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Possible quality issues in operational radar wind profiler data and methods for their mitigation

(Submitted by Volker Lehmann)

SUMMARY AND PURPOSE OF DOCUMENT

The paper discusses possible quality issues of operational radar wind profilers (RWP) and provides an overview of methods for resolving those issues.

Possible quality issues in operational radar wind profiler data and methods for their mitigation

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ABSTRACT

This document is intended as an input to the Joint Meeting of the CIMO Expert Team on Operational Remote-Sensing (First Session) and CBS Expert Team on Surface-based Remotely-Sensed Observations (Second Session), Geneva 5-9 December, 2011. The paper discusses possible quality issues of operational radar wind profilers (RWP) and provides an overview of methods for resolving those issues.

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 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 capability. Comparisons have shown that the accuracy of the wind measurement a well-operated and -maintained RWP is at least comparable to the accuracy of Radiosonde wind data.

1. Introduction

For ground based remote sensing systems, 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 minutes to years. RWP's are furthermore 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 is not used routinely due to the complexity of the measurement process. 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. This will not be discussed in the following, more information on RASS can be found in Peters et al. (1993); Lataitis (1993); Görsdorf and Lehmann (2000).

At present, the use of RWP's in atmospheric research is widespread, see e.g. Fukao (2007) and Gage and Gossard (2003). In a more operational setting, their data are mainly provided for assimilation in numerical weather prediction models (NWPM) (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, which is in contrast to most passive remote sensing systems. Furthermore, measurements can be made under almost all weather conditions. RWP measurements are also used 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),

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); Fukao (2007) and recently by Hocking (2011).

Due to the high temporal resolution of RWP observations, the data are especially well suited to describe the atmospheric state at the mesoscale (Browning, 1989; Park and Zupanski, 2003; Browning, 2005). The dramatic rise in computational capabilities during the last decades has lead to significant improvements in the discretization resolution of NWPM, see e.g. Lynch (2008). Global models are meanwhile using grid spacings of $O(10\text{ km})$ (Satoh et al., 2008), while high-resolution limited area models already use grid sizes of $O(1\text{ km})$ in an attempt to resolve small-scale meteorological processes (Bryan

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et al., 2003; Saito et al., 2007). Of course, this brings along the need to initialize the models with adequate observations of small scale atmospheric features (Lilly, 1990; Daley, 1991; Gall and Shapiro, 2000; Roebber et al., 2004; Sun, 2005; de Lima Nascimento and Droegemeier, 2006; Weisman et al., 2008). However, the current observation coverage at those scales is quite incomplete in space, time and also state variables of the models. 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 due to inadequacies in the initial and boundary conditions (Gallus et al., 2005), which means that forecasts of such systems require a much better observation network than what now exists. This need for high resolution initial data can partly be satisfied with data from RWP's.

A necessary prerequisite for a successful operational application of RWP is that the instruments must be able to provide high-quality measurements in an operational, fully automated fashion. This seemingly trivial requirement is indeed somewhat difficult to achieve, for the required high sensitivity of the radars make them vulnerable to unwanted and potentially quality-degrading effects, like echoes from various clutter sources and radio-frequency interference. In particular, the automated data processing must be capable of sufficiently suppressing these clutter effects.

1.1. Accuracy of RWP 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 concluded 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.

It must be stressed that these results are generally only valid for well-operated and well-maintained profilers. There is evidence in the European network, that the quality of data provided by different RWP can scatter considerably. As an example, Fig. 1 shows the operational monitoring statistics of ECMWF for a UHF wind profiler that is routinely assimilated. However, Fig. 2 shows the same statistics for a VHF system, which is not actively assimilated. This is due to the much larger Observation - Model differences, which are especially obvious in the bias and standard deviation for the wind speed. For example, the wind speed standard deviation for 07453 above 300 hPa is about 4 m/s and larger, whereas the same parameter for 10394 is about 3 m/s and less.

There are two pitfalls for an undiscerning user which can lead to significant quality problems, namely an erroneous system configuration and the occurrence of hardware failures that remain unnoticed. These can, at least in principle, be quite easily resolved, as discussed in section 3.

2. Fundamental aspects

For a general discussion of potential RWP quality issues it is useful to briefly review both the physical fundamentals and the technical constraints of these instruments.

2.1. Radar hardware

Depending on their particular hardware architecture, RWP can be classified into three main groups (Muschinski et al., 2005). This discussion will be limited to **single signal systems**, which are the most frequently used wind profiler type (Hashiguchi et al., 2004; Lehmann et al., 2003; Law et al., 2002; Steinhagen et al., 1998; Engelbart et al., 1996; Carter et al., 1995; Ecklund et al., 1988; Strauch et al., 1984). Single signal systems 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. A photograph of a single signal 482 MHz RWP/RASS system is shown in Fig. 3, technical details of the radar are given in Lehmann et al. (2003).

The general hardware architecture of RWP is shown in the simplified block diagram, see Fig. 4. The central unit is the radar controller, which uses a highly stable oscillator (coherent oscillator or COHO) as the single reference for all signals and is activated by the radar processor. The signal to be transmitted is generated by a waveform generator which can be looked at as a amplitude and phase modulator. After up-conversion and amplification (power amplifier) the transmit signal is delivered to the antenna. A duplexer allows the use of a single antenna for transmitting and receiving. It is often comprised of (a) solid-state ferrite circulator(s) and additional receiver protecting devices.

The antenna is typically an electronically steered phased array. Both active and passive arrays are used, with the passive variant still being more widespread. Beam steering is obtained through a distinct phasing of the individual array elements. This is mainly achieved through either mechanically relay-switched or electronically switched true-time delay components. While most RWP are only capable of steering the beam into a few (3-5) directions, there is an increasing number of systems which can steer the beam quasi-continuously in a cone over the antenna (McLaughlin and Merritt, 2005). In any case, most important in terms of data quality is the radiation pattern of the antenna. For the suppression of unwanted (clutter) echoes low sidelobes are generally required.

The receiver is of the classical superheterodyne type (Tsui, 1989). A rather broadband low-noise amplifier with an excellent noise-figure is required to raise the signal level of the weak atmospheric return for further processing. After down-conversion to an intermediate frequency (IF), the signal is bandpass-filtered with a filter characteristics that is matched to the spectrum of the transmitted pulse to maximize the per-pulse SNR (Zrnić and Doviak, 1978), demodulated and A/D converted for further digital processing in the radar processor. The 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). With regard to data quality, a very high dynamic range of the receiver is required to achieve a linear behavior during operation. This is necessary to preserve different signal components, e.g. a weak atmospheric signal in the presence of strong clutter echoes.

