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The right radar wind profiler for your application

Scott A. McLaughlin[1]

Radiometrics, Corp, 4909 Nautilus Court North Suite 110
Boulder, Colorado, 80301, USA
Telephone: +1-303-4499192, Fax: +1-303-786-9343,
Email: scott.mclaughlin@radiometrics.com, URL: www.radiometrics.com

ABSTRACT

Radar wind profilers (RWP) are all-weather vertical pointing pulse-Doppler radars which automatically and continuously measure profiles of wind speed and direction in the atmosphere. Depending on primary user requirements, such as maximum height, height resolution, and installation location, RWP models can be vastly different in antenna size, transmit power and frequency, and can have an order-of-magnitude or more difference in cost. To the non-specialist, determining which type of RWP is appropriate for their specific requirements can be daunting. This paper explains important user requirements and how they relate to radar specifications, design, and cost.

1 Introduction

Radar wind profilers (RWPs or just “wind profilers”) are pulse Doppler radar systems which continuously measure vertical profiles of horizontal wind speed and direction throughout the atmosphere. RWPs are very nearly all-weather devices, and the only ground-based remote sensing technology which can routinely (if specified correctly) make wind measurements regardless of atmospheric conditions. In fact, unlike lidar or sodar systems, radar wind profilers have increased signal-to-noise (SNR) when clouds or rain are present.

Horizontally scanning weather radars operate in the relatively small transmit frequency range of 3 to 10 GHz and are designed principally to obtain reflections from hydrometeors. While they can obtain velocity-azimuth display (VAD) winds (sometimes even in clear-air), the main use is for real-time tracking of weather events (e.g., fronts or storms). Vertically pointing wind profilers operate within a very large transmit frequency range, mostly in discrete frequencies located around 50 MHz, 400 MHz, and 1000 MHz. This wide frequency range is a result of the nature of the turbulent backscatter, which varies with height, so that low frequencies (i.e., long wavelengths) are used to obtain data at high altitudes, whereas high frequencies (i.e., short wavelengths) can be used to obtain data at lower heights. Commonly then, 50 MHz wind profilers are used to obtain data up to 20 km, 400 MHz radars are used to obtain data up to 16 km, while 1-GHz range systems are used to obtain data in the lower troposphere.

Besides the wavelength, depending with height, other complicating factors in specifying a wind profiler are the local climatology, seasonal variation, and latitude of the installed system. Near the equator, in clear air, 1-GHz band wind profilers can obtain data to 8 km or more, while the same profiler operating at a higher latitude might only obtain data to1 or 2 km. Also, in higher latitudes, when there are strong seasonal variations, or large changes in upper level water vapor content, a wind profiler’s maximum height could be 2 to 4 x’s higher in the summer than in the winter.

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[1] Formerly of DeTect, Inc. Radiometrics acquired the RAPTOR radar wind profiler product line in May 2016.

Other important factors to consider in selecting a wind profiler are the required range resolution, available space for the antenna, allowable transmit frequencies (usually country-specific), and of course the available budget. Besides the performance requirements, these all must be carefully considered before selecting and procuring the final system.

The following sections review some important factors for specifying and procuring a radar wind profiler. The material is presented in a generalized introductory tone. Background and suggested reading material is provided at the end.

2 Important Radar Wind Profiler Fundamentals

The following sections review some important factors related to the radar wind profiler performance.

2.1 RWP Height Coverage and the Atmosphere

Most users will consider height coverage the most important performance factor for a radar wind profiler. This section discusses several related atmospheric properties and how they affect radar wind profiler performance.

2.1.1 Height Coverage – General Information

Radar wind profilers are remote sensing devices, and as such, their height performance will vary depending on atmospheric conditions. Users need to understand that maximum height coverage is statistical in nature, and that without creating a very large and high power radar wind profiler, the altitude that the radar will obtain data from 100% of the time is much lower than they desire. In order to create a cost-effective solution, the user should think about what height they would like wind data about 80% of the time. The user should understand that the difference between 80% and 100% data availability could double (or more) the cost of the radar wind profiler.

