EPA/600/A-97/034

The Degradation of Doppler Sodar Performance Due to Noise

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ABSTRACT

Ambient background noise is a cause of poor Doppler sodar performance. This noise can be active or passive and broad-band or narrow-band. Active broad-band noise decreases the sounding range of the sodar by decreasing the signal-to-noise ratio. Active narrow-band noise can be interpreted as erroneous wind values. Passive noise sources are objects which reflect the transmitted acoustic pulse back to the sodar with zero Doppler shift. Use of acoustic shielding is discussed as a method of noise pollution control from the sodar by isolating the side lobe energy of the transmitted acoustic pulse. At the same time, the same acoustic shields are effective in blocking out active ambient background noise on the sodar. Previous studies which experienced noise interference are shown as examples of problems that are frequently encountered.

INTRODUCTION

The Doppler sodar has led to significant advances in our understanding of the planetary boundary layer (PBL) over the last 25 years. These ground-based acoustic wind profilers have demonstrated their usefulness in many studies throughout the world by characterizing the thermal structure and wind field of the PBL. Sodars have been particularly valuable in many air pollution studies, especially those conducted in urban regions.

Since a sodar utilizes acoustic pulses to remotely sense the overlying wind field, ambient background noise can degrade data quality. Special considerations must be made to avoid or minimize noise interference. This can be a difficult challenge in an urban setting where there are many sources that generate noise. In addition, the acoustic pulses emitted by a sodar can be a potential source of noise pollution. This paper examines how noise can adversely affect the operation of a sodar and outlines what steps can be taken to eliminate or minimize noise interference.

THEORY OF OPERATION

Sodars operate on the principle of acoustic backscattering. An electronic sound driver is used to transmit an acoustic pulse into the atmosphere with a frequency between 1 and 5 kHz. The duration of each pulse is usually between 50 and 300 ms. As the sound wave propagates through the atmosphere, a small fraction of its energy is scattered back to the surface by small-scale temperature inhomogeneities (~ 10 to 30 cm) whose scale is similar to that of the wavelength of the acoustic pulse. These temperature inhomogeneities are produced by turbulence in regions of larger scale potential temperature gradients, inversion layers, wind shear layers, or thermal plumes.

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The backscattered signal is amplified and digitally recorded at a rate of several hundred times per second. The time series is subdivided into smaller blocks, each representing a discrete layer in the atmosphere. Any number of algorithms can be used (Neff and Coulter, 1986) to determine the mean frequency of the backscattered signal. The Doppler shift, that is to say the difference between the transmitted frequency f and the backscattered frequency f_s, is directly proportional to the radial wind velocity along the acoustic beam axis. The radial wind velocity V_r is determined by

$$V_r = -\frac{C}{2}\left(\frac{f_s}{f} - 1\right)$$

where C is the speed of sound (~ 340 m s^{-1}). Determination of the total wind vector requires a minimum of three independent radial wind velocities.

The acoustic wave is attenuated as it propagates through the PBL. Classical attenuation (α_c) is due to the effects of viscosity, heat conduction, and molecular diffusion. Molecular attenuation (α_m) is due to the excitation of the internal energy modes of O_2 molecules during the passage of the acoustic wave. These coefficients are well known functions of frequency, temperature, humidity, and pressure with α_m about an order of magnitude larger than α_c. At an ambient temperature of 20 °C, the maximum values of α_m approach 20, 56, 139 and 226 dB km^{-1} for 1, 2, 5 and 8 kHz pulses, respectively (Harris, 1966). Excess attenuation (α_e) describes the loss of acoustic intensity due to turbulent beam broadening and refraction by the wind (Neff, 1978, Clifford and Brown, 1980). Excess attenuation (a function of wind speed, turbulence, acoustic frequency, beamwidth, and path geometry) causes a reduction in backscatter signal intensity; it is usually smaller than α_m most of the time (Aubry et al., 1974, Moulsley et al., 1979).

