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NOAA Technical Memorandum ERL WPL-222



FEASIBILITY STUDY FOR A LOW-ALTITUDE WIND AND TEMPERATURE PROFILER

J. R. Jordan
R. J. Lataitis

Wave Propagation Laboratory
Boulder, Colorado
May 1992

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NATIONAL OCEANIC AND
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FEASIBILITY STUDY FOR A LOW-ALTITUDE WIND AND TEMPERATURE PROFILER

J. R. Jordan and R. J. Lataitis

ABSTRACT. The feasibility of constructing a high-resolution, portable, wind and temperature profiling radar for boundary layer studies is examined. With the proposed five-beam radio acoustic sounding system, the sound speed difference between two opposed pairs of symmetric off-zenith beams can be used to profile the horizontal wind speed. The speed of sound as measured with a fifth vertical beam can be used to profile the temperature. This type of profiler can be operated in high-clutter urban environments, and can measure winds and temperature to 600 m under favorable conditions using reasonable levels of radar transmitter power. A radar equation for signal-to-noise ratio is used to calculate the maximum range for two sets of meteorological parameters corresponding to the best and worst case conditions.

1. INTRODUCTION

The National Oceanic and Atmospheric Administration's (NOAA) Wave Propagation Laboratory (WPL) is interested in developing a low-altitude wind and temperature profiler to use in aerosol dispersion experiments and to provide data at altitudes below the minimum sounding height of existing profilers. Boundary-layer wind profiling radars have minimum sounding heights of about 100 m (Ecklund et al., 1988). This paper examines the feasibility of constructing a small, portable radar capable of measuring high-resolution profiles of wind and temperature at heights of 10 to 200 m in high-clutter urban environments.

Clear-air wind profiling radars that scatter energy from turbulent fluctuations in the radio refractive index were developed in the 1980s (Strauch et al., 1984). A temperature profiling capability was later added to these radars using a hybrid radio acoustic sounding system (RASS) (Strauch et al., 1988). Profiles of wind speed and direction can also be derived from a RASS (Makarova, 1980), but it is generally used only for measuring temperature.

Clear-air radars with RASS suffer from clutter contamination and acoustic noise pollution. Radial velocities measured by boundary-layer clear-air radars are usually about $\pm 10 \text{ m s}^{-1}$. Because the energy scattered from the atmosphere is small, a very sensitive radar is required, which can easily be contaminated by ground or sea clutter. Clutter fences around the antennas are

necessary to operate in virtually any location, and many interesting sites have too much clutter for the radar to function satisfactorily (Russell and Jordan, 1991).

Clear-air radars must operate at wavelengths where turbulent eddies are one-half the radar wavelength. This means the maximum radar frequency is constrained by the inner scale of turbulence. Wind profilers operate from about 50 MHz to 1 GHz, and boundary layer systems operate near 1 GHz. The acoustic frequency necessary for these radars ranges from 100 to 2000 Hz. Due to the relatively low attenuation at these frequencies, acoustic sidelobe energy often annoys people living nearby. High sound levels limit the usefulness of RASS in urban environments, even with suppressed acoustic sidelobes.

To alleviate these two problems, WPL proposes to design this profiler to use the difference in the speed of sound in two opposite directions to measure the horizontal wind velocity and the magnitude of the speed of sound to derive temperature. This allows the video bandwidth to filter moving and stationary clutter and 60 Hz noise from the signal. Because the acoustic wave provides the scattering, the radar frequency can be selected independently of the inner scale of turbulence. Therefore, the frequency can be chosen sufficiently high so the acoustic attenuation of the atmosphere will reduce excessively high sound levels.

2. SYSTEM OVERVIEW

Low-altitude coverage and high range resolution requirements restrict this profiler to a frequency modulated, continuous wave (FM-CW) radar. FM-CW radars do not require that the receiver electronics settle after the transmitted pulse, which allows for much lower minimum sounding heights when compared to conventional wind profiling systems. The lower limit is determined by the crossover of the beamwidths for the separate transmit and receive antennas. High range resolution is easily accomplished in FM-CW radars by increasing the bandwidth of the sweep without changing the average transmitted power. Pulsed radars must use either short pulses, which reduce average transmitted power, or pulse coding, which further increases the altitude of the first range gate. The major drawback to FM-CW radars is that they require two antennas, transmit and receive, and high isolation between them.

Conventional Doppler FM-CW radars rely on backscatter from clear-air turbulence to measure wind (Chadwick et al., 1976). RASS has also been implemented on FM-CW radars (Peters et al., 1988). Using a multiple-beam RASS, it is possible to determine wind values by measuring the difference between the acoustic velocity in two opposite directions. Both the horizontal and

vertical components can be derived by switching through two opposed pairs of symmetric off-zenith beams orthogonal to each other. Adding a fifth vertical beam provides temperature capability. Errors introduced in the acoustic velocity by vertical motions in the atmosphere can be corrected with this scheme. The measurements of the acoustic velocity and vertical velocity, however, are not simultaneous. Samples must be acquired fast enough so that the vertical velocity does not change, or be averaged long enough so that the net vertical velocity is zero. Combining these two schemes can give reliable temperature data, because averaging can remove short-term fluctuations in the vertical winds and the derived vertical motions can correct longer term errors. In addition, this technique is insensitive to the fall velocity of hydrometers, which is a problem with conventional RASS systems.

