Chapter 10
Characterization of the Infrasonic Wavefield from Repeating Seismo-Acoustic Events

Steven Gibbons, Tormod Kværna and Peter Näsholm

Abstract Infrasound can provide unique data on extreme atmospheric events such as meteor impacts, severe weather systems, man-made explosions, and volcanic eruptions. Use of infrasound for remote event detection and location requires high-quality temporal and spatial atmospheric models, and infrasound generated by so-called Ground Truth events (for which the time and location are known) are necessary to evaluate atmospheric models and assess network performance. Large industrial blasts and military explosions are tightly constrained in time and space using seismic data and can generate infrasound recorded both regionally and at great distances. The most useful seismo-acoustic sources are repeating sources at which explosions take place relatively frequently. Over time, these may provide records of up to many hundreds of events from the same location from which characteristics and variability of the infrasonic wavefield and atmospheric conditions can be assessed on a broad range of timescales. Over the past 20 years or so, numerous databases of repeating explosions have been compiled in various parts of the world. Events are associated confidently with known sources, with accurately determined origin times, usually by applying waveform correlation or similar techniques to the characteristic seismic signals generated by each explosive source. The sets of sources and stations ideally result in atmospheric propagation paths covering a wide range of distances and directions, and the databases ideally include events covering all seasons. For selected repeating sources and infrasound arrays, we have assessed the variability of infrasonic observation: including the documentation of lack of observed infrasound. These observations provide empirical celerity, back azimuth deviation, and apparent velocity probability distributions. Such empirical distributions have been demonstrated in numerous recent studies to provide infrasonic event location estimates with significantly improved uncertainty estimates. Tropospheric, stratospheric, and ther-

S. Gibbons (✉) · T. Kværna · P. Näsholm
NORSAR, Kjeller, Norway
e-mail: steven@norsar.no

T. Kværna
e-mail: tormod@norsar.no

P. Näsholm
e-mail: peter@norsar.no

A. Le Pichon et al. (eds.), *Infrasound Monitoring for Atmospheric Studies*,
https://doi.org/10.1007/978-3-319-75140-5_10

mospheric returns have been observed, even at distances below 200 km. This information is now providing essential input data for studies of the middle and upper atmosphere.

10.1 Ground Truth Events

Microbarograph arrays are deployed globally to detect and classify infrasound signals generated by both natural and anthropogenic sources. In infrasound monitoring, for a given set of detected signals, we seek to locate and, if possible, identify the source which generated the signals. In infrasonic atmospheric imaging, for a given source, we seek to understand what state of the atmosphere could have resulted in the observed set of infrasound signals. The process is circular. On the one hand, the better the location and origin time of an event is known, the stronger the constraint is for estimating the state of the atmosphere. Similarly, the higher the quality of our atmospheric specification, the better the event location estimates are likely to be. We here use the word *event* to mean a source of seismic and/or acoustic waves that takes place over a very limited geographical region and that has a very limited time duration. For example, quarry blasting sequences excavate rock over a range of many tens of meters and consist of hundreds of small explosive charges detonated in ripple-fire salvos. These are considered to be events. The interaction between ocean waves can be a continuous source of seismic waves (so-called microseisms) and infrasonic waves (microbaroms) but these are not considered to be events here, both due to the large spatial extent of the source and its continuous nature. Volcanic sources may consist of events or may be an almost continuous source.

We define a Ground Truth, or GT, event as being an event for which the location (latitude, longitude, and either depth or altitude) and origin time are known. There is a long history in seismology for GT events, almost always explosions, being used for validating and refining models of Earth structure and wave propagation and for assessing the capability for locating seismic events using a given observational network. It became clear that true GT events, for which the source parameters are known exactly, were very few and far between. It was soon recognized that other events, including earthquakes, may not qualify as GT but could be well enough constrained to be useful for calibration purposes. Bondar et al. (2004), for example, derive conditions necessary for different levels of constraint on source parameters. GT5, for example, is used to denote an event whose epicenter is known to be within 5 km. The same principles apply to infrasound and a comprehensive overview of the use of GT events for interpreting the infrasonic (or seismo-acoustic) wavefield is provided by Green et al. (2009). Many of the largest GT infrasound sources are accidental explosions such as the blast at the Buncefield Oil Depot in the UK on December 11, 2005, or the Antares rocket explosion in Virginia on October 28, 2014. The location of such events is typically known exactly and the time is constrained by, for example, eyewitness reports or video footage. The explosions can be so large that multiple infrasound phases are observed over great distances (e.g., Ceranna et al. 2009; Pulli and Kofford 2015). Experimental explosions have enormous value given the a priori knowledge of yield and configuration of explosives (in addition to time and location). The best-recorded such events carried out for nuclear-test-ban treaty verification purposes are the Sayarim desert calibration explosions (e.g., Bonner et al. 2013). Such experiments however are carried out at great expense and can usually be performed a very limited number of times. Sayarim calibration explosions were carried out both in the summer and in the winter in order to assess propagation to both westerly and easterly stratospheric wind conditions.

In seismology, the propagation medium does not change over timescales of relevance and a single calibration explosion is essentially sufficient for a given observational network. Infrasound propagates through Earth's atmosphere, a medium in continuous motion and undergoing continuous change. Multiple events are therefore necessary to sample as many different atmospheric states as possible, ideally covering timescales ranging from hours to seasons and years. It is not realistic to use only purpose-performed calibration shots but there are fortunately many sources of repeating events, mainly for industrial and military purposes, which can be classified and used as GT or near-GT for calibrating models of infrasound propagation. Identifying existing repeating sources can be the key to accessing vast datasets for exploitation without needing to fund and carry out experiments. Most of the sources are ground-based and generate seismic signals which, due to the unchanging solid Earth, act as "fingerprints" for the specific source location. A characteristic seismic signal (or the absence of such a signal) provides a high degree of confidence that an explosion has (or has not) taken place at a given place and at an accurately determined time. Our intention is to provide a guide to identifying and exploiting repeating seismo-acoustic sources and discuss how infrasound observation can illuminate the spatiotemporal variability of the infrasonic wavefield and consequently improve atmospheric profiling and infrasound monitoring.

10.2 Studies of Repeating Seismo-Acoustic Events

The International Monitoring System (IMS) for verifying compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) comprises four components: seismic, infrasound, hydroacoustic, and radionuclide (Marty 2019). All technologies may be used to provide evidence of an explosion in the solid earth, the atmosphere, or the oceans, although the global infrasound network is primarily intended to detect atmospheric nuclear tests (e.g., Dahlman et al. 2011). When the CTBT was opened for signature in 1996, much of the seismic network was already in place since many of the stations were existing national infrastructure. In contrast, interest in infrasound monitoring had declined significantly since the cessation of atmospheric nuclear testing and the global infrasound network essentially had to be developed from scratch (Christie and Campus 2009). Significant studies have been carried out using historical data from atmospheric nuclear tests (e.g., Whitaker and Mutschlecner 2008) although the majority of the studies carried out have used data collected in the last 20 years.

Infrasound sensors deployed at sites of the TXAR seismic array in Texas, USA, were used by Sorrells et al. (1997) to detect atmospheric signals from mine blasts at distances up to several hundred km. This study demonstrated that infrasound was likely to be detected for larger blasts, at distances beyond 175–200 km, for which the source was "stratospherically downwind". Significantly, this paper pioneered the idea that Ground Truth Databases, constrained by seismic signals, could be used to provide a benchmark for the detection of infrasound signals in a monitoring context. Around the same time, microphones with simple wind-noise reduction systems were deployed at the Kurchatov seismic array in Kazakhstan. Hagerty et al. (2002) detected seismic signals resulting from mining blasts at the Ekibastuz quarry, 250 km to the NW of the sensors, and sought the more slowly propagating infrasound signals. Infrasound was detected for only about 10% of these events and there was a clear seasonality; all the detections were in the winter, consistent with the seasonal direction of the stratospheric waveguide.

