Probing the Atmosphere with Infrasound

Infrasound as a tool

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Probing or Imaging the Atmosphere with Infrasound

- CTBT Detection and Identification of nuclear explosions
  - Biggest boost in Infrasound research since 1971
  - Complemented with radionuclide technique

- Medium the Atmosphere and its associated processes
  - Dynamic, flow, elasticity and turbulence
  - Interaction with EM-radiation, gravity and Earth rotation
  - Most complex in the series Solid Earth, Oceans, Atmosphere

- Determination of Sources
  - Imaging instruments, sources scattering and reflection

- the idea behind imaging is like seeing, watching as we all do, with our eyes
CTBT Infrasound Network
Contents

- Receivers
  - Camera
  - Noise reducers
  - Large arrays

- Medium
  - Gravity waves
  - Sudden Stratospheric Warming

- Sources
  -Sprites
  - Rogue waves
Introduction to Infrasound and atmospheric pressure waves

- **Infrasound**: longitudinal sound waves lower than 20 Hz
  - “Sounds of silence”
  - Restoring force is pressure
  - Attenuation is low for moist air and extremely low for dry air

- **Gravity waves**: buoyancy waves in the atmosphere
  - Restoring force is buoyancy in the pressure and temperature gradients
  - Generally not in Numerical Weather Prediction Models

- **Rossby waves**: planetary waves due to the rotation of the Earth (Coriolis force)
  - Travel from East to West
  - Weather determining patterns
The atmosphere as seen by a meteorologist

Two low velocity layers

Velocity of sound proportional to the square root of the temperature

Highly variable winds both in strength and direction
Linear map of the atmosphere

These are averaged values
What is the scale of the waves?

<table>
<thead>
<tr>
<th></th>
<th>$\lambda/m$</th>
<th>$\tau/s$</th>
<th>$c_{ph}/m$ s$^{-1}$</th>
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<td>$10^{-2}$</td>
<td>$10^2$</td>
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<tr>
<td>inertia-gravity waves</td>
<td>$10^5$</td>
<td>$10^4$</td>
<td>10</td>
</tr>
<tr>
<td>Rossby waves</td>
<td>$10^6$</td>
<td>$10^6$</td>
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Characteristic scales in the Earth’s atmosphere:
Rossby wave pattern as seen from the North pole
Imaging and receivers

- The art to make pictures is
- to keep track of Intensity as a function of the \textit{angle of incidence}, and
- to get the \textit{lowest noise} possible and
- finally, to \textit{interpret} the objects on the picture in their context
Imagine......

Pinhole; simple solution
To enhance the intensity, suppose you use more than one pinhole. Prisms are needed to align the separate images. From pinholes via a lens to an array. An array makes use of the small time or phase differences of the arrivals. Works only with time resolved signals*.

When source and receiver can be interchanged: reciprocity

*in a hologram a time reference signal is also needed
Imagine..., 30 years ago

This is a picture of my younger brother Andries and my father in April 1976 by a home made pinhole camera. The exposure time was more than 1 minute, the pinhole diameter was 0.5 mm, the negative was 6 × 6 cm, 20 cm from the pinhole objective, f/d = 400.
Imaging optima forma

X-ray

MRI: magnetic resonance Imaging
All-sky image of the Neuschwanstein fireball from EN station #45 Streitheim on 6 April 2006.
Primitive image of the infrasonic surroundings with the use of a small array.

This time exposure was taken during a 6 hour period in a quiet night.

The array at de Bilt has the same aperture as the largest noise reducer ~ 70 m
Airplane passing over the a array
Infrasound noise reducers

- Integrators of turbulent pressure variations
- Multi element array (4 x 23) with zero time delay

Piñon Flat California IS57
Wind-Noise-Reducing Pipe Arrays

Construction of Pipe Arrays at IS07

Buried Pipe Arrays at IS07

70 m diameter pipe array
The path lengths from the inlets to the microbarometer are the same.

So, this 96 element array is looking to zenith.

For high frequencies this directivity effect is large.

