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EXPERIMENTAL STUDIES OF SOUND-PROPAGATION IN A STRONGLY STABLE ATMOSPHERIC BOUNDARY LAYER.

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ABSTRACT

The experiment series, Blast propagation through forest -Norwegian Trials were carried out in a forest region at Finnskogen, Norway (N 600 50', E 120 00'). The main purpose of these experiments was to gain more knowledge on the relationship between meteorology and sound propagation. Meteorological data were obtained by tethered balloons, radiosondes, automatic weather stations and turbulence measurements by eddy correlation method just above tree tops.

This study uses the data from one morning with a strong temperature inversion. From the measurements of that day horizontal homogeneity of the atmosphere was verified. The difference of sound propagation in upwind and downwind conditions quantified to about 30 dB transmission loss. Variation in recordings at single microphones during this morning was about 10 dB, with 50 dB transmission loss as an extreme value. The study ends with some attempts of modelling the sound propagation with a raytracing model and an FFP model.

INTRODUCTION

The environment is threatened by many kinds of pollution. One of them is noise. To gain knowledge on how to avoid unnecessary noise did the Norwegian Defence Construction Service (NDCS)in cooperation with others conduct the experiment series Norwegian Trials. This series consisted of four separate experiments. Two studies of sound-propagation over shorter distances (100 m to 1.2 km) and two studies of longer distances (1 km to 23 km), one summer and one winter experiment were done at each location.

This paper is based on the results from the summer experiment at the long distance location, more accurately the test series from the morning of 21 September 1994. That morning was chosen because of a strong temperature inversion in the atmospheric boundary layer. Horizontal homogeneity of the atmosphere will be verified for these tests. Effect of wind direction and variations at single microphones will be studied. The paper concludes with some use of numerical models, and an attempt to build a prognostic numerical model.

EXPERIMENTAL LAYOUTS.

The long range experiments were held in Finnskogen in the eastern part of Norway. It was laid out on a two-axis system, with meteorological and acoustical instrumentation at each end and in the centre. Sound was generated by explosions of 1, 8, and 64 kg C4 (TNT equivalent of 1.32) at certain well-defined locations on the axis.

TOPOGRAPHY AND FOREST OF THE AREA.

The area was a fairly flat and forested area in Finnskogen. Figure 1 contains a topographic map of the area. Position 112 and 0 were both at 400 metres above the sea. The ground between these two points got elevated to 450 metres above the sea 8 km north of 0 (position 108), and declined down to 390 metres above the sea 1 km south of 112. South of 0 does declines the terrain down to 290 metres at 5 km south of 0. Other topographic features of interest in the area: Risberget (479 m) 2 km north west of 0, Svartberget (524 m), Bukksen (630 m). The elevated terrain at 108 is a connecting ridge between Svartberget and Bukksen.

Figure 1 *Topographical map of the test region.*

The forest of the area was quite dense with a small tendency of higher and thicker trees in the southern part than the northern part.

METEOROLOGICAL INSTRUMENTATION.

The meteorological instrumentation consisted of Aanderaa Automatic Weather Stations (AWS), Tethered sondes, radio sondes, and an acoustic anemometer/thermometer. This paper will use the results of the AWS to verify horizontal homogeneity and results from the tethered sonde to find the vertical sound velocity gradients.

The directional sound velocities (DSV) were calculated with equation 1.

$$DSV(z) = C_0\sqrt{1 - T(z)/273.15} - V(z) * \cos(\alpha(z) - \beta) \qquad \textbf{(1)}$$

Where Co is the sound velocity at 0 oC, T(z) is the temperature at height z, V(z) is the wind velocity at height z, (z) is the wind direction at height z, is the source receiver bearing.

ACOUSTICAL INSTRUMENTATION.

The acoustical instrumentation consisted of microphones at various heights at each location. This paper will use the information gathered at 0 and 112. These two locations had microphones at 0, 2, 4, 8, 16, 30 metres above ground, 0 had an extra microphone at 24 metres. For more information on the acoustical instrumentation look ARA project No. 59991[1]

HORIZONTAL HOMOGENEITY BASED ON AWS;

Numerical models for sound-propagation in the atmosphere normally require only a vertical DSV profile, and assume horizontal homogeneity. The AWS at 112 and 0 had temperature, wind velocity, and wind direction sensors at 30 m above the ground. The instruments at these three locations will reveal information about the horizontal homogeneity during these tests.