The co-location of seismic and infrasound sensors led to the development of purpose-built small aperture seismo-acoustic arrays (Stump et al. 2004) which have been used to detect and characterize the seismic and acoustic signals from industrial blasts on the Korean Peninsula (Che et al. 2002). The arrays in this network were also able to detect both seismic and infrasonic signals generated by the underground nuclear tests carried out by the Democratic People's Republic of Korea (North Korea) in 2009 and 2013 (Che et al. 2009, 2014, 2019). Che et al. (2011) present a landmark study where the variability of infrasound observations was studied for over 1000 GT mining blasts at a single quarry in the Republic of Korea (South Korea) over a period of 2 years. Infrasound signals were examined at two stations, both within 200 km of the source but with one path mainly continental to the west with significant topography and the other to the east over the open ocean. Tropospheric signals were observed at both stations with very little seasonal variation. However, stratospheric signals observed over the oceanic path were observed with an almost constant celerity (the great circle distance divided by the traveltime) whereas stratospheric signals propagating over the continental path had an almost sinusoidal seasonal celerity variation. Failing to account for this variability when trying to invert for the source location was demonstrated to result in bias.

McKenna et al. (2007) examined infrasound recorded at the I10CA array in Canada generated by GT mining blasts at the Mesabi Iron ore mine in Minnesota and found that no reliable indication of the stated explosive yield could be determined from the infrasonic signals. A similar study by Arrowsmith et al. (2008), seeking infrasound generated by quarry blasts at the Black Thunder mine in Wyoming recorded at the PDIAR array, concluded that high noise levels at the station were the most likely cause of non-detection of infrasound from many events. One of the major catalysts for study of repeating events in the western United States was the deployment of the USArray Transportable Array (TA) of 400 seismic stations which recorded ground-coupled acoustic waves (i.e., infrasound signals converted to ground motion at the receiver). With a typical inter-site distance of 70 km, the TA provided an unprecedented high spatial coverage in recording the infrasonic wavefield. One of the most important repeating sources in this part of the world is the

Utah Test and Training Range (UTTR: 41.2°N, 113.0°W) which is the site of rocket destruction explosions generating infrasound recorded out to many hundreds of kilometers. These explosions have been used both to explore the extent and variability of infrasonic observations (e.g., Hedlin and Drob 2014; Nippress et al. 2014) and to explore methods for infrasonic event location (e.g., Modrak et al. 2010; Hedlin and Walker 2013). The Reverse Time Migration approach to event location using acoustic signals identified on the seismic network was used to find many more repeating sources (Walker et al. 2011). The network's recording of the infrasonic wavefield was so impressive that, in later years when the TA progressed to the eastern United States, an infrasound sensor was deployed at each site in addition to the seismic sensor.

Another part of the world where numerous studies have been performed on repeating explosions is the north of Fennoscandia which includes Arctic regions of Norway, Sweden, Finland, and Russia (Gibbons et al. 2015a). The interest in this region stems both from the large number of sources (with many open-cast mining operations and sites of military explosions) and the large number of receivers (with over two decades of continuous seismic and infrasound data) as displayed in Fig. 10.1. While recent studies of the infrasonic wavefield in the United States have been characterized by an unprecedented spatial resolution in the recordings, the European Arctic datasets provide an unprecedented temporal coverage. A source of enormous interest has been a military test range at Hukkakero in northern Finland. Expired ammunition is destroyed at this site in a series of explosions that takes place every year in August and September. There are usually between 10 and 30 explosions each year, most often on consecutive days, and with the yield of each explosion being approximately 20T. Each explosion generates a seismic signal on the ARCES array in Norway, at a distance of approximately 180 km, which is essentially identical from event to event (constraining the origin time, the simple source-time function, and the approximate size of the blast). Since 2008, the ARCES seismic array in addition features a set of co-located infrasound sensors. This infrasound array is named ARCI and Evers and Schweitzer (2011) provides an analysis of 1 year of acoustic and seismic data recordings collected at the station.

Gibbons et al. (2007) studied infrasound propagation using the ground-coupled airwaves recorded on the same sensors between 7 and 15 min later finding that, by contrast, the converted infrasonic (acoustic) waves varied enormously between events in amplitude, duration, and traveltime. An occasional tropospheric arrival was observed, as was an even rarer thermospheric phase. The majority of infrasound signals however are presumed stratospheric returns arriving some 600–650 s after the blast. While the events are limited in season, the regularity of explosions on consecutive days gives excellent resolution to the surprisingly smooth changes of the celerity on the day-to-week timescale. Israelsson (2013) provides an analysis of data recorded at the Swedish Institute of Space Physics (IRF) arrays JMT, LYC, KIR, and SDK associated with 19 Hukkakero events in 2009.

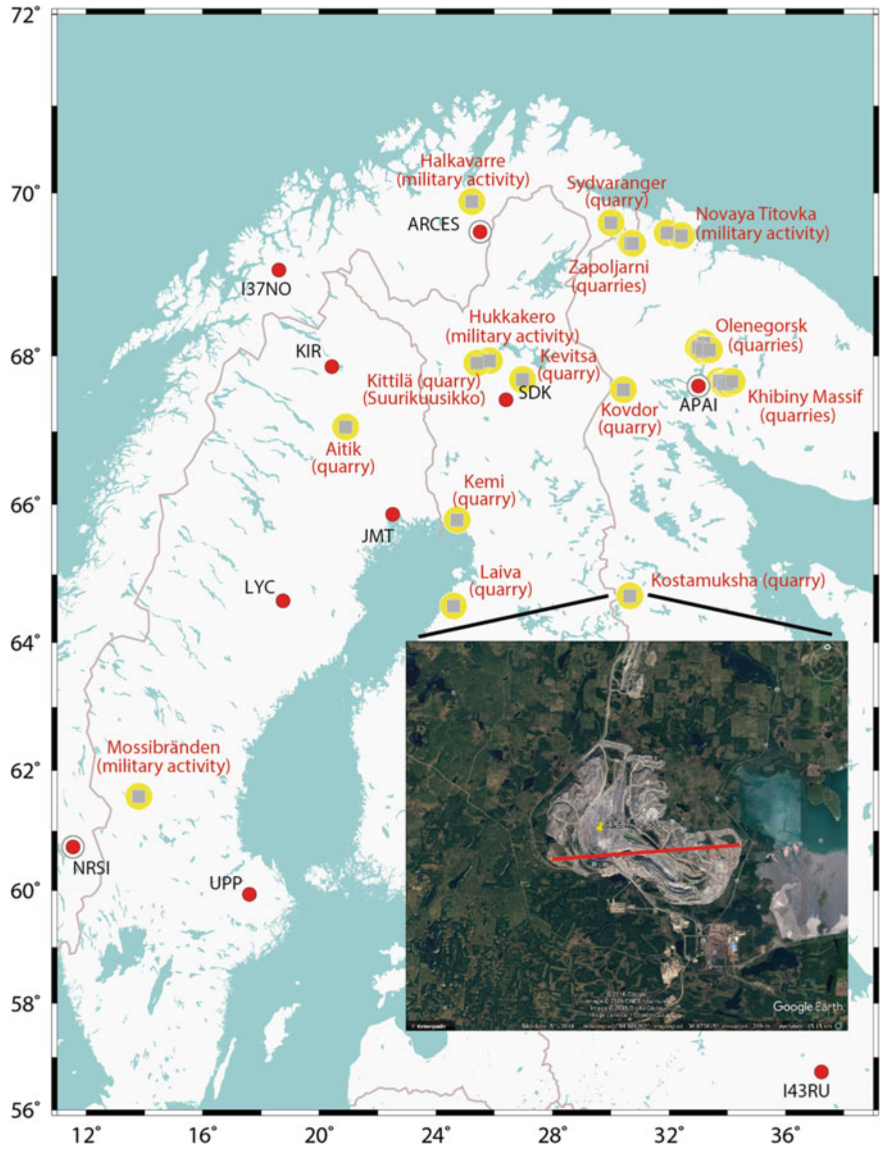

Fig. 10.1 Infrasound stations (red circles) and repeating sources of infrasound in Fennoscandia and North West Russia. The satellite image (from Google Earth) displays the Kostamuksha quarry in Russia where the length of the red line is 7.5 km. The yellow pin in the inset panel is centered on 64.687°N, 30.650°E

Gibbons et al. (2015a) provide an overview of other sources of repeating explosions in the European Arctic which have been identified from both seismic and infrasound recordings over the past 20 years or so. Like Che et al. (2011, 2019), Gibbons and Ringdal (2010) demonstrated that the seasonal variability of infrasound signals from repeating explosions in northwest Russia could differ enormously depending upon the source-to-receiver direction. More recently, Smets et al. (2015) exploited all-year-round open-cast mining blasts at Aitik in Sweden recorded at the I37NO infrasound array to assess the validity of atmospheric wind and temperature profiles. In this probabilistic approach, infrasound propagation was simulated within atmospheric ensemble temperature and wind profiles provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Such profiles are generated from realistic perturbations to the assimilated observations and initial estimate fields in the ECMWF atmospheric analysis product. The modeled and observed infrasound returns were then compared in order to approve (or refuse) the different member profiles in the ensemble set relevant to each event. Examples from this study will be presented later in this chapter.

