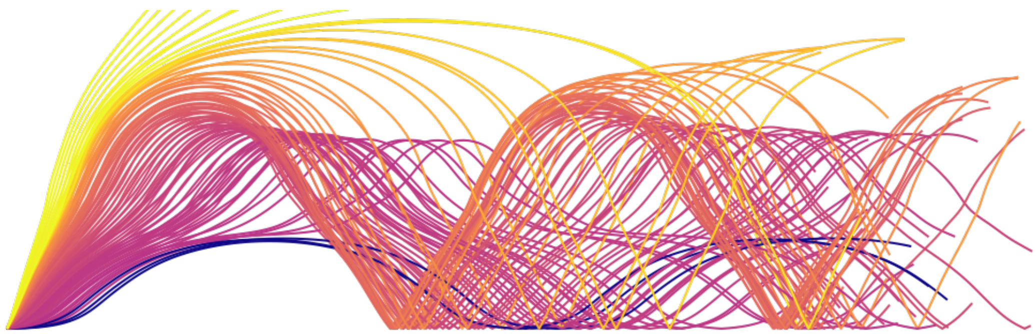
LETMA
MODELLING INFRASONIC PROPAGATION

LABEX CELYA
UNIVERSITÉ DE LYON



Waves & geosciences: Infrasound and beyond

Book of abstracts

Spring School, March 28th - April 1st, 2022, Lyon, France

Welcome

The spring school is organized by LETMA (Laboratoire Etudes et Modélisation Acoustiques) and the Labex CeLyA (Lyon Acoustics Center), which is a network linking together the researchers working in acoustics and vibration around Lyon.

LETMA
MODELLING INFRASONIC PROPAGATION

LETMA was created in March 2015 by four leading research institutions in France: the French Alternative Energies and Atomic Energy Commission (CEA), the French National Centre for Scientific Research (CNRS), Centrale Lyon and Sorbonne University. LETMA's research activities fall within the domain of low-frequency acoustics. The main objective of LETMA is to carry out basic research on infrasound propagation modelling in complex media, at different scales, and on applications of the results of that research. Infrasound are low-frequency sounds that are produced by a variety of geophysical processes including earthquakes, severe weather, volcanic activity, ocean waves, turbulence aloft, meteors and also by some man-made sources such as aircraft and explosions. Researchers collaborate with other organizations, other universities, and foreign scientists in a variety of fields that are related to fluid mechanics, computational physics, applied mathematics and geosciences. LETMA provides significant educational opportunities for students and postdocs.

Waves & geosciences: Infrasound and beyond - Program				
Monday March 28	Tuesday March 29	Wednesday March 30	Thursday March 31	Friday April 1
	08:00 - 08: 30 Welcome coffee	08:00 - 08: 30 Welcome coffee	08:00 - 08: 30 Welcome coffee	08:00 - 08: 30 Welcome coffee
	08:30 - 10 :00 Physics of infrasound propagation R. Waxler (NCPA)	08:30 - 10 :00 Presentations on LETMA's activities	08:30 - 10 :00 Contributed presentations	08:30 - 10 :00 Data assimilation O. Marsden (ECMWF)
	Coffee Break	Coffee Break	Coffee Break	Coffee Break
	10:30 - 12:00 Uncertainty quantification O. Le Maitre (CMAP)	10:30 - 12:00 Presentations on LETMA's activities	10:30 - 12:00 Machine learning in geosciences (online) S. Hosking (BAS)	10:30 - 12:00 Inverse problems for atmospheric dispersion L. Soulhac (LMFA)
13:00 - 14:00 Welcome coffee - Introduction	12:00 - 14 :00 Lunch break	12:00 - 14 :00 Lunch break	12:00 - 14 :00 Lunch break	12:00 - 14 :00 Lunch break
14:00 - 15:30 Atmosphere, structure and dynamics P. Salizzoni (LMFA)	14:00 - 15:30 Detection algorithm for infrasound A. Le Pichon (CEA) M. Charbit (Telecom Paris)	14:00 - 16:00 Lab session 1	14:00 - 15:30 Lightning T. Farges (CEA) F. Coulouvrat (SU)	
Coffee Break	Coffee Break	Coffee Break	Coffee Break	
16:00 - 17:30 CTBTO and advances in infrasound monitoring P. Mialle (CTBTO)	16:00 - 17:30 Infrasound sources in geosciences J. Assink (KNMI)	16:30 - 18:30 Lab session 2	16:00 - 17:30 Volcano acoustic M. Ripepe (Firenze U.)	
17:30 - 18:30 Gravity waves (online) A. de la Camara (UCM)			Gala dinner	

Lab session: 1. Infrasound detection, association and data analysis - J. Vergoz (CEA)
2. Infrasound propagation modeling (platform LETMA) - C. Khodr (LMFA)

Committees

Scientific organizing committee

Philippe Blanc-Benon, CNRS Director of Research - Centrale Lyon
François Coulouvrat, CNRS Director of Research - Sorbonne University
Didier Dragna, Assistant Professor - Centrale Lyon
Thomas Farges, Research Engineer - CEA
Regis Marchiano, Professor - Sorbonne University
Christophe Millet, CEA Director of Research - CEA

Local organizing committee

Philippe Blanc-Benon, Centrale Lyon
Agnès Delebassée-Nabet, Labex CeLyA
Didier Dragna, Centrale Lyon
Codor Khodr, Centrale Lyon
Marie-Gabrielle Perriaux, Centrale Lyon
Laurent Pouilloux, Centrale Lyon
Carine Zambardi, Labex CeLyA

Sponsors

The Spring School was organized thanks to the funding received from CEA and Labex CeLyA. The organizing committee would like also to acknowledge the financial support of Sorbonne-Université, Centrale Lyon and Région Auvergne-Rhône-Alpes.