3. RADAR EQUATION

An equation to predict the return signal power for a RASS system comprising a pulsed Doppler radar and an FM-CW source has been developed by Lataitis (1992). We use it here to estimate the effects of various engineering and environmental parameters on our proposed FM-CW RASS. This equation combines the effects of horizontal wind, turbulence, vertical temperature gradients, and acoustic attenuation. It also combines the effects of engineering parameters such as radar transmitter power, acoustic power, and radar wavelength. For this study, the equation was divided by receiver noise to yield signal-to-noise ratio, a more interesting engineering parameter. Because of the many variables involved, typical values for the meteorological parameters have been chosen to predict best-case and worst-case performances.

In a RASS, the refractive index perturbation induced by a spherical acoustic wave provides the scattering target for the radar. The spherical acoustic shells propagate vertically above the radar and, ideally, focus the radar beam back onto the receiving antenna. Atmospheric turbulence distorts these shells, which broadens the area of the RASS focal spot. Temperature gradients in the atmosphere also distort the spherical shells, which also broadens the spot. In addition, horizontal winds displace the spot away from the radar antenna. Acoustic attenuation in the atmosphere reduces the amount of acoustic power as a function of height. All these factors significantly affect the detected power.

The radar equation derived for this study is

$$SN(R) = 3.7 \times 10^{-14} \frac{\Delta}{(\lambda_R R)^2} \frac{P_a G_a (P_r \eta)}{BN_0} I, \quad (1)$$

where

$SN(R)$ = signal to noise ratio as a function of range R

Δ = radar range resolution (m)

λ_R = radar wavelength (m)

R = range (m)

P_a = transmitted acoustic power (W)

G_a = gain of acoustic antenna

P_r = radar transmitter power (W)

$B = 2\pi b/c_a$ = acoustic wavenumber bandwidth (m^{-1})

b = acoustic frequency bandwidth (300 Hz)

c_a = acoustic velocity ($m s^{-1}$)

N_0 = total receiver noise power (W)

η = antenna efficiency, assumed to be 0.8.

The factor I in the above equation describes the effect of the atmosphere on the received signal and is given by

$$I = \frac{1}{1 + \frac{W^2}{2\rho_0^2}} \exp \left(- \frac{4 \frac{\rho_t^2}{r_s^2}}{1 + \frac{W^2}{2\rho_0^2}} \right) 10^{-\frac{\alpha R}{10}}, \quad (2)$$

where

W = width of the radar beam at range R (m)

ρ_0 = transverse coherence length of the acoustic wave (m)

$$\approx (0.55 k_a^2 R \overline{C_n^2})^{-\frac{3}{5}}$$

$k_a = 2\pi/\lambda_a$, where λ_a is the acoustic wavelength

$\overline{C_n^2}$ = weighted path-average of the acoustic refractive index structure parameter C_n^2

ρ_t = vector displacement of the virtual acoustic source by the horizontal wind (m)

r_s = diffraction-limited focal spot radius (m)

α = acoustic attenuation (dB m⁻¹).

These equations were derived for a monostatic RASS and require that the acoustic beam be sufficiently broad that it always remains within the radar resolution cell, even under the influence of horizontal wind. For a Gaussian radar beam, $W \approx 4R/k_a D$, where $k_a = 2\pi/\lambda_a$, and $r_s \approx d/\sqrt{2}$, where D is the effective diameter of the radar antenna. Calculations for this study assume $D = 1$ m. The effects of temperature gradients were found to be negligible and are omitted for clarity. A detailed expression for the turbulence parameter ρ_0 is presented in Lataitis (1992) and is not repeated here. An example of the calculations carried out for this study is presented in the Appendix.

4. METEOROLOGICAL PARAMETERS

The performance of the proposed profiler is strongly influenced by the characteristics of the atmosphere. The maximum altitude coverage is affected by atmospheric attenuation, turbulence, and the horizontal wind. Radar equation calculations could be performed for a range of typical values for each of these parameters. However, these calculations would produce a multidimensional set of results. To simplify this scenario, two sets of meteorological parameters are defined: the best case, which represents a cool humid night with low winds, and the worst case, which is a hot, dry, windy day.

4.1. Atmospheric Attenuation

The maximum altitude coverage of a RASS is strongly affected by acoustic attenuation in the atmosphere. Acoustic attenuation for the acoustic frequency of 6.3 kHz is shown in Fig. 1 as a function of temperature and relative humidity (Acoustical Society of America, 1978). Our best-case calculation uses a value of 5 dB 100 m⁻¹, which represents cool and humid conditions. Worst-case attenuation can reach 20 dB 100 m⁻¹ on a dry, hot day. This high attenuation limits the altitude coverage of the radar but also makes it possible to operate in urban environments. The choice of the radar wavelength (and therefore acoustic wavelength) is a balance between height coverage and "annoyance."