Sodars which use acoustic frequencies less than 2 kHz generally have a maximum sounding range of 1 to 2 km (Clifford et al., 1994). The range of a sodar using acoustic pulses greater than 2 kHz decreases with increasing frequency because of the effects of molecular attenuation. A sodar with a transmit frequency of 4 to 5 kHz has a range of about 200 to 300 m. However, most environmental noise tends to exhibit frequencies less than 2 kHz; its spectrum falls off sharply as frequency increases (Simmons et al., 1971). The challenge is attempting to find a balance which will maximize a sodar's range and minimize noise interference.

THE EFFECT OF NOISE ON SODAR PERFORMANCE

The limiting factor in wind velocity determination is usually the amount of environmental noise included with the backscattered signal (Neff and Coulter, 1986). Thus, a sodar must be able to differentiate the Doppler-shifted backscattered signal from all other ambient background noise. These external noise sources can be classified as active or passive and as broad-band (i.e., white noise or random frequency) or narrow-band (fixed frequency). In general, a poor signal-to-noise ratio generally increases the variance of Doppler estimates and biases the backscattered signal to a zero Doppler shift (i.e., $V_r \rightarrow 0$ m s^{-1})

Most ambient background noise is active broad-band. Examples include highway and road traffic, heavy machinery, industrial facilities, power plants, and airplanes. These noise sources produce a wide-band signal which can overlap the frequency bandwidth used by a sodar. Active broad-band noise effectively decreases the signal-to-noise ratio which results in a decrease in the maximum vertical range of the sodar since the backscattered signal can not be discerned from the active broad-band noise. Higher sampling levels are more susceptible to being lost to noise interference because of an exponential decrease in backscattered power with height. In general, the performance of a sodar will degrade as noise levels increase from these nearby sources. Some active broad-band noise sources such as highway traffic may have a pronounced diurnal, weekly, or seasonal pattern.

Active fixed-frequency noise sources include the back-up beepers used on large trucks, forklifts, rotating fans, birds, and insects. These noise sources affect the performance of a sodar in different ways depending upon their type and proximity. If these noise sources have a frequency component in the sodar's operating range, they may be misinterpreted by the sodar as valid backscattered data. The result is an erroneous wind value that may be found in any number of the measurement heights which depend on the arrival time of the noise in relation to the initial transmit time of the sodar. Since a sodar expects only a very weak backscattered signal, strong active fixed frequency noise sources may saturate the received signal. When this happens, the sodar is unable to determine any value for wind velocity. Some of these sources can be identified during the site selection process. One approach to reducing the problem of fixed-frequency noise sources is to use a coded pulse. A return pulse would not be identified as data unless peak frequencies were found in the return signal the same distance apart as the transmit frequencies. Pinkel and Smith (1992) introduced a repeat-sequence coding technique for Doppler sonars and sodars which were found to increase the precision of velocity estimates.

If possible, a site should be free of extraneous ambient background noises. A noise survey can aid in the decision for site selection. The survey should at least cover diurnal and weekly patterns. A qualitative survey should be conducted to identify all active noise sources. The technology now exists to conduct a quantitative noise survey with minimal cost and effort. A simple noise meter can assess the overall intensity of the background noise. Noise levels less than 50 dB are the ideal. A portable laptop computer, sound card, microphone, and spectral analysis software can be used identify the amplitudes and frequencies of the measured background noise.

Passive noise sources are objects that reflect a transmitted acoustic pulse back to the sodar antenna. Examples of potential reflectors include buildings, trees, towers, and transmission lines. While most of the transmitted acoustic energy is focused in a narrow beam, side lobes do exist. This is illustrated in Fig. 1 which shows the gain pattern of a vertically oriented acoustic beam for five frequencies between 1 and 5 kHz. Note that substantial side lobe energy is generally associated with lower frequencies. Fixed-echoes are created when the side lobes reflect off of stationary objects and return the same acoustic frequency to the sodar receiver. A zero Doppler-shift would be interpreted by the sodar as a wind speed of 0 m s^{-1}. It is not always possible to predict which objects may be a problem. Antennas tilted at an oblique angle from the vertical that are used to determine the horizontal wind velocity components should be pointed in a direction away from those objects. Anything in the general direction of the antenna which is higher than several meters may be a potential reflector. It is important to construct an obstacle vista diagram prior to sodar installation which identifies the direction and height of potential reflectors relative to the sodar (Baxter, 1996). This diagram can be used to assess if nearby objects are creating fixed echoes.

