Infrasound Technology Workshop 2024 (ITW2024)

Monday 04 November 2024 – Friday 08 November 2024

VIC

Book of Abstracts

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Poster /

The Importance Placement of Infrasound Sensor In Indonesia (Monitoring of Potential Tsunami Non Tectonic)

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Indonesia is considered one of the zones prone to earthquakes and tsunamis due to its position in the boundary of 3 major tectonic plates, Indian-Australian, Eurasian, and Pacific. Currently, Indonesia has about 1,568 locations for seismic monitoring instruments, and it is supported by several tsunami monitoring. The instruments consist of 511 seismographs, 669 accelerographs, 400 intensity meters, four seismic boreholes (8 units), and 2 Seismic Health Monitors (12 units). However, monitoring subsurface disasters caused by non-tectonic earthquakes is not yet massively available. Indonesia has some locations with high levels of vulnerability to non-tectonic tsunamis, such as Semangka, Lampung, Pelabuhan Ratu, and Gorontalo Bay. Included active volcanoes in which eruption occurs to cause non-tectonic tsunamis, are Mount Anak Krakatau, Gamkonora, Ruang, Rokatenda, Ibu, Ile Lewotolok, and Lewotobi. Scientific analyst only refers based on infrasound sensors, I06AU, I07AU, I40PG, and I39PW. However, the long distances from the event location and several other factors potentially cause the information obtained to be not optimal and biased. Based on this reason, Indonesia urgently needs an infrasound station to monitor its potential for non-tectonic tsunamis. The recommended locations for installation are around the Sunda Strait and the Sea of Moluccas.

Keywords: seismic, tsunami, subsurface, infrasound, non-tectonic.

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Data Processing and Station Performance /

Towards Data-Adaptive Beamforming: Generalized Least Squares and other Subspace Methods

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Generalized least squares (GLS) beamforming is a method for determining the direction of arrival and trace velocity of transient infrasound signals that may be otherwise obscured by persistent, correlated background noise, such as microbaroms. This method complements the adaptive F-detector by using an estimate of the noise background to form a generalized power ratio, which is used to estimate plane wave parameters (trace velocity and back-azimuth). Using a suite of fully synthetic signals, we first investigate the resolving power of the GLS estimator as a function of signal to noise ratio compared with a conventional, non-adaptive estimator.
Recorded infrasonic signals from the Forensics Surface Experiment, where a persistent signal was observed from the south, will then be used to evaluate the GLS method. Initial analyses suggest that GLS beamforming results in a lower F-statistic during noise regions and a higher F-statistic value for transient signals compared to the Bartlett beam. Algorithmically determining an optimal window

to characterize the background noise presents a significant challenge and different approaches will be discussed. This talk will discuss our evaluation of the GLS method and initial steps in testing additional signal subspace algorithms.

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Poster /

Enhancing the detection capabilities of the Brasília Infrasound Station (IS09) for local and regional events

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The detection capability of infrasound stations with four-element arrays is limited by spatial aliasing for higher frequencies, causing erroneous frequency identification and signal distortion when sensor spacing is too large. The Brasília Infrasound Station (IS09) of the International Monitoring System, operated by the University of Brasília's Seismological Observatory, exemplifies this issue with its sensors spaced 1 to 2 km apart in Brasília National Park. The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization is modernizing these stations to improve performance and data accuracy. The CTBT verification system requires detecting nuclear explosions in the 0.02 to 4 Hz range, but IS09 currently detects frequencies below 1 Hz, missing higher frequencies in case of local and regional events. Therefore, there's a need to modernize IS09 by increasing the number of sensors with shorter inter-distances. In this work, modifications are proposed to the IS09 array, adding five new elements, aiming to improve the station's gain and extend the frequency band to satisfy the requirements for detecting local and regional events and mitigate the spatial aliasing for high frequencies. The new proposed array was tested for 40 days using low-cost equipment, achieving a significantly greater number of detections compared to the IS09 four-element array.

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Poster /

Micrometeorological and anthropogenic effects on acoustic background noise levels

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Acoustic networks often record background noise from both natural and man-made sources. Most of the time, wind and anthropogenic noise are higher during the day. A permanent acoustic network at the Nevada National Security Site (NNSS) captured background noise from a variety of sources over several months. These stations were deployed on canyon bottoms, hillsides, and mesas, each

of which have distinct topographically-driven micrometeorology. In addition, some were close to roads and buildings, but others were more remote. We examine how background noise on infrasound sensors varies across diverse topography and proximity to anthropogenic activity. We identify a pattern of activities across the site based on natural and anthropogenic acoustic signals. We found that timing and frequency content of noisy periods varied across topography and proximity to human activity – they did not always peak during the day. Understanding these acoustic "site effects" are important when selecting sensor deployment locations and assessing event detection thresholds.

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Sources and Scientific Applications /

Quantifying bolide energy through infrasound analysis: A case study of the 2023 Australian event

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Utilizing infrasound stations of the International Monitoring System (IMS) network has become increasingly prevalent over the past decade due to their ability to detect bolides. Infrasound data are often complemented by optical observations, providing essential ground truth information. We present infrasound detections of a bolide that exploded over Australia on 20 May 2023. The bolide entered the atmosphere over Queensland at a speed of 28 km/s. It disintegrated catastrophically at an altitude of 29 km, saturating ground-based cameras, thus hindering efforts to determine its full trajectory and obtain photometric measurements. The bolide deposited energy of ~7.2 kilotons of TNT equivalent, ranking it among the top 20 most energetic events reported in the JPL/NASA CNEOS database since 1988. The bolide was so bright that it was visible at a distance of 600 km. Infrasound signals from this event were detected at IMS stations located up to 6000 km away, with energy estimates derived from infrasound analysis aligning closely with values reported in the CNEOS database. We will present detailed infrasound observations of this energetic bolide event and discuss its implications for planetary defense and the characterization of similar events.
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Poster /

Deploying a Portable Infrasound Station in Jordan: Enhancing SHI Monitoring and Preparedness

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The Dead Sea Transform Fault (DSTF) have historically produced seismic events, positioning Jordan as a crucial location for monitoring infrasound waves generated by both natural phenomena, Man-Made activities, including mining quarries.

This poster examines the feasibility and strategic importance of deploying a portable infrasound station in Jordan. The proposed station aims to augment the existing seismic monitoring infrastructure by improving the detection and analysis of infrasound signals. Key considerations include the geological significance of the DSTF and Wadi Araba Fault, which contribute to regional seismic activity and infrasound generation.
Man-Made sources, such as phosphate mining and nearby conflict zones, further emphasize the necessity for comprehensive infrasound monitoring in Jordan.
Practical aspects of the site survey include assessing accessibility, safety, environmental conditions, and infrastructure requirements essential for deploying and maintaining the infrasound station. Additionally, this initiative offers an opportunity for capacity building within Jordan's National Data Center (NDC), fostering expertise in infrasound technology and promoting international collaboration in SHI monitoring efforts.
In conclusion, establishing a portable infrasound station in Jordan promises to enhance regional seismic monitoring capabilities, improve preparedness for natural and anthropogenic events, and contribute valuable data to global scientific endeavors in infrasound research.

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Poster /

Infrasound sources in Jordan and Deploying Portable Infrasound Station

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In my presentation, I will show the sources of infrasound waves in Jordan. Many of earthquakes are recorded at Dead Sea transform fault .These earthquakes are considered main source of Infrasound waves. The second source of infrasound waves is Phosphate mines which are located in the southeast part of Jordan. The other sources may be the explosions of WAR in Middle East. In addition, aircraft and machinery such as wind turbines. Studying the infrasound sources using IMS data and IDC bulletins using IMS products (PMCC, Geotool and etc.…). Infrasound monitoring is one of technologies used by the CTBT verification regime. Underground explosions can generate infrasound waves are detected by the infrasound portable station to detect low frequency sound waves in the atmosphere to distinguish between natural events or manmade event. So deploying portable infrasound station in the area is very important and the proposed location is northern part of Jordan (Ajlun and Jerash cities) .This area is characterized by forests, low surface wind speed and low background noise. This experiment aims to contribute in many important objects and training NDC-JO staff to understand the infrasound technique and understand infrasound sources in Middle East .

