2007 INFRASOUND TECHNOLOGY WORKSHOP

PROGRAM & ABSTRACTS

13 – 16 November 2007
Tokyo, Japan

Japan Weather Association
and
Center for the Promotion of Disarmament and Non-Proliferation
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2007 INFRASOUND TECHNOLOGY WORKSHOP
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Organized by:

Japan Weather Association  Center for the Promotion of
Disarmament and Non-Proliferation

With the Support of:

Ministry of Foreign Affairs Japan  Provisional Technical Secretariat
CTBTO/PTS/IMS

IS30 H1, Isumi
** Program **

** Tuesday, 13 November 2007 **

09:00–10:00  Registration of participants at the Japan Weather Association (JWA)

OPENING SESSION

10:00–10:10  Welcoming speech by H.E. Ambassador Takaya SUTO, Director of the Center for the Promotion of Disarmament and Non-Proliferation, Japan Institute of International Affairs

10:10–10:20  Opening remarks by CTBTO representative

10:20–10:45  Coffee break

SESSION I:  IMS Network and IDC Processing

Chairs: Paola Campus & Nicolas Brachet

Campus P. and the IMS/ICG/AM Unit Team

11:10–11:35  “Common problems of the field installations faced at the IMS infrasound stations”
Stefanova S.

11:35–12:00  “Smooth Introduction of Infrasound Data into the IDC Reviewed Event Bulletin
Part I: Procedure and recent Developments”
Nicolas Brachet, Abdou Salam Ndiath,
Misrak Fisseha, Ali Kasmi, Mehves Feyza Ocal,
Kirill Sitnikov, Gadi Turyomurugyendo, John Coyne

12:00–12:25  “Smooth Introduction of Infrasound Data into the IDC Reviewed Event Bulletin
Part II: Analysis and Results”
Mehves Feyza Ocal, Abdou Salam Ndiath,
Misrak Fisseha, Ali Kasmi, Kirill Sitnikov,
Gadi Turyomurugyendo, Nicolas Brachet
and John Coyne

12:25–12:50  “PTS Experimental Infrasound Array”
John Coyne, Nicolas Brachet, Paola Campus,
Pavel Martysevich
12:50–13:00  Administrative Remarks

13:00–14:30  Lunch hosted by CPDNP

SESSION II:  Infrasound Research at NDC’s and Research Institutes: experiments and methodologies
Chairs:  David Brown & Curt Szuberla

14:30–14:55  “Optimum array design for the detection of distant atmospheric explosions influence of the spatial correlation of infrasonic signals”
  Douglas R. Christie

14:55–15:20  “The automatic infrasound processing system at Geoscience Australia”
  David Brown

15:20–15:45  “Recent infrasound research at the Wilson Infrasound Observatories.”
  Curt A. L. Szuberla, Charles R. Wilson, John V. Olson, Kenneth M. Arnoult and Joseph R. Galbraith

15:45–16:10  coffee break

16:10–16:35  “Listen to the sounds of the Antarctic atmosphere”
  Ceranna, L., A. Le Pichon, and E. Blanc

16:35–17:00  “Surf infrasound from Oahu’s North Shore: Real-time monitoring of the Seven Mile Miracle”
  M. Garces and D. Fee

17:00–17:25  “Some Research on Infrasound Detection at NCICT”
  Wang Xiaohang, Wang Wei

17:25–17:30  Administrative Remarks

19:00–21:00  Welcome reception
**Wednesday, 14 November 2007**

08:30–09:00  Registration of participants at the Japan Weather Association (JWA)

SESSION III: Propagation and Modeling
Chairs: David Norris & Naoki Kobayashi

09:00–09:25  “Low-Frequency Acoustic-Gravity Waves Observed after the 2004 Sumatra Earthquake”
Takeshi Mikumo

09:25–09:50  “Infrasounds and background free oscillations”
N. Kobayashi, T. Kusumi and N. Suda

09:50–10:15  “Detection of vertical resonance modes of acoustic waves and its confirmation with geomagnetic field measurement”

10:15–10:40  “Modelling earthquake generated infrasonic waveforms using a Fraunhofer approximation at the ground-atmosphere interface.”
Green, D. N., Guilbert, J., Le Pichon, A., Sebe, O. and Bowers, D.

10:40–11:05  “Atmospheric Pressure Change Associated with the 2003 Tokachi-Oki Earthquake”.
Shingo Watada, Takashi Kunugi, Kenji Hirata, Hiroko Sugioka, Kiwamu Nishida, Shoji Sekiguchi, Jun Oikawa, Yoshinobu Tsuji, Hiroo Kanamori

11:05–11:30  Coffee break

11:30–11:55  “Radiation and trapping of acoustic and gravity waves in a compressible stratified fluid from a time-varying bottom boundary”.
Shingo Watada

11:55–12:20  “Waveform modeling and comparisons with ground truth events”
David Norris
12:20–12:45  “Impact of infrasound on temperature variations in the upper Mesosphere / lower Thermosphere altitude region”
Christoph Pilger and Michael Bittner

12:45–13:10  “Infrasound propagation calculation techniques using mesoscale atmospheric and terrain specifications”
Robert G. Gibson, Douglas P. Drob
and David E. Norris

13:10–14:30  Lunch break

14:30–14:55  “Temporal Morphology of Infrasound Propagation”
Douglas P. Drob, Milton Graces, Michael Hedlin,
and Nicholas Brachet

Roger Waxler, Kenneth Gilbert, Carrick Talmadge
and Claus Hetzer

15:20–15:45  “Analysis of regional infrasound signals at IMS infrasound array in Mongolia”
Bayarsaikhan, Ch., Le Pichon, A

15:45–16:10  “Infrasound generated by Atlantis over southern California and Nevada”
C. D. de Groot-Hedlin, M. Hedlin, K. Walker, D. Drob,
M. Zumberge

15:45–16:10  “Estimates of a relative delay time of signals through analysis of their forms”
S. N. Kulichkov, A.I. Chulichkov, and D.S. Demin

16:35–16:50  Coffee break

**SESSION IV: Volcano Monitoring**

**Chairs:** Milton Garces & Hitoshi Yamasato

16:50–17:15  “Infrasonic observation near active volcanoes in Japan”
Hitoshi Yamasato, Takayuki Sakai
and Yoshiaki Fujiwara

17:15–17:40  “Infrasonic arrays monitoring Italian volcanoes”
Maurizio Ripepe, Emanuele Marchetti, Claudio Ciamberlini, Pasquale Poggi, Stefano Sinopoli

17:40–18:05  “Real-time infrasound localization on active Italian volcanoes”  
Emanuele Marchetti, Maurizio Ripepe, Giacomo Ulivieri, Giorgio Lacanna

18:05–18:30  “Regional arrays for automatic remote sensing of hazardous volcanic eruptions.”
** Thursday, 15 November 2007 **

SESSION IV: Volcano Monitoring  
Chairs: Milton Garces & Hitoshi Yamasato

09:00–09:25  “Numerical investigations of the source of infrasound from long period events at Mount St. Helens”  
R.S. Matoza, M.A. Garces, B.A. Chouet, L. D'Auria, M.A.H. Hedlin

09:25–09:50  “Characterization of explosion signals from Tungurahua Volcano, Ecuador”  
David Fee, Milton Garces and Robin Matoza.

09:50–10:15  “Volcanic air pressure waves recorded on eruption movies”  
Akihiko Yokoo

10:15–10:40  “Seismoacoustics from Kilauea Volcano using multiple arrays”  
David Fee and Milton Garces

10:40–11:00  Coffee break

SESSION V: Source Localization  
Chairs: Láslo Evers & Douglas Drob

11:00–11:25  “Infrasound from lightning”  
Jelle Assink and Láslo Evers

11:25–11:50  “Preliminary results of localization and characterization of steady infrasound source as detected by I31KZ”  
A. Smirnov, V. Kunakov, A. Le Pichon, J. Guilbert

11:50–12:15  “The utilization of blasting information for infrasonic source location of small-magnitude surface explosions”  
Il-young CHE, Hee-il LEE

12:15–12:30  “The Buncefield explosion – A benchmark for infrasound analysis in Europe”  
Ceranna, L., D.N.Green, A. Le Pichon, and P. Mialle

J. Roger Bowman, Gordon Shields, and Michael S. O'Brien

12:55–14:00  Lunch break
14:00–14:25  “Toward Improved Location of Infrasound Events”
Michael S. O’Brien, Douglas P. Drob,
and J. Roger Bowman

14:25–14:50  “Analyzing the detection capability of infrasound arrays in
Central Europe”
Alexis Le Pichon, Lars Ceranna, Julien Vergoz

14:50–15:15  “Construction of 3D propagation tables for localizing
infrasonic event”
Pierrick Mialle, Alexis Le Pichon, Julien Vergoz,
Jean Virieux and Elisabeth Blanc

15:15–15:30  Coffee break

SESSION VI:  Signals, sensors and wind noise reducing systems
Chairs:  Douglas Christie & Henry Bass

15:30-15:55  “The IMS Infrasound Network: detection of a large variety of
events, including volcanic eruptions”,
Paola Campus

15:55–16:20  “Recent progress in wind noise reduction at infrasound
monitoring stations”
Douglas R. Christie

16:20–16:45  “A rotary subwoofer as an infrasonic source”
M. Garces and Park, J

16:45–17:10  “Hurricane Studies Using Infrasound”
Claus Hetzer, Roger Waxler, Carrick Talmadge,
Ken Gilbert, Henry Bass, Jay Williams,
Gary Harrington

17:10–17:25  Coffee break

17:25–17:50  “Recent developments in absolute infrasound sensors”
D. Ponceau, P. Dupont, S. Peyraud

17:50–18:15  “Resolving infrasound back azimuth with arrays of optical
fiber infrasound sensors (OFIS): low wind noise, superb back
azimuth resolution, and a compact design”
Kristoffer Walker, Mark Zumberge, Michael Hedlin,
Jon Berger, and Peter Shearer
18:15–18:40  “The Infrasound Database of the SMDC Monitoring Research Program”
J. Roger Bowman, Gordon Shields, Michael S. O’Brien and Hans Israelsson

18:40–18:50  Administrative Remarks

POSTER
“M-sequences and an array of speakers form a sensor calibrator down to 8 Hz Application to the OFIS at the new Camp Elliott OFIS array”
Kristoffer Walker, Matt Dzieciuch, Mark Zumberge, and Scott DeWolf
“Recent infrasound research at the Japan NDC”
T. Murayama, M. Nogami and N. Arai
** Friday, 16 November 2007 **

08:00–19:00 Site visit (infrasound station IS30 in Isumi) and the final summary session including the visit of the Kasamori-Kannon Shrine and of the Sōnan Museum, located in the Ōtaki Castle.
During the afternoon:
The final summary session (Summary of Results of the ITW2007 and Closing address by JWA and CTBTO representatives in total for one hour) will be held in the conference room beside the Ōtaki Castle.
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Session I: IMS Network and IDC Processing
Chairs: Paola Campus & Nicolas Brachet
THE IMS INFRASOUND NETWORK: CURRENT STATUS AND FUTURE PROSPECTIVES.