Algorithms have been developed which isolate and remove ambient background noise. Melling and List (1978) introduced a zero-crossing technique to extract wind velocities from the backscattered signal. Mastrantonio and Fiocco (1982) developed a technique to improve the accuracy and precision of sodar wind measurements by isolating the backscattered signal from ambient noise by a spectral integration. Good results have been obtained with a noise reduction scheme developed by Gardiner and Hill (1986). Some commercially available sodars have algorithms which identify fixed-echoes. These algorithms identify backscattered frequencies with zero Doppler shift which remain constant in space and over time. That peak frequency is eliminated and the next strongest backscattered frequency is selected to determine the wind velocity.

Numerous examples have been cited of noise interference with Doppler sodar operation. Unfortunately, the assessment of data loss in these cases is more qualitative than quantitative. For example, Casadio et al. (1996) reported that data obtained by a sodar located in Rome, Italy was often corrupted due to the relatively noisy city environment. No quantitative measure on the percent data loss was provided. Santovasi (1986) encountered problems with active broad-band noise both on diurnal and seasonal time scales. He evaluated the performance of a sodar for one year at the Mt. Tom Generating Station north of Holyoke, Massachusetts. Traffic-generated noise from nearby Interstate 91 adversely affected the sodar. Noise levels in excess of 70 dB were commonly observed during rush hour (early morning and late afternoon). This cut down on the sodar's range by decreasing the signal-to-noise ratio. The traffic noise problems were somewhat mitigated in the summer when the trees that lie between the sodar and highway were in full foliage. The leaves acted as an effective barrier against the noise. However, as noted by Hardesty et al. (1977) and Fanaki (1986), noise is often generated by strong winds blowing the tree leaves. The efficiency of the sodar also improved in the summer because of the increased convective nature of the boundary layer. Unfortunately, the same trees which shielded the sodar from highway noise in the summer were responsible for creating fixed-echoes.

Other investigators also observed problems with fixed-echoes from nearby obstacles. Balser et al. (1976) noted that a 150-m tower used to obtain *in situ* wind measurements during a intercomparison experiment may have caused some reflection of the acoustic signal from the sodar's bistatic transmitter located only 10 m away. Wittich (1990) encountered similar fixed-echo problems when the acoustic beam was reflected off a nearby 300-m tower which manifested themselves as strong backscattered signals at 250 and 300 m. Petersen and Jensen (1976) reported corrupted data between 100 and 130 m above ground caused by the fixed echoes from a nearby 123-m tower. Fixed-echoes were also encountered by Kurzeja (1994) during a year-long intercomparison experiment near the Savannah River Laboratory and by Vogt and Thomas (1994) at the Karlsruhe Nuclear Research Center. Kurzeja's sodar was located in an open meadow 15 m away the edge of the surrounding pine forest. The trees were approximately 10-15 m in height. The Karlsruhe sodar was placed about 200 m north of a meteorological tower in a meadow 60 m x 100 m in area. The meadow was surrounded by a pine forest 20 m in height. In both cases, fixed-echo returns due to the pine trees were observed. Kurzeja reported that the fixed echoes biased the backscattered frequency towards zero (i.e., wind velocity estimates were biased towards 0 m s^{-1}).

Tethersondes have been responsible for creating fixed echoes when the balloon drifted over the sampling volume of the sodar (Hall et al., 1975, Nater and Richer, 1977, von Gogh and Zib, 1978). Large numbers of airborne insects have also corrupted backscatter data (Riley, 1994). Nocturnally migrating insects have been found to congregate and form discrete, dense layers in the boundary layer. These insects are sometimes, but not always, collocated in inversions layers or zones of atmospheric convergence. The backscattering cross section of large insects has a scale similar to the turbulence which effectively scatters acoustic pulses of a sodar. If an insect layer is dense enough, it may create a fixed echo return. However, these echoes are not as obvious as those created by towers or balloons and may be misinterpreted as an inversion layer.

