Recent advances in infrasound monitoring technology

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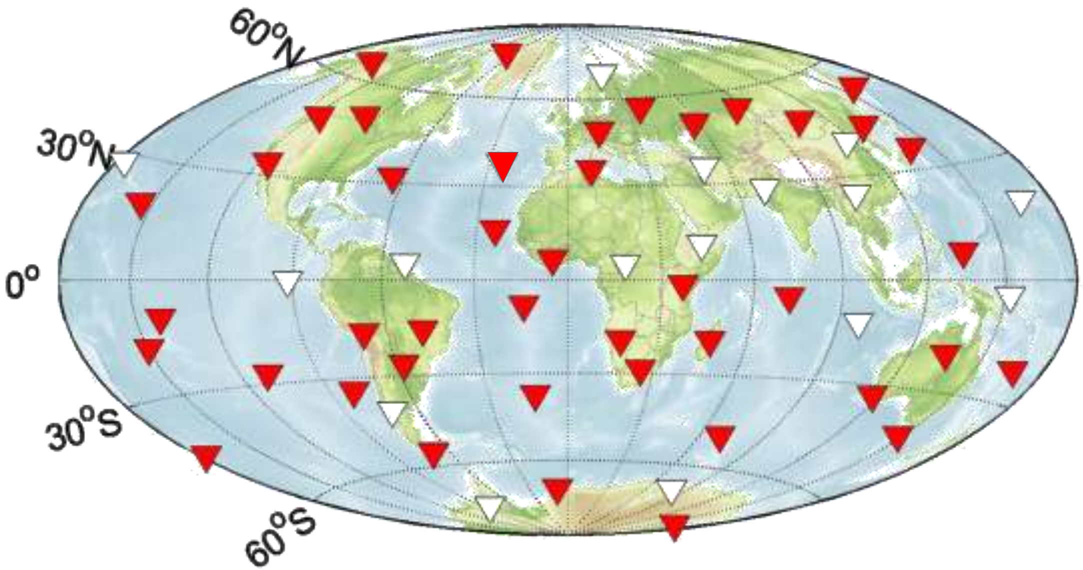
IMS Infrasound Network

- International Monitoring System (IMS)
  - ✓ Operational global network of 60 infrasound arrays
  - ✓ ~70% operating stations
  - ✓ Already allows studies on a global scale
- A "zoo" of infrasound sources (0.02-4 Hz)
  - ✓ Ocean waves, explosions, bolides, earthquakes, volcanoes, hurricanes…
- An opportunity to calibrate the network and promote civil and scientific applications



From atmospheric nuclear tests to IMS infrasound era

The early days of Infrasound

1960-1970: studying signals from large explosions and atmospheric nuclear tests (1945-1963)
(e.g. Benioff, 1939; Posey, 1971; Geophys. J. Roy. Astr. Soc., 1971; Flores, 1975)

1963: Limited Test Ban Treaty, infrasound research slowed with a reduced number of reference events:

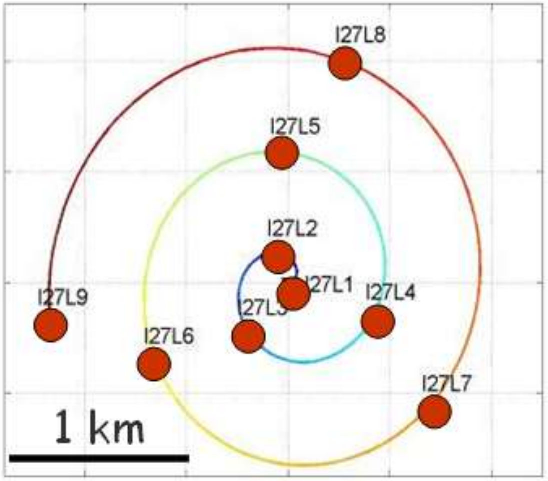
- explosive tests *(e.g. Al'Perovich, 1985; Whitaker, 1990)*
- industrial accidents *(e.g. Grover, 1974)*
- large natural events *(e.g. Donn, 1981)*

...

From atmospheric nuclear tests to IMS infrasound era

➢ 1994-1996: Geneva Conference on Disarmament - CTBT opened for signature, rapid advance in infrasound monitoring technology

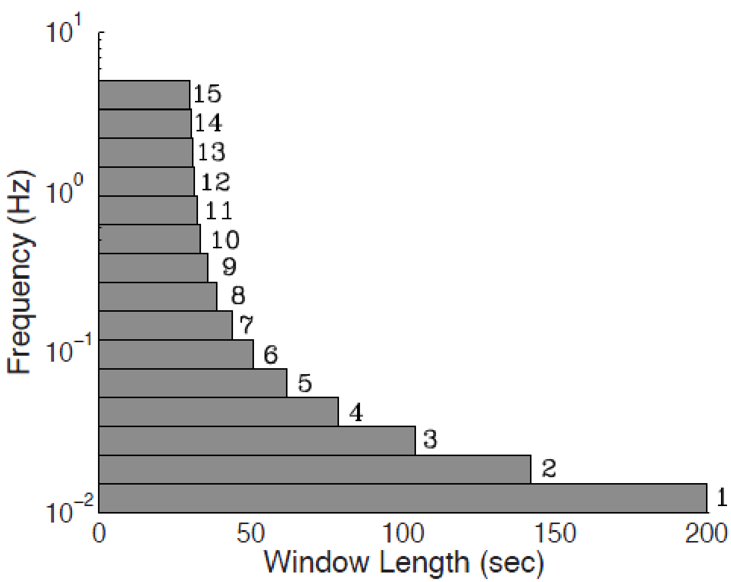
- Highly sensitive sensors
- New developments in filtering systems *(e.g. Christie, 2009; Walker, 2010)*
- Advances in array designs and processing methods *(e.g. Cansi, 1995; Olson, 2008)*



Infrasound data processing

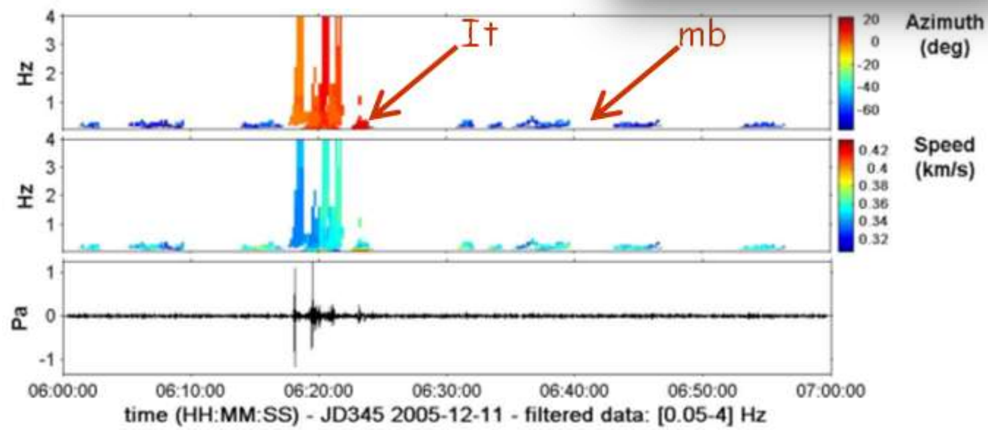
- Progressive Multi-Channel Correlation algorithm (PMCC) [Cansi, 1995]
- Time-domain correlation in a sliding time-window in narrow frequency bands

Log-scaled frequency bands
0.01-4 Hz

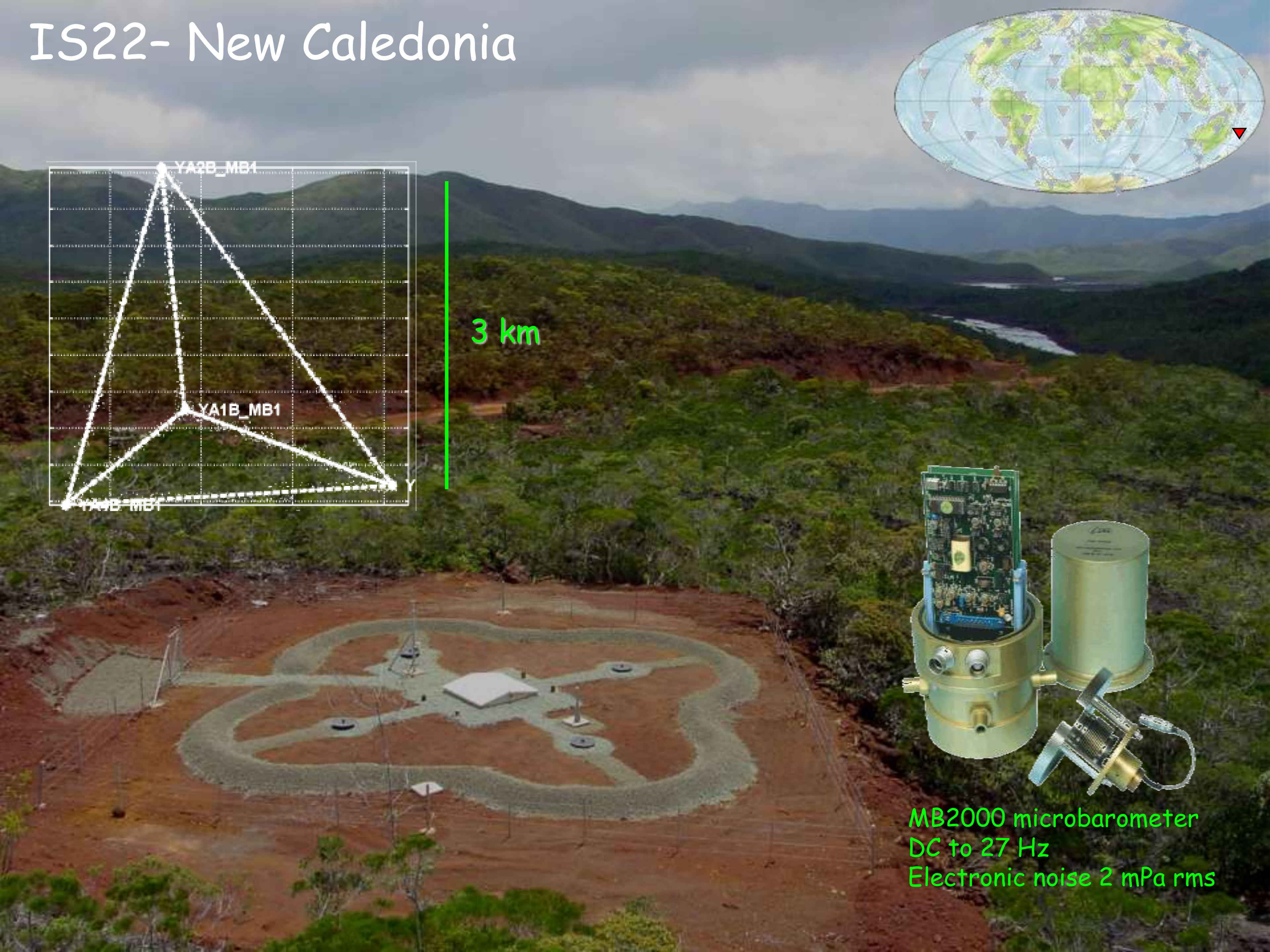


The Buncefield explosion
Dec. 11, 2005

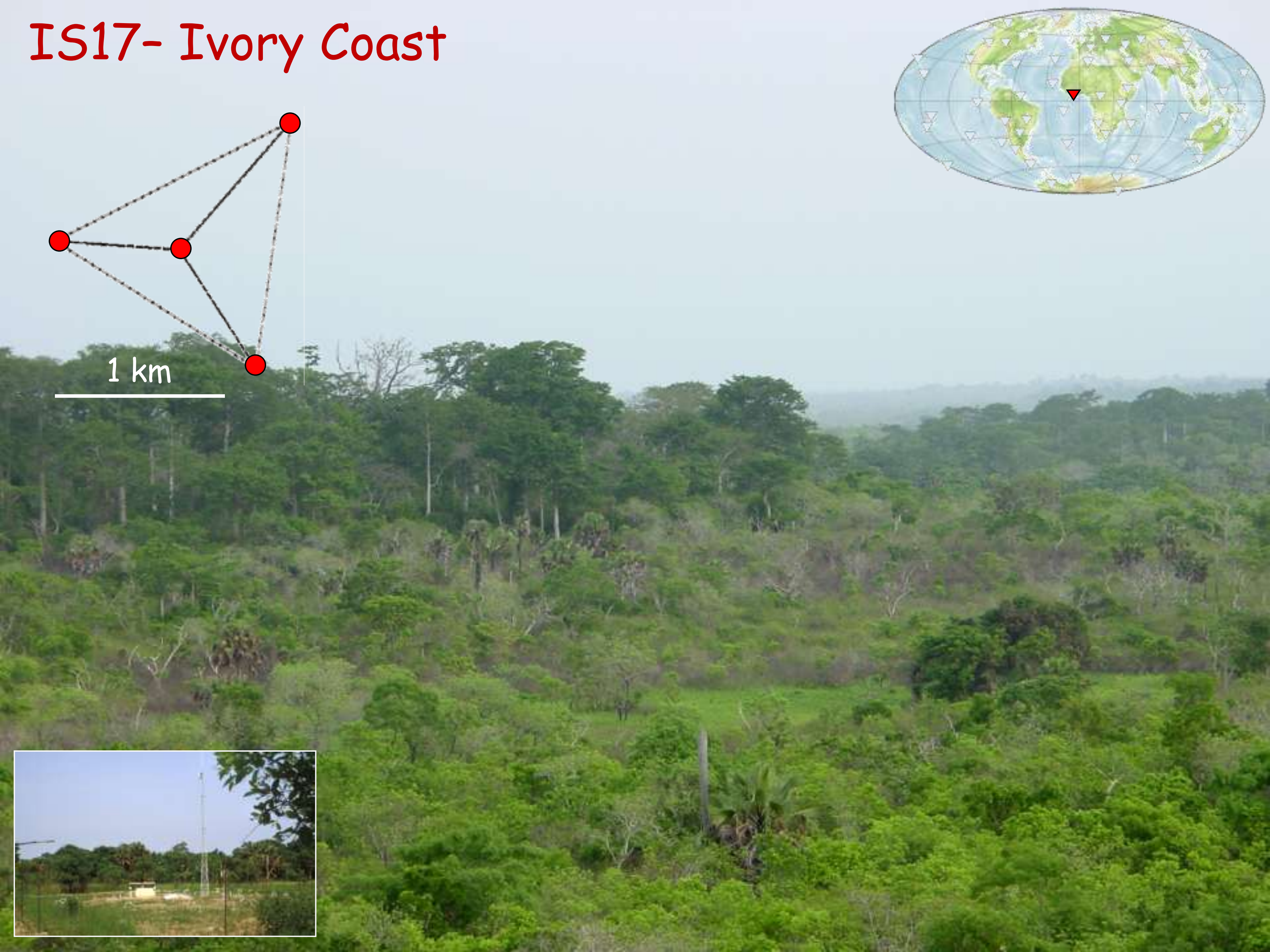
Flers – 335 km
0.01-4 Hz
15 bands (log-scaled)