Paola Campus and the IMS/ICG/AM Unit Team

The development of the IMS Infrasound Network has steadily progressed since one year ago. With more than 60% of the IMS infrasound stations installed around the world, new challenges for future installations are now showing up. A snapshot of the current status of the IMS infrasound network and of future plans for installations is provided.
COMMON PROBLEMS OF THE FIELD INSTALLATIONS FACED AT THE IMS INFRASOUND STATIONS

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During the period 1996 – 2007 IMS completed the installation of 63% of the infrasound station network. At each station specialized equipment was installed and high quality materials were used for the construction. The selection of materials was made with respect to the local natural surroundings and regulations, and depending also on the specific weather and environmental conditions. The design of the intra-site communication, power supply and wind noise reducing system was made with respect of the particular needs for each station. However, with the time, some field components of the stations started showing deterioration, mainly due to the harsh environment, the presence of groundwater, lightening, land movements, etc. Occasionally, the station design needed improvement or upgrade. This presentation shows examples of common problems faced at some IMS infrasound stations and the solutions implemented to resolve them.
SMOOTH INTRODUCTION OF INFRASOUND DATA INTO THE IDC REVIEWED EVENT BULLETIN –PART I: PROCEDURE AND RECENT DEVELOPMENTS

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In the first quarter of 2007, the International Data Centre (IDC) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Preparatory Commission in Vienna implemented a new procedure for smoothly re-introducing infrasound data into the Reviewed Event Bulletin (REB). New interactive review tools (Geotool-PMCC, Infrasound Intranet) have also been introduced or enhanced to facilitate the operational work of the IDC infrasound specialist group. As a consequence, a growing number of events built with infrasound data have begun to appear in the REB. However, the review of infrasound signals and their contribution to the REB remains incomplete. This work is currently done on selected events as human resources permit.

Work also continues on enhancing the performance of the automatic system for the detection of infrasound events. The cross correlation detection algorithm (PMCC) has been modified to process simultaneously low and high frequency signals, covering a larger spectrum of frequency bands between 0.04 and 4Hz (previously 0.1-4Hz). The installation of the new detection software, which requires more CPU time, was made possible with a major hardware upgrade (Linux implementation) in the runtime system of the development area. The detection sensitivity of PMCC has undoubtedly been increased especially for low frequency signals associated to very long range propagation (over several thousands of kilometers). The results produced by the new version of PMCC are currently being reviewed, as they are likely to impact on the performance of the automatic event bulletin.

This presentation will give an overview of the guidelines and best practices that are currently being used by the infrasound group for saving events in the REB. It will also show some of the latest IDC software developments and the forthcoming challenges for automatic and interactive processing of infrasound data.
SMOOTH INTRODUCTION OF INFRASOUND DATA INTO THE IDC
REVIEWED EVENT BULLETIN – PART II: ANALYSIS AND RESULTS

Mehves Feyza Ocal, Abdou Salam Ndiath, Misrak Fisseha, Ali Kasmi, Kirill Sitnikov, Gadi Turyomurugyendo, Nicolas Brachet and John Coyne
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The International Data Centre (IDC) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Preparatory Commission, in Vienna receives processes, distributes and archives data and products from a global network of seismic, hydroacoustic, infrasound and radionuclide stations.

Automatic event lists generated using detections from waveform data are reviewed by analysts to produce timely, high quality Reviewed Event Bulletins (REB). Currently, the REB is produced primarily using seismic and hydroacoustic data, as infrasound data are not fully operational yet. The events formed during analyst review of seismic and hydroacoustic data are saved as LEB (Late Event Bulletin) events. The members of the infrasound specialist group look for contributing phases from infrasound stations for selected LEB events. In addition, selected infrasound events in the automatic bulletin (SEL3) in the development environment are reviewed. The results of these review processes have lead to the increased contribution of infrasound data to REB and LEB events. This smooth transition of infrasound data to IDC Operations is being guided by the initial procedures for saving infrasound events during interactive review.

During this review, interactive tools that are internally developed are being used. Since July 2007, the interactive tool (ARS-Geotool-PMCC) is operational and allows analysts to review infrasound data during routine data analysis. Detailed information on infrasound event is collected and centralized on the IDC Intranet where it is accessible within the PTS. These efforts have facilitated the smooth transition of infrasound data into IDC Operations and have lead to a better understanding of infrasound data among staff.

This presentation will provide an overview of infrasound signals which contribute to REB events. These events are from a variety of sources, and include events which
are primarily observed only by infrasound stations.
PTS EXPERIMENTAL INFRASOUND ARRAY

John Coyne, Nicolas Brachet, Paola Campus, Pavel Martysevich

The array processing techniques used at the IDC for infrasound processing have demonstrated the exceptional capability of IMS network for detecting signals from a wide variety of natural or man-made sources (e.g., microbaroms, ocean surf, mountain associated waves, volcanoes, thunderstorms, meteorites, avalanches, aurora, rockets, aircrafts, mine blasts, accidental explosions, industrial noise). Unlike earthquakes for seismic technology, sources of infrasound signals are rarely energetic enough to be detected on a global scale by the IMS network. The cross correlation technique developed at the IDC is well adapted for the detection of infrasound signals as it offers optimum detection capability even in difficult cases of very weak signals. The counterpart of the method is that each IMS infrasound station produces a large amount of genuine signal detections from diverse origins. It is important for the PTS to understand and categorize these infrasound signals.

The IDC is building a catalog of sources of infrasound signals detected and identified at IMS infrasound arrays. However, the contents of the reference database are relatively limited due to the difficulties encountered in collecting metadata information about the sources, as well as the limited number of observations. In some cases a hypothesis can be formed concerning the potential source of a signal, e.g., industrial activity that could generate infrasound signals over local to regional distances. In order test such hypotheses, and to identify and catalog other infrasound signals near an IMS array, the PTS is procuring a portable infrasound IMS-type array that could be temporarily deployed in a region of interest.

This effort is seen as an opportunity for the PTS to work closely with National Data Centres and other interested parties to carry out scientific projects that would help to identify and categorize sources of infrasound signals detected at IMS infrasound arrays. This capability could also be used to assess both field techniques and data processing techniques used at the IDC. The equipment for this project is currently being procured, and is planned to be available for use in 2008. The PTS is looking forward to scientific collaborations with other institutes in order to better understand infrasound signals and their sources.
Session II:  Infrasound Research at NDC’s and Research Institutes: experiments and methodologies
Chairs:    David Brown & Curt Szuberla
OPTIMUM ARRAY DESIGN FOR THE DETECTION OF DISTANT ATMOSPHERIC EXPLOSIONS: INFLUENCE OF THE SPATIAL CORRELATION OF INFRASONIC SIGNALS

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Infrasonic array monitoring stations in the IMS network have been established with a wide variety of array configurations. Most of these stations have apertures between 1.0 km and 3.0 km and the number of array elements ranges from 4 to 9. Stations that were established during the early years of the CTBTO tended to be restricted to 4- or 5-element arrays. In contrast, stations installed during recent years have 8 or 9 array elements and the array configurations are usually designed to minimise spatial aliasing of high frequency infrasonic signals. Indeed, up until now, good side-lobe suppression has been the primary criterion used for the design of modern infrasonic arrays. However, an array geometry with good side-lobe suppression characteristics does not necessarily guarantee that the array will provide optimal detection capability for explosion-generated infrasonic signals in the primary monitoring passband (0.4 to 1.5 Hz); the influence of the spatial coherence of infrasonic signals also needs to be incorporated explicitly into the proper design of an optimal IMS infrasound monitoring array.

Detailed studies of the spatial correlation properties of infrasound signals have shown that a low degree of signal correlation between array elements can limit detection capability in the primary monitoring passband at a number of IMS stations. This is a particularly serious problem for arrays with only 4 or 5 array elements and with widely separated array elements. We have also found, however, that arrays with 8 or 9 elements may also have reduced detection capability due to signal correlation problems even when side-lobe-suppression characteristics are good. In order to quantify the importance of signal correlation properties on array detection performance, we have developed a procedure that determines the polar distribution of the array-averaged correlation coefficient for any array configuration in accord with the model of Mack and Flinn (1971). The angular distribution of the predicted array-averaged correlation coefficient
provides a unique array characteristic, which can be used as a measure of the quality of the array design.