Wind near the ground normally produces most of the ambient noise sensed by a sodar except in urban, industrial, and other populated areas where artificial noise often exceeds natural ambient noise (Simmons et al., 1971). Wind noise can be appreciable at exposed locations such as mountain tops and other terrain features with sharp relief (Asimakopoulos et al., 1980). Several investigators (Parry et al., 1975, Hardesty et al., 1977, Finkelstein et al., 1986, Evers and Neisser, 1990) have noted the loss or corruption of data due to wind-generated noise when horizontal wind velocities were greater than 10 m s^{-1}. High surface winds generate localized noise against the surfaces of the sodar antenna shields which results in a reduction in the sounding range.

Kaimal et al. (1980) discovered that Boulder Atmospheric Observatory's 300-m tower was a source of narrow-band noise. The closely spaced elements of the elevator/carriage support system on the tower generated noise with two spectral peaks when southwesterly winds exceeded 4 m s^{-1}. The first was located at 0.5 kHz and was of no consequence to any of the five sodars being evaluated. The second peak ranged between 1.1 and 1.3 kHz, depending on atmospheric conditions. A sodar designed and constructed by the Wave Propagation Laboratory operated at 1.25 kHz. As a result, the sodar data were occasionally corrupted and were considered unusable.

Not surprisingly, sodar data quality has been severely degraded when these systems have been located near the runways of airports and military airfields (Parry et al., 1975, Hardesty et al., 1977, Kaimal and Haugen, 1977). Aircraft-generated noise lead to at least 50% data loss for a sodar located adjacent to two runways during peak traffic hours in a study conducted by Beran et al. (1974) at Stapleton International Airport. Similarly, aircraft noise at Dulles International Airport often overwhelmed the backscattered signal and resulted in decreased data reliability (Parry et al., 1975, Hardesty et al., 1977). Even in remote sites away from airports, the noise of an aircraft passing over the sampling volume of a sodar can saturate the backscatter signal (Hall et al., 1975).

Many investigators (Parry et al., 1975, Kaimal and Haugen, 1977, Finkelstein et al., 1986, Santovasi, 1986) have reported that sodar data are often corrupted during episodes of moderate to heavy rainfall. Raindrops falling on the parabolic antenna dishes and acoustic transducers can cause a significant increase in system noise (Clifford et al., 1994). As a result, this noise overwhelms the weak backscattered signal. Santovasi (1986) reported that sodar performance was actually enhanced during light snowfall events. The falling snow provided a good reflective surface while absorbing much of the background ambient noise in the PBL. The sodar range was adversely affected only when the snow began to accumulate on the parabolic dish, thereby interfering with acoustic transmission and reception. In either case, the vertical wind velocity is contaminated since the backscatter frequency peak corresponds to that of falling precipitation.

Insects and birds which reside near sodar antennas have been known to generate noise which has lead to a decrease in the signal-to-noise ratio (Parry et al., 1975, Hardesty et al., 1977). Coulter and Martin (1994) found that sodar data was degraded because of noise generated by field mice that decided to make a home inside the antenna enclosure.

ACOUSTIC SHIELDING

The repetitious and often loud acoustic pulses emitted from a sodar can be an irritating nuisance, especially if the instrument is located in or near populated areas. Ironically, the use of a sodar in air pollution studies in urban environments could result in the sensor itself contributing to noise pollution. Piringer (1994) faced this problem when the residents from a nearby neighborhood complained about the repetitious beeping of the sodar at night. The acoustic power was reduced by 12 dB between the hours of 2200 to 0600 local time. That action limited the vertical range of the sodar. Vogt and Thomas (1994) encountered complaints from workers in a nearby building during the day. They reduced the power output by 12 dB which decreased the sodar's range by 100 m.