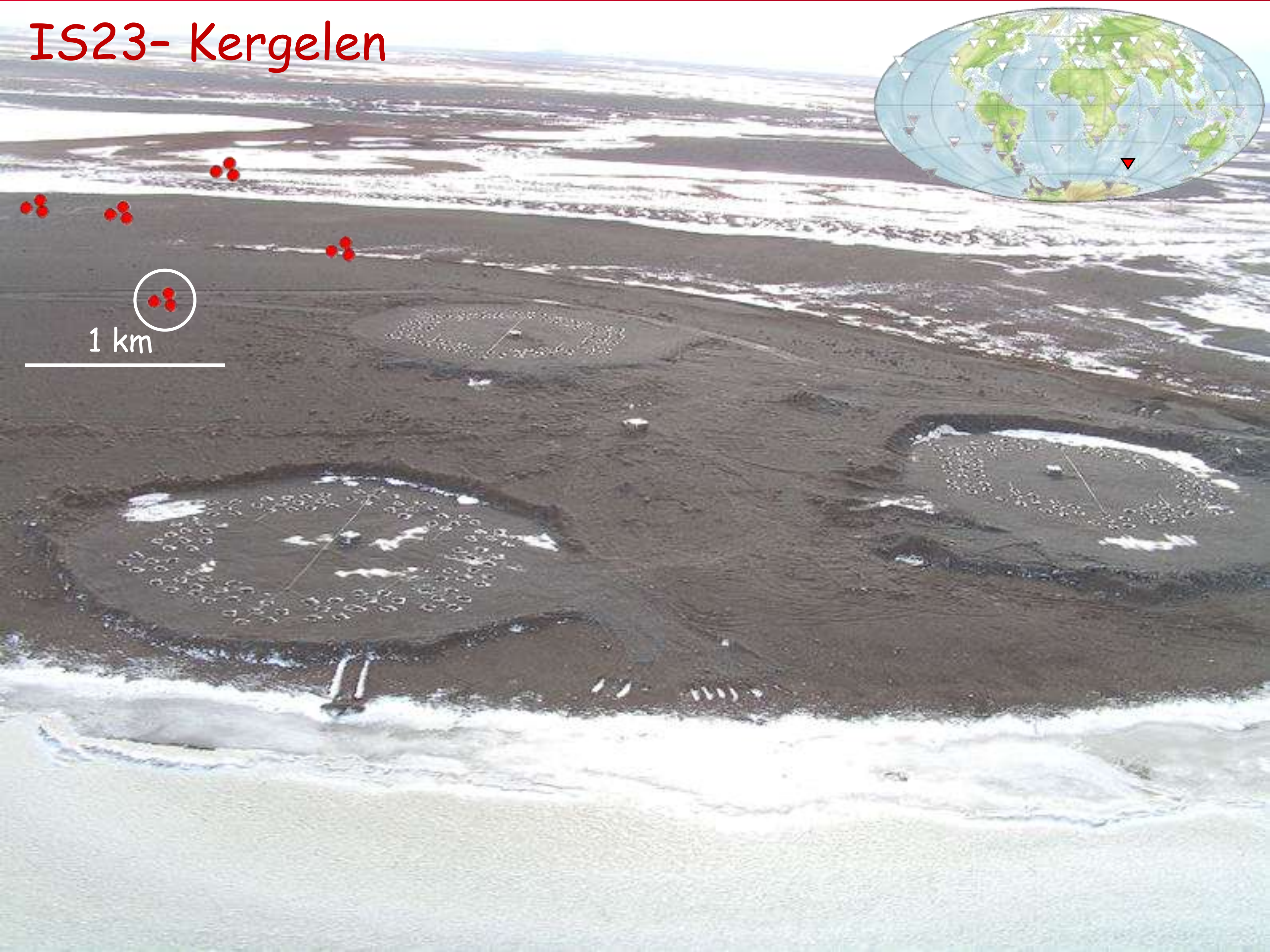
IS22- New Caledonia



IS17- Ivory Coast

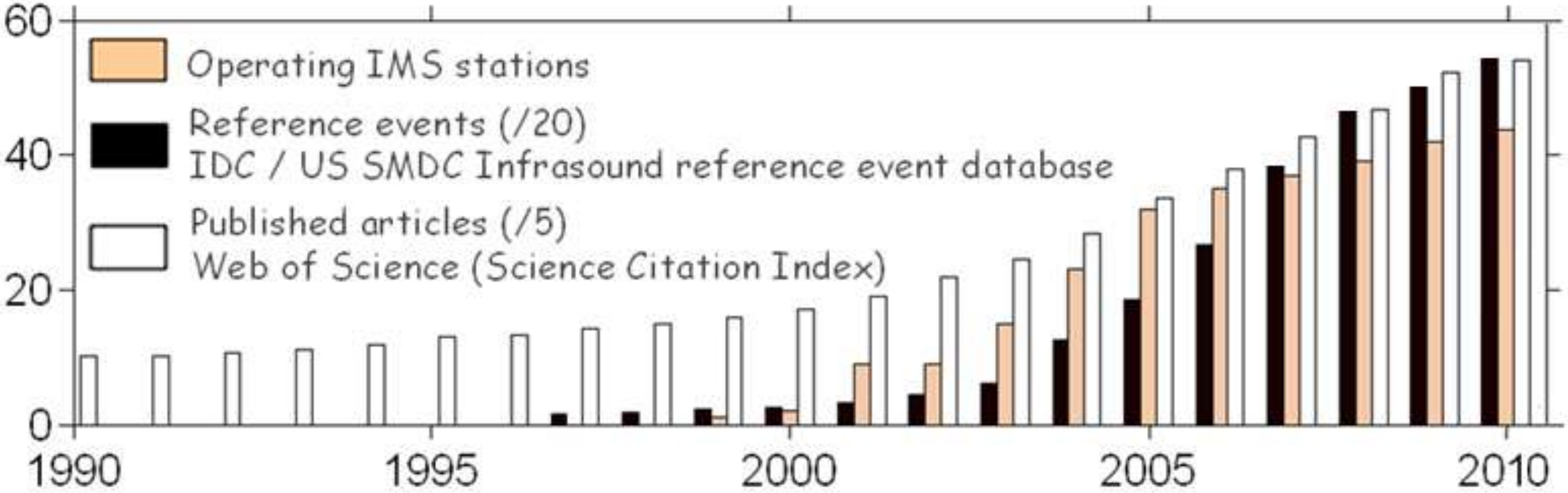


IS23- Kergelen



From atmospheric nuclear tests to IMS infrasound era

A technology more audible to the scientific community



Outline

- Main challenges for infrasound interpretation
- Evaluating the network performance
- Calibrating the network using reference events
- Potential benefit for civil and scientific applications
  - Source studies: ocean-earth-atmosphere interface
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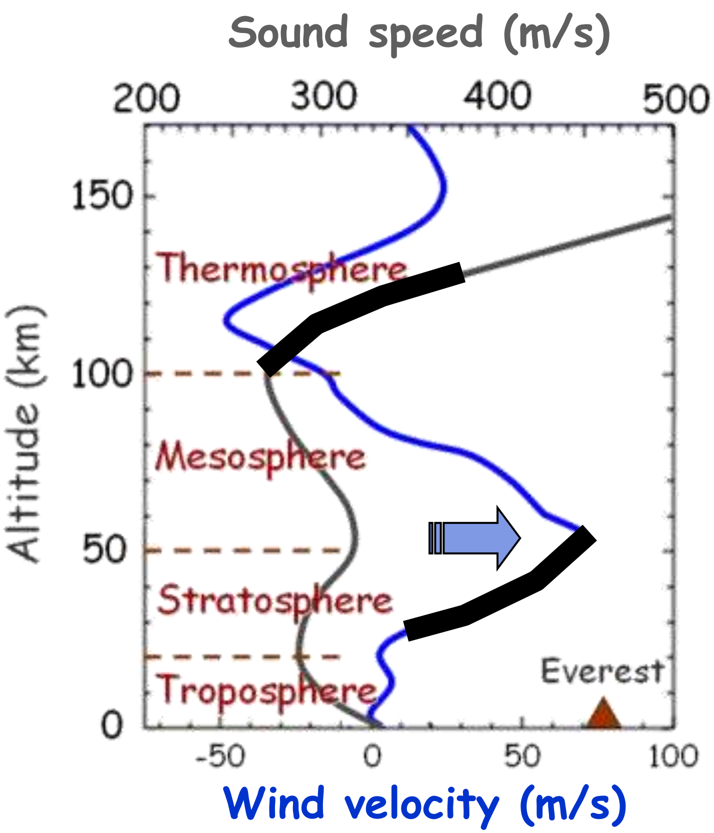
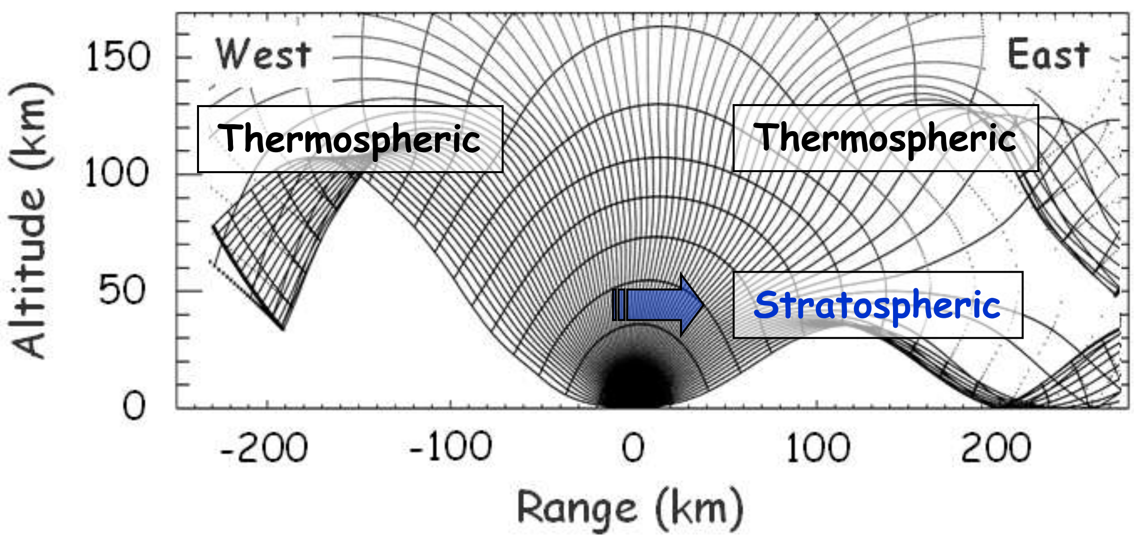
Main challenge for infrasound interpretation

- Highly variable winds in strength and direction
  - altitude





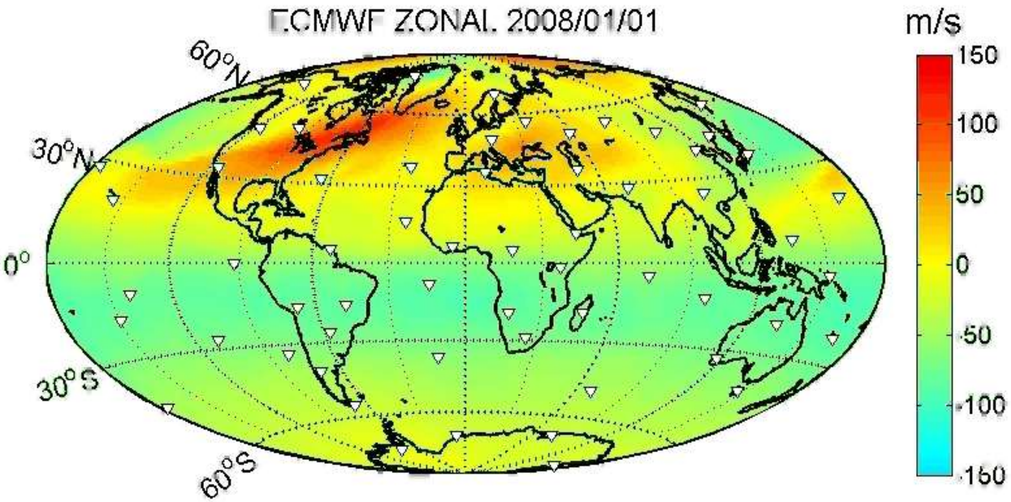
Main challenge for infrasound interpretation

- Highly variable winds in strength and direction
  - altitude
  - space and time

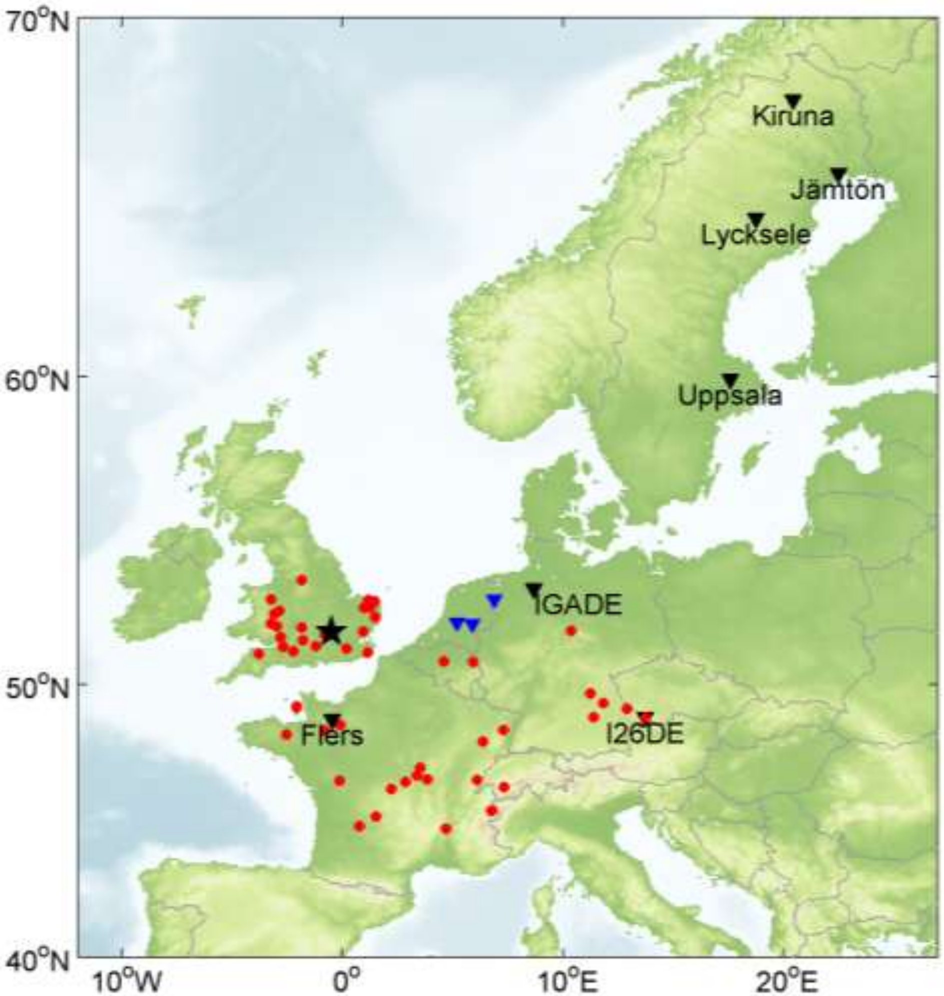
- Need to refine propagation models

- Infrasound reference events as calibration and validation tools

ECMWF
50 km altitude
Zonal (West-East)

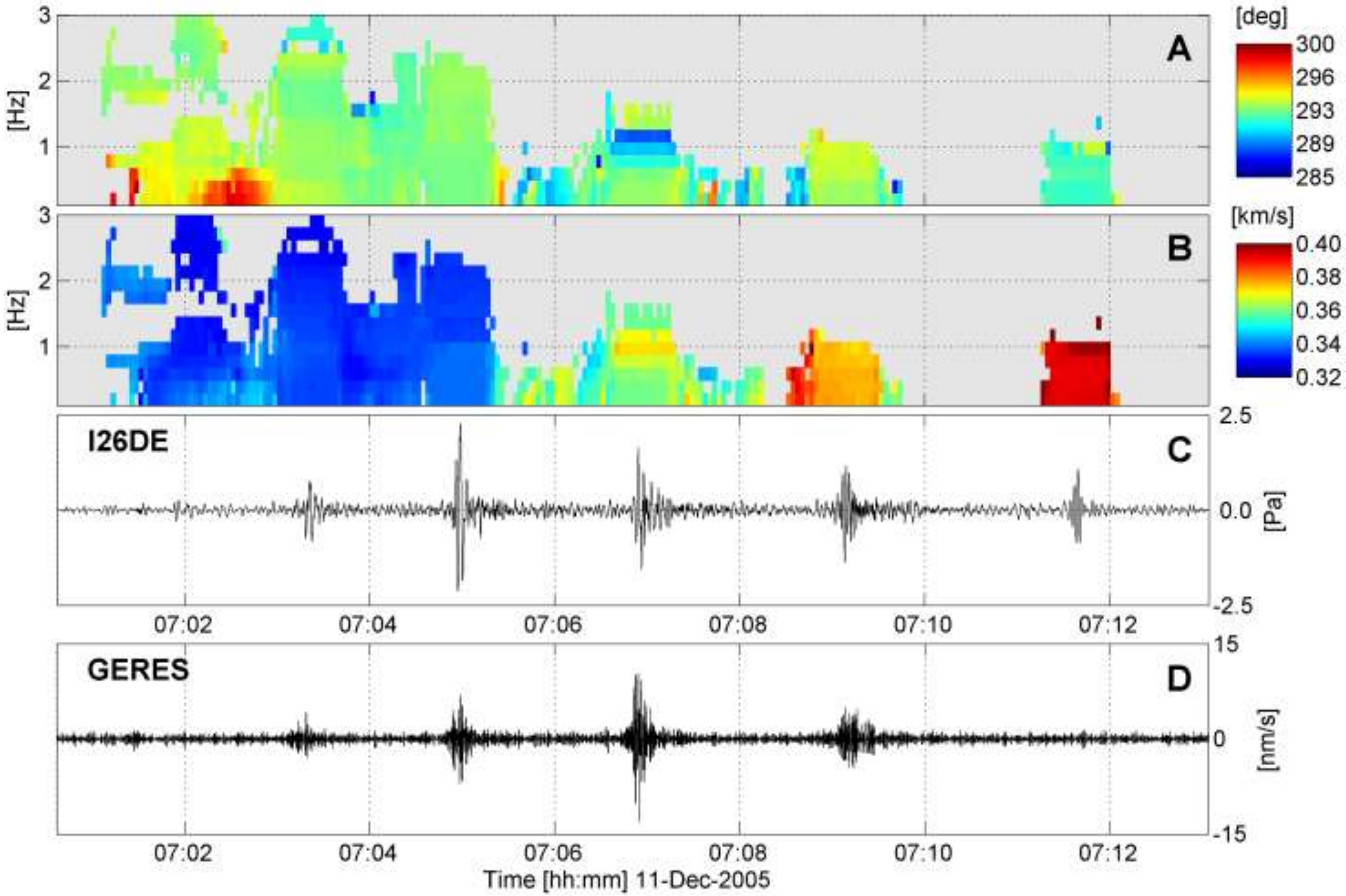


The Buncefield explosion



- ❑ 11-Dec-2005 06:01:32 (UTC) 51.78° N / 0.43° W (source: BGS)
- ❑ Hemel Hempstead, 40 km north of London
- ❑ Vapor cloud blew up (~80,000 m^2 and 1 to 7 m thick, ~300 t)
- ❑ Generated infrasound recorded all over central Europe

Infrasound recordings at IS26: 1057 km
Duration: 644 seconds, number of phases: 6

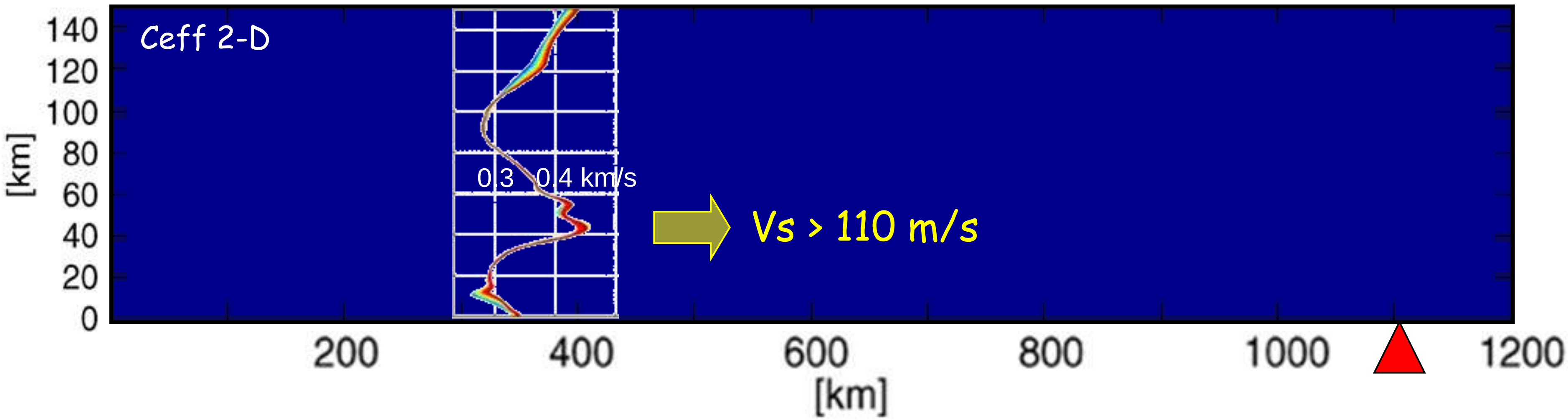


microbarometer

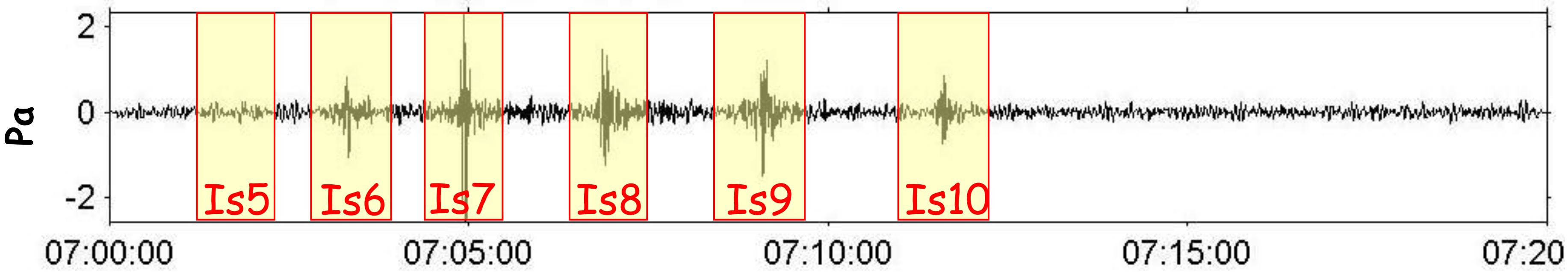
seismometer

Acoustic wave propagation, CPSM

Station IS26 - 1060 km



0.1-4 Hz



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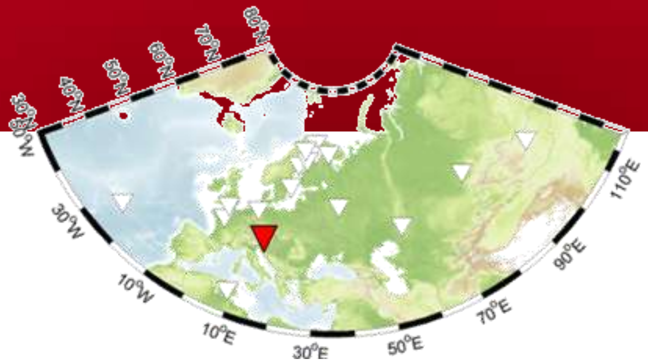
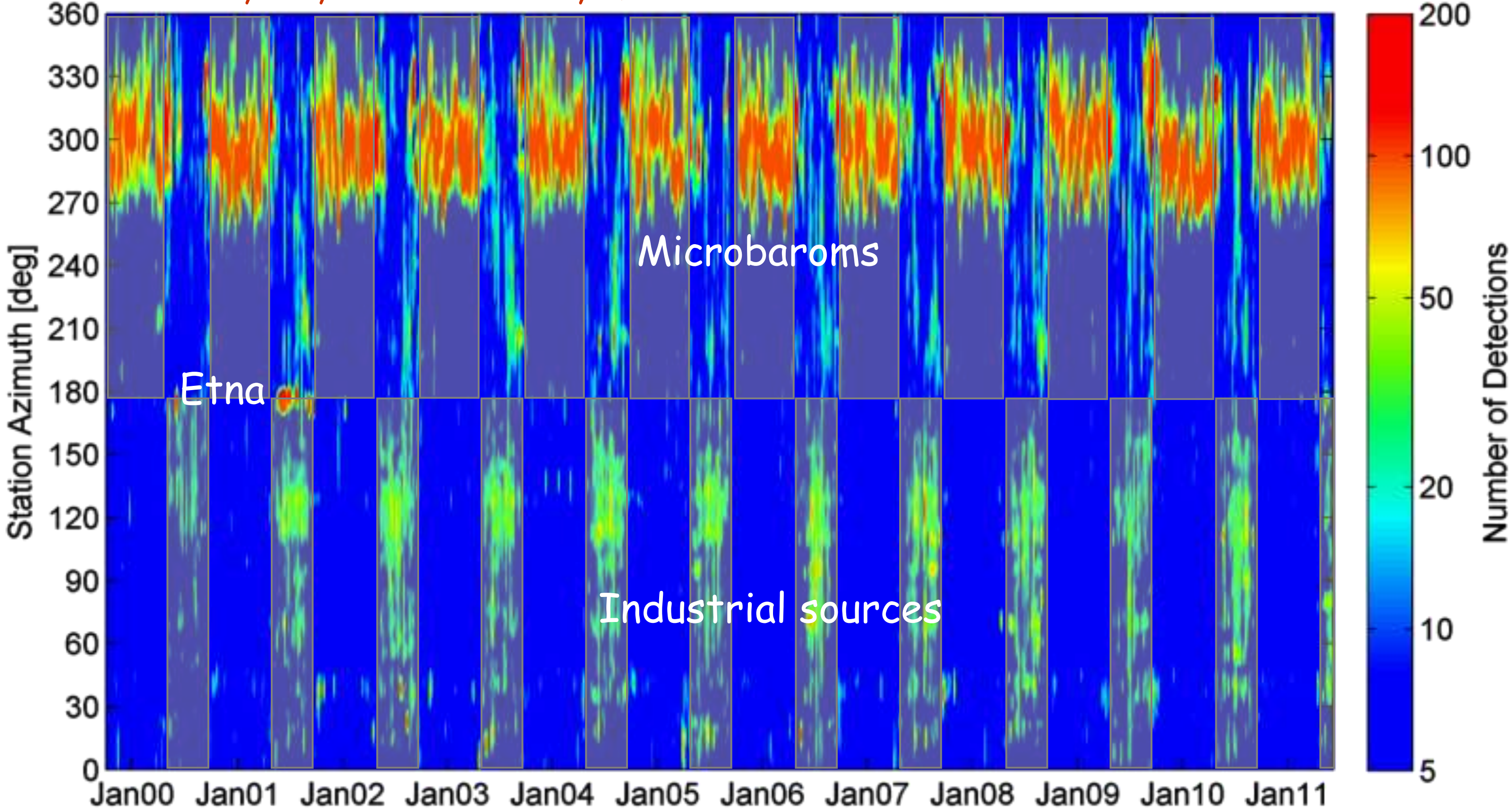
Results of multi-year operational processing