Initially, we applied this procedure to the study of the performance of selected tripartite sub-arrays at IS07 Warramunga and compared the predicted results with observed array-averaged correlation coefficients for signals at different frequencies from a wide variety of distant sources. The results predicted by the Mack and Flinn model were found to be in good agreement with the observations. As expected, we found that arrays with a small number of array elements and large apertures have very poor detection capability. We also found that the polar distribution of the array-averaged correlation coefficient may exhibit significant anisotropy. This investigation has now been extended to a number of complete IMS array configurations, including IS04, IS05 an IS07. The results show that problems with signal correlation may reduce the detection capability of some IMS arrays with 8 array elements. The significance of these results will be discussed and recommendations for an optimal infrasonic array design will be presented.
THE AUTOMATIC INFRASOUND PROCESSING SYSTEM AT GEOSCIENCE AUSTRALIA

David Brown

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The automatic processing of data retrieved from the Australian component of the IMS infrasound network has been a feature of the Geoscience Australia research effort since 2003. The processing system, based on the Australian National University ‘INFER’ Hough Transform infrasound detector, and the Neighbourhood Algorithm (NA) source location algorithm has gone through several development stages. The first-generation system, which only performed signal detection is essentially a research tool and has several operationally significant limitations. The second generation system is intended to form part of a robust operational volcano alert system and corrects some of these deficiencies. This processing system is nearing completion and will be discussed in this talk.
Apart from the on-going task of successfully operating and maintaining IMS arrays in the sub-arctic and Antarctica, the faculty and staff of the Wilson Infrasound Observatories have had a productive year since the last Infrasound Technology Workshop. This presentation comprises a précis of some aspects of that work. From the recent volcanic activity in south central Alaska, to the major landslide on Mt. Steele in Canada’s Yukon Territory, the I53US array continues to provide observations of a wide range of geophysical phenomena for study. Too, new work is being done with high trace velocity events, including mountain-associated waves, auroral infrasound and pulsating auroral infrasound. A comprehensive study was done to study the impact of the infrasonic noise field, at both I53US and I55US, on parameter estimation. And finally, the application of infrasound monitoring in the near field, at ranges from 1 m to 10 km, has been of particular interest.
LISTEN TO THE SOUNDS OF THE ANTARCTIC ATMOSPHERE

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The German infrasound array I27DE is in continuous operation since its deployment in January 2003. Using the PMCC algorithm coherent signals are observed in the frequency range from 0.002 to 4.0 Hz covering a large variety of infrasound sources as low frequent MAW or high frequency ice-quakes. However, the most prominent signals are microbaroms generated by the strong peri-antarctic ocean swells. In general, this station offers a powerful tool to measure permanently atmospheric waves at low latitudes. Moreover, Antarctic stations are especially interesting for studying gravity waves, since these waves are controlled by the polar vortex. Another advantage is that the gravity waves at low latitudes are rarely disturbed by those being caused by mountains, which is less important here than in the northern hemisphere. The monitoring of the gravity wave activity at I27DE reveals two active systems. One, characterized by an easterly azimuth, is produced in the troposphere by wind blowing over the mountain chain of the Antarctic Peninsula. The other one, showing a westerly azimuth, is correlated with wind and temperature gradients in the lower stratosphere and is directly related to the stratospheric polar vortex.

Again, a clear trend in the direction of the detected infrasound is observed, which is well correlated to the prevailing stratospheric wind direction and speed. Especially microbaroms are the appropriate signals to continuously monitor the atmosphere since they can be detected at I27DE up to wind speeds of 15 m/s. For this signals a strong increase in the trace velocity along with a decrease in the number of detections were observed during the Antarctic winter in 2006 indicating a collapse of the stratospheric duct. However, the reason for that is currently not clear.

Finally, a short overview on the forthcoming modifications for I27DE is given which are related to the construction of the new Neumayer III research base. Thereto belongs the installation of small wind turbines and how the are sited to minimize effects on the infrasound array.
SURF INFRASOUND FROM OAHU’S NORTH SHORE:
REAL-TIME MONITORING OF THE SEVEN MILE MIRACLE

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The ability to provide infrasonic estimates of breaking ocean wave height and period in shallow reefs, steep rocky coastlines, and sand beaches has been demonstrated in previous work.

We discuss preliminary results on real-time remote infrasonic monitoring of the surf zone on the North Shore of Oahu, Hawaii, during the 2006-07 Winter high surf season. We present our observations showing persistent infrasound was produced by the submerged lava tubes and ledges at Shark’s cove, the wedging shore pound at Log Cabins during predominantly Northerly swells, the barreling wave at Pipeline during predominantly Westerly swells, and by Waimea Bay during very high surf and favorable wind conditions.
SOME RESEARCH ON INFRASOUND DETECTION AT NCICT

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North China Institute of Computing Technology

Abstract: Signal Processing Department of North China Institute of Computing Technology (SPDN NCICT) is responsible for the IS15 and IS16 establishment and operation. During cooperating with PTS to perform site survey and to establish the two IMS infrasound stations, SPDN NCICT also does some researching works on infrasound detection, include infrasound sensor, experimental array and some experimentation on infrasound signal detection.
Session III: Propagation and Modeling
Chairs: David Norris & Naoki Kobayashi
LOW-FREQUENCY ACOUSTIC-GRAVITY WAVES OBSERVED AFTER THE 2004 SUMATRA EARTHQUAKE

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Infrasound waves have been observed by high-sensitive microbarographs at several stations after the 2004 Sumatra earthquake (Mw=9.2). Among these observations, very low-frequency (~0.0016 – 0.0025 Hz) acoustic-gravity modes with a group velocity around 305-315 m/s can be identified on the records at a few stations including the Matsushiro Seismological Observatory (at a distance of ~5,500 km) in central Japan. On the other hand, the occurrence of large-scale tectonic ground movements in the source region has been suggested from fault models of this megathrust earthquake, and actually confirmed from detailed field surveys on many islands along the Sumatra-Andaman arc extending over 1200 km in the Indian Ocean. We attempt to model synthetic barograms appropriate to the stations, on the basis of dynamic response of the lower atmosphere with realistic thermal structures up to an altitude of 220 km, taking into account the seismic information. For this modeling, we incorporate the spreading velocity of the source region, the source dimensions in different zones, the vertical displacements of ground uplift and subsidence, and their time constants. Some of various combinations of these source parameters provide the synthetics well consistent with the general features of the observed low-frequency records. The results suggest that the uplift in the south-central (Ache-Nicobar) region may be a few times larger than that in the other regions, and that the northern half of the entire region appears to contribute only a small portion to the generation of the acoustic-gravity waves. The time constant of the movements would not exceed a few minutes, as in the case of the 1964 Alaskan earthquake (Mw=9.0) that also accompanied large tectonic deformations and generated low-frequency atmospheric pressure waves.
Recently free oscillations of the earth have been reported to be continuously excited in the absence of great earthquakes. Average amplitudes of those modes are about 0.5 nano gal in the mHz band and the amplitudes vary annually or semi-annually about 15%. Modes at frequencies of 3.7, 4.4, 5.1 and 6.1 mHz have remarkably excess amplitudes. At those frequencies, the seismic Rayleigh branch is crossing over the infrasound branches of the atmosphere. To explain those excess amplitudes, we calculated the fundamental spheroidal modes and the acoustic modes in the mHz band to examine the effect of atmospheric structure on the normal modes. We found that the excess amplitudes of the modes at the branch crossings can be reproduced only in the case that the excitation source is at the bottom of the atmosphere. These results show that the atmosphere plays an important role in the excitation of the observed background free oscillations. We also applied this mechanism to the excitation problem of the infrasound modes and found that the fundamental acoustic mode $aP_{29}$ at 3.7 mHz is excited by the mechanism and has amplitude about 10 Pa that can be observable in the future observations of the atmospheric pressure variations.
DETECTION OF VERTICAL RESONANCE MODES OF ACOUSTIC WAVES AND ITS CONFIRMATION WITH GEOMAGNETIC FIELD MEASUREMENT

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We found evidences of ionospheric dyamo caused by vertical resonance of acoustic waves from geomagnetic and barometric observations. Because the magnetic field variation which correlates to pressure variation is most likely caused by ionospheric dynamo, it reflects the pressure variation (i.e., vertical wind motion) at ionospheric height. Therefore we can discuss the resonance mode by using both magnetic field and pressure variation data. For this purpose, we deployed barometers at several points in Japan, Thailand and Turkey. We report our recent progress in this comparative study.
MODELLING EARTHQUAKE GENERATED INFRASONIC WAVEFORMS USING A FRAUNHOFER APPROXIMATION AT THE GROUND-ATMOSPHERE INTERFACE.

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Earthquake-generated infrasound signals are the result of a three stage process: propagation of seismic energy from the source to the location at which energy couples into the atmosphere, the seismic to infrasound coupling, and the atmospheric propagation of infrasound. We extend the method of Le Pichon et al., (2003, GRL 30(15) 1814) in order to generate synthetic infrasonic waveforms resulting from topographically controlled ground-to-air coupling. We present the method, based upon the Fraunhofer approximation to the Rayleigh integral, and discuss its applicability and limitations with reference to the 28th April 2007 Ml 4.2 Folkestone, UK, earthquake recorded acoustically at FLERS, France.

The infrasound signal generated by the Folkestone earthquake was unexpected: the earthquake magnitude (Ml 4.2) is low compared to others that are known to have generated infrasound, and it occurred in a coastal region without pronounced topography. The signal was of low amplitude (0.01Pa) and short duration (40s) and crossed the FLERS array with a horizontal trace velocity of 332±6 m/s. The advantage of studying such a small earthquake is that the infrasound signals are not contaminated by earthquake source directivity and finite fault length effects.

The local ground motion is well constrained using records from a strong motion seismic sensor located less than 5km from the epicentre. This allows the study to focus on the effects of ground-to-air coupling. We test the hypothesis that the infrasound signals are consistent with the generation of infrasound by the motion of near-vertical sea cliffs in close proximity to the earthquake epicentre. Synthetic barograms, generated by the summation of contributions from a series of cliff segments, exhibit durations and amplitudes comparable to the recorded signals.

