The Deelen Infrasound Array for Recording Sonic Booms and Events of CTBT Interest

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ABSTRACT
The Seismology Division of the Royal Netherlands Meteorological Institute (KNMI) has built up expertise in infrasound measurements by investigating low frequency events in order to distinguish between seismic and sonic events. KNMI operates, amongst others, a sixteen element microbarometer array with an aperture of 1.5 km, the Deelen Infrasound Array (DIA). Sonic booms and events of Comprehensive Test Ban Treaty (CTBT) interest are detected and identified within the frequency range of 500 seconds up to 40 Hertz. Recently, KNMI and Microflown Technologies B.V. started a collaboration concerning infrasound measurements. This paper reports on the use of a novel sensor. The so-called Microflown[1] is a micro-machined particle velocity sensor, sensitive to frequencies from 0Hz up to at least 1kHz. Experiments with the Microflown for infrasound detection show promising results.

1. INTRODUCTION
Recently, the significance of infrasound measurements has been established in the Comprehensive Test Ban Treaty (CTBT) as a technique to detect and identify possible nuclear explosions. For this purpose a world-wide network of 60 infrasound arrays is presently being constructed. KNMI has, since 1999, operated an experimental array in the Netherlands. The Deelen Infrasound Array (DIA) consists of in-house developed micro-barometers, based on a differential pressure sensor. Detailed array response calculations have resulted in an omni-directional sensitive array configuration. Efficient discrimination between infrasound events and noise, is done by a detector based on Fisher statistics. Characteristic values like apparent sound velocity and azimuth, can be derived. Including the data of two other small arrays (aperture of 100 meters) results in an accurate event location, through cross-bearing, and origin time. Pressure variations consist of compression and dilatation with a certain frequency. The frequency is resolved by the Microflown through the frequency of the induced temperature differences. The Microflown has advantages, which are tested together with KNMI for infrasound applications, compared to micro-barometers and pressure microphones. The Microflown has no moving parts, which make it very reliable. Resonances do not occur. Given its underlying
thermal principle, the self-drying Microflown is moisture resistant and it is made from inert materials (platinum, silicon) so no corrosion problems can be expected. All materials used tolerate high temperatures. The Microflown was developed at the University of Twente and commercialised by Microflown Technologies B.V. [3]

2. THE DEELEN INFRASOUND ARRAY

In general, an array consists of a number of instruments which is, through its layout, able to detect signals and localise the incoming direction of energy. The array configuration controls the resolution of the array. An optimal array is equally sensitive to all infrasonic signals, independent of incoming angle and direction. Array design and calculations are based on signal coherency. The optimal array is capable of homogeneously sampling the surrounding atmosphere. [4] Figure 1 displays the layout of the 16 micro-barometers and corresponding response. To each micro-barometer six porous hoses are connected in star configuration to reduce noise. The circular response implies an optimal array.

Figure 1. Deelen Infrasound Array (DIA), instrument lay-out on the left and array response on the right

Figure 2a. Examples of infrasonic signals. Sonic boom
3. INFRASONIC SIGNALS

Sources of infrasound emit pressure fluctuations between 500s and 40Hz. Examples of infrasonic sources are: planes flying through the sound barrier, meteors entering the earth’s atmosphere, volcanic explosions, nuclear explosions etc. Wind causes noise within the same frequency band, between 1 and 10 Hz. Figure 2 shows two examples of infrasound recorded by the 16 micro-barometers, a high frequency sonic boom (Figure 2a) and a lower frequency meteor detection (Figure 2b). Two packages of incoming energy can be distinguished in the meteor recording. The delay time of the secondary arrival of 50 seconds and its lower frequency contents (with respect to the first arrival) indicate a probable thermospheric reflection.\(^6\)

4. DATA PROCESSING: FREQUENCY SLOWNESS ANALYSIS

As proposed by\(^5\), data processing at KNMI is done on the basis of a frequency slowness, being the inverse of apparent sound velocity, analysis combined with Fisher statistics. Frequency domain processing, instead of conventional time domain, enables the development of detection tools by making use of phase, amplitude, frequency and coherency characteristics. Fisher values are a measure for the signal coherency. An infrasonic wave which travels over the array coherently will add up to high Fisher values. Uncorrelated signals, like wind, will result in low Fisher values, typically between 0 and 4. Mathematically the Fisher value represents a signal to noise ratio scaled with the number of instruments minus one.