It is important that sodar antennas produce sharply-defined, highly-directive acoustic beams with minimal side lobes (Hall and Wescott, 1974). Acoustic sounding is done primarily with the main beam while most of the unwanted background noise originates near and propagates along the surface of the earth. As Fig. 1 shows, most of the acoustic energy of a paraboloid-type antenna is focused in a relatively narrow beam. As a result, the amount of environmental noise received by the sodar depends not only on the noise levels existing at the antenna, but on the antenna's sensitivity in the direction of incidence (Simmons et al., 1971). The polar diagrams show that lower acoustic frequencies have larger side lobes. These side lobes radiate out along the surface which create noise pollution. It is important to minimize the reception of unwanted noise approaching the sodar antenna at 90° to the main beam and minimize the transmission of acoustic energy through the side lobes.

A significant reduction in both radiated and received side lobe acoustic energy can be achieved with anechoic shields. Shielding placed around sodar transmitters is quite helpful in reducing the level of sound emitted outside the main acoustic beam. This, of course, lessens the potential for annoyance. At the same time, the use of acoustic shielding also reduces the amount of lateral ambient noise being received by the sodar. Properly designed acoustic shields are also effective in reducing local wind-generated noise (Simmons et al., 1971).

The important side lobes to consider lie in the range of 70° to 90° from the main lobe (Simmons et al. 1971, Hall and Wescott, 1974). The 20° spread is to allow for atmospheric refraction of acoustic pulses during strong temperature inversions. In such an event, the acoustic energy radiated in the side lobe 20° above the horizon could be refracted downward towards the surface. This phenomena, sometimes referred to as ducting, can produce strong, unwanted fixed echoes from nearby obstacles and can also produce an unacceptable level of noise pollution if the sodar is located near a residential community.

The materials used to construct anechoic shields have been designed to isolate side lobe energy from propagating horizontally from the antenna while guarding from outside noise interference. The insides of the shields are lined with an acoustically-absorbing material which helps maintain the narrow focus to the transmitted acoustic pulse while absorbing the side lobe energy.

Simmons et al. (1971) made measurements of the effectiveness of acoustic shielding in reducing the level of urban noise received by a sodar antenna. Their results showed an improvement of about 17 dB in noise rejection at frequencies from 1 to 3 kHz; an improvement of 6 to 7 dB was observed at frequencies above 3 kHz. Hall and Wescott (1974) demonstrated that clearly defined backscatter data was acquired up to 700 m above the ground from an acoustically shielded sodar located near a noisy interstate highway in downtown Denver.

Simmons et al. (1971) and Hall and Wescott (1974) were able to significantly reduce the radiated and received side lobes by constructing a crude cylinder of hay bales around a sodar antenna 3 m in diameter and 2.5 m above the antenna aperture. The measured 90° side lobe of the antenna without acoustic shielding was approximately 38 at 1 kHz and 50 dB at 5 kHz below that of the main beam. Their data showed that this shield provided an additional suppression of 22 to 32 dB of 90° side lobe and between 16 and 20 dB of the 80° side lobe. While crude, the use of hay bales as acoustic shielding is still commonly employed (Fanaki, 1986, Vogt and Thomas, 1994).

Russell and Uthe (1978) used sand-filled plywood walls with foam lining. Haugen and Kaimal (1978) constructed a four-sided plywood enclosure flared at an angle of 11° and lined with convoluted foam. They later designed a shield which was a fiberglass conical enclosure flared at an angle of 16°. This shield was lined with a sound absorbing material consisting of a lead septum sandwiched between layers of foam. Haugen and Kaimal (1978) found that side lobe suppression was significantly improved with the later design. Kaimal and Haugen (1977) designed a hexagonal shield that was 1.8 m high and lined with 5 cm of foam. Sandwiched in the foam was a lead septum that was effective in blocking acoustic transmission through the shield walls. A similar construct of wood, lead, and foam was used for a sodar by Asimakopoulos et al. (1980) to improve the signal-to-noise ratio. Coulter and Martin (1986) used a hexagonal enclosure made of plywood lined with acoustically absorbing foam. Liu and Bromwich (1993) used fiberglass cylinders lined with acoustically-damping foam. Crease et al. (1977) recommended using a 5-cm thick polyurethane foam as a lining since this material has good sound absorbing characteristics. Degradation of the acoustic foam lining caused a decrease in the performance efficiency of the Mt. Tom sodar (Santovasi, 1986). The quality of the foam lining suffered from subsequent freezing and thawing during the winter and exposure to ultraviolet radiation. An increase in the sodar's range of 100 m was reported when the foam lining was replaced.