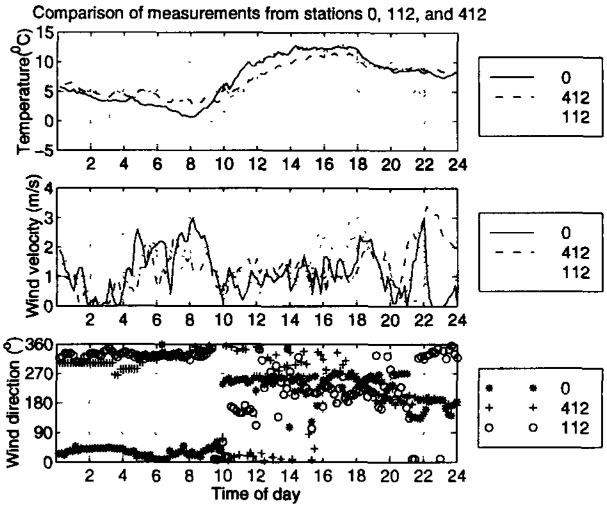

Figure 2 *Comparison of AWS meaurements from three stations. The measurements are from the morning of 21. September 1994.*

DSV profiles based on tethered sonde measurements. The experiments are from the morning of 21 September 1994 and held at: Test 17 07.00, test 18 08.00, test 19 09.00, test 20 10.00.

Comparison of the temperature recordings from 21 September 1994 reveals a difference of about 5 oC early in the morning. 112 is the one that differs from the others, but during the day does the temperature at 112 increase more rapidly than the other, and at 10.00 to 20.00 is there no significant difference. It looks like 112 has a greater temperature amplitude of the diurnal cycle than the others. The wind measurements are consistent during the day. Wind direction at 0 is a bit different from the other two. The wind velocity is quite similar the three sets of measurements, even the gusts seem to hit simultaneously. After 10.00 is the wind direction quite chaotic, this is probably due to the breakup of the inversion. The comparison shows that the horizontal homogeneity was good during the tests.

DSV PROFILES BASED ON TETHERED SONDE MEASUREMENTS.

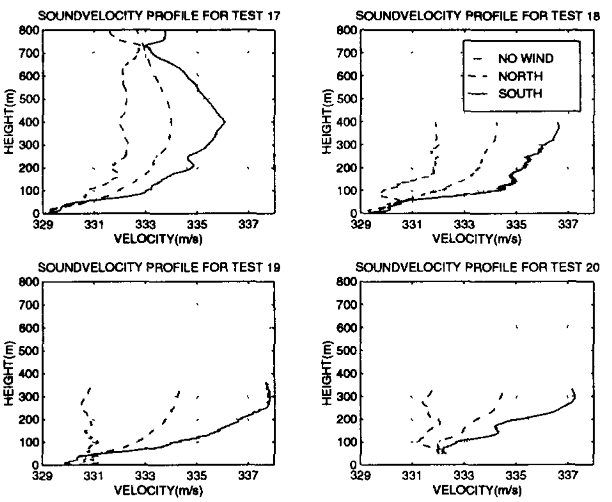

Figure 3 DSV profiles from the tests series used in this paper.

DSV profiles of the atmosphere were calculated with equation 1 and tethered sonde measurements. The result for the four tests used in this study are presented in figure 3. There were distinct differences between northwards and southward profiles, this difference is due to the wind direction (bottom part of figure 2). The curve marked NO WIND is calculated without the wind. An important feature of the profiles is in the northward curves. Early in the morning (test 17, 18) has both northwards and southward profiles a DSV inversion (sound velocity increases with height), this is due to the temperature inversion. As the temperature inversion is broken up, does the DSV inversion in the northward profiles disappear. This shows the need of detailed information of both wind and temperature to compute the sound propagation.

AFFECT ON DSV AND SOUND PROPAGATION BY CHANGES IN WIND AND TEMPERATURE

One part of this study was to see if temperature or wind affected sound propagation most. To find that, an obvious step is to look at which part affects DSV and DSV profiles most. An analytic solution of equation 1 for wind and temperature is impossible because of the square root in the equation. The problem was solved by a numerical solution. The result gave that 1 oC had the same effect as 0.61 m/s nd wind would be about the same. In reality the wind will have a greater effect than temperature. This is due to what kind gradient one would expect in vertical profiles of wind and temperature. Normally a temperature gradient of more than 2 oC / 100 m will be very rare, but wind velocity gradients of more than 2 m/s / 10 m will be common.