2.2. Scattering mechanisms: Atmospheric echoes vs. clutter echoes

The unique characteristic of RWP is their use of longer wavelengths, in comparison with classical weather radars, which range from about 20 cm (L-Band) to about 6 m (VHF). Electromagnetic waves of this length 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 understood on the basis of the theory of radio-wave propagation through the turbulent atmosphere. The theory to explain scattering from the clear (particle free) atmosphere was pioneered by V. Tatarskii; it is a synthesis of Maxwell's classical Electrodynamics and Kolmogorov's statistical turbulence theory (Tatarskii, 1971; Muschinski, 2004). While this is the main reason for calling RWP's clear-air radars, other scattering processes are sometimes acting as well and need to be taken into account. The following scattering and echoing mechanisms are regularly observed:

- 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)

The first and 'classical' meteorological scattering process for RWP is 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 aperture (high gain) antennas are therefore required.

The second meteorological scattering process is due to 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. Furthermore, the scattering is assumed to be incoherent. The whole process is 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.

The remaining scattering or echoing mechanisms are considered as clutter, that is unwanted echoes. The high sensitivity of wind profilers makes them obviously vulnerable. Scattering at the plasma in lightning channels is sometimes observed (Petitdidier and Laroche, 2005), but it is usually 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 are far more relevant, they are often observed due to ubiquitous sidelobes of finite aperture antennas (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). A particular difficult class of ground clutter are echoes from the rotating blades of wind energy turbines, due to their intricate spectral signature. 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 another type of unwanted echoes, often termed intermittent clutter. These are quite frequently observed and it can hardly be denied that such effects are relevant 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.

2.3. Radio frequency interference to profilers

Radio frequency interference (RFI) to profilers is caused by all electromagnetic signals that are sufficiently strong to be detected by the profilers receiver and processing system. Following Law et al. (1993), it is useful to discriminate between *coherent interference* and *incoherent interference*:

Coherent interference is any signal, that will be interpreted by the profiler as a valid signal in its Doppler spectrum. This is the most disruptive to profiler operation, because it may wrongly be interpreted as a valid atmospheric signal.

Incoherent interference in contrast is any signal, that is not detectable as a distinct peak in the Doppler spectrum but raises the noise level of the system. This would not generate false estimates for atmospheric returns, but degrade the SNR and thus reduce the height coverage of the radar. Of course this means that the interfering signal is sufficiently wide-band to the frequency response of the profiler and has a "white" spectral structure.

The effect of the additional noise contribution is a de-sensitization of the profiler which obviously leads to a decreased height coverage. However, this reduction in height coverage is very difficult to quantify. The reason is the high dynamic range of volume reflectivity which accounts for the radar returns. The structure parameter of the refractive index c_n^2 may vary more than 20 dB daily and 20 dB annually (Law et al., 1993).

An illustrative, albeit extreme example of coherent interference is the RFI 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. 5 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.

An example of incoherent interference is the effect of the GNSS GALILEO E6 signal on L-band RWP operating at 1.29 GHz, see section 3.

2.4. Signal processing

The purpose of RWP signal processing is to convert the measured electrical signal to meteorological parameters (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 the confidence/accuracy of the measurement and to mitigate effects of clutter or interfering signals (Keeler and Passarelli, 1990; Fabry and Keeler, 2003). Obviously, the accuracy and precision of the final data is largely determined by the quality of signal processing.

Due to the nature of the (theoretical) atmospheric backscattering, signal processing for RWP is largely build upon spectral estimation methods. A typical atmospheric signal achieves a sparse representation in Fourier space, meaning that it can be sufficiently described with only a few parameters. However, practical deviations from this assumption make additional processing steps necessary. In general, the following sequence of processing steps are applied to the RWP receiver signal:

- 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

2.4.1. Generic signal processing for RWP

The majority of RWP's today is build upon the same standard signal processing (Woodman, 1985; Tsuda, 1989; Röttger and Larsen, 1990). This is due to the underlying theoretical assumption that 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 consisting of a echo and a noise component (Lehmann and Teschke, 2008).

After demodulation and range gating, the receiver signal $\mathbf{S}$ at one particular range gate forms a discrete complex time series for $k = 0, \ldots, N_{ci} \cdot N_p \cdot N_s - 1$ (The length of the time series is written as a product of three integers for later convenience, $i = \sqrt{-1}$):

$$S[k] = S_I[k] + iS_Q[k] \; . \tag{1}$$

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

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

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). Note that the signal can have a large dynamic range: The range of backscatter signals from the atmosphere can easily exceed 10 orders of magnitude (White et al., 2000). For N_s segments of length N_p without overlapping of the blocks, N_s single spectrum estimates are obtained as

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

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

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. An example of a coherently averaged time series and its corresponding Doppler spectrum is shown in Fig. 6.

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:

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

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

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

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

2.4.2. Signal detection in the low SNR regime

Because of the weak scattering at refractive index fluctuations, wind profiler processing has frequently to deal with very small SNR values. This is almost always true for the uppermost range gates. Consequently, one has to use some kind of a-priori information to discriminate between the atmospheric signal component and noise.

A prominent method is the so-called consensus averaging (Fischler and Bolles, 1981; Strauch et al., 1984). The a-priori assumption used here is that the Doppler shift of the atmospheric signals should be quasi-stationary over sufficiently short periods of time. Sufficiently here means less than 1 hour. This assumption makes it possible to use a very low SNR detection threshold in the Doppler spectrum, with the consequence that the probability of false alarm is as high as the probability of detection in the case of weak signals (Ferrat and Crochet, 1994). The estimator employed selects the maximum peak in the Doppler spectrum in a range that is above the mean noise level (Strauch et al., 1984; May and Strauch, 1989). Without further measures, this would lead to an inevitably high number of bad estimates.

The probability density function (pdf) of this estimator $\hat{v}$ for the true mean Doppler velocity v in case of a signal composed of a quasi-stationary atmospheric echo and white noise (SNR parameterized by $0 \leq b \leq 1$) is a Gaussian superposed on white noise (Frehlich and Yadlowsky, 1994):

$$p(\hat{v}) = \frac{b}{2v_N} + \frac{1-b}{\sqrt{2\pi}g} e^{-\frac{(\hat{v}-v)^2}{2\sigma^2}} \tag{8}$$

The Gaussian is more pronounced for a higher SNR (a smaller value of b) or less pronounced for a low SNR (a higher value of b). In other words, a low SNR increases the chance that the estimated Doppler velocity estimate is drawn from the white noise part of the pdf. To avoid a selection of these noise caused estimates, consensus averaging achieves a nonlinear digital filtering (or suppression) of bad estimates. The consensus methods has therefore the following two purposes:

1. It acts as a decision statistics to discriminate between (false) Doppler estimates caused by random noise peaks and (correct) estimates which are due to stationary atmospheric returns.
2. It is a homogeneous, nonlinear estimator for the Doppler velocity that includes outlier suppression

Other nonlinear filters are possible as well (for instance the Median), but consensus has proven its robustness and accuracy Strauch et al. (1984). The principle is illustrated in Figure 7. It is certainly possible to use other a-priori a-priori information for signal detection, like a statistically derived minimum SNR threshold (Riddle et al., 2011), but the consensus based method has clearly its strengths.