A more extreme method for isolating a sodar antenna from background noise is to place the antenna in a pit (Crease et al., 1977). To reduce background noise, Beran et al. (1974) placed sodar antennas in bunkers beneath the earth's surface. Sound-absorbing foam plastic was added to critical areas in the bunker to increase noise rejection. Comparison of this configuration against an above-ground antenna showed a 15 to 20 dB improvement. To limit the effect of wind-generated noise, Gardiner and Hill (1986) placed an antenna dish in a 2 m deep pit. The sides of the hole were lined with 5 cm thick acoustic foam. In addition, a wind shield of straw bales 1 m high and 0.5 m thick were placed around the rim of the pit to provide further noise reduction.

SUMMARY

The limiting factor in wind velocity determination from a Doppler sodar is usually the amount of ambient noise included with the backscattered signal. Noise sources can be classified as active or passive and as broad-band and narrow-band. Examples include highway traffic, urban regions, power plants, aircraft, birds, insects, rainfall, and wind-generated noise. A carefully designed noise survey that covers diurnal and weekly patterns can aid in site selection. A qualitative survey should identify all active noise sources. A quantitative survey can be conducted with the use of a simple noise meter, portable laptop computer, sound card, microphone, and spectral analysis software. A site should be relatively clear of obstacles that could act as fixed-echo reflectors. The antennas tilted at an oblique angle from the vertical should be pointed in a direction away from those objects. Some commercially available sodars have algorithms which identify and remove back-scattered frequencies with zero Doppler shift which remain constant in space and over time.

Greater sounding ranges can be achieved by sodar using lower acoustic frequencies. However, most ambient background noise tends to possess lower frequencies which can interfere with sodar operation. In addition, more side lobe energy exists for lower frequencies. Because of molecular attenuation, higher acoustic frequencies have a very limited sounding range. The advantage of higher frequencies is an increased antenna directivity with smaller side lobes and a lack of sensitivity to low frequency ambient noise. A significant reduction in both radiated and received side lobe acoustic energy can be achieved with anechoic shields. Past studies have demonstrated that these shields significantly reduce the amount of ambient noise being receiver by the sodar while at the same time reducing the transmitted side lobe energy which is a source of noise pollution.

ACKNOWLEDGMENTS

This research was sponsored by the U. S. Environmental Protection Agency under an interagency agreement with the National Oceanic and Atmospheric Administration.