Program of the spring school

Monday 28 March, 2022

Chair Person: Christophe Bailly

14:00	**Atmosphere, structure and dynamics** P. Salizzoni	8
15:30	Coffee break	
16:00	**CTBTO and advances in infrasound monitoring** P. Mialle	9
17:30	**Gravity waves** A. de la Cámara	10

Tuesday 29 March, 2022

Chair Persons: Christophe Millet, François Coulouvrat

08:30	**Physics of infrasound propagation** R. Waxler	11
10:00	Coffee break	
10:30	**Uncertainty quantification and Bayesian calibration in computational geosciences** O. Le Maître	12
12:00	Lunch break	
14:00	**Algorithms for infrasound detection and wave parameter estimation: state-of-the art and new approaches** M. Charbit, A. Le Pichon	13
15:30	Coffee break	
16:00	**Infrasound sources in geosciences** J. Assink	14

Wednesday 30 March, 2022

Chair Person: Regis Marchiano

08:30	**Presentation of LETMA's activities I**	15
10:00	Coffee break	
10:30	**Presentation of LETMA's activities II**	15
11:30	**Flash poster presentation**	18
12:00	Lunch break	
14:00	**Lab session I**	21
16:00	Coffee break	
16:30	**Lab session II**	21

Thursday 31 March, 2022

Chair Persons: Thomas Farges, Daniel Juvé

08:30	**Contributed presentations**	22
10:00	Coffee break	

10:30 **Machine learning in geosciences** 23
S. Hosking

12:00 Lunch break

14:00 **Lightning** 24
T. Farges, F. Coulouvrat

15:30 Coffee break

16:00 **Volcano acoustic** 25
M. Ripepe

Friday 1 April, 2022

Chair Person: Philippe Blanc-Benon

08:30 **Data assimilation** 26
O. Marsden

10:00 Coffee break

10:30 **Inverse problems for atmospheric dispersion** 27
L. Soulhac

12:00 Lunch break

Monday 28 March, 2022 - 14:00 / 15:30

Atmosphere, structure and dynamics

Pietro Salizzoni (LMFA, Centrale Lyon, France)

The Earth's atmosphere is a unique environment, within which take place a huge variety of physical phenomena. Among these, our focus is on those that produce the climatic and meteorological conditions having a direct impact on our every day life. Radiative properties of the atmosphere, as determined by its chemical composition, play an essential role in mitigating the climatic condition on Earth. Simple mathematical model of these transfers enlighten the role of the atmosphere in warming the Earth surface, through the well known green-house effect, and allow for a relatively accurate estimate for the height of the troposphere, the region within which most of meteorological phenomena occur. To obtain realistic estimate of the vertical temperature gradient within the atmosphere, we have however to include another phenomenon, notably the heat (sensible and latent) transfer between the earth surface and the lower atmosphere. This forcing gives rise to a complex motion of masses of air on a wide variety of temporal and length scale, which is in turn deeply affected by the rotation of Earth. The latter is responsible for the characteristic dynamics that can be observed at the synoptic scales: the recirculation of cyclones and anticyclones, the rising of high altitude air streams (characterised by very intense velocities), and the occurrence of large scale waves surrounding the polar regions. The modelling of the dynamics of the atmosphere represent nowadays several challenges. Most of these deal with dynamical and thermodyanmical phenomena related to the changing state of water, that further amplify the complexity of the turbulent atmospheric motions, and call into question our ability in making prediction both for short term weather forecasts and long term climate scenarios.

About the speaker:

Pietro Salizzoni holds a Bachelor degree in Environmental Engineering from Politecnico di Torino and a PhD in Environmental Fluid Mechanics. He is currently Professor at École Centrale de Lyon. His teaching and research activities address physical phenomena associated with natural and technological risks, both accidental and persistent, with a focus on the dynamics of environmental flows. In particular, his studies deal with pollutant dispersion in the urban atmosphere, the propagation of hot smokes in free and confined environments, the ventilation of road tunnel in case of fire, the characterization of atmospheric dispersion of toxic and flammable substances, the transfer within the environment and food chain of dioxin and other persistent organic pollutants.

Monday 28 March, 2022 - 16:00 / 17:30

CTBTO and advances in infrasound monitoring

Pierrick Mialle (CTBTO, Austria)

For 25 years, the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) operates the International Monitoring System (IMS), which comprises four networks with different sensor technologies: seismic, hydroacoustic, infrasound and radionuclides (Kalinowski and Mialle, 2021). The purpose of the IMS sensor network is to detect, identify and locate nuclear explosions underground, underwater or in the atmosphere. Upon completion, the infrasound component of the IMS network will consist of 60 infrasound stations to survey the atmosphere of which 53 are operational as of March 2022. In 2001, when the first data from an IMS infrasound station started to arrive in near real-time at the International Data Centre (IDC), its infrasound processing system was in a premature state. The IDC embarked for a multi-year design and development of its dedicated processing system, which led to operational IDC automatic processing and interactive analysis systems in 2010. In the next ten years the IDC produced over 40,000 infrasound events reviewed by expert analysts.

In an effort to continue advancing its methods, improving its automatic system and providing software packages to CTBTO users, the IDC focuses on several projects. First, the automatic system for the identification of valid signals that has been redesigned with the development of DTK-(G)PMCC (Progressive Multi-Channel Correlation) in collaboration with the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), and which is made available to CTBTO users within NDC-in-a-Box. And second in order to replace its legacy network processing system, an infrasound model was developed for the automatic waveform network processing software NET-VISA with an emphasis on the optimization of the network detection threshold by identifying ways to refine signal characterization methodology and association criteria.

Ongoing and future improvements of the IDC processing system are planned to further reduce IDC analyst workload and offer better capabilities to CTBTO users that includes atmospheric propagation modeling and enhancements of the automatic pipeline components.

About the speaker:

Pierrick Mialle is seismic-acoustic officer at the Comprehensive Nuclear-Test-Ban Treaty Organization in Vienna. Since 2008, he is a scientist and project manager at the International Data Centre (IDC) with a focus on infrasound technology. He leads the IDC infrasound programme. His area of expertise includes waveform data processing, the study of natural and man-made events using infrasound technology. He also has a strong interest for civil and scientific applications using CTBT data and products. Prior to that Pierrick Mialle was a researcher at the Commissariat à l'Energie Atomique et aux Energies Alternatives (Atomic Energy and Alternative Energies Commission) in France.

Monday 28 March, 2022 - 17:30 / 18:30

Gravity waves

Alvaro de la Cámara (Universidad Complutense de Madrid, Spain)

Gravity waves in the atmosphere are oscillations maintained by the vertical stratification of density in the atmosphere. They have spatial scales that range from tens to hundreds of kilometers, which makes their observation a challenge. Observational platforms typically have to decide between spatial coverage (regional versus global) and resolution (capturing the full spectrum versus just the larger scales). Their effects on atmospheric dynamics are multiple; they interact with turbulence in the planetary boundary layer, with cirrus cloud formation in the upper troposphere, modify the paths of infrasound propagation, or maintain a much warmer wintertime mesopause than the summer counterpart, just to mention a few.