As an example, Figure 1 shows performance data from 29 404-MHz radar wind profilers in the US NOAA Profiler Network (NPN), over almost two years starting in June 1992. Like most radars, the NPN radars operate in multiple pulse width modes (“Low” and “High”) in order to maximize range resolution down low, and height coverage up high. While the radar systems represented here are over 20 years old, the general nature of the fall-off of percent coverage with height is simply following the laws of physics and applies to all wind profilers. Note that modern signal processing has significantly helped in percent of recovered date, especially down low. Also note that the High mode obtains data at higher altitudes through the use of more average power (a longer transmit pulse and pulse coding), but also by sacrificing range resolution.

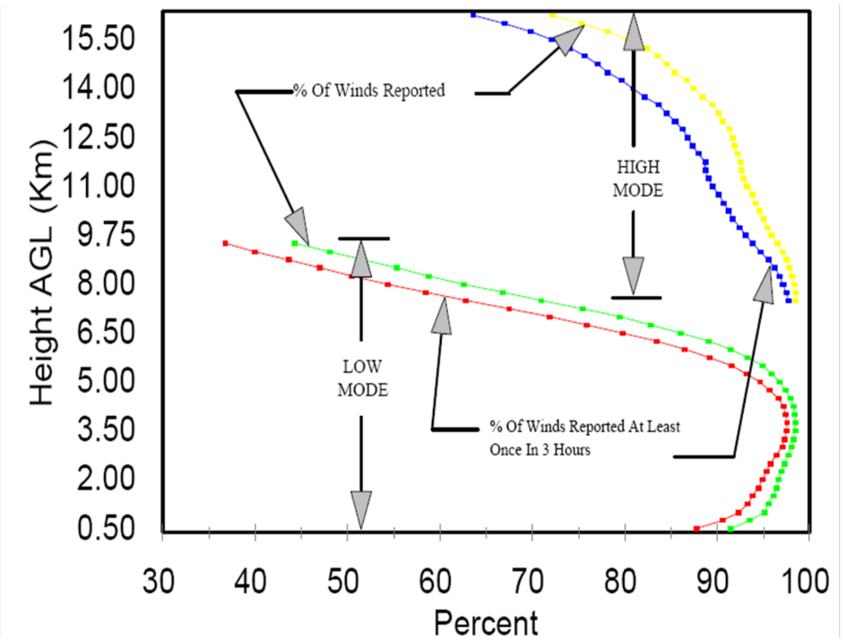

Figure 1: Example of height coverage of the original NOAA 404 MHz network profilers (Beran et al, 1998).

2.1.2 Height Coverage and Backscatter

Clear-air turbulence is the primary backscatter mechanism for a radar wind profiler. Clear-air turbulence is composed of minute changes of humidity and temperature present in variously sized turbulent eddies existing at all levels through the atmosphere. An analogy is soap bubbles in a bathtub, where there are various sizes from large to very small. Figure 2 imagines what these atmospheric turbulent eddies might look like.

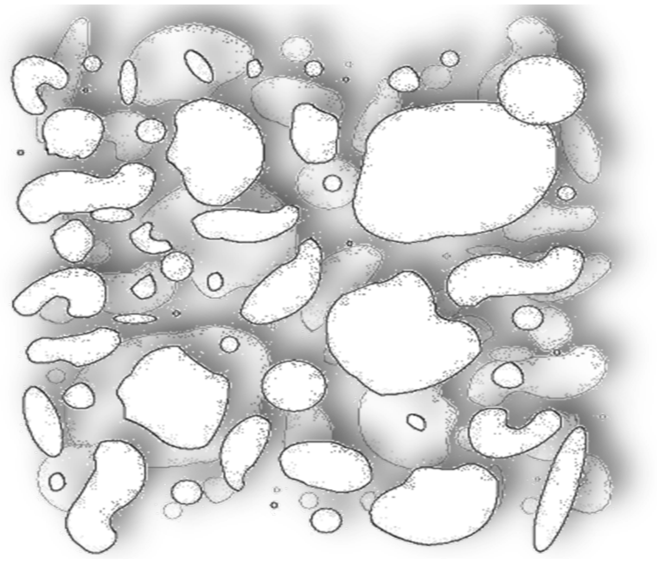

Figure 2: Graphic of various size imaginary turbulent eddies in the atmosphere.

Clear-air turbulence can be quantified with the parameter C_n^2, which is known as the index-of-refraction structure function (pronounced “C sub n squared”). The amplitude of C_n^2 is usually much larger close to the ground (due to solar heating) and usually drops off by more than 3 orders of magnitude at an altitude of 18 km.