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Poster /

Improvement project for the infrasound station I17CI (Cote d'Ivoire) detections: increase from 4 to 8 sensors

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In CTBTO monitoring system (IMS), Côte d'Ivoire benefits from two (2) primary stations: seismic (PS15) and infrasound (I17CI) respectively for monitoring underground and airborne nuclear tests. Upgrading the infrasound station I17CI from 4 to 8 sensors is part of the CTBTO's medium-term objectives, which include upgrading the world's other infrasound stations. Thus, this research project is part of the preliminary studies prior to the implementation of this major CTBTO project.

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Modelling and Network Processing /

Quantifying Atmospheric Uncertainty and Detection Quality Impacts on Infrasonic Localization

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An event-specific localization for regional infrasonic analysis has recently been developed using a Bayesian statistical framework and time-reversed ray tracing methods. Auxiliary parameters previously introduced to solve the transport equation as well as identify eigenrays are used to map confidence in direction-of-arrival of detected signals into spatial and temporal variances in the ray-based likelihood. Atmospheric uncertainty is quantified in the analysis using an ensemble of possible atmospheric states which can be tuned using recently developed atmospheric statistics methods or obtained from numerical weather prediction systems. The impact of finite detection quality has been investigated and compared with the impact of varying degrees of uncertainty in the atmospheric state. An overview of the method as well as the localization confidence as a function of atmospheric uncertainty and detection quality will be presented.

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Poster /

Leveraging infrasound detected by stations of the IMS network for estimating the characteristics of shock waves generated by large bolides

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Theoretical models suggest that the infrasound signatures of bolides carry valuable information about their source, potentially revealing characteristics such as type and altitude of the shock. To

fully exploit infrasound for characterizing bolides, it is imperative to have ground truth and accurate atmospheric conditions. However, dynamic atmospheric changes occurring over minutes to hours can degrade the information carried by infrasonic waves, while unexpected propagation paths may lead to unanticipated signal detection or lack thereof. A notable example is the 23 July 2008 bolide over Tajikistan, detected at two infrasound stations of the CTBT IMS network, at distances of 1500-2100 km from the source. While propagation modeling using realistic atmospheric specifications predicted signal arrival at one station, the opposite was observed for the other station. This unexpected detection was attributed to acoustic energy trapped in a leaky stratospheric AtmoSOFAR duct, a phenomenon previously theorized but recently confirmed through high-altitude balloon-borne infrasound experiments. The primary mode of shock production in this event was a spherical blast generated by the main fragmentation episode. The efficacy of infrasound in characterizing such events will be explored further in this discussion.

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Sources and Scientific Applications /

Leveraging multi-station infrasound detections for characterization of high-altitude fireballs

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A rare class of meteoroids known as earthgrazers enter the atmosphere at shallow angles, with some returning to space after a brief hypersonic flight through the upper atmosphere. We present the detection and analysis of infrasound from a rare horizon-to-horizon earthgrazer event observed over northern Europe on September 22, 2020. The fireball generated ballistic shockwaves which were detected by three stations of the Royal Netherlands Meteorological Institute (KNMI) network. Despite the high-altitude trajectory, the pressure wave reached the ground at low frequencies detectable by infrasonic instruments. The infrasound signal exhibited a high trace velocity, indicative of near-vertical arrival angles, with most energy concentrated <~4 Hz. The modeled and observational data revealed that infrasound emanated from three distinct parts of the fireball trail. This finding marks a significant milestone, representing the first documented evidence of capturing ballistic shocks from multiple distinct parts of the trail of a high-altitude fireball using infrasound. Another notable aspect of this fireball was that it was detected despite its very high altitude (>90 km). This event reinforces the potential of infrasound as a tool for monitoring and detecting unconventional high-altitude sources, such as fireballs.

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Measurement Systems /

Infrasound Sensor Performance at Extreme Temperatures and Low Frequencies

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Earlier evaluations of infrasound sensor performance have shown that frequency response can be impacted by environmental conditions, including both temperature and barometric pressure, with calibrations performed in laboratory and field environments. These laboratory evaluations were limited to temperatures as cold as -20 C and from 0.1 to 10 Hz. Since then, investigations into frequency response issues observed with sensors deployed in field environments colder than -20 C have indicated that there may be issues at frequencies below 0.1 Hz. Subsequent laboratory evaluations have been performed to evaluate the change in frequency response for multiple infrasound sensor models at temperatures down to -36 C and over the 0.01 to 10 Hz frequency passband. These results further highlight the importance of characterizing sensor performance over the range of environmental conditions at which instrumentation is expected to operate.

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Poster /

Enhanced NDC-NG Capability for Nuclear Explosion Monitoring

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The Nigerian NDC has struggled with a lack of qualified personnel and inadequate training, especially in data analysis. However, better utilization of IMS data and to support complementary nuclear explosion monitoring has resulted from increased capacity building. This study aims to analyze SHI data to ascertain the events recorded between 2000 and 2024. The seismic, infrasound, and hydroacoustic waveform data were accessed through the Global Communication Infrastructure and the Secured Web portal. For the seismic data, the P and S phases were carefully picked and other associated hybrid phases like the Pn, Pg Lg Sg, etc., were identified using the Geotool software. The magnitudes, locations, azimuth and back azimuth, and depths of the selected events were determined. For hydroacoustic data, the data was processed using TDK PMCC and Geotool software to determine both T or H phases, and the respective sources of the signals were determined accordingly. The azimuths from the infrasound data were also determined to establish the sources of signals. The results are presented in this study. This research has demonstrated the improved capacity of NDC-NG towards meeting one of its significant roles: the capability for complementary monitoring of nuclear explosions using the IMS waveform data.

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Sources and Scientific Applications /

Infrasound signals likely to be excited by submarine volcanic activity around Tori-shima in the Izu-Bonin islands arc on 8th October 2023.

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Last autumn, small-scale events have occurred near Tori-shima, in the Izu-Bonin Islands arc, located about 600 km south of Tokyo. At least 14 T-phases were observed at seismic stations around Tori-shima between 19:00 and 21:30 UTC on 8th October 2023. These T-phases were estimated to have been caused by the events whose hypocenters were determined by the US Geological Survey to be near Sofu-gan, which is a rock reef and locates near Tori-shima. Since floating pumices were found near the epicenters later, it is thought that some kind of volcanic activity may have occurred under the sea.
After T-phases were observed, infrasonic signals were detected at I30JP. As a result of array analysis, these signals were estimated to have come from the direction of the events. Furthermore, as in the T-phase, infrasound signals were observed at intervals of several minutes, so it is considered that infrasound were excited by the events that was the source of the T-phases. In addition, the estimated arrival time of signals at I30JP based on the ray tracing is consistent with observed data. Thus, it is considered that infrasonic signals observed at I30JP are likely to be caused by a series of events near Tori-shima.

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Sources and Scientific Applications /

Infrasound detections of the OSIRIS-REx Sample Return Capsule re-entry

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On 24 September 2023, NASA's OSIRIS-REx mission achieved a significant milestone by successfully returning particles from a nearby asteroid to Earth via a Sample Return Capsule (SRC). The SRC generated shock waves as it entered the atmosphere, traversing California, Nevada and Utah before landing at the Utah Test and Training Range (UTTR). Since SRCs are well-characterized objects with known parameters, their re-entries can be leveraged towards studying meteor phenomena, characterizing high-altitude shock wave dynamics, improving entry and propagation models, and advancing global monitoring efforts. Under desirable conditions, SRCs generate infrasound which can be detected by microbarometers. We deployed ground-based and balloon-borne infrasound sensors in Nevada and Utah to capture the signals as a function of distance from the trajectory and from different parts of the trail. We will present signal characteristics at different stations, and how these might relate to SRC altitude and point(s) along the trajectory. These findings not only hold promise

for enhancing future observational campaigns on Earth but also offer valuable perspectives into the detection and characterization of shock wave signatures on extraterrestrial bodies with atmospheres, including Mars, Titan, and Venus.