This presentation will provide an overview of the general characteristics of atmospheric gravity waves, some of their impacts on the circulation of the atmosphere, and the treatment they require in general circulation models.

About the speaker:

Alvaro de la Cámara is an associate professor with the Department of Earth Physics and Astrophysics at Universidad Complutense de Madrid, Spain. Before, he worked as a postdoctoral researcher at LMD and CMLA (CNRS) in France, and NCAR (National Center for Atmospheric Research) in the USA. His research interests and experience are on the topics of middle atmospheric dynamics and modeling, including stratosphere-troposphere interactions, climate variability and gravity wave parameterizations for climate models.

Tuesday 29 March, 2022 - 8:30 / 10:00

Physics of infrasound propagation

Roger Waxler (NCPA, USA)

The physics of infrasound propagation in the atmosphere will be discussed. Fluid Mechanics, in which sound arises as compression/rarifaction waves, will be taken as the fundamental, underlying physical model. The linear approximation to the equations of Fluid Mechanics will be introduced. It will be seen that superposition and spectrum preservation are features of the linear approximation, and thus approximations themselves. Non-linear corrections will be touched upon. We will then focus on the linear approximation. Acoustic attenuation will be introduced and its physical basis described. Sound propagation models will then be developed. Refraction by temperature gradients and by wind shear will be illustrated using propagation models. This will require specification of the atmospheric state at the time of propagation. The prominent features of the Earth atmosphere, and their role in infrasound propagation will be discussed as will the available atmospheric specifications. Finally, we will discuss the role of non-linearity in atmospheric infrasound.

About the speaker:

Roger Waxler is a Mathematical Physicist by training who started his scientific career proving theorems about mathematical problems that arise in Quantum Mechanics. He drifted into Atmospheric Acoustics a bit more than twenty years ago and was delighted to see that much of the mathematics needed was similar to that used in Quantum Mechanics. Since then he has been involved in the development of the NCPAprop infrasound propagation sofware package. He has taken part in the design and execution of numerous field experiments, and has learned just enough signal analysis to deal with the resulting data.

Tuesday 29 March, 2022 - 10:30 / 12:00

Uncertainty quantification and Bayesian calibration in computational geosciences

Olivier Le Maître (CMAP, France)

Uncertainty quantification (UQ) is crucial to simulations in geo-science. The last decade has witnessed the fast emergence of large-scale simulation infrastructures (HPC) and experimental capabilities (monitoring, imaging). This progress has raised the expectation of effectively improving numerical predictions by relying on complex computational models calibrated on massive measurements. Unfortunately, these promises remain out of reach and do not transform into reality. This presentation will show several advanced UQ techniques and calibration approaches applied to geoscience problems. These examples are selected to illustrate the need for holistic approaches in predictive simulations and the risk of focusing on one specific aspect (physical modeling, numerical modeling, or data collection) rather than balancing their respective contributions.

About the speaker:

Olivier Le Maître is a CNRS senior researcher at the Center for Applied Mathematics of the Ecole Polytechnique (France). Before joining CNRS in 2009, he was a Professor Assistant in the Mechanical Engineering Department of the University of Evry Val d'Essonne (France). Affiliated to LIMSI from 2009 to 2019, he held multiple visiting research and professor positions at Johns Hopkins University and Sandia National Laboratories. From 2013 to 2015, he was Visiting Professor at Duke University and Visiting Faculty at the King Abdullah University of Science and Technology (KAUST). He is currently a permanent member of the joint Inria-CNRS-Polytechnique team PLATON. After a Ph.D. (1998, Université du Havre, France) on non-linear fluid-structure interaction problems, he started a long term collaboration with Pr. Omar Knio (Johns Hopkins University) on Uncertainty Quantification (UQ) with the development of stochastic spectral methods and their applications to a broad range of non-linear models. Over the years, his research has evolved to encompass sensitivity analysis, Bayesian inference, robust optimization, and other thematics related to uncertainty management. He has published more than 100 paper and his contributions range from the formulation of UQ problems to their efficient numerical solution and HPC implementations. They have been applied in several domains, including environmental and geo-sciences, fluid engineering, nuclear engineering, combustion and reactive systems, aerospace (reentry, launchers), and naval engineering.

Tuesday 29 March, 2022 - 14:00 / 15:30

Algorithms for infrasound detection and wave parameter estimation: state-of-the art and new approaches

Maurice Charbit (Institut Mines-Telecom, France), Alexis Le Pichon (CEA, France)

Infrasound are low-frequency acoustic waves with frequencies less than 20 Hz. An important property of these waves is their capability to travel through the atmospheric waveguide structure over thousands of kilometers. The infrasound technology is one component of the International Monitoring System (IMS) being used to monitor compliance with the Comprehensive Nuclear Test-Ban Treaty (CTBT). The performance of IMS infrasound network strongly depends on station-specific environmental noise, which exhibits significant spatial-temporal variation. Its detection capability is a key concern since ubiquitous coherent noise generated by repetitive natural or anthropogenic made processes interfere with the detection and identification of explosive events. The two main issues are the detection of signals of interest embedded in the background noise and the estimation of the direction of arrivals of the coherent waves. The need to distinguish between incoherent wind noise and real coherent infrasonic wave signals has motivated the development of different approaches.

We first review state-of-the-art methods which include the Time Difference Of Arrival (TDOA) method on which the Progressive Multi-Channel Correlation (PMCC) is based, beamformer and focusing techniques, as well as algorithms based on subspace decomposition developed initially for multi-source narrowband signals (e.g. MUSIC, CLEAN). We also present new results derived from the likelihood function of a parametric stochastic model. We establish the expressions of both the Generalized Likelihood Ratio Test (GLRT) and the Maximum Likelihood Estimator (MLE) of the wavefront parameters (e.g. back-azimuth, trace velocity). The major results are on one hand the expression of the asymptotic distribution of the GLRT under null hypothesis (absence of spatially coherent signals), leading to the p-value computation, and on the other hand the expression of the asymptotic covariance of the MLE.