Figure 3 shows modeled profiles of optical C_n^2 for a theoretical maximum, average and minimum (Gurvich model as from Ricklin 2006). These profiles are a good guide for the variation of radar wavelength clear-air turbulence, but as discussed later, other atmospheric factors must be considered in predicting radar wind profiler performance. [The difference between optical wavelength and radar wavelength C_n^2 mostly is related to humidity. In the lower boundary layer the optical turbulence has higher magnitude, but above the boundary layer, with lower humidity, they are very similar.]

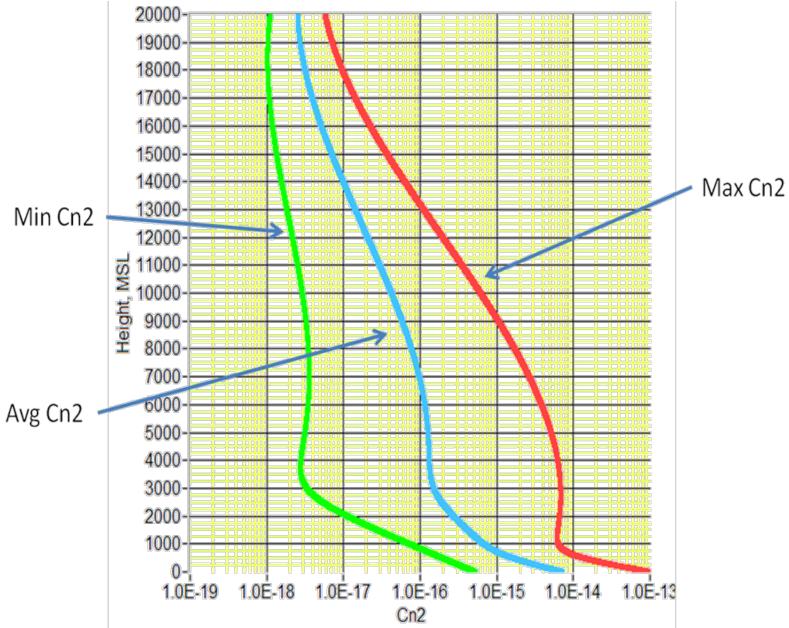

Figure 3: Modeled profile of C_n^2 versus height, showing modeled minimum, average and maximum.

The fact that the backscatter mechanism changes with height (i.e., distance from the radar) for a radar wind profiler is not *at all* the same as for a horizontally-scanning weather radar or even a surveillance radar. For weather radar, the reflectivity of a large thunderstorm is the same at 30 km distance as it is at 100 km distance. And for a surveillance radar, the radar cross section of a fighter jet is also the same regardless of the distance from the radar. Of course this makes perfect sense since the reflectivity of the target is a property of the target. The difference for a radar wind profiler however, is that the target reflectivity is actually changing with height; that is, C_n^2 amplitude falls off with height.

All radar systems experience free-space loss, which is caused by the natural spreading of the radar beam (and lowering of the energy density) with increased distance. For a point target, this loss over distance or range (R) is experienced as range to fourth power (R^4). For a volume scattering radar such as a wind profiler or weather radar, the loss is experienced as range to the second power (R^2). But a vertically pointed radar wind profiler experiences an additional reduction of reflectivity due to the change of the property of the target itself (C_n^2). For a surveillance radar, the counter intuitive equivalent would be that the radar must be able to observe increasingly smaller targets with increasing range.

The net effect of the decrease in the reflectivity of the target (C_n^2) and the normal free-space loss is that radar wind profilers quickly become more expensive and need to be more powerful as the user specifies higher and higher heights. Therefore the user should not take lightly the desired maximum height for which they require wind data.

2.1.3 Height Coverage and Radar Wavelength

Another factor unique to radar wind profilers is that the physical-size makeup of the target changes with height (not just the amplitude or reflectivity). Specifically, the size distribution of turbulent eddies changes with height. A radar wind profiler obtains its reflection from clear-air turbulence from what is called Bragg scatter. Bragg scatter occurs when the eddy is ½ (half) the radar wavelength, so there is an additive reflection from the both front and back sides. The size spectrum of turbulent eddies change with height, with a larger number of small eddies close to the ground and with a preponderance of larger eddies up high. Practically speaking, this means smaller and lower cost high frequency radars can be used down low to measure wind, whereas larger and more expensive low frequency radars must be used to measure winds with increasing altitude. Generally speaking then, 1-GHz band wind profilers are used in the boundary layer, 400-MHz band for the troposphere and lower stratosphere, and 50-MHz band for the troposphere and stratosphere. [Note that there are some exceptions to this rule where 50-MHz and 400 MHz band radars have been used for boundary layer winds using a technique called Spaced Antenna (SA). SA seems to be generally proven for use in this manner, but is not widely used in comparison to traditional Doppler Beam Swinging (DBS) radars.]

