# Seismo-acoustic signatures from near surface phenomena

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Among numerous sources emitting pressure waves a few are known to generate acoustic signals both in the earth, as seismic waves, and in the atmosphere, as infrasound, which were recorded over large distances. Those sources are near surface phenomena like volcanic eruptions, explosions, and ocean waves, which all occur at the boundary between the solid earth and the atmosphere, either shallow above or below the ground and the ocean surface, respectively. The aim of the presentation is to provide an overview of such phenomena. Therefore examples are given showing the close connection of seismic waves and infrasound: the infrasonic and seismic activities in Europe dominated by quarry blasts, the Buncefield accidental explosions, the Tarapaca earthquake, and the North Atlantic's ocean swell. Moreover, this expanded abstract contains an overview on infrasound being not part of the presentation. The overview starts with a short history of infrasound, which underlines that the strongest developments have recently been made since infrasound is a verification technology for nuclear-test-ban treaty monitoring. It also gives an introduction to basic physical principles of sound propagation in the atmosphere along with its peculiarities caused by an anisotropic four-dimensional moving media.

## The Renaissance of Infrasound

Infrasound monitoring is a key technology for detecting and locating (nuclear) explosions in the atmosphere, because most of the energy of such events (approximately 50 %) is released in the atmosphere as a blast wave. The generated pressure pulses are propagating away from the source as sound waves. Since attenuation in the atmosphere of sound waves is frequency dependent, infrasound, which is inaudible to humans at frequencies below 20 Hz, can propagate over large distances reaching altitudes in the atmosphere of more than 120 km. Low-frequency compressional waves were firstly observed on a global scale after the eruption of the Krakatoa volcano, Indonesia, in 1883, where the infrasound circulated several times the earth. In the twentieth century infrasound technology was intensively used to detect atmospheric nuclear weapon tests. While large explosions with yields of several Mega-tonnes (Mt) TNT-equivalent generated waves with periods up to a few minutes circulating around the earth, smaller explosions in the range of a few kilo-tonnes (kt) emitted infrasound with frequencies between 0.01 and 10 Hz. In all cases clear signals were detected at stations thousands of kilometres away from the origin. First examples of systematic recordings of (nuclear) explosion clearly demonstrated the potential of infrasound recordings to identify strong atmospheric events. This technology was therefore widely-used to detect atmospheric nuclear weapons tests, however, the interest dramatically decreased with the cessation of atmospheric tests due to the Limited Nuclear-Test-Ban Treaty in 1963 prohibiting any nuclear test in the atmosphere.

In 1996, when the Comprehensive Nuclear-Test-Ban Treat (CTBT) has been opened for signature, the infrasound technology, as part of the verification regime, experienced a renaissance. To fulfil the compliances with the CTBT, a global network of infrasound stations was designed. This network, being part of the International Monitoring System (IMS), comprises 60 infrasound stations uniformly distributed over the globe (Figure 1). Currently, approximately 70 % of the stations are in operation providing data in near real-time; whereas the first stations were certified in 2001 and others were added from year to year constantly improving the network's global coverage. All stations are sited in different environmental conditions ranging from tropical to polar and from humid to arid regions exposed to different local wind conditions. The turbulence effects of these winds are the origin of infrasound background noise which is reduced by spatial filters composed of pipe arrays.
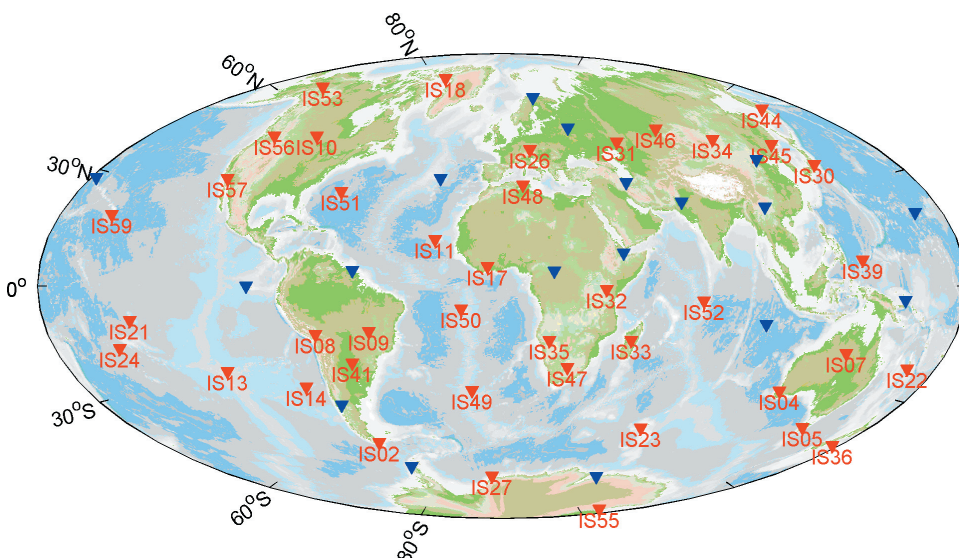