The Multi-Channel Maximum-Likelihood (MCML) detection and estimation method is implemented in the time-frequency domain in order to avoid the presence of interfering signals. Extensive simulations with synthetic signals show that MCML outperforms the state-of-the-art multi-channel correlation detector algorithms in terms of detection probability and false alarm rate in poor signal-to-noise ratio scenarios. We illustrate the use of the MCML on real data from the International Monitoring System (IMS) and show how the improved performances of this new method lead to a refined analysis of events in accordance with expert knowledge.

About the speakers:

Maurice Charbit is a Professor Emeritus at Telecom-Paris since 2013. He is also Research and Development Officer at OZE-energies, since October 2016 for energy/comfort management of office buildings. He has been a consultant with CEA since 2010 and was a consultant for CTBT in Vienna in 2016, 2017 and 2018. His domains of interest cover statistics for signal processing, array processing and data sciences.

Alexis Le Pichon is geophysicist at CEA, in charge of Infrasound research activities on topics relevant to Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), including operation of low-frequency microphone arrays, automated signal processing for detection and source location or atmospheric remote sensing methods. He received in 2003 the award Science and Defence, delivered by Ministry of Defence for the development and optimization of infrasound monitoring techniques at CEA DAM.

Tuesday 29 March, 2022 - 16:00 / 17:30

Infrasound sources in geosciences

Jelle Assink (KNMI, Netherlands)

Infrasound waves are low-frequency acoustic waves with frequencies between 3 mHz and 20 Hz, which are inaudible to humans. Because infrasound waves undergo very little absorption, infrasound can propagate over thousands of kilometers through atmospheric waveguides. The atmospheric 'soundscape' consists of contributions from both geophysical and man-made infrasound sources, that can be detected across the infrasonic frequency band as small-amplitude pressure waves, even over very large distances. Sensitive barometers, or microbarometers, are used for the detection of infrasound waves. At longer ranges, infrasound arrays are in place to detect coherent infrasound with amplitudes below the noise level. Over the past decades, infrasound has evolved as a monitoring technique for various sources of interest, including volcanoes, meteors, earthquakes and calving glaciers. The International Monitoring System (IMS) that has been installed for the verification of the Comprehensive-Nuclear-Test-Ban-Treaty (CTBT) has been the backbone for much of the infrasound research around the world. In this lecture, we will review several sources that are routinely detected on the global infrasound network. The elegance of infrasound is that it is a passive monitoring technique that allows one to learn something about a geophysical source by simply listening to it. The available datasets allow for studies with temporal resolutions ranging from seconds to decades, which begin to allow for climatological studies.

About the speaker:

Jelle Assink is a Senior Geophysicist with the Seismology and Acoustics department at the Royal Netherlands Meteorological Institute (KNMI). He makes use of seismic and acoustic data for the study of these waves in the Earth, Ocean & Atmosphere. His efforts have contributed to the use of infrasound for atmospheric remote sensing, the monitoring of natural hazards and the verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). For his research, he has developed algorithms for data processing and infrasound propagation modelling. He is currently responsible for the operations of KNMI's microbarometer array network and he is interested in synergies with other measurement techniques. Before joining KNMI in 2015, he worked at the National Center for Physical Acoustics in Oxford, MS, USA and the Alternative Energies and Atomic Energy Commission (CEA) near Paris, France.

Wednesday 30 March, 2022 - 08:30 / 10:00 - 10:30 / 11:30

Presentation of LETMA's activities

This session aims at presenting the recent activities carried out within LETMA. The time allocated for each presentation is 15 minutes.

PLetma—Parallel software package for intensive infrasound simulation
Codor Khodr (LMFA, Centrale Lyon, France)

The Plateform of the Laboratory of Studies and Modeling in Acoustics (PLetma) is a suite of scientific softwares developed by the partner institutions of LETMA since 2015. Currently under development, it contains four different models, namely 3D ray-tracing, 3D non-linear one-way equation, 3D normal modes and 2D direct Navier–Stokes, as well as user interfaces for model execution and data visualization. The aim of this package is to provide a set of complementary tools for the modeling of broadband infrasound signals in a moving inhomogeneous atmosphere. It allows to cover a large panel of low-frequency propagation problems arising in geophysics or engineering. Implemented with MPI and OpenMP, the package relies on parallelism to improve computational efficiency of simulations. Comparisons between the four methods are presented for a test case on long-range infrasound propagation.

3D nonlinear propagation in heterogeneous atmosphere with the software FLHOWARD3D
Regis Marchiano (Sorbonne-Université, France)

FLHOWARD3D is a one-way numerical method developed to simulate the propagation of nonlinear waves through heterogeneous media. It has been designed to be a good tradeoff between a high-fidelity solver incorporating different physical effects and the computational time thanks to its one-way nature and its efficient parallelization. It manages diffraction, nonlinear propagation, absorption, relaxation, effects due to both scalar and vectorial heterogeneities. Therefore, it is well suited to study the propagation of low frequencies waves with high amplitude through realistic atmospheres. During the talk, the model and the numerical procedure will be explained. Then, several examples will be presented to evaluate the relevance of this method in the context of low frequency waves.

Complex ray tracing algorithm for infrasound propagation in the atmosphere
Annie Zelias (Sorbonne-Université, France)

In the framework of the Comprehensive nuclear-Test Ban Treaty, micro-barometric stations of the International Monitoring System network detect various powerful natural and anthropogenic infrasound sources. For impulsive ones recorded at distances less than thousand kilometers, stations are frequently located in geometrical shadow zones, where the ray tracing method cannot predict the acoustic signal. This can however be overcome by generalizing the method to complex ray tracing, which takes into account diffraction effects required to simulate arrivals into the shadow zone. This method is here applied to long range infrasound propagation in a stratified and moving atmosphere by a numerical algorithm computing both real and complex eigenrays. This method provides wave arrival times, azimuths, apparent velocities and over-pressures at a set of stations, including those in the shadow zone of caustics. Algorithm efficiency and robustness are illustrated by two numerical examples: explosion at a ground-based point source and the sonic boom from a meteorite atmospheric entry.