Figure 3 shows the result of the frequency domain processing. All frames have the same time axis. The top frame displays the best beam or the sum of all signals. The lower three frames represent three parameters each. Frequency and time axes are the same for all frames, but in each frame a third parameter is plotted (as a grey coloured contour). Coherency is plotted in the middle frame as Fisher value. Resolved event characteristic: azimuth and velocity are plotted.
in the lower two frames. Azimuth is defined as the angle from which the energy comes with respect to the North. The resolved velocity is the apparent sound velocity or the projection of the sound velocity on the horizontal.

As follows from the Fisher values, coherent energy is present throughout the recording between 0 and 3 Hz. This can be seen as the presence of light to dark grey colours between 0 and 3 Hz. The major arrival after 85 seconds results in the highest Fisher values of 160, due to its high amplitude and preserved waveform while travelling over the array.

The coherency of the signal is also reflected when evaluating the incoming angle of the energy. The band of light grey colours between 0 and 3 Hz roughly indicate that the source is located to the North-west of the array, i.e. an azimuth of 330 degrees.

The apparent velocity in the lower frame seems less well resolved. A mix of all grey colours appears between 0 and 3 Hz. The lobe of light grey between 2 and 3 Hz around 85 seconds correspond to reasonable apparent sound velocities
of 350 m/s. To obtain exact values for the apparent sound velocity and azimuth, a detailed analysis is done.

Results from detailed frequency slowness analyses of the sonic boom, are displayed in Figure 4. Frequency slowness power can be interpreted as a shifted array response due to the phase differences of the signal travelling over the array. The highest values of the fp-power correspond to the value for slowness for which the signal characteristics are best resolved. In Figure 4 the maximum coherent energy around 0.5 Hz at 85 seconds is exactly located. The white slowness vector resolves an apparent sound velocity of 350 m/s, being its length. The source is located to the North-west of the array by the angle with respect to the North of the slowness vector, being 324 degrees.

5. INSTRUMENTS

5.1 The KNMI Micro-barometer

When developing an infrasound sensor one can either choose to make a low frequency microphone or a barograph high frequency. KNMI choose the later approach for amongst others robustness with respect to field applications. Figure 5 shows the in-house developed micro-barometer based on a differential pressure sensor. The pressure fluctuations are measured with respect to the backing volume. Doing so, one would also measure very low frequency meteorological pressure variations. Therefore, a thin capillary is included within the backing volume, as a leak. Through its acoustical resistance, the capillary controls the low frequency cut-off of the micro-barometer, this being 500 seconds.

5.2 The Microflown

The Microflown is a silicon-based sensor that is fabricated in a cleanroom. It is in fact a highly sensitive mass flow sensor (a sensor that is designed to detect DC flow) made in such a way that it has a very fast response time. The result is
an acoustic sensor that is capable of measuring the particle velocity from DC (0Hz) up to 1kHz with a flat frequency response and with a high signal to noise ratio. The Microflown has a decay in response for frequencies higher than 1kHz. The polar pattern or directivity is a figure of eight at all frequencies.

Since its invention in 1994 it has mostly been used for measurement purposes (1D and 3D-sound intensity measurement, or acoustic impedance). The Microflown is also used for measuring DC flows. DC flow is in fact particle velocity with a frequency of 0Hz. Nowadays sound-energy determination and three-dimensional impulse response are under investigation.\textsuperscript{2,3} The Microflown is capable of measuring particle velocity instead of sound pressure, closely related to the pressure gradient. So in an audio perspective the Microflown can be seen as a pressure gradient microphone (with a figure-of-eight directivity pattern) having a high signal to noise ratio from 0Hz up to 1kHz. The Microflown itself consists of two very closely spaced thin wires (spacing 350\,\textmu m) of silicon nitride with an electrically conducting platinum pattern on top of them. A SEM photograph of a Microflown is depicted in Figure 6. The size of the two wires is 1000x10x0.5 micrometer (lxwxh). The metal pattern is used as temperature sensor and heater. The silicon nitride layer is used as a mechanical carrier for the platinum resistor patterns. The sensors are powered by an electrical current, causing the sensors to heat up. The temperature difference of the two cantilevers is linearly dependent on the particle velocity. The two squares S1 and S2 in Figure 7 represent the two temperature sensors of the Microflown. The temperature sensors are implemented as platinum resistors and powered by an electrical current dissipating an electrical power $P_{el}$, causing it to heat-up, leading to a typical operational temperature of about 200°C to 400°C. When the temperature of the sensors increases the resistance will also increase. When
particle velocity is present, it alters the temperature distribution around the resistors. The temperature difference of the two sensors quantifies the particle velocity. When no particle velocity is present all the heat is transferred in the surrounding air ($q_{\text{stat.}}$). When particle velocity is present a convective heat transfer of both sensors ($q_{\text{conv.1&2}}$) will cause a temperature drop of both sensors. The upstream sensor however, will drop more in temperature than the downstream sensor since the downstream sensor is heated by the upstream convective heat loss ($q_{\text{conv.}}$), see Figure 7. A temperature difference will be the result. The temperature difference is proportional to the particle velocity. Not all the convective heat loss of $S_1$ will be transferred to $S_2$, a certain percentage ($\xi$) will be lost. This percentage will rise if the sensors are positioned further apart from each other. If, on the other hand, the sensors are brought closer together another phenomenon will become dominant. The particle velocity induced temperature difference will cause a conductive heat flow in the opposite direction. This feedback heat flow will temper the sensitivity. The closer the sensors are placed, the more conductive heat flow will take its effect. Several temperatures of the two sensors of the Microflown are shown in Figure 8. Due to the thermal mass of the sensors and diffusion effects, after 1kHz the sensors cannot follow the thermal signal. The Microflown exhibits a high frequency roll-off because of this.

