Infrasound Monitoring in the Netherlands

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Abstract

The Royal Netherlands Meteorological Institute (KNMI) monitors infrasound in the Netherlands with a series of microbarometer arrays. Infrasound is inaudible sound; its lower frequency cut-off is limited by the thickness of the atmosphere. The KNMI has developed a microbarometer capable of measuring infrasound between 500 seconds and 40 Hz. Wind noise reduction is of major concern in infrasound measurements. Arrays are deployed to increase the signal-to-noise ratio (snr) by averaging out the incoherent wind signals. Wind noise is also reduced at each array element, the microbarometer, by applying eg. porous hoses or pipe arrays. Doing so, the wind noise is further reduced at each element by sampling the atmosphere over an area rather than at one point. The direction of arrival and apparent sound speed can also be determined by the array to characterize the signals. Multiple arrays are used for localization of the source. KNMI operates four infrasound arrays varying in aperture between 35 and 1500 meters while 6 to 16 elements are used. Sources of infrasound are: explosions, severe weather, meteors, sonic booms, sea waves, volcanoes, nuclear tests, .. Coherent infrasound of unknown origin is also detected at the arrays. The motivation for measuring infrasound is twofold. Firstly, as Seismology Division one has to discriminate between sources causing vibrations from the solid earth, earthquakes, and from the atmosphere, eg. sonic booms. Secondly, infrasound is applied to verify the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Worldwide 60 arrays are currently constructed to monitor the atmosphere for clandestine nuclear tests. Infrasound can travel over large distances with minimal damping due to its low frequency contents.

This paper describes the technique of infrasound measurements and the use of array processing techniques, like beamforming, and detection algorithms. These subjects will be exemplified with infrasound from a sub sonic air plane.

Introduction

Infrasound is inaudible sound with frequencies below the human hearing threshold of 20 Hz. The lower frequency cut-off of infrasound is limited by the thickness of the atmosphere or a ducting atmospheric layer. In general, infrasound is measured within a frequency range of 0.005 (200 s) to 20 Hz. Within this frequency band a lot of sources of both known and unknown origin generate infrasound. Impulsive sources are for example: sonic booms, explosions, nuclear test and meteors. Sources that can often be detected for hours or days are: volcanoes, sea waves, mountain associated waves and aurora.

KNMI measures infrasound to discriminate between sources in the solid earth, ie earthquakes, and sources in the atmosphere also causing vibrations, like sonic booms. Worldwide infrasound is one of the verification techniques of the Comprehensive Nuclear-Test-Ban Treaty. Currently, 60 infrasound arrays are worldwide being installed to monitor the atmosphere for clandestine nuclear test, see Figure 1. KNMI contributes with research to the CTBT on verification capability of infrasound as monitoring technique.
Figure 1: 60 infrasound arrays for the verification of Comprehensive Nuclear Test-Ban Treaty.

Figure 2: The KNMI microbarometer.
Measurements technique

Infrasound can be measured with either a low frequent microphone or a high frequent barometer. KNMI chose to develop a microbarometer because of its robustness with respect to the field application and durability. Furthermore, a microbarometers can measure down to much longer periods than a microphone. Figure 2 shows the differential microbarometer, ie the sensor measures air pressure fluctuations with respect to the pressure in the backing volume. Within the backing volume a capillary is mounted that acts as leak back to the atmosphere. The acoustic resistance of the capillary determines the lowest frequency the microbarometer can measure, currently 0.005 Hz.

Measuring infrasound means dealing with wind noise. Therefore, arrays of microbarometers are used to increase the signal-to-noise ratio (snr). Furthermore, arrays enable the determination of source characteristics like: apparent sound velocity and direction of arrival or back azimuth. A source can be located by cross bearing the observed back azimuths from two or more arrays.

Wind noise is further reduced by applying an analog filter at each array element, ie the microbarometers. Examples of analog filters are large wind screens, soaker hoses, pipe arrays. KNMI applies soaker hose, or porous garden hose, to reduce wind noise at each microbarometer, see Figure 3. By applying this technique, the pressure field is averaged over an area rather than measured at one point. Doing so, incoherent wind noise will cancel out while the signal of interest, with much larger coherency lengths, will remain unaffected.

Figure 3: The field installation of a microbarometer with a noise reducer attached constructed with soaker hose.
KNMI operates 5 infrasound arrays in the Netherlands, the number of sensors vary from 6 to 16 while the array aperture ranges from 30 to 1500 m, see Figure 4. The size of the array is often limited by infrastructural considerations and determines the lowest possible frequency that can be resolved. Figure 5 shows the response of EXL to a monochromatic plane wave.
Figure 5: The EXL infrasound array, part of LOFAR, and its response.

The shown response has several important characteristics:

1. The circular shape of the main lob. This means the atmosphere above the array is uniformly sampled; the array shows no directionality. The array will be equally sensitive to all infrasonic energy independent of its incoming angle.

2. Side lobs are of low amplitude and located at considerable distance of the main lob. This implies a unique identification of infrasonic sources; the energy is mainly concentrated in the main lob.
3. The main lob has a sharp and peaked form. This will result in a high resolution array. The resolved source characteristics, like apparent velocity and back azimuth, will have small errors.

All of these characteristics were optimized through a genetic algorithm leading to the unique array configuration. The EXL array is part of the astronomical LOFAR initiative, see also www.lofar.org or www.lofar.nl.

