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Tracking of fine scale infrasound IMS network performances in near real time

J. Vergoz[1], A. Le Pichon[1], C. Listowski[1], P. Hupe[2]

[1] CEA, DAM, DIF, F-91297 Arpajon, France
[2] BGR, B4.3, D-30655 Hannover, Germany

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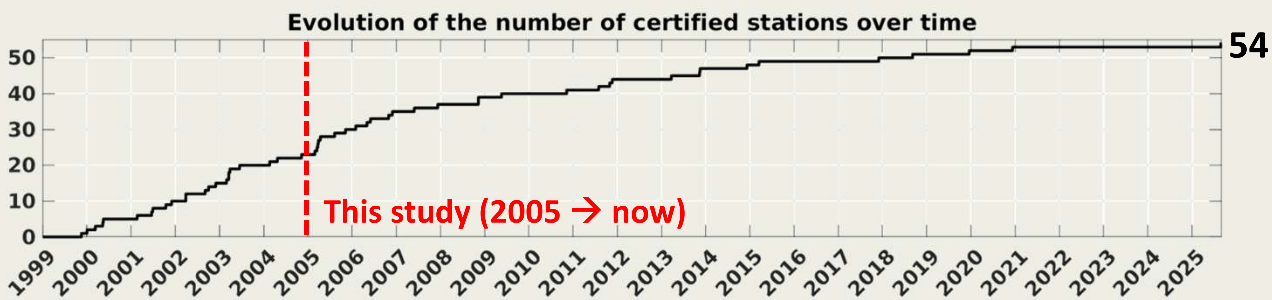
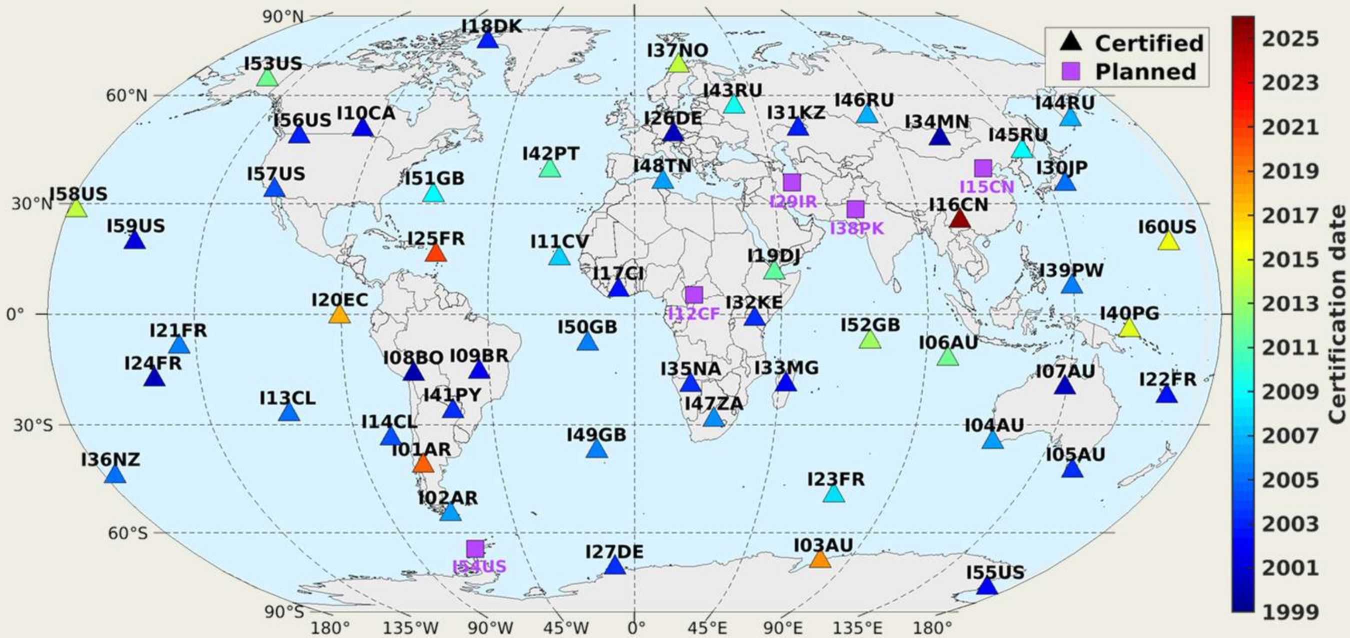
The IMS Infrasound Network: World's Only Global Network





- Unique global infrasound network
- The IMS infrasound network is 90% complete (54/60)
  - I16CN certified on 2025/08/26
  - Provides very high DA (> 98% in 2025)

Opportunity to track performance enhancement of the network over time through its densification