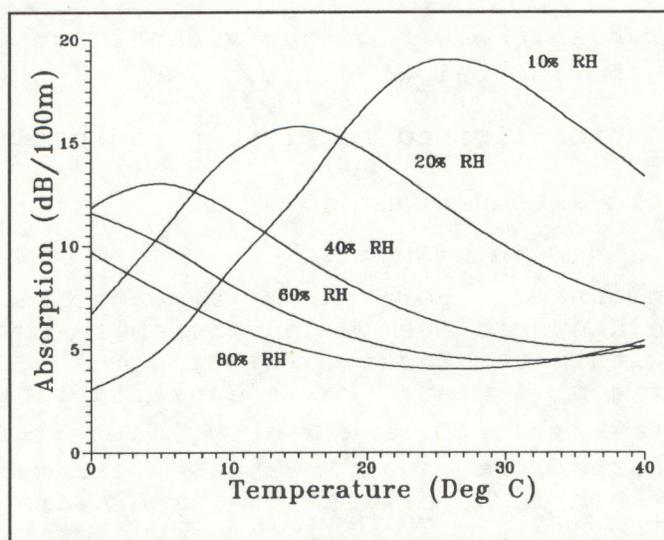


Figure 1. Acoustic absorption at 6.3 KHz as a function of temperature and relative humidity.

4.2. Atmospheric Turbulence

The extent of broadening of the RASS focal spot due to turbulence is determined by the transverse coherence length ρ_0 of the acoustic wave. If the transverse coherence length is the same as or smaller than the width W of the radar beam, there will be significant broadening of the spot. The acoustic wavelength considered for this system ($\lambda_a \approx 5$ cm) has such a short transverse coherence length that turbulence is smaller than W throughout the entire height range of interest.

The transverse coherence length is calculated from a weighted path average of the acoustic refractive index structure parameter C_n^2 . A typical C_n^2 profile in the planetary boundary layer for an air temperature of 283 K is given by Brown and Clifford (1976) and is presented in the Appendix. This profile must be initialized by the turbulence strength C_{n0}^2 , at the assumed acoustic source height of 2 m. C_{n0}^2 can be estimated from the following formula, given by Brown and Clifford (1976):

$$C_{n0}^2(R_0 = 2 \text{ m}) = \frac{C_T^2(R_0)}{4T^2} + \frac{C_V^2(R_0)}{C_a^2}, \quad (3)$$

where

$$C_T^2(R_0) = \text{temperature fluctuations structure parameter at } 2 \text{ m}; = 2.9R^{-\frac{4}{3}};$$

$$C_V^2(R_0) = \text{velocity fluctuations structure parameter at } 2 \text{ m}; \\ = 2\epsilon^{\frac{2}{3}} \text{ (Kaimal, 1973), where } \epsilon = \text{dissipation rate (m}^2 \text{ s}^{-3}\text{);}$$

Measured values of the dissipation rate ϵ at 4 m can range from $0.0005 \text{ m}^2 \text{ s}^{-3}$ on a calm night to $0.05 \text{ m}^2 \text{ s}^{-3}$ on a warm convective day with 9 m s^{-1} winds (J. C. Kaimal, personal communication). We assume that these ϵ values are also representative of conditions at 2 m. The corresponding calculated values for C_{n0}^2 at 2 m are $4.113 \times 10^{-6} \text{ m}^{-2/3}$ for the best case and $6.193 \times 10^{-6} \text{ m}^{-2/3}$ for the worst case. Our best case corresponds to a lower value for C_{n0}^2 which may at times lead to a poorer performance. For example, under windless conditions, turbulence reduces the returned power because the focal spot is broadened. In the presence of winds, however, the turbulence-induced smearing of the spot results in an increase in the maximum range.

4.3. Horizontal Wind

The effect of horizontal winds is modeled as a displacement of the RASS focal spot from the radar antenna. To simplify calculations, the wind is assumed to be constant over the entire

range of interest. Although this may not be a realistic assumption for all cases, it gives an upper bound to the wind effect. The radar equation used here was derived for a collocated acoustic source and radar antenna. Many RASS systems, however, use several acoustic sources spaced around the antenna. This provides acoustic shells distributed around the radar that can be advected into the radar beam, enhancing the altitude coverage in medium to high winds. The proposed profiler will use several acoustic sources and should therefore have significantly better range coverage than that calculated here. The best-case parameter set uses 1 m s^{-1} winds and worst-case uses 9 m s^{-1} winds.

5. ENGINEERING PARAMETERS

The important variables for a radar designer are radar wavelength, range resolution, antenna sizes, radar transmitter power, acoustic power, receiver noise figure, and signal-to-noise ratio. Once again, calculating all the parameters over a typical range would produce an unmanageable amount of information. Therefore, many parameters have been assigned specific values.