The infrasound propagation is modelled using atmospheric profiles provided by the ECMWF. Both Is and Iw phases are permissible, although due to the short (285km) propagation distance and wind conditions at the time of the event it is difficult to identify which is the correct path for the observed signals.
ATMOSPHERIC PRESSURE CHANGE ASSOCIATED WITH THE 2003 TOKACHI-OKI EARTHQUAKE

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Clear atmospheric pressure changes associated with the 2003 Tokachi-Oki, Japan, earthquake with Mw 8.3 were recorded with the microbarographs distributed in Japan. The pressure change starts at the arrival of seismic waves and reaches its maximum amplitude at the arrival of Rayleigh waves, suggesting that the observed pressure change was driven by the ground motion of seismic waves passing by the site. We computed the seismic-to-pressure transfer function (i.e., the spectral ratio of the pressure change to the vertical ground motion velocity) for periods between 10 to 50 s from the co-located barograph and seismograph records. Comparison of the observed transfer function with the theoretical one including the finite frequency and wavelength effects for a gravitationally stratified isothermal atmosphere confirms that the observed amplitude and phase of the pressure change are explained by the acoustic coupling between the atmosphere and the ground just beneath the sensors.
RADIATION AND TRAPPING OF ACOUSTIC AND GRAVITY WAVES IN A COMPRESSIBLE STRATIFIED FLUID FROM A TIME-VARYING BOTTOM BOUNDARY

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Acoustic waves and gravity waves are generated by a large-scale motion of the bottom boundary of the atmosphere such as earthquake and tsunami. The pressure records from those phenomena contain information of the temporal and special variation of the bottom boundary. Radiation of acoustic and gravity waves and excitation of boundary waves in a gravitationally stratified isothermal compressible inviscid fluid from a time-varying bottom boundary is investigated. Impedance $Z$, the ratio of the bottom vertical displacement and fluid pressure above it, is a function of frequency and horizontal wave number of the bottom boundary. The amplitude and phase of $Z$ at the bottom boundary characterize the wavetype generated by the time-varying bottom boundary. Near the acoustic cut-off and the buoyancy frequencies, the amplitude of $Z$ is reduced compared with the cases of the acoustic waves without gravity and incompressible gravity waves. In contrast to pure acoustic or gravity wave, the phase of $Z$ is continuous, but changes quickly along the regime boundary between the radiating waves and trapped waves in the frequency and horizontal wave number coordinates, except the Lamb wave branch along which amplitude is zero and across which the phase jumps by $\pi$. 
WAVEFORM MODELING AND COMPARISONS WITH GROUND TRUTH EVENTS

David Norris  
BBN Technologies

Research advances have been made in the areas of advanced model development, ground truth (GT) event studies, and model validation. They are focused on understanding the driving mechanisms that affect measured waveforms, and quantifying the prediction performance of new modeling capabilities. High fidelity predictions of infrasonic waveforms properties, including travel time and amplitude, improve source localization. These advances also support discrimination between various infrasonic impulsive events. In this presentation, advances in waveform modeling using the Time Domain Parabolic Equation (TDPE) model are discussed. These advances include a characterization of terrain. The waveform predictions are compared to measurements from GT events to assess the relative influence that environment properties have on the propagation.
IMPACT OF INFRASOUND ON TEMPERATURE VARIATIONS IN THE UPPER MESOSPHERE / LOWER THERMOSPHERE ALTITUDE REGION

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Measurements of mesopause temperatures are performed at DLR by means of observing the Hydroxyl (OH*) airglow emission in the near infrared spectral region using ground-based spectrometers (GRIPS 3 and 4) in order to study atmospheric dynamics on different scales. The objective is to better understand small scale structures such as gravity waves but also of planetary scale waves and long term temperature trends.

Temperature fluctuations with periods below the acoustic cut-off frequency are frequently observed. In order to better quantify whether such fluctuations are due to gravity or infrasonic waves, modeling to understand the impact of infrasound on temperature variations is performed.

Infrasound propagation is described by ray-tracing methods. To consider realistic atmospheric background conditions, the ray-tracing is supplemented by temperature and wind climatologies as well as attenuation modeling. The amplification of an acoustic signal due to decreasing air pressure with height leads to detectable temperature variations in the upper mesosphere/lower thermosphere altitude region. First results show that smaller scale temperature fluctuations measured in the mesopause altitude region might be attributed, at least in part, to infrasonic wave activity.
Numerical calculation of infrasound propagation paths is necessary to support accurate infrasound event identification, phase association and source location. Predicting the details of infrasound propagation relies both on propagation models that capture the fundamental physical processes and on characterization of the propagation medium, namely the global atmosphere from the ground to altitudes above 100 km. Therefore the accuracy of propagation modeling depends in part on the fidelity of the atmospheric characterization. Furthermore, for infrasound propagation at regional and local ranges, characterized by higher frequencies than propagation at global ranges, effects of the boundary conditions of the propagation domain, in particular the terrain elevation, become increasingly important.

Recent efforts develop techniques for utilizing accurate, high-resolution regional atmospheric specifications and terrain elevation databases with infrasound propagation modeling codes. Mesoscale atmospheric models, which focus on the meteorology of a specific region, can account for and resolve important wind and temperature phenomena relevant to regional and local infrasound propagation. Such models can also provide atmospheric profiles that are consistent with the variable terrain elevation in a region. By investigating realistic atmospheric models and terrain specifications at a range of resolutions, we seek insight into the appropriate spatial and temporal scales that are necessary for achieving improved infrasound predictions at the relevant frequencies. Ground truth events are studied in order to assess performance of techniques for incorporating mesoscale atmospheric models and terrain specifications with propagation models and to evaluate the benefits for infrasound monitoring.
TEMPORAL MORPHOLOGY OF INFRASOUND PROPAGATION

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Expert knowledge suggests that the performance of automated infrasound event association and source location algorithms can be greatly improved by the ability to continually update station travel time curves to properly account for the hourly, daily, and seasonal changes of the atmospheric state. With the goal of reducing false alarm rates and improved network detection capability, we endeavor to develop, validate, and integrate this capability into infrasound processing operations. Numerous studies have demonstrated that utilization of G2S environmental specifications in calculations of infrasound signal travel time and azimuth deviations yield significantly improved results over that of climatological atmospheric specifications, specifically for tropospheric and stratospheric modes. A robust infrastructure to generate G2S coefficients on a real-time basis (every 3- to 6-hours) currently exists.

Thus the next requirement in this endeavor is to develop robust numerical procedures to quickly calculate infrasound propagation characteristics for automatic infrasound arrival identification and network detection/location algorithms. We present results from a new code that for any location on the globe given a G2S vector spherical harmonic coefficient set, integrates the local (range independent) tau-p equations for travel time, range, turning point, and azimuth deviation via an accurate numerical technique capable of addressing square root singularities. This program is designed to be run either in batch mode via a shell script for all IMS station locations, e.g. following the generation of a G2S coefficient hourly update, or easily invoked by an analyst in interactive mode. For the purpose of understanding the impact of our current working knowledge on the overall objective, results from the G2S/TauP calculation system are presented which investigate the seasonal variability of propagation characteristics over the course of a five year time series for different IMS stations. The statistical behavior or occurrence frequency of various propagation configurations are discussed. Representative examples of some of these propagation configuration states will also be shown.
THE EFFECT OF FINITE OCEAN DEPTH ON THE MICROBAROM / MICROSEISM SPECTRUM.

Roger Waxler, Kenneth Gilbert, Carrick Talmadge and Claus Hetzer

At microbarom/microseism frequencies the acoustic wavelength in the ocean is about 7.5 km. This is greater than typical ocean depths. Previous treatments of the microbarom/microseism radiation have often assumed the ocean to be infinitely deep. Assuming the ocean’s depth to be constant and the earth to be an infinite, homogeneous, elastic solid, a form for the microbarom/seism source spectrum has been obtained. The ocean depth is seen to have a large effect.
ANALYSIS OF REGIONAL INFRASOUND SIGNALS AT IMS INFRASOUND ARRAY IN MONGOLIA

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The RCAG of Mongolia and DASE of France jointly designed, installed and operated 3 km aperture IMS (CTBT) Seismic and Infrasonic array southeast of Ulaanbaatar, Mongolia.

Seismic and acoustic recordings are particularly important to help identifying and locating industrial blasting sources. We have analyzed seismo-acoustic signals from mine blast for 2000 and 2005 in order to determine detection seismo-acoustic signals of explosion by seismic and infrasound stations.

Several large mines in the region routinely generate explosions that are detected seismically and with infrasound. The mine range in distance from 40-500 km from the seismic, infrasound array. In last few years mining activity in Mongolia significantly increased. The corresponding number of infrasound detection is found to be dependent upon the regional weather condition, which is included air temperature, epicentral distance, wind force and velocity. We present the seismic and infrasound IMS stations and some results of analysis.
INFRASOUND GENERATED BY ATLANTIS OVER SOUTHERN CALIFORNIA AND NEVADA

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Inclement weather in Florida forced the shuttle Atlantis to land at Edwards Air Force base in southern California on June 22, 2007. The Atlantis reentry was parallel to the southern California coastline. As it decelerated from Mach 7 along its northward trajectory, it passed near three infrasound stations and several hundred seismic stations in northern Mexico, southern California and Nevada. Acoustic energy from the shuttle was recorded by these stations well above noise to a range of over 400 km. NASA provided us with the Atlantis positional data. The high signal to noise ratio, remarkably dense receiver coverage, and the source positional information allows us to test our atmospheric modeling capability over a large region in an unprecedented fashion. We adopt a source model where rays are launched at right angles to the conical shock front surrounding the shuttle, and ray-traced through a standard atmospheric model as well as global and mesoscale G2S models. Our goals are to predict travel times and to predict which stations would be located in shadow zones.