For low frequencies the sensitivity is the same in every direction.
New developments in noise reducers

- Replace the discrete inlets by pressure sensors and treat the total of the inlets of the noise reducer as an array.
- The pressure sensors might by cheap low noise classical instruments or micro-machined autonomous sensing and data sending sensors.
- Array technology and processing should prove the advantages by regarding this array as a single element of the larger array.
- A test is foreseen in the Netherlands with 100 sensors in the frame of the Dutch LOFAR initiative.
Gravity waves

- The lower frequency branch of atmospheric disturbances
- Certainly visible in the acoustic recordings world wide
- Of direct influence of the energy balance in the atmosphere, especially in the higher atmospheric layers
- The high amplitude waves can break and lead to turbulence in the higher atmospheric layers
Gravity waves, internal waves

The cut off of the acoustic waveguide: 275 seconds

The characteristic periods of gravity waves begins at 304 seconds (Brunt-Väisälä frequency)
The pattern of particle movement and wave propagation of a gravity wave
Generation of gravity waves
Moisture is indicating the air flow of gravity waves
Multiple breaking water waves
Multiple breaking gravity waves, billow waves, indicating shear instability, which could lead to Clear Air Turbulence, also called Kelvin-Helmholtz instability
Further research on low frequency waves

- Arrays for gravity wave research are not very common
- The Netherlands is going to test these large arrays in the frame of the LOFAR initiative building an array that is larger than the US Large Aperture Microbarograph Array (LAMA)
The “Zoo” of Infrasound Sources

- Explosive sources
  - Nuclear, chemical, volcanic, meteoritic
  - Lightning, sprites, shockwaves, sonic booms, artillery, rockets, quarries in mines

- Wave like sources
  - Microbaroms, mountain associated, earthquakes, aurora, geomagnetic storms, severe weather

- Miscellaneous
  - Elephants, waterfalls, avalanches, calving of icebergs, surf, tunnels and flyovers, diesel engines, traffic, windmills, chimneys, large structures

- Lack of controlled continuous sources such as subwoofer loudspeakers or Helmholtz oscillators
Nuclear explosion
Volcanic explosion with cloud of ashes during the Mount St. Helens sequence of events in 1980.

The ashes will severely danger airliners.
Gas pipe line explosion Belgium.

Such an explosion has forensic aspects that could be sorted out by international cooperation.
Meteor near De Bilt

19 February 2003
18h18m24.08s UT
Wave front development of a meteor with end explosion in a realistic atmosphere without wind, example of spherical wave front healing (CEA, France and BGR, Germany)
Aurora
Sonic boom as a source of infrasound. The boom is produced during the period that the velocity of the plane is above the sound speed. Condensation of expanding air shows the Mach-cone.
Interfering high waves in the North Sea cause infrasound. The exceptionally high waves (monster or freak waves) can damage oil platforms and ships.
Signature of the Draupner freak wave

SWH: 11-12 m, max: 18.5 m, $P = 1:10^8$
Wind turbines can cause infrasonic signals over an extended period of time. Observed in Germany and UK.

Impression of the size of the wings of the wind turbines.
Geomagnetic storm, 2003/11/21, recorded at Hobart, Australia, IS05
Lightning is a source of infrasound. Also, the recent discovered sprites.
This dramatic, garishly colored image was captured with a low-light level camera on June 7, 2001. It shows what appears to be a "burning tree", or red sprite, above the National Cheng Kung University campus in Tainan City, Taiwan. Credit: ISUAL Project, NCKU/NSPO, Taiwan
Electrical phenomena between thunder clouds and ionosphere
Elves and Sprites
E-M signals from Sprites

Here Schumann Resonances are excited the lowest frequencies in the electromagnetic waveguide between surface of the earth and ionosphere (8 Hz)

Lightning and sprites are a source Very Low and Extremely Low Electromagnetic Frequencies
A typical infrasonic chirp. The x-axis in number of samples (18 Hz sampling rate) (from Liszka)
Overview of infrasound sources (Bedard)
Local signals → Local knowledge

- The consequence from the Zoo of Sources is that local station operators and NDCs should have a strong role in understanding the nature of these sources, they could be the local experts who exchange their knowledge by international cooperation.
- Think globally act locally
- As the most common sources are of relatively high frequency, adequate support should also be given to lower frequencies, i.e. the frequency band of nuclear explosions
New developments in Infrasound

- Cooperation and synergies with other fields of research
  - Meteorology
    - Sprites, Clear Air Turbulence
    - Wind, temperature profiles, atmospheric modeling
  - Seismology, Volcanology
    - Combined observations
  - Oceanography
    - Wave properties, extremes
  - Radio science
    - Ionosphere
  - Micro electronics, micro machining
    - Autonomous smart sensors

- Continued cooperation among existing research groups
  - Station operators, NDCs, *yearly infrasound workshop*

- Focus on low frequencies
  - Gravity waves
The Netherlands is the country with the highest density of infrasound arrays.
Low Frequency Array