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Poster /

Deployment of a portable low-cost infrasound array on Terceira Island, Azores, Portugal

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Two seismo-volcanic crises are ongoing on the Azores. A volcanic unrest on a fissural system begun on March 19, 2022, on a São Jorge Island. On June 24 seismicity increased in Santa Bárbara central volcano, on Terceira Island, followed by ground deformation. A portable four-element infrasound array (SJ1) was deployed on São Jorge Island in collaboration with the University of Florence. Learning from this experience, a six-element portable infrasound array (TER) was designed, built and deployed on Terceira Island, in April 2024.
TER is composed of differential sensors, five with a sensitivity of 800 mV/Pa (0.04-100 Hz) and one with a sensitivity of 25mv/Pa (0.1-100 Hz). The potential locations were selected mainly based on its distance from the volcano, the SNR, and GSM coverage. However, due to noise sources, terrain surface and land-permits, the array deployment was not located on none the planned sites.
The array is located 6 km apart from the volcano caldera, although without the ideal SNR. TER has a centred pentagonal geometry, with a maximum aperture of 105 m, positioning the less sensitive at the centre.
Background noise was evaluated, and efforts are being made to move the array to a less noisy site.

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Poster /

Analysis and identification of meteor signals detected by the IMS infrasound stations in South America

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Celestial objects from space have long aroused curiosity and fear worldwide. According to NASA, scientists estimate that approximately 48.5 tons of meteoric material fall to Earth daily, penetrating the atmosphere at supersonic speeds, far exceeding the speed of sound. These outer space objects, which can be fragments of comets and asteroids, are referred to as meteoroids. The infrasound stations of the International Monitoring System (IMS), a global network designed to detect nuclear explosions in compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT), contribute not only to monitoring clandestine atmospheric nuclear tests but also to studying other natural and anthropogenic events. One such application is the study of meteoroids entering the atmosphere at high speeds, which can generate infrasonic waves (f < 20 Hz). This work analyzes data from IMS infrasound stations located in South America to identify infrasonic events generated by meteors. A catalog for the period of 2018-2024 is presented. Confirmation of these events was conducted using data from the Center for Near-Earth Object Studies (CNEOS) and the Brazilian Meteor Observation Network (BRAMON). This study can also be useful for verifying the IMS detection threshold and providing an approach to understanding celestial events, their dynamics, and their impacts on Earth.

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Modelling and Network Processing /

Comparison of 2-D and 3-D finite-difference simulations for infrasound propagation in heterogeneous atmospheres

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Finite-difference methods are widely used to simulate infrasound propagation in the atmosphere. Flexibility of finite-difference scheme allows to implement highly heterogeneous media for sound propagation with complex source models. Full 3-D finite-difference methods have been utilized for local infrasound propagation with pronounced topography and showed that the 3-D nature of topography and weather conditions can affect infrasound propagation and waveforms significantly. In contrast, 2-D modeling has been preferred for regional and global propagation as full 3-D methods generally require enormous computational resources and time for simulations. In 2-D methods, 3-D features of medium variation are ignored or approximated by 2-D. However, it is not certain how accurate the 2-D approximation is for sound propagation in various conditions. In this study, we theoretically compare 2-D and 3-D finite-difference methods for infrasound propagation and evaluate the accuracy of 2-D approximation in various atmospheric conditions. The 2-D and 3-D comparison was performed using various methods (e.g., finite difference vs. PE method) for limited cases, but we use the exact same governing equation and high-order finite-difference scheme to exclude errors due to numerical methods. Our quantitative evaluation of the 2-D approximation will provide useful criteria to justify 2-D modeling for 3-D sound propagation.

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Sources and Scientific Applications /

Infrasound signatures from powerful rocket launches for space missions

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Rocket launches are a source of infrasound detectable at infrasound arrays in thousands of kilometers distance. Recorded signatures originate from the ignition, launch, supersonic movement, stage separation and reentry of rockets within the first about 100 kilometers of altitude in the atmosphere. We use IMS infrasound data to localize and characterize rocket launches all over the world.

During the last 20 years, an increasing number of annual space missions was conducted from various globally distributed space ports. These missions were mainly launched to inject satellites in Earth's orbit, but also for space station flights and the exploration of the Moon and other bodies in the solar system.
We investigate and present infrasound detections of interest, including NASA's Artemis 1 Moon mission using the Space Launch System in 2022, SpaceX's orbital flight tests of Starship in 2023 and 2024 and ESA's first launch of the new Ariane 6 rocket in 2024. Furthermore, we highlight a systematic analysis of infrasound recorded from multiple, regularly launched vehicles like Ariane 5, Falcon 9, and various Soyuz and Long March rocket types.

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Data Processing and Station Performance /

The use of IDC bulletins in assessing of Romanian infrasound stations performance to detect coherent infrasound sources at near-regional distance

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Two infrasound stations are deployed on the Romanian territory: IPLOR 4-element array of 0.6 km aperture, and BURARI 6-element array of 0.7 km aperture. Infrasound data are processed and analyzed on routinely basis at NIEP by using infrasound detection-oriented software (DTK-GPMCC and DTK-DIVA) packaged into NDC-in-a-Box. This study focuses on the high frequency signals (above 1 Hz) detected by the two arrays mainly from sources related to the intense military activity (bombardment and shelling) during Ukraine war.
In order to automatically associate these signals with LEB events provided by IDC/CTBTO, observed and expected values of backazimuths and arrival times for LEB events were compared. The expected arrival time of infrasonic signal was estimated by adding time of infrasound wave to propagate to arrays straight from source, with an average speed of 0.34 km/s, to origin time of the LEB event. Allowed deviations between observed and expected values were considered as ±10 degrees for backazimuth and ±10 minutes for arrival time. Approx. 30% of LEBs could be associated to infrasound detections. Almost 60% of associated events are ranging between 230 and 1000 km from arrays, whilst for 93% of these events backazimuth interval is between 10 and 120 degrees.

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Modelling and Network Processing /

Machine learning categorization of infrasound detections across the Central and Eastern European Infrasound Network

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The Central and Eastern European Infrasound Network (CEEIN) has been operational since 2019 as a collaboration of Czech, Austrian, Hungarian, Ukrainian and Romanian research institutes. For this study five infrasound arrays were selected from the CEEIN. Over 70,000 detections were processed by the Progressive Multi Channel Correlation method and classified manually afterwards using ground truth information. The classes include signals from thunderstorms, volcanic activity of Etna and sources associated with human activity – quarry blasts, powerplants as well as the war in Ukraine. A hybrid model that combines Convolutional Neural Networks and Random Forests is proposed for the automatic discrimination. To measure the performance of the model the f1 score was selected, also the confusion matrices are analyzed. The results over 0.9 f1 score show a great step in the direction of automatic signal classification in the scope of network processing.

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PTS Infrasound Technology Projects /

Improvements made and proposed with a focus on the upcoming recapitalization of I02AR

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The I02AR infrasound station located in Tierra del Fuego, Argentina celebrates 20 years since its certification. Over the years the I02AR has undergone two complete rebuilds and this year begins the first part of the third. The aim of this presentation is to show to the Infrasound community the implications of climatic and environmental conditions on engineering that have arisen throughout these years and how the ARN and PTS have worked and are working to correct them.

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Poster /

IMS INFRASOUND STATION 132KE,MONITORING,PERFORMANCE AND DETECTION IMPROVEMENT

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The infrasound station I32KE installed in 2002 at Karura in Kenya, was composed of seven array elements equipped with 18-meter wind noise reducing system (WRNS). Each WRNS is supported by four rosettes of twenty-four inlet ports combined with galvanized pipes, brass summing manifolds and resonance suppressors. Despite high data availability, this system experienced data quality problems affecting its monitoring capabilities. The challenges included blocked inlet ports, leaking junctions, faulty connections to the micro barometer's nozzles and deterioration due to old age. Based on data analysis by the local NDC as well as quality follow up by the CTBTO, IDC, helped in detecting data quality problems which triggered timely intervention in 2019.
This presentation work therefore aims to produce statistics on events from before and after the replace met of the galvanized WNRS with stainless steel. The data also makes comparison on the detection capabilities, Buffering and performance from the station for both the old and the new sensors.

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Poster /

Relationships Between Thunderstorms and Lightning Activity in Florida.

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The U.S. state of Florida has a warm subtropical climate with mild winters and long, hot and humid summers that are characterized by intense thunderstorm activity. As a result, Florida is considered one of the most lightning prone regions in the U.S.A, with an annual average lightning flash density of around 35 flashes/km2/yr. In this study we use the infrasound data from the IRIS Data Management Center (DMC)'s Infrasound Event Database and the lightning data from the World Wide Lightning Location Network (WWLLN) to characterize the thunderstorm activity in Florida, for the five year period, 2011 to 2015. We also use the complementary thunderstorm datasets from the NOAA National Severe Storms Laboratory and the climatological datasets from the Florida Climate Center for the same period to investigate the relationships between other key meteorological parameters such as wind, temperature and preciptation and the temporal and spatial distributions of lightning and thunderstorm activity in Florida.

