THE DEELEN INFRASOUND ARRAY FOR RECORDING SONIC BOOMS AND EVENTS OF CTBT INTEREST

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## 1.	ABSTRACT

The Seismology Division of the Royal Netherlands Meteorological Institute (KNMI) has build 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 recorded within the frequency range of 100 seconds and 40 Hertz. Recently, KNMI and Microflown Technologies B.V. started a collaboration concerning infrasound measurements. This paper reports the use of a novel sensor. The so-called Microflown [1] is an acoustic sensor, sensitive for frequencies from 0Hz up to 1kHz. The Microflown is developed at the University of Twente and commercialised by Microflown Technologies B.V [3].

## 2.	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 operates since 1999 an experimental array in the Netherlands. The Deelen Infrasound Array (DIA) consist of in house developed microbarometers, based on a differential pressure sensor. Detailed array response calculations have resulted in a omni-directional sensitive array configuration. Efficiently discriminating between infrasound events and noise, is done with 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 microbarometers 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 occur. All materials used are corrosion resistant and sustain high temperatures.

3. THE DEELEN INFRASOUND ARRAY

In general, an array is 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 microbarometers and corresponding response. To each microbarometer six porous hoses are connected in star configuration to reduce noise. The circular response implies an optimal array.
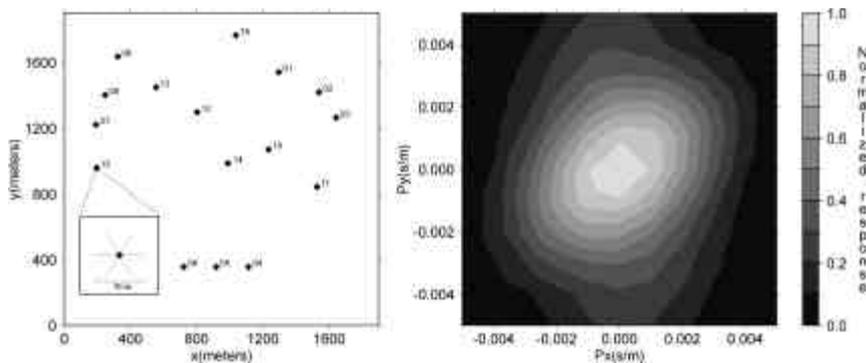

Figure 1: DIA array layout (left) and corresponding response (right)

4. 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, volcano explosions, nuclear explosions etc. Wind causes noise within the same frequency band, between 1 up to 10 Hz. Figure 2 shows two examples of infrasound record by the 16 microbarometers. A high frequent sonic boom on the left and a low frequent meteor detection ant the right.
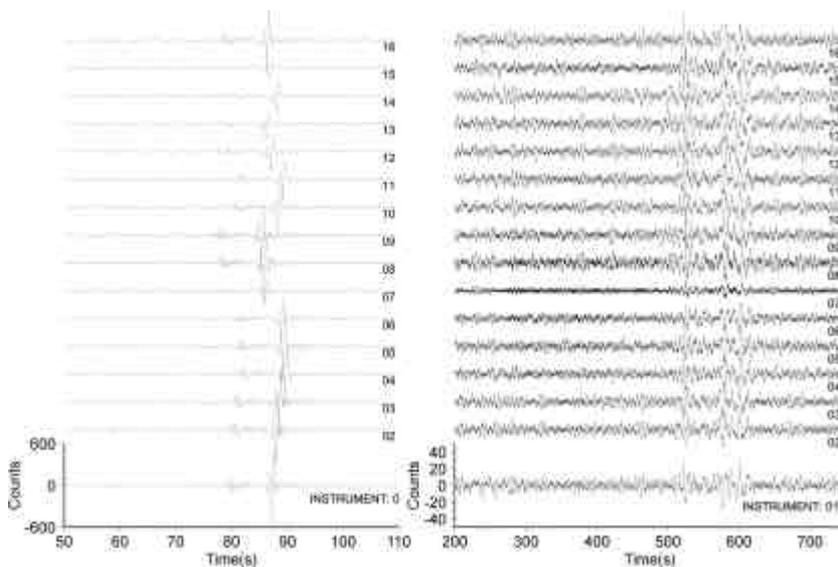

Figure 2: Examples of infrasound, sonic boom (left) and a meteor(right)