IS26 ~1,050,000 detections, 0.05-4 Hz



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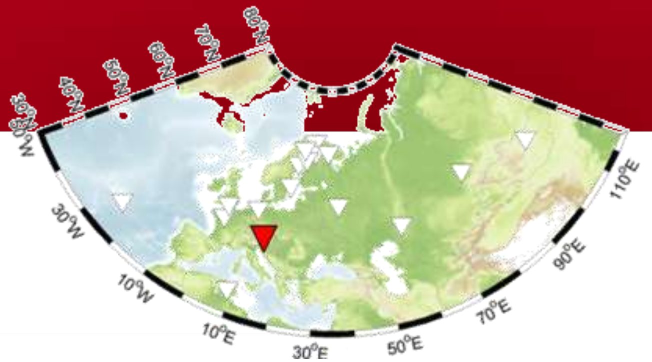
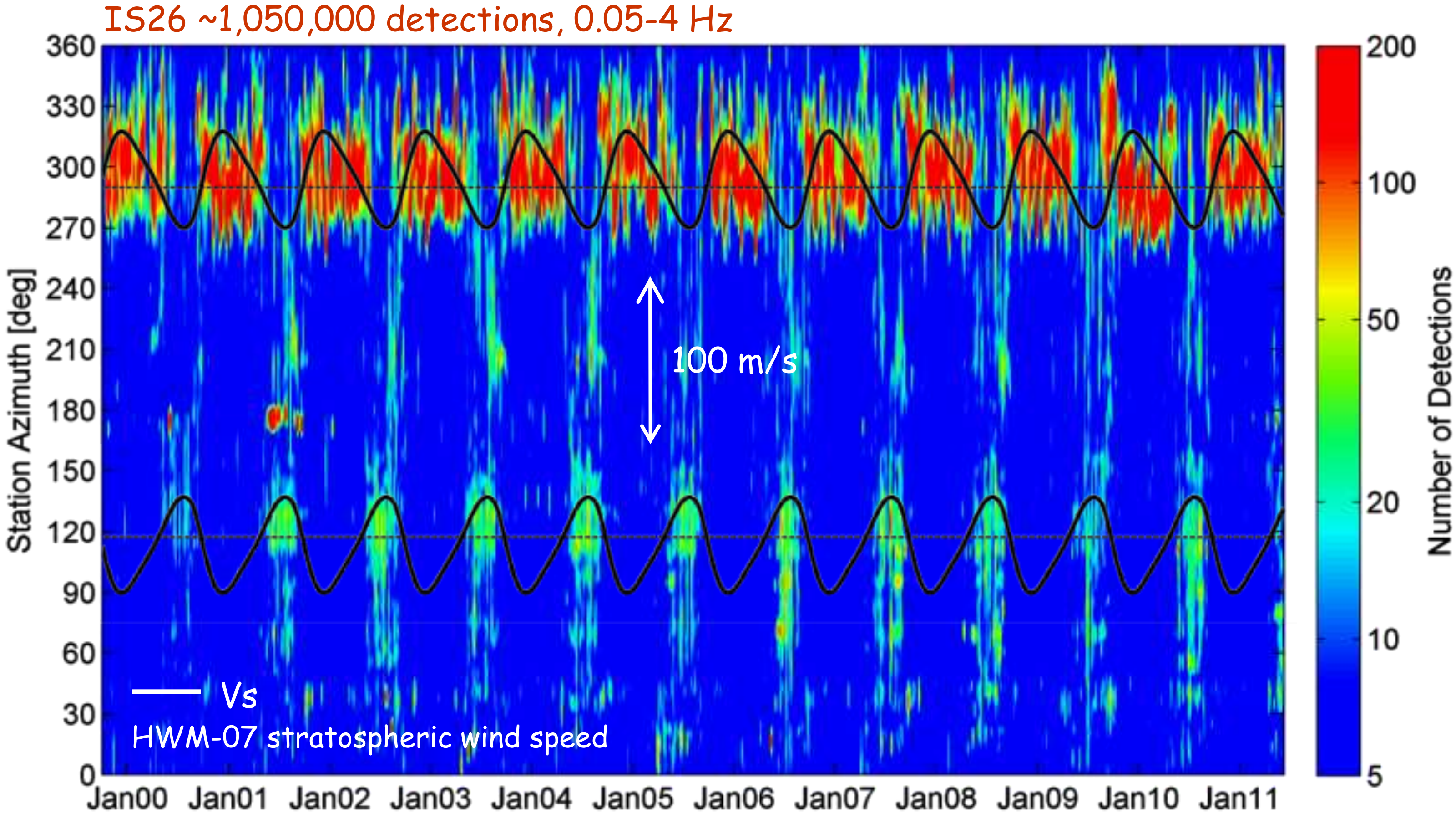
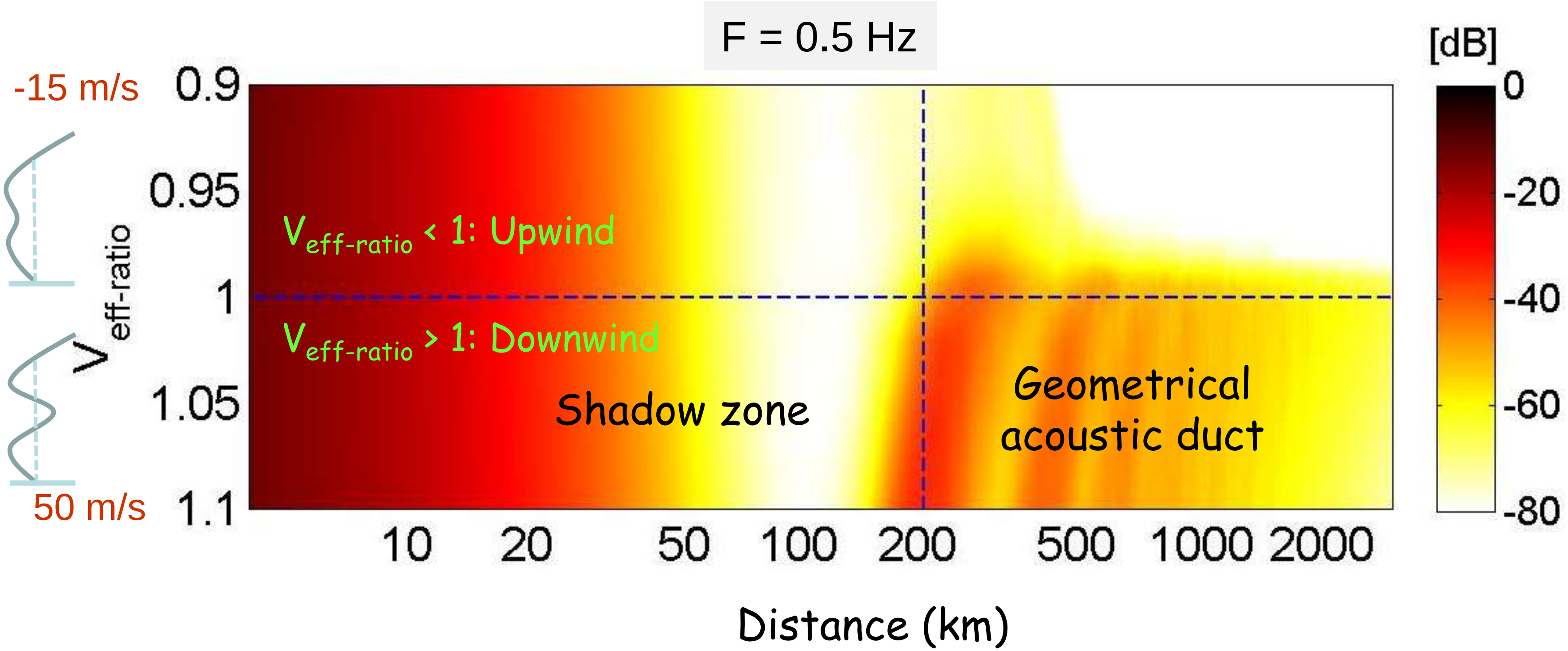


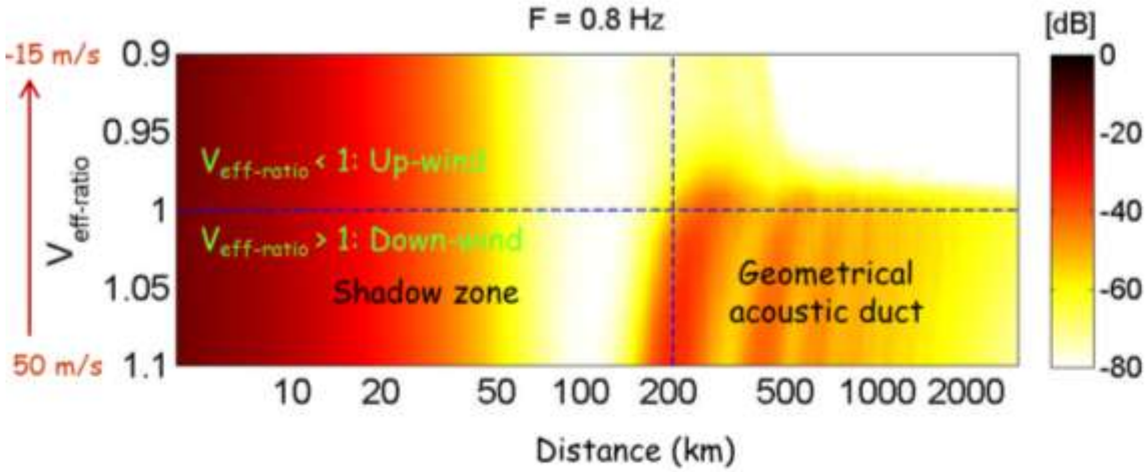


Towards more realistic attenuation relation
Full wave modeling



- Full-wave forward simulations (PE method, Lingevitch et al., 2002)
  - $V_{eff\text{-}ratio} < 1$: signals strongly absorbed above 50 km
  - $V_{eff\text{-}ratio} > 1$: stratospheric duct efficiently propagates acoustic energy

Towards more realistic attenuation relation
Full wave modeling



- At large distance, downwind, the attenuation weakly depends on wind conditions
- A "binary"-like pattern

$$P_{receiver} / P_{source} = R^{-1} \cdot 10^{(\alpha \cdot R)/20} + R^{\beta} / (1 + 10^{(\delta - R)/\sigma})$$

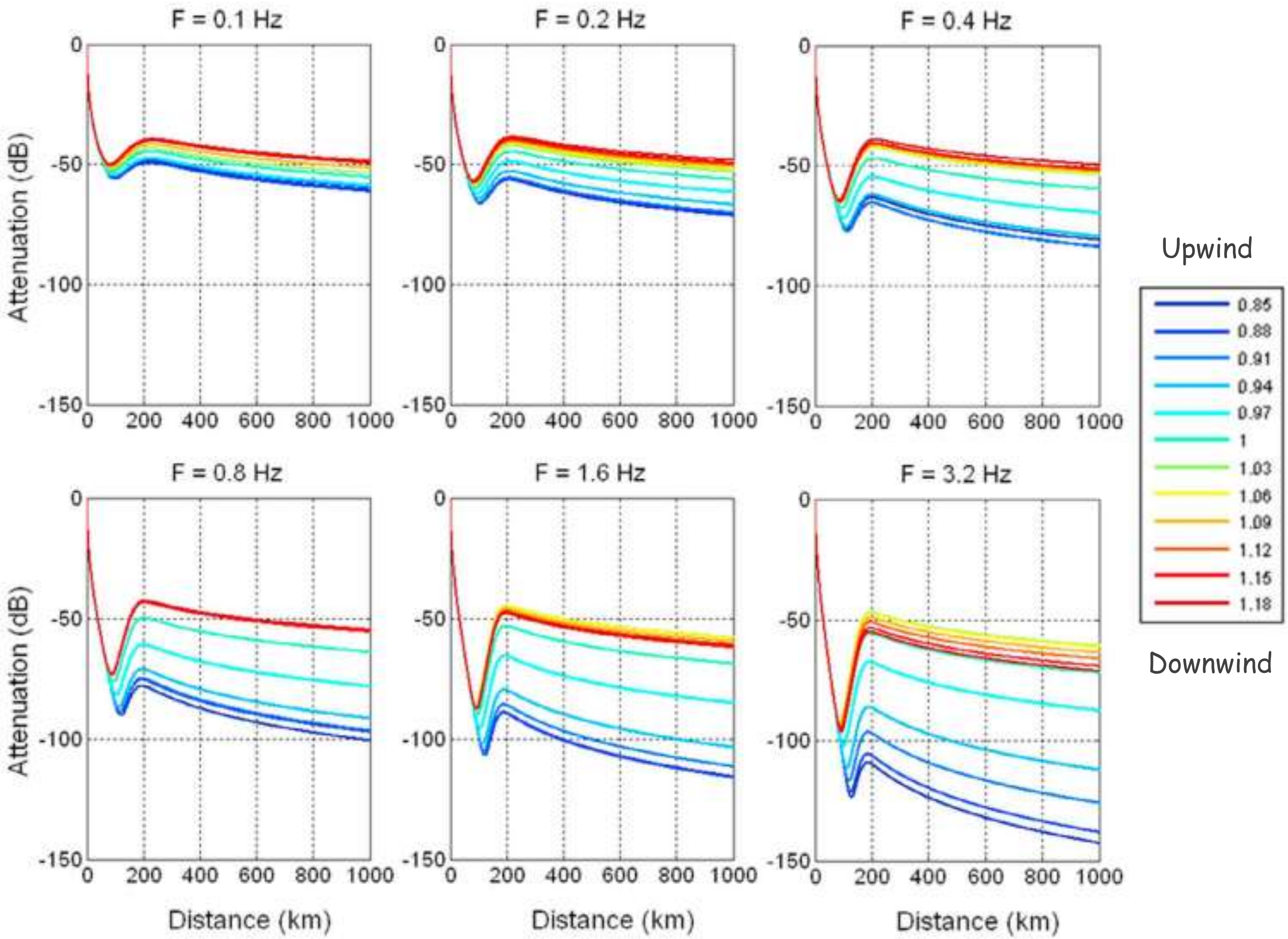
Near-field   Far-field

- α (f) : air losses of direct waves (e.g., Beranek 1954)
- $\beta(V_{eff\text{-}ratio}, f)$: geometrical spreading of ducted waves
- δ(cst) : width of shadow zone (ranges between 120 and 250 km)
- σ(f) : std deviation of shadow zone's width

Le Pichon et al., JGR, 2012

Towards more realistic attenuation relation
Full wave modeling

- Upwind: the attenuation strongly increases with frequency
- Below 0.1 Hz, the attenuation weakly depends on $V_{eff-ratio}$



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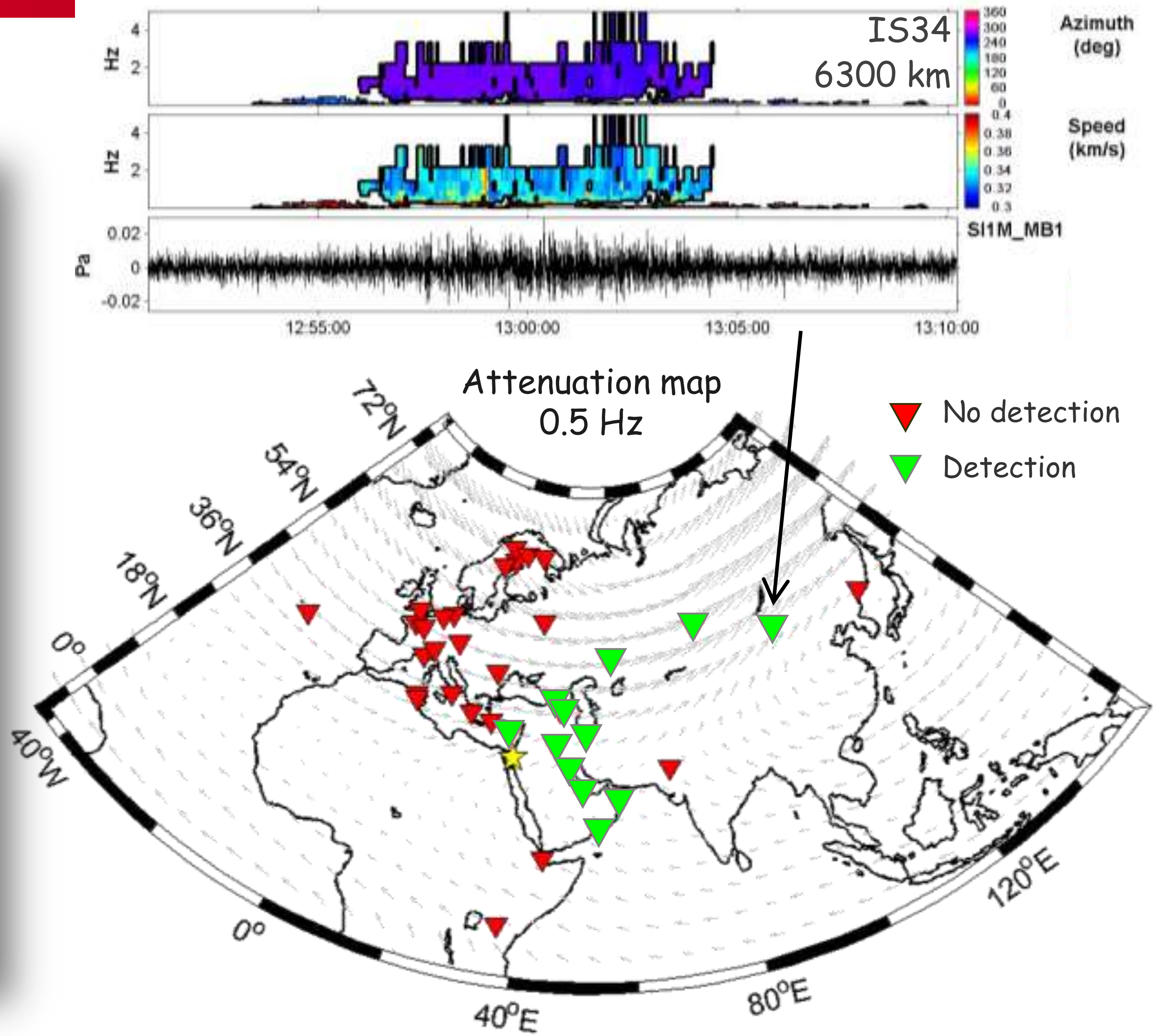
Evaluating the network performance

