Use of Monostatic Sodar in Probing the Lower Atmosphere*

S. P. SINGAL, B. S. GERA, S. K. AGGARWAL & MRS M. SAXENA
National Physical Laboratory, New Delhi 110012

Received 29 April 1975

Experiments conducted earlier with the help of a colocated acoustic sounder system had demonstrated the potential of the received back-scattered acoustic signals to give information about the thermal structure of the lower atmosphere. To overcome problems like transducer alignment, directivity, efficiency, beam drift, large transmitted signal and cost of antenna encountered with colocated systems, the earlier equipment has been converted into a monostatic system using a reflector horn as transmit-receive antenna. The necessary electronic circuit including an electronic T-R switch required for a monostatic system has been designed. The facsimile records obtained with this arrangement show the typical thermal plume structure formed on a bright sunny day and the radiation inversion structure formed on a clear windless night. Day-to-day observations give details of the continually varying atmospheric structure indicating the presence of complex phenomena in the lower atmosphere. Wave-like structures have been observed in the vertical and horizontal planes. While the horizontal wave motion is superimposed on the stratified laminar layers, has a time period of a few minutes, is discontinuous and lasts for many hours, the vertical wave motion is very regular, has a period of a fraction of a second and is short lived. The tropospheric turbulence seen by sodar as horizontal wave motion in the lower atmosphere has also been observed by the microwave link and the satellite beacon experiments operating simultaneously at the National Physical Laboratory.

1. Introduction

A number of remote sensing techniques have been developed to probe the lower atmosphere in time and space using radio, optical and acoustic waves. Of all these, the acoustic technique has been found to be more sensitive to atmospheric fluctuations than any other technique and can be effectively used to probe the lower atmosphere up to a range of 1 km which can be extended up to 10 km under favourable conditions. The rapid progress made with sodar in recent years has demonstrated the value of this technique to probe the planetary boundary layer with applications in atmospheric research, meteorological monitoring and forecasting, air pollution studies, communication and aviation studies. Sodar systems operating from ships or buoys can extend the studies of the boundary layer processes even over the ocean which can be of particular value for complementing operational data collection with high resolution at low altitudes. Gilman, Coxhead and Willis were the first to report in 1946 the detection of acoustic echoes of unexpected high intensity from the lower atmosphere while they were investigating anomalous microwave transmission in the atmosphere, work which has been extended recently at a number of research centres.

Following Kallistratova, Tatarskii and Monin, and applying Kolmogorov spectrum of turbulence, the scattered acoustic intensity $\sigma(\theta)$ at scattering angle $\theta$ due to the effects of wind and temperature fluctuations in dry air at wave length $\lambda$ per unit volume per unit incident intensity per unit solid angle with the direction of propagation can be given as:

$$\sigma(\theta) = 0.03 \lambda^{1/3} \cos^2 \theta \left( \frac{C_v^4}{C^2} \cos^2 \frac{\theta}{2} + 0.13 - \frac{C_t^4}{T^2} \right) \times \left( \sin \frac{\theta}{2} \right)^{-11/3}$$

where $k = 2\pi/\lambda$ is the wave number of the acoustic wave, $C$ is the mean velocity of sound, $T$ is the mean temperature (Kelvin) of the scattering volume and $C_v^4$ and $C_t^4$ are respectively the velocity structure and thermal structure parameters defined as:

$$C_v^4 = \frac{u(x) - u(x + r)^2}{r^{1/3}}; \quad C_t^4 = \frac{T(x) - T(x + r)^2}{r^{1/3}}$$

Here $u$ and $T$ are respectively the wind speed and temperature at a place distant $x$ in the $X$-direction. Direct back-scatter for a scattering angle of 180° is exclusively a function of thermal structure which offers a simple method of studying the temperature inhomogeneities in the lower atmosphere. The magnitude of this back-scattered power $Pr$ can be estimated by the sodar equation:
where $P_t$ is the transmitted power, $\tau$ the pulse length of the transmitted waves, $A$ the area of the receiving antenna, $R$ the range of back-scatter, $\sigma$ the back-scattered cross-section and $L$ denotes losses due to absorption and equipment efficiencies.