2.5. Consequences of clutter echoes and RFI for signal processing

Historically, the development of RWP signal processing was based on the assumption that the voltage signal at the antenna output port is comprised of only two stationary components: The atmospheric contribution due to Bragg scattering and the ubiquitous thermal noise of the receiver electronics. Insufficient hardware capabilities were also a limiting factor that prevented the use of overly sophisticated processing method for quite some time. In the last decade, the hardware capabilities have been drastically improved, however the development and implementation of processing algorithms has proceeded at a much slower pace and some of the limitations in current RWP systems are therefore rather legacy problems.

In the presence of clutter echoes, the receiver signal becomes multi-component and it may even become non-stationary. Consequently, the assumptions used for deriving the standard signal processing are no longer fulfilled and the signal processing needs to be modified to filter the unwanted contributions and retrieve the atmospheric echo.

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 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; Lehmann, 2011).

Stationary clutter components will give rise to a Doppler spectrum with additional (multiple) signal peaks. Examples are ground clutter echoes (e.g. Fig. 6) and RFI signals (e.g. Fig. 5). Such a situation needs to be accounted for. It is obvious, that especially the consensus method is unable to discriminate between a signal that is due to the atmospheric echo and any other stationary clutter or RFI signals.

To remedy this problem, a variety of so-called multi-peak algorithms have been proposed. Among them are simple and robust 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; Weber et al., 2004). The number of existing algorithms is symptomatic for the many different approaches to tackle the multiple peak problem. Unfortunately, there are only very few validation attempts (Cohn et al., 2001; Gaffard et al., 2006; Hooper et al., 2008). The operational experience is unfortunately still indicative of problems with almost all of these complex methods. The most important problem in these algorithms is the excessive use of weakly justified a-priori assumptions, like vertical continuity constraints, for peak selection. More work is needed to assess and refine multi-peak processing.

2.6. 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. 8. 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:

$$\begin{pmatrix} \sin(\alpha_1)\sin(\varepsilon_1) & \cos(\alpha_1)\sin(\varepsilon_1) & \cos(\varepsilon_1) \\ \sin(\alpha_2)\sin(\varepsilon_2) & \cos(\alpha_2)\sin(\varepsilon_2) & \cos(\varepsilon_2) \\ \sin(\alpha_3)\sin(\varepsilon_3) & \cos(\alpha_3)\sin(\varepsilon_3) & \cos(\varepsilon_3) \\ \sin(\alpha_4)\sin(\varepsilon_4) & \cos(\alpha_4)\sin(\varepsilon_4) & \cos(\varepsilon_4) \\ \sin(\alpha_5)\sin(\varepsilon_5) & \cos(\alpha_5)\sin(\varepsilon_5) & \cos(\varepsilon_5) \end{pmatrix} \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} v_{r1} \\ v_{r2} \\ v_{r3} \\ v_{r4} \\ v_{r5} \end{pmatrix}$$

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, during strong gravity wave activity or in patchy precipitation (Adachi et al., 2005). A discussion of the DBS method can be found in Koscielny et al. (1984); Strauch et al. (1987); 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.

2.7. Postprocessing data quality control

Most RWP perform an additional quality control (QC) processing of the final wind measurements to detect and remove erroneous data. This check can be based on spatio-temporal continuity and internal consistency of the measurements. An example for the first option is the QC method developed by Weber and Wuertz (1991), see also Weber et al. (1993). This method utilizes checks for consistency between adjacent data points using a technique that is based on pattern recognition methods. Spurious data points are highlighted and can be automatically rejected in an operational setting. The general problem with continuity based methods is that it is difficult to draw a line between good and bad measurements that is solely based on continuity. Furthermore, RWP wind profile measurements are not always vertically contiguous, so it is difficult to objectively judge a cluster of equally looking winds that is detached in height and/or time from the bulk of the other measurements.

Consistency checks can also be based on a verification of underlying assumptions, like wind field linearity, spatial homogeneity and stationarity, see e.g. Hooper et al. (2008); Goodrich et al. (2002) or even on simple thresholds based on climatology (Lambert et al., 2003). The main advantage of this approach is its simplicity. For example, a homogeneity test of a 5-beam DBS wind measurement can be easily implemented on the basis of the five radial velocity values. Any inhomogeneity can only be due to either an inhomogeneous wind field itself, or due to clutter issues in individual beams. In both cases it is prudent to flag the measurement as dubious and to exclude it from operational data dissemination. Of course, such checks are by definition unable to remove all erroneous data, so they must be understood only as a last resort.

3. Operational aspects

There can be no doubt that high-quality wind observations of RWP are beneficial for NWPM, but the challenge for operational networks is to provide such 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. Additionally to the previous discussion, a few important practical aspects of the operational use of RWP are given in the following.

3.1. 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 recently undertaken to investigate the best possible protection from this RFI source in the future.

The sharing of profiler frequency bands with other services is obviously inescapable, but coexistence is often possible. Of advantage is the nearly vertical direction of the profiler beams, which naturally enhances the protection against horizontally propagating waves as they are used in terrestrial communication links. An example: 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 rare and 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 QC procedures must consider such potentially quality-degrading interferences, with the goal of eliminating all spurious data in such cases.

3.2. System setup and signal processing

Wind profilers were developed for research and it is therefore no surprise, that both sampling and processing can be set-up in a variable way. After the first commercial radars were available, most research users were indeed 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, even the chain of signal processing algorithms can be fully configured. That is, the operator can not only 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 whole processing steps can be daisy-chained in various ways. This option has clear advantages for addressing site-specific clutter issues, but deriving a good set-up requires experience. 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.

3.3. Technical issues and the importance of monitoring

A continuous data quality evaluation is necessary for operational profilers, because the systems are unattended and there is usually no operator at the site for intervention in case of technical malfunctions. In contrast to the situation with one-time usage instruments like Radiosondes, technical failures of a radar will lead to data quality issues which are going to persist

*http://www.erodocdb.dk/Docs/doc98/official/pdf/ECCREP090.PDF over time until they are resolved. Such problems can lead to serially correlated errors in the data (Daley, 1992) which can hardly be dealt with correctly in current NWP data assimilation schemes.

Fortunately, a specialist is usually able to narrow down the technical problem(s) remotely, 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 pointed toward a hardware problem in the beam steering unit (phase shifter). As this could not be explained by any scattering or echoing mechanism, a hardware issue was suspected and a subsequently scheduled site visit indeed identified a failure in the beam steering unit of the profiler.

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 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 data. A very important tool in that respect is the monitoring information provided by state-of-the-art NWPM's. 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 misalignment in height of the high mode data of 470 m. This lead to a negative bias of the wind speed below and a positive bias above the wind maximum. The effect is also 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 a hardware component on Jan 08, 2008. Although the spare part was apparently identical in hardware, the system delay was obviously different. As this was not expected at the time of the replacement, the system delay was consequently not re-calibrated. This case is an example that clearly demonstrates the usefulness of the monitoring information provided by NWP models.