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Sources and Scientific Applications /

Characterization of an algerian fireball using local infrasound and seismic signals

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For the First time in Algeria, a fireball was characterized for the first time in Algeria using 14 seismic stations from the Algerian digital seismic network and two newly installed infrasound stations (Network in progress). The event occurred on the night of May 7, 2023, in an area not far southwest of the Algerian capital. Infrasound signals were employed to determine the location of the fragmentation, as well as to estimate the energy, mass, and size of the fireball. Using the seismic data, the 2D trajectory was determined by plotting isochrones.

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Poster /

Seismoacoustic Signals from Quarry Blasts at Eastern Helwan, 2022.

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Although Seismometers are usually used for monitoring such these quarry blasts, a part of the explosion energy emits on atmosphere and make a clear remark for these surface explosions. A temporary infrasound array station with small aperture of 150 meter, was deployed in Helwan since May 2022. The array consisted of five infrasound sensors and one collocated seismometer.

In this study we addressed our infrasound acquisition system in Helwan. MB3d was compared with a inexpensive sensor manufactured in Japan (INF04). Several seismo-acoustic signals were detected in our array for a period of six months. Moreover, these impulsive signals were declared by applying a recursive Short term average / Long term average (STA/LTA) trigger algorithm to all sensors. The recorded events were compared by the Egyptian Seismic Bulletin records. In addition, the infrasound propagation models from the quarries location toward our infrasound array and the FK-analyses of

the events were investigated.
In conclusions, our infrasound system could be able to detect the near quarries in Eastern Helwan using recursive trigger algorithm. The FK-analyses and infrasound propagation models support the directions and the locations of the recorded quarries. For events involving higher frequencies, inexpensive sensors can be a convenient solution.

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Modelling and Network Processing /

Prediction of the Infrasound Transmission Loss Probabilities for New Station Deployment Using LSTM

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Infrasound propagation depends on the winds and temperature in the atmospheric column. These are highly variable, making it difficult to predict propagation conditions in the future based on those in the past. Recently, this problem has been addressed by studying the statistical properties of historical atmospheric profiles in order to generate statistical models for the signal propagation. Previous studies have focused on long-range propagation in the stratosphere. Here, we focus on shorter range propagation, restricted to the troposphere and use a machine learning model investigate the robustness of such an approach.
In this study a large number of historical WRF (Weather Research and Forecasting) atmospheric profiles between 2018 to 2024 were generated for March. Transmission losses (tlosses) were estimated from PE simulations for 1 to 4 Hz with a range of 100 km from the desired source. In addition, the atmospheric parameters for March 2018 to 2022 and the equivalent Probability Density Functions (PDFs) of tlosses were trained using Long Short-Term Memory (LSTM) algorithm.
In conclusion, the resulted trained models can be used to predict the hourly PDFs of tlosses for March 2023 and 2024. Furthermore, these models' usage can extend to different untrained source points with different atmospheric conditions.

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Poster /

Repeatedly detected ambient noise at I30JP

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In ITW2022, the Romanian NDC analyzed data at the Romanian infrasound stations by DTK-GPMCC software and presented results of coherent infrasound noise. Their found that signals from artificial sources such as refineries and power plants, as well as natural sources such as microbaroms, were regularly detected. They plotted the detected signals by color-coding the trace velocity, with the horizontal axis representing the predominant frequency and the vertical axis representing the direction of arrival, making it easier to grasp the difference between artificial and natural sources.
I wanted to know about ambient noise in I30JP as well, so I created a similar graph. A PMCC analysis was performed on 1/3 octave using I30JP data for one year in 2022. In I30JP, signals from microbaroms and artificial activity were repeatedly detected and concentrated in specific frequency bands and directions of arrival. In addition, despite the ocean stretching from the northeast to southwest of Japan, microbaroms were not detected from the southeast to south of I30JP. In I30JP, we will show what kind of signals are coming from which direction and introduce possible sound sources.

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Poster /

Infrasound Monitoring of volcanic activity Etna Volcano using IMS data in July 2024

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Etna Volcano increased its activity in July 2024, and this was monitored by the International Monitoring System (IMS) infrasound network. At NDC Iraq, we will present an analysis of data from Etna Volcano in Italy, using the IMS stations I48TN, I26DE, I42PT, and I11CV. This analysis will utilize the NDC-in-a-box tools and will focus on the events of July 2024. We used International Data Centre (IDC) products related to volcanic activity to locate and analyze the data using DTK-GPMCC and Geotool software.
In this work, we will check the events on July 7, 2024, July 15, 2024, and July 23, 2024, in the Etna Volcano area and correlate them with the LEB and REB Bulletins.

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Data Processing and Station Performance /

Enhancing Infrasound Monitoring in South America through Automated Algorithms

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In this study, we focus on recent advancements in infrasound research and the operational capabilities of regional networks in South America. Our work involves developing an innovative algorithm using the ObsPy library and custom Python routines to enhance the analysis of infrasound data from the International Monitoring System (IMS) network. By applying techniques similar to Progressive Multi-Channel Correlation (PMCC), the algorithm autonomously processes time-series data to identify consistent signals across various frequencies. It calculates key parameters such as backazimuth and signal characteristics, enabling reliable detection and characterization of infrasound events. Additionally, the algorithm evaluates detection parameters like signal-to-noise ratio and consistency, logging timestamps, key features, and graphical outputs for each event. It also identifies operational issues at specific infrasound stations, ensuring data integrity.

Our work aims to develop Chilean monitoring capabilities while expanding the analysis to the broader South American network, thus enhancing event detection in the Global South. A new agreement between the Chilean National Data Center (NDC) and the University of Concepción (UdeC) establishes UdeC as an Establishment of the NDC, thereby enhancing the NDC's infrasound monitoring capabilities. This partnership highlights the importance of our efforts to improve infrasound monitoring and data processing across South America.

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Poster /

Low Frequency Acoustic Signals Detection of a Mine Explosive Blast Occurrence in Bogoso, Ghana

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An explosion occurred on 20 January 2022 in a suburb of Bogoso, in the Western part of Ghana. The blast was as a result of a collision between a truck transporting mine explosive materials with a motorcycle. The incident produced a major explosion in the surrounding areas which was observed by many residence and destroyed lives and property devastating the township. As a result, the blast energy produced was propagated through the atmosphere with infrasound waves generated. This low-frequency waves generated were detected by pressure sensors of the infrasound network of the International Monitoring System (IMS). The infrasound signals from this explosion was propagated to range of ~325 km to be recorded at I17CI station of the IMS network.

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Poster /

Observed Infrasonic Signals of Auroral Electro Arcs Detections at I37NO Station in 2020

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In the polar latitudes regions, both the Northern and Southern Hemispheres of the Earth, one of the natural phenomena observed periodically is the occurrence of auroral displays in the sky. Low frequency signals are generated with the production of the auroral electrojet arcs in the atmosphere which are sensitive to microbarometer sensors of the infrasound array network when the wind direction favours their propagation for detection. Such event detection though non-treaty relevant, is vital for assessing the capability of the array network for the verification regime. In 2020, the observed infrasound signal detection from the auroral occurrences in the atmosphere over Northern Norway was studied for their propagation parameters. The frequency content of the infrasound signals associated with these auroral electrojet arcs was <0.1 Hz, typical of this source. They showed pulsating infrasound signals with trace velocities <1 km/s. The signals observed, generally showed azimuths indicative of a direct line of source overhead in the atmosphere.

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Poster /

Python Processing of an Infrasound mSeed File

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Infrasound is known as very low frequencies that humans cannot hear but can be picked up or retrieved by sensors. It can be used to detect and verify different processes and phenomena that may be going on in the environment. This work focuses on creating data processing methods using Python to evaluate mSeed files from commercial off the shelf systems, such as the Raspberry Shake & Boom. This analysis is completed through the usage of spectrograms visualizing Short-Term Fourier Transforms. The method begins by analyzing the waveform, then creating both low and high pass filters, adjusts DC bias by removing the near 0 Hz frequencies, and ends by generating a spectrogram with customizable features with an option to regenerate itself based off inputted arguments by the user, such as length of evaluation. This method of data processing will enable rapid infrasound data analysis through Python utilizing any commercial sensor.