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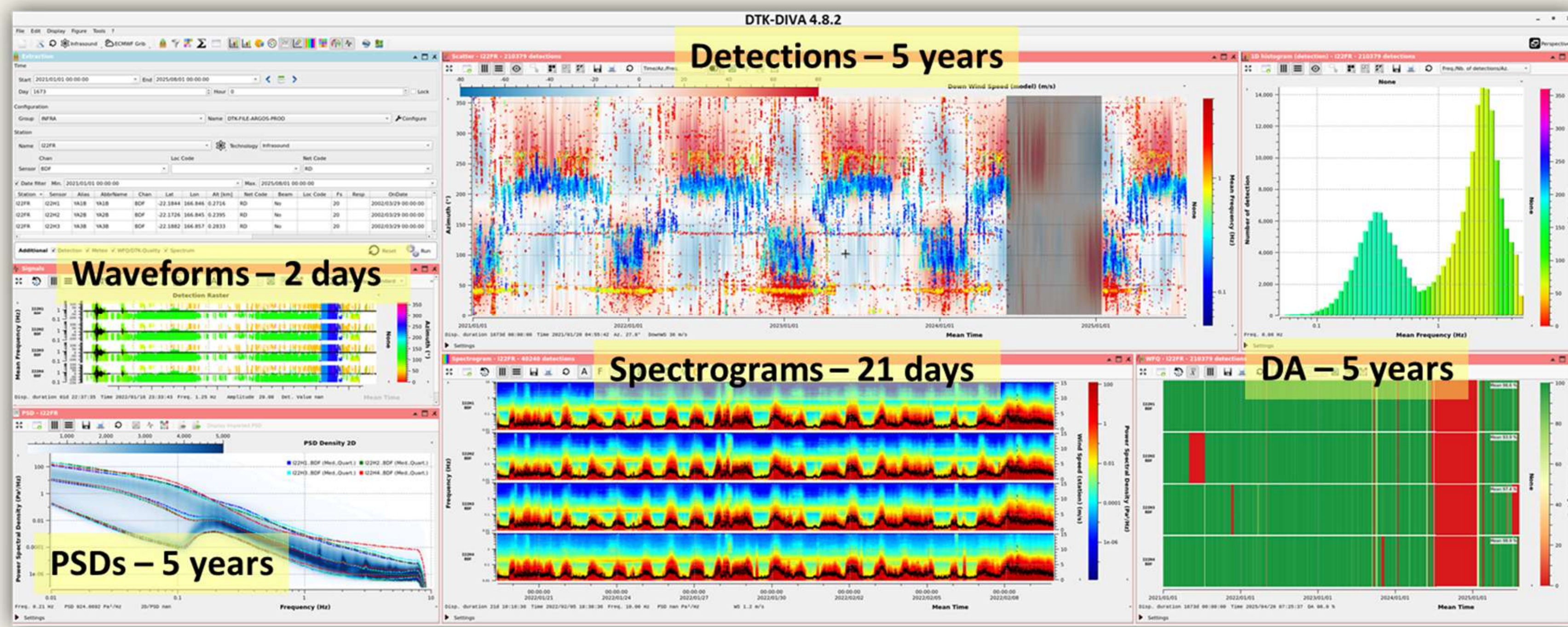
Assessing Detection with Higher Precision under Operational Constraints

- **Objective: Assessing IMS infrasound network detection capability for explosions with better precision**
  - **Realistic explosive source spectrum / frequency-dependent distributions of transmission loss statistics** (in contrast to **Le Pichon, 2008**)
  - **Realistic atmospheric specifications** (in contrast to **Green, 2010**)
  - Account for **frequency-dependent noise levels** (and **Data Availability**) at wave **arrival times** (in contrast to **Blom, 2023**)

I22FR (New Caledonia) – 5 years



DTK-DIVA snapshot (part of NDC-In-A-Box)

Visit booth 3 (CEA) for a live demo!

Methodology : A Statistical Framework (Blom, 2023 and Le Pichon, 2025 (under review))

- **Near source spectral amplitude** (in Pa/Hz) (Kinney and Graham, 1985; Blom et al., 2018)

$$P_{KG}(W_J, f, R_{ref})$$

- **Propagation-based probability distribution** of the source spectral amplitude at the receiver

$$\rho_{arr}(W_J, f, r, c_{effr}, P_{KG}) = \frac{2m^m}{\Gamma(m)\Omega^m} \times P_{KG}(W_J, f, r)^{2m-1} \times e^{-\frac{m}{\Omega} \times P_{KG}(W_J, f, r)^2}$$

where $m = \frac{(\sigma_{TL}{}^2 + \mu_{TL}{}^2)^2}{4\mu_{TL}{}^2 \sigma_{TL}{}^2}$, $\Omega = \mu_{TL}{}^2 + \sigma_{TL}{}^2$

- **Probability that the noise at the station has a spectral amplitude less than or equal to that of the signal**

$$\rho_{det}(W_J, f, r, c_{effr}, N) = \int \rho_{arr}(W_J, f, r, c_{effr}, P_{KG_{dB}}) \times R_{ns}(P, f, r, N)\, dP$$

- **Cumulative distribution of the noise statistics**

$$R_{ns}(P, f, r, N) = \int_{-\infty}^{P} \rho_{ns}(P', f, r, N) dP'$$

- **Probability distribution of the effective noise** (Pa/Hz)

$$\rho_{ns}(f, r, N) = \sqrt{PSD(f) \frac{\tau(r)}{N}}$$

t(r): wavetrain duration ; N: number of array elements (Green and Nippress, 2019)

➔ In this study, we consider the 90% probability of detecting a given explosive yield

Dataset and Computational Scale

20-YEAR DATASET (2005 - 2025/09/01)

- **~5 TB of raw waveforms** of all IMS infrasound stations (SDS miniSeed)
- **15 MB of station metadata** extracted from IDC external database
  - **Critical to account for station changes over time**
- **320 GB of PSDs (~61 Million of calculated PSDs)** computed with **DTK-QUALITY**
  - **1 PSD/hour**/per array element
- **~1 TB of ECMWF IFS analysis atmospheric specifications** (Grib2)
  - 1 file/day, 1° horizontal resolution, 91-137 levels
  - Available period : 2006/02/01 - now

DTK-QUALITY is a SHI station noise tool developed by CEA
DTK-QUALITY will be integrated into NDC-in-a-Box in the near future, following a contribution in kind from France
→ Visit booth 3 (CEA) for demo of DTK-QUALITY

See also Poster P4.1.666 by PTS (Friday 12 September, 09:00) : Towards a modern and robust quality control tool based on DTK-QUALITY data (Ketata et al.)

