Estimation of Wind and Turbulence in The Lower Atmosphere with a Bistatic Radio Acoustic System

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Abstract

We use a radio acoustic system to measure the displacement of the acoustic phase front induced by the wind. The height and the shape of the narrow volume of Bragg scattering depend strongly on the acoustic frequency. The received signal spectrum relates to wind strength and air turbulence. Experimental results match well with both our theoretical studies and in-situ instrumentation.

Introduction

Remote sensing of wind and temperature is mostly done by estimating the acoustic Doppler shift and the acoustic phase velocity with a radio acoustic sounding systems (RASS) or a sound detection and ranging system (Sodar) [1].

We use a bistatic CW radio acoustic system to estimate the displacement and distortion of the acoustic phase front induced by wind and turbulence. The setup is symmetric with the acoustic loudspeaker array on the center point between the receiving and the transmitting electromagnetic antennas. To enhance scattering from a particular height we choose the acoustic frequency to fulfill the criteria for Bragg scattering in this height. The acoustic energy influenced by wind and turbulence generate scattering from a narrow volume. The received electromagnetic field thus carries the information of how the acoustic field is distorted by wind and turbulence.

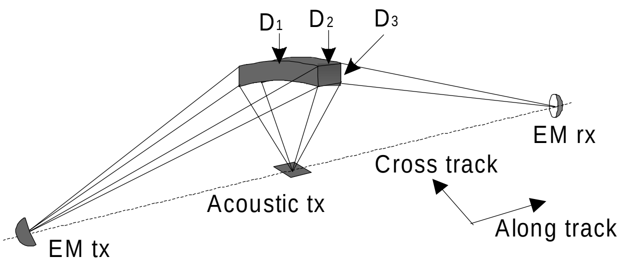

Figure 1. The electromagnetic common volume is illuminated by acoustic energy. Transmitting the proper acoustic frequency generates a narrow volume of Bragg scattering. The electromagnetic energy scattered from this volume is shifted by the acoustic frequency.

Basic scattering theory

Pressure variations induced by the sound waves leads to variations in the relative electric permittivitty ε_r of air.

The scattered electromagnetic field is [2]

$$\mathbf{E_s} = \frac{k^2}{4\pi R} \oint_V E(\mathbf{r})(\varepsilon(\mathbf{r})-1)\exp(-j\mathbf{K}\cdot\mathbf{r})d^3\mathbf{r}\,, \quad (1)$$

where r is the position vector, R is the distance from the point of reference to the scattering volume and $E(r)$ is the incident electromagnetic field.

This integral has a sharp response at

$$\mathbf{K} = (\mathbf{k_s} - \mathbf{k_i})_{\mathbf{RF}} = -\mathbf{k_{ACO}}\,, \quad (2)$$

where $\mathbf{k_{ACO}}$ is the acoustic wavenumber and $\mathbf{k_i}$ and $\mathbf{k_s}$ is the incident and the scattered electromagnetic wavenumber. This is the well-known Bragg condition. Eq. 2 leads to

$$F_{ACO} = \frac{2F_{RF} \times C_{ACO} \times \sin(\theta/2)}{C_{RF}}\,, \quad (3)$$

where θ is the scattering and $\theta/2$ equal the elevation angle of the electromagnetic antennas.

Eq. 3 is a relation between frequency and scattering angle. For a given setup, with a given electromagnetic frequency and assuming constant air temperature, the acoustic frequency relates directly to scattering height.

The scattering volume

The size of the scattering volume can be described with the parameters D_1, D_2 and D_3 seen in fig 1. D_1 is the cross track extension of the scattering volume, D_2 is the along track extension and D_3 is the vertical extension of the scattering volume.

In the cross track direction, D_1, both the EM iso-phase lines and the acoustic phase front are circular, thus the limiting factor is the smallest of the acoustic beam and the electromagnetic beam. The beamwidth is given by

$$D_1 = \frac{\lambda R}{d}, \qquad (4)$$

where λ and d are wavelength and aperture size.

For the along track direction of the scattering volume, D_2, the elliptical shape of the iso-phase lines are close to be horizontal in the common volume compared to the acoustic phase front. Therefore the limiting factor is the smallest of the acoustic beamwidth, given by eq. 4, or the Fresnel limitation of the acoustic phase front given by

$$D_2 = 2\sqrt{\lambda H}\,.$$

Here λ is the acoustic wavelength and H is th
where the Bragg condition is fulfilled.

In the vertical direction, D_3, the limitin
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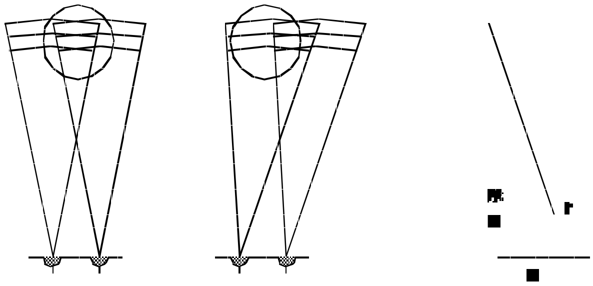
Doppler shift or the acoustic phase velocity, but the displacement of the acoustic phase front induced by the wind.