10.3 Detecting and Classifying Seismic Events Using Seismic Data

An ideal form for Ground Truth is the reporting of an exact location and time by those carrying out the explosion. This occurs very rarely in practice since most of the explosions take place for military or industrial reasons, and not for the sake of observational geophysics. It is quite common that mine operators will be able to indicate that an explosion took place at a given mine in a certain time window (for example to within an hour) and that checking against a local seismic station will provide an accurate origin time (e.g., Harris et al. 2003; McKenna et al. 2007). If we are very fortunate, we will have an on-site seismic instrument which will provide sub-second accuracy of explosion time (c.f. Che et al. 2011). The advantages of on-site recording are so great that a considerable effort has been invested in designing specialized seismic and acoustic instruments to record both the ground motion and near-field airwave (Taylor et al. 2011).

More typically, we are restricted to remote sensing with the closest seismic stations at tens or even hundreds of kilometers from the source. However, given the longer timescales of atmospheric sound propagation, a source location error of a few kilometers (or an origin time error exceeding a second or two) will not necessarily mean that an event is not sufficiently well constrained for infrasound GT purposes. If a mine is the only source of significant seismic signals over a large region, we may be able to constrain the source location from satellite imagery and constrain the origin time to far greater accuracy than would be possible if the source location were subject to seismic network-related uncertainties. This is the case for the Kostomuksha mine in Russia; explosions at this mine are recorded well by stations at distances exceeding 1000 km. Network location estimates from distant seismic stations (e.g., IMS seismic arrays) may have uncertainties exceeding 25 km. Google Earth reveals that 64.69°N, 30.65°E is contained within a large open-cast quarry system. A large explosion (almost always at 09:00 or 10:00 UT) near these coordinates is essentially constrained to have taken place within this complex (approximately 7.5 km across). Taking a single first seismic arrival at one of the most sensitive seismic stations (the FINES and ARCES seismic arrays) and calculating the time back to the source region is likely to constrain the origin time and location far more accurately than consulting a network bulletin.

Identical explosions that take place at a given location generate identical seismic signals (e.g., Geller and Mueller 1980). The solid earth is unchanging and the radiating seismic waves follow the same paths which results in the same ground motion at each sensor, time after time. Given truly identical sources, the only differences in the seismic signals recorded at any station will be the result of background noise and unrelated seismic energy. Very closely spaced seismic events, which generate almost identical signals, can often be located relatively with great accuracy by correlating the waveforms and measuring the very small shifts in the arrival times (e.g., Waldhauser and Ellsworth 2000). The seismic signals may be weak and correlation detectors may also provide the best way of detecting events (the sources discussed by Gibbons and Ringdal (2010) are detected seismically to 200–300 km whereas the infrasound generated is observed at far greater distances). The multi-channel waveform correlation procedure, described in detail by Gibbons and Ringdal (2006), is illustrated in Fig. 10.2 for the detection of a low yield surface explosion at Hukkakero. The seismic signal at ARCES is below the background noise level but gives a clear correlation (or matched filter) detection when the signal from an earlier event is available as a waveform template. The screening criteria of Gibbons and Ringdal (2006) provide a high level of confidence that there is indeed a signal at this time from the site being monitored and, in this case, this can be confirmed by a signal at a far closer station. Infrasound from this small blast was recorded at several infrasonic arrays in Fennoscandia.

Correlators have limitations for detecting sources which result in significantly different seismic waveforms from blast to blast. This is typically the result of ripple-firing practices in which the total yield of the explosion is split between multiple small charges detonated with tiny delays. The orientation of the rock face being excavated can also be of significance and a gradual change in the nature of the seismic signal resulting from excavation of rock in the source region can frequently be observed. This need resulted in the application of subspace methods (e.g., Harris 1991; Harris and Dodge 2011) that generalize correlation detectors to consider linear combinations of signals from multiple master events (see, e.g., Chambers et al. 2015, for a recent application). Both correlation and subspace detectors are more powerful when stacking over multiple seismic sensors is possible. A mine with dimensions of many kilometers may require multiple templates to provide sufficient coverage given that the seismic signals are typically of high frequency (small wavelength) and the geographical footprint of a single signal may cover only a small fraction of the mine.

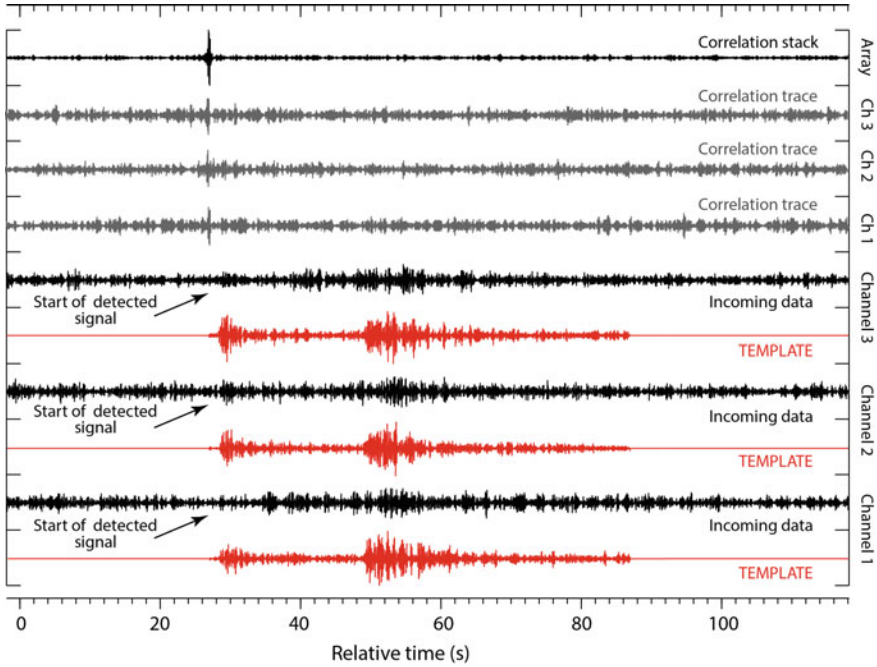

Fig. 10.2 Detection of a very low yield explosion at Hukkakero using multi-channel waveform correlation with the seismic signal from a larger explosion at the same location as a template. The master event signals from each sensor of the ARCES seismic array (red, only three channels displayed) are correlated tracewise, sample by sample, with the incoming datastreams (black). The resulting single channel correlation traces (gray) are stacked to give an array detection statistic with a greatly increased detection capability (top)

If a seismic array is available, an even more powerful method for identifying the signals with significant differences in the source-time function may be applied; empirical matched field processing (EMFP, Harris and Kværna 2010). EMFP is also a pattern detector but, rather than comparing the ground motion as a function of time, it compares narrow frequency band phase and amplitude relations between the signals recorded on different sensors in an array or network. The fact that the signal is broken down into narrow frequency bands makes EMFP robust to differences in the source-time function (e.g., when ripple-firing is used). The principle is demonstrated in Fig. 10.3. A coherent wavefront passing over two sensors an array will, for a given frequency, be observed as a sinusoid with a phase shift (represented by a color in Fig. 10.3). When we estimate the direction of an incoming wavefront using a seismic array, we are essentially testing to see which set of modeled phase shifts best matches the set of phase shifts that the incoming wavefront displays. Given the imperfect earth, with its faults and contrasts, the observed phase shifts (displayed on the right of Fig. 10.3) are often significantly different from those predicted by a simple plane wavefront model (on the left). However, the set of observed phase