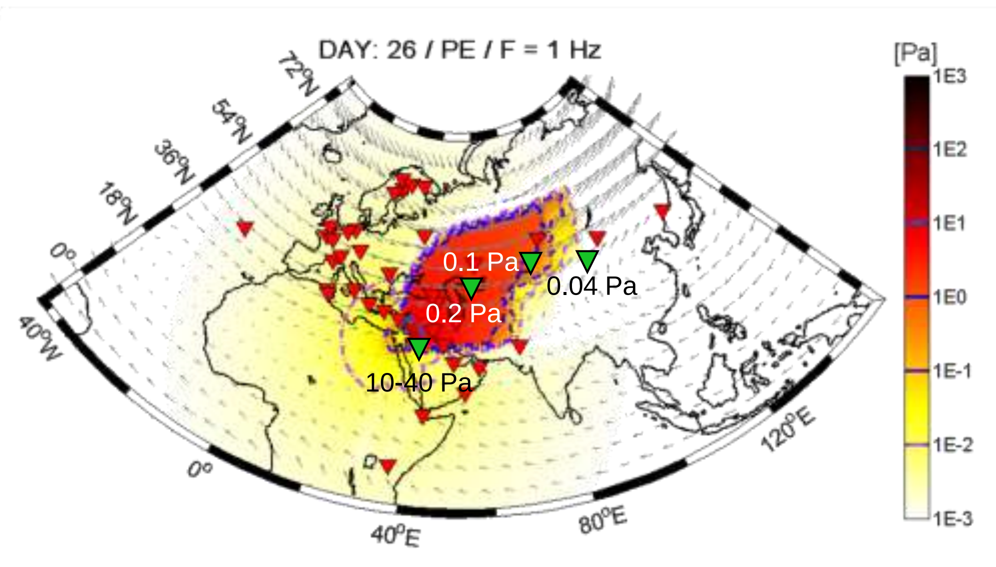
Sayarim, Israel
Calibration experiment coordinated by PTS/CTBTO (~80t TNT)
Jan. 2011

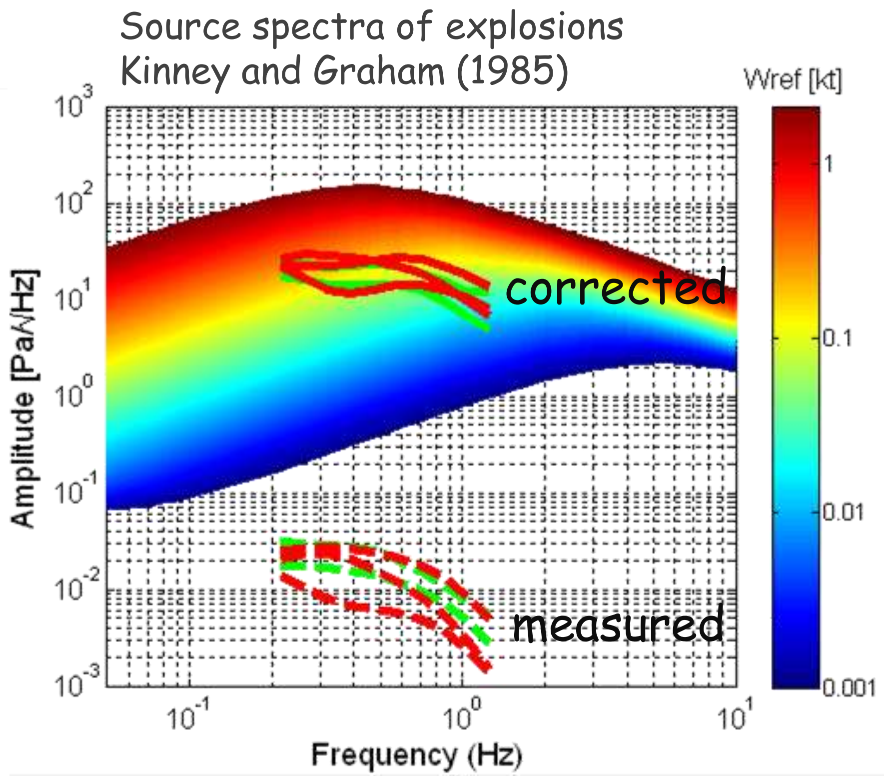
Participants :

- Geophysical Institute of Israël
- Geophysical Institute of Alaska, US
- SAIC, US
- Univ. Mississipi, US
- Univ. Hawaii, US
- National Observatory, Athens
- University of Firentze
- PTS/CTBTO
- CEA/DASE



Network calibration experiment

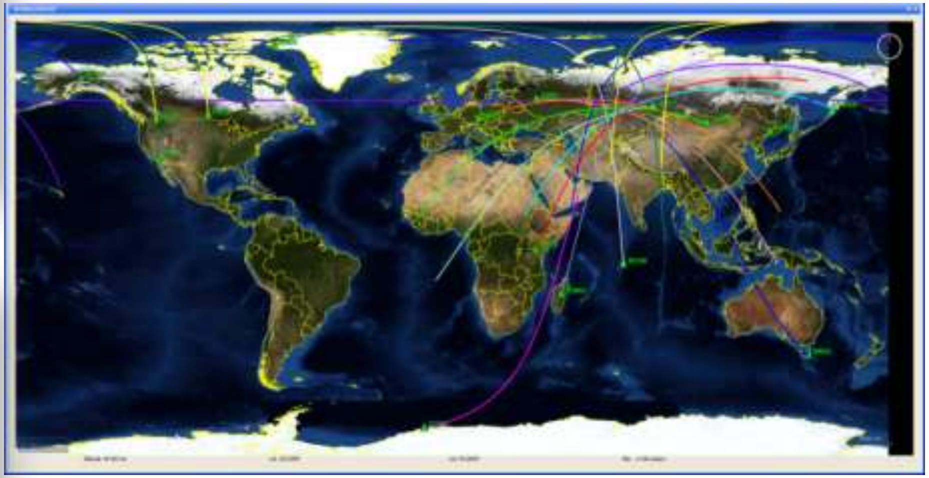




PE yield estimates: 30-150 t (Empirical: 10-800 t)

Network calibration

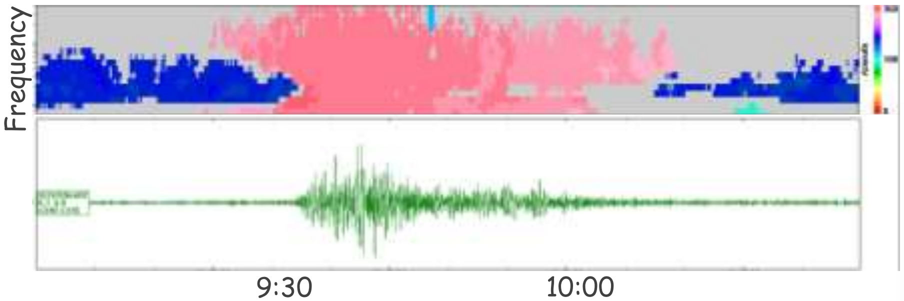
Global detection of the Chelyabinsk fireball, 15/02/2013



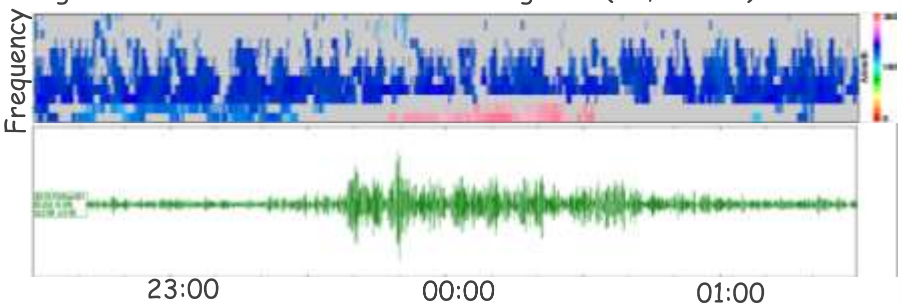
- 20 IMS stations
- 30 arrivals
- Period: 20-80 s
- Duration: 10 min – 3 hours
- Max distance: 86,600 km

Russian Fireball – 2013/02/15
Detection by IS53 (Fairbanks, Alaska)

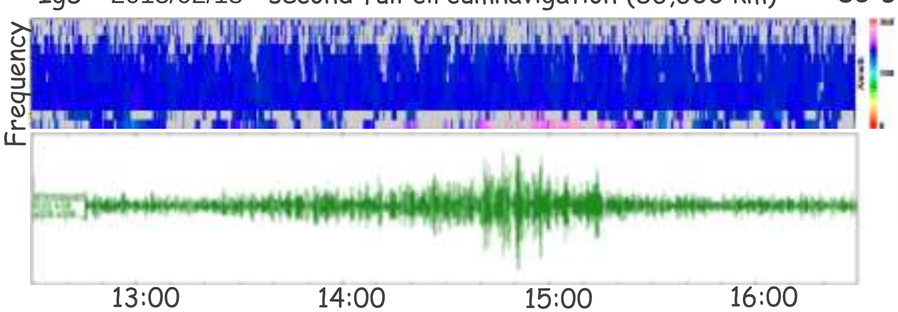
Ig1 - 2013/02/15 – first arrival (6,500 km) **~30 s**

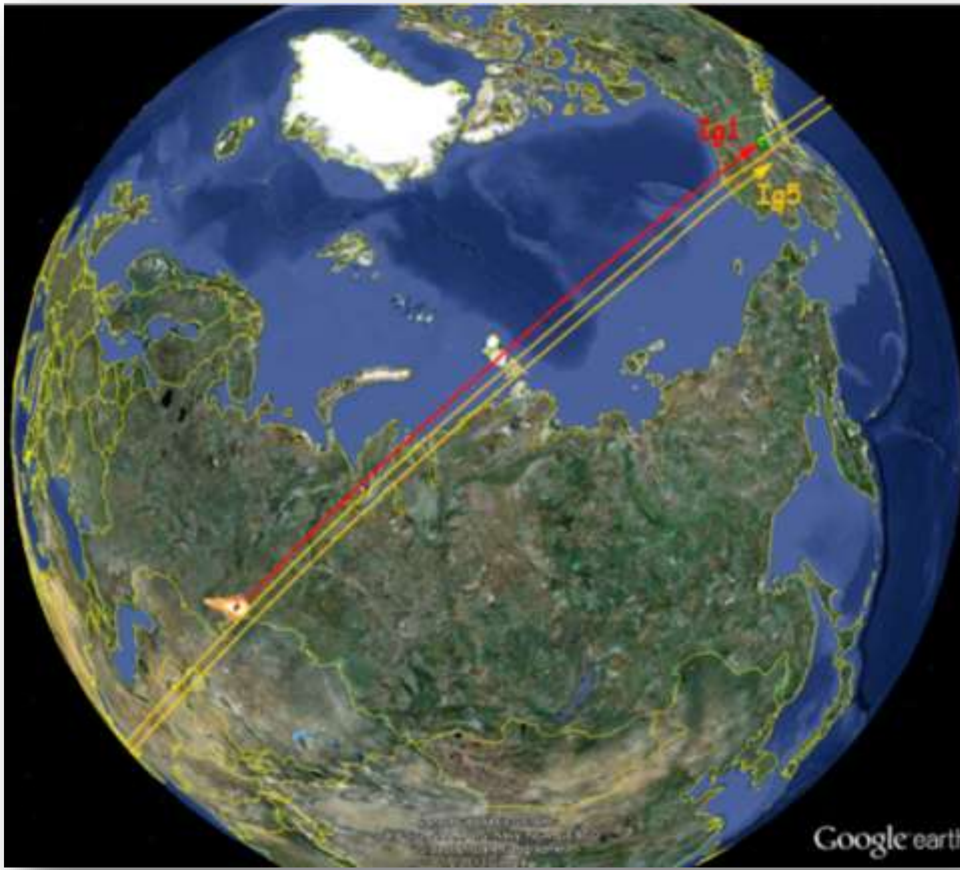


Ig3 – 2013/02/16 - first full circumnavigation (46,600 km) **~50 s**



Ig5 – 2013/02/18 - second full circumnavigation (86,600 km) **~80 s**

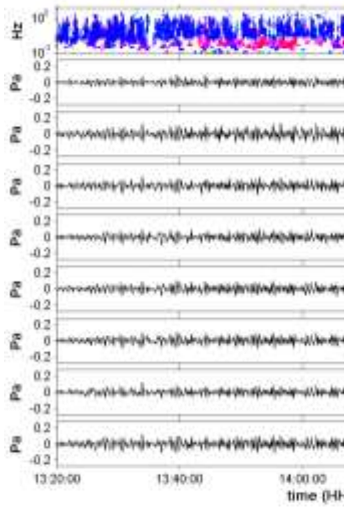




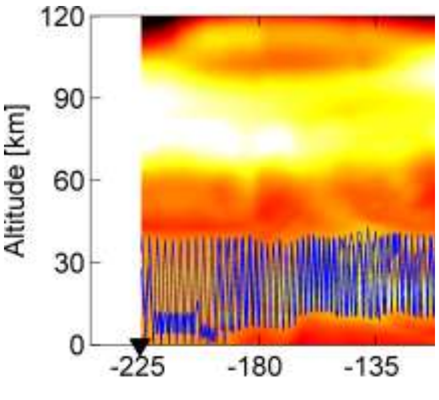
Network calibration

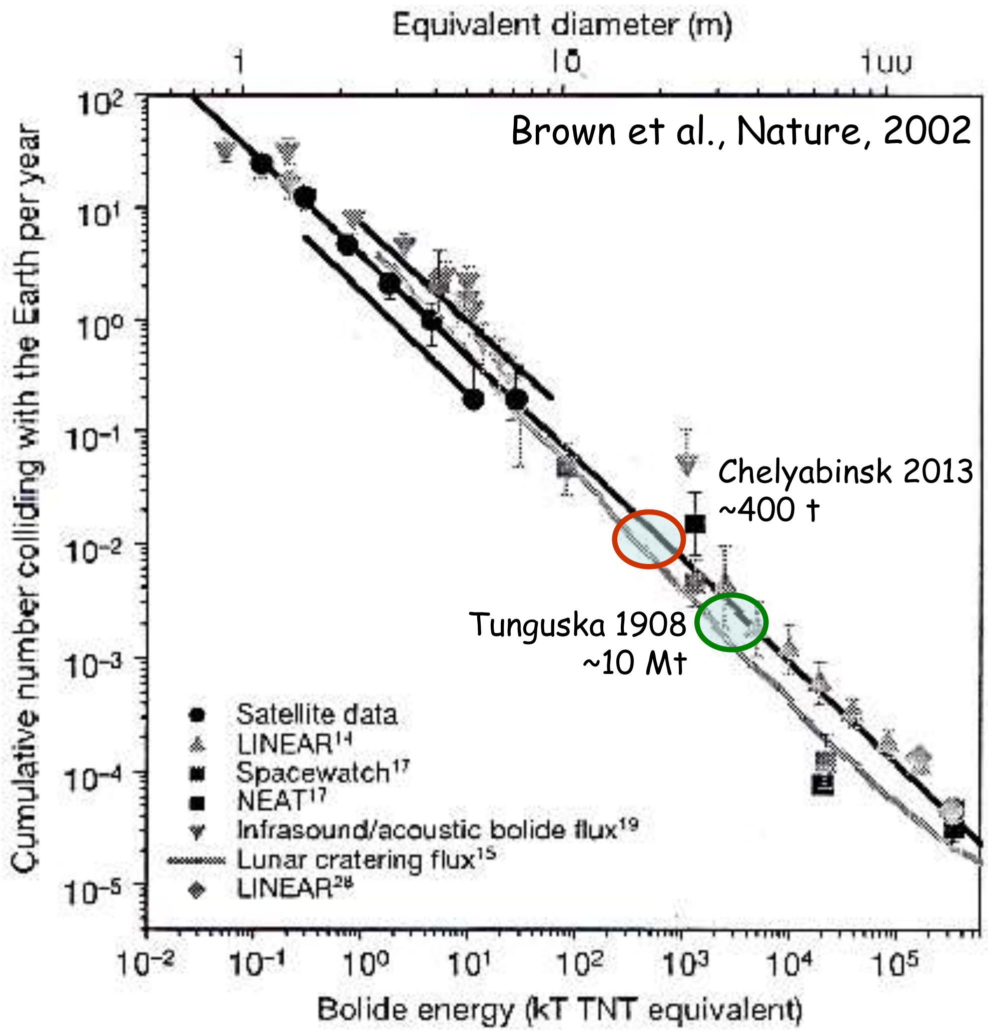
Global detection of the Chelyabinsk fireball, 15/02/2013

IS53 Alaska (Ig5,



Ig3





od: 39 s

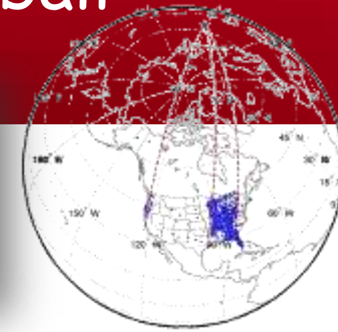
d: ~450 kt of TNT

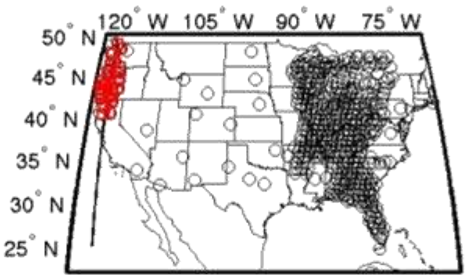
$.14 \log(\tau) - 3.61$

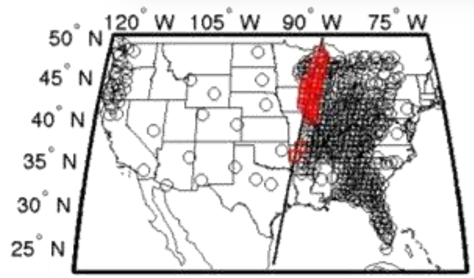
echnical Center

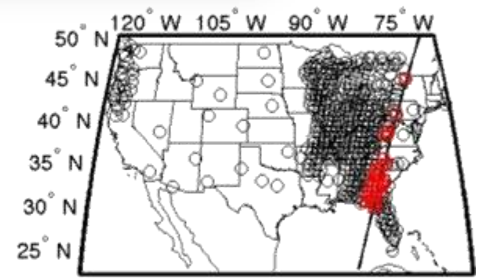
ard associated

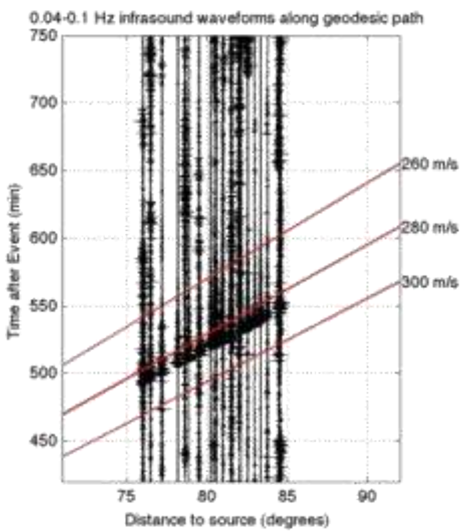
Global detection of the Chelyabinsk fireball 15/02/2013