A colocated sodar unit had been operating at NPL in the back-scatter mode using a square array as the transmitting antenna and a reflector horn as the receiving antenna. The system was being used to map the temperature inhomogeneities in the lower atmosphere up to an altitude of 340 metres. To avoid alignment problems and beam drift which will always creep in the colocated mode, however, close the antennas may be, as also to use the same directivity and efficiency of the antenna, we set up a monostatic system. Furthermore, this latter system could also incorporate a blanking device which could get rid of the large signal received initially from the direct transmitted signal, the ground reflections and ringing of the antenna.

Keeping in view the above mentioned objective, a monostatic system has been set up at NPL using a reflector horn as the transmit-receive acoustic antenna. In the following discussion the salient features of the system, the design of the electronic circuit and the results obtained therefrom during its operation are presented.

2. The Monostatic System

The schematic diagram of the monostatic system is shown in Fig. 1 and its operating parameters are given in Table 1. The mechanical trigger from the facsimile recorder serves as the master control centre of the system. Converted into a suitable electrical signal, it triggers the tone burst generator and the receiver gate. The tone burst generator is capable of emitting a pulse of adjustable width between 20 and 100 msec repeated every two seconds. During each burst, the power amplifier delivers an electrical output of 40 watt to the acoustic transducer (driver) through the back to back diodes of the transmit-receive circuit. This driver coupled to the reflector horn antenna emits an acoustic tone burst of about 10 acoustic watt power.

The acoustic transducer (driver and horn) acts as a microphone during the reception of echoes. It is connected to a low noise preamplifier through a microphone transformer and a transmit-receive switch. The transformer has a step-up ratio of 1:22. It increases the received signal to a level where it exceeds the intrinsic self noise of the preamplifier. The preamplifier (Fig. 2) uses a 741 operational amplifier filtered with a twin-T wide band filter at 1000 Hz. The output of the preamplifier after reduction to 400 mV

![Fig. 1—Schematic block diagram of the monostatic acoustic sounder (Sodar)](image)
Fig. 2—Circuit diagram for the preamplifier and receiver gate

(r. m. s.) by the back to back silicon diodes (BY 126) is applied to a receiver gate. The gate which is an FET solid state switch is opened and closed for desirable periods by rectangular pulses developed by the monostable multivibrator triggered by the control trigger available from the facsimile recorder. The purpose of the receiver gate is two-fold. It can suppress the small amount of signals that leak through the transmit-receive circuit during the transmitted tone burst, and secondly, it can keep the receiver input grounded for a controllable period (typically about 250 msec) until the ground reflections and the ringing of acoustic transducer have subsided and it has fully recovered its sensitivity as a microphone. The amplified echo signals from the preamplifier are able to reach the receiver as soon as the receiver gate opens. The preamplifier complete with the microphone transformer and the receiver gate, offers a gain of 50 dB to the received signals.

The receiver is an active filter commercially available from NAL, Bangalore. It is a low noise solid state instrument which can be tuned sharply at 1000 Hz. It has a variable $Q$ so that the filter band-width can be varied from 10 to 100 Hz. It can receive signals over a wide voltage range from a few microvolts to about one volt. It offers a gain of about 30 dB to the received signals. The width of the filter is chosen to accommodate the radiated band-width and the Doppler shift of the received echo signals. It has been found that the filter band width of 30 Hz is suitable for tone bursts lasting about 60 msec in the present case.

The output of the receiver shunted with back to back silicon diodes is applied to a potential divider which reduces the output signals by 1 : 22. The reduced signals from the potential divider are applied to the facsimile recorder which displays the received signals as functions of altitude and the time of the day.

The system is capable of receiving signals of the order of a fraction of a microvolt and above. Noise levels in the receiving chain of the system generally determine the operating limits of the sounder under any conditions as these noise levels control the signal to noise ratio which is desired to be at least 15 dB. The back-scattered signal is extremely low because of the scattering cross-section being small (of the order of $10^{-9}$), the transmitted energy suffering geometrical spreading and the attenuation of the acoustic waves in the atmospheric air being large; on the other hand the noise levels, both ambient and electrical, in the system are very large. The electrical noise of the system has been controlled by using operational amplifiers in the preamplifier stage, effective electrical shielding and use of a narrow band filter, and the ambient noise has been reduced by using a directional acoustic horn.