*Figure 1: Global distribution of the 60-element IMS infrasound network: 42 stations are in operation (red triangles), 17 arrays are still under construction or planned (blue triangles), and one site is still to be determined.*

All technical aspects of infrasound monitoring were re-developed for CTBT verification. It uses all state-of-the-art advances to form a system which has never been available up to now: Sensors are designed for the detection of small events with high sensitivity

and low instrumental noise. Their large dynamics allows observation of both very strong events close to the station and very small ones at distances of few thousands kilometres. The mini-array stations, composed of four to nine sensors, are arranged in an optimal configuration, with one to three kilometres aperture, and can be considered as very sensitive acoustical antennas. Using efficient algorithms for detecting coherent waves within non-coherent noise, the recordings provide azimuth and apparent wave velocity of infrasound signals which can be used to characterise them. Along with the high quality of the recorded data, first studies have demonstrated that various kinds of events can be identified due to their wave parameters measured at different stations. In the last years a catalogue of such events has been established, providing a data-base of events with well identified characteristics and known sources.

Ground-Truth (GT) events are used to estimate the network performance. Moreover, they are referenced to study infrasound propagation effects in the atmosphere, and vice versa to probe the atmosphere using data from repeating sources. Advances in infrasound technology have benefited not only from progress in engineering sciences; also advances in meteorology and climatology have helped a lot to interpret the recordings. As observed in the beginning of infrasound recordings from strong atmospheric nuclear tests, the azimuth of infrasound propagation has a strong impact on dynamic and kinematic characterisation of the signals, demanding precise horizontal wind and temperature profiles to describe the status of the atmosphere.

