

Ground based VHF radar for observations of the atmosphere

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Abstract Radar is used to make measurements of the dynamics and structure of the atmosphere by detecting irregularities in refractive index due to variations in humidity and temperature in the lower atmosphere ($0 - 20$ km), and due to variations due to fluctuations in electron density in the Mesosphere Lower Thermosphere (*MLT*) region of the upper atmosphere ($50 - 110$ km). Wind Profiling Radars operating in the lower *VHF* band have been used for about 25 years to investigate the Stratosphere Troposphere (*ST*) region, but only routinely in the last 15 years. Considerable development has occurred within the past decade and a number of rocket launch sites now utilize Wind Profilers for launch support. They are also becoming increasingly common for airport operations. Here we provide a very brief overview.

Key words: VHF Radar, Wind Profiler, BLT radar

1. Introduction

Wind profilers are atmospheric radars specifically designed to measure vertical profiles of horizontal wind speed and direction from near the surface to above the tropopause. They are also capable of providing height profiles of virtual temperature and turbulence intensities. Profilers generally operate at a fixed frequency and are roughly categorized by the three frequency bands allocated by the International Telecommunications Union (*ITU*) to their operation. These are bands around 50 MHz, 400 MHz and 1 GHz. Generally, the highest operational height decreases with increasing frequency and the range resolution improves with increasing frequency. The GHz profilers are used for Boundary Layer (*BL*) observations (< 3 km) while the *VHF* systems are used for the *ST*-region. Several networks of profilers now operate and profilers are gaining acceptance as a regular part of the meteorological observational network. The European experience is comprehensively summarized by *Dibbern et al.*, (2003) and *Benjamin et al.* (2004) discusses the US experience.

Profilers are also being installed at rocket launch sites for both launch support and as complementary instruments for research rockets. For example, a profiler was installed at Kennedy Space Centre in 1990 for launch support (*Schumann et al.*, 1999) and research systems / profilers are installed at the Swedish launch facility at Kiruna (see e.g., *Chilson et al.*, 2002) and at the Norwegian launch facility at Andøya¹. Recently the Japan Aerospace Exploration Agency (*JAXA*) installed a profiler at Woomera to support the *SST* trials there², and a number of profilers have been installed at launch sites in China (see *Figure 5*). These all operate at frequencies near 50 MHz. It is noteworthy that India is currently planning a 200 MHz profiler at its *SHAR* launch facility, but this frequency is not one allocated by the *ITU* to Wind Profiler operation and is not available in most locations.

In this paper we will concentrate on radars operating in the 50 MHz band. However, we briefly note the various radar types that can be used to measure neutral wind velocities in the *ST*-region in

¹ http://www.iap-kborn.de/radar/Radars/ALWIN/index_eng.htm

² <http://www.iat.jaxa.jp/info/prm/2005/009/01.html>

Table 1 below.

2. Background

Most atmospheric radars for wind profiling operate in a monostatic configuration in a pulsed mode and utilize backscatter from irregularities in the refractive index of the atmosphere. Operating frequencies range from around 45 to 1000 MHz, with the higher frequencies being utilized for observations in the lowest part of the atmosphere. Some of the various radar types are summarized in Table 1. The diurnal variation in performance for MLT radars reflects the solar control of the ionization of the 60 to 80 km height region, and the consequent availability of free electrons to act as tracers for the neutral motions.

There are two main mechanisms believed to result in the return of radio waves from irregularities in the atmosphere of interest here. These are scattering from turbulence (“Turbulent” Scatter), and Fresnel Reflection or Fresnel Scatter.

less than about $\lambda/4$. In practice, the minimum horizontal extent of the irregularity needs only be greater than that of the radar beam, and steps in refractive index of vertical extent less than $\lambda/4$ will often contain Fourier scales strong enough to produce radar returns. Fresnel scatter results when the scattering medium is coherent in the two dimensions transverse to the probing wave, and random in the direction parallel to the radiowave vector.

Atmospheric radars use the gradients in the refractive index as targets to determine the motion of the background wind and turbulence intensity using a variety of techniques. The refractive index, n , of air at frequencies greater than around 30 MHz is given by

$$n = 1 - 0.373 \frac{e}{T^2} + 77.6 \times 10^6 \frac{p}{T} - 40.3 \frac{N_e}{f^2}, \quad (1)$$

where e is the humidity, T the temperature, p the pressure, N_e the electron density and f the frequency. Fluctuations in e , T and N_e with a scale the order of half a wavelength produce Bragg scatter. Discontinuities in refractive index of the order of less than a tenth of a wavelength also act as targets.