Experimental studies on the propagation and reflection of shock waves at the laboratory scale
Sébastien Ollivier (LMFA, Centrale Lyon, France)

The experimental study of the phenomena of propagation in the atmosphere or reflection on the ground of acoustic waves of high level and of finite duration such as the sonic boom or detonations (of natural or human origin) is generally difficult for several reasons: the source of noise is generally not controlled (time of appearance, position, characteristic of the source); (ii) neither the propagation medium nor the reflection surface are well characterized at acoustic scales; (iii) the ability to measure waves is limited (number of sensors, positioning, spectrum). Small-scale experiments carried out in the laboratory make it possible to observe phenomena of propagation or reflection of shock waves in a controlled environment, and provide additional information to numerical simulations and large-scale observations. We will present experimental methods and examples of results obtained with this approach.

Propagation of spherical weak blast waves over rough surfaces
Didier Dragna (LMFA, Centrale Lyon, France)

The reflection of weak blast waves over rough surfaces is analyzed. First, an experimental study at the laboratory scale is presented. Compared to a smooth reference surface, the rough surface induces a reduction of the Mach stem height. Oscillations on the pressure waveforms are observed near the surface and can induce an increase of the peak overpressure. Numerical simulations are performed and allow a good quantitative agreement with the measurements. Second, a numerical study is then carried out in order to analyze in detail the effect of roughness on the reflection pattern of a weak blast wave. The trajectory of the triple point is investigated depending on the roughness scale. The oscillations on the waveforms are related to the presence of surface wave, that propagates along the rough surface.

Propagation of uncertainty for the prediction of hurricane-induced storm surges
Pierre Sochala (CEA, France)

We present a polynomial chaos-based framework to quantify the uncertainties in predicting hurricane-induced storm surges. Perturbation strategies are proposed to characterize poorly known time-dependent input parameters, such as tropical cyclone track and wind as well as space-dependent bottom stresses, using a handful of stochastic variables. The input uncertainties are then propagated through an ensemble calculation and a surrogate model is constructed for performing the statistical analysis that includes a global sensitivity analysis. Using the ADvanced CIRCulation model, the procedure is illustrated by simulating the flooding caused by Hurricane Gustav 2008 where the track and intensity are perturbed along with the bottom friction coefficients. To extend this work, the use of infrasound may be relevant for the characterization of the uncertainties related to the track and wind field of the hurricane. Indeed, some studies have shown that relationships exist between the microbarom signal generated by storms and their forward speed and intensity.

Insight of the glacier dynamics in the region of Qaanaaq, Greenland, using infrasound data
Sentia Oger (CEA, France)

Polar ice caps represent the largest reservoir of freshwater on Earth, with ice volumes of 57.9 m and 7 m sea level equivalent. In the context of climate change, we observe an increase of ice discharge in the Ocean. In Greenland, fractures (i.e. calving) and submarin melting of marine-terminating (tidewater) glacier account for more than 80% of the Greenland ice loss. However, because the mechanisms at play are still unresolved, it is not possible to predict the future behavior of these glaciers and its associated sea -level rise. Dynamics of tidewater glaciers generate seismic waves that propagate in the atmosphere through infrasound. Consequently, infrasound data could help in detecting ice discharge and documenting the associated mechanisms, on top of existing deployed technologies. In the framework of the Comprehensive Nuclear-Test-Ban Treaty aimed to detect nuclear test explosions, an infrasound station was set up in Qaanaaq in Northwest Greenland, and certified in 2003. We show that the most detected frequencies point local glaciers, and that their mean seasonal cycle present peaks in summer, when glaciers are the most subject to an acceleration of ice flow. A comparison with ice discharge outputs from regional general circulation models confirm these findings. All together, this preliminary study gives the potential of studying infrasound data in the arm of expending our knowledge of the dynamics of tidewater glaciers.

Blast waves propagation through an uncertain stratified atmosphere

Roman Leconte (Sorbonne-Université, France)

A database of blast wave signatures from more than 600 industrial explosions has been collected by the CEA at the pyrotechnic site of Rivesaltes between 2015 and 2018. The signatures were recorded at stations located between 300 m and 20 km from the source. Source characteristics, topography and meteorological conditions at different positions and altitudes are available. In this presentation, the source and meteorological conditions are first described. The temperature and wind speed profiles are divided into 3 groups according to the wind speed: the "upwind" group, the " weak wind" group and the " downwind" group. For the "upwind" group, a simulation of the propagation is calculated for 20 atmospheric profiles and the results are compared to the measurements. In a second part, a statistical study is performed. In order to minimize the number of random variables, the atmospheric profiles are parameterized by a Principal Component Analysis (PCA), and two variables are considered sufficient to statistically describe the observed variations. A quantification of the uncertainty is then performed with the generalized polynomial chaos (gPC) method, and a good agreement is found between the model and the measurements.

Wednesday 30 March, 2022 - 11:30 / 12:00

Flash poster presentation

Acoustical characterization of lightning flash: three-dimensional distribution of thunder radiation
Damien Bestard (Sorbonne-Université, France)

From September 13th to October 12th 2018, the EXAEDRE field campaign took place in Corsica, dedicated to the characterization of thunderstorm clouds and electrical activity. Among a wide range of observation instruments, an array of 4 microphones, arranged on a 30-m wide triangle located near the island eastern coast, recorded with a sampling frequency of 250 Hz the acoustical signal, or thunder, associated to lightning flashes. The search for coherent signals between the four sensors within prescribed frequency bands allows to reconstruct in three dimensions the various positions of coherent sound sources within a single lightning flash. The detection algorithm PMCC also provides the various RMS pressure levels of each detection. Assuming each sound point source radiates a spherical wave in a homogeneous atmosphere, propagation attenuation can be compensated so that the thunder source powers can also be localized within the flash with their absolute levels. In some cases, surprisingly strong heterogeneity is observed with most of the power located in only a little portion of the return stroke.

Towards forecasting geophysical data using Koopman autoencoders
Xavier Cassagnou (CEA, France)

In the context of the verification regime for the Comprehensive Nuclear-Test-Ban Treaty, the International Monitoring System is made of over 300 stations worldwide to detect signs of nuclear explosions. The collected data can also be used to spot earthquakes, eruptions... or prevent tsunamis. In this work, we train an interpretable machine learning model for capturing the predictive components of signals (turbulence related noise and recurrent events such as volcanos, microbaroms, etc.), to facilitate categorization. We based our theoretical approach on approximation of the Koopman operator, using an autoencoder architecture. Further, we have used the Takens Embedding theorem to represent the observable as a sequence of real inputs of the neural network (i.e. the autoencoder). It is proved that the Koopman operator of the embedded dynamical system is spectrally equivalent to that of the original system. We present results for linear systems (pure point spectrum), Lorenz system (continuous spectrum) and real-world data. Through intensives simulations, we show the influence of hyperparameters on the prediction performance, and on the capacity of the autoencoder to restore the spectral properties of the system.