COMPUTATIONAL SCALE

- **Time resolution (source origin times) : 3h => 60 380 time steps (~ 20 years)**
- **Source grid : 1 degree** 360x180 = **64 800 source points**
- **Stations : 20 - 54** (time-dependent)
- **Frequency resolution : 16 values (0.1 Hz and 4 Hz, third octave, log-spaced)**

→ **~3x10^{12} transmission loss calculations**

*LP25 (**Le Pichon, 2025**) analytic law analytical law is essential to avoid prohibitive computation times*

- **Explosive yield resolution : 100 values (1 t – 100 kt, log-spaced)**

- **Total computation time: ~4 weeks on 256 CPU cores**
- **Unitary computation cost (1 time step): ~ 40 s**
- **Size of the results dataset : 15 GB**
- **Compatible with operational implementation**

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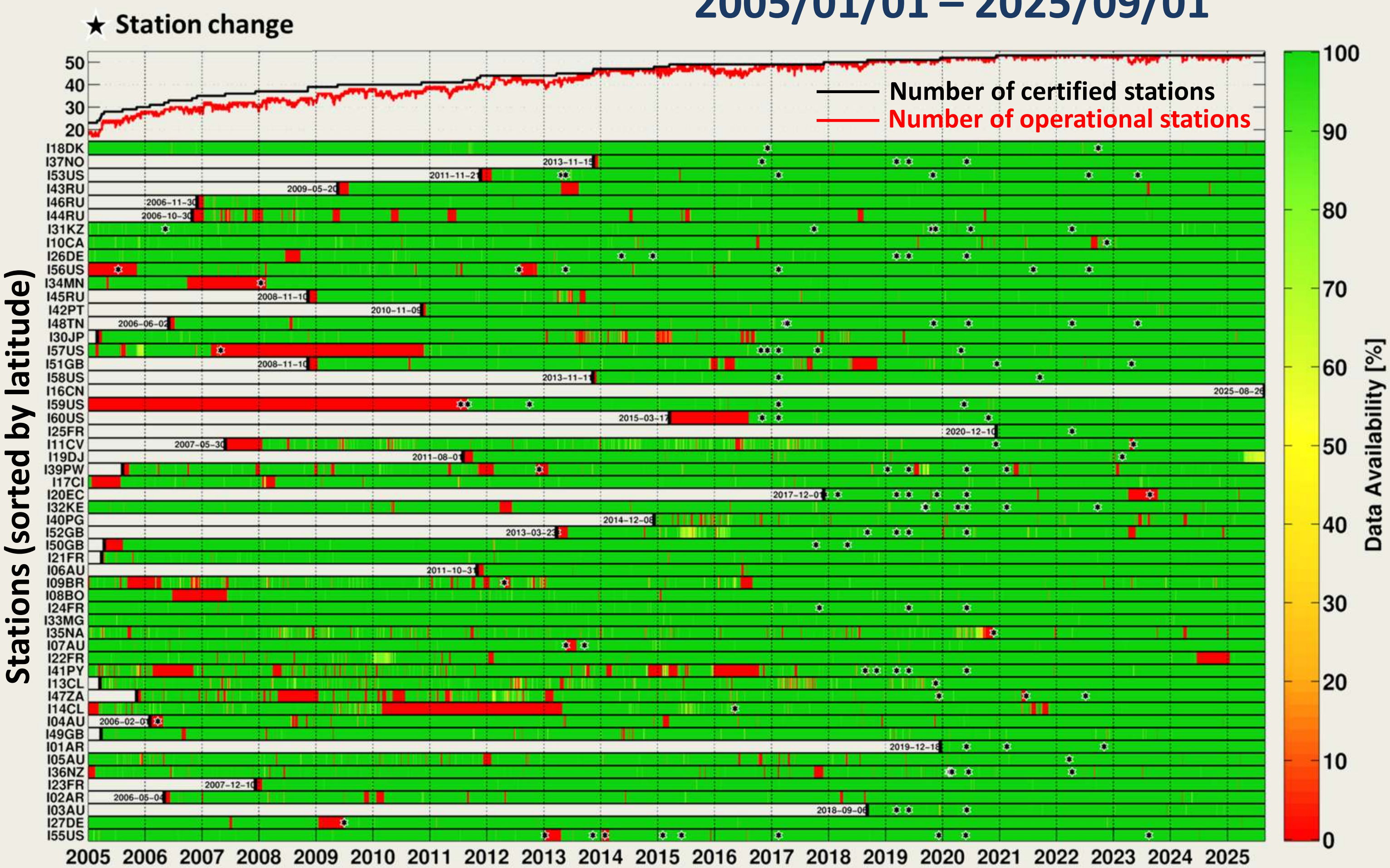
20-Year Snapshot of Data Availability 2005/01/01 – 2025/09/01



- **Data Availability improves over time**
- Since 2017, data **gaps** have **significantly decreased**
- Time intervals with less than two operational array elements result in 0% data availability

Accounting for data availability is essential when evaluating network performance