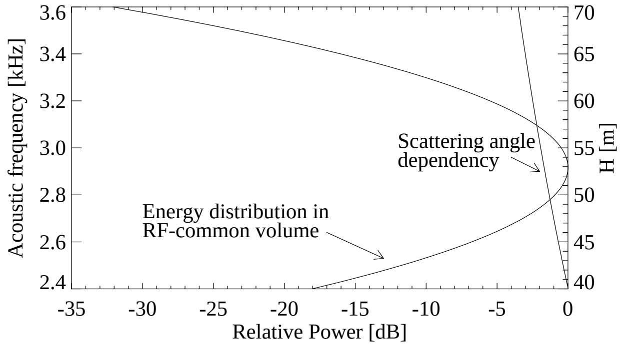


Figure 7. The scattering angle dependency and the EM common volume Gaussian energy distribution plotted versus the height and matching frequency (for zero degrees air temperature).

An acoustic frequency sweep is equivalent with a sweep of scattering angle and matching height. The radar equation contains two parameters that are strongly dependent on the scattering angle. The scattering volumes size and the total electromagnetic transmission path. The scattering angle dependency is shown in fig. 7 together with the Gaussian energy distribution of the EM common volume.

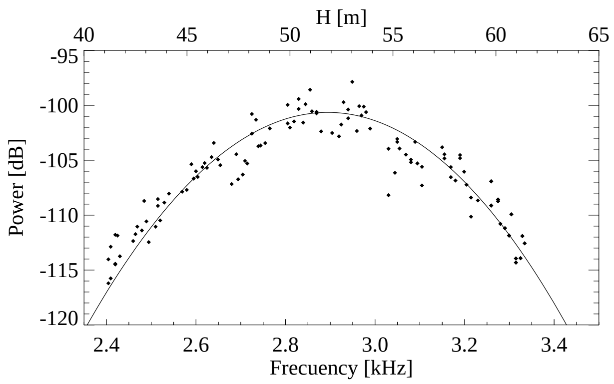


Figure 8. Experimental data (dots) and the theoretical curve for energy distribution and scattering angle dependency. Each point of data represents 6 seconds integration time. The measured points match the theoretical curve well.

Wind influence on the frequency spectrom

Wind influence on the signal spectrum.The effect wind and turbulence has on the received signal spectrum is demonstrated in these results from earlier measurements.

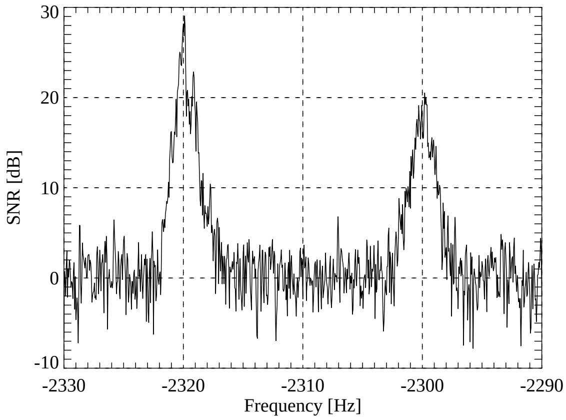


Figure 9. Power spectra of a received EM signal Wind during measurement: –1.3 m/s cross track and – 5.5 m/s along track.

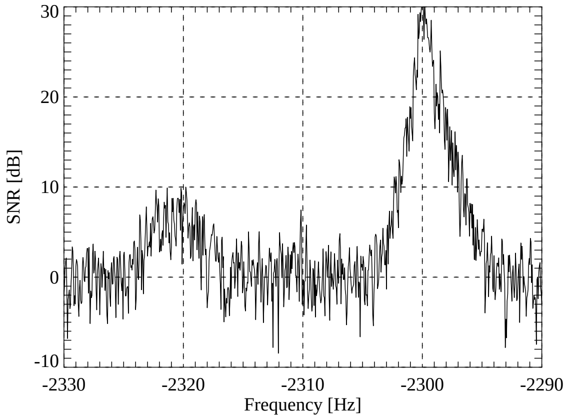


Figure 10. Power spectra of a received EM signal. Wind during measurement: 4.0 m/s cross track and – 9.0 m/s along track.

In figure 9 and 10 we see the power spectra of signals scattered by two acoustic frequencies at different time intervals. The configuration in this experiment was as described in fig. 1 and 4. In figure 9 the cross track wind of -1.3 m/s has shifted the acoustic beam (2300 Hz) out of the electromagnetic common volume, thus the SNR is reduced. In figure 10 the wind direction and strength has changed (4.0 m/s cross track wind). The one beam (2320 Hz) blown out of the common volume fairly contributes to the scattering, while the scattering from the other (2300 Hz) have increased.

There is a notable difference in the shape of the two signal spectrums. The overall wind strength is greater in figure 10, producing more turbulence. This make the signal broader, more Gaussian like, than those of figure 9.

In fig. 11 we have plotted wind estimated by our radio acoustic system and wind estimated by a Gill anemometer mounted on a column 10 m above ground. There is high correlation between the two curves. As a result of the difference in height (50 m verses 10 m), the wind estimates from the radio acoustic system seems to have [illegible]her variance than the wind estimates made by the C[illegible]anemometer.