From acoustic waves modeling to the study of the earth's atmosphere
Solène Gerier (ISAE-SUPAERO, France)

Infrasound, in their generality, can be perceived as the marks of events. It is possible, thanks to the Navier Stokes equations, to model their propagation over several hundred kilometers. Our objective is to model the infrasound emitted by real events such as the Flores earthquake and the Tonga eruption. Moreover, the propagation of infrasound is different according to the characteristics of the atmosphere. We aim here to invert the Navier-Stokes equations to study and characterize more finely the atmosphere.

Influence of an embedded Structural Health Monitoring (SHM) system into a Carbon Fiber Reinforced Polymer (CFRP) on the ultrasound transduction

Nina Kergosien (LTDS, Centrale Lyon - ONERA - CEA, France)

Composites represent approximately 50% of the weight of structural parts in new aircrafts. Damages could occur on these parts and their monitoring is required for the safety of users. Companies set up maintenance and in order to improve their methods, design a monitoring suitable to each aircraft. A solution is the use of a Structural Health Monitoring (SHM) system composed by a Lamb's waves generator and a sensor. This system allows detecting such damages in real time or inspecting airplane structure parts that are not accessible by standard Non-Destructive Testing (NDT) inspections. This study interests in the influence of the SHM system integration, on the transducer properties and on the ultrasound transduction.

In-situ calibration and modelisation of infrasound wind noise reduction systems

Samuel Kristoffersen (CEA, France)

Infrasound stations, including the those of the IMS, are used to determine the location of infrasound sources (such as earthquakes, volcanoes, explosions etc.). The triangulation of these sources is done by considering the delay of the arrival times of the signal at several detectors at precisely known locations in an array with an aperture of typically a few kilometers. It is, therefore, of great importance that the amplitude and, especially, the phase of the signal at each detector is precisely known. Although the calibration of microbarometers can be performed in a laboratory setting, it is much more difficult to determine the transfer function of the wind noise reduction systems (designed to reduce the wind associated noise). In-situ calibration of these WNRS's can be performed using a co-located reference sensor, and comparing the response coherent to that of the array sensor to determine the relative response of the WNRS. In addition, the effects of damage or blockages in the system can have significant impacts on the response. Comparisons between models of these blockages (or other damage) and experimental results will allow for the characterization of their effects on the measurements and improvements of the models and WNRS designs. The results of these calibration experiments, and simulated blockages will be presented, as well as compared with models.

Physics-informed deep learning: application to meteorological problems

Thi Nguyen Khoa Nguyen (ENS Paris-Saclay, France)

Physics-informed deep learning (PIDL) approaches have gained much attention in various fields of engineering thanks to their capability of incorporating the physical laws into the models. However, the assessment of PIDL in meteorological applications is still an active research topic. In this work, we investigate the application of PIDL to a meteorological problem of mountain waves produced by a stratified shear flow with boundary layer. We demonstrate the effectiveness of PIDL when dealing with ill-posed and parameterized problems, which are impractical to solve by classical numerical discretization methods. The results in this work show that, in ill-posed problems where the boundary condition is unknown and only the buoyancy is measured, PIDL can successfully infer the solution for the velocity and the pressure fields. When the problem is parameterized by a parameter, we show that the algorithm is able to predict the solution for all physical fields for unseen values of the considered parameter.

The Multi-Channel Maximum-Likelihood (MCML) method: a new approach for infrasound detection and wave parameter estimation

Benjamin Poste (CEA, France)

We are presenting a new and novel approach to the detection and parameter estimation of infrasonic signals. Our approach is based on the likelihood function derived from a multi-sensor stochastic model expressed in different frequency channels. Using the likelihood function, we determine, for the detection problem, the Generalized Likelihood Ratio Test (GLRT) and, for the estimation of the slowness vector, the Maximum Likelihood Estimation (MLE). We establish new asymptotic results (i) for the GLRT under the null hypothesis leading to the computation of the corresponding p-value and (ii) for the MLE by focusing on the two wave parameters back-azimuth and horizontal trace velocity. The Multi-Channel Maximum-Likelihood (MCML) detection and estimation method is implemented in the time-frequency domain in order to avoid the presence of interfering signals. Extensive simulations with synthetic signals show that MCML outperforms the state-of-the-art multi-channel correlation detector algorithms like the Progressive Multi-Channel Correlation (PMCC) in terms of detection probability and false alarm rate in poor signal-to-noise ratio scenarios. We also illustrate the use of the MCML on real data from the International Monitoring System (IMS) and show how the improved performances of this new method lead to a refined analysis of events in accordance with expert knowledge.

Wednesday 30 March, 2022 - 14:00 / 16:00 - 16:30 / 18:30

Lab sessions

Multi-level exploration of the infrasonic soundscape with DTK software developed at CEA/DAM
Julien Vergoz (CEA, France)

DTK-GPMCC and DTK-DIVA software are developed at CEA/DAM and are routinely used by infrasound analysts of the French National Data Center. For array stations, the combined usage of both tools allows to discover the infrasonic station-dependent soundscapes, and to study signals of interest in detail. During the training session, the exploration of several months of IS22 data (IMS infrasound station located in New Caledonia) will be used to identify the different sources of coherent noise detected by this station (microbaroms, volcanoes, storms, local explosions. . .), and to understand which parameters affect the station detectability (in terms of source, propagation and background noise effects). A special focus will be given on the eruptive sequence of the Hunga Tonga Volcano (December 2021 to January 2022), which largest eruption of the episode produced the most powerful blast recorded in the last century.