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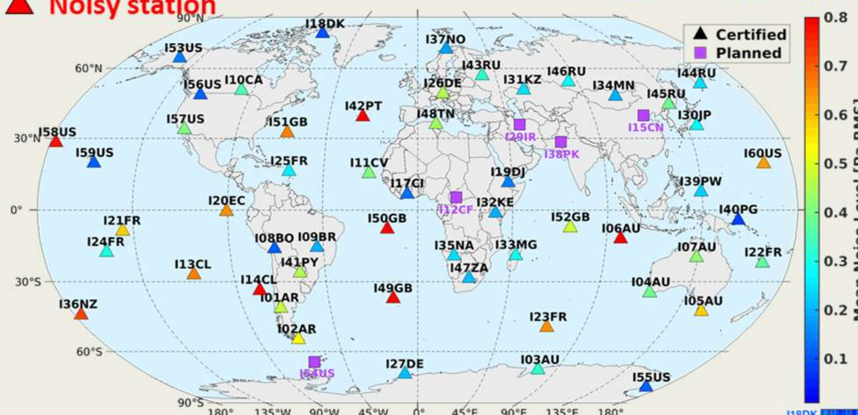
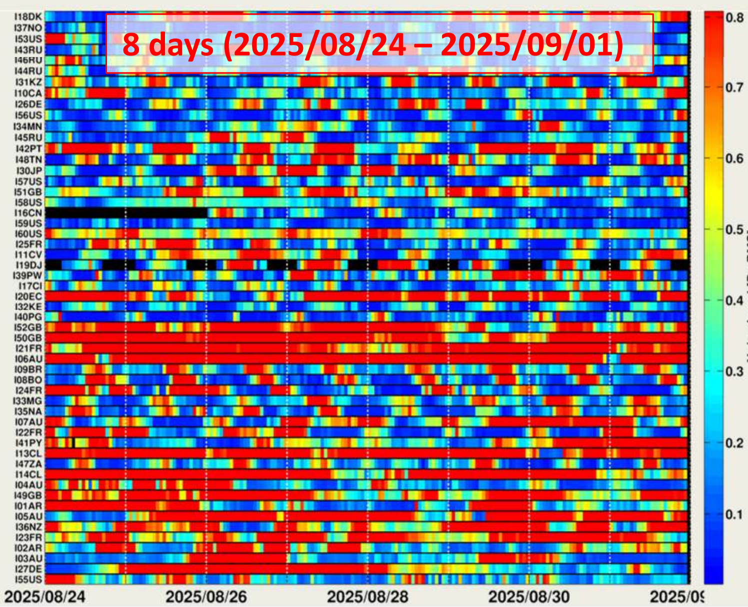
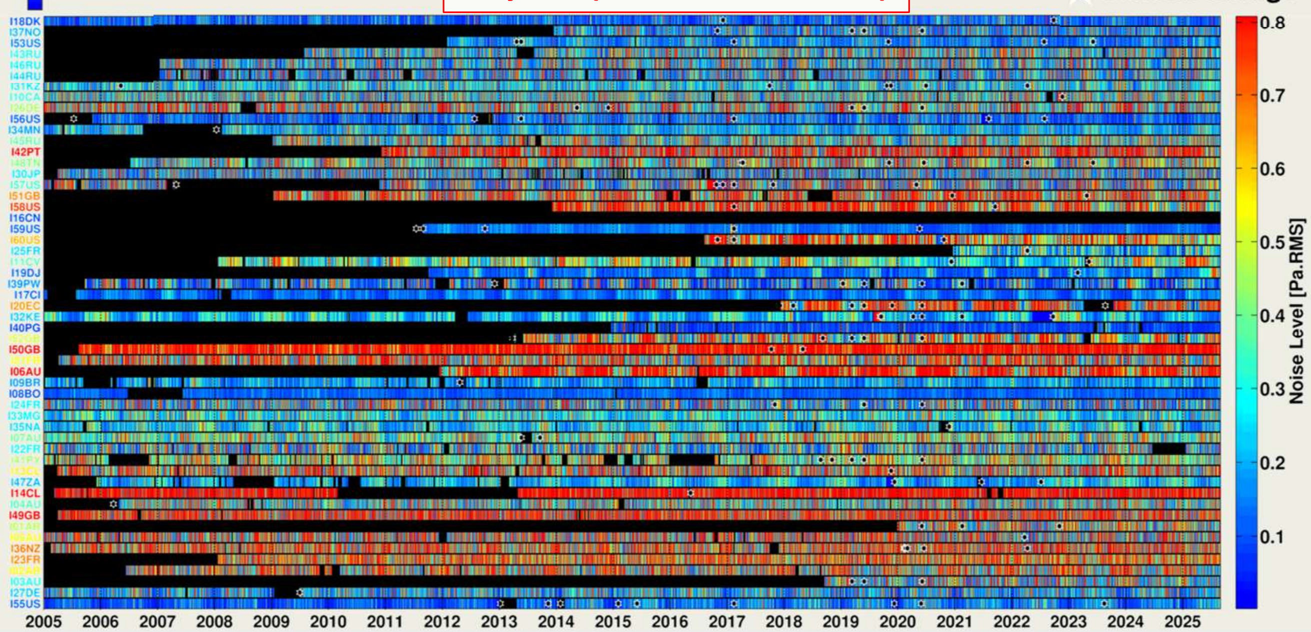
20-Year Snapshot of Background Noise



- RMS station noise levels are calculated from PSDs in the [0.01–0.5] Hz freq. band
- **Station noise levels vary significantly between stations (spatial variability)**
- **Station noise levels fluctuate across seasonal, diurnal, and hourly time scales**

For more details, see Poster P3.5-855 by P. Hupe (Thursday 11 September, 11:00) : High-resolution analysis of spatio-temporal ambient noise variations across the IMS infrasound network