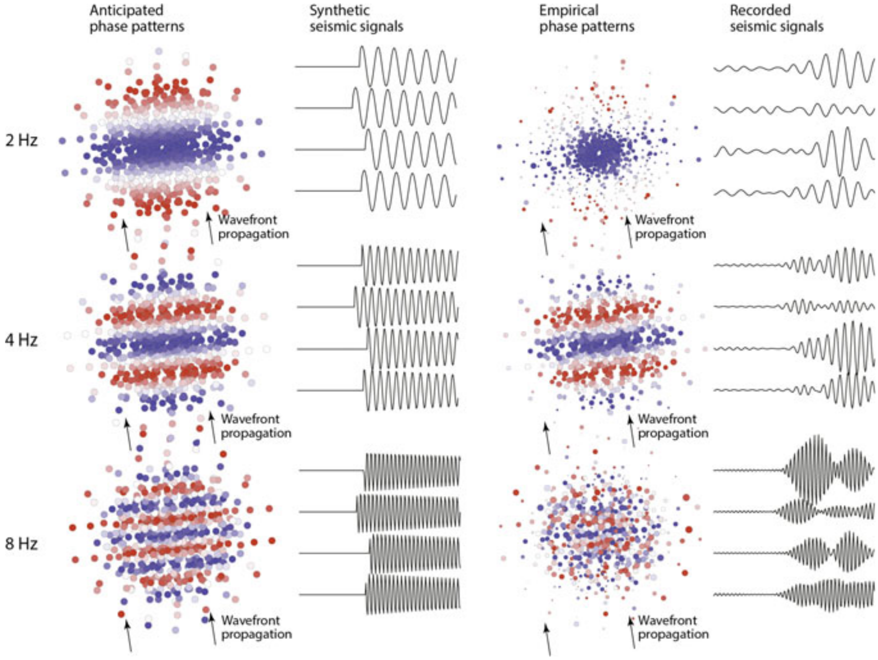

Fig. 10.3 Empirical matched field processing (EMFP) can identify the source of seismic signals even when waveform correlation fails, usually due to differences in the source-time function (as is common in ripple-fired quarry blasts). In EMFP, the signal over a seismic array is broken down into very narrow frequency bands and the pattern of phase differences between each pair of sensors is measured (see Harris and Kværna 2010). The colored symbols indicate the theoretical phase shifts (left) and the measured phase shifts (right) for a P-wave at the ARCES array from a Hukkakero explosion. The size of the symbol indicates coherence and the location of the symbol indicates the displacement vector between the two sensors. These phase-shift patterns are calculated for many very narrow frequency bands (only three are displayed) for a master event and this complex vector is stored as a signal template in the same way that a waveform is stored as a template for the correlation detector. A detection statistic measuring the similarity between this vector and the corresponding vector measured at any specified time can tell us if a new occurrence of this signal is observed

shifts for wavefronts arriving from explosions at the same site is usually very characteristic, even when the source-time function of the source is very different. Harris and Kværna (2010) demonstrate the enhanced resolution of EMFP for signals from different closely spaced mines, compared with the resolution possible using correlation detectors. This may significantly improve the source identification for infrasound modeling given many sources over a wide region, if very close seismic stations are not available.

We have reviewed several classes of seismic monitoring techniques that are applicable to different situations, in the absence of local monitoring. We suggest that a single site of large events, far from other sources of seismicity, is monitored adequately by standard network procedures (e.g., Ringdal and Kværna 1989) whereas pattern

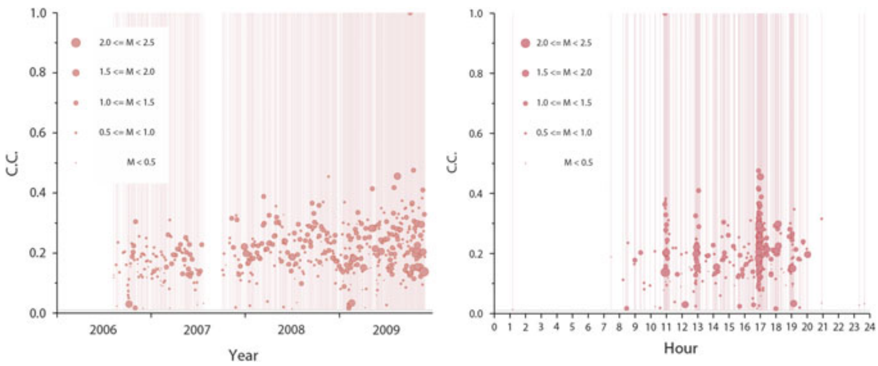

Fig. 10.4 Correlation (or matched filter) detections for a signal template at ARCES for a mining blast at Suurikuusikko (see Gibbons et al. 2015a). The detector was run on all continuous ARCES data from the start of 2006 to halfway through 2009. Each point represents a detection plotted against time (left) and time of day (right) with the symbol size representing the size of the event. No direct confirmation of events from the mine was available but analyses such as this, showing no detections at all at night, and none before the start of operations in summer 2006, indicate that there are essentially no false alarms. The screening criteria of Gibbons and Ringdal (2006) are essential for running such a detector at these low thresholds with this low false alarm rate

detectors are usually necessary for sources of weaker seismic signals or sources that are geographically close. The most sensitive form of pattern detector is the multi-channel correlation detector, but the applicability of this method decreases with differences between the seismic signals generated. In cases of signal diversity, subspace and/or matched field detectors perform better. Regardless of the method used, some form of validation check is required. The Suurikuusikko gold mine near Kittilä in northern Finland generates seismic signals recorded on the ARCES array 180 km away. Production started in the summer of 2006 and events were monitored using a single multi-channel correlation detector at ARCES. Of the 389 correlation detections displayed in Fig. 10.4, we see that none occurred prior to July 2006 and that only three occur between the times of 22h00 and 07h00 UT. Examining the plot of detections versus time of day shows a distribution which indicates industrial practice and provides confidence in the signal detector false alarm rate.

The sequence of multiple seismic events is difficult to discern from the resulting superimposed seismogram. Figure 10.5 displays the ARCES seismograms for a number of these events aligned according to the maximum correlation with the signal template. The signals, all plotted to a common vertical scale such that the relative amplitudes of the signals are real. The form of the infrasound signals recorded at Sodankylä (presumed to be tropospheric phases) appears to be quite simple and consistent from event to event, in contrast to the presumed stratospheric arrivals observed at 180 km (Gibbons et al. 2007). One of the apparent double events is indeed associated with a double acoustic signal, as indicated in the figure. Double infrasound signals can also occur from multipathing so care needs to be applied when the source-time function of the explosion is complicated.

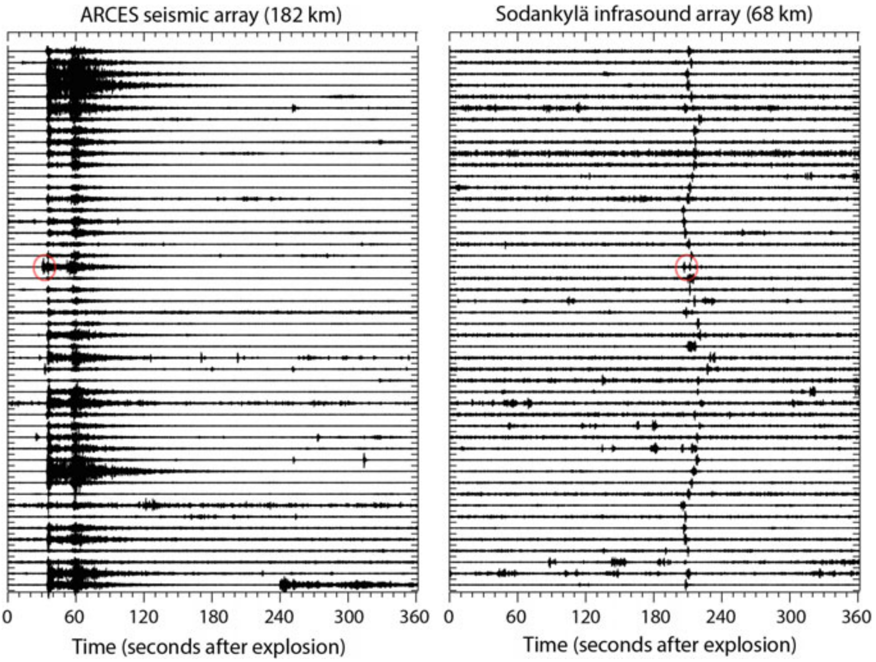

Fig. 10.5 Seismic and infrasound signals generated by different blasts at the Suurikuusikko mine in northern Finland. The seismic signals are aligned according to the maximum correlation with the master event used for the detector displayed in Fig. 10.4. Seismic signals which appear misaligned are likely due to double events. One such seismic arrival is indicated by a ring, as is the corresponding pair of infrasonic arrivals. The infrasound signals recorded at Sodankylä are of relatively short duration and arrive between 195 and 220 s after each explosion

10.4 Exploiting Infrasound Ground Truth Events for Atmospheric Modeling and Event Location Calibration

The stratosphere has a role in weather and climate predictability beyond a few days horizon (e.g., Karpencho et al. 2016). Better modeling and understanding of the stratospheric circulation and its interaction with planetary-wave generation is crucial for improving predictability in the weeks-to-months timescales. Studies have demonstrated that atmospheric infrasound data can be exploited in the evaluation of numerical weather forecasts e.g., in assessing forecast skills around an SSW (e.g., Smets et al. 2016). Smets et al. (2015) assessed ensembles of perturbed analyses provided by the ECMWF using constraints given by infrasound data combined with wave-propagation modeling. Other papers where atmospheric infrasound is used to verify, parameterize, or update atmospheric models include Chunchuzov et al. (2015), Le Pichon et al. (2015), Assink et al. (2014), Arrowsmith et al. (2016), and Lalande et al. (2012), Chunchuzov and Kulichkov (2019), Assink et al. (2019). A more general overview of the role infrasound can play in helping us to understand the earth system is provided in Hedlin et al. (2012), de Groot-Hedlin and Hedlin (2019).