The second two terms in equation (1) refer to fluctuations in the neutral atmosphere, with the humidity term dominating at heights below around 5 km. The last term refers to fluctuations in electron density in the ionosphere, and is important at heights above around 50 km.

The nature of the irregularities themselves is not well understood. However, there are two limiting cases. These are scatter from isotropic turbulence and scatter from a single, sharply bonded discontinuity. The power P_R returned in the case of isotropic turbulence when volume scatter occurs is given by

$$P_R = \frac{\pi P A \alpha \Delta R}{64 R^2} \eta, \quad (2)$$

where P is the transmitted power, A is the effective antenna area, α is the total efficiency factor of the system, ΔR the radar pulse length range, R the range, and η the volume reflection coefficient, a measure of the strength of the turbulence.

Scatter also occurs from sharp steps or gradients in refractive index. In this case, the scatter is termed Fresnel scatter or Fresnel reflection. The power returned is given by

Type	Frequency	Winds
Mesosphere Stratospheric Tropospheric (MST) Radars	45 – 65 MHz	1 – 20 km 60 – 80 km (day)
Stratospheric Tropospheric Radars	45 – 65 MHz	1 – 20 km
	400 – 490 MHz	0.5 – 18 km
Boundary Layer Troposphere (BLT) Radars	45 – 65 MHz	0.2 – 8 km
Boundary Layer (BL) Radar	915 – 1300 MHz	0.1 – 3 km

Turbulent (or Bragg) scatter results from the production of irregularities in refractive index by turbulence, for which the dominant Fourier scales correspond to half the projection of the wavelength of the radar onto the radiowave vector. Fresnel reflection (also known as partial reflection) results from the presence of irregularities in refractive index transverse to the radio wave propagation direction that are thin compared to the radar wavelength. For vertical incidence, true Fresnel reflection requires that the horizontal extent of the irregularity be greater than one Fresnel zone, which is $(\lambda z)^{1/2}$, where λ is the wavelength and z the height of scatter, and that the vertical extent of the irregularity be

$$P_R = \frac{PA^2\alpha}{4\lambda^2R^2}|\rho|^2, \quad (3)$$

where λ is the radar wavelength, and ρ is the amplitude reflection coefficient.

Radar returns from the atmospheric at frequencies lower than *UHF* usually consist of a mixture of both Bragg and Fresnel types of scatter, and exhibit considerable aspect sensitivity, with maximum returns from the zenith.

The performance of an atmospheric radar system can be roughly described by the product of P and A , the ‘‘power aperture product’’ that appears in equations (2) and (3). Here we will concentrate on *50 MHz* profilers, and generally, at *VHF*, a power aperture product exceeding around $5 \times 10^7 \text{ Wm}^2$ would provide a measurement capability throughout the *1* to *15 km* height region, and provide a limited daytime mesospheric (*60 – 80 km*) measurement capability. There are two main approaches used for *50 MHz* Wind Profiling radars. These are the Doppler Beam Swinging (*DBS*) technique and the Spaced Antenna (*SA*) technique. Most current *VHF* radars utilize the *DBS* technique.

3. 50 MHz Wind Profiling Radars

3.1. Doppler Beam Swinging (*DBS*) Technique

The *DBS* technique uses multiple narrow Doppler beams to measure the radial velocity v_r in a number of beam directions. An idealized power spectrum $P(f)$ of a radar time series for one beam is shown in *Figure 1*.

The Doppler shifted scattered signal can be characterized by the first three moments of the spectrum; the height P_s , the mean Doppler shift, f_D and the width of the spectrum, $W(f)$. The radial velocity is related to the mean Doppler shift of the spectrum f_D , as $v_r = -\frac{\lambda}{2}f_D$. The width of the signal is a measure of the effect of turbulence, and of the finite beam-width and vertical shear in the horizontal velocity within the radar pulse volume (see e.g., *Doviak and Zrnica, 1993*).

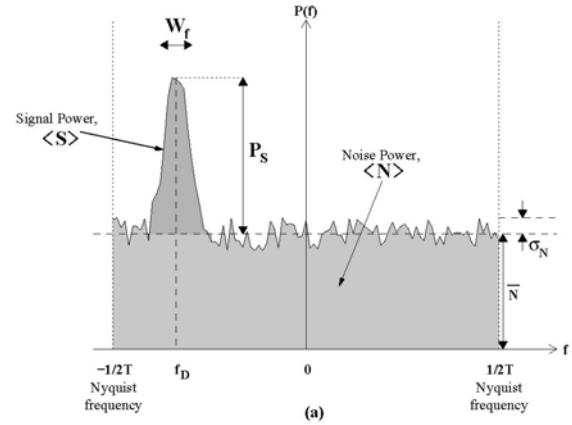


Figure 1: Schematic of the Doppler spectrum $P(f)$ showing the mean Doppler shift in terms of frequency, the spectral width, noise and signal powers.