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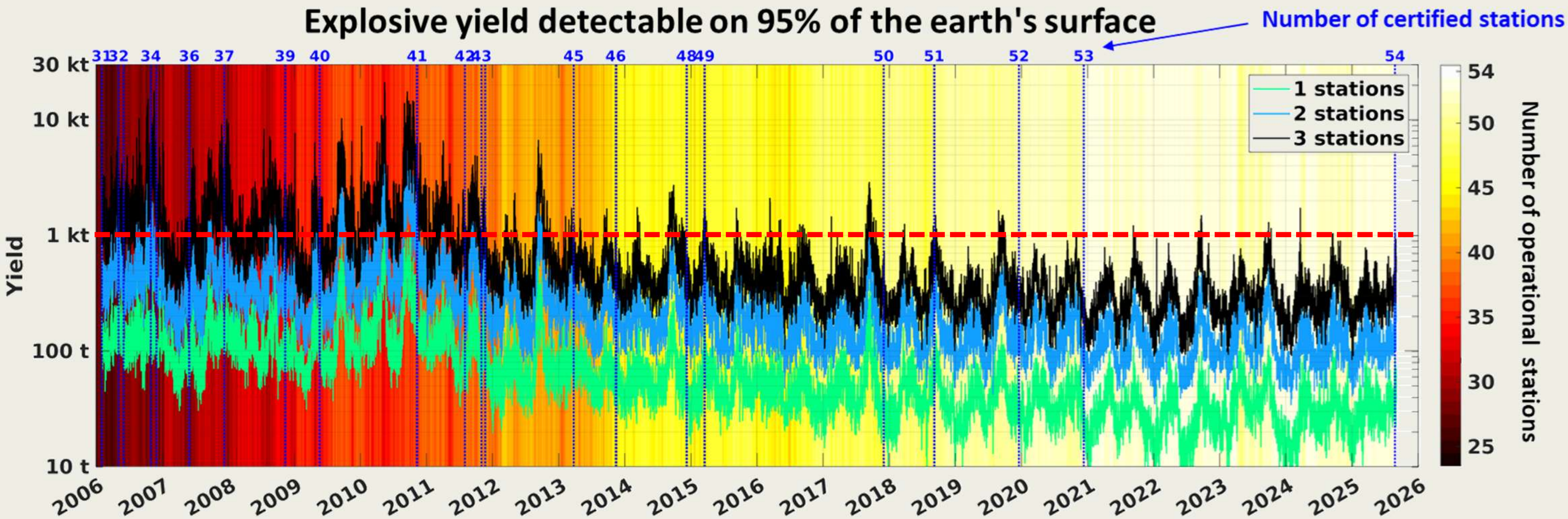
20 Years of Global Simulations: Detectability Time Series at 1, 2, and 3 Stations



- Network performance improves substantially over time
- (Sub-)seasonal variations: more than one order of magnitude
- Highly short-time scale threshold variability

- During the 2021-2025 period (53 stations):
  - 2-station threshold: 80 t – 600 t
  - 3-station threshold: 100 t – 2 kt
    (<1 kt over 90% of the globe)

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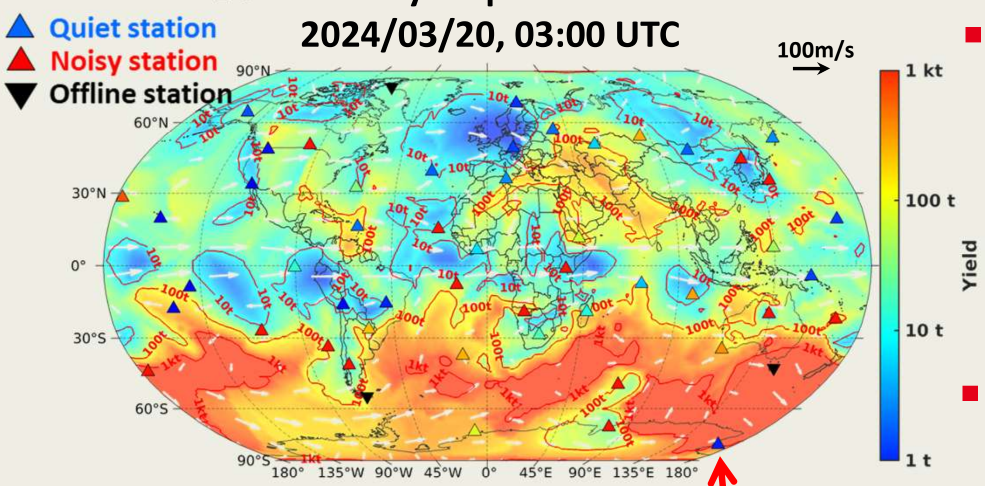
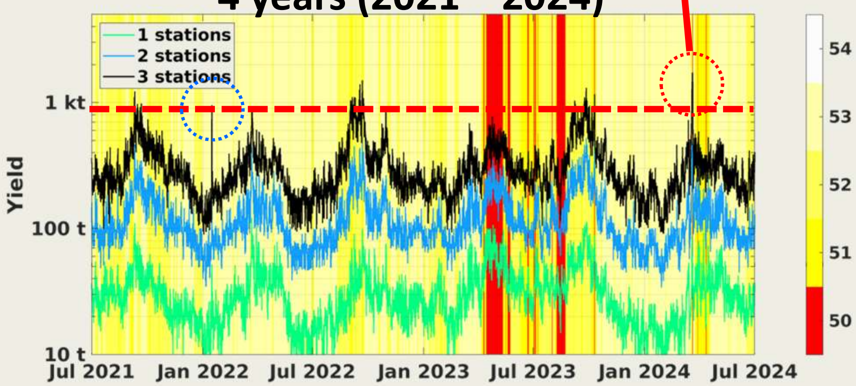
Detailed View and Results Interpretation