5.   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, in stead of conventional time domain, enables the development of detection tools by making use phase, amplitude, frequency and coherency characteristics. Figure 3 shows the result of the frequency domain processing. The top frame displays the best beam or the summed signal with azimuth and velocity for which the maximum coherency is found. Coherency is plotted in the middle frame as Fisher value (which is a scaled signal to noise ratio). Clearly, coherence increases around the meteor detection. The secondary arrival is more low frequent, combined with its delay time with respect to the first arrival, a probable thermospheric reflection is seen [6]. Resolved angles are plotted in the lower frame. The meteor energy is coming from the North-east while other coherent signal seems to come form more North-western angles.
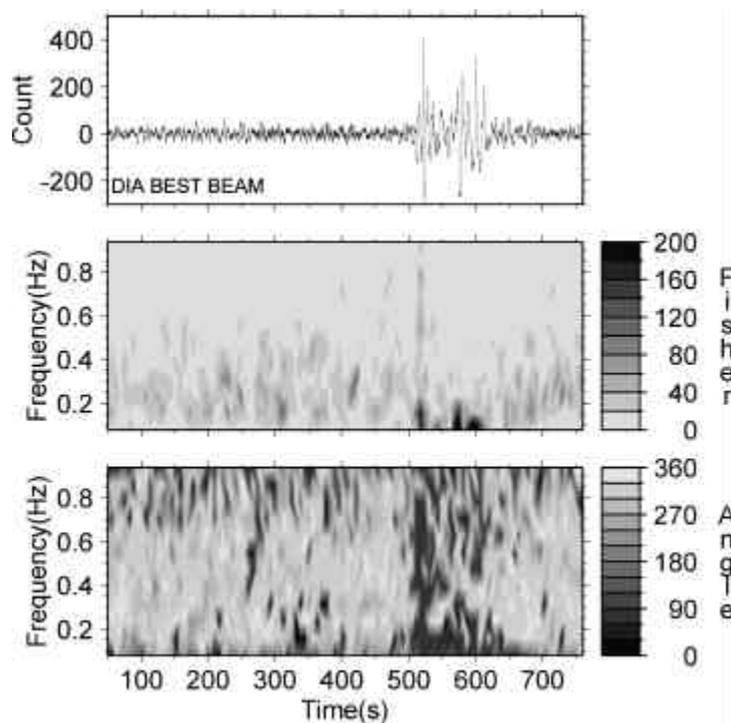
Figure 3: Best beam (top frame), coherency or Fisher value (middle frame) and resolved angle (bottom frame) for the meteor signal (right in Figure 2)

Results from detailed frequency slowness analyses of the two sources of infrasound shown in Figure 3, are displayed 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 is best resolved. The meteor energy in the right frame is coming from 82 deg East. A storm depression on the Atlantic ocean generated standing waves in the ocean. These standing waves create low frequent signal, so-called microbaroms, through its atmospheric coupling. This energy comes from the North-west with respect to the array and is shown in the left frame of Figure 4.

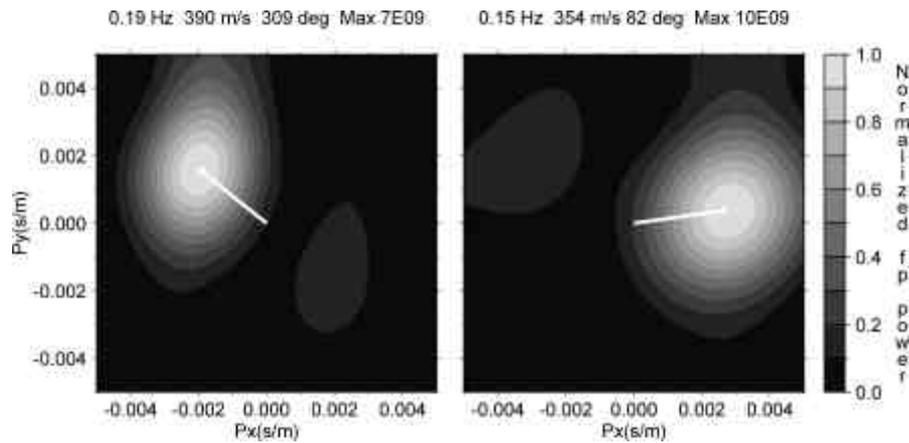0.19 Hz 390 m/s 309 deg Max 7E09   0.15 Hz 354 m/s 82 deg Max 10E09

Figure 4: Frequency-slowness power plots. The vector denotes the resolved apparent sound velocity by its length and resolved azimuth by its angle with respect to the North