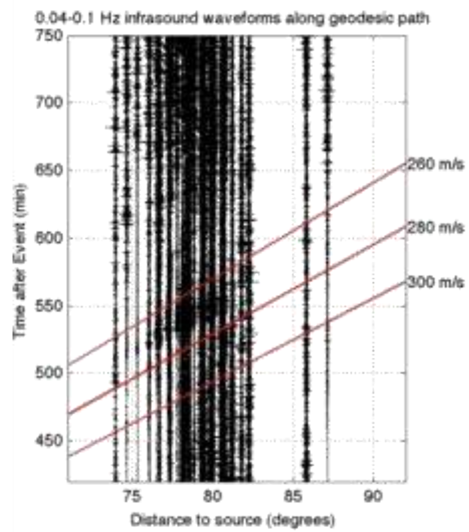


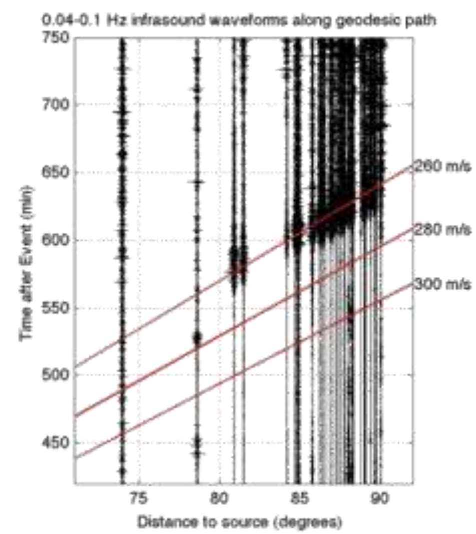












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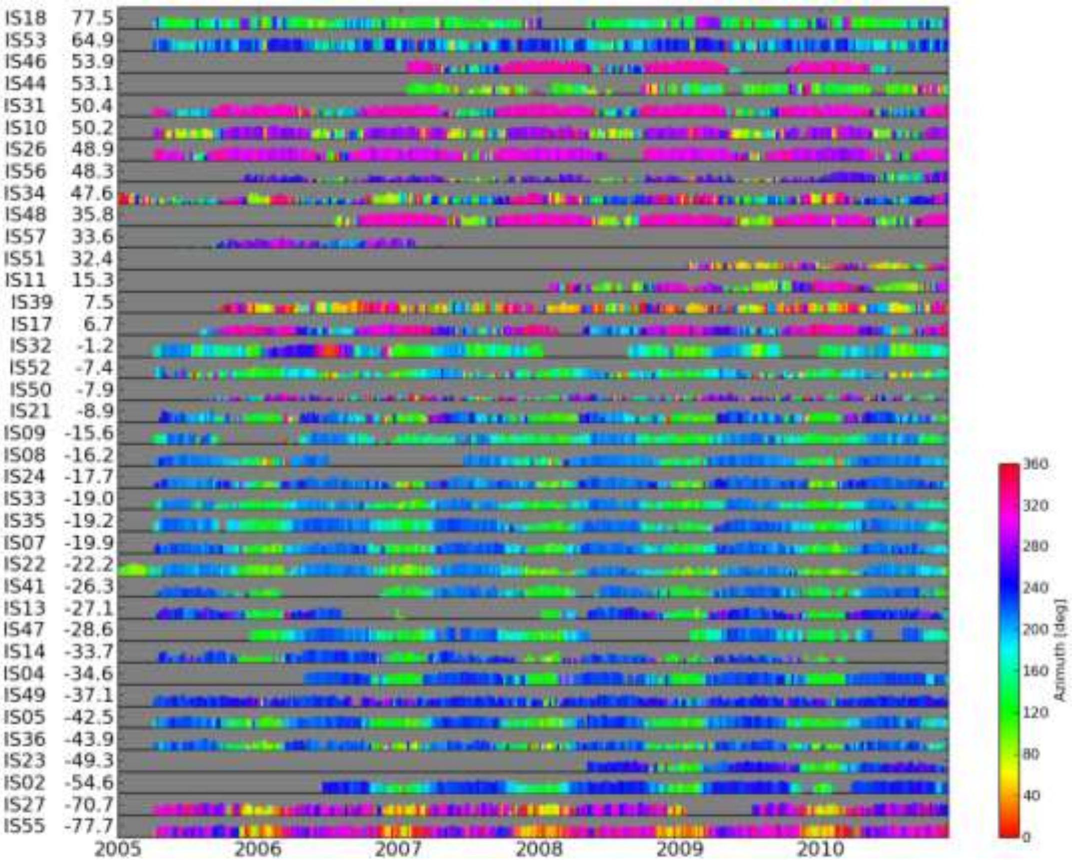
Deciphering the song of the sea

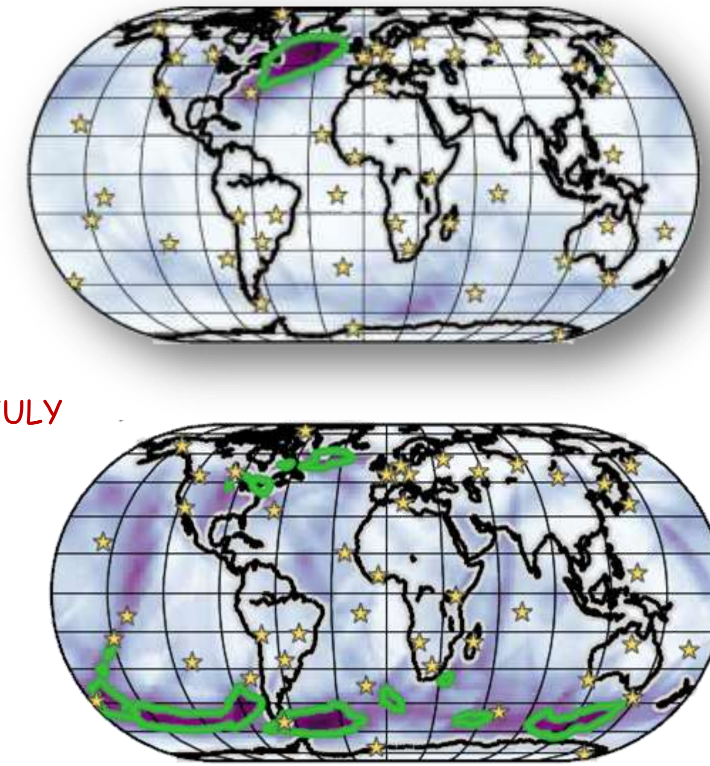
Monitoring microbaroms on a global scale (5-7 s)



JANUARY

Observations

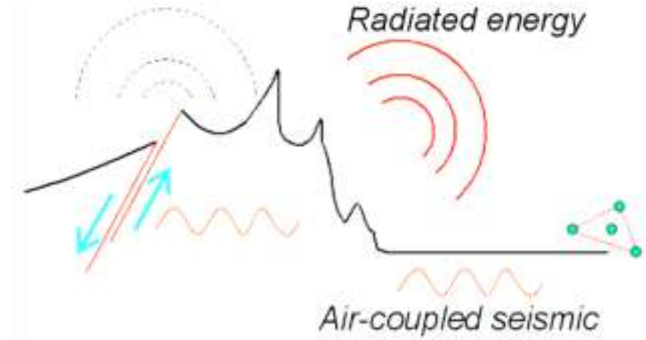
JULY



Landès et al., GRL, 2012

- Infer source location and strength
- On going studies (Kedar et al., 2008)
- Better constrain source and atmospheric models

Observations of earthquake-generated infrasound



Coupling →

Seismic Source → *Seismic Waves* → Epicenter Land masses → *Infrasound Waves* → Infrasound Array

Source Parameters ↑ (Seismic Source)

Earth Velocity Structure ↑ (Seismic Waves)

Topographic Parameters ↑ (Epicenter Land masses)

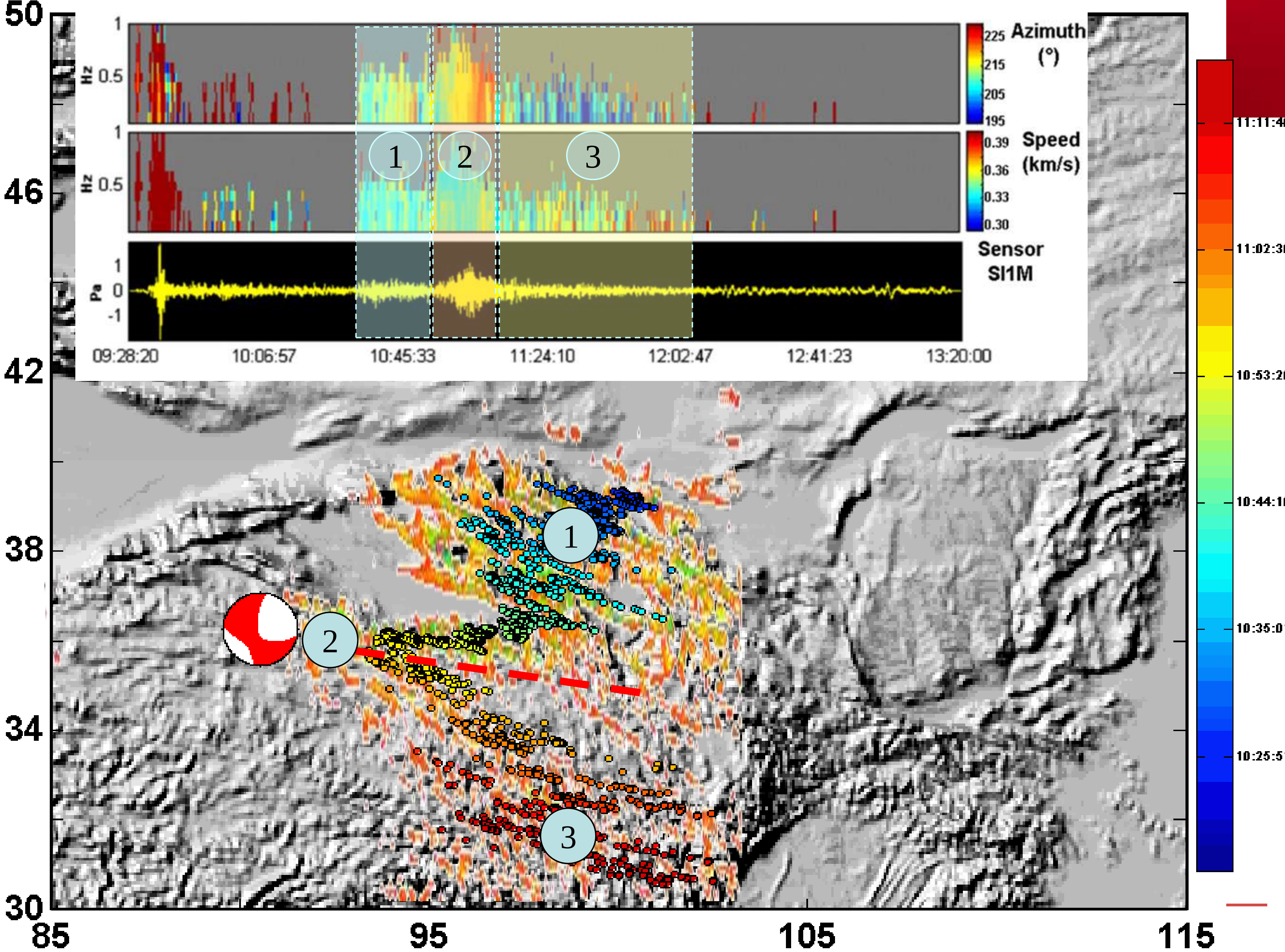
Atmospheric Velocity Structure ↑ (Infrasound Waves)

Instrument Response ↑ (Infrasound Array)

Donn and Posmentier, 1964
Young and Greene, 1982
Mutschlecner and Whitaker, 2005
Le Pichon et al., 2009

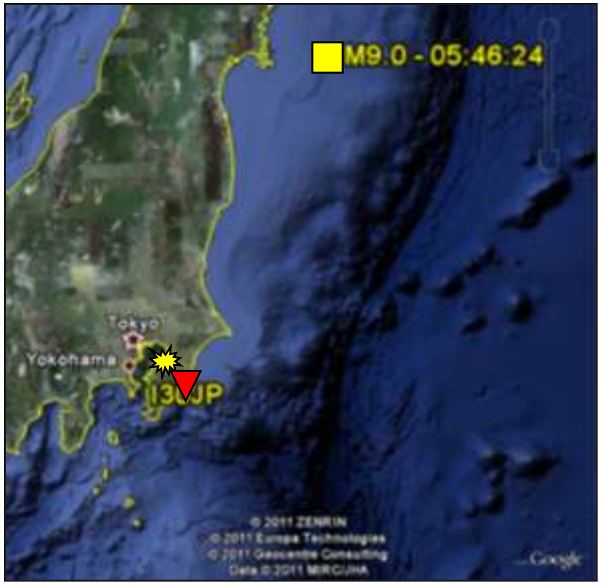
The coupling problem: From ground-motion to pressure fields

- Simulation of the RMS of 3C broad band synthetic seismograms (Bouchon, 1981)
- Far-field approximation of the Helmholtz-Huygens integral formulation (seismograms + ETOPO30)
- Infrasound propagation using 3D ray-tracing through realistic atmosphere (Virieux et al., 2004)



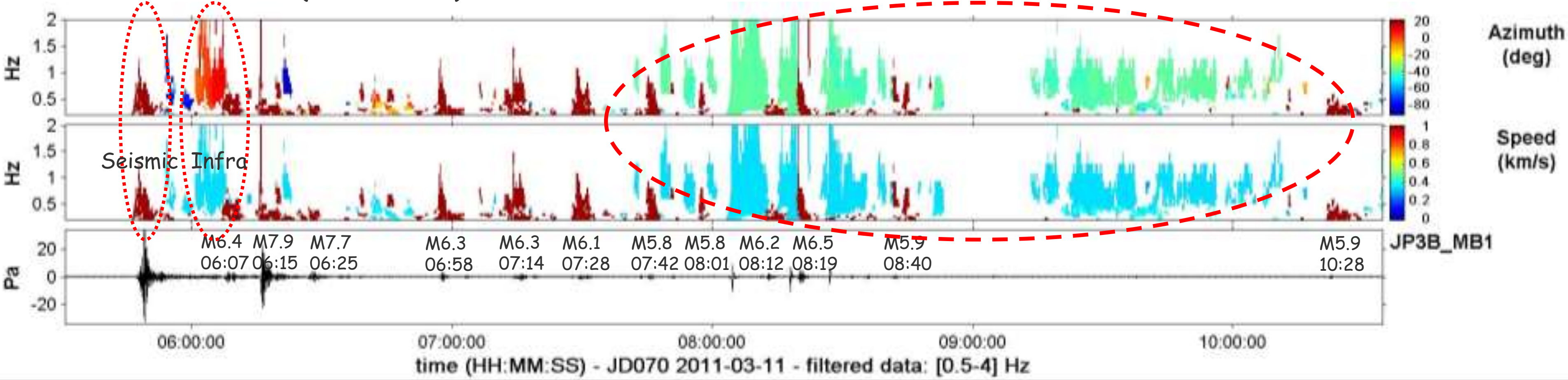
Azimuth (°)
225
215
205
195
Speed (km/s)
0.39
0.36
0.33
0.30
Sensor SI1M
Hz
0.5
Pa
09:28:20
10:06:57
10:45:33
11:24:10
12:02:47
12:41:23
13:20:00
1
2
3
11:11:40
11:02:30
10:53:20
10:44:10
10:35:01
10:25:51
50
46
42
38
34
30
85
95
105
115

M9.0 earthquake – East coast of Japan
March 11, 2011



Fire in Ichihara oil refinery

IS30 – 385 km (0.05-2 Hz)



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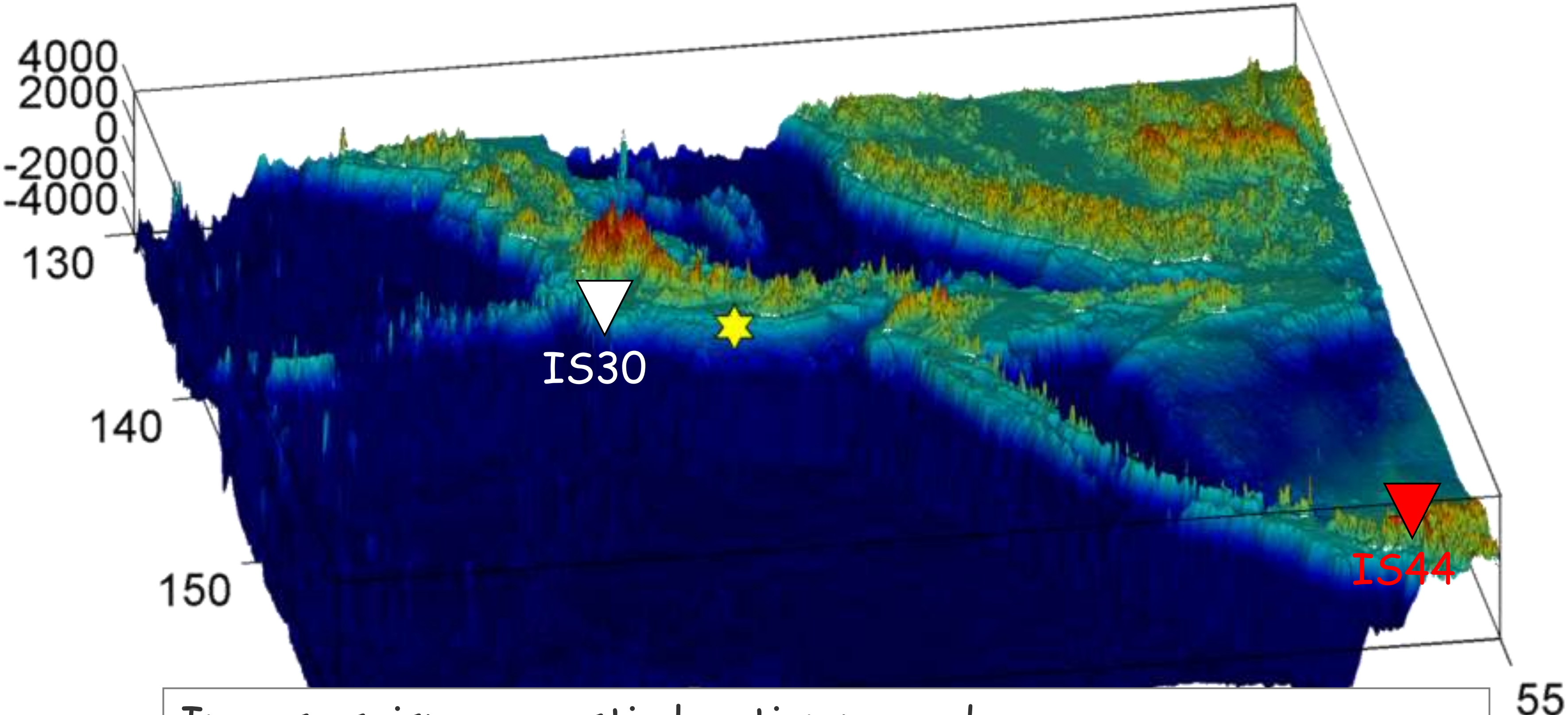
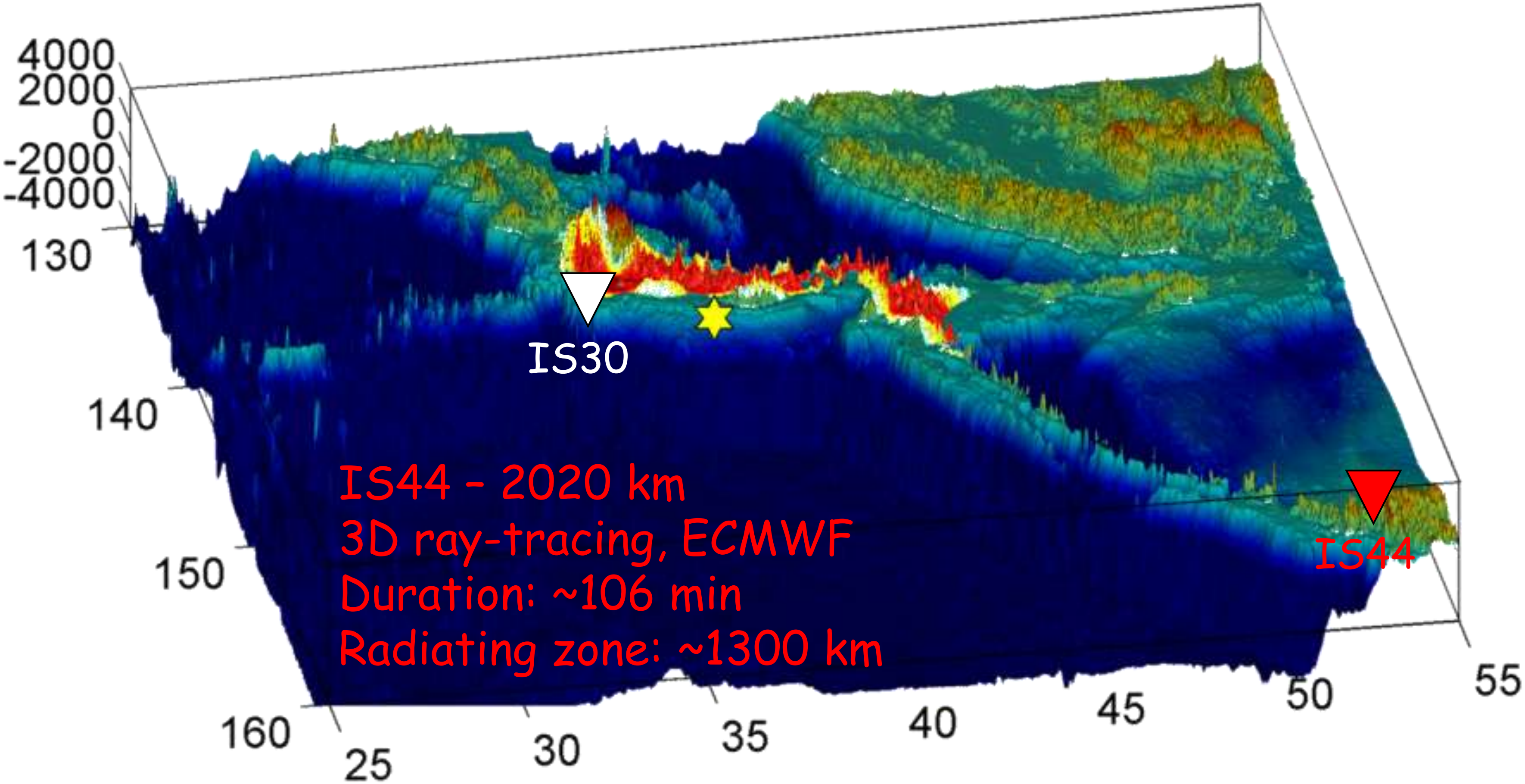