Detectability map for an event at 2024/03/20, 03:00 UTC



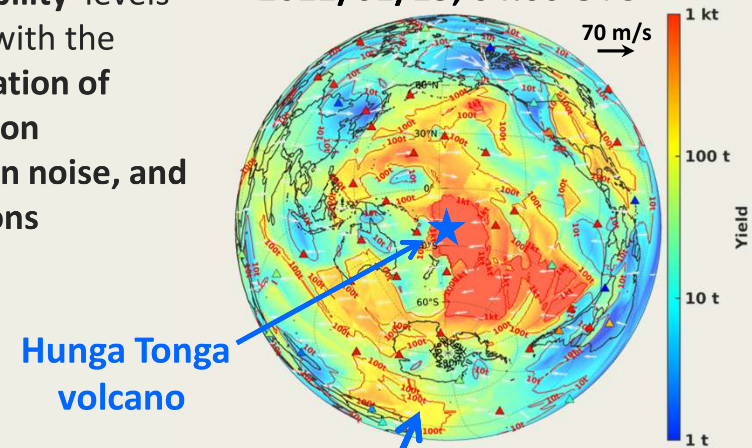
4 years (2021 – 2024)



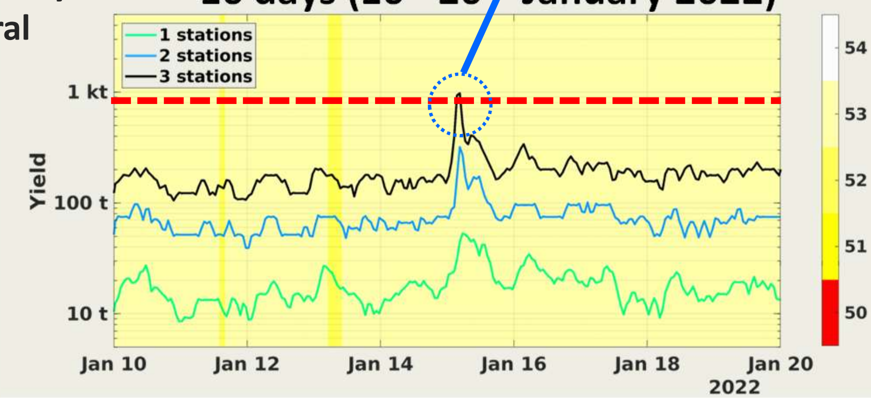
- Peaks of **poor detectability** levels (> 1kt) are associated with the **simultaneous combination of unfavorable propagation conditions, high station noise, and non-operational stations**

- **The 15 January 2022 Hunga Tonga eruption degraded global detectability levels for several days**

Detectability map for an event at 2022/01/15, 04:00 UTC



10 days (10 - 20 January 2022)



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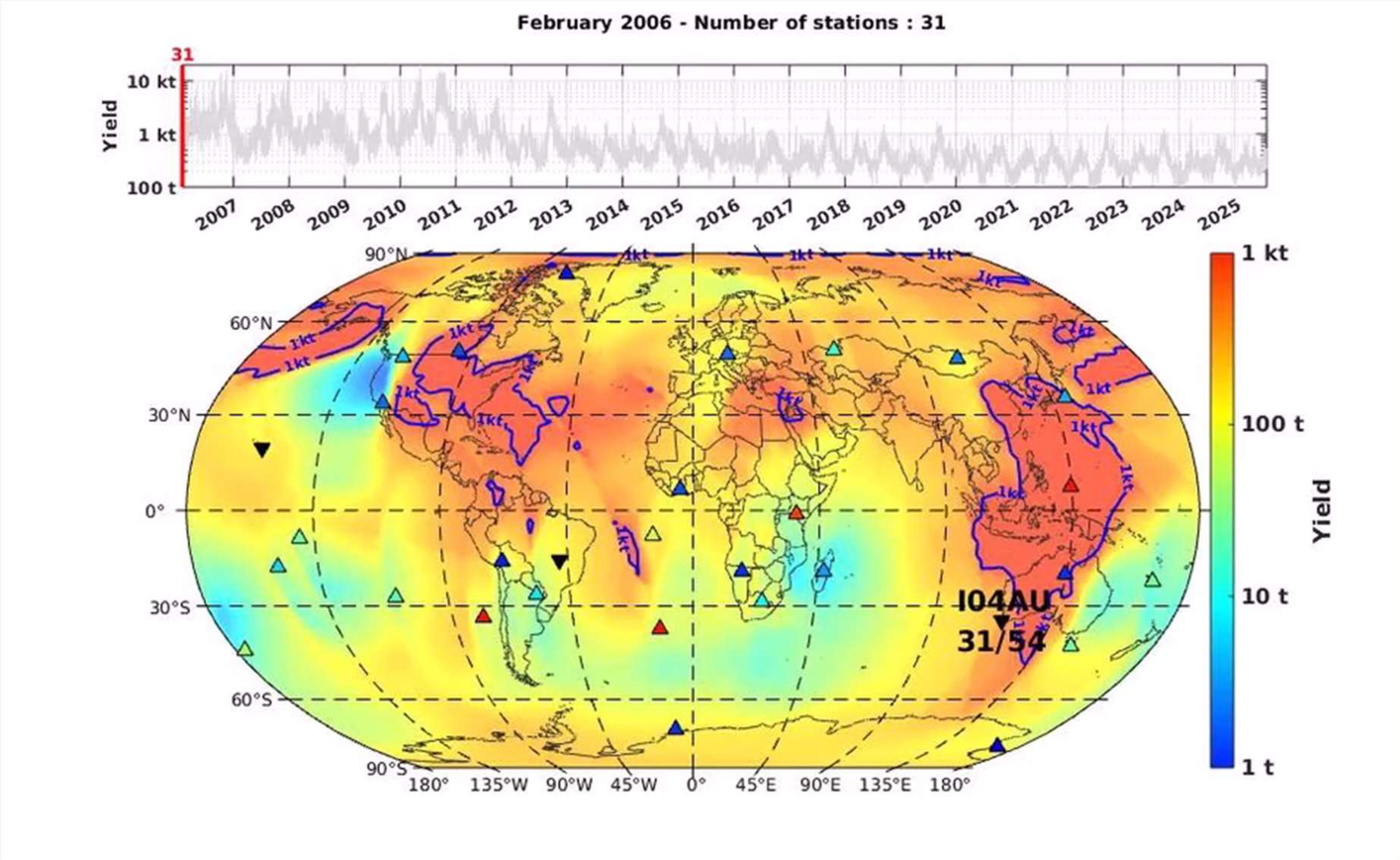
From Two Decades to 45 Seconds: 3-station Detectability at a Glance



