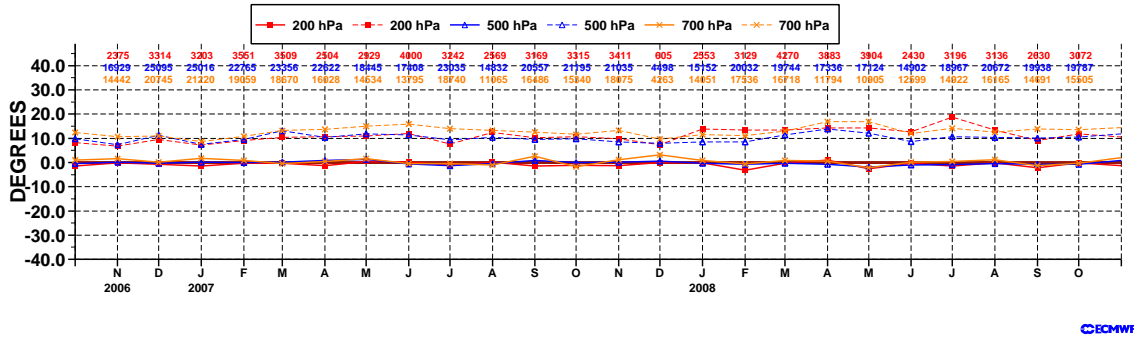


Figure 9. Stacked Doppler spectra obtained with the 482 MHz RWP at Ziegendorf, Germany, on September 15, 2007 at 12:35:46 UTC. Several irregularly distributed signal peaks are visible. This unusual data lead to the assumption of a hardware failure in the beam steering unit which was later confirmed by special hardware tests in the field.

data. An important tool in that respect is the monitoring information provided by state-of-the-art NWPM's. Of course, this can only be done on a statistical basis. An example for the identification of a rather subtle hardware problem with the 482 MHz RWP at Bayreuth is presented in the following. In March of 2008, the RWP Bayreuth was removed from the 'whitelist' at ECMWF due to a bad wind speed statistics (Observation - First Guess) above 400 hPa. Figure 10 shows the time-series of the monitoring statistics of ECMWF over the course of two years that shows this effect for the 200 hPa level. Unfortunately, this information was announced with a delay of several months, so further diagnostics about possible causes started only in early summer. No obvious problems could be found in the profilers raw data, but an unusual wind speed difference between high and low mode of up to 10 m/s was found in the vicinity of a jet-stream, which was observed on March 03. This prompted for a check of the profilers range calibration (essentially an estimate of the group delay in the radar hardware). During a site visit on Sep. 18, a calibration error was indeed found which had caused a wrong assignment in height of the high mode data - the height error was about 500 m. This lead to a negative bias of the wind speed below and a positive bias above the wind maximum. The effect is clearly visible in an a-posteriori comparison of the profiler data with the COSMO-EU model of DWD (Schättler et al., 2002-2008), see Fig. 11. The cause of this erroneous calibration could be traced back to a change of the radar computer on Jan 08, 2008. Although the spare computer was apparently identical in hardware, the system delay was obviously different.

Station 10678(-) (50N, 012E) Elevation: 514 m
OBS-FG WIND DIRECTION: BIAS and STD (ALL TIMES)



Station 10678(-) (50N, 012E) Elevation: 514 m
OBS-FG WINDSPEED: BIAS and STD (ALL TIMES)

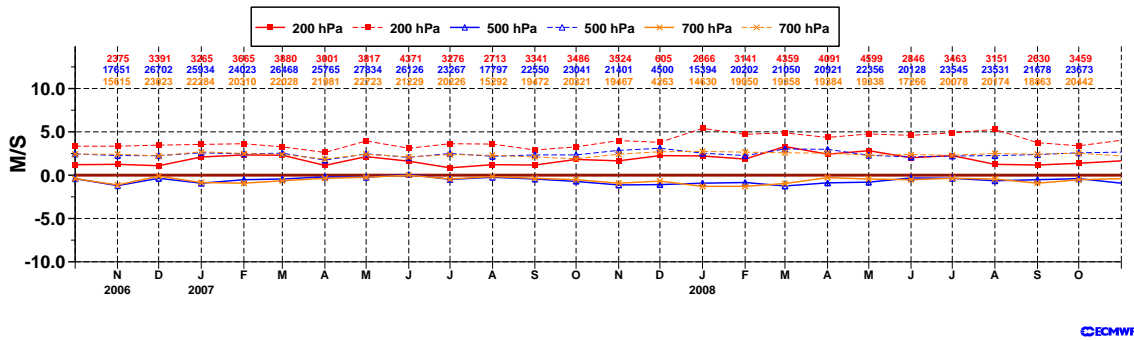
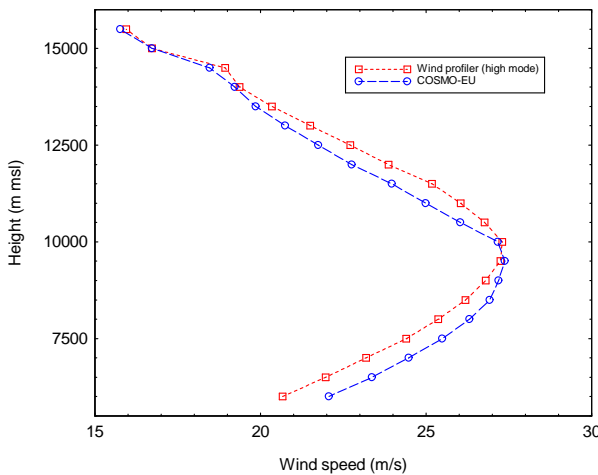


Figure 10. Time-series of the monitoring statistics of the ECMWF T799L91 model (Observation - First guess) for data provided by the 482 MHz RWP at Bayreuth, Germany, from October 2006 until October 2008. (Graphics courtesy Antonio Garcia-Mendez, ECMWF). For the 200 hPa level, the values of the standard deviation for wind speed are unusually high from Jan. 2008 to Aug. 2008. This was caused by a range calibration error in the high mode data of Bayreuth during that time.

Mean wind speed Bayreuth (Jan 15 - March 31, 2008)



Mean wind speed Bayreuth (Sep 19 - Nov 30, 2008)

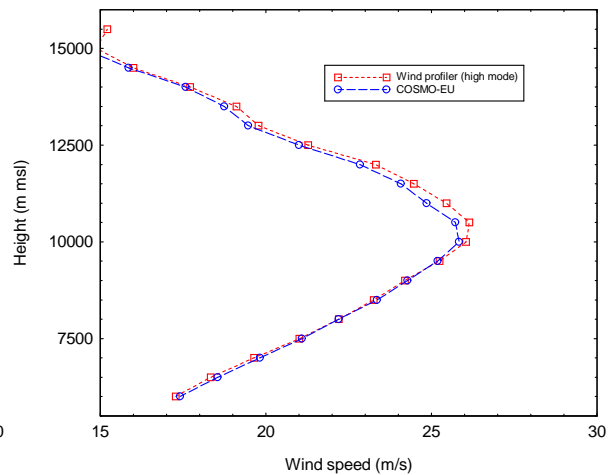


Figure 11. Vertical profile of the mean horizontal wind speed as measured by the high mode of the 482 MHz RWP at Bayreuth and analyzed by the COSMO-EU model of DWD for two time periods. The period from Jan 15- Mar 31 clearly shows a clear vertical shift between the two profiles. This is not the case for the second period from Sep 19 - Nov 30. The reason for this discrepancy was an erroneous range calibration of the wind profiler.

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