Inverse seismo-acoustic location procedure

- ✓ Seismic source: T0/ lat/ long/ depth, Vs
- ✓ Infrasound measurements: arrival time, back-azimuth, celerity

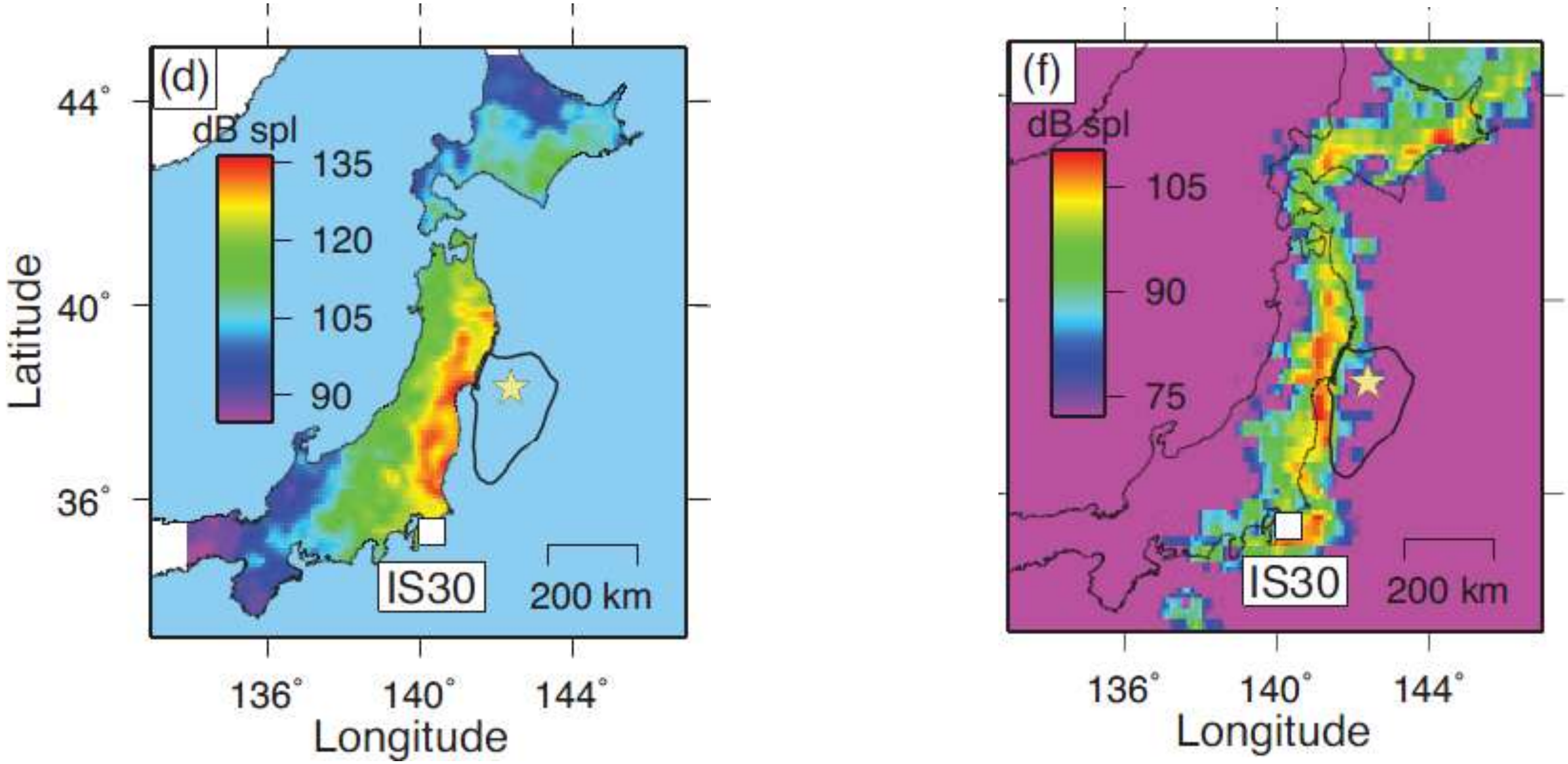
M9.0 earthquake – East coast of Japan March 11, 2011



M9.0 earthquake – East coast of Japan March 11, 2011

Acoustic peak surface pressure from peak acceleration (KNet network)

Infrasound back projected to the source region from array IS44 (Kamchatka)



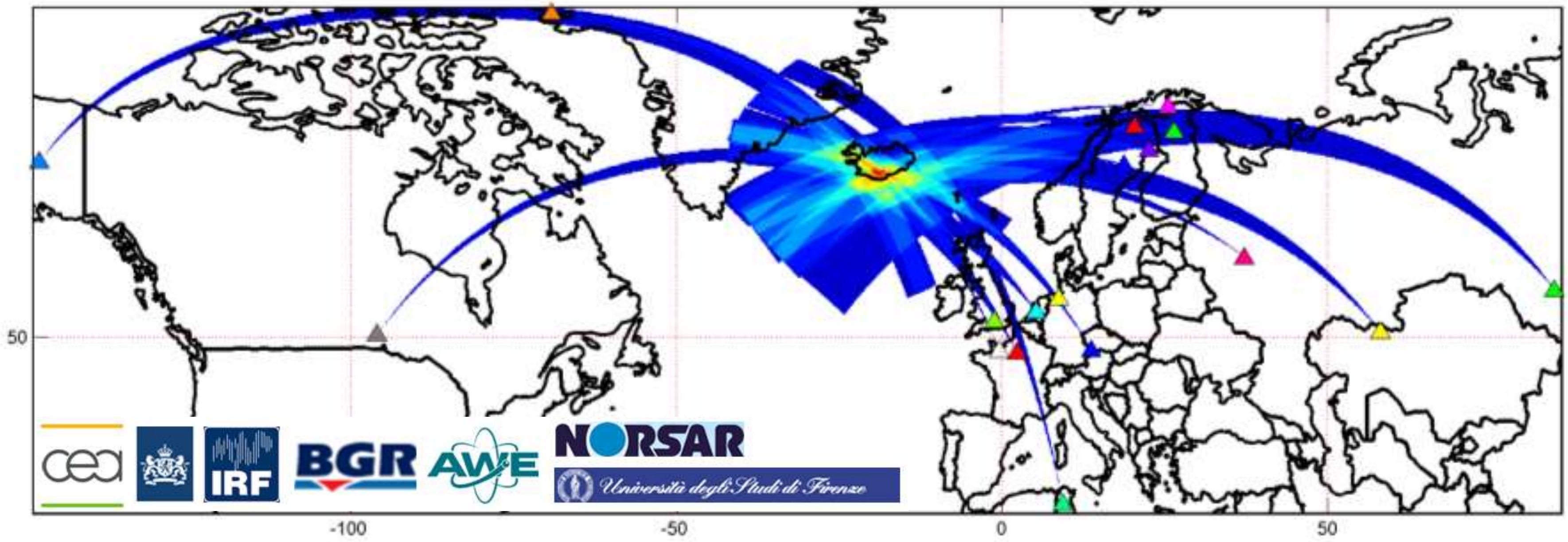
Hedlin et al., JGR, 2013

- ➔ Source distribution in good agreement with areas of strong ground motions
- ➔ Civil: improve procedures for rapid estimation of ShakeMaps

Telesonic infrasound from Eyjafjallajökull Island, April-May 2010

- Global detection of modest size eruption
- 15 detecting stations (1700-6000 km)
- Cross-bearing location at ~50 km North of the volcano
- Valuable signals for network calibration and atmospheric studies


Credit: P. Nielsen

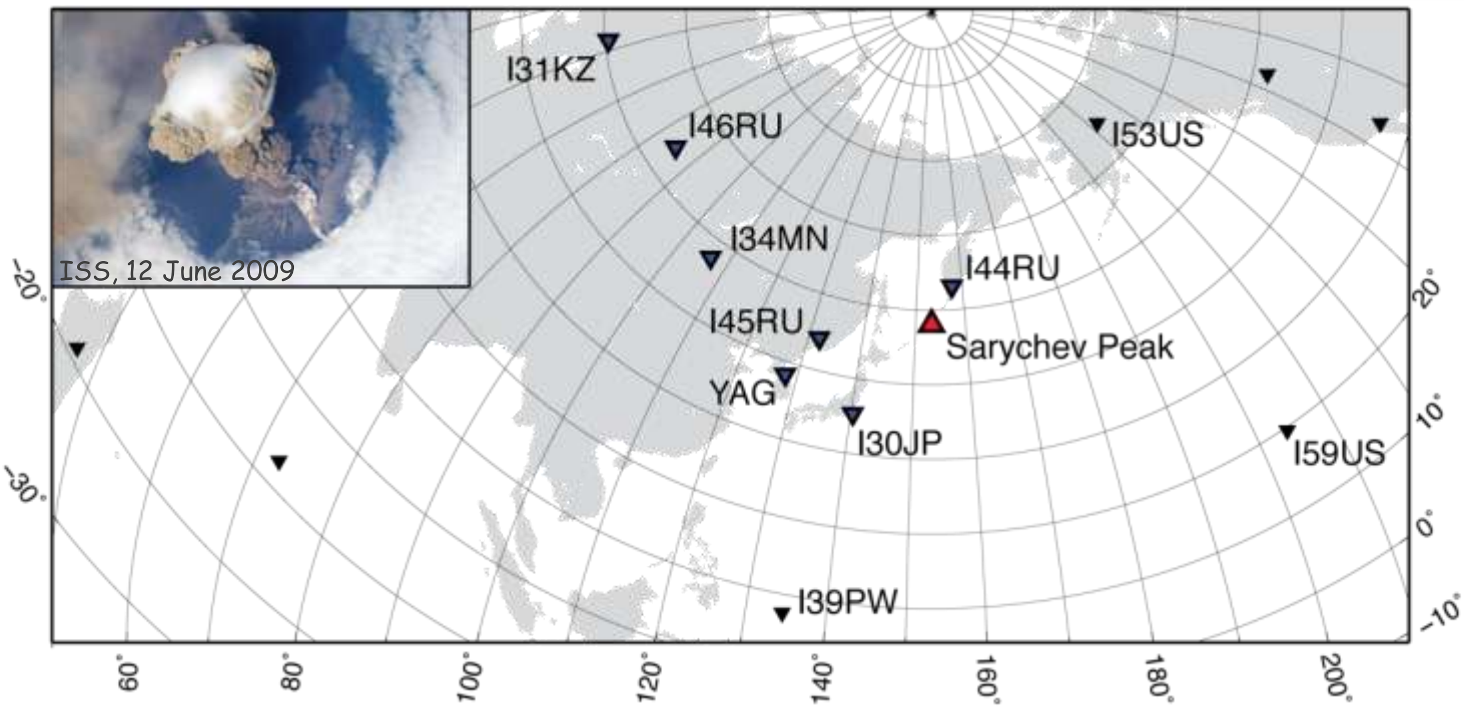


Matoza et al., GRL, 2011

Sarychev Peak eruption, Kuril Islands

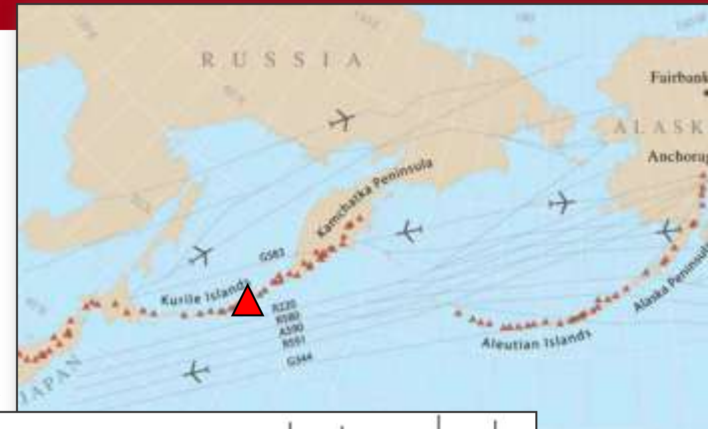
- Large-scale eruption: 11-16 June 2009
- Air traffic: unscheduled fuel stops, flight re-routes
- Seismic network sparse
- Monitored mostly by satellite data (SVERT, KVERT)

Neal et al., 2009
Salinas, 2010



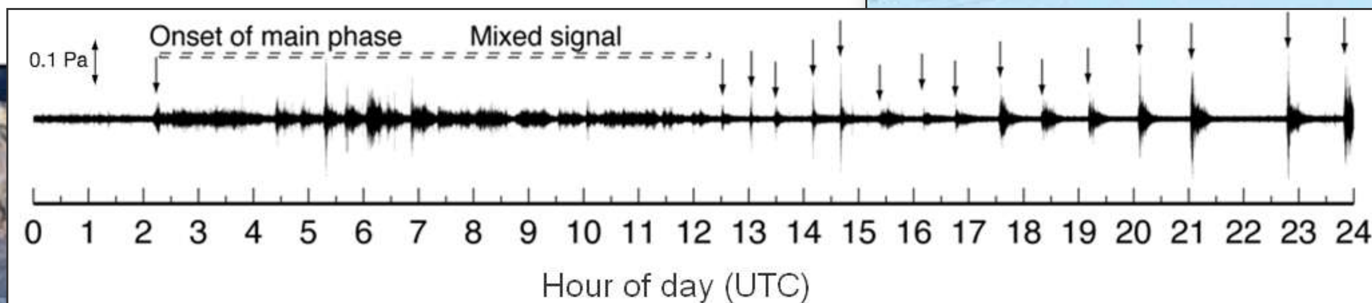
Matoza et al., GRL, 2011

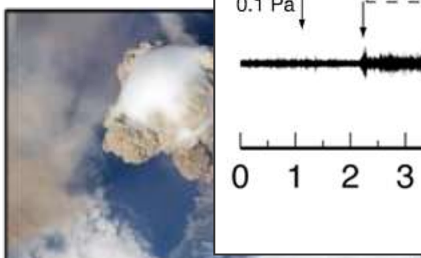
Sarychev Peak eruption, Kuril Islands



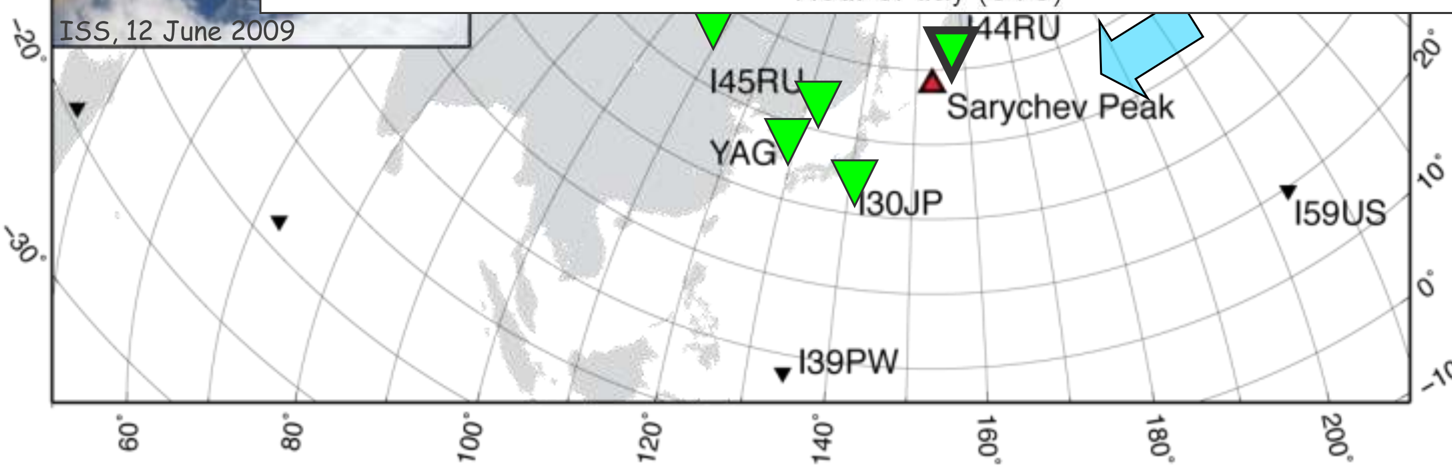
- 6 IMS infrasound arrays + KIGAM stations (Korea)
- Downwind detecting stations
- 640 - 6400 km range

12 June 2009 – 643 km





ISS, 12 June 2009



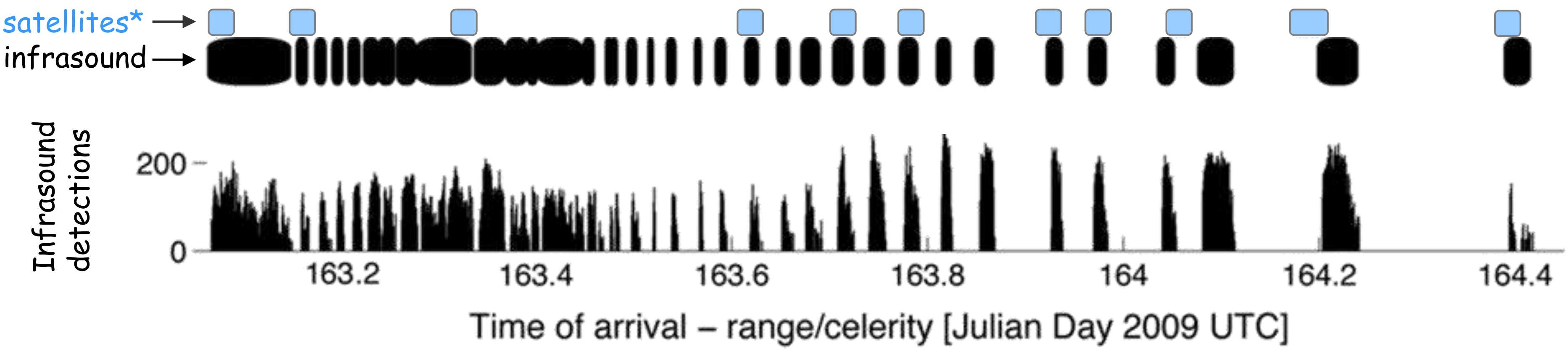
et al., 2009

as, 2010

Cargese Workshop, April 22-27

Matoza et al., GRL, 2011

Sarychev Peak eruption, Kuril Islands
Detailed explosion chronology



- Infrasound data can provide detailed explosion chronology
- Higher temporal resolution than satellite data