The overall travel time predictions were very accurate ranging down to ~ 0.1% of the overall propagation time, comparable to modeling global seismic phases. However, regardless of whether we used a global, mesoscale, or a purely climatology model appropriate to this region and time, the observed signals were consistently early, with an average residual of 2-3 seconds. Although all models accurately predicted the edge of the primary ensonification zone beneath the shuttle, details of the longer range propagation involving sound refraction within the stratosphere are less accurately predicted. To the northwest of Edwards AFB, the atmospheric models predict narrow regions of ensonification separated by wide shadow zones. In contrast, the observations indicate wide areas of ensonification separated by narrow shadow zones. For most of those northwest stations that are predicted to observe a signal, the predicted times match well. All the models predict increasing complexity of the recorded waveforms with increasing distance, in line with observations.

In this talk we review the observations and predictions and discuss the implications for atmospheric modeling.
ESTIMATES OF A RELATIVE DELAY TIME OF SIGNALS THROUGH ANALYSIS OF THEIR FORMS

S. N. Kulichkov, A.I. Chulichkov, and D.S. Demin

A method of estimating the delay time of acoustic signals recorded on different microphones is proposed. The method is based on an analysis of signal forms. The method is especially efficient in analyzing isolated signal fragments whose durations are shorter than a characteristic period of signal. It is suggested that this method be used for the problems of infrasonic explosion monitoring, when an informative signal is recorded against the background of an intensive natural acoustic noise.
Session IV:  Volcano Monitoring
Chairs:      Milton Garces & Hitoshi Yamasato
INFRASONIC OBSERVATION NEAR ACTIVE VOLCANOES IN JAPAN

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In order to survey volcanic activities, Japan Meteorological Agency (JMA) is operating monitoring networks at active volcanoes in Japan. Their observation system includes visual, seismic, geodetic and other equipments. Infrasonic observation is also one of the most important methods in volcano monitoring. JMA is carrying out infrasonic observation using infrasonic microphone near active volcanoes in Japan. It was started for Sakurajima volcano in 1983.

For Sakurajima volcano, where explosive eruptions have been frequently occurring, infrasonic microphones detect not only explosive infrasonic signal for each explosion but also harmonic infrasound associated with harmonic volcanic tremor (e.g., Sakai et al., 1996). During the activity at Unzen volcano in 1990's, we detected infrasonic signals from low frequency earthquakes during dome growth and from dome collapses and pyroclastic flows, and determined source locations of the infrasonic signals using infrasonic microphone network. In this analysis, we could estimate the speed and the direction of the pyroclastic flows (Yamasato et al., 1993; Yamasato, 1997; Yamasato, 1998).

On the basis of these researches, JMA have installed infrasonic microphones near several active volcanoes since 1990's. During the phreatomagmatic/phreatic eruptions at Usu and Miyake volcanoes in 2000, we detected infrasonic signals from the eruptions and the data were used for the evaluation of the volcanic activity. Also for Usu volcano, we identified the source locations of the infrasonic signals from eruptions at the three craters with a microphone network and could distinguished the activity at each crater (Yamasato et al., 2002). At Miyakejima, large amplitude infrasonic waves were observed associated with large eruptions in August 2000 and we could know the sequence of the eruptive activity (Japan Meteorological Agency, 2006).

In present, JMA is carrying out infrasonic observation at 25 active volcanoes. Most of the microphones are installed within 5 km close to the active craters and their data are continuously telemetered to four Volcano Observation and Information Centers at Sapporo, Sendai, Tokyo and Fukuoka.

Many kinds of signals have been observed by our network and used for monitoring the volcanic activities.

At Vulcanian explosive eruption of Asama volcano on 1 September 2004, infrasonic signals were observed not only near the volcano but also by infrasonic microphones at other volcanoes more than 1000 km distant from Asama volcano (Fujiwara et al., 2004).

Infrasonic observation produces important information on the mechanism of volcanic eruption and other phenomena. We have found out small signals preceding explosive pulses from explosive eruptions at some volcanoes (Sakai et al., 2001; 2004). Dilatational infrasonic pulses are observed with large amplitude low frequency earthquakes (Fujiwara et al., 2006).

Propagation of infrasonic wave is affected by meteorological condition, especially by wind direction and speed. We are investigating the effect of meteorological conditions to infrasonic signals aimed at more precise source determination.
(Fujiwara et al., 2007).
INFRASONIC ARRAYS MONITORING ITALIAN VOLCANOES

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Italian active volcanoes are monitored acoustically with small aperture infrasound arrays positioned at short distances from explosive sources. Portable, robust, low power arrays were specifically designed to operate in hostile environments at elevations ranging between 1000-3000 meters a.s.l., and distances of 0.4-5 km from the explosive sources.

Although not specifically designed for such purpose, electret microphones after accurate calibration are used as infrasonic sensors as they provide a precise timing of the event and, given the low power requirements, allow a long efficiency of the system. Wind effects are reduced by burying the sensors underground, and the risk of damages related to lightning required the use of fiber optic rather than copper in permanent setups. Sampling rate (50 Hz) and array geometry and spacing are chosen to describe precisely the infrasonic emission and to achieve a good azimuthal resolution of the infrasonic wavefield.

In the last 4 years 3 small aperture permanent arrays have been deployed on Stromboli and Etna volcanoes, providing a continuous description of infrasonic activity radiated during explosive and degassing activity. We present also a portable array that can be deployed in few hours during eruptive crises for Italian Civil Protection. This array has been used on Vesuvio volcano during the MESIMEX (Major Emergency SIMulation EXercise) simulation coordinated for European Community by Italian Civil Protection in October 2006. All the arrays are controlled remotely (up to distances of 25 km) through low-power radio link, turning the arrays into efficient tools for real-time monitoring of volcanic activity.
REAL-TIME INFRASOUND LOCALIZATION ON ACTIVE ITALIAN VOLCANOES

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Volcanic activity at Etna and Stromboli volcano has been monitored for the last 4 years with two small aperture infrasound arrays deployed at short distances (0.4-5 km) from the explosive sources. In order to achieve a real-time location of the explosive/degassing processes with the deployment of low computing resources, we have specifically developed a fast locating algorithms, based on a line- and grid-searching procedure.

At short distance from the explosive source, our locating procedure allows a good resolution of source position (5-10 m) with the use of a single personal computer. Efficiency of the locating procedure has been validated with standard array processing analysis and finite difference numerical modeling (FDTD) of pressure wave propagation, considering the real volcano topography and homogeneous atmosphere.

This procedure allows us to locate infrasound produced by various volcanic processes, with amplitude spanning between small gas bursting to large strombolian explosions, and to discriminate between infrasound released from different vents even positioned only few meters apart from each other within the same volcanic crater, thus providing critical constraints to image the shallow feeding system. Moreover, infrasound array analysis leads to clearly discriminate explosive ejection in the atmosphere from volcano-tectonic earthquakes, and to identify and locate infrasound produced by magmatic dick propagation and landslides, leading in real-time to a complete and detailed description of ongoing volcanic activity.
REGIONAL ARRAYS FOR AUTOMATIC REMOTE SENSING OF HAZARDOUS VOLCANIC ERUPTIONS.

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The Acoustic Surveillance for Hazardous Eruptions (ASHE) project aims to develop and evaluate the capability to use low frequency sound to provide robust, low-latency (5-20 minute) notifications of volcanic eruptions at regional distances. Infrasound monitoring complements both seismic observation and satellite remote sensing to improve continuous monitoring of wide regions of potential eruption hazard at modest cost. The ASHE stations use infrasound arrays deployed sufficiently far from volcanic devastation zones to promote ease of maintenance, survivability, and observational continuity during destructive eruptive episodes. We describe current field deployment of the arrays in Ecuador and preliminary comparisons of infrasound data and ground based observations of ash release. The monitoring stations send continuous real time data to a central facility where automatic analysis techniques for eruption detection are being prototyped. For the ASHE stations automated notification products are sent on a test basis to the Washington DC Volcanic Ash Advisory Center for comparison and possible integration with their existing warning systems.
NUMERICAL INVESTIGATIONS OF THE SOURCE OF INFRASOUND FROM LONG PERIOD EVENTS AT MOUNT ST. HELENS

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M.A. Garces, Infrasound Laboratory of the University of Hawaii at Manoa
B.A. Chouet, US Geological Survey
L. D’Auria, Osservatorio Vesuviano
M.A.H. Hedlin, Scripps Institution of Oceanography

In volcano seismology, one of the most important signals for monitoring is the long period (LP) event (0.5-5 Hz). These transient, volumetric signals result from oscillations of the fluid, and are considered the impulse response of the resonant system that generates the more continuous volcanic tremor. The utility of LP events for short-term eruption forecasting is well demonstrated, because changes in the timing and vigor of the signals commonly accompanies the pressurization of the volcanic system prior to and during eruption. The Mount St. Helens ASHE array at 13 km range intermittently records infrasonic signals associated with a sustained sequence of seismic LP events. Whenever present, the infrasonic signals are shorter in duration and more impulsive than the seismic LP events, lacking the characteristic resonant long period coda.