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Sources and Scientific Applications /

Regional infrasound detections of the Osiris Rex capsule re-entry

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In a recent paper, Phil Blom et al. [JASA 155 (3), March 2024] developed
a method to predict regional infrasound originating from supersonic sources. These results were integrated into InfraGA, LANL's infrasound ray-tracing library. The September 2023 re-entry of the OSIRIS-Rex capsule presented an excellent opportunity to test these results against a known source. Three arrays were deployed at regional distances with locations determined by InfraGA. Additionally, data from the re-entry was gathered from several other existing arrays. In this talk we present a brief description of the mach cone ray-tracing prediction, along with beamformed results from the arrays.

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Poster /

Use of IMS Infrasound Stations for Earthquake Detection: Case Study of the February 6, 2023, Türkiye Earthquake.

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On February 6, 2023, a devastating earthquake occurred in a transcontinental area located between Europe and Asia, east of Nurdagi, in the Turkish province of Gaziantep, at an estimated depth of 24.1 kilometers. This earthquake caused damage to approximately 170,000 buildings. It is one of the largest earthquakes recorded in the region in over 100 years, with a magnitude of 7.8 Mw, resulting in a regrettable death toll of more than 59,000 fatalities and 107,213 injuries. This event marks a significant turning point in global seismological research and the field of earthquake-resistant engineering, following the reported ground accelerations during the event.
In terms of energy, this earthquake released an amount 500 times greater than the energy released by the Hiroshima bomb. This paper presents the results of the analysis of the available data from the IMS infrasound stations for the detection of this event, using DTK-PMCC.

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Measurement Systems /

Assessing the Effects on Response of Infrasound Sensors Deployed in Harsh Desert Environments

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We recently conducted a limited frequency response calibration of 43 Hyperion 3000 and 5000 series infrasound sensors. These sensors have been utilized in a number of temporary deployments in the

high desert of the Nevada National Security Site (NNSS), northwest of Las Vegas, Nevada, USA. The sensors were not installed in a manner consistent with an IMS station installation; rather these sensors were deployed on the surface, with porous hose wind filters, and in less-than-ideal locations. The sensors were produced as early as 2012. Their desert field deployments included exposure to high temperatures, and in some cases, exposure to flooding and rodent, insect, and spider infestation. Sensors utilizing "garden-hose" type inlets were opened and cleaned, and had their transducers visually inspected prior to testing. We evaluated their sensitivity and frequency response from 0.01 Hz through 10 Hz and present results of these evaluations.

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Modelling and Network Processing /

Signal arrival databases for Ground Truth infrasound events

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Seismo-acoustic waveform model development serves to improve both precision and accuracy in event characterization estimates through the application of more robust travel time models for infrasound signal propagation. Development requires the ability to validate models with real data against meaningful metrics. Comparisons across a suite of ground truth (GT) events provides the ability to evaluate model performance across a broad spectrum in both space and time. Current infrasound GT data is limited for several reasons, including but not limited to, a lack of acoustic signals from naturally occurring events and a lack of broad global network coverage. Data is particularly limited for regional networks where sensors are located between 100-600 km from a source of interest. Numerous boutique experiments have historically been conducted by researchers with varying degrees of openly available data; however, none of these datasets exist in a singular place. Here, we present a curated dataset of 119 GT infrasound events suitable for algorithm evaluation. Our database identifies signal arrivals and characteristics for each of the GT events, capturing all available regional signal arrivals in an open-source repository.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

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Measurement Systems /

Wind Noise Reduction System Impacts on Sensor Cavity Temperature

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Earlier studies into the impacts of environmental variables on infrasound sensors have demonstrated that the frequency response can be susceptible to temperature changes. Infrasound stations are typically configured to prioritize thermal stability, either by installation in an underground vault or the use of an insulated enclosure, and the air temperature around the sensor can be monitored. However, one challenge for infrasound sensors is that they must be ducted to the outside air, typically via a Wind Noise Reduction System (WNRS), potentially exposing the transducer to different temperatures than the vault interior. We have completed a long-term study monitoring the temperatures of the outside air, vault interior air, and sensor transducer cavity temperature using different styles of WNRS. The results of this study comparing the variability of temperature measurements around the sensor are shown here.

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Sources and Scientific Applications /

Characterization of the 2022 South Atlantic fireball using IMS infrasound recordings

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On 7 February 2022, a large meteoroid entered the Earth's atmosphere around 500km off the coast of Namibia and South Africa. NASA's Center for Near Earth Object Studies (CNEOS) lists the event as a fireball with an impact energy of 7kt TNT equivalent. This energy estimate is about 60 times lower than for the 2013 Chelyabinsk fireball (440kt, CNEOS). For Chelyabinsk, IMS infrasound data analysis revealed that it was the strongest event ever recorded by the IMS infrasound network at that time, when 20 out of 42 existing stations detected it. The second-strongest event of this type in the IMS era was the Bering Sea bolide in December 2018 (49kt, CNEOS), with a comparable portion of infrasound stations detecting it (25 out of 51).
For the 2022 South Atlantic fireball, we identify signatures at 25 IMS infrasound stations (out of 53). We further characterize the event using the observations and propagation models, and assess the detection capability to explain the large number of detecting stations. We also use the IMS data for estimating an energy release, and revisit previous strong events such as Chelyabinsk using state-of-the-art array processing methods and enhanced configurations. These comprise, for instance, the Multi-Channel Maximum-Likelihood (MCML).

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Sources and Scientific Applications /

Can we use infrasound data from bolides to constrain global celerity models?

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Global celerity and back azimuth deviation models are used within infrasound detection association and event location estimation algorithms. A previous study, InfGEM (Infrasound Global Empirical Models), used a database of ground-truth mine blasts and chemical explosions to derive a celerity-range model, using the arrival time of the maximum peak-to-trough amplitude to calculate celerity for each detection. The majority of arrivals used to build the InfGEM celerity-range model are at station to event ranges of less than 2000 km, with only a few detections out to 6000 km. To further constrain celerity models at ranges greater than 2000 km we assess the feasibility of adding bolide data into InfGEM. A bolide is a meteor that explodes in the atmosphere producing an infrasound signal that is often detectable at long ranges. We analyse signals generated by 10 well characterised bolides that were recorded on International Monitoring System (IMS) stations with a maximum station to event range of at least 5000 km. We compare celerities of bolide signals with those that constrain the InfGEM model, to assess the potential of bolide detections to provide celerity range information for distances greater than 2000 km.

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Modelling and Network Processing /

Infrasound Arrivals in the International Data Centre Bulletins: Reviewing 14 Years of Results and Celerity-Range Model Changes

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Following recent analysis of infrasound signals generated by the 2018-Dec-18 Bering Sea bolide, it became apparent that the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO), International Data Centre (IDC), Reviewed Event Bulletin (REB) observed celerity for the closest station (~1200 km distance) was outside the bounds of the Brachet et al. (2010) model. Using the signal arrival time, event origin time and the time residual, the model celerity is calculated as ~310 m/s, rather than the Brachet et al., (2010) model celerity of 295 m/s at this distance. Analysis of the model celerity through time (2010-2024) of all detections associated with infrasound-only and seismo-acoustic events in the IDC bulletins, identifies celerity model changes in May-2017 and again in August-2020, coinciding with the deployment of major software updates at the IDC. In this study we investigate the impact of these celerity model changes on detection distributions and event locations.

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Poster /

Infrasound monitoring in Kenya: Potential applications for Scientific and Civil application

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Kenya is host to infrasound Station IS32 in Kenya. Infrasonic waves can be used for various purposes which include mining, control of deforestation, documentation of climate change issues such as heavy rains, high temperatures, and even human-wildlife conflict issues. This presentation gives results of the use of infrasound technology for these varied applications.

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Poster /

Identifying infrasound sources using nearby and co-located infrasound and seismic sensors

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An eight-station seismic network and a four-element infrasound array detected an uncategorized seismo-acoustic event in Sete Lagoas, a city in southeastern Brazil. The area contains quarries that frequently conduct unannounced explosions to extract limestone. The network and array were deployed to distinguish signals from these explosions and natural events, as tectonic activity occurs both near and within the mine caves, likely induced by stress release from the extensive material removal over time. Unfortunately, neither tectonic events nor explosions were recorded; instead, an unusual event was detected, where the wavefront arrived simultaneously at both the co-located infrasound and seismic sensors, with waveforms that were very similar and difficult to interpret. The event was reported by many residents of Sete Lagoas as a ground vibration, sometimes followed by a boom or bang. However, by analyzing the signal characteristics, it was possible to identify an acoustic signal, based on measurements of the wavefront arrival times, frequency content, and speed. The event was located near Sete Lagoas City and was classified as an acoustic event, possibly generated by a bolide explosion in the atmosphere. In this study, we analyze different potential infrasound sources to accurately classify the event.