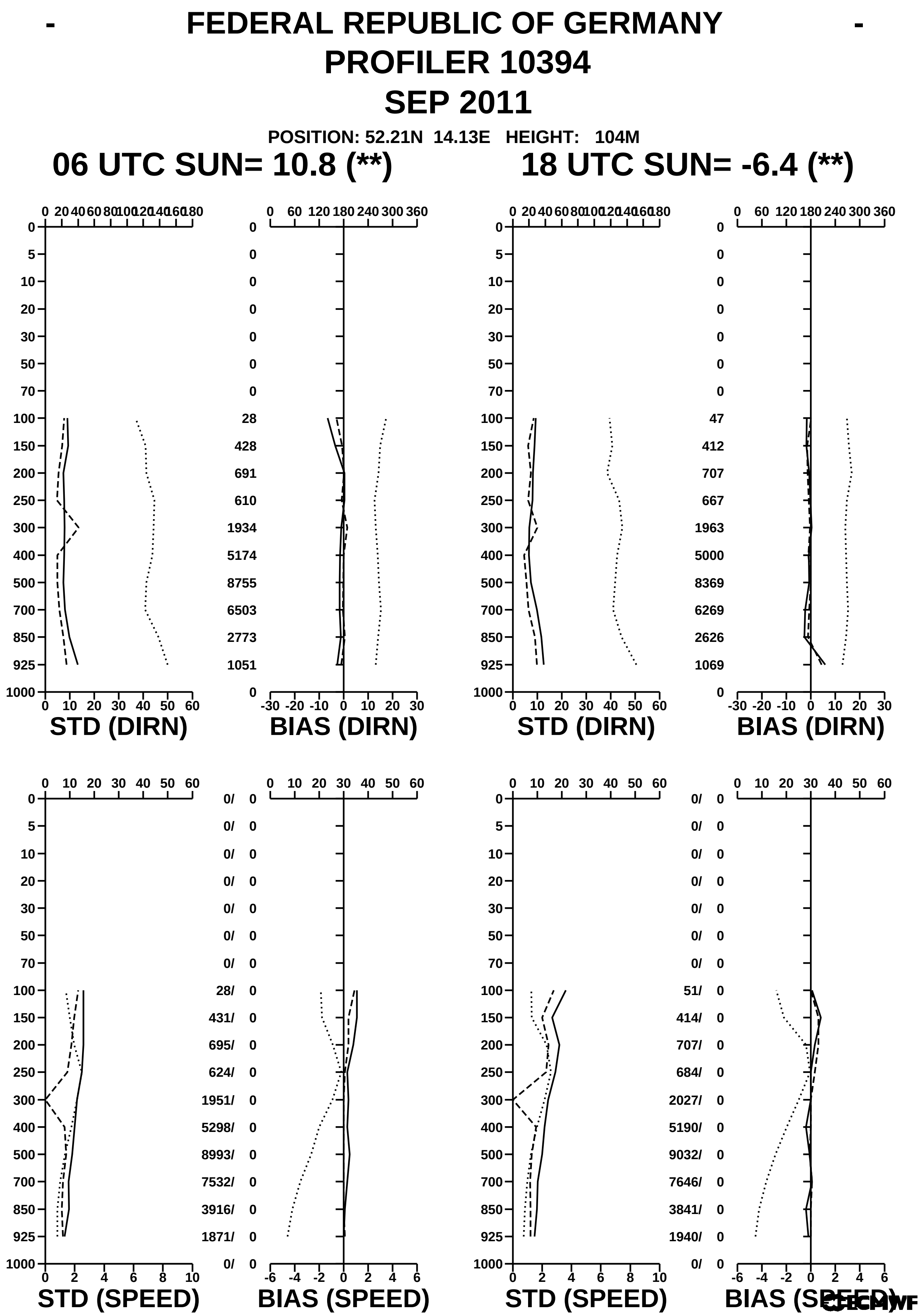

Figure 1. Monitoring statistics of the ECMWF T1279L91 NWPM for data provided by the European wind profiler 10394, for September 2011. Full line is OBS-FG, the dashed line OBS-AN and the dotted line the observation mean. (Graphics courtesy of ECMWF)

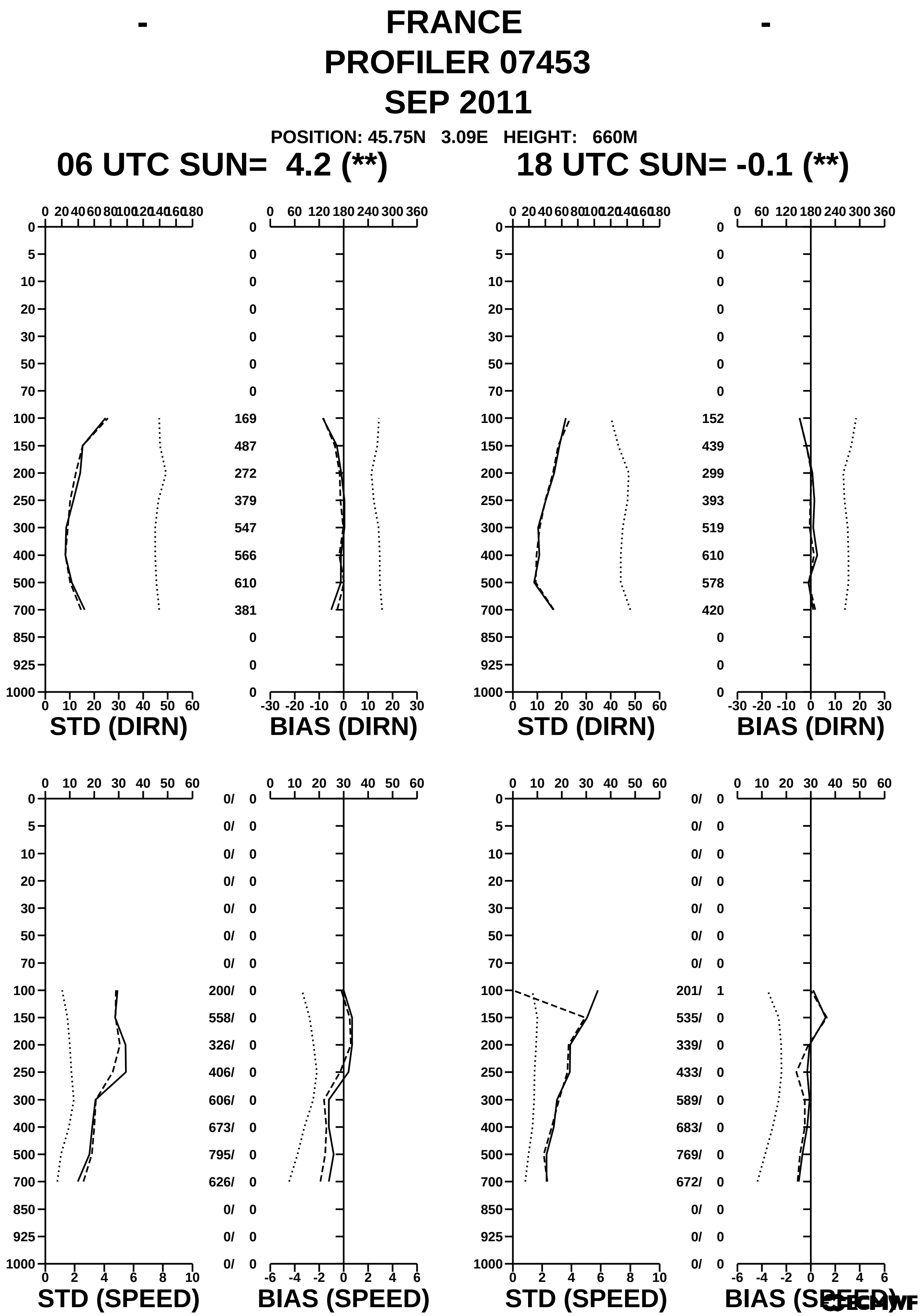

Figure 2. Same as Fig.1, but for the European wind profiler 07453. (Graphics courtesy of ECMWF)