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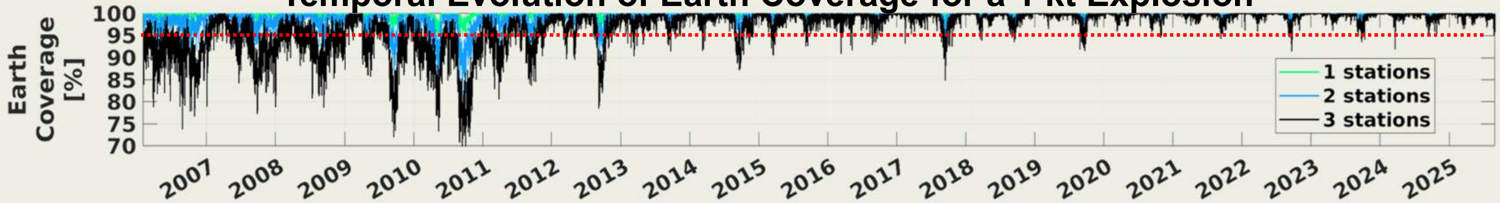
1 kt Detectability: 3-station Temporal and Spatial Evolution

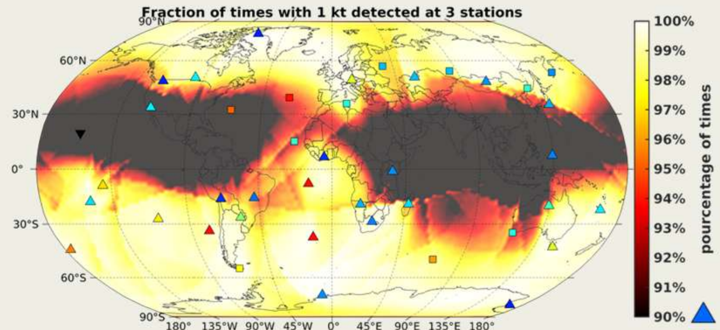
Temporal Evolution of Earth Coverage for a 1 kt Explosion



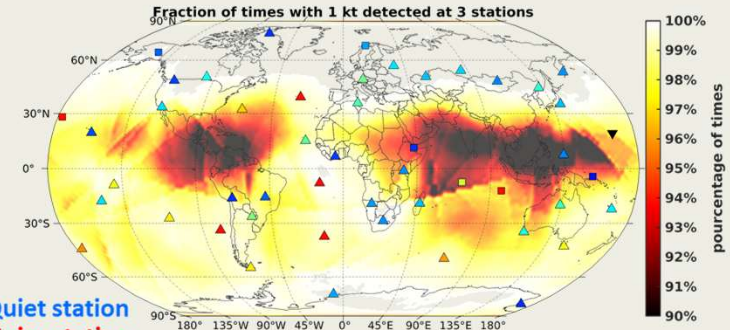
95% earth coverage

- Map percentages are fractions of times for which 1kt is detected by at least 3 stations
- Detectability levels are lowest in equatorial regions
- Planned stations are expected to enhance the weakest detectability areas