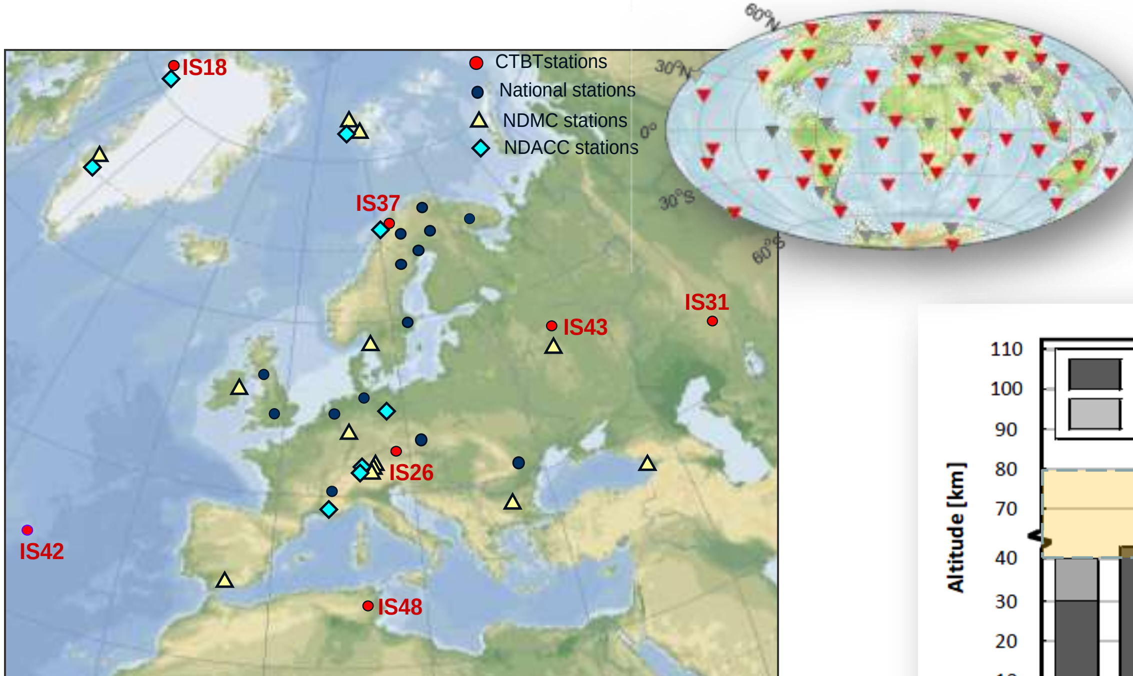
*Satellites observations: Sakhalin Volcanic Eruptions Response Team (SVERT), Yuzhno-Sakhalinsk, Russia

Matoza et al., GRL, 2011

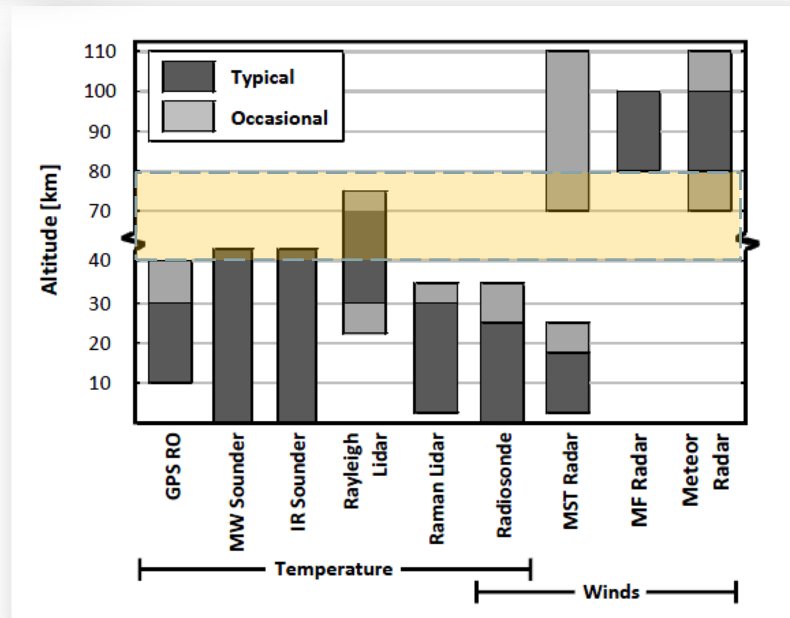
Outline

- Main challenges for infrasound interpretation
- Evaluating the network performance
- Calibrating the network using reference events
- Potential benefit for civil and scientific applications
  - Source studies: ocean-earth-atmosphere interface
  - Geophysical hazard warning systems
  - Better resolve upper atmospheric models

ARISE Atmospheric dynamics Research InfraStructure in Europe
Design Study project 2012-2015 - Infrastructure Program



- **Infrasound**: CTBT and national networks
- **Mesosphere**: NDMC - Airglow layer
- **Stratosphere**: NDACC - Lidar



- ❖ Extreme event monitoring
- ❖ Better resolve upper atmospheric models
- ❖ Improve weather forecasting

Coordination: CEA France
12 partners, 21 associate members

Department of Meteorology

University of Reading

The Sudden Stratospheric Warmings of Winter 2012/13

Christopher F Lee[1] | Pieter Smets[2,3] | Andrew J Charlton-Perez[1] | R Giles Harrison[1] | Philippe Keckhut[4] | Carston Schmidt[5] | Sabine Wüst[5] | Michael Bittner[5]

[1]Department of Meteorology, University of Reading, UK. [2]KNMI, Netherlands. [3]CTG, Delft University of Technology, Netherlands. [4]LATMOS, IPSL, France. [5]DLR, Oberpfaffenhofen, Germany.

Forecasting & SSWs

Major Sudden Stratospheric Warmings (SSWs) present a challenge for weather forecasting. ARISE measurements can provide valuable information on atmospheric dynamics before and during such events. Comparing ARISE observations of the Winter 2012/13 SSWs with forecasts reveals:

- Cooling around the mesopause proceeded both major SSWs.
- Difficultly in forecasting vortex positions after the vortex split.
- Changes in polar vortex winds substantial altered infrasound propagation.

ARISE Instruments

DLR's **GRIPS instrument** measures airglow – faint luminescence of atmospheric gasses (in this case, OH) – to infer temperatures between 83 and 90km above OHP.

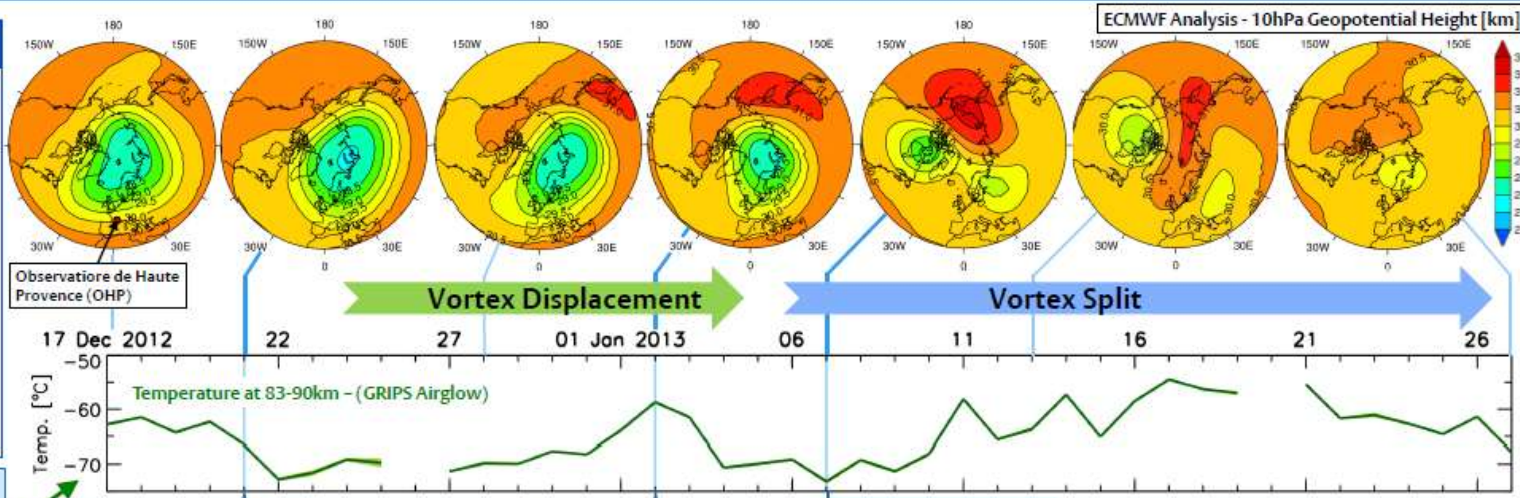
Rayleigh lidar measures temperature profiles between 30 and 90 km above OHP.

Infrasound monitoring stations measure microbaroms (ocean wave noise) from different regions as SSWs alter wind and temperature patterns in the stratosphere.

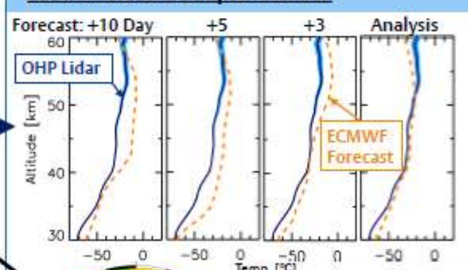
Further information

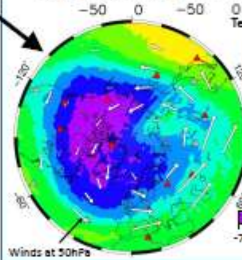
- Contact e-mail: c.f.lee@reading.ac.uk
- Poster 10079 (Z183) has more details on infrasound propagation during SWWs.

This project is funded by the European Union under the 7th Framework Programme.

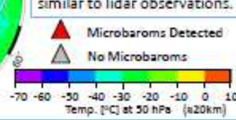


Before Vortex Displacement

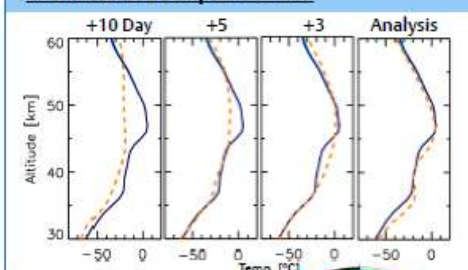




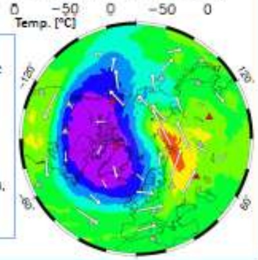
Strong westerly winds of the polar vortex carry microbaroms to most stations. Temperature profiles over OHP, from later forecasts, are similar to lidar observations.



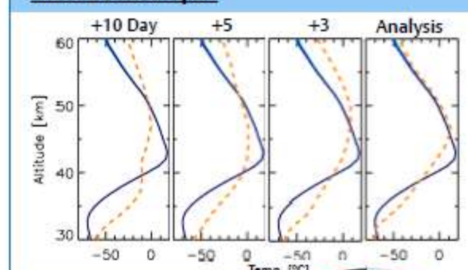
After Vortex Displacement



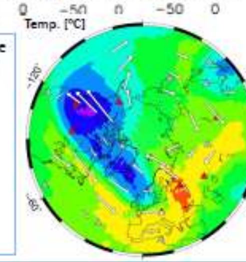
Temperature profiles from forecasts out to seven days are consistent with OHP lidar observations, and the analysis replicates the temperature structure at all altitudes. Changes in polar vortex winds alter microbarom propagation, with only four stations measuring microbaroms.



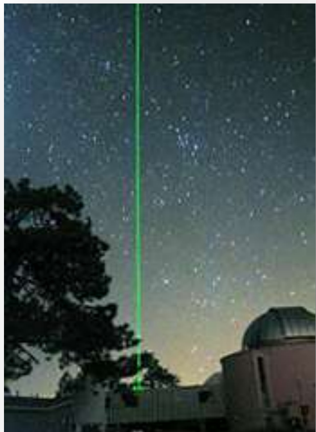
After Vortex Split



Forecasts struggle to replicate the temperature profile at all altitudes, and the upper stratosphere is poorly represented in the analysis (attributed to poor forecasting of split-vortex positions).
Weakening of vortex winds again alters patterns of microbarom detection.

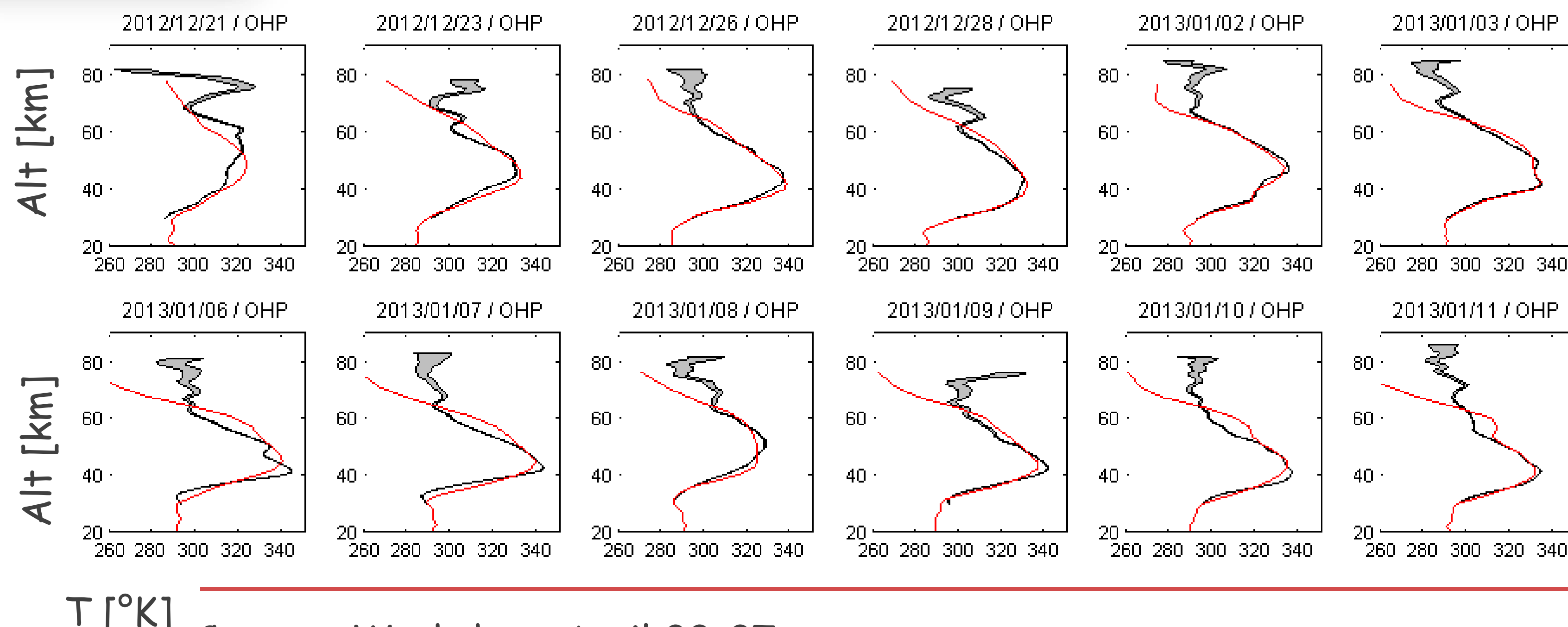


Quantifying uncertainties in temperature profiles using LIDAR



NDACC LIDAR
Observatoire
Haute-Provence,
France

- Small-scale perturbations filtered out
- Temperature largely underestimated above 60 km

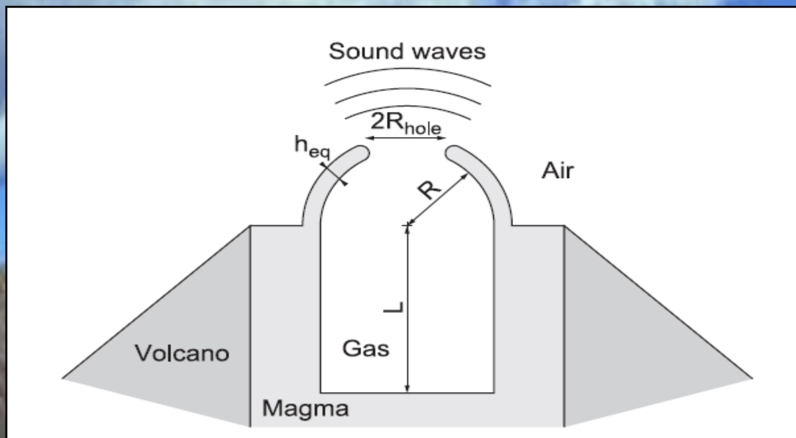


- Infrasound from volcanoes are very valuable for atmospheric studies
- Such studies provide a powerful tool to validate propagation models

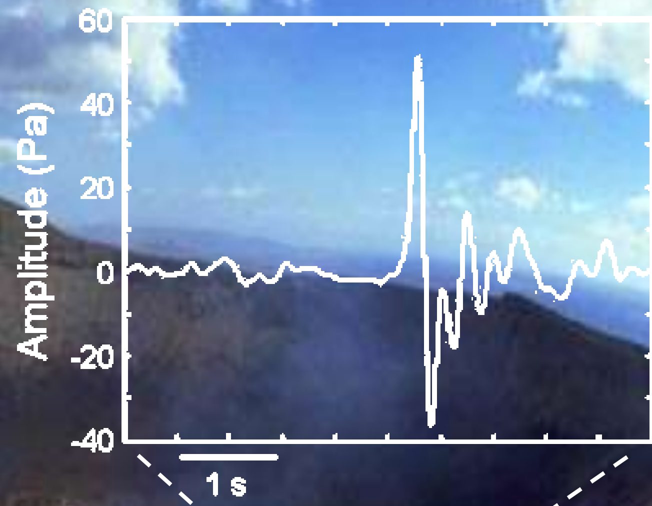
Yasur (19.52S, 169.42E, 360 meters high)


Ambrym
Paama
Lopévi
Nouméa
I22FR
~400 km
~650 km
Yasur
Port-Vila
Lopevi
Ambrym
© 2006 Europa Technologies
Image © 2006 NASA
Image © 2006 TerraMetrics
©2006 Google™

Infrasound from Yasur
Near field measurements



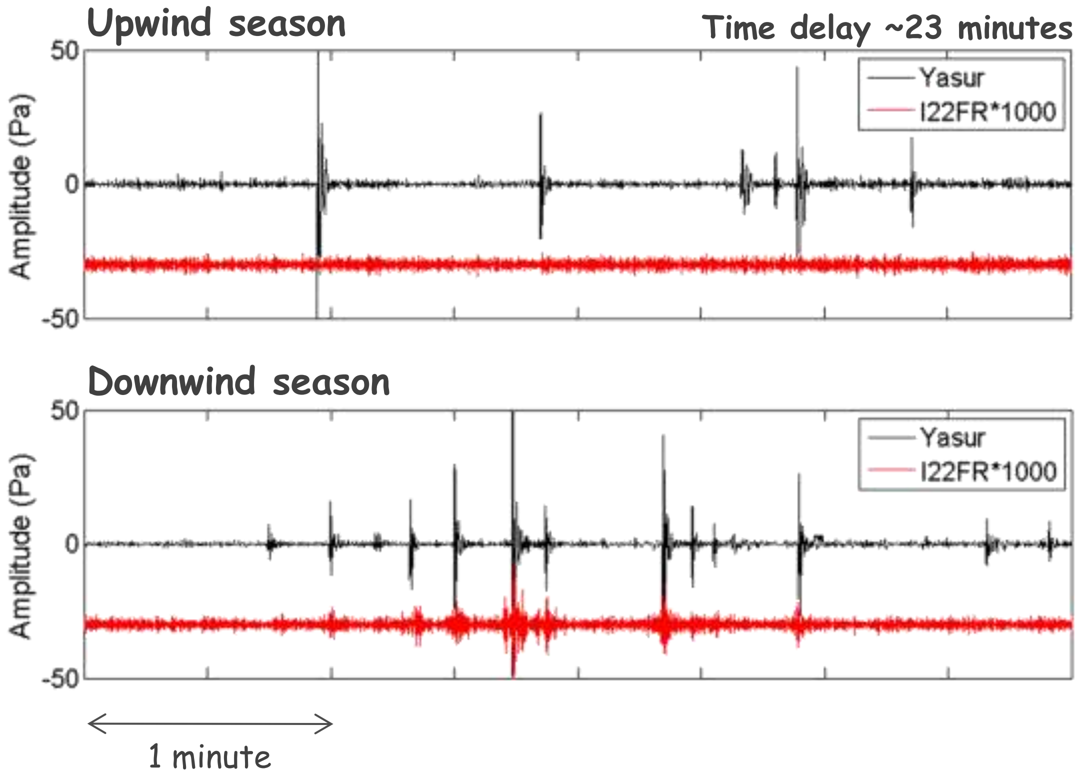
[Vergniolle and Brandeis, 1994]



Calibrating the atmosphere using volcanoes

Microbarometer near Yasur (~200 m)

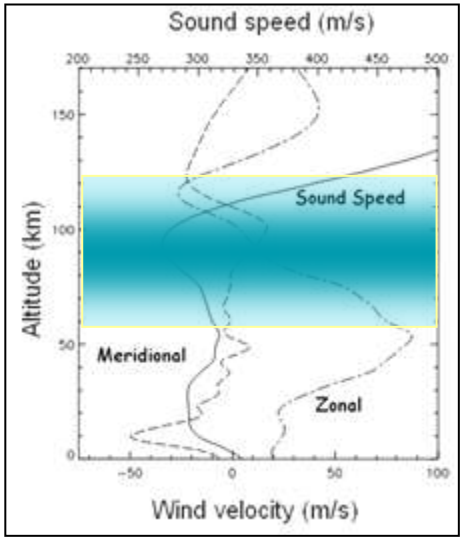
Station I22FR (~400 km from Yasur)



- Time sequences in near and far field correlate well during downwind season
- ~60 dB attenuation

Atmospheric remote sensing methods

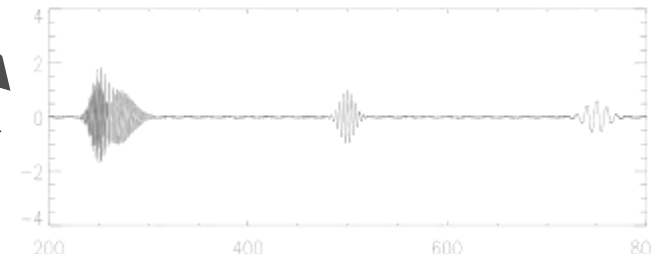
Atmospheric profiles: m



Propagation model with model atmosphere
$G(\underline{m},S) = d_m$

Location, origin time, source amplitude, pulse shape...