Using the specifications given in Table 1, the ambient noise to be expected at the receiving transducer during winter months is of the order of $-26$ dB in nighttime and $-6$ dB in daytime (ref. $10^{-13}$ watt/m²). These values increase by as much as 10 dB during summer months. Calculations made of the signal power received by the NPL sodar for a range of 500 metres show that the received signals exceed the expected interference noise power during winter by about 24 dB during nighttime and by about 4 dB during daytime. This indicates that the interference noise power during daytime is more or less compara-
able with the power received. This may not allow the sounder to be operated very successfully beyond a range of 200 metres during periods of excessive noise.

The above analysis necessitates further suppression of the ambient noise at the sounder antenna for operating it in different terrains and environments. We estimate that to operate the sounder in the noise of representative environments (say an airport with peak noise levels of 130 dB), the receiving sensitivity of the 90° side lobe of the antenna should be about 90 dB below the central lobe—the condition which is not available at the moment but will have to be achieved in the long run. For the present set up, the ninety degree side lobe is about 50 dB below the central lobe of the antenna.

3. Results and Discussion

A monostatic sodar system receives only back-scattered signals from the atmosphere caused by the thermal structure which may either be random temperature inhomogeneities or uniform temperature gradients. The sounder used in the back-scattering mode may thus give details of a structure associated either with thermal plume activity offering a measure of the convective instability in the atmosphere during daytime or with temperature inversions responsible for ducting and instabilities under stable atmospheric conditions. Of course, much of the value of this sensing technique lies not in its ability to reproduce the kinds of quantitative data the meteorologist is generally accustomed to but in their presentation and ability to provide data in real time and space.

3.1 Thermal Plumes

Several investigators have reported the presence of thermal plumes in the lower atmosphere. It is a phenomenon of the rise of thermally non-uniform parcels of air on bright, sunny days under light wind and clear skies. These plumes become prominent near midday when the temperature is convectively unstable and heat is being conducted rapidly to the low-lying levels of the lower atmosphere from the solar heated ground. The rising parcels tend to be accelerated upward as long as the surrounding air is colder but are decelerated at levels where the temperature of the surrounding air becomes equivalent to the rising parcels.

Heating from below in calm or light wind results in the formation of three distinct layers in the lower atmosphere: (1) a shallow surface layer with a definitely superadiabatic (greater than adiabatic) lapse rate with values very much higher near the ground, (2) a thick central layer with a lapse rate very nearly adiabatic, and (3) an upper layer having stable conditions. The thermal turbulence in the central part of the unstable boundary layer is relatively intense because of the great speed of the ascending and descending parcels of air, while close to the ground turbulence is slight due to the small speed of the ascending parcels. On a windy day, the mechanical turbulence may not allow this central homogeneous layer to be formed. Figure 3 shows the successive schematic warming on a morning under (a) calm clear conditions, and (b) windy conditions depicting clearly the above effect. In the late afternoon or under cover of clouds the heating from below may stop or get reduced in intensity; under such conditions, the superadiabatic surface layer may disappear immediately and the central homogeneous layer may change slowly to stable equilibrium unless some turbulent process like wind may either not allow it to be formed or may destroy it.

The columns of sodar echoes in a layer very near the ground surface should, thus, show signs of formation of thermal plumes and breaking of stable structure as the ground heating commences—a process which should develop with time and may extend up to the central layer. Under favourable conditions, the thermal plumes may go as high as 300 metres by mid-day surrounded by areas of undetectable echoes. In the afternoon, the solar heating is reduced making the stable layers to start descending again and by early evening as the solar radiation stops altogether and radiative cooling starts, the sodar echoes should start showing the formation of stable atmosphere (inversion structure) in the layers very near the ground.

Fig. 3—Successive schematic warming on a morning for heating from below over land: (a) calm clear morning; (b) windy morning.
Figure 4 shows the thermal plume structures as seen by NPL sodar on two different days. It is seen that the vertical organization of these plumes starts with daybreak with the stratified layer structure above, slowly builds up as the day advances reaching the maxima of its activity by mid-day (note the fountain-like character of the convective activity throughout the record) when the layer structure completely disappears. In the afternoon this structure starts stratifying again. The plume structure is seen to exist up till a height of about 200 metres which is practically the limit of observation of the sounder during daytime. On windy days thin layered wind shear structure is generally formed over-riding the thermal plume structure. Delhi is generally prone to surface winds for most of the year during daytime and a clear thermal plume structure is very rarely seen. The record also shows sometimes dark vertical strips across the entire height interval. These strips correspond to man-made discrete noises from the vicinity of the sounder.