MEASURED DIFFERENCE BETWEEN SOUND PROPAGATION IN UPWIND AND DOWNWIND CONDITIONS.

In the last paragraph it was shown that the wind velocity had a great impact on DSV profiles. This chapter will be used to quantify the difference between upwind and downwind conditions.

The analysis of wind directions effect was quite simple. The measurements were split into different frequencies by fourier analysis, and 6 narrow band frequencies were chosen. The comparison is then just looking at the difference between measurements at same distance in upwind and downwind conditions. The extreme differences here were 70 dB difference in

Variation of measurements at single microphones. Figure contains data from all series of both upwind and downwind conditions.

transmission loss, and 2 dB more in downwind than upwind. The mean difference over all frequencies and distances were 36 dB, with the lower frequency slightly less affected than the higher frequencies. It also seems like the effects are stronger on shorter distances. Compared with the difference at single microphones, which gives the variation in measurements between series at each microphone as a mean and standard deviation value, is the average effect wind direction 20 dB stronger than changes in DSV profiles with the same main wind direction.

Frequency	1 km		11 km	
	Mean value	Standard deviation	Mean value	Standard deviation
2	33.55	4.22	10.87	12.34
10	35.08	5.78	26.72	9.02
25	46.90	11.69	33.89	11.66
50	47.24	12.68	34.52	12.19
75	50.35	12.52	33.41	15.10
100	49.10	12.28	29.90	12.40

Table 1 Mean value and standard deviation of difference in transmission loss between upwind and downwind propagation sorted on frequency and distance.

VARIATIONS IN MEASUREMENTS AT SINGLE MICROPHONES DUE TO CHANGES IN DSV PROFILES.

To quantify the effect of changes in DSV profiles without changing the wind direction has the variation at different microphones been analysed. The extreme differences here were 50 dB transmission loss. Mean value of the variation was about 10 dB, a bit dependant on frequency and range. Lower frequencies less effected than higher, stronger affects on longer distances. All the variation is due to variations in the DSV. Such variations may produce areas of whit acoustic focuses and shadows. The variation in a microphone is partly due to positions of focus and shadow sones versus the position of the microphones, and partly due to the total amount of sound that get refracted down to the ground. An example of recordings with a clear focus is shown in figure 5. Those recordings are from test 18 measured at 112. The contour plots bear clear signs of an acoustic focus near 4 kilometres, and weaker signs near 14 km. The other series showed similar signs of focus and shadows.

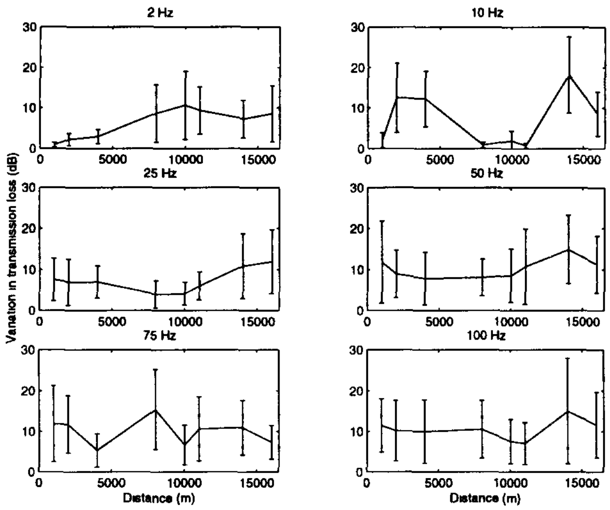

Figure 4 *Variation of measurements at single microphones. Figure contains data from both upwind and downwind measurements.*