**Infrasound Propagation**

Infrasound propagates at sound speed through channels in the atmospheric formed by temperature gradients. The increases of temperature in the stratosphere and thermosphere produce refraction and reflections of the infrasound which is ducted between ground and temperature increases in the different layers of the atmosphere (see Figure 2).
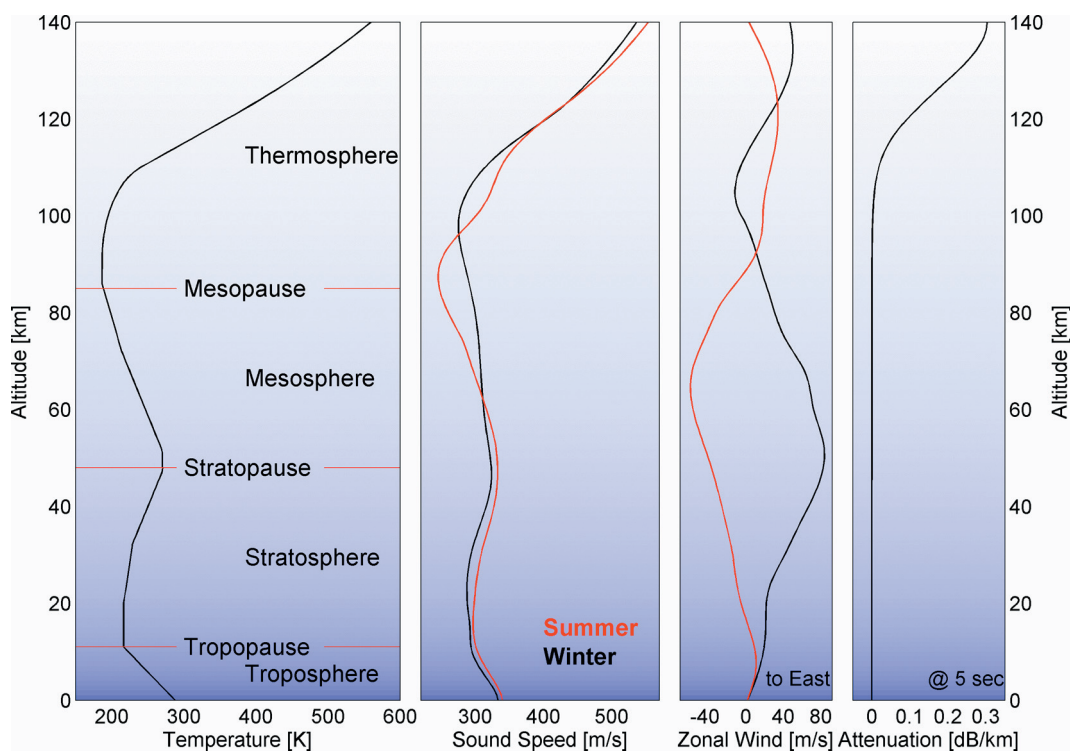


Figure 2: A standard atmosphere showing the temperature as a function of altitude and labelling the different layers (left). Climatology model for central Europe in summer (red) and winter (black) describing the sound speed and the zonal wind speed positive to the east. The right panel displays the attenuation being negligible up to the mesopause but significant in the thermosphere.

The winds, which can exceed 100 m/s in the stratosphere, favour the propagation in the direction of the blowing winds. These winds are essentially zonal winds, directed to the west in the summer in the northern hemisphere, and to the east in the southern hemisphere, the opposite occurring in winter. Infrasound can follow different propagation paths before being detected at an array, where different signal phases, corresponding to different arrival times, usually can be distinguished.