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Modelling and Network Processing /

Studying infrasound propagation in the middle atmosphere with ICON and UA-ICON: comparison with the IFS and ground-based remote sensing

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Infrasound signals are used to monitor various anthropogenic and natural sources. To determine accurate source locations and energy, an accurate model of wind and temperature from the surface up to the lower thermosphere is necessary, hence operational NWP products are of great importance for routine infrasound monitoring activities. However, many of these models focus on tropospheric conditions, and the middle atmosphere (MA), where the relevant infrasound waveguides for long-range propagation are found, is not well represented. UA-ICON is an upper atmosphere version of the ICON model that provides modelled atmospheric parameters up to 150 km.
First, to assess ICON and IFS operational analysis products, comparisons to lidar observations are made. The main differences between both products were analysed with respect to winds and temperatures in the MA, and hence with respect to the infrasound guide prediction. Second, UA-ICON simulations were performed to demonstrate the increased wave activity above ~30 km with UA-ICON. The added value of UA-ICON with respect to ICON and IFS products for infrasound propagation simulations is discussed. The comparisons between the remote sensing instrumental results and the models will be presented, as well as comparisons between modelled and measured infrasound propagation for known events such as Hukkakero.

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Modelling and Network Processing /

Deep learning surrogate model for near real-time estimation of ground-level infrasound transmission losses

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Accurate modeling of infrasound transmission losses (TLs) is essential to assess the performance of the global International Monitoring System infrasound network. Among existing propagation modeling tools, parabolic equation method (PE) enables TLs to be finely modeled, but its computational cost does not allow exploration of a large parameter space for operational monitoring applications.

To reduce computation times, Brissaud et al. (2022) explored the potential of Convolutional Neural Networks (CNN) trained on a large set of regionally simulated wind fields (< 1000 km from the source) to predict TLs with negligible computation times compared to PE simulations. However, this emulator shows difficulties in upwind conditions, especially at high frequencies, and causal issues with winds at large distances from the source affecting ground TLs close to the source.

In this study, we have developed a Recurrent Convolutional Neural Network (RCNN) designed to minimize prediction errors while predicting TLs from globally (< 4000 km) simulated combined temperature and wind fields. Our approach enhances the previously proposed one by implementing key optimizations that improve the overall performances. The implemented model predicts TLs with an average error of 9 dB in the whole frequency band (0.1 – 1.6 Hz) and explored realistic range-dependent atmospheric scenarios

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Measurement Systems /

Infrasound uncertainty propagation: ensuring traceability from the laboratory to the field

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Confidence in the quality of infrasound measurements is at the heart of the operational requirements linked to the detection and assessment of geophysical and industrial events. The entire measurement process, from laboratory calibration to the field, must be considered to estimate the confidence level of the measurement through the associated uncertainty. As part of the European Infra-AUV (metrology for low-frequency sound and vibration) project, a field calibration campaign was performed to complete the calibration chain to the sensors in the field. This paper presents a methodology to obtain traceable measurements of the infrasound wave parameters, taking into account the entire calibration traceability chain and other uncertainty sources arising from a thorough analysis of the measurement process. We present an in-situ calibration method of infrasound sensors to be used in conjunction with the Gabrielson on-site calibration to provide field traceability of measurements under varying environmental conditions. In the context of this application, the resulting uncertainties in the back azimuth, between 0.05 and 7°, and trace velocity between 0.2 and 60 m/s (from high to low frequency), were predominantly due to the Gabrielson phase uncertainty. The amplitude uncertainty of approximately 0.2 dB also had significant contributions from the temperature and pressure susceptibilities.

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Data Processing and Station Performance /

The Multi-Channel Maximum-Likelihood (MCML) method: extension to multisource estimation and evaluation

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We present a novel approach to the detection and parameter estimation of infrasonic signals: the Multi-Channel Maximum-Likelihood (MCML) method [https://doi.org/10.1093/gji/ggac377]. MCML is based on the likelihood function derived from a multi-sensor stochastic model expressed in different frequency bands. Using the likelihood function, we determine, for the detection problem, the Generalized Likelihood Ratio (GLR) associated to the p-value as a threshold and, for the estimation of the slowness vector, the Maximum Likelihood Estimation (MLE). Statistical evaluation on synthetic dataset shows that MCML outperforms the state-of-the-art multi-channel correlation detector algorithms like the Progressive Multi-Channel Correlation (PMCC) in terms of detection probability and false alarm rate in poor signal-to-noise ratio scenarios. MCML is applied on historical data from the International Monitoring System (IMS). We show how MCML reprocessing results overall improve the station detection capability and the characterization of the coherent background noise. A mathematical extension of MCML is implemented in order to detect overlapping coherent signals in the same time frequency domain. This extension is based on a cost-effective iterative signal deflation. This approach is evaluated various scenarios varying signal-to-noise ratio (SNR), frequency bands and array geometry.

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Modelling and Network Processing /

Construction of statistical models for infrasonic propagation: application to the detection capability of the IMS network.

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The detection capability of the International Monitoring System (IMS) deployed to monitor compliance with the Comprehensive Nuclear-Test ban Treaty (CTBT) is highly variable in space and time. Previous studies estimated the source energy from remote observations using empirical yield-scaling relations. However, these relations simplified the complexities of infrasound propagation as the wind correction applied does not account for an accurate description of the middle atmosphere along the propagation path. In order to reduce the variance in the calculated transmission loss, massive frequency and range-dependent full-wave propagation simulations are carried out, exploring a

wide range of realistic atmospheric scenarios. A cost-effective approach is proposed to estimate the transmission losses at distances up to 4,000 km along with uncertainties derived from multiple gravity wave realizations. Transmission loss statistics are combined with an explosive source model and noise statistics to quantify the 90% probability detection threshold of the IMS network. In the context of the future verification of the CTBT, this approach helps advance the development of network performance simulations in higher resolution and the evaluation of middle atmospheric models at a global scale with limited computational resources.

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Poster /

Design and assembly of a low-cost experimental infrasound array for seismo-volcanic monitoring

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A seismo-volcanic crisis on Terceira Island led us to design and build a mobile low-cost experimental array, based on our previous experience of a successful collaborative deployment of an infrasound array from the University of Florence (UNIFI) on São Jorge Island, in April 2022.
We present the details of the design, the hardware and the assembly of a 6-element low-cost experimental array, deployed in April 2024 and designated as TER. This includes the data acquisition, which comprises the digitizer, the 4G (GSM) router, the signal conditioning circuit and their respective interconnectivity, the 6 boxes with differential pressure sensors, and an innovative mechanical Wind Noise Reduction System (WNRS). The communication between the sensors and the data acquisition box is assured by six 100-meter-long protected electrical cables. The energy for the array is supplied by a system of batteries coupled with solar panels.
The deployment took two working days, including site clearance, testing and adjustments in a densely forested area.

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Sources and Scientific Applications /

Estimating Crustal Velocity Structure in Alaska from Acoustic-to-Seismic Coupling from the 2022 Hunga, Tonga Eruption

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The 2022 climactic eruption of the Hunga volcano in the Kingdom of Tonga generated broadband acoustic waves observed over 10,000 kilometers away on pressure and seismic sensors in Alaska. The arrival of high-amplitude acoustic energy at a regional network of colocated sensors provides a unique opportunity to examine acoustic-to-seismic coupling and use these observations to estimate crustal elastic parameters. We compute coherence between pressure and vertical seismic channels and identify three bands of strong coupling centered on 1.0, 0.03, and 0.007 Hz. We exploit the fact that coupling ratios in these bands are sensitive to bulk elastic parameters to depths of 0.03, 1.7, and 7.2 kilometers to estimate shear-wave velocities. Our results generally agree with existing velocity models for Alaska, exhibiting the remarkable ability of an acoustic wave to probe crustal depths of over 7 kilometers. We compare results at two stations to estimates obtained using the 2013 Chelyabinsk bolide as a source and obtain velocities to within a percent, indicating estimates are robust. We note that coupling on horizontal components is more complex and often disagrees with theory.
This work was supported by the Nuclear Arms Control Technology (NACT) Program at Defense Threat Reduction Agency (DTRA). Cleared for Release.