5.1. Radar Wavelength

By choosing not to use clear-air scattering, we can select any radar wavelength. Since acoustic attenuation increases rapidly with frequency, the choice becomes a balance between maximum altitude coverage and annoyance. The particular radar wavelength of 10 cm and its associated RASS frequency of about 6 kHz were selected because of available surplus hardware for that frequency. A prototype of this profiler can therefore be economically built. Also, a frequency allocation is available for 2.8-3.0 GHz.

5.2. Range Resolution

One of the features of an FM-CW radar is its capability for very high range resolution. However, the range resolution must be matched with the cross range resolution for wind profiling. We chose a 10-m range resolution as a good compromise for this system. In addition, the available FM source has a maximum 15 MHz bandwidth, which corresponds to a 10-m resolution.

5.3. Radar Antenna

It is interesting to note that the radar equation for RASS does not include the radar antenna gain. Since the equation assumes the acoustic beamwidth is larger than the radar

beamwidth, all the transmitted power is ideally focused back onto the antenna. Thus, the received power is independent of the radar antenna gain. Radar antenna size enters into the calculations for the horizontal wind displacement. For these calculations a 1-m diameter was chosen, which corresponds to about a 7° half-power beamwidth. This is a typical value for wind profiling radars. An operational profiler would require an electronically steered, phased-array antenna system with five beams, at least a 15 MHz bandwidth, and a 75 dB isolation between the transmit and receive antennas. A pair of 2.5 m vertically pointing dishes is available for testing a prototype profiler.

5.4. Acoustic Antenna

The received power at the radar depends on the acoustic antenna gain. As discussed above, the acoustic beamwidth must be broad enough to fill the radar beam even during high winds. A 20° acoustic beamwidth was selected for this parameter. At 6 kHz, this only requires a 0.35-m-diameter dish, with a gain of 75. This is much smaller than the acoustic sources currently in use for RASS.

5.5. Radar Transmitter Power

Received power is also determined by the radar transmitter power. Unlike pulsed radar systems, FM-CW radars require low noise transmitters, making solid-state amplifiers a logical choice. If higher power tube amplifiers such as traveling wave tubes (TWT) are used, they need to be selected for low noise. For the calculations presented here, the transmitter power was varied from 1 to 100 W.

5.6. Acoustic Power

The acoustic power selected for these calculations was 10 W, which corresponds to 100 electrical W speakers with 10% efficiency. The radar equation used in our calculations corresponds to a single collocated acoustic source and a radar antenna. Our proposed system will use four acoustic sources spaced around the radar antenna. A recent analysis of this configuration showed an additional 10 dB of loss near the ground if the acoustic sources are placed right next to the radar antenna. This loss, however, is compensated by an additional 12 dB of acoustic power gained by using four sources in place of one. Thus, the expected height coverage predicted by our radar equation using 10 W acoustic power should be close to what can be expected from our proposed RASS comprising four acoustic sources.

5.7. Receiver Noise Figure

A prototype profiler will be constructed with its receiver noise figure as low as possible. Selecting noise figures for these calculations requires an understanding of FM-CW front ends. Figure 2 shows a block diagram of the proposed front end. Most FM-CW radars have homodyne receivers, which mix the microwave signals directly to baseband. Therefore, the gain and the noise figure of the preamplifier and video amplifier are important. The 10 dB cable loss between the preamplifier and mixer is necessary to attenuate round trip reflections in the cable that appear as ghosts of a point target.

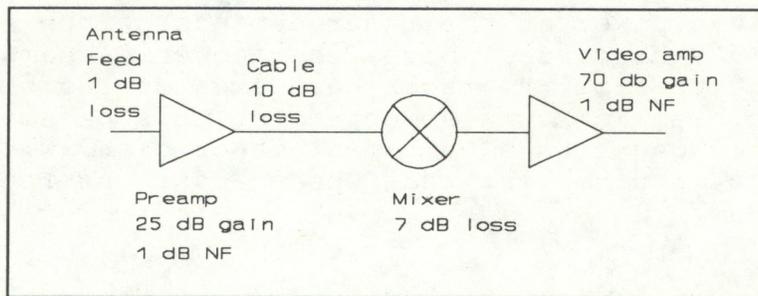


Figure 2. Block diagram of an FM-CW radar front end showing important parameters for noise calculation.

Another criterion is the dynamic range of the receiver. Although the profiler design is insensitive to clutter contamination, reflections from the clutter must not saturate the receiver. A high-gain preamplifier would dominate cable loss in the cascaded noise of the receiver. However, a low-gain preamplifier would have a higher dynamic range. Figure 3 shows the total receiver noise figure in decibels as a function of video amplifier noise figure for several different preamplifier gains calculated for a preamplifier noise figure of 1 dB. Below 25 dB gain, the total noise figure is strongly degraded by the cable loss. Therefore, a 25 dB gain preamplifier should be chosen. A total receiver noise figure of 2.2 dB was selected for these calculations.