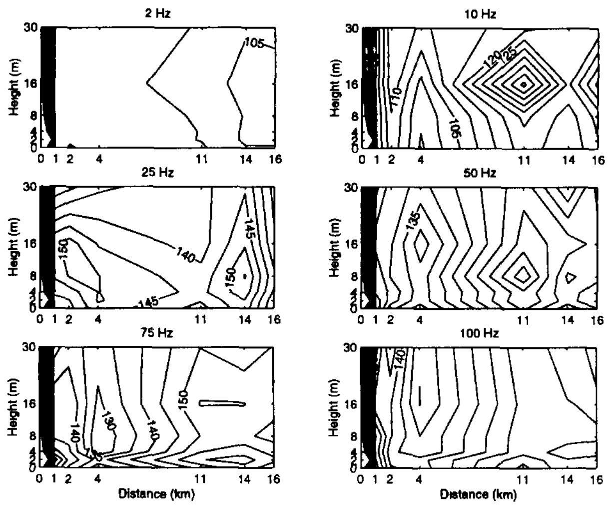

Figure 5 *Contour plots of test 18 measured at the north tower.*

NUMERICAL MODELLING.

Two different numerical models were applied on the data, one raytracingsmodel and one FFP model.

The raytracer was very simple and calculated the sound in a given position by summation of rays that hit the ground within one kilometres, called Larkhill method by G. Kerry.[2] The rays were calculated with Snell s law:

$$\frac{DSV(z)}{\cos(\theta(z))} = constant = \frac{DSV(0)}{\cos(\theta(0))} \qquad (2)$$

The FFP model used in this study was developed by Franke and Swenson[3], Li and White[4,5,6] have refined the model.

RESULTS FROM LARKHILL METHOD.

The Larkhill method gave peak overpressure from the explosion at given distances. Comparison of measurements and the Larkhill method shows that the method performed well on long distances with an average of less than 5 dB difference between model and observations with an average difference of 10 and 15 dB at 1 and 2 km respectively. Statistical results of the comparison is shown in figure 6.

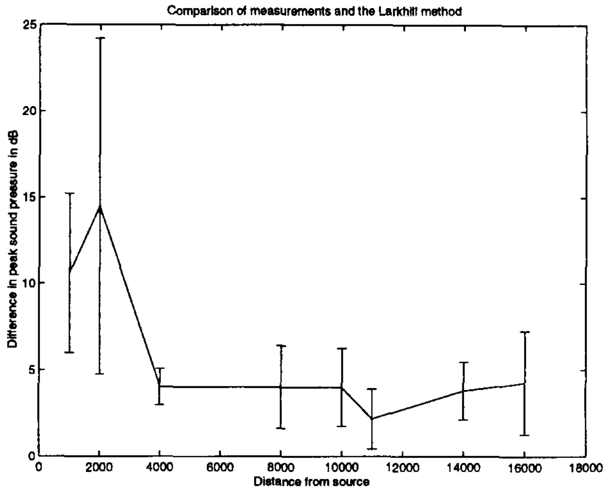

Figure 6 *Comparison of measurements and the Larkhill method. The figure contains both upwind and downwind measurements.*

RESULTS OF THE FFP MODEL.

The FFP model gave transmission loss as a function of distance. The model worked in 1/3 octave bands. It is chosen to show the calculations with 10 and 100 Hz as central frequency in this paper. These two calculations were done with receivers at 16 m height. These two calculations represents the results fairly well as the difference between measurements and calculations varied a bit, but usually less than 10 dB.

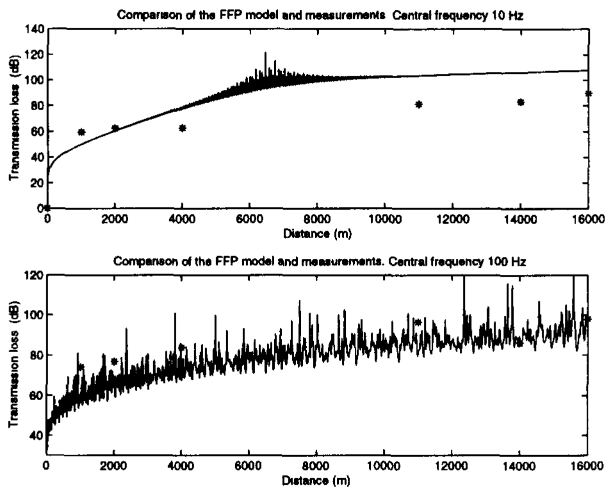

Figure 7 *Results from the FFP model. Top part for 10 Hz, bottom part for 100 Hz.*

ATTEMPT TO BUILD A PROGNOSTIC MODEL FOR NOISE PROPAGATION.

This work concludes with a attempt to build a prognostic model for sound propagation. This model consist of two components. Firstly a prognostic meteorological model, secondly a diagnostic acoustical model that used the output from the meteorological model.