DISCLAIMER

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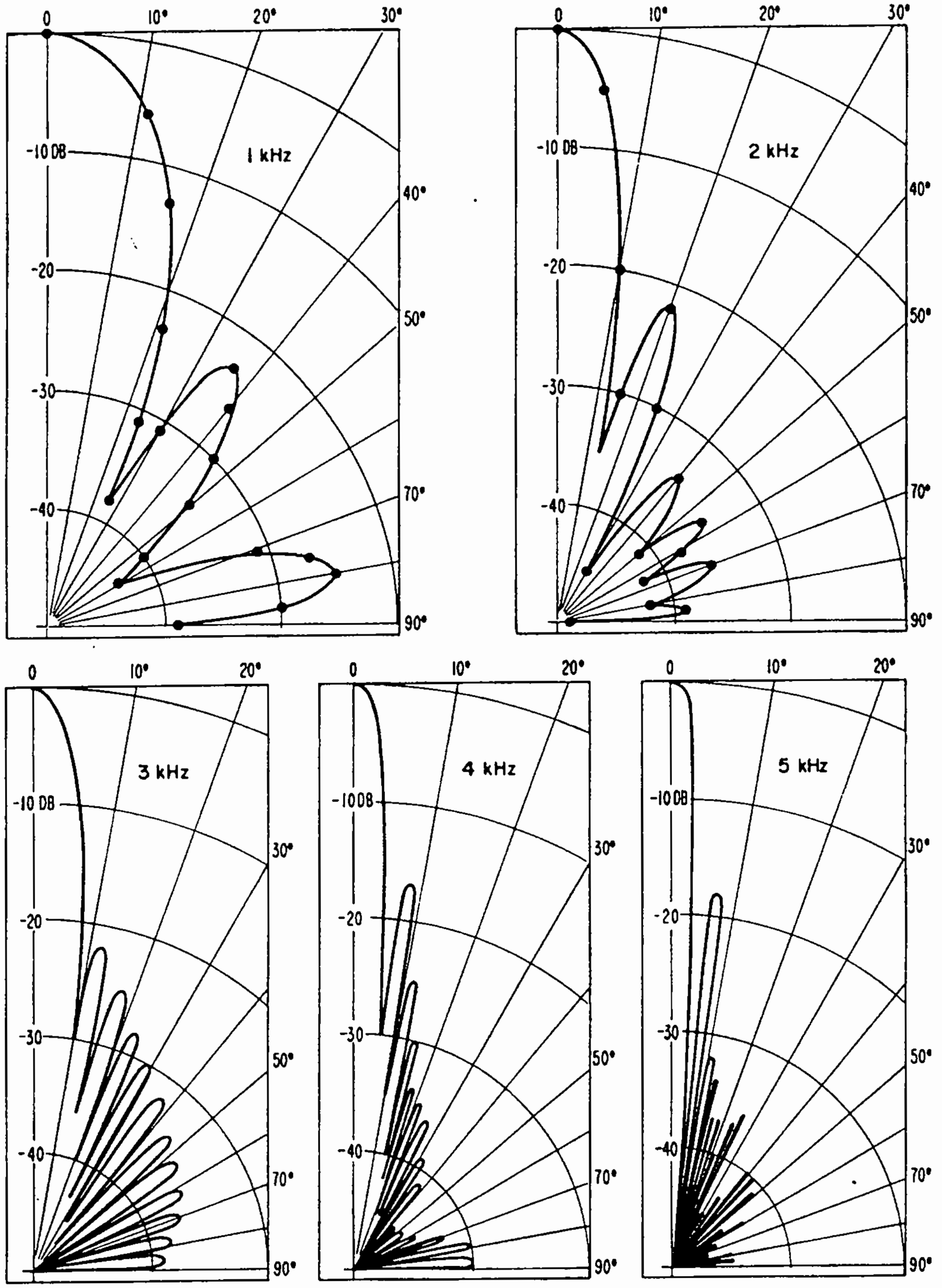

Figure 1. Polar diagrams of the gain pattern of a vertically oriented acoustic beam originating from an unshielded, conical horn reflector acoustic antenna (from Simmons et al., 1971).

TECHNICAL REPORT DATA

1. REPORT NO. EPA/600/A-97/034	2.	

4. TITLE AND SUBTITLE The Degradation of Doppler Sodar Performance Due to Noise	5. REPORT DATE
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) CRESCENTI, Gennaro H.	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Same as Block 12	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Exposure Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE EPA/600/9

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Ambient background noise is a common problem for poor Doppler sodar performance. This noise can be active or passive and broad-band or narrow-band. Active broad-band noise decreases the sounding range of the sodar by decreasing the signal-to-noise ratio. Active narrow-band noise can be interpreted as erroneous wind values. Passive noise sources are objects which reflect the transmitted acoustic pulse back to the sodar with zero Doppler shift. Use of acoustic shielding is discussed as a method of noise pollution control by isolating the sidelobe energy of the transmitted acoustic pulse. At the same time, the same acoustic shields are effective in blocking out active ambient background noise. Previous studies which experienced noise interference are shown as examples of problems that are frequently encountered.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/ OPEN ENDED TERMS	c. COSATI

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES
	20. SECURITY CLASS *(This Page)* UNCLASSIFIED	22. PRICE