The relationship between the zonal (u), meridional (v) and vertical velocities (w) and the radial velocity in terms of the azimuth (ϕ) and zenith angles (θ) is

$$v_r = u \sin \phi \sin \theta + v \cos \phi \sin \theta + w \cos \theta, \quad (4)$$

where $U = (u, v, w)$. Inspection of this equation indicates that a minimum of three beams are required to recover the three dimensional wind field. In fact, most Doppler radars now utilize a symmetric five-beam arrangement, both for redundancy in the measurement of the horizontal wind and also to permit the determination of additional parameters including the density normalized upward flux of horizontal momentum (see e.g., *Vincent and Reid, 1983*).

A major consideration with radars operating in the lower *VHF* band is the effect of the atmospheric aspect sensitivity on the antenna polar diagrams. For the *DBS* technique, with off-vertical beams, the effect is to bias the polar diagrams back towards the zenith. With relatively broad beams (or relatively small antenna arrays, say $> 4^\circ$) the effect can result in severe underestimation of the radial velocities. However, by steering the beam off-zenith by at least 15° this effect can be minimized and relatively small antenna arrays (array dimensions of around eight wavelengths, so beamwidths $\sim 7^\circ$) can be used.

This is the configuration used with the Woomera *VHF ST* radar system and the *Vaisala LAP-12000* wind profiler installed

for the UKMO in northern Scotland [see e.g., Winston, 2004] and at a number of sites in China (see Figure 5). It is the most common configuration provided by ATRAD Pty Ltd³. Photographs of such a radar array are shown in Figure 2a, b and the corresponding schematic is shown in Figure 3.



Figure 2a (left): Photograph of the Jiuquan Wind Profiler in China with the launch facilities in the background. There are 144 Yagi antennas arranged on a square grid. The radar equipment is housed in the building to the centre left of the image. Figure 2b (right): The Jiuquan VHF radar, showing the antenna array. The individual antennas are three element Yagis with a folded dipole driven element. The basic array square grid spacing is $\lambda/\sqrt{2}$, which makes the largest inter-antenna distance λ . This ensures that there are no grating lobes associated with the array polar diagram. There are 36 feeds into the array. These are split into 4 separate feeds which then drive 4 separate individual antennas. This arrangement is shown schematically in Figure 3 below. The radar beamwidth is about 7° and the 5 radar beams are directed E, W, N, S and vertical at 15° off-zenith in sequence. The array dimensions are given in wavelengths. For frequencies near 50 MHz the array dimension is about 50 m on edge.

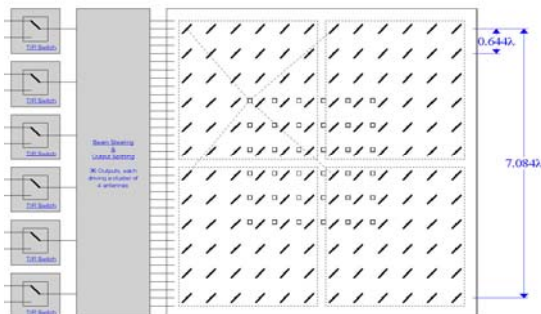


Figure 3: Schematic of the profiler antenna array shown in Figure 2

Typical results for several days of operation of the Woomera radar are shown in Figure 4 below and the operating parameters for this period are shown in Table 2. Because of logistical considerations, this radar operated only as required to support rocket launches.

Peak power	82 kW
Pulse repetition frequency, Hz	6720
Number of coherent integrations	336
Effective sampling time, s	0.05
Number of samples	1100
Time series length, s	55
Pulse type	Uncoded/Gaussian
Pulse width, m	600
Receiver filter width, kHz	72.5
Start height, km	1
End height, km	19.6
Sampling range resolution, m	300
Transmitter output power, %	100
Receiver gain, dB	80