Different simulation tools for infrasound propagation are now available ranging from multi-dimensional ray tracing to full-wave solutions of the governing equations. All these tools make use of the most accurate atmospheric models, enabling a detailed analysis of recorded signals, and helping to understand atmospheric propagation effects. An example is given in Figure 3, demonstrating both the impact of prevailing stratospheric winds and attenuation on infrasound propagation in the atmosphere.
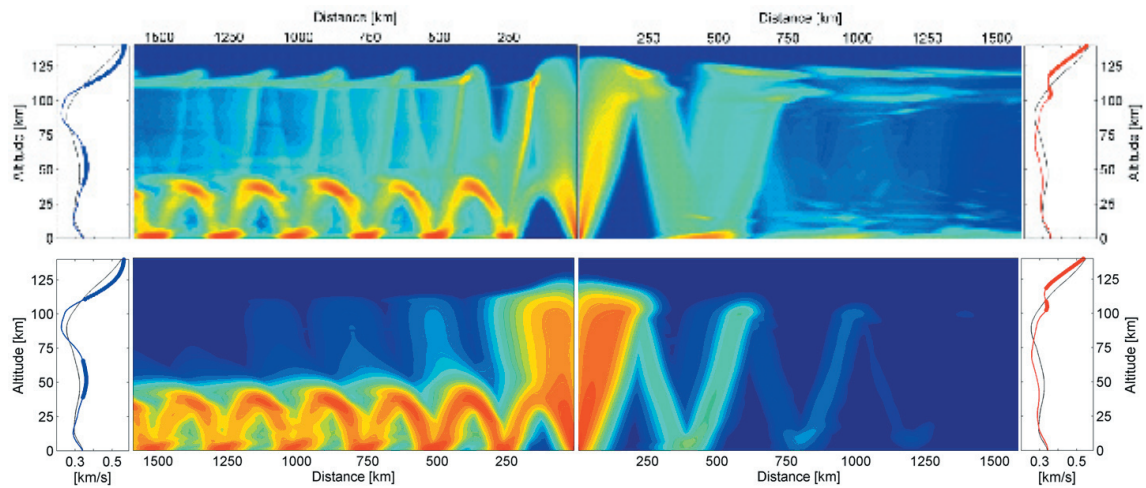
*Figure 3: Infrasound propagation along a west to east profile in central Europe during summer. Westward propagation (left panels) shows a downwind scenario with both stratospheric and thermospheric refractions and to the east (right panels) an upwind scenario allows only for thermospheric retractions. Infrasound propagation is demonstrated both in an atmosphere without damping (upper panels) and with damping (lower panels) at a reference period of 5 s. The red (upwind) and blue (downwind) curves are the effective sound speed profiles with refraction heights marked bold.*

## Data Analysis and Network Processing in Europe

Beside the IMS infrasound network, which is a unique and highly sensitive instrument to monitor the acoustic activity on a global scale, a regional network in Central Europe has been established. Several years of continuous infrasound waveform data are available for eight stations in Sweden, France, and Germany; whereas only one of them is part of the IMS the others are scientific infrasound arrays. This exquisite setting with an average inter-station distance below 500 km allows the analysis of natural and artificial infrasonic activity across Europe. First, each infrasound array is individually analysed with a cross-correlation technique for detecting and identifying coherent signals and second, second, all individual detection lists are merged to form a network event bulletins. This bulletin comprises supersonic activities from military aircrafts, quarry blasts, and accidental explosions; whereas the latter ones also have a seismic imprint being used to identify the sources. Especially repeating events as quarry blasts provide the opportunity to test and validate procedures for automatic (re-)location considering various data sets and atmospheric descriptions as ECMWF profiles for estimating appropriate celerity values and back-azimuth corrections.

Moreover, a seasonal variation of this network's detection capability has been observed, which is dominated by the prevailing stratospheric winds. This is in accordance with an empirical relation describing the infrasonic amplitude as a function of distance and effective stratospheric winds in the direction of propagation. This relation is based on recordings from chemical and nuclear explosion and allows determination of network detection and location capabilities. Maps providing the minimum detectable energy by the considered infrasound network are computed. They strongly depend on the atmospheric wind conditions the stratosphere, showing roughly a double peak pattern for Europe: The best performances are predicted around January and July when the prevailing zonal winds are stable and strong; during the equinox periods, around April and October, higher thresholds are explained by the zonal wind reversals.

## Common Seismic and Infrasound Recordings

Considering large explosions, the synergy with seismic data allows a more detailed event analysis, especially by improving source location; this is important for developing a successful monitoring regime for atmospheric or surface events. Dense seismic networks are therefore proposed to systematically identify and precisely locate infrasound events which can be used as GT events, to evaluate location methods and to validate infrasound propagation simulations. Such an event occurred at the Buncefield Oil Depot, United Kingdom, on the 2005 December 11, as the result of a spillage of 300 tonnes of petrol. The explosion generated large amplitude infrasonic signals that were recorded across Central Europe at infrasound arrays and seismometers measuring air-to-ground coupled arrivals. At that time, exceptionally high amplitude stratospheric winds were prevailing, propagating east-southeast with speeds of up to 130 m/s, yielding an efficient stratospheric duct. Significant improvements have been made in phase identification using accurate atmospheric parameterisations and 3-D modelling instead of climatological atmospheric models and 1-D ray tracing, which were in-adequate for such peculiar atmospheric conditions. Additionally, various location scenarios were considered, including cross-bearings and least-squares travel-time and back-azimuth inversion, all of which estimated locations within 35 km to GT, as well as a novel single array location method using multiple phases. However, yield estimates exhibited one order of magnitude variability across the network, clearly demanding improved empirical relations.