The meteorological model was build on the energy balance of an inversion during breakup, the local radiation balance, and the first law of thermo dynamics. The atmosphere was simplified to three layers, bottom and top layers with constant sound velocity, and a middle layer with a constant gradient in the sound velocity (figure 8). The bottom layer grew as the inversion broke up.

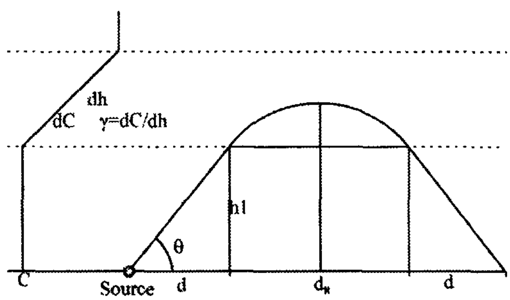

Figure 8 *Prinsiple of the prognostic mode. Left part the DSV profile, rigth part the coresponding soundray.*

The acoustical model build on the Larkhill method. The rays were calculated with straight lines from the source to the middle layer, then the radius of curvature was used to calculate the distance the middle layer accounted for, and ending in a straight line to the ground (figure 8).

$$D=2*\left(\frac{\sqrt{\frac{dQ}{\gamma_T*\rho*C_p}}}{\tan\theta}+\frac{C}{\gamma_{DSV}}*\sin\theta\right)$$

Where the first part calculates the height of the neutral layer beneath the capping inversion, and horizontal distance of the ray beneath the refracting layer. The second part calculates the horizontal distance within the refracting layer. D is the distance from the source to the ray hit he ground, dQ is the energy used to break up the inversion so far, T the lapse rate of the temperature in the inversion, the density of air, DSV the vertical gradient in the directional speed of sound, angel between the ray and the ground at the source. When a ray broke into the top layer the calculation stopped. The sound was calculated with the Larkhill method.

To test the model was the weather situation from the morning of 21 September 1994 used. The radiation balance was calculated in four parts: incoming and reflected shortwave, and incoming and outgoing longwave. The incoming shortwave was calculated with SLOPERAD, reflected shortwave was the incoming shortwave with an albedo for forested area. Outgoing longwave was calculated with Plank s law, and incoming shortwave was calculated with Swinbanks formula. The net-radiation was used as input in the model. The model calculated the transmission as a function of time and distance. This gave nice looking plots, but no realy useful results, the difference were about 20 dB to measurements. Figure 9 shows an example of output compared to measurements from test 18. The difference of about 20 dB is partly due to the simplification of the atmosphere.

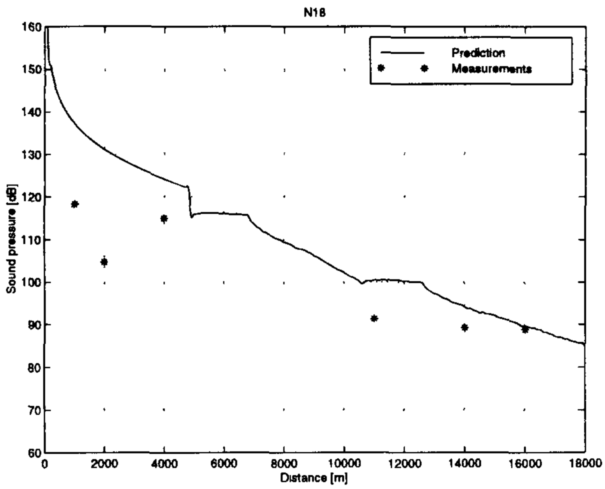

Figure 9 *Comparison of the prediction model and measurements for test 18 eith propagation direction nrthward (upwind)*

CONCLUSIONS AND SUGGESTIONS OF FUTURE WORK.

The first conclusion is quite obvious, one need detailed knowledge of temperature and wind to predict the sound propagation. This is based on a numerical solution of equation 1 and the sound velocity profiles used in this text.

The next conclusion is almost as obvious, and slightly contradicting the first. Based on the difference in transmission loss from upwind and downwind conditions is it clear that the wind direction is the single parameter with the strongest effect on the sound propagation.

Working with numerical models shows that there will be possible to estimate the transmission loss, but detailed knowledge of DSV profiles are necessary.

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