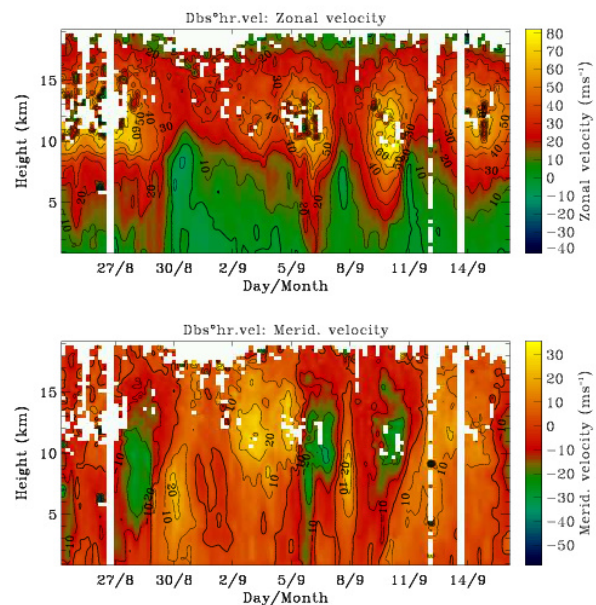


Figure 4: Wind velocity measurements as a function of height and time from the Woomera Profiler for several days. Maximum height is about 18 km.

This basic Wind Profiler type shown in Figures 2 and 3 has been installed at a number of locations around the world as shown in Figure 5. A number of these systems also have the capability of operating in spaced antenna mode which we now discuss.

3.2. Spaced Antenna Techniques

Another technique, which does not require the formation of narrow off-zenith beams or for beam steering, is becoming more common for smaller Wind Profilers operating in

³ www.atrad.com.au

the Boundary Layer and lower Troposphere. This is the Spaced Antenna (SA) technique. The *DBS* and *SA* methods use the same information. The *DBS* technique exploits the change in the mean Doppler shift with azimuth angle, and samples small spatially separated volumes.

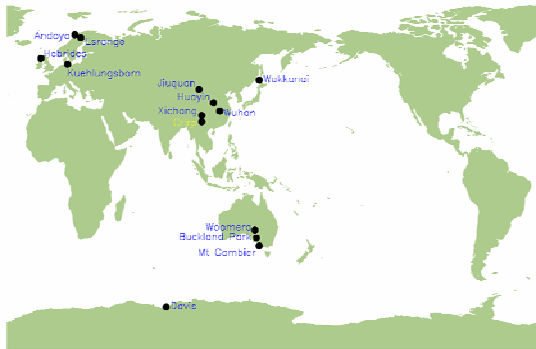


Figure 5: Location of ATRAD Wind profiling radars based on the schematic design shown in Figure 3. Radars at Buckland Park, Mt Gambier, Wakkanai, Hebrides, Wuhan and Kuhlungsborn are used for atmospheric research. The remainder are located at launch facilities. The radars at Hebrides, Jiuquan, Huayin and Xichang are joint Vaisala / ATRAD projects.

The *SA* methods make use of the fact that the variation in the Doppler shift with angle is such that the resultant electric field moves over the ground as a random pattern with a velocity twice that of the horizontal wind at the backscatter height (Briggs, 1980). A minimum of three receiving sites are required to sample the ground diffraction pattern and correlation techniques are then used to infer the velocity of the irregularities producing the diffraction pattern and hence that of the wind. The advantage of *SA* techniques is that small antenna arrays can be used, because only broad, vertically directed beams are required.

For the *SA* technique, the aspect sensitivity of the atmosphere results in a narrowing of the vertically directed beam pattern, and this generally has no adverse effect on the technique. There are several variants of the technique that utilize various antenna arrangements, which result in the same basic data, but which are analyzed in different ways (see e.g., Holdsworth and Reid, 2004).

Reid et al. (2005) in summarizing the operation of a 144 Yagi antenna 50 MHz *SA* system suggest that the most appropriate

technique for a *VHF* profiler with an array size greater than around 8 to 10 wavelengths diameter is the *DBS* technique, applied with off-zenith beam angles of around 15°. When observations are only required to altitudes of 6 to 8 km, the *SA* technique applied on small (27 antenna) arrays with peak powers of around 10 kW may be the most appropriate technology. These smaller profilers have the advantage of compactness and simplicity, in that no beam-forming or beam-steering is required. Furthermore, they are able to make wind measurements down to heights of about 300-m. Larger 50 MHz *DBS* systems are limited to starting heights near 1 km because of the need to form beams (and so for larger antenna arrays) and by their higher powers (and so for higher power / slower *T/R* switches). At many locations *BLT* radars are able to make wind measurements well into the tropopause as shown by one example in Figure 7a.

3.3. The Boundary Layer Troposphere (BLT) VHF Radar

This spaced-sensor technique was first applied to small Boundary Layer Tropospheric (*BLT*) radars operating at frequencies near 50 MHz by Vincent et al., (1998). They used 12 antennas arranged in three groups of four antennas. It has more commonly been applied using 27 antennas arranged in three groups of nine antennas, but has also been successfully applied with three antennas.