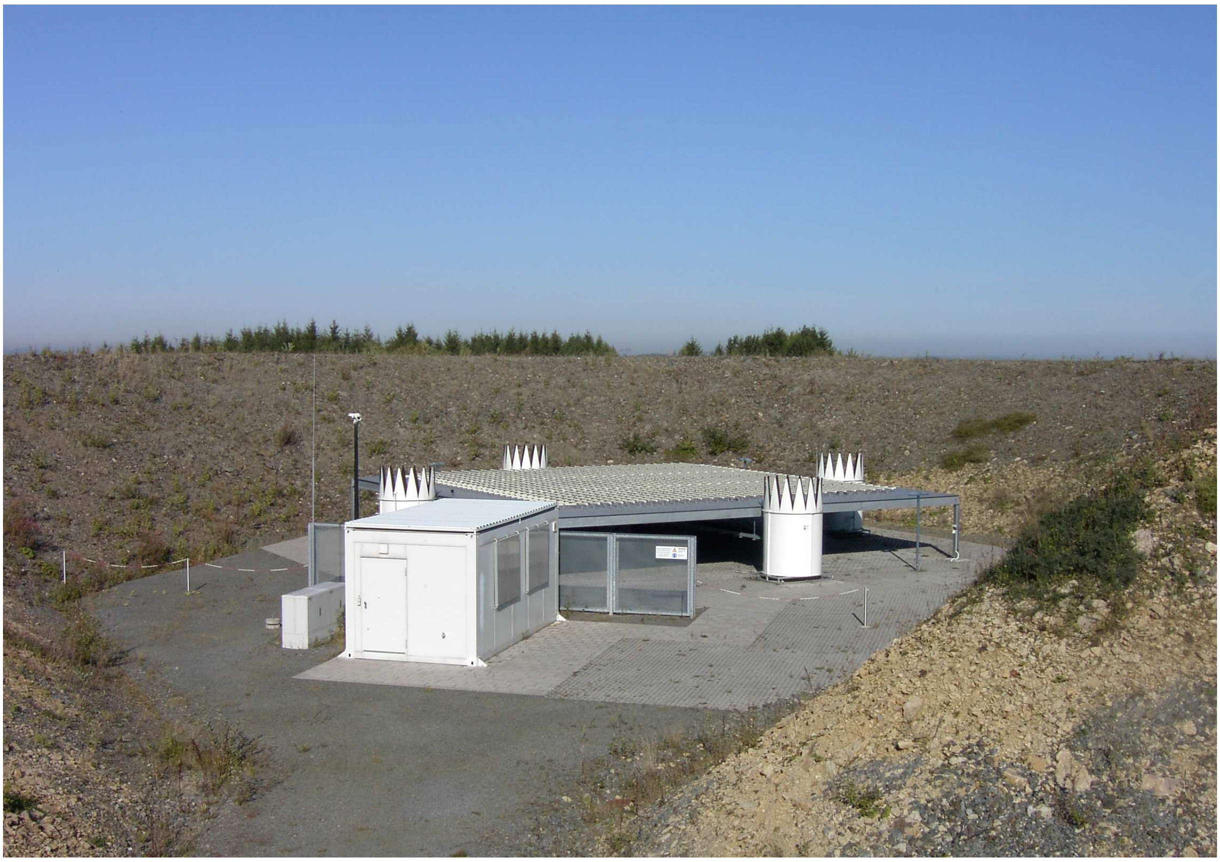

Figure 3. Photograph of the 482 MHz RWP installation of DWD at Bayreuth (Oschenberg), showing the antenna array platform surrounded by four acoustic sources for RASS and the shelter containing the radar electronics.