Modeling an infrasound event with the PLetma package: the 2022 Hunga Tonga eruption
Codor Khodr (LMFA, Centrale Lyon, France)

The PLetma software package is an infrasound modelling tool built by the partner institutions of LETMA, with the aim to centralise infrasound modelling capabilities. Among the recent geophysical events of interest, the 2022 Hunga Tonga eruption is one of the most remarkable as it generated an important shock wave that was recorded by numerous infrasound stations around the world. The PLetma package is used to model propagation between the volcano site and the I22FR station at 1848 km to the West, where a great amount of arrivals have been identified. Finite-Difference Time-Domain simulations, based on the 2D Navier-Stokes equations, have been performed to model the infrasound component of the event, between 5×10^{-3} Hz and 0.1 Hz. Simulations suggest the presence of non-linear effects in the near field, as well as significant waveform dispersion at the receiver. In this laboratory session, a ray tracing tool will be used to further investigate the effect of local stratification of the atmosphere around the event site. Indeed, favourable propagation conditions, under the form of a strong stratospheric jet, are identified in the azimuthal direction between the Hunga Tonga site and I22FR. This leads to a number of high-amplitude stratospheric arrivals, which are the dominant effects for the distances under consideration.

Thursday 31 March, 2022 - 08:30 / 10:00

Contributed presentations

Numerical modeling of infrasonic waves in the Earth's atmosphere
Roberto Sabatini (Embry-Riddle Aeronautical University, USA)

Infrasonic waves are inaudible acoustic waves with frequencies between 3 mHz and 20 Hz. They are generated by natural events, such as volcanic eruptions or earthquakes, and anthropogenic sources, like nuclear or chemical explosions and supersonic booms. They propagate through the layers of the atmosphere up to considerable distances (from hundreds to thousands of kilometers) and potentially carry relevant information about their sources. For this reason, direct and indirect measurements of infrasound-induced disturbances constitute a unique tool for the remote sensing of natural hazards and artificial sources.

The propagation of infrasonic waves is primarily driven by the vertical gradients of the speed of sound and the winds. Nevertheless, several complex phenomena may also affect the infrasonic signals traveling through the different atmospheric layers. A non-exhaustive list includes nonlinear steepening and lengthening, diffraction at caustics, scattering or partial reflections by small-scale atmospheric turbulent fluctuations, energy absorption by viscous stresses, thermal conduction, and vibrational relaxation.

The numerical modeling of infrasound propagation has been historically based on various approximations of the Navier-Stokes or Euler equations. Among the most widely employed techniques are ray tracing, normal modes, and one-way methods. Unfortunately, albeit computationally efficient, these approaches are generally unable to account for all the aforesaid physical phenomena. For this reason, over the past decade, significant efforts have been made to carry out infrasound studies via the direct numerical resolution of the complete set of equations of fluid mechanics.

In this talk, I will summarize some of my recent investigations on the propagation of infrasonic waves based upon the direct numerical simulations of the Navier-Stokes equations. I will particularly focus on the numerical aspects of the computations as well as on selected physical phenomena not accurately predicted by classically employed approaches.

Observation and modeling of the acoustic response of the ionosphere to earthquakes and volcano eruptions
Lucie Rolland (Geoazur, France)

Natural Hazards such as earthquakes, tsunamis and volcano eruptions can strongly affect the upper atmosphere. This presentation will show how sudden coseismic motions and explosive eruptions trigger acoustic waves that propagate upwards and impact the upper atmosphere. Observations of upper atmospheric motions can be conducted routinely using ionospheric monitoring methods, mostly using Ground Positioning System techniques. After reviewing state-of-the-art numerical methods used to model these phenomena, we will present simulations of observations conducted after the Hunga Tonga eruption.

Thursday 31 March, 2022 - 10:30 / 12:00

Machine learning in geosciences

Scott Hosking (BAS, UK)

Machine learning (ML) methods have the potential to advance our understanding within geoscience and unlock new scientific discoveries. However, not all geoscience problems can or should be tackled with ML. In this presentation I will highlight some use-cases where ML has worked well and provide some insight into how we got there - the challenges and decisions that needed to be made along the way. I will comment on where I see ML is going within the geosciences, and what is needed to get us there over the next 10 years. This will include a discussion on nurturing and contributing to open-source communities, building networks of collaborators and partners spanning the traditional science disciplines, and I will address the current buzz around the development of Digital Twins of the natural environment.

About the speaker:

Dr Scott Hosking is the leader of the AI lab at the British Antarctic Survey (BAS). He is also a co-Director of the UKRI Centre for Doctoral Training in the Application of AI for the study of Environmental Risks at the University of Cambridge and BAS, and a Senior Research Fellow at The Alan Turing Institute, UK.

Thursday 31 March, 2022 - 14:00 / 15:30

Lightning

Thomas Farges (CEA, France), François Coulouvrat (Sorbonne-Université, France)

Lightning generates infrasound and sound waves (thunder). Acoustic measurements in networks since the early 2000s allow to revisit the mechanisms of thunder formation. After a brief review of the physics of lightning and a description of the main characteristics of thunder, we present what acoustic networks can tell us about the tracking of lightning at short and long distances. Principles of complex sources localisation and reconstruction will first be recalled and illustrated by two measurement campaigns performed in Southern France in 2012 (in Cévennes region) and 2018 (in Corsica). At long range, the tracking of thunderstorm cells is possible up to at least 500 km, allowing to probe the middle atmosphere. At short range (less than 20 km), the 3D reconstruction of the lightning channel provides information on the structure of discharges, both within the clouds or between the clouds and the ground. These measurements lead us to propose a model of thunder generation taking into account the observed spectra, especially at low frequencies. This model identifies a near field (typically at less than 3 km) where the detailed source geometry must be considered, behaving mostly as a cylindrical one but with a high variability due to the tortuosity. In the far field, this variability is reduced and the lightning source can be seen as spherical. The comparison of the results of the model and the measurements allow for the first time to quantify the energy deposited by the discharge in the lightning channel, which turns out to be more intense than intracloud discharges. Recent analysis show however that the power distribution is not uniform along the lightning channel, with strong observed heterogeneities.

In addition, the electric field of particularly strong lightning can produce transient light phenomena occuring in the upper atmosphere. They are called sprites. These sprites last a few milliseconds and have a vertical spatial extension of more than 40 km and a horizontal extension of 1 to 100 km. The impacted space can be heated by a few degrees Kelvin. When sprites are very extended, this heating can generate a pressure wave in the infrasound range. These signals have a different acoustic signature than thunder that will be discussed.