Smets et al. (2015) demonstrate that applying small-scale fluctuations to the applied wind and temperature profiles may not always be necessary to match modeled predictions with observed infrasound returns. Mining explosions at Aitik in Sweden were identified from remote seismic monitoring and, for each event, infrasound propagation simulations were carried out through ensembles of realistic atmospheric model profiles. These ensembles were provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the profiles result from realistic perturbations both to the initial atmospheric state and to the assimilated observations. The infrasound observed at I37NO (245 km to the North West) is displayed in Fig. 10.6 and Smets et al. (2015) discuss how well these observations are matched by predictions, both with the standard and perturbed analyses. Many of the signals are predicted by the unperturbed analysis; others are predicted by particular classes of perturbations applied. A parabolic variation in celerity is observed for stratospherically downstream events (c.f. Che et al. 2011) with little observed at other times

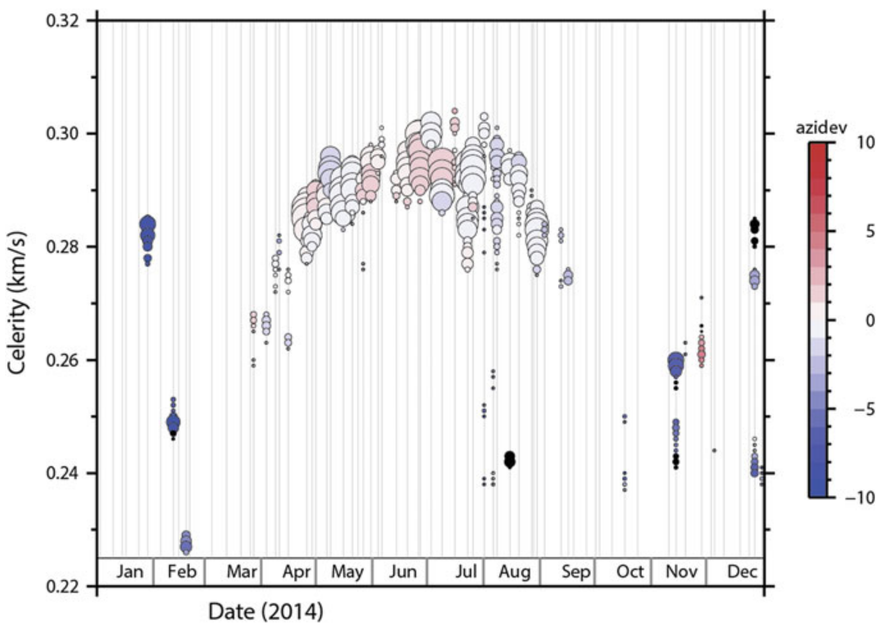

Fig. 10.6 Infrasound signal coherence at I37NO for seismically confirmed mining blasts at the Aitik quarry near Gällivare in northern Sweden (distance approximately 245 km). Each vertical line indicates an explosion at this pit and a symbol is displayed for each 10 s interval of I37NO data, bandpass filtered 1–4 Hz, for which the coherence exceeded 0.05, the apparent velocity was between 0.32 and 0.40 km/s and for which the back azimuth was between 145° and 165°. The sizes of the symbols are proportional to the coherence with the largest symbols approaching a coherence of unity

of the year. The few observations in the winter months, with significant azimuthal deviation, would be likely candidates for incorrectly associated infrasound signals. However, Smets et al. (2015) show that several of these are in fact predicted both by perturbed and unperturbed analyses.

While the Aitik explosions take place all year round, they are usually carried out once or sometimes twice per week. The Hukkakero explosions do not sample all seasons but do allow an assessment of the change in infrasound propagation over shorter timescales. Figure 10.7 displays broadband signals at I37NO (distance 320 km) for the 15 Hukkakero events from 2014. Gibbons et al. (2015a) demonstrated a relatively smooth change in the traveltime of the stratospheric phase with a moveout of up to 30 s relative to the seismically constrained origin time, but with over a minute in the variability of the arrival time of the thermospheric arrivals. In addition, the phase velocity of the stratospheric arrivals are essentially constant from day to day (indicating a consistent reflection altitude) whereas the phase velocity of the thermospheric arrivals varies significantly over the same timescales (indicating differences in the angle of descent and turning height). Figure 10.7 also indicates significant changes in the form of the signals from day to day.

Uncertainty in the anticipated celerity has consequences for the uncertainty in event location estimates (e.g., Modrak et al. 2010). The stratospheric anisotropy (which favors infrasound propagation in one direction and inhibits infrasound propagation in the other direction) means that we almost always have a large azimuthal gap

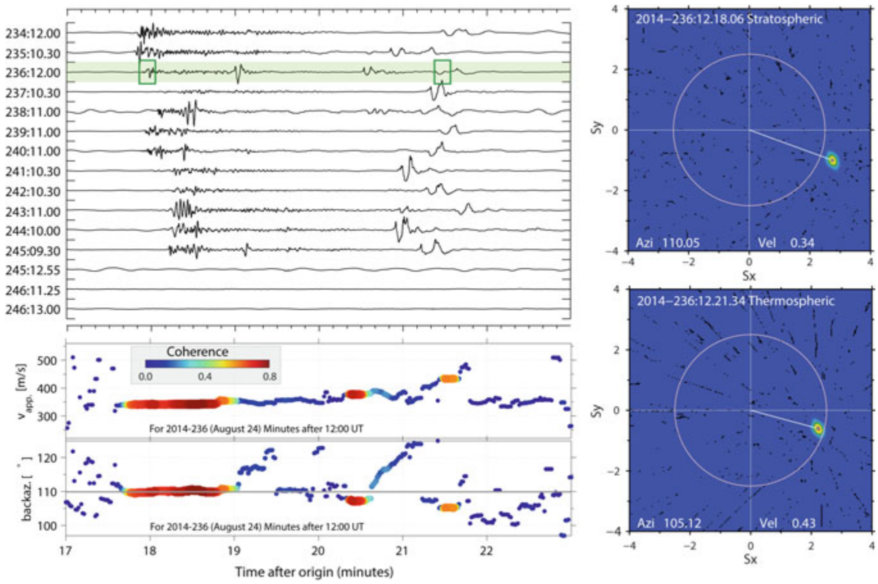

Fig. 10.7 Waveforms on I37NO for 15 explosions at Hukkakero in August and September 2014 as indicated. Waveforms in the main panel are bandpass filtered 0.03–1.50 Hz whereas the slowness analysis and processing results are performed in the 1–4 Hz band