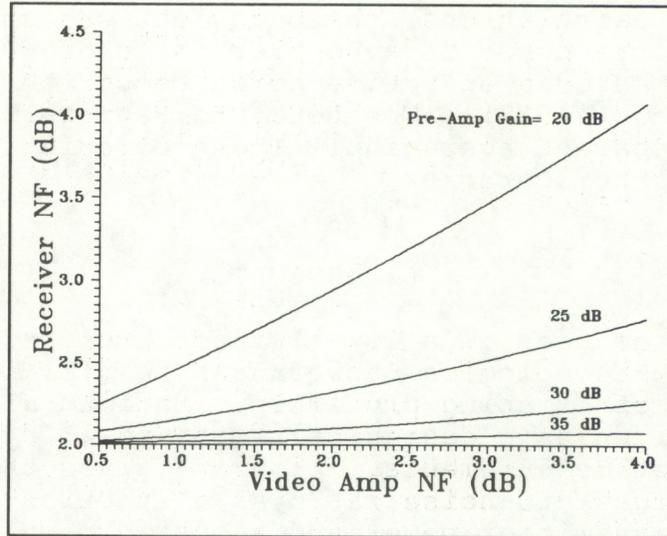


Figure 3. Receiver noise figure as a function of video amp noise figure for various preamplifier gains. Preamplifier noise figure assumed to be 1 dB.

5.8. Signal-to-Noise Ratio

Experience with current wind profilers shows that signals can be detected for a signal-to-noise ratio as low as -15 dB. A value of -10 dB was selected for these calculations as a conservative threshold for detectability. The receiver noise was calculated by

$$N_0 = kbw (F T_r + \eta T_a) , \quad (4)$$

where

k = Boltzmann's constant ($1.38 \times 10^{-23} \text{ J K}^{-1}$)

bw = bandwidth (Hz)

F = receiver noise figure (2.2 dB)

T_r = reference temperature (290 K)

T_a = antenna effective temperature (K).

For these calculations, the bandwidth was chosen to be 8 kHz, which corresponds to a Doppler shift of 400 m s^{-1} radial velocity. The antenna effective noise temperature is estimated to be 10 K (Kraus, 1982). The total noise power is further reduced by incoherent averaging. These calculations have assumed 32 spectra will be averaged.

6. RESULTS

The expected uses of a low-altitude profiler would be to replace 100-m meteorological towers and to fill in data below the minimum height of existing profilers. Maximum altitude coverage of 200 m was given as a design criterion to allow overlap between the two profiler measurements. Figure 4 gives the maximum range for a -10 dB signal-to-noise ratio as a function of the product of the radar transmitter power and acoustic power for best-case and worst-case meteorological parameters. Designing a profiler to operate in an urban environment requires a trade-off between expensive microwave power and annoying acoustic power. The power product in Fig. 4 corresponds to 10 acoustic W and a radar transmitter power of 1-100 W.

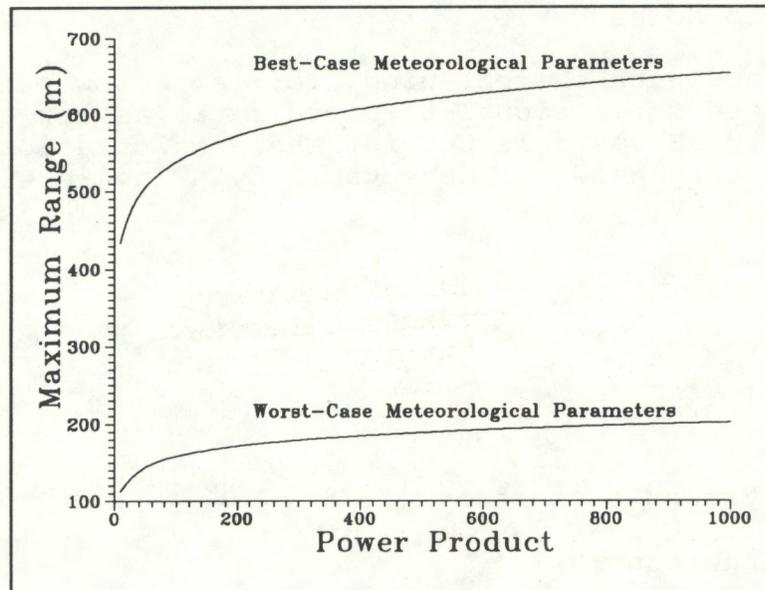


Figure 4. Maximum range as a function of the product of radar transmitter power and acoustic power. Results shown for best-case and worst-case meteorological parameters.

From Fig. 4, maximum range coverage should vary from about 150 m to 600 m between best and worst cases. Worst-case range coverage is dominated by the horizontal wind speed of 9 m s^{-1} and should be considered an underestimate because of the assumptions used.