One note about frequency is that any transmitting device must receive clearance to operate in the specific country where it will be installed. This imposes an additional constraint over choosing a frequency based on the desired height. Users should determine which frequency will be allowed in their country and specific location *before* the procurement effort.

2.1.4 Height Coverage and Latitude

The compositional height cross-section of the atmosphere (i.e., temperature and humidity) is not the same at lower latitudes as it is at higher latitudes. For example, the tropopause is much higher near the equator than at high latitudes. This also means radar wind profiler performance is very different near the equator than at higher latitudes. For example, in the summer, at a latitude of 40°, a boundary layer wind profiler might routinely obtain data to 3 km, but near the equator, the same model might routinely obtain data to 8 km. This large performance difference makes it difficult for radar wind profiler vendors to clearly state the expected altitude performance of a system. For the same height requirement, this might mean that a 1-GHz band system could be used near the equator, whereas a 400-MHz band system would be needed at higher latitudes. This latitude difference must be carefully examined when specifying the radar model type as well as other factors affecting the local climatology. The best guide would be if a radar wind profiler has already operated near that location.

2.1.5 Height Coverage and Seasonal Variation

As is for latitude, seasonal variations also change the composition of the atmosphere and therefore the performance of radar wind profilers. Especially for 1-GHz band boundary layer systems operating at higher latitudes, the altitude performance change can be quite significant. In the winter, a boundary layer wind profiler may only obtain data to 1 km, but in the summer the same system can obtain data to 3 or 4 km. Frontal passages or large weather changes can also significantly change the height performance. This is less true for 400-MHz band systems, but these will also see weather related or seasonal changes in performance. For a high-power higher-altitude 400-MHz band system, or a 50-MHz band system designed to obtain data to 16 km and higher, these seasonal or weather related variations are less noticeable.

2.2 Power-Aperture Product

The following sections describe background material necessary to understand power-aperture product (PAP). PAP is similar to the horsepower rating for an automobile. The best method to compare the expected performance of similar radar wind profilers is to use PAP.

2.2.1 Antenna Area

The antenna's function is to focus the transmitted energy in a specific direction and then receive and concentrate the backscatter energy for processing by the receiver. In general, one can say, the larger the antenna the better. Larger antennas have higher gain and allow the radar to have higher sensitivity. The size of the antenna is also a property of the radar frequency; lower frequency radars naturally have larger antennas than higher frequency radars—even as both antennas have the same gain.

Larger antennas also allow for aperture illumination tapering. Aperture illumination tapering is a design technique where (typically) more power is concentrated in the center of the antenna then toward the edges. Tapering will slightly reduce gain and increase the beamwidth, but can significantly reduce sidelobes to help improve data quality. All antennas have sidelobes, whereby the antenna transmitted power is directed to, and receive signal comes from, an undesired location. This is something designers try to prevent in order to reduce interference from birds, traffic, or other radio signals, all which can interfere with the wind signal. Illumination tapering helps reduce these other interfering signals.

As previously mentioned, the antenna size is frequency dependent. For 1-GHz boundary layer radar wind profiler, the antenna might be as small as 2-m in diameter. For a 400-MHz band unit, the antenna will typically be between 6 to 12 m in diameter. As for a 50-MHz stratospheric radar, the antenna can be as large as 150 m in diameter. Figure 4 illustrates the wide variation of antenna size for a boundary layer (BL), tropospheric (T), stratospheric-tropospheric (ST) and mesospheric-stratospheric-tropospheric (MST) radar wind profiler types.