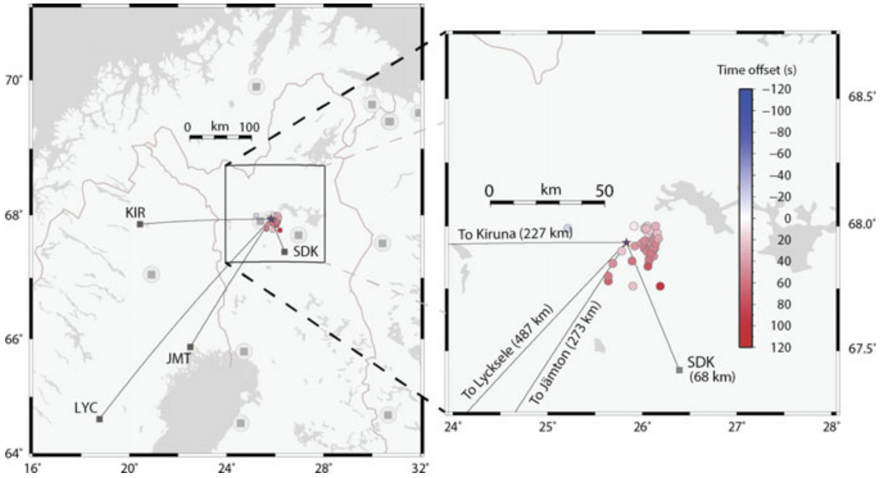

Fig. 10.8 Three-station infrasound location estimates in the CEA bulletin for 40 explosions confirmed to have taken place at the Hukkakero site (GT location 67.934°N, 25.832°E, asterisk) between 2007 and 2012. The event locations are based mostly on detections at the four Swedish Institute of Space Physics (IRF) stations shown though not all stations necessarily contribute to all events. The color of the location estimates indicates the time offset of the infrasound origin time estimate; a positive number of seconds indicated that the origin time is estimated later than the seismically confirmed GT origin time

in infrasonic event location. The back azimuth estimates of infrasound arrivals are consequently more important in the location problem than is typical in seismology. Figure 10.8 shows the location estimates made by the Commissariat à l'énergie atomique et aux énergies alternatives (CEA) for events, with contributions from at least three infrasound arrays, that were confirmed by independent seismic analysis to have taken place at Hukkakero. The detections are dominated by the Swedish Institute of Space Physics (IRF) JMT, LYC, KIR, and SDK arrays which, with apertures of only 100 m, have more limited back azimuth resolution than the considerably larger IMS infrasound arrays. However, almost all location estimates fall within 25 km of the GT location. Figure 10.8 displays the tradeoff between the location and origin time estimates and almost all events are estimated later than the seismically confirmed explosion time. The GT collection will provide empirical traveltime distributions which will allow a better calibrated location procedure and hopefully reduce significantly the spread in the location estimates.

10.5 Conclusions

Knowing the time and the location of explosive sources of atmospheric sound serves several purposes. It allows a generated infrasound signal to be used for probing the state of the atmosphere or evaluating methods for modeling atmospheric sound propagation. If we have a location and time estimate for an event which would be expected to generate infrasound, we have a test of detection capability for a network and, in the case of an infrasonic event being formed, a calibration for the location estimate and uncertainty. At an even more fundamental level, a known source may be able to explain an infrasound signal that is detected but not necessarily associated or characterized. Figure 10.9 displays a weak, low frequency, infrasound signal detected at I18DK, Qaanaaq, Greenland. In the context of the global IMS network, this detection is one of many from which no event is constructed. Our seismic and near-regional infrasonic monitoring of northern Fennoscandia pinpoints the time of a Hukkakero explosion to 08:00 UT on August 15, 2007. This source is consistent both in direction and celerity with the signal detected almost 3 h later and 3000 km away. This signal will now contribute to our understanding of probabilistic infrasound detection at large distances.

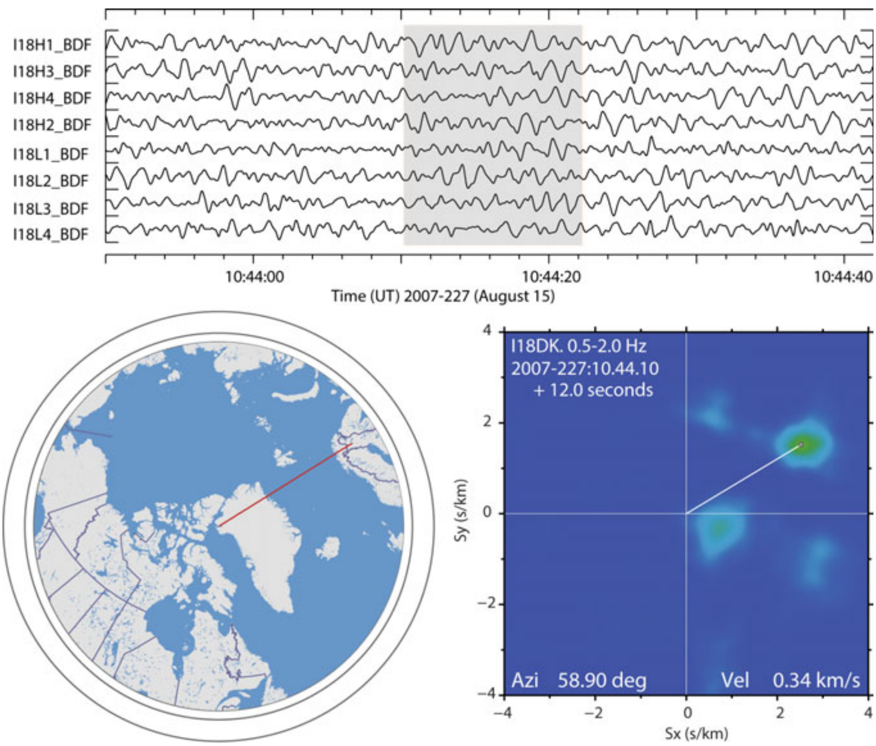

Fig. 10.9 A detection on the IMS infrasound array I18DK at Qaanaaq, Greenland, which is consistent both in time and direction with the signal from an explosion at Hukkakero (distance 2923 km). The seismic signal at ARCES indicates an origin time of 08:00 for the explosion, giving an infrasound celerity to I18DK of 0.297 km/s. The waveforms are displayed and processed in the 0.5–2.0 Hz band

Our focus has been on ground-based explosions as these typically generate seismic signals which constrain both source time and source location. While seismic monitoring is ideally performed locally, this is most often not feasible and we may be limited to remote sensing. Even at distances of several hundred kilometers, seismic recordings may constrain the source location to the order of 1 km and the source time to the order of a second: a far higher accuracy than is needed to be useful for infrasound propagation over scales of hundreds of kilometers. We have, in this paper, provided an overview of the most applicable seismic methods for constraining sources of different kinds. If a very comprehensive seismic catalog is available for a region, e.g., with completeness to below magnitude 1, we may be able to eliminate almost all ground sources for events solely constrained by infrasound signals. In a test-ban treaty monitoring context, a large number of screened events (i.e., events that can be assigned with a high level of confidence to a known source) will allow targeting of resources to signals of unknown origin.

There are numerous issues of scale, both related to the source and to the observations. For the source, the scale is mostly related to the size of the event: how much energy is released. Events that generate infrasound detected at great distances are (fortunately) few and far between. They are usually catastrophic and damaging events and, while providing unique insights into propagation modes for atmospheric sounds, sample only a single state of the atmosphere and will give little insight into the detectability of infrasound that can be expected from smaller events. Routine industrial blasts at open-cast mines generate infrasound recorded at much shorter distances but provide typically hundreds of events over timescales of years that sample many different atmospheric paths and enhance our understanding of the statistical expectation of the observed infrasound (see, e.g., Morton and Arrowsmith 2014; Smets et al. 2015; Cugnet et al. 2019). Atmospheric sound propagation at even shorter distances can be studied in detail with far smaller, nonexplosive, infrasonic sources (e.g., Jones 2014). The recent study of de Groot-Hedlin and Hedlin (2015), de Groot-Hedlin and Hedlin (2019); also includes an extensive catalog of routine industrial explosions in the USA.

Regarding the spatial scale at which the infrasonic wavefield is observed, while the global network was designed to detect large atmospheric explosions detected at multiple stations at distances of several thousand kilometers, the increasing array of civil infrasound applications has led to the deployment of many national facilities with far denser coverage than the IMS network. The lowering of the detection threshold provided by additional sites is discussed by, e.g., Le Pichon et al. (2008) and Tailpied et al. (2013). Many of the sources discussed in this paper are small with infrasound only detected out to relatively short distances. To understand the capabilities of civil infrasound monitoring, we must also understand the limitations; under which circumstances can we and can we not expect to detect infrasound from a source of interest? We have seen examples where the direction and the path over which an infrasound signal propagates has large consequences for the likelihood of detection and the expected celerity. Regarding the temporal scale, we note the value of long-term time-series data which can cover variability in the expected infrasound propagation from scales of hours and days, to seasons and years. Only now are we approaching an era where timescales of several decades will be represented with continuous infrasound data.