Major earthquakes in mountainous regions generate also infrasound beside the vast amount of seismic waves. An example is the M7.8 earthquake occurred in the Tarapaca region, North Chile, on 2005 June 13. At large distances from the epicentre, this event produced coherent infrasonic waves detected by three IMS infrasound arrays. Wide regions in the Andes Mountains radiated infrasound being suggested by both azimuth variations and long signal dura-

tions. Actually, the source regions were reconstructed based on the observations. Such an event recorded by multiple stations has offered an unique opportunity to evaluate the relative contributions of the different source mechanisms involved in large earthquakes, as well as to improve the understanding of ground displacement's amplification caused by topography. With a review of infrasound signals from past earthquakes, extended empirical scaling relations were derived showing that magnitude, depth, radiation pattern, and topography are key parameters for the emission of infrasound.

Another source leaving an imprint on both seismic and infrasonic recordings is the ocean swell. While its non-linear interaction with the atmosphere generates infrasound (microbarom), the interaction with the sea floor emits seismic ground roll (microseism). Usually, microbaroms have a sinusoidal wave character with a dominant period of 5 s. Due to low damping at such periods in stratospheric wave duct microbaroms are observed over large distance ranges up to a few thousand kilometres. Microseisms arise as an increase in seismic background noise between 4 and 40 s; whereas the primary and secondary peak at 7 and 14 s are dominating.

For a time period of ten years, a comparison between broad-band seismic and infrasound recordings at the same site in the Bavarian Forest, Germany, has revealed that power spectral noise amplitudes correlate well at the microbarom peak (Figure 4). To what extend microseismic background noise at lower periods is affected by atmospheric coupling of microbaroms is still an open question and needs to be discussed taking the ocean swell's hindcasts and infrasound propagation from the North Atlantic to station sites into account.
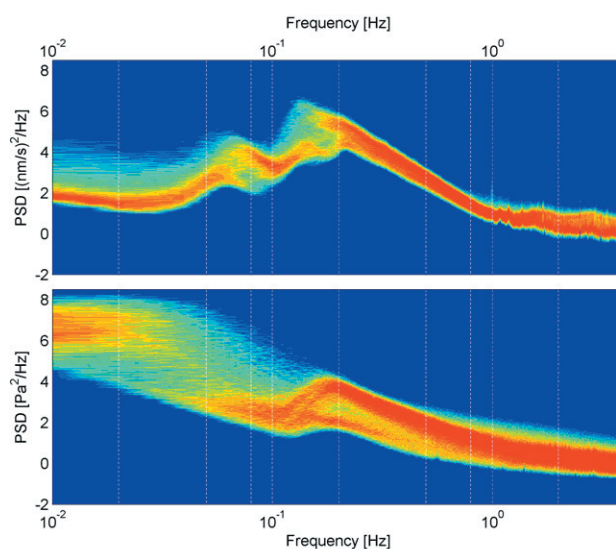


*Figure 4: Hourly computed power spectral densities (PSD) curves for broad-band seismic station GEC2 (vertical component, upper panel) and for infrasound station I26H3 (lower panel). Both stations are sited in the Bavarian Forest, Germany, only a few hundred metres apart. The colours mark the relative frequency of each PSD values at a certain frequency: blue is low and red is high. Beside the primary and secondary microseism peaks at 7 and 14 s, respectively, the seismic background noise also exhibits a peak at 5 s being in accordance with the microbarom peak.*