We summarize the observations and then present preliminary numerical investigations of the coupling mechanism between seismic and acoustic LP events using a 2.5D finite difference representation of the elastodynamic and acoustic wave equations, including the effects of topography and wind. We use source-time functions corresponding to the moment tensor and single forces obtained through inversion of seismic data.
CHARACTERIZATION OF EXPLOSION SIGNALS FROM TUNGURAHUA VOLCANO, ECUADOR

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Robin Matoza
Laboratory for Atmospheric Acoustics (L2A)
University of California, San Diego

Volcanic eruptions can produce substantial acoustic energy and a wide variety of infrasonic signals. As part of the ASHE project, a 4 element infrasound array with collocated seismometer has been deployed 37 km from Tungurahua Volcano, Ecuador since February 2006. During this period Tungurahua has been in near-constant eruption, with the activity ranging from background Strombolian to destructive Vulcanian. A combination of STA/LTA ratios and PMCC results have been used to identify over 8000 explosions to date. Acoustic source energies, gas fluxes, and peak pressures are calculated and presented for all the recorded explosions. In order to minimize propagation effects, acoustic energies are referenced to a single “typical” explosion. By doing this a threshold energy level may be used in an alert system. Further, large initial pressure amplitudes are not necessarily the most energetic, as the duration and frequency content of the event also contribute. Cross-correlation between the explosions and a reference explosion are also explored in hopes of understanding eruption evolution. This presentation will summarize the multitude of identified explosions and examine how they can help identify volcanic activity levels and eruption dynamics.
At explosive volcanic eruptions, it's well known that strong atmospheric pressure perturbations are generated and propagated as infrasound waves to the range of several hundreds km away from volcano. These waves have been usually observed by LF microphones and microbarographs around the volcanoes. Occasionally, they are visualized at just above the crater by appearances and/or disappearances of clouds (phase change of H₂O in the air), and changes of refractive index of the air. These visualized waves may give us some constraints for understanding dynamics of volcanic eruptions, for instance, expanding and collapsing processes of the crater bottom. Even if we can not directly observe them by the naked eyes because these pressure waves have instant and weak natures, we have a chance to recognize them on the movies using a simple imaging method: that is a focusing the change of luminance data. In this talk, I'll show several examples of these visualized volcanic air pressure waves which were recorded on movies of Japanese volcanic eruptions (e.g., Vulcanian eruptions of Sakurajima volcano). And, we'll also show that such phenomenon would be one of good keys to understand source processes of volcanic eruptions.
SEIMAOACOUSTICS FROM KILAUEA VOLCANO USING MULTIPLE ARRAYS

David Fee and Milton Garces
Infrasound Laboratory, University of Hawaii, Manoa

Three infrasound arrays recorded a multitude of signals from Kilauea volcano during 2007. A semi-permanent array 12.5 km from the vent recorded near continuous infrasonic tremor from the relatively steady-state eruption of the Pu'u 'O'o crater complex. However, clear temporal variations exist. To help better constrain the eruption and supplement the existing array, a temporary infrasound array and collocated seismometer were placed 2.5 km from Pu'u 'O'o. A sharp, complex spectral peak of ~0.6 Hz is present in both datasets, and tends to bifurcate and shift frequency over time. Although the seismic wavefield at Kilauea is complex and path effects appear to be present, this spectral peak is also manifested in the seismic data.

On June 19th, magma drained from Pu'u 'O'o rapidly and eventually reached the surface 6 km to the west. Although difficult to determine visually and seismically, the timing and location of the lava outbreak were determined acoustically using array processing. Two distinct acoustic pulses were recorded from the correct azimuth, both exhibiting harmonics. After this brief lava outbreak magma returned to Pu'u 'O'o, only to be followed by a series of fissure eruption to the east. Significant infrasound was recorded from these fissure eruptions as well. A third infrasound array was placed ~7 km from the vent and active fissure. Because of its location, array processing of this array data can help differentiate signal between Pu'u 'O'o and the active fissure.

Seismic data from the Hawaiian Volcano Observatory is also used to supplement the infrasound recordings during periods of interest.
Session V: Source Localization
Chairs: Láslo Evers & Douglas Drob
INFRASOUND FROM LIGHTNING

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The Royal Netherlands Meteorological Institute (KNMI) operates a network of lightning detection antennas based on electromagnetic (EM) signals. This so-called FLITS system (Flash Localization by Interferometry and Time of Arrival System) exploits EM waves emitted from thunderstorms to detect and localize thunderstorm discharges both with very-high frequency (VHF) and low frequency (LF) antennas. FLITS provides information on the origin time, location and type of discharge, either a cloud–cloud (CC) or cloud–ground (CG) discharge. In case of an CG, also the strength of the discharge is derived in terms of the amount kilo-amperes (kA).

Thunderstorms are expected to generate infrasound through various mechanisms:
1. the thermally driven expanding channel model describing acoustic energy emission from a blast wave generated by the lightning channel [Few (1969)]
2. the convective system as a whole emits infrasound through vortices and other large mass displacements [Bowman and Bedard (1971)]
3. the electrostatic mechanism where infrasound is generated within discharged clouds that tend to restore to atmospheric pressure equilibrium from their destabilized state [Dessler (1973)]

KNMI also operates a variety of infrasound arrays, ranging from 6 to 16 microbarometers per array with apertures between 60 and 1500 meters. In this study, detections from FLITS are compared to infrasound detections in order to quantify the detectability of infrasound from lightning.

Several interesting conclusions can be drawn from the fusion of the EM and infrasound dataset:
1. CG discharges can be detected at least over a range 50 km, CC discharges are much harder to identify
2. the typical blast waveform is retrieved in support of the thermally driven expanding channel model
3. infrasound signal coherency is, in general, low and small inter-microbarometer distances are needed within the array, typically 25-100 meters, for detection purposes
4. attenuation of the infrasound indicates point source behavior for near-field and cylindrical spreading for far-field infrasound
5. large sub-sonic pressure variations correspond to the passage of the thunderstorm front, the associated pressure drop or “nose” is well detected by infrasound arrays

Future work will concentrate on investigating the atmospheric attenuation and geometrical spreading in relation to the behavior of the source.
PRELIMINARY RESULTS OF LOCALIZATION AND CHARACTERIZATION OF STEADY INFRASOUND SOURCE AS DETECTED BY I31KZ

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The infrasound station I31KZ was commissioned in 2001. Since the beginning of its installation, this station has been recording repetitive signals of steady source located southward. One possible source is the Zhanazhol oil and gas field generating gas flairs. First results were presented during the ITW 2006 workshop in Fairbanks, Alaska.

The PMCC analysis of the automatic processing results shows clear seasonal trends in the measured backazimuth and horizontal trace velocity. Sine variations of the azimuth deviation is noted within a range of 15°. Such source provides a powerful way to understand and quantify the relationship between infrasonic observables and atmospheric specification problems.

Recently, in collaboration with CEA/DASE, the KNDC installed a temporary infrasound array approximately 200 km south – east from I31KZ in order to confirm the origin of the source. Preliminary results of the investigation are shown in this presentation.
THE UTILIZATION OF BLASTING INFORMATION FOR INFRASONIC SOURCE LOCATION OF SMALL-MAGNITUDE SURFACE EXPLOSIONS

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Korea Institute of Geoscience & Mineral Resources (KIGAM), Daegu, Korea.

The surface blastings of industrial mines are the good example of point-sources producing impulsive infrasonic signals, where well-defined blasting information can be used to study characteristics of infrasound propagation and to verify infrasonic source location method for surface explosion. For the utilization of blasting information, we surveyed and identified one open-pit limestone mine where 2~10 tons of ANFO charge are blasted nearly every day. This mine located at the east coast of South Korea could be considered as an infrasonic bell because many infrasonic signals from the mine were recorded at the Korean Infrasound Network (KSGAR, CHNAR, BRDAR, KMPAR, and TJIAR) since 1999.

One temporary seismo-acoustic station was deployed inside of the mine to record near-field seismic and infrasonic signals of blastings and exact source information. During 45 days operation, total 61 blastings were conducted and infrasonic signals of 19 blastings were recorded at more than two distant infrasound arrays. Non-linear grid-search method was used to localize source locations using the travel times of infrasound recorded at the distant arrays, and initial information including a celerity model, seismic location in catalogue. The location determined is compared with exact mining location and others, such as seismic locations in catalogue and intersection points of infrasonic back-azimuths. The comparison shows that location accuracy of the method is comparable to that of seismic location. And this kind of infrasonic signals regularly generated could be effectively used for studying the effect of local weather condition and atmospheric modeling in infrasound research.
THE BUNCEFIELD EXPLOSION: 
A BENCHMARK FOR INFRASOUND ANALYSIS IN EUROPE

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A large explosion occurred at the Buncefield oil refinery in Hemel Hempstead, 40 km north of London, on December 11, 2005 at 06:01:33 UTC. At this event a large vapor cloud blew up. The vapor was formed by fuel split over the top of a tank and was spread over an area of ~80,000 m² with thickness ranging from 1 to 7 m. The accident’s effects were felt by many people up to a distance of 60 km. The explosion generated also strong infrasound signals which were recorded all over central Europe. In detail, recordings are analyzed from infrasound stations in France, Sweden, and Germany and from seismic stations in the United Kingdom, France, Belgium, and Germany. This event is of great interest due to the high number of stations detecting signals, the large number of recorded arrivals, and the exceptional wind conditions in the stratosphere at this particular day. Therefore, the Buncefield explosion is a benchmark for analyzing the capability of automatic signal processing, phase labeling, propagation modeling using different wind and temperature profiles, and acoustic event location.
INFRASOUND STATION AMBIENT NOISE ESTIMATES AND MODELS: 2003-2006

J. Roger Bowman, Gordon Shields, and Michael S. O'Brien
Science Applications International Corporation

The objectives of this study are to characterize the noise environment of many existing infrasound stations using a standard methodology and to define models for infrasound noise under different conditions. Spectral amplitudes are measured for the reference sites of all 39 infrasound arrays for which data are available. Of these stations, 34 are part of the International Monitoring System (IMS), and five are research stations in North America. Power Spectral Densities (PSDs) are estimated for 21 consecutive 3-minute segments of data taken four times daily from January 2003 through August 2006. For stations having both high- and low-frequency sites, spectra are estimated separately for one site of each type. Three million spectra are calculated and displayed in 16 plots per station (four times a day for four seasons) for frequencies from 0.03 to 7 Hz.