6.   INSTRUMENTS

6.1   The KNMI microbarometer

When developing an infrasound sensor one can either choose to make a microphone low frequent or a barograph high frequent. KNMI choose the later approach for amongst others robustness with respect to the field applications. Figure 5 shows the in house developed microbarometer 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 frequent 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 microbaromter, being 500 seconds.
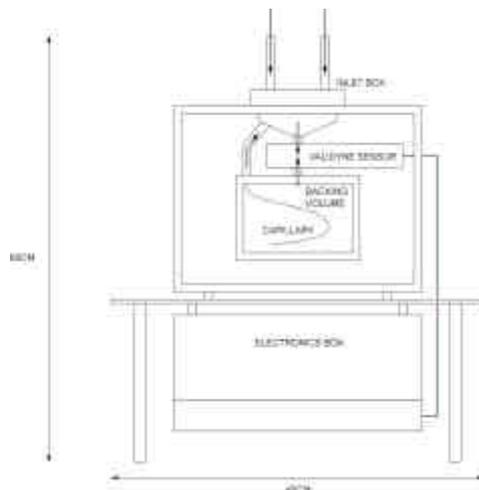

Figure 5: Schematic drawing of the KNMI microbarometer based on a differential pressure sensor

6.2   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 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 polar pattern or directivity is a figure of eight at all frequencies.

Since its invention in 1994 it is mostly 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 [2], [3]. The Microflown is capable of measuring particle velocity in stead 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. For frequencies higher than 1kHz the frequency response has a decay of -6dB/oct. The Microflown itself consists of two very closely spaced thin wires (spacing 350μm) 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 $1000\times10\times0.5$ micrometer (l$\times$w$\times$h). 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 linear 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 200ºC to 400ºC. 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 ($q_{stat.}$). When particle velocity is present a convective heat transfer of both sensors ($q_{conv1\&2}$) 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 ($q_{conv.}$), 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 (ξ) 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, after 1kHz the sensors cannot follow the thermal signal. The Microflown exhibits a -6dB/oct high frequency roll of because of this.
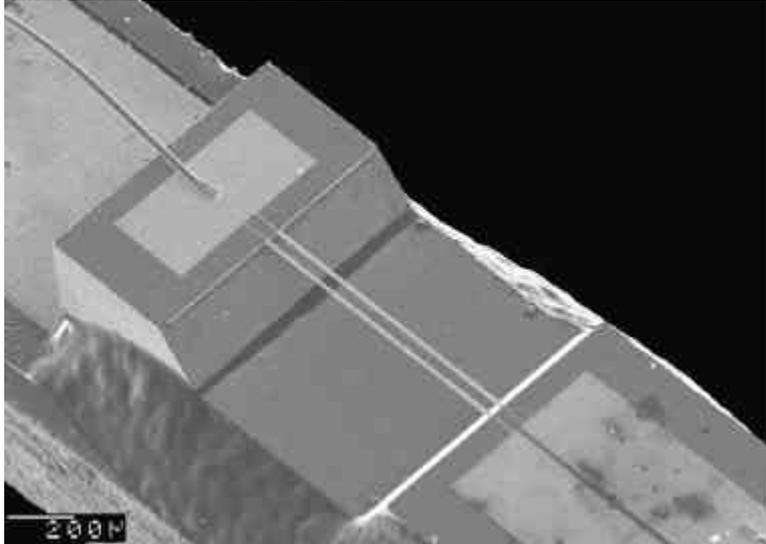
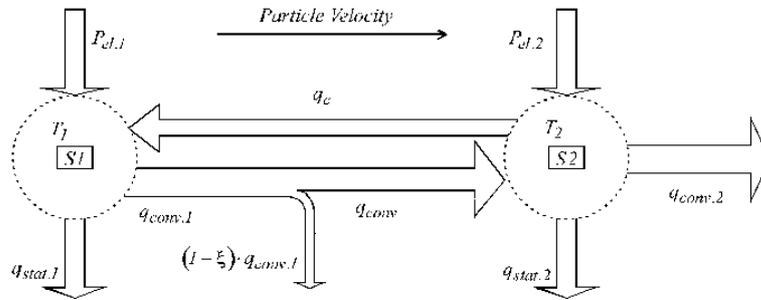Figure 6: A Photo of a part of a Microflown..