It is interesting to note that a RASS was tested on WPL's FM-CW radar in the 1970s and achieved a maximum range between 500 and 600 m (R. B. Chadwick, personal communication), approximately the same as predicted by these calculations.

7. CONCLUSIONS

A radar equation for the signal-to-noise ratio of a RASS system was used to calculate the maximum expected range of a low-altitude wind and temperature profiler for two extremes of meteorological parameters. Our calculations show that the proposed FM-CW RASS should be capable of measuring wind and temperature profiles to maximum sounding heights of 150 m under worst-case conditions and 600 m under best-case conditions, using reasonable levels of radar transmitter and acoustic power. The expected range resolution and minimum height are both 10 m. These calculations suggest that a practical, high-resolution, FM-CW, boundary-layer, wind and temperature profiler can be built for a reasonable cost.

ACKNOWLEDGEMENT

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APPENDIX

The detailed calculations performed for this feasibility study are presented along with plots of interesting parameters. The appendix is presented directly from the software package used to do the calculations. MKS units are assumed.

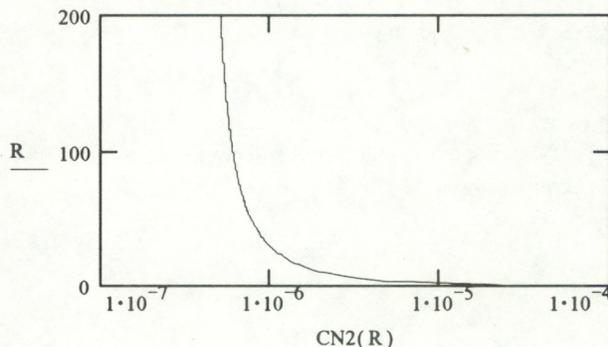
R := 1 .. 200 Range is defined from 1 to 200 m in 1 m increments.

Rb := 1200 Daytime boundary layer height.

The weighted path-average of the turbulence structure parameter is given below. The value at 2 m of 6.193×10^{-6} is for the worst-case turbulence on a windy afternoon.

$$CN2(R) := \left[2.32 \cdot 10^{-4} \cdot \left(\frac{R}{Rb}\right)^{-\frac{4}{3}} + 5.79 \cdot 10^{-3} \cdot \left(\frac{R}{Rb}\right)^{-\frac{2}{3}} + 6.11 \cdot 10^{-2} + 2.75 \cdot 10^{-4} \cdot \left(\frac{R}{Rb}\right)^3 \right] \cdot 6.193 \cdot 10^{-6}$$

Below is a plot of the weighted path-averaged turbulence structure parameter used in these calculations.



$\lambda := .1$ The radar wavelength is defined as 10 cm for a 3 GHz frequency.

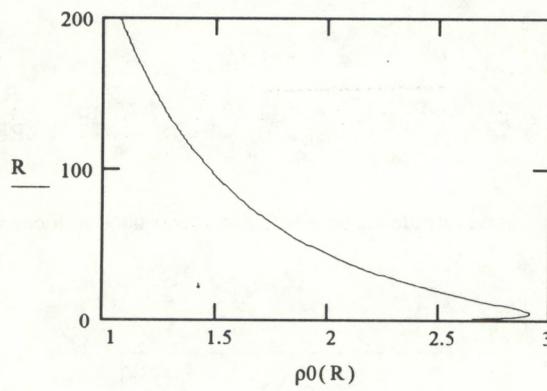
$\lambda_2 := \frac{\lambda}{2}$ The acoustic wavelength is one half the radar wavelength.

The transverse coherence length of the acoustic wave is calculated as a function of range and weighted path average of the acoustic refractive index structure parameter.

$$ka := \frac{(2 \cdot \pi)}{\lambda 2} \quad \text{Acoustic wave number.}$$

$$\rho_0(R) := \left(0.546 \cdot ka^2 \cdot R \cdot CN_2(R)\right)^{-\frac{3}{5}} \quad \text{Transverse coherence length.}$$

The transverse coherence length of the acoustic wave is plotted below as a function of range.



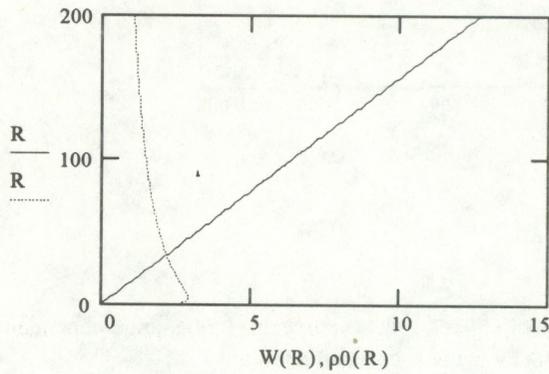
The width of the radar beam at range R is calculated and compared to the transverse coherence length of the acoustic wave.

$$kr := \left(\frac{2 \cdot \pi}{\lambda}\right) \quad \text{Radar wavenumber.}$$

$$D := 1 \quad \text{Effective radar antenna diameter set to 1 m.}$$

$$W(R) := \frac{(4 \cdot R)}{(kr \cdot D)} \quad \text{Width of radar beam at range R.}$$

The width of the radar beam is larger than the transverse coherence length of the acoustic wave for most of the range of interest. Therefore, turbulence will significantly broaden the spot.