About the speakers:

Thomas Farges is a researcher at CEA and member of LETMA. He is interested in thunderstorms and transient luminous events. He studies their electric field, their optical emissions and their acoustic waves (thunder). He is particularly interested in showing how thunder can help to characterize lightning. He led several acoustic measurement campaigns in this perspective. Recent topics of study are: 3D reconstruction of lightning from microphone arrays, variation of amplitude with distance and detection, monitoring of thunderstorms with acoustic measurements, and modeling of the source, ...

François Coulouvrat is a CNRS researcher at Institut Jean Le Rond d'Alembert (Sorbonne Université, Paris, France) and member of LETMA. He is interested in the theoretical modelling and numerical simulation of atmospheric propagation of sound and weak shock waves, including the physical phenomena of refraction, diffraction, absorption, scattering and non linearities. He contributed to the development of various numerical solvers, from ray tracing to one-way approximations. He studied various types of low frequency sound sources, namely sonic boom from supersonic aircraft and meteoroids, and lightning. In the recent years, he contributed with Thomas Farges to the 3D reconstruction of lightning from microphone arrays, and to the analysis of lightning as sound source of thunder, in particular in terms of energy.

Thursday 31 March, 2022 - 16:00 / 17:30

Volcano acoustic

Maurizio Ripepe (University of Firenze, Italy)

Volcanoes are a very efficient source of pressure waves both in the acoustic, acousto-gravity and gravity frequency range. Gas rapidly expanding in the atmosphere produce pressure perturbation which contains valuable insights into eruption dynamics. Linear theory of sound is currently used to explain acoustic pressure below 20 Hz (infrasound) in terms of mass flow rate with strong implications for explosive dynamics and risk assessment. According to the explosive mechanisms acoustic waves can be modeled as a compact point source with wave field directivity strongly dependent on the crater rim geometry, ground topography and atmospheric conditions. Violent explosive eruptions can propel a plume of 1-10 km3 of hot ash and scoriae at tens of kilometers high into the atmosphere. This large mass flux induces acousto-gravity oscillation of the atmosphere which can be recorded at thousands of kilometers away at a global scale. But volcanoes can also generate acoustic waves by non-explosive non-point sources such as pyroclastic flows, which can be tracked in real-time using array techniques methods.

About the speaker:

Maurizio Ripepe is lecturer in Geophysics and Physical Volcanology at the Department of Earth Sciences of the University of Firenze. He was teaching Geophysics and Seismology at the University of Camerino and University of Siena. External Professor at the Open University, Milton Keans (UK) and Member of the Graduate School of Rio Negro University (Argentina). He was Visiting Professor at the University of Southern California (Los Angeles, USA), Earthquake Research Institute (Tokyo, Japan), The Leeds University (Leeds, UK) and Ecole Normal Superioure (Lion, France). Responsible for the Double PhD Degree in geophysics with the Tohoku University (Sendai, Japan).

He is responsible for the Laboratory of Experimental Geophysics (LGS) of Florence University and for the Center of Excellence in Volcano Monitoring, of the Italian Department of Civil Protection. He was scientific consultant during the 2003 Stromboli eruption for the Ministry of Interiors, Department of Civil Protection. He is member of the Seismic Microzoning Group of the Seismic Service of the Italian Civil Protection, member of the Great Risk Commission of the Italian Prime Ministry Council and member of the INFN (National Institute of Nuclear Physics) for VIRGO interferometer (gravitational waves). He is the coordinator of Project on Seismic Vulnerability of the City of Florence and scientific consultant on seismic risk for the Cultural Heritage of the Opera del Duomo of Florence. He was team Expert for the European Civil Protection Mechanism in Guatemala during the 2018 eruption of El Fuego volcano.

He cooperates with several research centers for the infrasonic monitoring of volcanoes and snow avalanches in Iceland (IMO), Japan (ERI), Montserrat (MVO), Ecuador (IGPN), Guatemala (INSIVUMEH), Costa Rica (OVSICORI), Peru (INGEMMET), Argentina (SEGEMAR), Chile (OVDAS) and Swiss (SLF).

Friday 1 April, 2022 - 08:30 / 10:00

Data assimilation

Olivier Marsden (ECMWF, UK)

Data assimilation can be described as the blending of observations of a system with a model of the system's evolution, in order to obtain an estimation of the state of the system at a point in time. It is essential to the field of Numerical Weather Prediction, as observational data of the earth system is vastly insufficent to fully constrain the set of initial condition required for a numerical weather forecast. An overview of different facets of data assimilation will be provided, with examples taken from the field of NWP. A brief description of some of the main data assimilation techniques will be given, along with how these techniques can be implemented in NWP systems.

About the speaker:

Olivier Marsden is a computational scientist working at the European Centre for Medium-range Weather Forecasts (ECMWF), focusing on the computational efficiency of the IFS weather prediction suite. Before working at ECMWF he was a lecturer in fluid mechanics and aeroacoustics at the Ecole Centrale de Lyon.

Friday 1 April, 2022 - 10:30 / 12:00

Inverse problems for atmospheric dispersion

Lionel Soulhac (LMFA, INSA Lyon, France)

Atmospheric turbulent dispersion of pollutant material is an important subject in different contexts: air quality, industrial safety, transport of hazardous material, terrorist attacks. Pollutants are transported by the turbulent flow field induced in the atmospheric boundary layer by the interaction between the large scale geostrophic wind and the complexity of the Earth surface, with exchanges of mass, momentum, energy and humidity. If the characteristics of the source of pollutants are known, direct numerical models are useful to predict the concentration field and its time evolution. But when the characteristics of the source (position, emission rate, etc.) are unknown, an inversion modelling approach can be applied to estimate the source parameters starting from measurements of concentration in the atmosphere. The inversion strategy has to take into account the number of unknown parameters and the type of measurements used (uncertainty, fixed or mobile, etc.). This presentation will overview some recent works done in the AIR group of the LMFA on inversion modelling of atmospheric dispersion for different operational applications.

About the speaker:

Lionel Soulhac is professor and deputy head of the Fluid Mechanics and Acoustics Laboratory, at INSA Lyon. For the last 25 years, his research has been dedicated to the modelling and simulation of atmospheric flow and dispersion at local scale, in the atmospheric boundary layer. Lionel Soulhac has developed several dispersion software (SIRANE, SLAM, etc.) that are operationally used by engineers in national or local authorities and in industrial or consulting companies.