The ambient noise at infrasound stations is highly variable by season, time of day, station, and site type. Noise spectra for some individual stations vary by four to six orders of magnitude at any given frequency across the frequency band analyzed. Noise levels are typically highest near local noon. Median noise levels in the microbarom band centered on 0.2 Hz vary smoothly in an annual pattern. Most stations observe maximum noise in this band during local winter. Ambient noise varies significantly between the high- and low-frequency sites of some arrays. We define infrasound noise models using data for 29 stations having a complete year’s data. These models can be used as references for evaluating sensors and the effectiveness of current and planned sites. The median noise model represents “typical” ambient noise, including all times of day and seasons. The low-noise model is based on the 5th percentile noise estimates and represents ideal conditions at each frequency.

We rank the 29 stations used for the noise models according to the percentage of time each has noise in the network-wide 25th percentile at 0.2 and 1 Hz. At 0.2 Hz the three quietest stations are I32KE (Kenya), I17CI (Côte d’Ivoire), and I09BR (Brazil), and the three loudest stations are I36NZ (Chatham Island), I05AU (Australia) and I39PW (Palau). At 1 Hz the quietest stations are I53US (Alaska), I32KE, and I09BR, and the loudest stations are I39PW, I50GB (Ascension Island) and I36NZ. We also compare station noise with distance to the nearest ocean and vegetation density, and find that noise correlates inversely with both station properties.
TOWARD IMPROVED LOCATION OF INFRA SOUND EVENTS

Michael S. O’Brien¹, Douglas P. Drob², and J. Roger Bowman¹
Science Applications International Corporation¹ and Naval Research Laboratory²

The purpose of this project is to improve the ability to locate infrasound events by improving the Horizontal Wind Model (HWM) used in the prediction of infrasound observables, in particular, travel time and back azimuth. Our general approach uses new wind data to develop a higher-resolution and more accurate HWM and tests the performance of Ground to Space (G2S) specifications based on the new HWM, relative to those based on HWM-93 using a large set of ground-truth events. We assembled a preliminary data set of 180 events with which to exercise our statistical framework for testing the effect of atmospheric wind models on the accuracy of infrasound event locations. We also assembled wind data representing a 100-fold increase compared to those used for HWM-93 and incorporated these wind data into the mechanism used to generate improved HWMs. We applied this mechanism to construct a preliminary version of HWM-07, and demonstrated that this preliminary model displays some important features that were missing from HWM-93, such as wind velocities of up to 70 m/s at an altitude of 110 km. We created an efficient mechanism to trace rays through atmospheric models for a large suite of infrasound source-station pairs. Initially, we have based our generation of travel-time and back-azimuth predictions on the HARPA 3-D ray-tracing programs. We refined the statistical framework for testing the effect of atmospheric wind models on predictions and applied it to first arrivals for a preliminary data set of 251 source-receiver pairs from 108 events to evaluate and compare predictions made against the existing, baseline atmospheric specifications for our study, G2S and HWM-93/MSISE-00, on which it is based, above 50 km. As expected, we find that G2S more often and more accurately predicts stratospheric first arrival times and back azimuths, whereas the two models are both equally poor at predicting thermospheric arrival times and back azimuths. It is for thermospheric arrivals that we expect the most improvement to result from the improvements of HWM-07.
ANALYZING THE DETECTION CAPABILITY OF INFRASOUND ARRAYS IN CENTRAL EUROPE

Alexis Le Pichon$^1$, Lars Ceranna$^2$, Julien Vergoz$^1$

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The infrasound network of the International Monitoring Network (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO) is currently not fully established. However, it has demonstrated its capability for detecting and locating infrasonic sources like meteorites as well as volcanic eruptions on a global scale. Unfortunately, such ground truth events are rare. Therefore, regions with dense infrasound networks have to be considered in order to test and calibrate detection and location procedures. In Central Europe, several years of continuous infrasound recordings are available for many infrasound arrays, where not all of them are part of the IMS. Since 2000, the infrasound data from Flers (France) and I26DE (Germany) are routinely processed in the [0.02 4] Hz frequency band using PMCC as a real-time detector. Furthermore, the Swedish stations in Uppsala, Lycksele, Jämtön, and Kiruna are also routinely processed in the frequency range from 0.7 to 4 Hz. In 2005, the station IGADE was deployed in Northern Germany which is now part of this network. The results of the association of multiple arrays will be presented based on seven years of all available bulletins. The network capability as well as the location results is improved by adding the IGADE bulletins. The main objective of this study is to investigate the seasonal variations in the detection capability of this network along with the prevailing stratospheric winds.
CONSTRUCTION OF 3D PROPAGATION TABLES FOR LOCALIZING INFRASONIC EVENT

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Keywords: infrasound, propagation, phase identification, localization

A method to build infrasound propagation tables, station and time dependent, is introduced. Tables are based on simulations carried out using the WASP-3D paraxial ray-theory based method (Windy Atmospheric Sonic Propagation) which account for the temporal and longitudinal variations of the horizontal wind terms along the ray paths.

The calculated tables describe the spatial variations of the main infrasound observables over a grid source centered on the receiver. Hence, such tables offer an unique snapshot on range-dependent infrasound propagation for each type of simulated phases. Parameters such as celerity, azimuth deviation, attenuation and turning height are thus predicted for all simulated ray trajectories. They are used for the purpose of phase identification and to improve the accuracy of the source localization.

As examples, propagation tables built for IMS stations nearly located along a meridian – I18DK, I51UK, I25FR, I08BO, I01AR, I02AR and I54US are compared. Results obtained using the MSISE90/HWM-93 and ECMWF atmospheric models are discussed considering different periods of the year and times of day.
Session VI: Signals, Sensors and Wind Noise Reducing Systems
Chairs: Douglas Christie & Henry Bass
Nearly ten years ago, none of the 60 infrasound stations belonging to the International Monitoring System (IMS) Network of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) existed. Since then, a significant effort has been made to establish the Infrasound Network, which now has 63% of its stations operational.

The increased number of stations, located all around the world, has permitted to detect several types of events, both man-made and natural, in very different geographical areas, opening the way to a broader analysis of the performance of the Infrasound Network.

It is becoming everyday more clear that the potential for detection of events of the IMS Infrasound Network is very high.

In particular, it has been repeatedly observed that, besides its mandate, to monitor the potential occurrence of nuclear tests and verify compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) together with the other verification technologies, the IMS Infrasound Network has the potential to provide a significant contribution to the monitoring of volcanic eruptions around the world.

A number of examples of events detected by the IMS Infrasound Network is presented.
RECENT PROGRESS IN WIND NOISE REDUCTION AT INFRASOUND MONITORING STATIONS

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Wind-generated background noise is a potentially serious problem at many infrasonic monitoring stations. Wherever possible, IMS infrasound stations have been located in forests in order to shield the station from wind-generated turbulence. However, it has been necessary in some cases to establish stations in areas with little, if any, protection from the ambient wind. For example, a significant number of stations are located on remote wind-swept islands, in desert and semi-desert areas and in the ice-covered wastes of the polar regions. Even stations that are located in forests may be subject at times to unacceptably high levels of background noise, especially if the array elements are located near the edge of the forest, or if the area around the array elements has been cleared.

Up until now, wind-noise reduction at IMS infrasound stations has been achieved by using a carefully designed pipe array connected to the microbarometer sensor at each array element. These noise-reducing arrays are constructed from either a number of porous hoses arranged in a radial pattern or a series of pipes connected to a large number of low impedance discrete inlet ports. Wind-noise-reducing pipe arrays are very effective in modest winds. However, these pipe arrays fail to provide adequate noise reduction for reliable signal detection in most environments when the ambient winds at a height of 2.0 m exceed a few m/s. It seems unlikely that existing pipe array designs can be improved significantly since the number of inlet ports and the area covered by the pipe array have reached practical limits. Wind noise reducing pipe array systems also have some disadvantages. The response of these systems is not always well known. In addition, they may be subject to unwanted resonances and may distort and attenuate higher frequency signals.

A preliminary report on a new approach to the problem of wind noise reduction was presented at the 2006 Infrasound Technology Workshop in Fairbanks Alaska. This new approach is focussed on techniques which reduce wind noise levels by degrading turbulent eddies that generate noise in the primary monitoring passband using turbulence-reducing structures constructed from robust screens stretched over a rigid framework. A wide variety of turbulence-reducing enclosures have been tested during the past year and this has led to a highly efficient design consisting of a number of chambers and baffles with excellent noise-reducing performance characteristics. The design and performance of this effective wind noise-reducing system will be described in detail. It will be shown that this system can be used to substantially enhance the performance of existing IMS pipe arrays or, in some cases, as a very efficient stand alone wind-noise-reducing system that does not require a pipe array.
A ROTARY SUBWOOFER AS AN INFRASONIC SOURCE

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Infrasound Laboratory
HIGP, SOEST, University of Hawaii, Manoa

A stable, portable infrasound source would provide a valuable tool for the free-field calibration of distributed infrasonic sensors and wind noise reduction systems. Such a source may also allow atmospheric soundings and a statistical evaluation of waveguide transfer functions. A commercial off-the-shelf rotary subwoofer intended for enhancing high-fidelity home theatre systems is presently being evaluated as an infrasonic source. We present preliminary results for its electrical to acoustic transfer functions (amplitude and phase input-output relations) between 1 and 20 Hz, and characterize the spatial radiation pattern into free space.
HURRICANE STUDIES USING INFRASOUND

Claus Hetzer, Roger Waxler, Carrick Talmadge, Ken Gilbert, Henry Bass
National Center for Physical Acoustics
University of Mississippi
Jay Williams, Gary Harrington
Miltec Research & Technology, Inc.