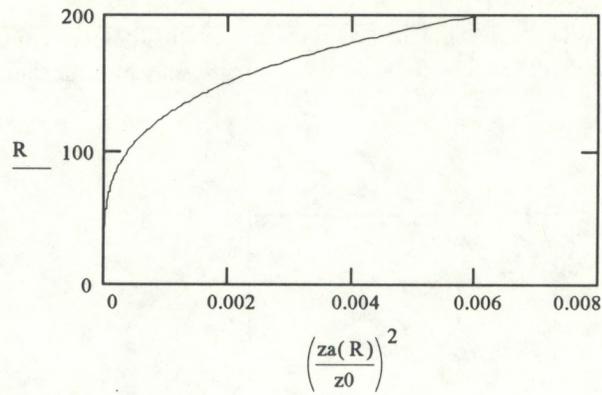
The virtual vertical displacement of the acoustic source due to the temperature gradient is calculated for a large temperature gradient of 7 degrees / 200 m and found to be trivial compared to turbulence effects.

$$\Gamma := \frac{7}{200} \quad \text{Temperature gradient of 7 degrees / 200 m.}$$

$$z_0 := \frac{(\pi \cdot D^2)}{(2 \cdot \lambda)} \quad \text{Virtual vertical displacement for which gradient-induced spot spread equals diffraction-limited spot size.}$$

$$z_a(R) := \frac{(\Gamma \cdot R^2)}{(4 \cdot 285)} \quad \text{Virtual vertical displacement of the acoustic source due to temperature gradient.}$$

The quantity of z_a over z_0 squared is plotted below to show the small effect of temperature gradients at these low altitudes.



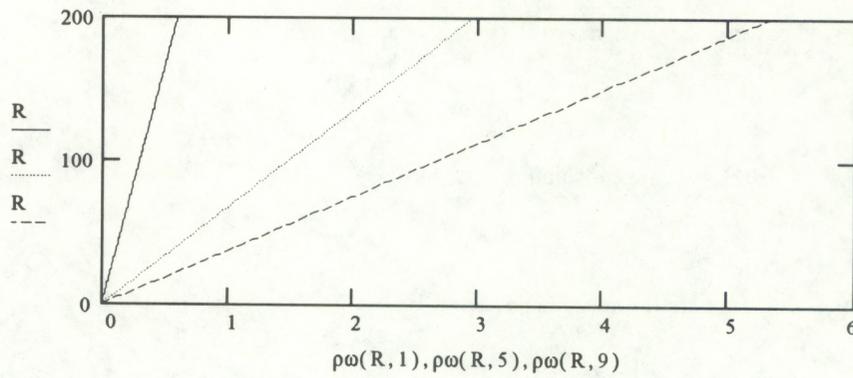
The total transverse vector displacement of the acoustic source due to the range-dependent horizontal wind is calculated assuming the wind is constant with range.

$$rs := \frac{D}{\sqrt{2}} \quad \text{Diffraction-limited focal spot radius.}$$

$$ca := 338 \quad \text{Acoustic velocity.}$$

$$\rho\omega(R, vw) := \frac{(vw \cdot R)}{ca} \quad \text{Total transverse displacement of the acoustic source where } vw \text{ is the horizontal wind speed.}$$

The total displacement of the acoustic source due to a uniform horizontal wind is displayed below for wind speeds of 1, 5, and 9 m/s. Notice that the displacement is much greater than the antenna size for any appreciable wind velocity.



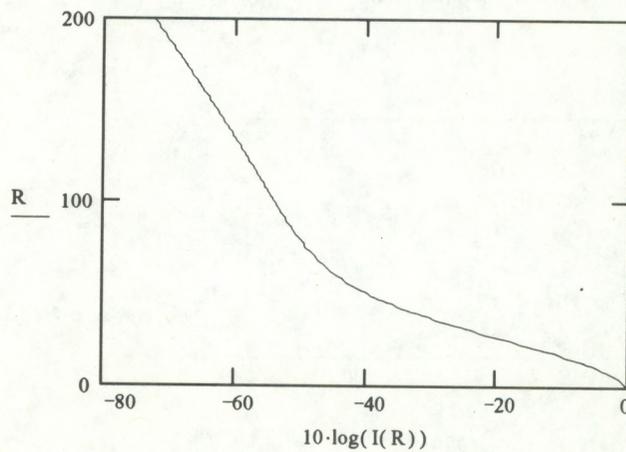
Now that all the terms are calculated, the attenuation of the received signal due to atmospheric effects is calculated without the terms for temperature gradients.