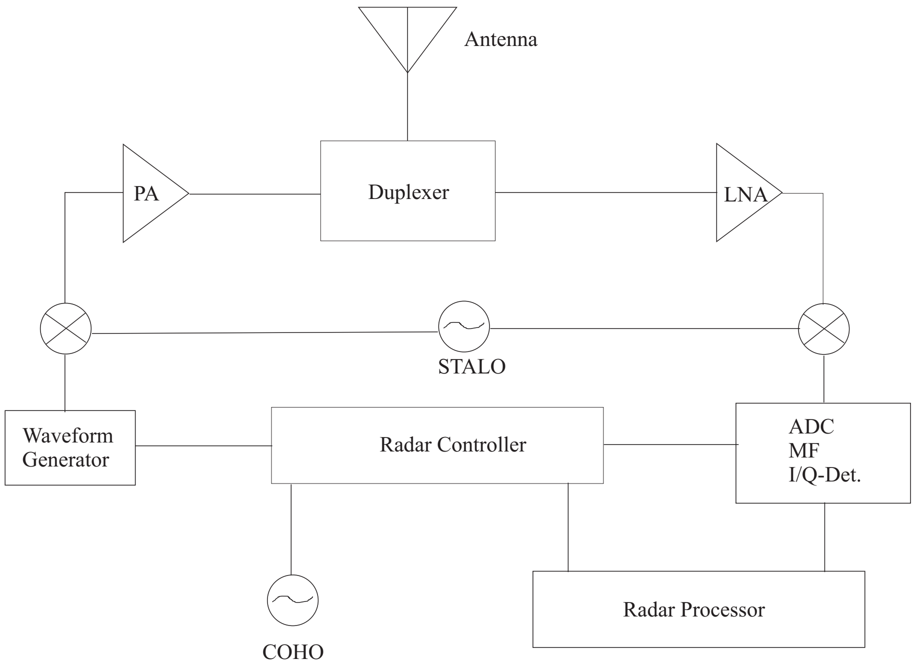

Figure 4. Simplified block diagram of a typical DBS radar wind profiler

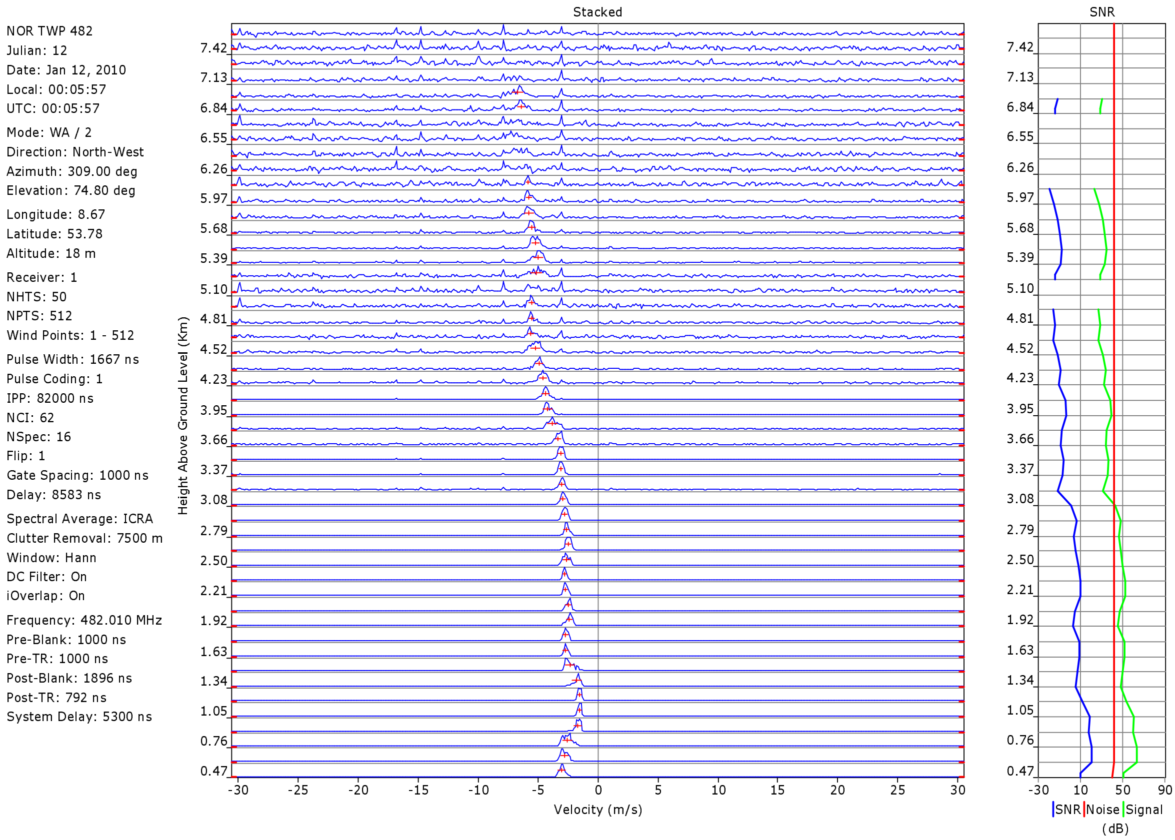

Figure 5. Stacked Doppler spectra obtained with the 482 MHz RWP at Nordholz, Germany, on January 12, 2010 at 00:05:57 UTC. External Radio Frequency Interference due to an external digital television signal is visible in the upper gates.

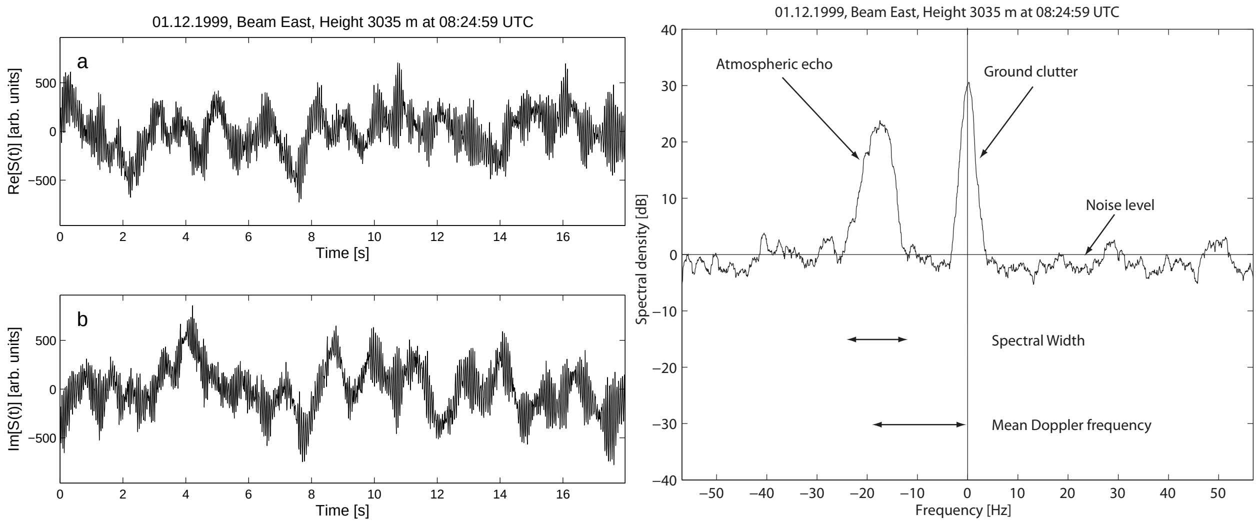

Figure 6. Coherently average I/Q time-series (left) and estimated Doppler spectrum (right) of a 482 MHz radar wind profiler (adapted from Muschinski et al. (2005). Visible are two distinct signal components (atmospheric echo and clutter) and noise.)