Infrasound from a subsonic airplane

The De Bilt Infrasound Array DBN often measures infrasound from passing sub-sonic airplanes. Figure 6 shows the recording of such an event on 2003, August 18. The time axis gives the time in seconds since 01h12m34.0s GMT. Coherent infrasonic signal is visible in the individual traces between at least 250 and 370 seconds. The air pressure fluctuations are measured with microbarometers. The addition of "micro" is validated by the measured amplitude values of approximately 0.2 Pa. This value corresponds to a drop in air pressure in the atmosphere experienced over a height of 1.5 cm, i.e. moving the microbarometer over a distance of 1.5 cm upwards will give a reading of 0.2 Pa.

Array measurements enable the detection of signal on the basis of coherency. A coherent signal can be detected by evaluating the Fisher ratio. The Fisher ratio is a statistical measure of signal-to-noise ratio (snr) and describes the signal likelihood. The usage of arrays also enables the characterization of an event in terms of back azimuth and apparent sound speed. The apparent sound speed is the horizontal fraction of the true sound speed as measured by
the planar array. The higher the apparent sound speed, the more vertical incident the infrasonic wave is. An infinite apparent sound speed means that all microbarometers measured the coherent wave at the same time, thus the energy came from right above the array. The apparent sound speed equals the true sound speed in case of far-field sources because of the wind gradient in the atmosphere.

Figure 7: Results of the array data processing on the basis of Fisher ratio. The time axis is the same for all four frames. The lower frame gives the Fisher ratio, the middle two frames give the resolved apparent sound speed and back azimuth corresponding to the calculated Fisher ratio. The top frame gives the best beam corresponding the the higher Fisher ratio.
In Figure 7 the results are shown of the array data processing. The Fisher ratio is plotted in the lower frame as function of time. The Fisher ratio increases around the time of the event indicating that a coherent infrasonic wave travelled over DBN. The plane could be followed for more than 2 minutes. The apparent sound speed also increases during the passage of the plane as can be seen in the second frame. This implies that the plane nearly flew over the array. The back azimuth, in the third frame, clearly shows a moving source. The plane flew from 40 to 190 degrees, i.e. from the East towards the South relative to the array location. In the top the best beam is plotted, this beam is the sum of the time shifted traces. The time shift is calculated for the event characteristics corresponding to the maximum Fisher ratio, that is 114 deg and 811 m/s as indicated by the purple circles.

Is there a model that can explain the observed values for back azimuth and apparent sound speed? A simple model can explain the observation, this model is valid for a plane flying with a constant speed at a fixed height.

**Back azimuth**

\[ Azi(t) = \text{Atan}\left(\frac{S_0 - vt}{d}\right) \]

*\( t \): time
*\( S_0 \): initial distance
*\( v \): speed of the object
*\( d \): horizontal distance of closest approach

**Elevation**

\[ El(t) = \text{Atan}\left[\frac{h}{\sqrt{(S_0 - vt)^2 + d^2}}\right] \]

*\( h \): height of the object

**Slowness**

\[ Sl(t) = \frac{1}{c} \cdot \text{Cos}(El(t)) \]

*\( c \): sound speed

In Figure 8 the blue curves show the result. The blue curves follow from the model for a plane flying at a height of 7 km with a speed of 500 km/h. The closest horizontal distance of approach to DBN is 3 km. There is a strong similarity between the observations, dots, and the model, blue curves. Therefore, the plane has been localized and could be identified with available flight records.
Infrasonic wave propagation is in first order dependent on the wind and temperature structure of the atmosphere. Both down wind and a high temperature are favourable conditions for wave propagation. Furthermore, a temperature inversion, increasing temperature with height, can cause infrasonic to bend back towards the earth's surface. Models for wind and temperature are assembled by the European Center for Medium range Weather Forcasting (ECMWF), among others based on KNMI balloon measurements. Figure 9 gives the wind and temperature profiles for 2003, August 18 at 00h00 GMT in the vicinity of De Bilt.
The atmospheric trajectories of infrasound can be modeled with raytracing. The model in Figure 9 serves as input model for the raytracing algorithm. The modeled and measured sound intensity can be compared to validate the model. Figure 10 shows how the rays, in white, travel from the airplane to DBN. The airplane is located at a height of 7 km, see the blue rectangle. DBN is situated at 3 km distance and is given by the red triangle. The coloured atmospheric layers represent the effective sound speed. The effective sound speed is the temperature dependent sound speed including the component of the wind in the direction from source to receiver. Figure 11 gives the traveltime of the infrasonic waves as function of the distance. It takes the infrasound from the airplane 25 seconds to travel to DBN at its closest approach of 3 km. The sound intensity decreases with distance. Infrasound can at least be measured up to a distance of 30 km. This maximum distance highly depends on the state of the atmosphere.

Figure 10: The atmospheric trajectories of the infrasound from the airplane at 7 km height, blue rectangle, to DBN at a distance of 3 km, red triangle.
Conclusions

Infrasound can be detected with arrays of microbarometers. The usage of arrays leads to wind noise reduction and the ability to determine source characteristics like apparent sound speed and back azimuth. A wide variety of sources of both human and natural origin generate infrasound. Infrasound is measured to distinguish between earthquakes and sources in the atmosphere both causing vibrations. Infrasound is applied as monitoring technique for the Comprehensive Nuclear-Test-Ban Treaty. The processing and interpretation of infrasound recordings has been illustrated with data from a subsonic airplane. Current research effort concentrate on: association, array design, source identification and atmospheric processes controlling the propagation of infrasound.