We use infrasound signals to help characterize the sources of seismic signals (e.g., to provide a means of discrimination: Stump et al. 2002; Che et al. 2019) and use seismic signals, for example, to constrain the time and location of infrasound sources. An increasing interest in the seismo-acoustic wavefield (e.g., Arrowsmith et al. 2010; Hedlin et al. 2012) is likely both to increase the volume of data and enhance its exploitation. The majority of the studies discussed are made possible due to the availability of both seismic and infrasound data. The cases for augmenting seismic sensors with microbarographs (e.g., Stump et al. 2004) and infrasound arrays with seismic sensors (e.g., Gibbons et al. 2015b) are both compelling.

Acknowledgements We are grateful to Alexis Le Pichon for providing the infrasound event bulletin of the CEA (Commissariat à l'énergie atomique et aux énergies alternatives).
We thank Hans Israelsson for his lists of IMS infrasound detections associated with Ground Truth events at Hukkakero.
Data from the Sodankylä (SDK) array is obtained with thanks from the Swedish Institute of Space Physics (IRF) and data from I18DK was obtained from the International Data Center of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, Vienna.
Data from ARCES and I37NO are available from NORSAR from
`http://www.norsardata.no/NDC/data/autodrm.html`
Graphics are generated using the GMT software (Wessel and Smith 1995).
The IRIS reference event infrasound database is found at
`http://ds.iris.edu/ds/products/infrasound-taired/` (last referenced January 2016).

References

Arrowsmith SJ, Hedlin MAH, Stump B, Arrowsmith MD (2008) Infrasonic signals from large mining explosions. Bull Seismol Soc Am 98:768–777. https://doi.org/10.1785/0120060241

Arrowsmith M, Arrowsmith S, Marcillo O (2016) Using sounds from the ocean to measure winds in the stratosphere. EOS 97: https://doi.org/10.1029/2016EO042563

Assink JD, Le Pichon A, Blanc E, Kallel M, Khemiri L (2014) Evaluation of wind and temperature profiles from ECMWF analysis on two hemispheres using volcanic infrasound. J Geophys Res Atmos 119(14):8659–8683. https://doi.org/10.1002/2014jd021632

Assink J, Smets P, Marcillo O, Weemstra C, Lalande J-M, Waxler R, Evers L (2019) Advances in infrasonic remote sensing methods. In: Le Pichon A, Blanc E, Hauchecorne A (eds) Infrasound monitoring for atmospheric studies, 2nd edn. Springer, Dordrecht, pp 605–632

Arrowsmith SJ, Johnson JB, Drob DP, Hedlin MAH (2010) The seismoacoustic wavefield: a new paradigm in studying geophysical phenomena. Rev Geophys 48:RG4003+. https://doi.org/10.1029/2010rg000335

Bondar I, Engdahl ER, Yang X, Ghalib HAA, Hofstetter A, Kirichenko V, Wagner R, Gupta I, Ekstrom G, Bergman E, Israelsson H, McLaughlin K (2004) Collection of a reference event set for regional and teleseismic location calibration. Bull Seismol Soc Am 94(4):1528–1545. https://doi.org/10.1785/012003128

Bonner J, Waxler R, Gitterman Y, Hofstetter R (2013) Seismo-acoustic energy partitioning at near-source and local distances from the 2011 Sayarim explosions in the Negev desert. Israel. Bull Seismol Soc Am 103(2A):741–758. https://doi.org/10.1785/0120120181

Ceranna L, Le Pichon A, Green DN, Mialle P (2009) The Buncefield explosion: a benchmark for infrasound analysis across Central Europe. Geophys J Int 177:491–508. https://doi.org/10.1111/j.1365-246x.2008.03998.x

Chambers DJA, Koper KD, Pankow KL, McCarter MK (2015) Detecting and characterizing coal mine related seismicity in the Western U.S. using subspace methods. Geophys J Int 203:1388–1399. https://doi.org/10.1093/gji/ggv383

Che IY, Jun MS, Jeon JS, Min KD (2002) Analysis of local seismo-acoustic events in the Korean Peninsula. Geophys Res Lett 29:1589+. https://doi.org/10.1029/2001gl014060

Che IY, Stump BW, Lee HI (2011) Experimental characterization of seasonal variations in infrasonic traveltimes on the Korean Peninsula with implications for infrasound event location. Geophys J Int 185:190–200. https://doi.org/10.1111/j.1365-246x.2011.04948.x

Che IY, Park J, Kim I, Kim TS, Lee HI (2014) Infrasound signals from the underground nuclear explosions of North Korea. Geophys J Int 198:495–503. https://doi.org/10.1093/gji/ggu150

Che IY, Park J, Kim TS, Hayward C, Stump B (2019) On the use of a dense network of seismo-acoustic arrays for near-regional environmental monitoring. In: Le Pichon A, Blanc E, Hauchecorne A (eds) Infrasound monitoring for atmospheric studies, 2nd edn. Springer, Dordrecht, pp 409–448

Che IY, Kim TS, Jeon JS, Lee HI (2009) Infrasound observation of the apparent North Korean nuclear test of 25 May 2009. Geophys Res Lett 36(22):L22,802+. https://doi.org/10.1029/2009gl041017

Cugnet D, de la Camara A, Lott F, Millet C, Ribstein B (2019) Non-orographic gravity waves: representation in climate models and effects on infrasound. In: Le Pichon A, Blanc E, Hauchecorne A (eds) Infrasound monitoring for atmospheric studies, 2nd edn. Springer, Dordrecht, pp 827–844

Christie DR, Campus P (2009) The IMS infrasound network: design and establishment of infrasound stations. In: Le Pichon A, Blanc E, Hauchecorne A (eds) Infrasound monitoring for atmospheric studies. Springer, Netherlands, chap 2, pp 29–75. https://doi.org/10.1007/978-1-4020-9508-5_2

Chunchuzov I, Kulichkov S (2019) Internal gravity wave perturbations and their impacts on infrasound propagation in the atmosphere. In: Le Pichon A, Blanc E, Hauchecorne A (eds) Infrasound monitoring for atmospheric studies, 2nd edn. Springer, Dordrecht, pp 551–590

Chunchuzov I, Kulichkov S, Perepelkin V, Popov O, Firstov P, Assink JD, Marchetti E (2015) Study of the wind velocity-layered structure in the stratosphere, mesosphere, and lower thermosphere by using infrasound probing of the atmosphere. J Geophys Res Atmos 120(17):8828–8840. https://doi.org/10.1002/2015jd023276

Dahlman O, Mackby J, Mykkeltveit S, Haak H (2011) Detect and deter: can countries verify the nuclear test ban? Springer Science and Business Media B, Dordrecht, The Netherlands. https://doi.org/10.1007/978-9-4007-1676-6

de Groot-Hedlin CD, Hedlin MAH (2015) A method for detecting and locating geophysical events using groups of arrays. Geophy J Int 203(2):960–971. https://doi.org/10.1093/gji/ggv345

de Groot-Hedlin C, Hedlin M (2019) Detection of infrasound signals and sources using a dense seismic network. In: Le Pichon A, Blanc E, Hauchecorne A (eds) Infrasound monitoring for atmospheric studies, 2nd edn. Springer, Dordrecht, pp 669–699

Evers L, Schweitzer J (2011) A climatology of infrasound detections in northern Norway at the experimental ARCI array. J Seismol 15:473–486. https://doi.org/10.1007/s10950-011-9237-8

Geller RJ, Mueller CS (1980) Four similar earthquakes in Central California. Geophys Res Lett 7(10):821–824

Gibbons SJ, Asming V, Eliasson L, Fedorov A, Fyen J, Kero J, Kozlovskaya E, Kværna T, Liszka L, Näsholm SP, Raita T, Roth M, Tiira T, Vinogradov Y (2015a) The European Arctic: a laboratory for seismoacoustic studies. Seismol Res Lett 86:917–928. https://doi.org/10.1785/0220140230

Gibbons SJ, Kværna T, Mykkeltveit S (2015b) Could the IMS infrasound stations support a global network of small aperture seismic arrays? Seismol Res Lett 86:1148–1159. https://doi.org/10.1785/0220150068

Gibbons SJ, Ringdal F (2006) The detection of low magnitude seismic events using array-based waveform correlation. Geophys J Int 165:149–166. https://doi.org/10.1111/j.1365-246X.2006.02865.x

Gibbons SJ, Ringdal F, Kværna T (2007) Joint seismic-infrasonic processing of recordings from a repeating source of atmospheric explosions. J Acoust Soc Am 122:EL158–EL164. https://doi.org/10.1121/1.2784533