Figure 6a: Photo of the Sydney Airport BLT radar system.

An example of this radar type is shown in Figure 6a, b. This system operates at 55 MHz with a peak power of 7.5 kW. The array consists of three groups of nine three-element Yagi antennas and the system has a PA product of $3.5 \times 10^4 \text{ Wm}^2$. Other operating parameters are given in Table 3. This system is installed at Sydney Airport and is operated by the Australian Bureau of Meteorology as an operational profiler. They operate others at

Canberra and Launceston Airports. Adelaide University operates a BLT radar at Adelaide Airport and near Darwin. Results from these radars are available online⁴. An example of the application of this type of radar in a research campaign is given by Vincent *et al.* (2004).

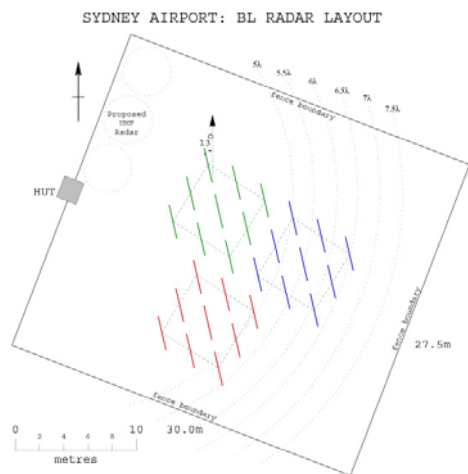


Figure 6b): Schematic showing the spaced antenna layout for the Sydney BLT system. Data from the three antenna sub-groups are used with the FCA analysis to yield horizontal wind velocities in the 0.3 to 8 km height region. .

Figure 7a, b show typical wind velocities obtained in low and high mode operation for the Sydney BLT radar. The displays use the meteorological convention for wind direction and magnitude with the additional of color for clearer display of magnitude. Note that winds are regularly obtained down to about 300-m and up to 4-km, and that winds are measured to 8-km much of the time.

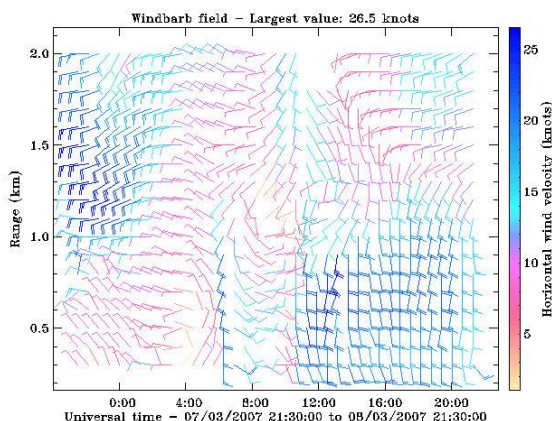


Figure 7a: Winds for low mode operation of the Sydney BLT radar.

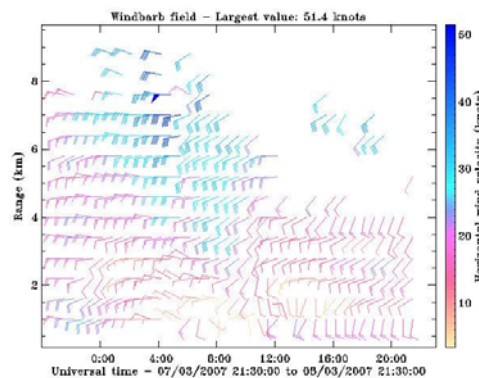


Figure 7b: Winds for high mode operation of the Sydney BLT radar.

Table 3. BLT Profiler Typical Operating Parameters		
Operating Parameters	Low Mode	High Mode
PRF, Hz	20,000	8000
Pulse length, m	100	600
Range, km	0.3– 3.8	2.0– 10.0
Range sampling, m	100	300
Receiver bandwidth, kHz	404	253
Coherent integrations	1000	400
Number of samples	1100	1100
Acquisition length, s	55	55
Nyquist velocity, m s ⁻¹	±27.7	±27.7

4. Conclusion

Wind Profilers operating near 50 MHz provide wind profiles in the 300-m to 18-km height region with a time resolution from 10-min to 1-h. Two distinct approaches are being applied. These are the application of the SA technique for small systems for use observing the 0.3 to 8-km height region and the DBS techniques for larger more powerful systems for observing the 1-18 km height region.

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⁴ <http://www.atrad.com.au/results.html> and

<http://www.physics.adelaide.edu.au/atmospheric/results.html>