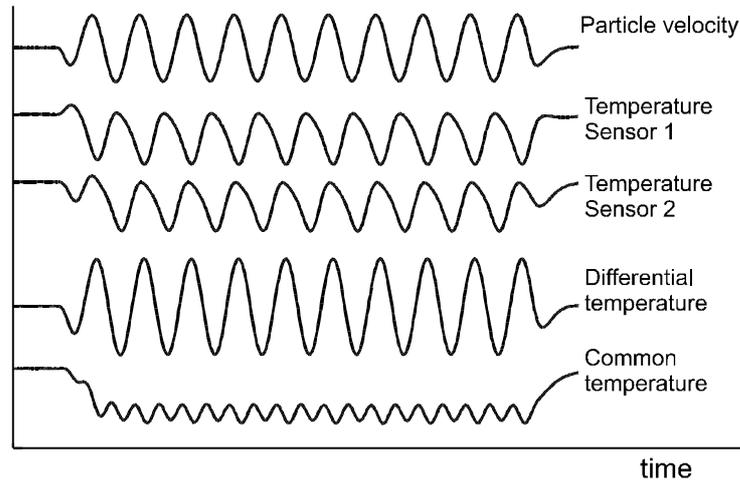Figure 7: Schematic overview of the heat flows around a Microflown.

Figure 8: The (measured) temperatures of the Microflown as 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.

7.   MEASUREMENTS

7.1   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 microbarometer 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 microbarometer were respectively 85mV and 20mV, their noise levels about 0.2mV and 2mV. A rough estimation would be that that the signal to noise ratio of the Microflown is about 30dB higher than the microbarometer. The lateral reduction at 20Hz was measured 40dB. The measurement was performed by rotating the Microflown and in a normal room.

7.2   The Microflown with a (wind) noise reducing mounting

The Microflown is a particle velocity sensitive microphone. It is therefore very sensitive for wind (even more than pressure sensors). Two ways of reducing wind have been tested. First we mounted foam in front of both inputs of the Microflown. This resulted in a reasonable reduction of the wind noise for an open structure foam. A more dense foam reduced the wind noise more but also damped the sensitivity. The Microflown was tested outdoors overnight under rather windy and rainy conditions. Although the Microflown itself showed no physical damage, the noise reduction appeared insufficient.

Another attempt showed more promising results. 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 noise reducing will make the set up sensitive to sound pressure in stead 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 0.6l. 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.
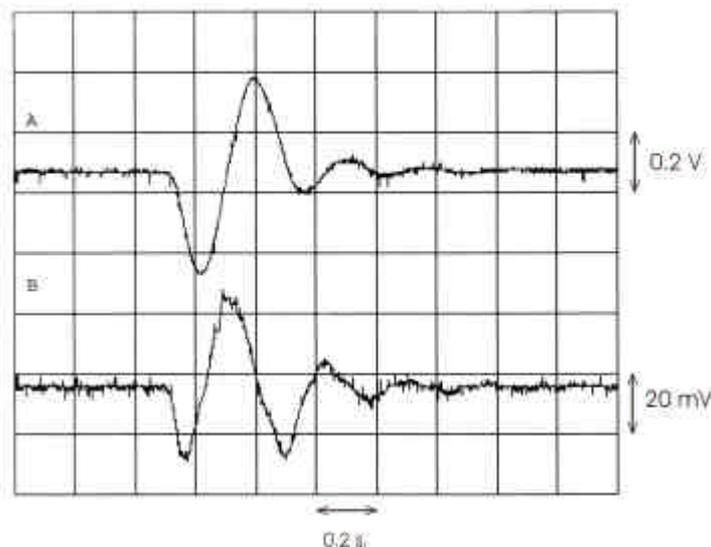

Figure 9: The measured signals of a microbarometer (A) and a Microflown (B) as result of a atmospheric distortion in a room with a volume of 144m^3.

8.   CONCLUSIONS

The Deelen Infrasound Array is capable of detecting and localising infrasound. Identification of different sources of infrasound occurring in the same frequency band is possible with the high resolution array (p.e. microbaroms, sonic booms and meteors). Experiments with the Microflown have shown promising results, as low noise, directional and particle velocity sensor. Proven durability in the field and developments to obtain a proper low frequency cut-off, will allow the Microflown to be a highly competitive infrasound sensor.

9.   REFERENCES

[1]   H-E. de Bree et al., The Microflown: a novel device measuring acoustical flows, Sensors and Actuators A 54, 1996, pp. 552-557

[2]   W.F. Druyvesteyn et al., A new acoustic measurement probe; the Microflown IOA London, volume 21, pt3 1999, pp. 139-149

[3]   www.microflown.com

[4]   H.W. Haak, An acoustical array for subsonic signals, Tech. Rep. WR96-03, KNMI, De Bilt, the Netherlands, 1996, 22 pp

[5]   E. Smart and E.A.Flinn, Fast frequency-wavenumber analysis and Fisher signal detection in real-time infrasonic array data processing, Geoph. J. R. astr. Soc., volume 26, 1971, pp. 279-284

[6]   Garcés et al., Traveltimes for infrasonic waves propagating in a stratified atmosphere. Geoph. J. Int. Volume 135, 1998, pp. 255-263