3.2 Temperature Inversions

Quite a different type of acoustic echo is observed on the facsimile display under stable conditions in the boundary layer. On clear nights due to the greater thermal radiation from the earth's surface than from atmospheric air, the temperature gradients in the atmospheric boundary layer may fall below the adiabatic lapse rate and change sign. This does not allow the denser lower mass to go up and the lighter upper mass to come down, a condition responsible for static stability or temperature inversion. These heat conduction losses continue throughout the night which can make the depth of the cold layer of air on the earth's surface increase usually as the square root of the time interval after sunset.

The modifications in the structure can only be affected by mechanical turbulence and can extend up to the layer of frictional influence. Convection is impossible by definition. Large temperature, humidity and refractivity gradients extending to relatively high levels are possible. Both temperature excess and wind speed can affect the amount of mechanical mixing. Light winds and a large temperature excess will give rise to small amounts of mixing in the very low layers of the atmosphere while strong winds and a small temperature excess will develop a relatively large amount of mixing extending up to the height of frictional influence and may lead to conditions more nearly like those during the processes of heating from below. The temperature distribution with height is shown schematically in Fig. 5 under both these conditions. For moderate mixing, temperature inversions
Fig. 5. - Temperature distribution with height for cooling from below over land: (a) light wind and large temperature excess; (b) strong wind and small temperature excess

usually occur at some intermediate height while under strong mixing conditions, a shallow surface temperature inversion and an elevated stable layer (turbulence inversion) with a thick homogenous layer in between are the possible structures.

The acoustic sounder record should show the cold surface air separating from the warmer air above with the sounder detecting a random thermal structure throughout the deepening cooler air. Figure 6 shows the type of structure as obtained by the NPL sounder on two different days. It is seen that strong temperature inversions occur up to a height of about 200 metres on both the days throughout the night. These structures start breaking off with the daybreak when thermal plume activity starts with the heating of the ground surface with solar radiations. Inversion structures are also seen beyond a height of 200 metres; however, their intensity is low on both the days. The elevated stable layer at a height of about 300 metres seen for a short while in the lower record starting at 0245 hours can be a turbulence inversion or wind shear. These structures clearly bring out the turbulent eddy diffusion process produced by the gustiness of wind in the boundary layer under light wind conditions. Under strong wind conditions, only a thin fine layer structure extending over only a few tens of metres above the sounder has been seen.

Most often the lower atmosphere under stable conditions is split up into horizontally stratified layers. The low altitude layers amongst these are generally associated with inversions that cap convective activity transporting turbulence in the stable zone while the high altitude layers are associated with pronounced vertical wind shear. Flow of warmer and usually more humid air over colder and dry air as encounter-
ed in fronts, turbulence which disturbs the adiabatic gradient making it colder at the top and warmer at the bottom, convection and overflow may be some of the factors responsible for the stratification of the clear atmosphere.

Figure 7 shows the stratified layer structure seen under stable conditions on two different nights up to a height range of 300 metres. These layers show undulations of varying wave periods which may correspond to internal gravity waves generated near the ground. Occasionally, these layer structures may continue throughout the day changing the layer height in such a way that it ascends gradually until about noon and descends slowly after that.

Radio refractivity $N$ defined as $N = (n - 1) \times 10^6$ where $n$ is the refractive index, decreases monotonically with height in the homogeneous troposphere (Fig. 8a). However, under inversion conditions in the first few hundred metres of air, a layer of atmosphere can exist wherein the refractivity may decrease rather sharply with height (Fig. 8 b & c). Such a layer acquires the characteristic of trapping radiation of certain wave lengths depending on the duct height, reflecting radiations of wavelengths longer than the duct width and offering a random perturbation for very long wavelengths. The trapped radiations are guided around the curved surface of the earth by an action similar to a wave guide. Such trapping layers are known as surface ducts and are generally less than 100 metres in width with occurrence of ground level or elevated ducts fairly frequent. Such ducts can trap radiations of frequencies up to 100 MHz or more for a good part of the time. A knowledge of the characteristics of ground level ducts becomes thus vital for the operation of communication links. The wavelength of these trapped waves depends on the height of the duct and can be calculated from the following relationship:

$$\lambda_{\text{max}} = \frac{0.236}{h^{3/2}}$$

where $\lambda_{\text{max}}$ is the maximum trapped wavelength and $h$ is the height of the duct from the ground surface, both being measured in metres. The duct thickness $d$ can also be determined in terms of $\lambda_{\text{max}}$ and is given by $d(m) = 113 \lambda_{\text{max}}^{2/3}$ where $d$ and $\lambda_{\text{max}}$ are both measured in metres.

Rapid rise of temperature in an inversion layer under stable conditions or the sharp boundary between air masses of contrasting temperatures are the conditions responsible for the formation of ducts. In
3.3 Stable Waves

Nonlinear wave patterns associated with small scale overturning and turbulence have frequently been seen on sodar and radar records \(^1\) under conditions of considerable wind shear in the stable atmosphere. The wind shear in such cases may supply enough energy to set up wave motion in much the same way as waves are formed at the surface of the ocean with gravitation acting as a stabilizing or restoring force. The anomaly occurs within stable regions in zones of enhanced static stability with vertical shear of the horizontal wind accentuated due to the deformation of the wind field by dynamical processes like internal fronts, gravity waves and momentum waves, etc. The local Richardson's number is generally much less than 0.25 for these instabilities to originate.\(^3\) The breakdown can occur within a thin lamina or over a large vertical depth occurring periodically. The instability generally takes the form of regularly spaced two dimensional rolls of lateral extension with the structure characteristics of a billow cloud and is often referred to as unstable Kelvin-Helmholtz waves. These waves break after some time and result in turbulent motion. The breaking waves present a herringbone type structure.

Figure 9 display the horizontal sinusoidal wave like turbulence superimposed on the laminar layers as seen by the NPL sounder. Shown on the same record is also the radiosonde data as obtained at the Ayanagar Observatory (IMD Delhi) on the following morning. The turbulence originates in the early hours of the night with its amplitude reaching a maximum at about midnight after which it starts subsiding and disappears completely in the early hours of the morning. This wave motion is being seen throughout the volume of the atmosphere, is not continuous and has a period of a few minutes. There was no perceptible surface wind during the night which was clear and the preceding day had been cloudless, bright and sunny.

Figure 10 shows the vertical wave like turbulence originating in the lower atmosphere, probably at the ground level. This wave structure which is being seen in the early hours of the night, is very regular unlike the horizontal wave structure, has a period of a fraction of a second and lasts for only a few minutes.

A comparison of the horizontal wave pattern as seen by the NPL sounder with the stable waves seen by Bean \(et\ al.\)\(^3\) during one of their observations (Fig. 11) indicates that the observed structure may correspond to stable waves which grow with time and gradually disappear because of internal forces within the wave. It is of further interest to mention that tropospheric turbulence similar to that observed by sodar has also been seen on the microwave link and the satellite beacon experiments at NPL.

4. Conclusions

Stable and unstable conditions and instabilities under stable conditions can be easily identified and categorized on the sodar facsimile records. On examining carefully the general behaviour, the sodar records can always be used to forecast inversion break-up a few hours before it actually occurs. The study of the height and distribution of thermal plumes, inversion
Fig. 9—Development of turbulent wave motion (horizontal) under stable conditions

Fig. 10—Development of turbulent wave motion (vertical) under stable conditions
layers and the formation of ducts in the boundary layer of the atmosphere plays a significant role in air pollution, communication and aviation situations. The technique offers the inherent advantage of being sensitive under clear air turbulence conditions in the cloudless part of the free atmosphere where the turbulence is rarely of sufficient intensity to affect the common meteorological sensors. This can lead to the development of new forecasting techniques based solely on acoustic sounder records.

Acknowledgement
We thank Mr S. C. Garg for his help in the design of the electronic circuit for the monostatic set up, and India Meteorological Department for lending the facsimile recorder and the radio sonde datr.

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