Simulations: d_m



Time (s)

Agreement?

$$\left|\Delta\chi^2\right| < \varepsilon$$

Adjust atmosphere
$\rightarrow$ m + Δm

$$\left[\frac{\partial G}{\partial m}\right]^{-1}$$

No

Yes

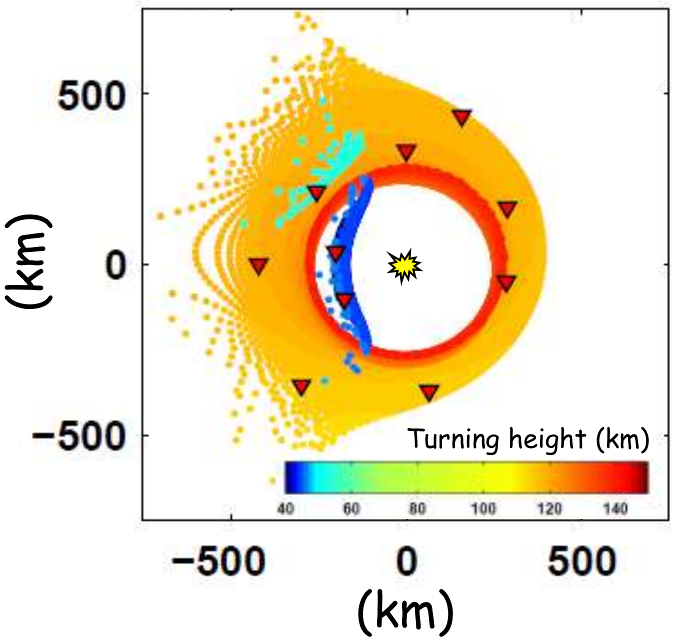
Improved
Atmospheric Specifications

Observations: d_{obs} (travel time, backazimuth, phase velocity...)

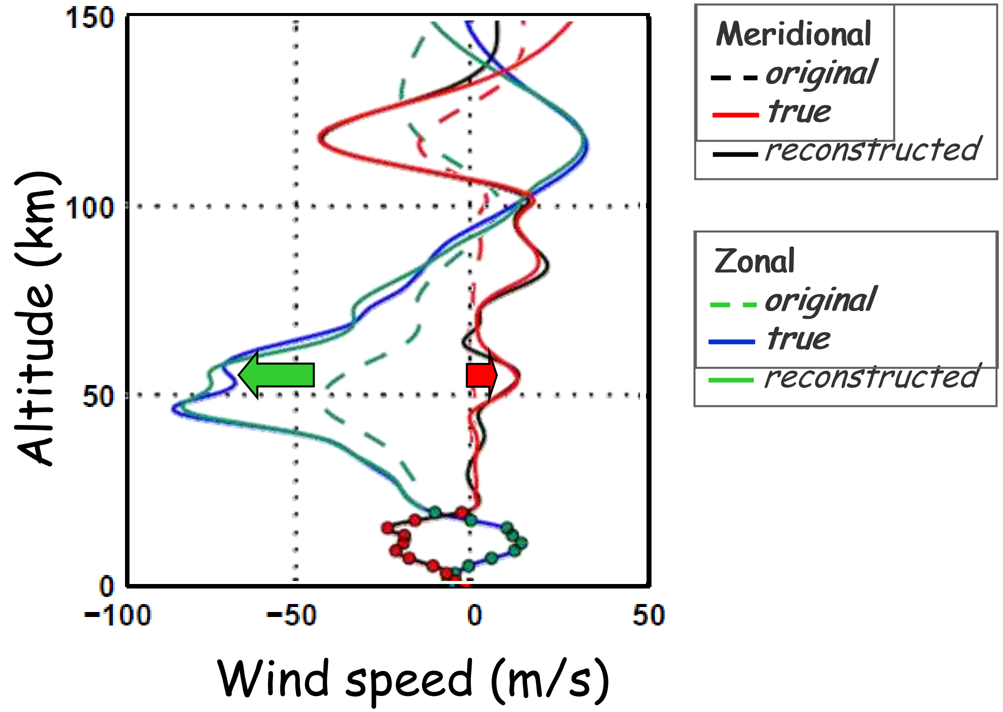
Atmospheric remote sensing methods

- Input parameters: arrival times, incidence angle, direction of arrival
- Objective function minimization *(Tarantola, 2005)*
- Conjugate gradient algorithms LSQR *(Paige and Saunders, 1982)*
- Assessment on synthetic dataset

Synthetic data set

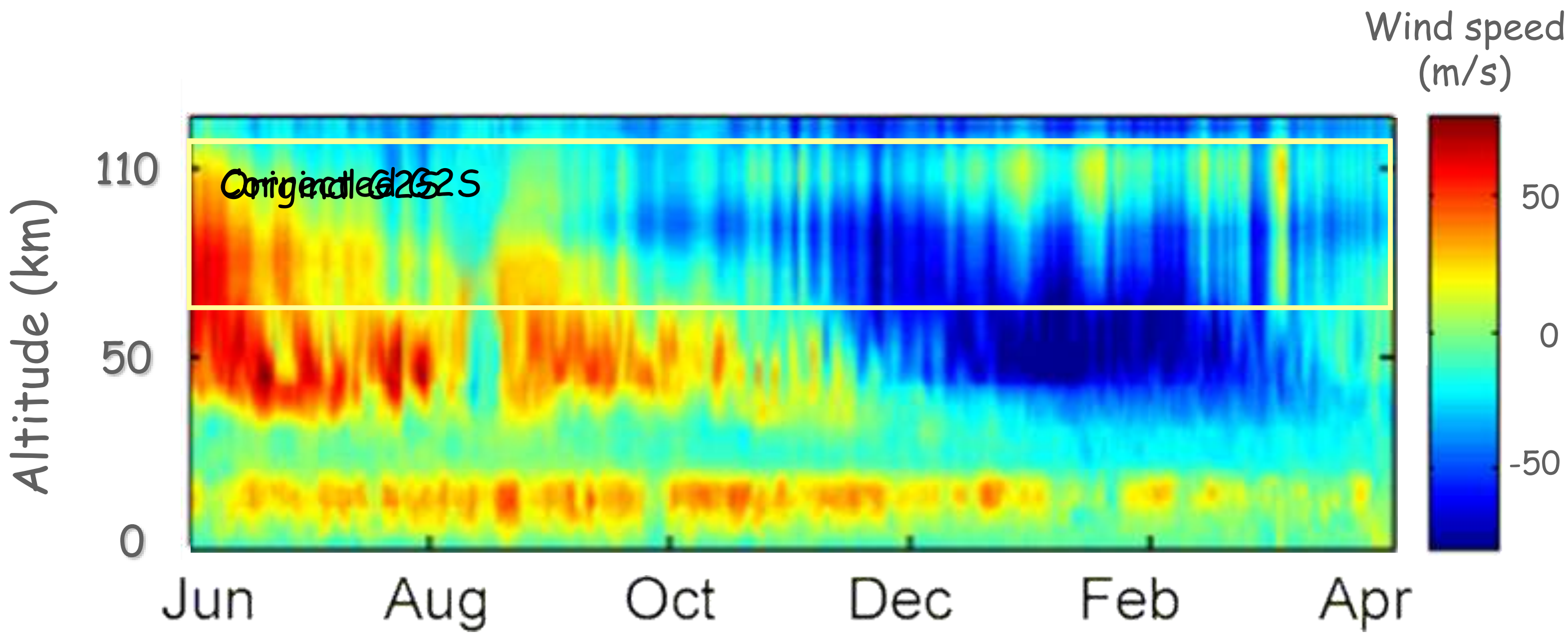


Wind profiles



Lalande et al., 2012

Reconstruction of upper-wind profiles

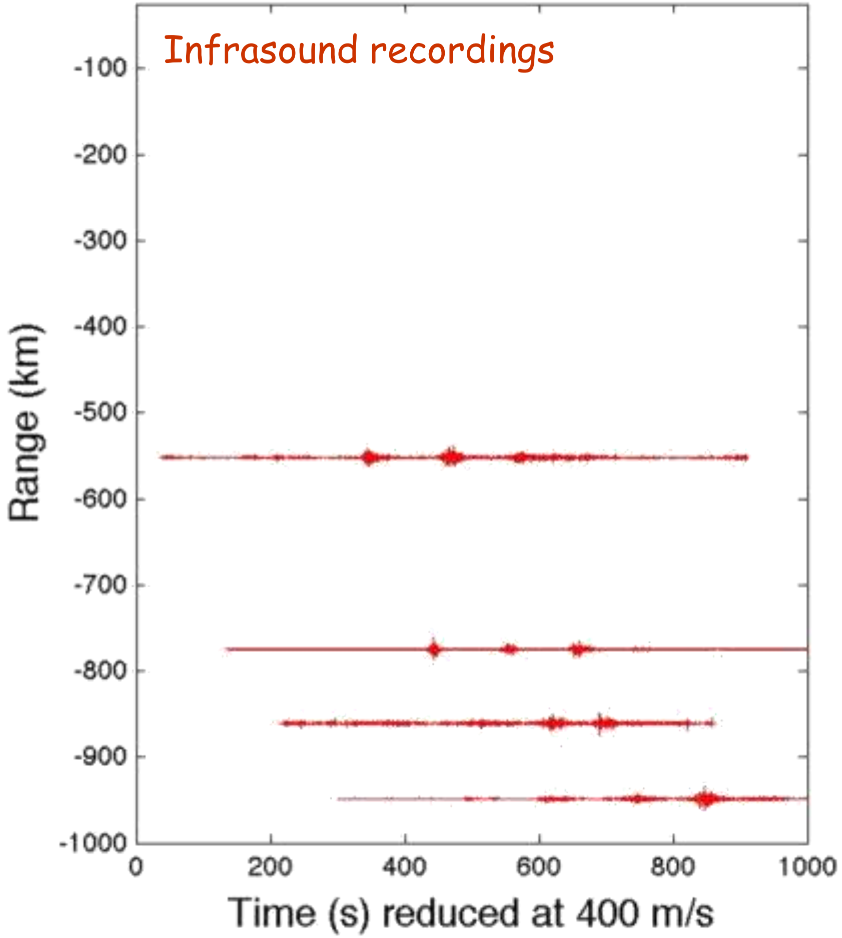


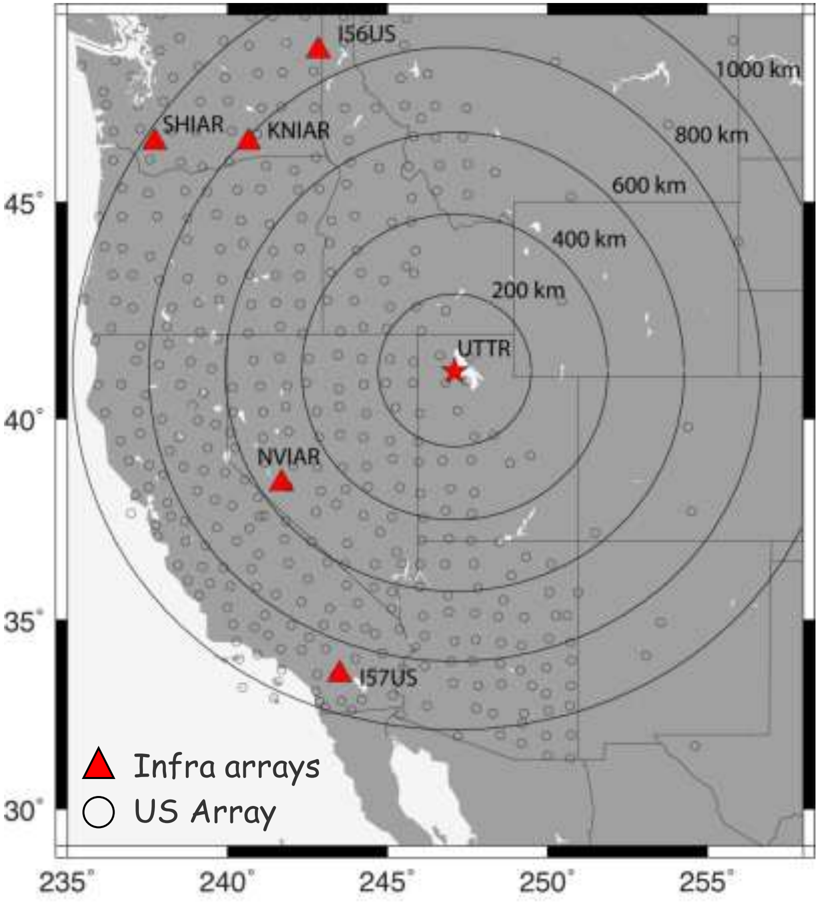
- Reconstruct short time-scale stochastic variations in the MLT
- Mesospheric zonal wind jets generally underestimated by **~20 m/s**
- In agreement with recent wind measurements in the MLT which indicate that HWM underestimates wind velocities by few 10-30 m/s

Le Pichon et al., JGR, 2005
Lalande et al., JGI, 2012

Seismic network studies of the atmosphere

UTTR 2007, 0.8–3.0 Hz (Hedlin et al., 2011)





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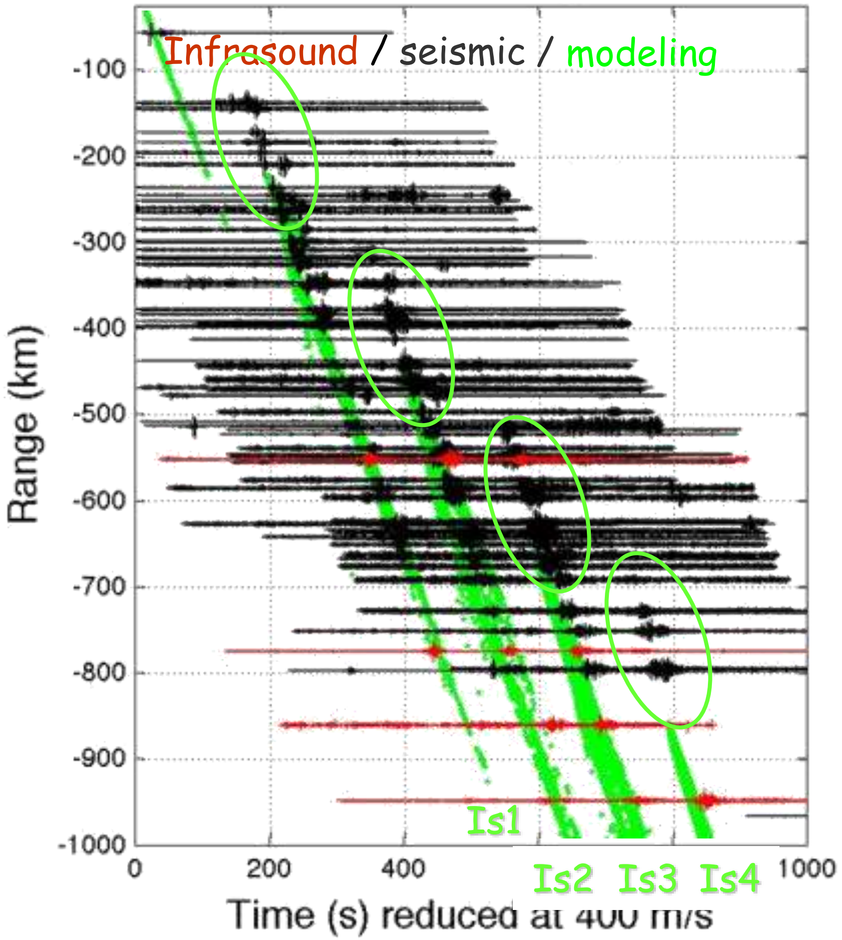

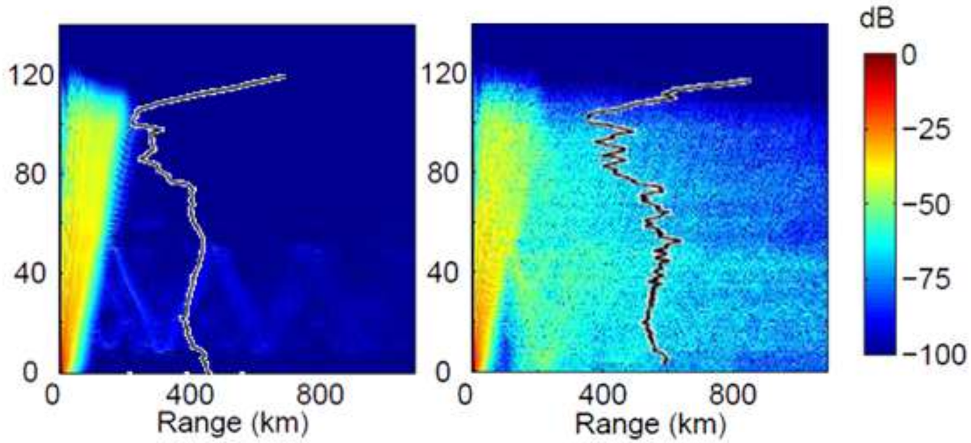

- ✓ Ground footprint of stratospheric returns
- ✓ Discrepancies explained by lack of resolution of models
- ✓ Infer small scale atmospheric structures from ground observations (Drob et al., 2013)

Conclusion and Perspectives

- The IMS network provides a unique global coverage of infrasound
  - ✓ Far larger and much more sensitive than any previously operated network
  - ✓ Reference events are more frequently observed
  - ✓ Understand details of infrasound propagation

- Infrasound has developed into a broad interdisciplinary field
  - ✓ Civil applications: monitoring naturally occurring phenomena (severe weather), geophysical hazard warning systems
  - ✓ Scientific applications:
    - Earth-ocean-atmosphere interactions
    - Global and massive sensor networks available: 3D-t imaging (weather forecasting…)
    - Remote sensing methods: applicability of noise correlation technique