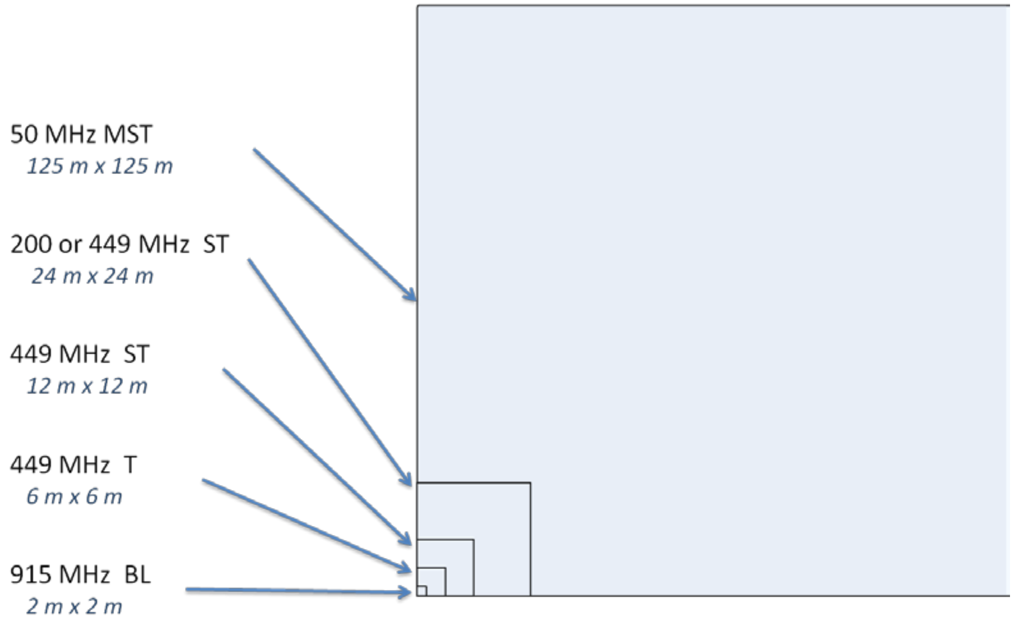

Figure 4: Comparative antenna sizes for various radar wind profiler types.

Practically speaking, while a large antenna is best, the antenna is also an expensive part of the radar; so to control costs, the smallest antenna needed is used. Additionally, there might not be room for large antennas. Some antenna types are size scalable, and can be made to fit the performance requirements, the available space, as well as the cost budget.

Antennas are not 100% efficient, so the term “effective aperture” (A_e) is used to describe the theoretical size of the antenna as if it were 100% efficient (and used in calculating PAP). Different antennas types and implementation techniques have different efficiencies, and factors such as amplitude tapering or types of phase shifters also will affect the overall antenna efficiency. The effective aperture is always less than the actual geometric antenna area; and often is about 50% of the actual antenna size. Note that antenna designers will make their antennas as efficient as possible.

2.2.2 Duty-cycle, Peak and Average Power

A pulse-modulated radar transmits for a small amount of time and then receives or “listens” for a much longer amount of time (and repeats this for 1,000’s of time for a single coherent dwell). The percent of time it transmits for each pulse cycle is called the duty-cycle. The pulse cycle is typically referred to as the inter-pulse period or IPP, and represents the amount of time which is required for the radar pulse to travel (at the speed of light) from the radar antenna to the furthest required distance and back. In practice, due to various operational factors for the radar, the IPP is set slightly larger than what is mathematically required to obtain data at the furthest range of interest. For example, if the IPP is 100 µs, then the furthest possible range (R) is equal to R = c*IPP/2 (where c is the speed of light), or about 15 km. If the transmit pulse is 1 µs, then the duty-cycle is equal to 1 µs / 100 µs or 1%.

Peak power is the maximum amount of power a radar transmitter can instantaneously create. Average power is the integrated power sent within an IPP cycle. To calculate average power (A_{avg}) one simply multiplies the peak power times the duty-cycle. In the previous example, if the peak power is 1000 W, then the average power is equal to 1000 W * 1% or 10 W.

In practice, what matters for radar sensitivity is average power, not peak power, so the goal is to have as much average power as possible. Another way to look at the previous example is if the peak power were 100 W (instead of 1000 W), but the duty-cycle was 10% (instead of 1%), the average power would be the same (100 W * 10% = 10 W), so the radar sensitivity would be the same. To maximize radar range (and sensitivity), without having to use a large antenna or a higher peak power transmitter, average power is increased. Average power is a very important figure of merit and used in calculating PAP.