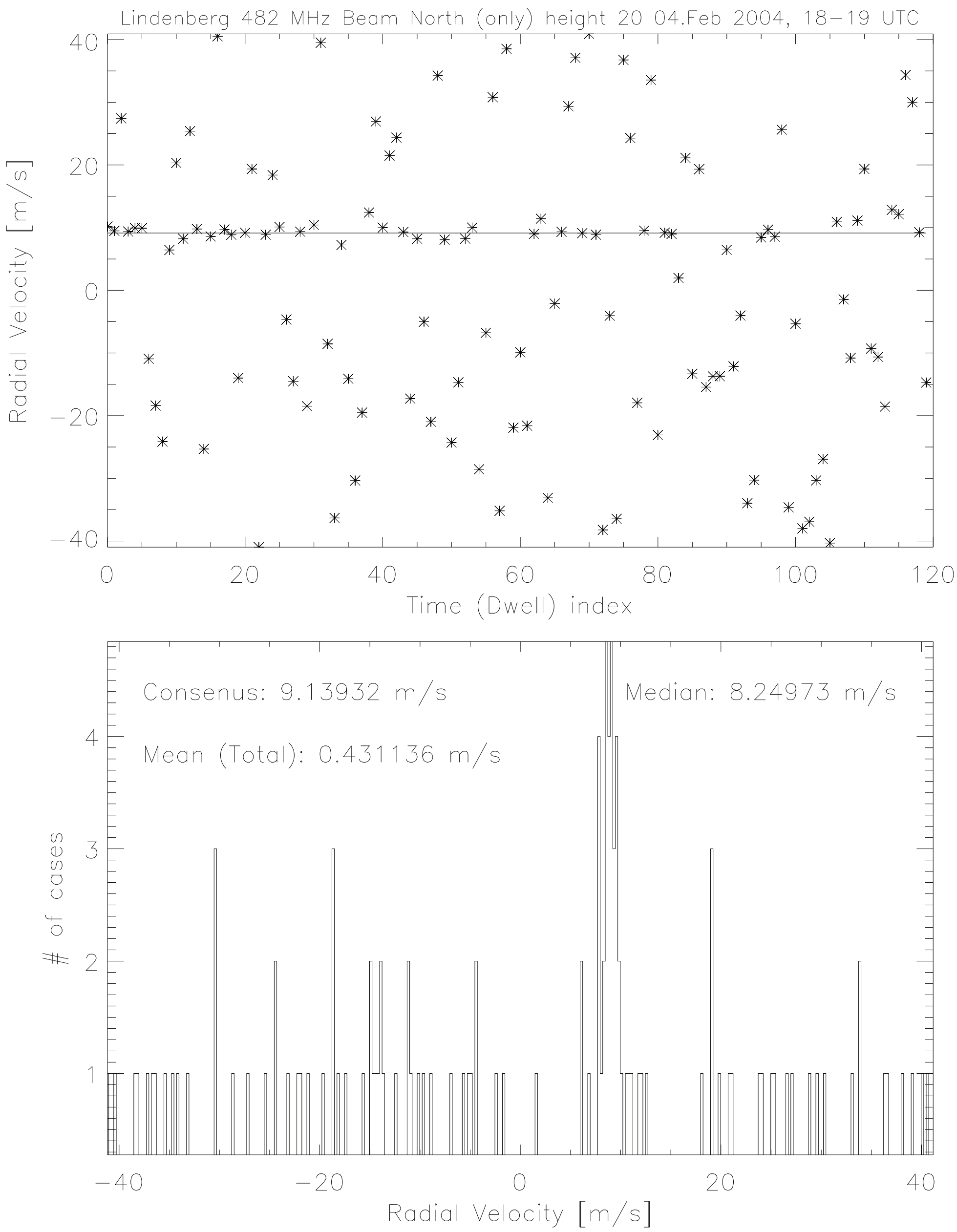

Figure 7. Illustration of the consensus principle: The upper part shows the distribution of 120 individual maximum energy based estimates for the Doppler velocity at one range gate of a UHF wind profiler measured over one hour. The line shows the consensus estimate. The lower part shows the histogram (distribution) of the individual estimates. Note that this resembles the pdf discussed above. A distinct maximum of Doppler estimates can be seen near 9 m/s - this is in agreement with the value estimated by the CNS. Median values and arithmetic mean are given for comparisons.