Under quiet conditions, the microbarom noise peak at 0.2 Hz is observed worldwide on infrasound stations. This peak is understood to be associated with interacting ocean surface waves. It is well known that the intensity of microbaroms (and microseisms) increases dramatically on inland infrasound stations when a hurricane is offshore and within a few thousand kilometers. A hurricane thus provides a useful means for investigating the fundamental mechanisms for microbarom and microseism generation. We review recent infrasound and seismic data and examine existing theories for the generation of microbaroms by ocean waves. In particular we examine two possible models for the generation of hurricane microbaroms. In the first model the microbaroms are generated near the eye of the hurricane, while in the second they are generated by counterpropagating wave fields created by the hurricane but relatively far from the eye. Bearing data from infrasound stations will be presented that appear to support the second model.
In order to simplify absolute infrasound sensors installation and operation, DASE has given some modifications to these sensors. First, MB2005 microbarometer power consumption has been reduced to less than 1.5 W instead of 3 W. Its input voltage range has been increased to [9 36] V.

DASE also developed a new sensor from MB2005 microbarometer and from the seismic sensors it manufactures. This sensor consists in improved mechanics from MB2005 and in a movement transducer which allows it to provide a voltage directly proportional to variations in pressure all over IMS bandwidth and even more: sensor response phase is purely independent from environment (temperature, condensation…) all over IMS bandwidth. Moreover, thanks to its very simple design this sensor needs very low power and is lighter, smaller and less expensive than previous generation sensors. In order to simplify its deployment, it can be installed everywhere all over the word without mechanical adjustment and can be calibrated from the acquisition unit. Associated with new low power acquisition units, this results in a portable measuring chain well adapted to IMS requirements.
RESOLVING INFRASOUND BACK AZIMUTH WITH ARRAYS OF OPTICAL FIBER INFRASOUND SENSORS (OFIS): LOW WIND NOISE, SUPERB BACK AZIMUTH RESOLUTION, AND A COMPACT DESIGN

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Institute of Geophysics and Planetary Physics, University of California, San Diego

The detection of infrasound in the presence of wind is challenging. Increasing wind speeds lead to higher noise floors. While the exact nature of the noise is still a subject of investigation, several technologies and array configurations have been developed in an effort to maximize the signal to noise ratio and lower the signal detection threshold. Optical fiber infrasound sensors (OFIS) are compliant tubes wrapped with two optical fibers that integrate pressure change instantaneously along the length of the tube with laser interferometry. Spatially incoherent wind noise is naturally attenuated relative to spatially coherent infrasound. Because the signal pressure variation is integrated along the length of the tube, the instrument response is a function of the orientation of the OFIS arms relative to the orientation of the infrasound wavefront. We show with theory, synthetic data, and real infrasound data recorded at Piñon Flat Observatory in southern California that this spectral property can be exploited with multiple OFIS arms in different ways to determine the phase velocity direction (back azimuth and elevation angle) of infrasound signals with an accuracy and precision at least equal to a larger aperture 18-meter rosette pipe array. We determine the optimum of these methods, and also derive and demonstrate a new deconvolution technique for removing the instrument response to accurately recover the true infrasound signal. The additional spectral resolution of the phase velocity direction and the favorable known wind noise reduction properties of the OFIS permit us to propose two hypothetical OFIS configurations that should perform at least as well as (and probably better than) rosette pipe arrays while occupying less area.
THE INFRASOUND DATABASE OF THE SMDC MONITORING RESEARCH PROGRAM

J. Roger Bowman, Gordon Shields, Michael S. O’Brien and Hans Israelsson
Science Applications International Corporation

The Infrasound Database contains information on atmospheric and subsurface events that produced infrasound recorded by microbarographs. As of August 2007, the database includes 239 events of eleven source types, including 22 historical nuclear explosions, 112 mine blasts, 28 other chemical explosions, 24 bolides, and 24 explosive volcanic eruptions. It contains source locations and origin times with related metadata, associated parametric data, such as arrival times and azimuths of observed signals, and associated waveform data for those stations having open data distribution policies. A systematic approach for establishing and documenting the accuracy of ground truth source parameters has been developed and applied.

About half the event and arrival attributes derive from a standardized methodology for establishing origin metadata and analyzing signals. This provides a consistent set of attributes that allows comparisons across the database. The precisely defined origin uncertainties mean the events can reliably be used in location and meteorological model studies. Consistently calculated signal features provide a basis for a systematic analysis of signal properties.
M-SEQUENCES AND AN ARRAY OF SPEAKERS FORM A SENSOR CALIBRATOR DOWN TO 8 Hz: APPLICATION TO THE OFIS AT THE NEW CAMP ELLIOTT OFIS ARRAY

Kristoffer Walker, Matt Dzieciuch, Mark Zumberge, and Scott DeWolf
Institute of Geophysics and Planetary Physics, University of California, San Diego

Optical fiber infrasound sensors (OFIS) are long compliant tubes wrapped with two optical fibers that integrate pressure variation along the length of the tubes via laser interferometry at the speed of light. We have previously shown techniques that use several OFIS arms to resolve the back azimuth and elevation angle of infrasound signals. These techniques rely on our ability to predict accurately the impulse response of the OFIS as a function of frequency and angle between the incoming signal and the OFIS. In this paper, we show that M-sequences transmitted by a square array of eight, 500-Watt subwoofers can generate infrasound down to 8 Hz with good signal to noise ratio at a range of at least 250 meters. We were not able to detect signals below 20 Hz with a single subwoofer, which suggests that either the additional source power or the larger effective source dimension of the array is the key to the success of this technique in the infrasound band. Using this calibrator, we were able to (1) calculate the OFIS impulse response at several angles and frequencies, (2) investigate the coherence time of the atmosphere over several days, and (3) compare different sensors and wind filters for wind noise reduction. These are preliminary results of an ongoing investigation at our new five-arm OFIS array at Camp Elliott, just north of San Diego.
RECENT DETECTED EVENTS BY PMCC ANALYSIS AT IS30, ISUMI, JAPAN

Nobuo Arai, Takahiko Murayama and Mami Nogami

Japan Weather Association

We are analyzing the observed data at IS30 by autoPMCC automatically everyday. AutoPMCC analysis started from March 2007, we now have been detecting many signals, which are frequency 0.01 Hz to 4 Hz. We have identified these signals generated by large earthquakes, thunders, rockets, eruptions of volcano, low pressure systems, airplanes and so on.

We prepared autoPMCC’s output from March to October, 2007. We have been analyzing some of these in detail by using winPMCC, but most of daily signals have not been identified yet. We are looking forward to discussing these detected signals with all of participants.

Acknowledgment:
We’d like to say to thank again France CEA and Dr. Le Pichon by installing this software, teaching us how to set some parameters and analyze the detected signals.
### Schedule

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00</td>
<td>Pick-up at Hotel Bellclassic Tokyo and Departure</td>
</tr>
<tr>
<td>10:30-11:15</td>
<td>Visit to Kasamori Kan-non (Temple)</td>
</tr>
<tr>
<td>11:30-12:30</td>
<td>Lunch at Restaurant in Isumi City</td>
</tr>
<tr>
<td>12:30-14:00</td>
<td>Visit to Infrasound Station “IS30”</td>
</tr>
<tr>
<td>14:20-15:00</td>
<td>Visit to Otaki Castle</td>
</tr>
<tr>
<td>15:00-15:40</td>
<td>Summary of Results, Closing Address at Meeting Hall beside the Castle</td>
</tr>
<tr>
<td>16:40-17:30</td>
<td>Visit to “Umi-hotaru”</td>
</tr>
<tr>
<td>19:00</td>
<td>Return to Hotel Bellclassic Tokyo</td>
</tr>
</tbody>
</table>
**Information**

**Kasamori Kan-non(Temple)**
Kasamori-Kannon was founded by Saicho (the founder of the Tendai Sect of Buddhism) in 784 A.D. with an image of an eleven-faced Kan-non (Goddess of Mercy) enshrined at the top of the mountain. Kan-non-Do (the temple dedicated to Kan-non) was build by the direct order of Emperor Go-ichijo in 1028 A.D., and is registered as national important cultural property.

**Infrasound Station “IS30”**
The infrasound array station IS30 is one of 60 infrasound stations of the IMS(International Monitoring System). IS30 is located in Isumi-town where is in the middle-east of the Boso peninsula in the Chiba Prefecture approximately 60 km south east of Tokyo. This region has many rice paddies on the flat valley plains and cedar and bamboo groves on and around the surrounding hills. The IS30 was installed between 2004 and 2005 and certified as IMS infrasound station in March 2005 by CTBTO/PTS/IMS. This infrasound station comprises a 6-element array. Five elements are arranged in an irregular pentagon with sides approximately 1.2 km long. IS0H1 element is located within the pentagon. All array elements are located within cedar and bamboo, and that area is about 20 m squares. Each array element comprises a wind-noise-reducing pipe array.
Otaki Castle
It is said that this castle was constructed by a warlord Nobukiyo Mariyatu in 1521, and the castle was located on other small hill rather than current hill at that time. But his heir Tomonobu Mariyatu lost the castle to warlord the Satomi’s general Tokishige Masaki in 1544. Then, the castle was passed from father to son for three generations.
Because the Satomis was expropriated their territory in 1590, founder of the Edo Shogunate Ieyasu Tokugawa’s general Tadakatsu Honda became its owner. Tadakatsu reconstructed the castle considerably including addition of large castle tower and constructed the town around the castle. After that, this castle had played an important roll as the base of administration for long time.
But the castle tower was burnt down in 1842, and then the castle was eliminated in 1868 because of the Meiji Restoration. The current castle tower was reconstructed as museum in 1975.

Umi-hotaru
"Umi-hotaru (Sea-firefly in English)" is an artificial island with a rest area consisting of restaurants, shops and amusement facilities. This island locates on the bridge-tunnel crossover point of the “Tokyo Bay Aqua-Line” which is highway crossing Tokyo bay. You can enjoy 360-degree panoramic views at mid of Tokyo bay.