2.2.3 Range Resolution and Pulse Coding

The range resolution (or height resolution for a wind profiler) of a radar is directly related to the pulse width. Very short pulses allow for high range resolution—but a short pulse reduces the average power and thus reduces the radar sensitivity. This is an important trade-off to understand; increasing the pulse width 2x’s is equivalent to increasing the peak power 2x’s or increasing the antenna area 2x’s. The latter two are very expensive, whereas increasing the pulse length (and therefore the average power) usually involves simply changing operating parameters.

As noted, decreasing the pulse width in order to increase range resolution will result in a loss of sensitivity of the radar. To overcome this and keep the average power high, pulse coding is used. Pulse coding is a technique where short modulated pulse “chips” are sent together in a longer chain. On return, the longer pulse chain is demodulated to obtain resolution of the shorter chips. The advantage is that the average power is based on the total length of the pulse train whereas the range resolution is based on the individual chip size. Using the previous example of 1 µs pulse with a 100 µs IPP (which results in a 1% duty-cycle), with pulse coding we can use an 8-bit code (8-each 1-µs chips) to increase the average power 8x’s (9 dB), without any loss of the range resolution (which is based on the 1-µs chip). The two caveats though are that the transmitter must be capable of the larger 8% duty-cycle and that the lowest range gate will now be much higher (since the receiver cannot listen while the longer pulse train is still transmitting).The lower range gate issue is typically solved by operating the wind profiler in a Low (no pulse coding) and High (uses pulse coding) mode.

Also note that the range resolution and range gate size are not necessarily the same thing and are often confused in radar wind profiler tenders. Most radars operate with relatively long pulses, then sample the return time-series at a higher rate in order to produce smaller range gate sizes (i.e., with higher resolution than the original pulse width would mathematically allow). Oversampling up to about 3x’s still allows some independent data in the range gates, so are useful, but this is not the same as transmitting and sampling in a one-to-one fashion.

2.2.4 Power Aperture Product (PAP)

The power-aperture product (PAP) is the multiple of the average power (P_{avg}) and the effective aperture (A_e), so PAP = $P_{avg} * A_e$. PAP is one of the most important figures of merit for a radar wind profiler since it takes into account the antenna size, the transmitter average power capability, and the available pulse coding. The relationship between these factors is linear. For example, if the antenna area is reduced by one-half, the transmitter average power can be increased by 2x’s so that the radar sensitivity stays the same. This might mean, for example, that one vendor supplies a high peak power transmitter, whereas another specifies a low peak power, but if the resulting average power is the same (i.e., due to pulse coding or duty-cycle or both), then the radar sensitivity will be the same. Another example might be that a large antenna with a low power transmitter is used on one vendor’s wind profiler, whereas a small antenna with a high power transmitter is used on another. In this case, one might be able to show through the PAP that the sensitivity of the radar systems is the same. If the tender specifies a PAP, vendors then can choose how to best meet the requirement without the tender specifically requiring an antenna size or transmitter power.

3 Choosing the Correct Wind Profiler

Building on the previous discussion, the following sections contain tips and information for correctly specifying the right wind profiler for the job.

Note, that in a tender it is important to not over-specify, or in effect, force the creation a new wind profiler model. For example some users will combine specifications from multiple radar vendor’s data sheets, in effect designing a new model wind profiler (a “Frankenstein” version). The user must be careful to determine performance requirements that do not force engineering changes in various vendor’s models and allow vendors to offer already designed and already proven equipment which meets the users primary needs.

3.1 Desired Height Coverage

Desired height coverage is the most important starting point in picking a radar wind profiler. If the application is operational support, the user might have a 100% height requirement (possibly regardless of cost), whereas a research user might have a fixed budget and simply wants the best radar wind profiler they can afford. For any tender the user should try and state what their 100% data-availability requirement is, and what the 80% data-availability requirement height is; any ambiguity here could allow vendors to state that a model will collect data at some height, even if only 5% of the time.

Because the height coverage has such a profound effect on system cost, users must not over-specify this requirement and need to understand all of the previously mentioned factors and trade-offs for height coverage. And due to the seasonal and latitude related variations, users will need to work with radar wind profiler experts (vendors, experienced researchers, or both) to fully understand what type (i.e., frequency band) of wind profiler is best for their height requirement in their specific location. If no radar wind profilers have previously operated in that location, the user might be better off focusing on their available budget and buying the best wind profiler they can afford (with the maximum height performance a secondary consideration). In that case, focusing on the highest PAP is good option (given a fixed budget).