Gibbons S, Ringdal F (2010) Detection and analysis of near-surface explosions on the Kola Peninsula. Pure Appl Geophys 167:413–436. https://doi.org/10.1007/s00024-009-0038-8

Green DN, Le Pichon A, Ceranna L, Evers L (2009) Ground truth events: assessing the capability of infrasound networks using high resolution data analyses. In: Le Pichon A, Blanc E, Hauchecorne A (eds) Infrasound monitoring for atmospheric studies. Springer, Netherlands, chap 19, pp 599–625. https://doi.org/10.1007/978-1-4020-9508-5_19

Hagerty MT, Kim WY, Martysevich P (2002) Infrasound detection of large mining blasts in Kazakstan. In: Der ZA, Shumway RH, Herrin ET (eds) Monitoring the comprehensive nuclear-test-ban treaty: data processing and infrasound, Pageoph Topical Volumes, Birkhäuser Basel, pp 1063–1079. https://doi.org/10.1007/978-3-0348-8144-9_9

Harris DB (1991) A waveform correlation method for identifying quarry explosions. Bull Seismol Soc Am 81:2395–2418

Harris DB, Dodge DA (2011) An autonomous system for grouping events in a developing aftershock sequence. Bull Seism Soc Am 101:763–774

Harris DB, Kværna T (2010) Superresolution with seismic arrays using empirical matched field processing. Geophys J Int 182:1455–1477. https://doi.org/10.1111/j.1365-246x.2010.04684.x

Harris DB, Ringdal F, Kremenetskaya EO, Mykkeltveit S, Schweitzer J, Hauk TF, Asming VE, Rock DW, Lewis JP (2003) Ground-truth collection for mining explosions in Northern Fennoscandia and Russia. In: Proceedings of the 25th seismic research review, nuclear explosion monitoring building the knowledge base, LA-UR-03-6029, Tucson, Arizona, 23–25 Sept 2003, pp 54–63

Hedlin MAH, Drob DP (2014) Statistical characterization of atmospheric gravity waves by seismoacoustic observations. J Geophys Res Atmos 119(9):2013JD021,304+. https://doi.org/10.1002/2013jd021304

Hedlin MAH, Walker KT (2013) A study of infrasonic anisotropy and multipathing in the atmosphere using seismic networks. Philos Trans R Soc A Math Phys Eng Sci 371: https://doi.org/10.1098/rsta.2011.0542

Hedlin MAH, Walker K, Drob DP, de Groot Hedlin, (2012) Infrasound: connecting the solid earth, oceans, and atmosphere. Annu Rev Earth Planet Sci 40:327–354. https://doi.org/10.1146/annurev-earth-042711-105508

Israelsson H (2013) Recordings from Hukkakero explosions in 2009 at infrasound stations of the IRF network. Technical report SIR 01-2013, SeismicInfra Research, Washington DC

Jones KR (2014) Infrasound generation from the HH seismic hammer. Technical report. SAND2014-19350, Sandia National Laboratories, Albuquerque, New Mexico. http://prod.sandia.gov/techlib/access-control.cgi/2014/1419350.pdf

Karpechko A, Tummon F, Secretariat W (2016) Climate predictability in the stratosphere. World Meteorol Organ Bull 65. https://public.wmo.int/en/resources/bulletin/climate-predictability-stratosphere

Lalande JM, Sèbe O, Landès M, Blanc-Benon P, Matoza RS, Le Pichon A, Blanc E (2012) Infrasound data inversion for atmospheric sounding. Geophys J Int 190:687–701. https://doi.org/10.1111/j.1365-246x.2012.05518.x

Le Pichon A, Assink JD, Heinrich P, Blanc E, Charlton-Perez A, Lee CF, Keckhut P, Hauchecorne A, Rüfenacht R, Kämpfer N, Drob DP, Smets PSM, Evers LG, Ceranna L, Pilger C, Ross O, Claud C (2015) Comparison of co-located independent ground-based middle atmospheric wind and temperature measurements with numerical weather prediction models. J Geophys Res Atmos 120(16):8318–8331. https://doi.org/10.1002/2015jd023273

Le Pichon A, Vergoz J, Herry P, Ceranna L (2008) Analyzing the detection capability of infrasound arrays in Central Europe. J Geophys Res Atmos 113(D12):D12,115+. https://doi.org/10.1029/2007jd009509

Marty J (2019) The IMS infrasound network: current status and technological developments. In: Le Pichon A, Blanc E, Hauchecorne A (eds) Infrasound monitoring for atmospheric studies, 2nd edn. Springer, Dordrecht, pp 3–62

Modrak RT, Arrowsmith SJ, Anderson DN (2010) A Bayesian framework for infrasound location. Geophys J Int 181:399–405. https://doi.org/10.1111/j.1365-246x.2010.04499.x

McKenna MH, Stump BW, Hayek S, McKenna JR, Stanton TR (2007) Tele-infrasonic studies of hard-rock mining explosions. J Acoust Soc Am 122:97–106. https://doi.org/10.1121/1.2741375

Morton EA, Arrowsmith SJ (2014) The development of global probabilistic propagation look-up tables for infrasound celerity and back-azimuth deviation. Seismol Res Lett 85(6):1223–1233. https://doi.org/10.1785/0220140124

Nippress A, Green DN, Marcillo OE, Arrowsmith SJ (2014) Generating regional infrasound celerity-range models using ground-truth information and the implications for event location. Geophys J Int 197:1154–1165. https://doi.org/10.1093/gji/ggu049

Pulli JJ, Kofford A (2015) Infrasonic analysis of the October 28, 2014 Antares rocket failure at Wallops Island, Virginia, using video recordings as ground truth. J Acoust Soc Am 137(4):2372. https://doi.org/10.1121/1.4920619

Ringdal F, Kværna T (1989) A multi-channel processing approach to real time network detection, phase association, and threshold monitoring. Bull Seismol Soc Am 79:1927–1940

Smets PSM, Assink JD, Le Pichon A, Evers LG (2016) ECMWF SSW forecast evaluation using infrasound. J Geophys Res Atmos 121(9):4637–4650. https://doi.org/10.1002/2015JD024251

Smets PSM, Evers LG, Näsholm SP, Gibbons SJ (2015) Probabilistic infrasound propagation using realistic atmospheric perturbations. Geophys Res Lett 42(15):6510–6517. https://doi.org/10.1002/2015gl064992

Sorrells GG, Herrin ET, Bonner JL (1997) Construction of regional ground truth databases using seismic and infrasound data. Seismol Res Lett 68:743–752. https://doi.org/10.1785/gssrl.68.5.743

Stump BW, Hedlin MAH, Pearson DC, Hsu V (2002) Characterization of mining explosions at regional distances: implications with the international monitoring system. Rev Geophys 40:1011+. https://doi.org/10.1029/1998rg000048

Stump B, Jun MS, Hayward C, Jeon JS, Che IY, Thomason K, House SM, McKenna J (2004) Small-aperture seismo-acoustic arrays: design, implementation, and utilization. Bull Seismol Soc Am 94:220–236. https://doi.org/10.1785/0120020243

Tailpied D, Le Pichon A, Marchetti E, Ripepe M, Kallel M, Ceranna L, Brachet N (2013) Remote infrasound monitoring of Mount Etna: observed and predicted network detection capability. Inframatics 2:1–11. https://doi.org/10.4236/inframatics.2013.21001

Taylor SR, Harben PE, Jarpe S, Harris DB (2011) Development of mine explosion ground truth smart sensors. In: Proceedings of the 2011 monitoring research review: ground-based nuclear explosion monitoring technologies, Tucson, Arizona, 13–15 Sept 2011. Report LA-UR-11-04823, pp 850–860

Waldhauser F, Ellsworth WL (2000) A double-difference earthquake location algorithm: method and application to the northern Hayward fault. California. Bull Seismol Soc Am 90(6):1353–1368

Walker KT, Shelby R, Hedlin MAH, de Groot-Hedlin C, Vernon F (2011) Western U.S. infrasonic catalog: illuminating infrasonic hot spots with the US array. J Geophys Res Atmos 116(B12):B12,305+. https://doi.org/10.1029/2011jb008579

Wessel P, Smith WHF (1995) New version of the generic mapping tools. EOS Trans Am Geophys Union 76:329

Whitaker RW, Mutschlecner JP (2008) A comparison of infrasound signals refracted from stratospheric and thermospheric altitudes. J Geophys Res Atmos 113(D8):D08,117+. https://doi.org/10.1029/2007jd008852