- Astronomical initiative (~50M€)
- Infrastructure fiber optics, internet
- Geophysical sensor network
- Combined seismic/infrasound recording
Cabauw: meteo tower in The Netherlands

- Combined meteo/infrasound project
- Gravity waves: energy transport, boundary layer
- Infrasound: relation with meteo variables
One year infrasound in DBN + meteo
**SSW: Sudden Stratospheric Warming**

- Abrupt slowing down or reversal of the polar vortex in winter
- Tens of degrees temperature increase in a few days
- Growing planetary waves 1 and 2 propagate into the stratosphere
- Minor warming: short periods, every winter around 30 mbar or ~25 km
- Major warming: once every couple of years around 50 mbar or ~20 km
Infrasound during stratospheric warming

![Graph showing infrasound data during stratospheric warming]

- Back azimuth (deg)
- Apparent velocity (m/s)
- Signal to noise ratio
Infrasonic energy return height

- Full strato warming
- Halfway strato warming
- Full strato warming
- Turning
- Lost in space
- Before strato warming
Some conclusions

- Processes leading to a reduction in detection capability:
  - Temperature decrease stratospheric ozone layer
  - Slowing down of polar vortex during SSW or reversal
  - Mushrooms: intensified convection during daytime

- Processes that may lead to increased capability:
  - Vortex reversal during major SSW
  - Temperature increase in lower strato during SSW
  - Occurrence of (un)usual ducts

- Couple detections to the state of the atmosphere to quantify the detection capability
The atmosphere:
the wildest place on earth .....!
Forensic use of the seismo-acoustic analysis of a gas pipe line explosion

Explosion details

- High pressure gas pipe 1m
- 30.07.2004 06h57 UT
- Crater 19-20 m width
- 2 million m³ gas
- Flames up to 200 m
- Radius 300 m
Major questions

- At what time did the explosion(s) occur?
- How many explosions happened?
- What is the yield of the explosion?
- Are there any precursory events?
Explosion site and recording stations
Seismic and infrasound recordings

30.07.2004 06h55m27±2s UT  Acknowledgements: Royal Observatory of Belgium
Examples of PMCC analysis

FLERS
$\Delta=370 \text{ km}, \beta=54^\circ$

I26DE
$\Delta=743 \text{ km}, \beta=289^\circ$
Infrasound Analysis DIA

Broad band event 0.1 to 2 Hz; dominant frequency 0.2 Hz
Gradual loss of higher frequencies

Average characteristics:
222.1±0.1° (true 222.9°)
346.1 m/s

17 min of coherent infrasound;
includes the roaring of the flames
See also Koper et al. 2003

Hugh increase in Fisher ratio
SNR of 5.5
Cross bearing results

- Discard incompetent arrays: relation source, distance and layout
- Forensic use of infrasound: broad-band is arrays
Cross bearing results

Derived:
50.75° N ± 0.17
03.90° N ± 0.33

Ground truth:
50.63° N
03.78° E
Comparison between measured and synthetic data (I)
Comparison between measured and synthetic data (II)

- ∆T=-90 s, $V_{app}=[0.34\ 0.34]$ km/s
- ∆T=-80 s, $V_{app}=[0.36\ 0.36]$ km/s
- ∆T=70 s, $V_{app}=[0.35\ 0.36]$ km/s
- ∆T=0 s, $V_{app}=[0.34\ 0.35]$ km/s
- ∆T=0 s, $V_{app}=[0.36\ 0.36]$ km/s
Raytracing towards Flers – ECMWF models
Yield from LANL HE relation

\[ SR = \left( \frac{R}{2Y} \right)^{0.5} \]

\[ P_{WCA} = 0.6 \times 10^{04} (SR)^{-1.41} \]

\[ \log(P_{WCA}) = \log(P_{RAW}) - 0.018V_d \]
Concluding remarks

- Seismo-acoustic analysis reveals source characteristics
- Accuracy of location depends on source, distance and aperture
- Added forensic value in yield estimate
- 15 to 40 Ton TNT from crater size and LANL HE relation
New developments in meteorology

- Modeling the atmosphere
  - High resolution (regional) models
  - Non-hydrostatic models
  - More focus on the stratosphere and mesosphere
- High resolution data
  - Satellite data
  - Land based data
- Data assimilation
  - Divers datasets

In general we see developments in understanding the complex physics of the atmospheric/solid earth/ocean system, most results can be accommodated in the models. Improvements of both short time weather and climate predictions are foreseen as to contribute to safety, environment and economics.
The atmosphere: the wildest place on earth ....!