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**Figure 6.** Photo of a part of a Microflown

**Figure 7.** Schematic overview of the heat flows around a Microflown
6. MEASUREMENTS

6.1 The Microflown without a (wind) noise reducing mounting

With the use of a 12” loudspeaker a 20Hz sine tone was generated. Signals and noise levels of the micro-barometer and the Microflown were compared. The distance between the loudspeaker and the transducers was 50cm. Furthermore the on- and off axis output of the Microflown was measured. The output signals of the Microflown and the micro-barometer were respectively 85mV and 20mV, their noise levels about 0.2mV and 2mV. A rough estimation would be that the signal to noise ratio of the Microflown is about 30dB higher than the micro-barometer. The lateral reduction at 20Hz was measured at 40dB. The measurement was performed by rotating the Microflown in a normal room.

6.2 The Microflown with a (wind) noise reducing mounting

At one input of the Microflown a closed rigid tube was mounted and at the other a flexible tube was mounted. A sound pressure wave would deform the flexible tube and not the rigid one, inducing a particle velocity inside the mounting. This way of reducing noise will make the set up sensitive to sound pressure instead of particle velocity; the directivity properties of the Microflown will therefore be lost. The rigid tube will act as backing volume. We used a volume of 0.61. We expect the system to measure lower frequencies if the backing volume is enlarged. Opening the door of the lab resulted in signals shown in Figure 9. Despite the difference in transducing, the general trend of the signal is similar. The “noise” seen on the Microflown is due to electronic interference, it is not selfnoise. The flexible tube is used as a pressure to particle displacement converter. We expect a higher sensitivity and a better noise reduction when the length of the tube is increased.

Figure 8. The (measured) temperatures of the Microflown as the result of a particle velocity wave. A particle velocity wave will cool down both sensors in a different manner. The difference signal of both sensors represents the particle velocity and the sum (the common signal) the cooling down
6.3 Microflown and microphone experiments in the field

The Microflown has been tested in the field. For this purpose, the Microflown was incorporated in an existing array of six microphones (figure 10). Wind reduction for the Microflown was achieved with foam.

Figure 11 shows the performance of the different instruments. A sonic boom coherently travelled over the array. Although exactly locating the energy is not the purpose of this experiment, clearly the energy is coming from the northwest since the Microflown and microphone number 1 were the first to detect the signal. The highly sensitive Microflown, measuring particle velocity, shows a good performance with respect to the microphones. The Microflown trace seems more noisy, this is mainly due to the primitive wind reduction. Currently, research concerns the construction of a robust instrument and noise reduction for durable operation in the field.
7. CONCLUSIONS

The Deelen Infrasound Array is capable of detecting and localising infrasound. Identification of sources of infrasound is achieved by using frequency-slowness analysis combined with Fisher statistics. Experiments with the Microflown have shown promising results, as a low noise, directional and particle velocity sensor. Proven durability in the field, developments to obtain a proper low frequency cut-off and wind noise reduction will allow the Microflown to be a highly competitive infrasound sensor.

REFERENCES

3. www.microflown.com