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Modelling and Network Processing /

Infrasound signals generated by production blasts in a nearby quarry

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The infrasound array ISCO was installed 2021 on the grounds of the Conrad-Observatory in Austria. Since 2022, a large number of signals caused by production blasting in a nearby quarry have been recorded and analysed. The aim of this study is to reveal source and Green's function of the observed signals. We start from the hypothesis that the interaction of the rock masses with the atmosphere is the source. Photogrammetric models provide quantitative data for this study. Videos qualitatively convey the entire blasting process. Using numerical modelling, we determine the temporal change in the volume of the rock masses from detonation to final deposition.

The dominant wavelength of the observed infrasound signal is ~500 m, which is well above the dimensions of the blast site. We therefore consider the temporal course of the entire process as a 1D-process. We test source functions based on the direct effect of the time-delayed detonations. The evaluationcriteria of the respective source function is the shape of the Green's function. The source function based on the pulsating sphere model is the one that produces a physically interpretable Green's function. The convolution of these source and Green's functions describes the shape of the signal very well.

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Data Processing and Station Performance /

Towards Improving Infrasound Station Data Availability with State-of-Health Encoded Feature Clustering

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Ensuring IMS station data availability is critically important to the mission of the Comprehensive Nuclear Test-Ban-Treaty Preparatory Commission Organization. Monitoring a wide range of state-of-health (SOH) metrics in the power system of an array can help maximize station uptime. The Wilson Alaska Technical Center of the University of Alaska Fairbanks is continuously working on techniques to improve station performance monitoring. In this research, we present a technique that leverages our growing data set of SOH metrics and machine learning. Using an autoencoder, we compress daily SOH time series segments into lower dimensional encoded features, which we then cluster into groups representing physical states of the system. Additionally with this technique, we set thresholds on the autoencoder's ability to reconstruct the original data, so that segments that are not reconstructed well represent data abnormalities. We use this technique operationally at the I52GB infrasound array, where technicians are notified daily of the current state of a component of the power system. Improving this technique to incorporate multiple metrics at once can further improve monitoring and ideally limit station downtime.

This work was supported by the Nuclear Arms Control Technology (NACT) Program at Defense Threat Reduction Agency (DTRA). Cleared for release.

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Measurement Systems /

Large-chamber primary calibration for microbarometers

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In previous work, the National Center for Physical Acoustics at the University of Mississippi designed and built a large chamber for secondary (referenced) calibration of microbarometers. Sandia National Laboratories (SNL) then refined and implemented this chamber at their Facility for Acceptance, Calibration, and Testing (FACT) site. This large (1400 L) steel chamber incorporates two moving coil loudspeakers capable of operating in receive and transmit mode, and in more recent work, the Penn State University (PSU) and SNL used these loudspeakers to develop and implement a reciprocity-based primary (non-referenced) calibration technique for the chamber. While this technique has been shown to have suitable accuracy and uncertainty above 0.05 Hz, uncertainty increases rapidly below this frequency due to reduced loudspeaker response and increasing noise within the

chamber. Due to this, the authors are investigating additional calibration techniques that may be applied in the lower band (0.01 to 0.05 Hz) to enable primary calibration over the full band of interest (0.01 to 10.0 Hz). This talk will discuss the challenges of the reciprocity method in the lower band, and provide an early look at additional primary calibration techniques that may find utility in the chamber.

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Modelling and Network Processing /

Learning Long-Range Infrasound Propagation Using Neural Operators

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Recent advances in machine learning have shown that neural networks can approximate operators through specialized architectures known as neural operators. In this work, we investigate the use of Fourier Neural Operators (FNOs) to model the physics of infrasound propagation in randomly layered media, mapping sound speed fields to acoustic waveforms. This method is evaluated by predicting the scattering of both broadband and narrowband acoustic wave packets by stochastic Gravity Wave (GW) fields, which are known to significantly influences atmospheric infrasound variability. We compute GW fields using a stochastic multiwave series that captures the vertical wavenumber power spectral density and introduces intermittency. Inspired by reduced-order modeling, we propose a variant of FNOs that learns the optimal number of modes for representing the integral kernel in the Fourier layers. These modes enable the FNOs to accurately capture the complex interactions between incoming infrasound and vertically distributed small-scale structures in the sound speed profile. When applied to the inverse problem of estimating GW fields from acoustic waveforms, this approach proves to be orders of magnitude more efficient compared to traditional finite-difference solvers.

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Poster /

Designs and performances of Wind Noise Reduction Systems and Vault Solutions for infrasound stations

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Enviroearth has been manufacturing standardized Wind Noise Reduction System (WNRS) and vault solutions which are able meet all requirements and configuration for each of the infrasound stations

topology of the IMS Network, thanks to continuous improvements to their designs and development of new features. This poster aims to present the wide range of WNRS and vaults Enviroearth can propose, resulting of the long-term collaboration with CTBTO, including a focus on their key characteristics and performances.

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Measurement Systems /

Is calibration really worth the effort?

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The calibration of IMS infrasound sensors has been the subject of intense research in recent years, but are the benefits really worth all the effort? From an accuracy perspective alone, it is difficult to argue the case for calibration. However, the question is intentionally provocative, as the rationale for calibration is not only about accuracy. For traceable calibration, the unbroken link with a primary realisation of the measurement quantity demonstrates that IMS data, and the field parameters derived from it, represents something physically meaningful. This principle is vital in all areas of science and technology, trade and everyday life where measurements are important. It brings measurement data within the globally recognised SI system, effectively eliminating concerns about transparency and impartiality, and enabling confidence and trustworthiness in the data to be quantified. In practice, this translates into confidence in the decisions derived from that data, whether that relates to fault diagnosis, the overall operational status of a monitoring station, or evidence of a detection. In the overall remit of the IMS, it is these decisions that ultimately matter, and without reliable data these decisions will always include an element of doubt and be open to challenge.

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Sources and Scientific Applications /

IMS-based probing of the polar cap stratosphere: regime identification, altitude sensitivities, and contributions from different stations

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There is evidence from previous works that global ambient noise infrasound data recorded on by the IMS station network are highly sensitive to the stratospheric polar vortex and its regimes.

Vorobeva et al. (2024) used a data-driven approach to map between microbarom-band array signal processing output from the three northernmost IMS infrasound stations and the ERA5 re-analysis polar cap mean eastward wind at around 50 km altitude. This average can be seen as a proxy for the polar stratospheric circulation regime.

The current work extends this in several ways. We use the same database but include a greater number of stations. The data are also fed into a data clustering algorithm, and we explore to what extent this relates to the stratospheric circulation regimes represented in ERA5 re-analysis model data. Moreover, we assess for what stratospheric altitudes and for what IMS station combinations that we can provide the best data-driven mapping from our data to the average polar-cap eastward wind.

Our study is motivated by a long-term ambition in our research community to exploit global infrasound datasets to enhance the wind representation in high-top atmospheric models. This can have a significant impact on long-term weather forecasting and subseasonal-to-seasonal prediction.

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Sources and Scientific Applications /

Investigating the subsurface using earthquake-generated infrasound

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The deployment of ground-based seismic or infrasound instruments can be complex and costly in remote regions on Earth, or in harsh environments like the surface of Venus. Recent studies have demonstrated that as an alternative, balloon platforms can be used to monitor seismic activity from the atmosphere, at a comparably low operational cost. Such balloons carry pressure sensors and can record infrasound waves resulting from the coupling of seismic waves into the atmosphere. The analysis of these signals represents an enticing alternative to traditional ground-based seismology for seismic source characterization and subsurface exploration.

Seismic infrasound signals show similar dispersion properties as surface waves recorded at the ground, enabling the use of classical inversion techniques to retrieve source and subsurface properties. However, it remains unclear how acoustic and instrumental noise, path effects, and the lack of polarity information translate into posterior distributions of source and subsurface parameters.

In this contribution, we explore different inversion scenarios based on the characteristics of available Earth observations. We propose a Bayesian Markov chain Monte Carlo inversion method to assess the sensitivity of inversion results to the prior knowledge of the subsurface, the data quality, the number of balloons, and the types of acoustic arrivals.