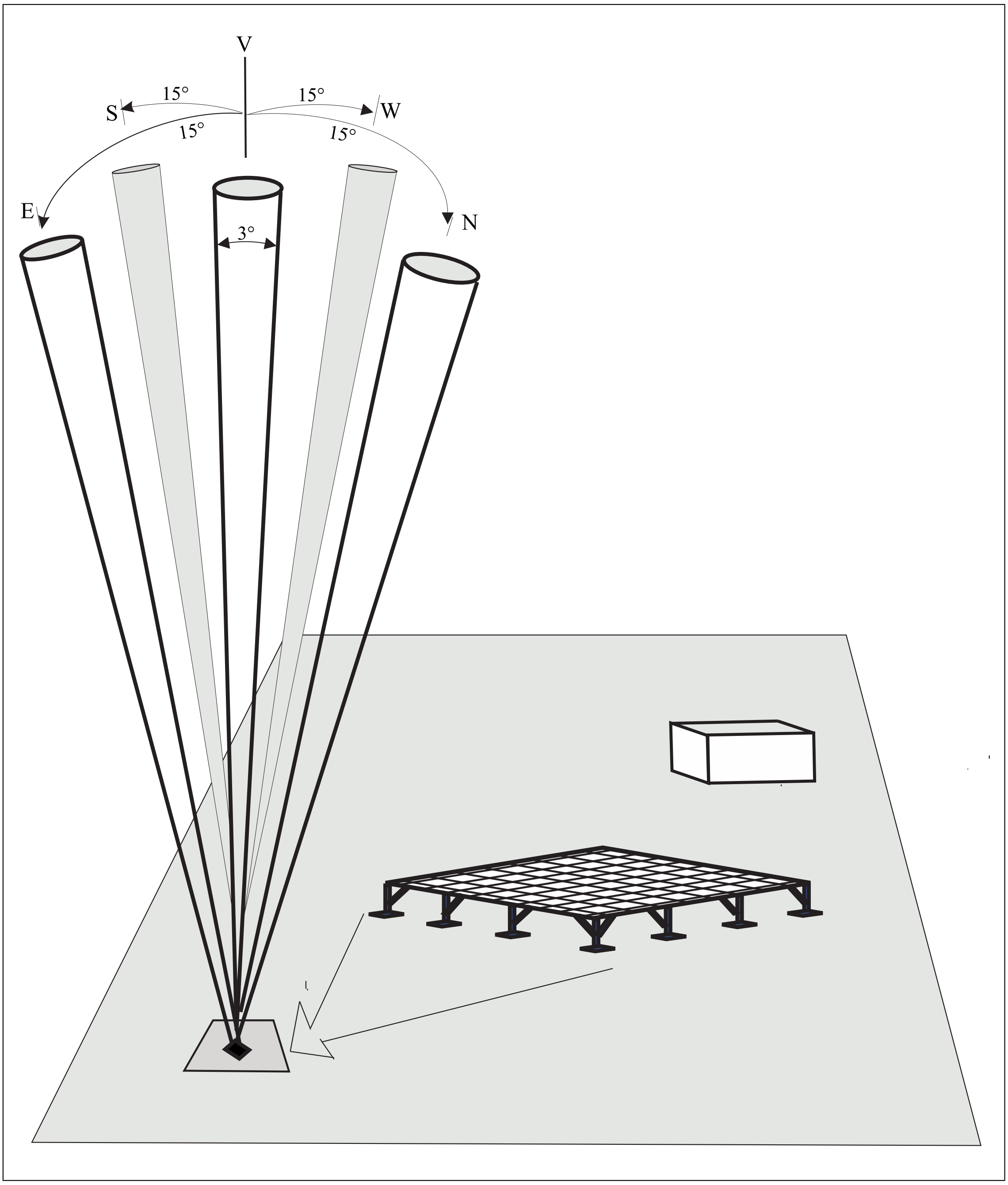

Figure 8. Beam pointing configuration of a five-beam DBS radar wind profiler

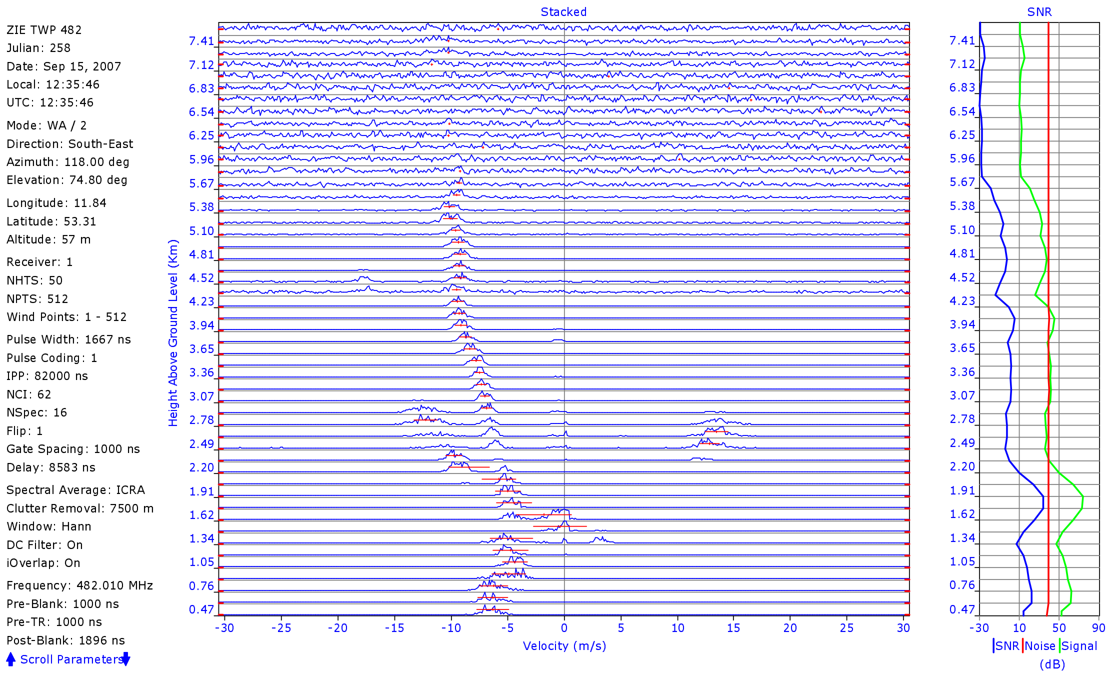

Figure 9. Stacked Doppler spectra obtained with the 482 MHz RWP at Ziegendorf, Germany, on September 15, 2007 at 12:35:46 UTC. Several irregularly distributed signal peaks are visible. This unusual data lead to the assumption of a hardware failure in the beam steering unit which was later confirmed by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

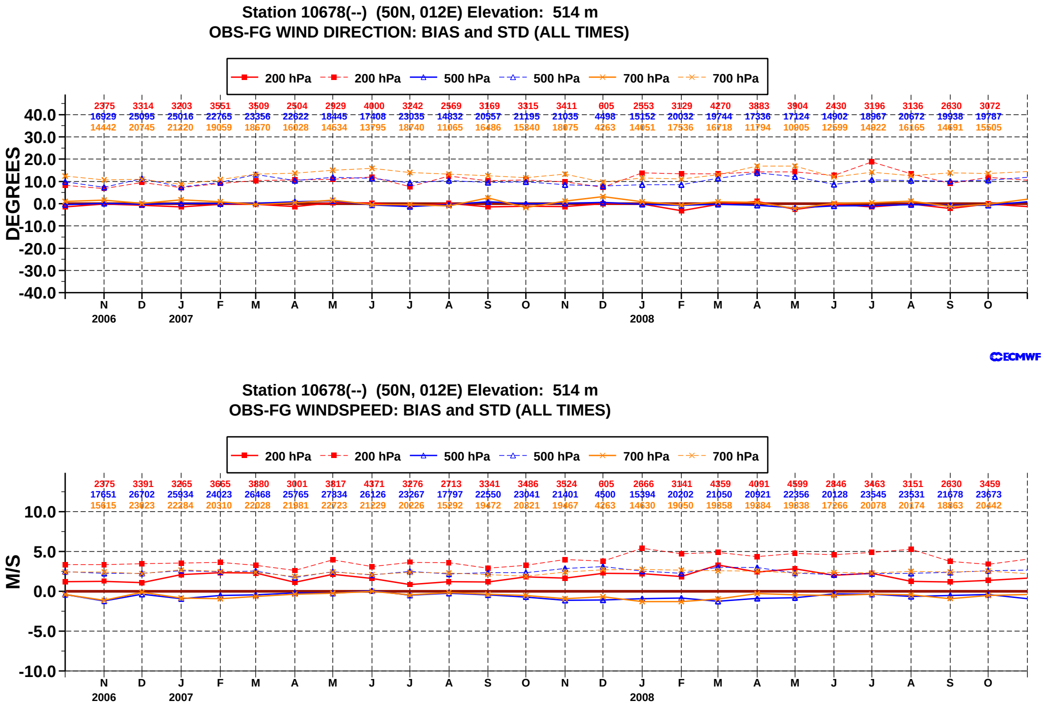

Figure 10. Time-series of the monitoring statistics of the ECMWF T799L91 model (Observation - First guess) for data provided by the 482 MHz RWP at Bayreuth, Germany, from October 2006 until October 2008. (Graphics courtesy Antonio Garcia-Mendez, ECMWF). For the 200 hPa level, the values of the standard 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.

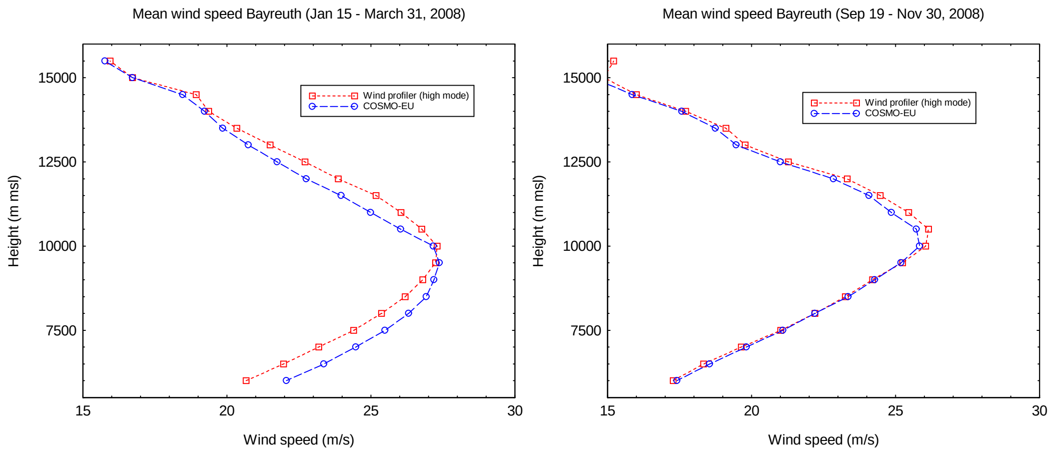

Figure 11. Vertical profile of the mean horizontal wind speed as measured by the high mode of the 482 MHz RWP at Bayreuth and analyzed by the COSMO-EU model of DWD for two time periods. The period from Jan 15- Mar 31 clearly shows a clear vertical shift between the two profiles. This is not the case 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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