Note that many vendors have the ability to scale their system (either transmitter power or antenna size or both) to either reduce cost or to improve performance in order to best meet the desired height coverage. Users should familiarize themselves with the various vendor offerings in order to create a tender document that vendors can bid without costly redesign.

3.2 Frequency Band

Most vendors will have radar wind profilers designed for some or all of the three previously mentioned frequency ranges (50, 400 and 1000 MHz). Once the user determines the best frequency band for their height requirement, they should immediately start working with their local frequency authority to obtain an approved licensable frequency. It is not cost effective for the customer, or the vendor, to design radar wind profilers for many different frequencies for many different countries. To the extent possible, the user should try and get approval for the already existing and commonly used radar wind profiler frequencies. (49.25 MHz, 449 MH, 482 MHz, 915 MHz, 1290 MHz, 1357 MHz, etc.). Importantly, the frequency to be used must be specified in the tender at the time of release, not sometime later (e.g., after award). The cost and schedule to specify and build a radar is directly related to the transmit frequency and it is very difficult to bid on a tender when the frequency is left as an open item.

3.3 Range Resolution

The desired range or height resolution is also a parameter which should not be over-specified. Since the range resolution directly affects the sensitivity of the radar, the user should choose a height resolution that meets but does not exceed their needs. Specifying 50 m resolution when 100 or 200 m would simply increases the cost of the final radar. In the tender, range resolution should be specified as a range so that various vendor’s data systems can meet the requirement without redesign. Radar wind profilers usually operate in one to three sequential pulse modes in order to both meet the height resolution requirement and the maximum desired height requirement (with “high” modes using pulse coding). Especially for high altitudes, high range resolutions are not normally required and again, should not be required unless absolutely needed by the user. Over-specifying this will raise the radar's cost.

3.4 Acceptance Testing

Acceptance testing procedures for new systems are often not fully thought through during the procurement stage. Often the tender specifies requirements which are difficult to prove. For example, going back the desired height performance example, if the tender simple states that the maximum height requirement is 8 km—does this refer to above ground level or above mean sea level? And does it necessarily imply that the radar must obtain data at 8 km 100% of the time? And no matter the installation location or the season? And even if the requirement states that it must obtain data to 8 km 80% of time, is that for an entire year? If there are seasonal variations, the only way to prove the radar will obtain data 80% of the time is to test for an entire year. And the year will need to be statistically averaged, since the atmosphere will certainly be different, on average, from year to year.

The above example points out how difficult it might be to prove a radar wind profiler is meeting a height performance measure. This same measure is further complicated by what range resolution the radar is operating, whether there was pulse coding, and what the resulting average power was.

Also, by what comparison measure will it be proven that the data from the wind profiler is in fact correct? Radiosondes are the primary method to compare with and validate radar wind profilers. A few radiosonde flights are sufficient to verify the basic operation and proper installation of wind profiler, but to truly validate the system, many more flights over long time periods are needed. In fact, to properly compare periodic point measurements made by the radiosonde, with the virtually continuous volume measurements of the radar wind profiler, potentially hundreds of radiosondes will need to be launched over many days and even months. Even then, one must keep in mind that the radiosonde data could be erroneous for comparison if it has drifted 100 km away from the radar wind profiler site. For most users, long-term radiosonde comparisons are not feasible, so the user and vendor must agree ahead of time what standards will be used to validate the radar wind profiler.

Another factor to consider is that the radar wind profiler site might ultimately prove to be a bad location for a wind profiler. Perhaps there is low-level radio frequency interference (RFI) raising the noise floor, or stronger RFI simply masking the data. Maybe local bird activity or migrations unexpectedly interferes with the data collection during the validation period. Some factors can be checked ahead of time, others may not be apparent until after installation.

These operational and acceptance testing difficulties point out that real-world performance testing can produce confusing results. Engineering and functional testing can usually be more quantitative, and is one of the reasons why the customer should specify PAP as a requirement. The average transmitted power and effective aperture can be calculated allowing the customer to compare “apples to apples” regardless of the difficulties of the final performance testing.

In any case, it is to the customer's benefit to examine each of their tender requirements and determine the best way to test the radar wind profiler for final acceptance.

4 Recommended Reading

The following references are recommended reading by radar wind profiler users.

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