$\alpha = .2$ Atmospheric acoustic attenuation in decibels per meter. The value chosen is 20 dB / 100 m, the worst-case value for a dry, hot day.

$$I(R) := \frac{1}{\left[1 + \frac{W(R)^2}{(2 \cdot \rho_0(R)^2)} \right]} \cdot \exp \left[\frac{-4 \cdot (\rho \omega(R, 9)^2)}{rs^2} \right] \cdot 10^{-\frac{(\alpha \cdot R)}{10}}$$

Attenuation of the received signal due to atmospheric effects. Worst case wind speed of 9 m/s is assumed.

The attenuation is plotted below in decibels relative to zero range for the worst-case meteorological parameters.



The received power is calculated for selected radar parameters.

$\Delta := 10$ Radar range resolution in meters.

$P_a := 10$ Transmitted acoustic power.

$P_t := 5$ Radar transmitter power.

$G_a := 75$ Gain of the acoustic antenna.

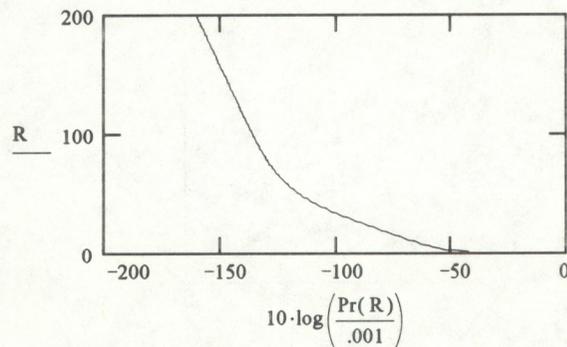
$B := \frac{(2 \cdot 300)}{338}$ Acoustic wavenumber bandwidth for 300 Hz RASS bandwidth.

$\eta := .8$ Radar antenna efficiency.

$$Pr(R) := 3.7 \cdot 10^{-14} \cdot \left[\frac{\Delta}{(\lambda \cdot R)^2} \right] \cdot \frac{(P_a \cdot G_a \cdot (P_t) \cdot \eta)}{B} \cdot I(R)$$

Radar equation for the received power for a RASS system.

The plot of radar received power is plotted below in decibels relative to a milliwatt.



A more interesting parameter is signal-to-noise ratio. Therefore, the noise power of the receiver is calculated.

$$k := 1.38 \cdot 10^{-23} \quad \text{Boltzman's constant.}$$

$$b := 8 \cdot 10^3 \quad \text{Receiver bandwidth.}$$

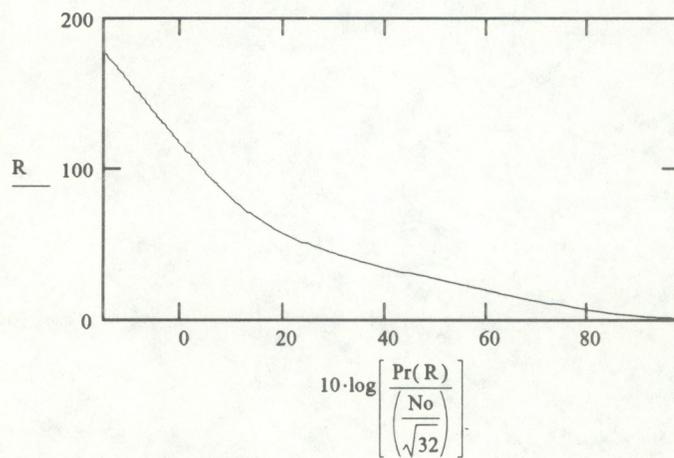
$$F := 10^{\left(\frac{2.2}{10}\right)} \quad \text{Receiver noise figure.}$$

$$T_a := 10 \quad \text{Antenna temperature.}$$

$$T_r := 290 \quad \text{Noise figure reference temperature.}$$

$$N_o := k \cdot b \cdot (F \cdot T_r + \eta \cdot T_a) \quad \text{Total receiver noise power.}$$

Signal to noise ratio is plotted below as a function of range in decibels. The total noise power has been reduced by 32 incoherent averages.



The maximum range for a given signal-to-noise ratio is calculated by finding the range where signal to noise ratio equals -10 decibels.

$$sn := 10^{\left(\frac{-10}{10}\right)} \quad \text{Signal to noise ratio of -10 decibels.}$$

$$SN(R) := \left[3.7 \cdot 10^{-14} \cdot \left[\frac{\Delta}{(\lambda)^2 \cdot R^2} \right] \cdot \frac{(Pa \cdot Ga \cdot (Pt) \cdot \eta)}{\left(B \cdot \frac{No}{\sqrt{32}} \right)} \cdot I(R) \right]$$

Equation for calculating signal to noise ratio as a function of range. Assumes 32 incoherent averages.

$$R := 100 \quad \text{First guess for maximum range.}$$

$$answer(R) := \text{root}(SN(R) - sn, R) \quad \text{Find the root where signal to noise minus -10 dB equals zero.}$$

$$answer(R) = 157.569 \quad \text{The maximum range for a profiler under worst case meteorological conditions.}$$