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Poster /

Developing a Reliable Infrasound Early Warning System for Indonesia: Integrating Scattering Methods and Seismic Data

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Indonesia, particularly prone to natural disasters like volcanic eruptions, tsunamis, landslide and earthquakes, requires a reliable early warning system.

This study introduces a new approach to develop an Infrasound Early Warning System (IEWS) for Indonesia by utilizing the scattering method and highlighting the essential need to have operational infrasound stations in Indonesia.

In 2004, with the support of DASE (French CEA), BMKG established an experimental infrasound station in Palangkaraya, Kalimantan. Unfortunately, this station is no longer operational, necessitating reliance on IMS - infrasound stations in neighboring countries, such as I06AU, to gather data and detect local events in real time.

This study integrates infrasound data with seismic data to improve the detection of low-frequency signals associated with events such as volcanic eruptions and earthquakes. Furthermore, it optimizes the strategic placement of infrasound stations in Indonesia; to enhance signal capture and minimize noise interference, providing comprehensive recommendations for station design and equipment.

In conclusion, this paper highlights the essential need to establish infrasound stations in Indonesia to improve monitoring capabilities.
The development of an early warning system that utilizes the scattering method and integrates infrasound and seismic data provides a strong solution for improving disaster preparedness and response efforts.

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Poster /

A new method for regional infrasound events auto-association and scanner

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This paper proposes an automatic correlation and scanning method for regional infrasound events. The correlation rules of infrasound networks in different regions and the effective monitoring areas of specific infrasound networks are determined. The multi-features including signal amplitude, frequency, correlation coefficient travel time and signal azimuth interval of different infrasound stations in the designated area are established . For all automatically detection signals, firstly match

the signal characteristics to screen the infrasound signals from the selected area. Then the target area is grid processed, by match the travel time and azimuth of each grid point, signal are evaluated to screen out the grid point with the highest matching degree together with the associated signal, then station association is realized. The test is conducted by using the historical infrasound events of the International Data Center, and the method can efficiently associate the infrasound stations within 10 ° 10 ° area and rapidly scanning out the events. When the number of reference events in the target area is more than 5, an effective infrasound signal feature model in this region can be established, and automatic association and rough location of infrasonic event under small sample conditions can be realized.

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Measurement Systems /

Establishing traceability for Infrasound: Calibration Innovations and Inter-Laboratory Comparisons from the INFRA-AUV Project

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For any physical measurement to be meaningful, it must ultimately be traceable to an absolute realization of the parameter, or primary standard. Waveform measurements are no exception , in particular the infrasound. However, until recently, no primary standards existed for infrasound at the frequencies of interest to the IMS. The INFRA-AUV project aimed to develop both primary and secondary calibration methods to address this need. One of the critical final stages of the project involves ensuring the validity of the calibration results provided by the various developed systems. For this purpose, two comparisons were organized in the infrasound field. During this exercise, microphones and barometric pressure sensors were circulated for measurements. This presentation illustrates the measurements from the four participants, describes their calibration methods, and provides an analysis of the degree of equivalence between laboratories.

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Measurement Systems /

Exploiting the outcomes of recent research in metrology for the benefit of the IMS.

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The EURAMET Infra-AUV project ended in Dec-2023 and made significant progress on laboratory-based metrology for the calibration and traceability of seismic and infrasound sensors, and conducted several field studies providing new insights for on-site calibration. These advances in metrology are now ready to be exploited for maximum advantage at CTBTO. Perhaps the most significant of the recent developments is the provision of measurement traceability for infrasound across the whole IMS range of frequencies, allowing CTBTO to take up the new calibration offerings into the existing procedures. The new calibration capabilities now allow measurement uncertainty to be systematically assessed and propagated from the laboratory primary standards to the field sensors. This enables the working tolerances and accuracy assumptions specified in documentation describing the operation of stations to be verified. The now well-established process for on-site calibration of infrasound sensors using a reference senor can also be reviewed in the light of the recent research, especially in terms of added value that can be extracted from the rich source of calibration data, which can potentially improve confidence in the operation of the station on an ongoing basis.

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Modelling and Network Processing /

A Seiscomp pipeline for seismo-acoustic events

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The department of Seismology and Acoustics (RDSA) at the Royal Netherlands Meteorological Institute (KNMI) monitors seismic and acoustic activity in the Netherlands with a dense network of seismometers and infrasound sensors. A important motivation for measuring infrasound in the Netherlands is to discriminate between vibrations originating from the solid earth, e.g. earthquakes, and from the atmosphere, e.g. sonic booms and explosions. This information is used to inform the general public.

KNMI's infrasound network consist of multiple array stations of various apertures. The waveform data of these stations are freely available, both through FDSN webservices and the Seedlink protocol. The arrays allow to (1) discriminate between coherent sound and incoherent noise and (2) determine the angle-of-incidence of the coherent sound waves. Localisation of acoustic events is possible by combing time-of-detection and the angle-of-incidence.

In this presentation we present a recent development to develop an acoustic pipeline in Seiscomp for the automatic processing and localisation of acoustic events. The acoustic pipeline is running in parallel to existing seismic pipelines in AWS. We discuss the design of the pipeline, which consists of multiple Seiscomp modules, including automatic array processing. We present our first experiences with the pipeline and real-data examples.

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Opening Ceremony /

Opening Ceremony

Speakers:
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IMS updates /

The International Monitoring System Infrasound Network: current status and existing challenges.

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The Comprehensive Nuclear-Test-Ban-Treaty (CTBT) International Monitoring System (IMS) infrasound network consists of 60 facilities distributed worldwide. In approximately 25 years, 88% of the network was build and certified, highlighting its relevance both in nuclear test monitoring and in civil and scientific applications.
The Provisional Technical Secretariat (PTS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is currently dealing with two major challenges: bringing to completion the IMS infrasound network and sustaining the existing infrasound facilities. Both challenges entail the use of the most appropriate instrumentation, as well as technical and engineering solutions that are capable of ensuring long-term robustness and stability of performance of the stations. These activities should also consider compliance with the minimum requirements for the IMS infrasound facilities and the continuously evolving environmental conditions. The presentation will provide an overview of the status of the IMS infrasound network and of the recent activities and engineering projects focused on addressing the above-mentioned challenges.

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IMS updates /

Quality assurance for IMS measurements: Insights from the 2023 Science and Technology Conference

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Since 2011, the PTS for the CTBTO has collaborated with the global community to establish a robust Quality Assurance (QA) framework for IMS measurements, with special focus on infrasound technology. These efforts have resulted in notable progress with setting standards and refining calibration methodologies, as evidenced by discussions and presentations provided during the CTBTO Science and Technology Conference in 2023 (SnT2023).
The outcomes from SnT2023 will be summarized, highlighting the potential for leveraging existing national network best practices and recent advancements, including IMS seismic facilities, with the goal of ensuring a broad quality spectrum for IMS seismoacoustic measurements. In addition, the advantages of increased collaboration with the metrology community will be emphasized. Key benefits of the robust QA framework include a) broader adoption of measurement traceability, b) global acceptance of calibration capabilities, c) improved comprehension of uncertainty in measured parameters, such as amplitude and phase responses, d) better assessment of sensor susceptibility to environmental and installation factors, and e) enhanced interoperability through standardized equipment specifications and operating procedures.
Such benefits would enhance all areas of the IMS seismoacoustic network operations, from equipment specification and type approval process to on-site calibration.

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SSI hardware recent developments

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There have been recent developments in the SSI software, including its operability on the Linux Rocky 8 Operating System, and this has been paired with the need for adopting a new generation of computers. These developments have been dictated both by the progressive obsolescence of the existing computer models installed at the IMS facilities and by the limitations in performance derived from the use of old operating systems that are not capable of supporting the newest SSI version.
The deployment of new computers at International Monitoring System facilities is subject to a full hardware/software Verification and Validation (V&V) testing. In this framework, the next-generation computers V&V process was coordinated and conducted by the Seismic and Infrasound Team of the IMS Engineering and Development (ED) Section in collaboration with the SSI software Contractors. The thorough testing, in line with the development and consolidation of robust Quality Assurance processes, led to the validation of five (5) ruggedized low-power DC Stealth computers (LPC-845, LPC-870, LPC-915, LPC-960 and LPC-965). An overview on the most recent developments of SSI and of the testing of Stealth computers will be provided.

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