2006 - 2010

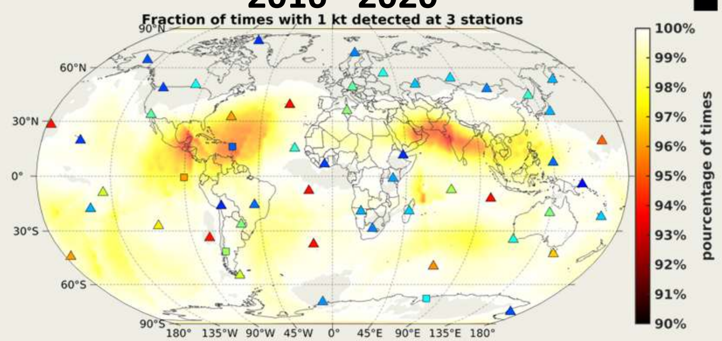


2011 - 2015

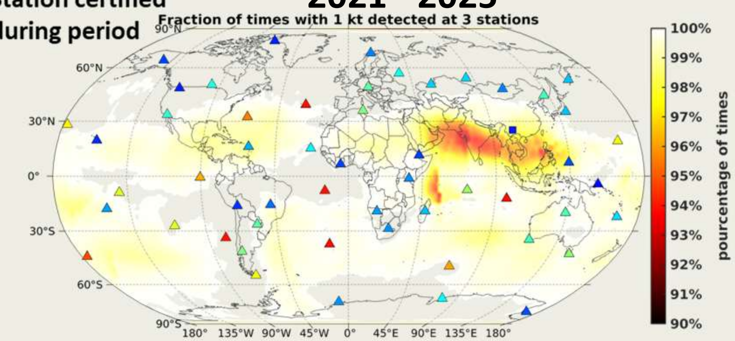


Quiet station
Noisy station
Station certified during period

2016 - 2020



2021 - 2025



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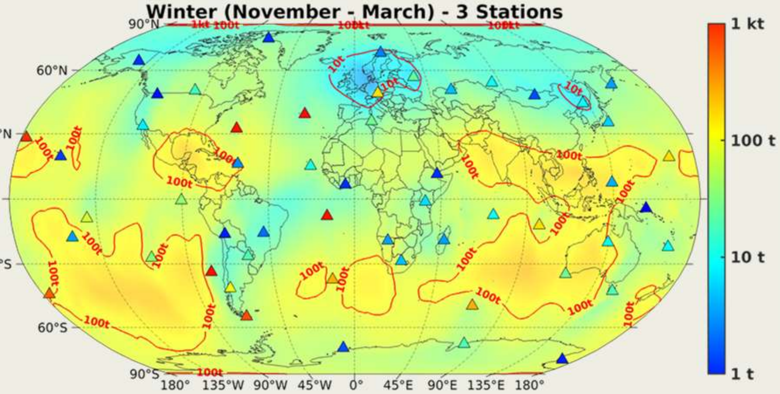
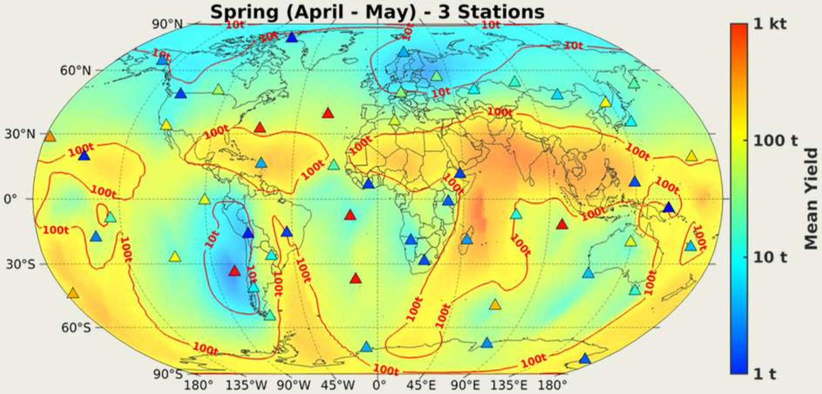
3-station Seasonal Effects, 2021-01-01 to 2025-09-01 (53 stations)

WINTER

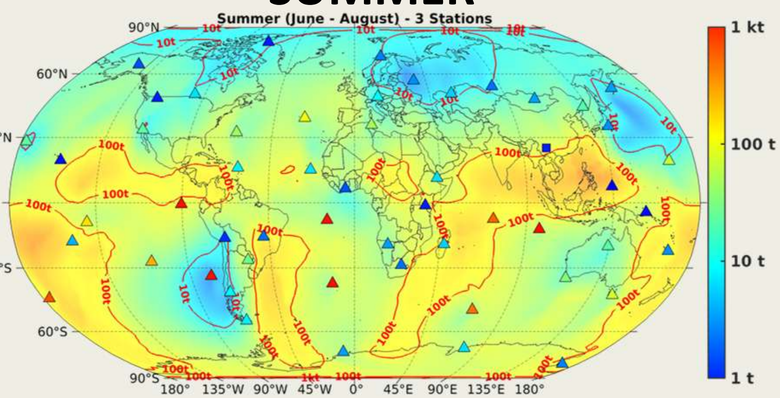


SPRING

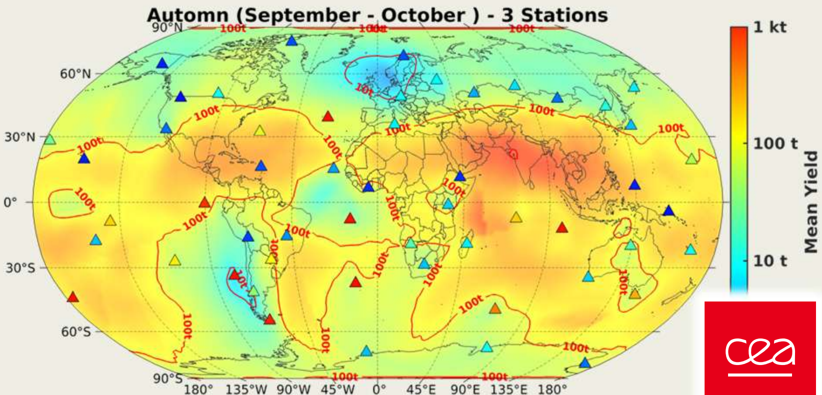


- Better overall performance during winter and summer (solstices)
- Lowest performance in autumn
- High threshold variability persists across all seasons

SUMMER



AUTUMN



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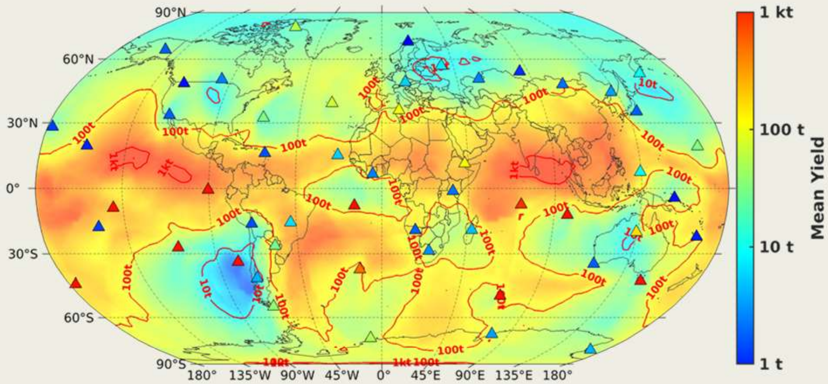
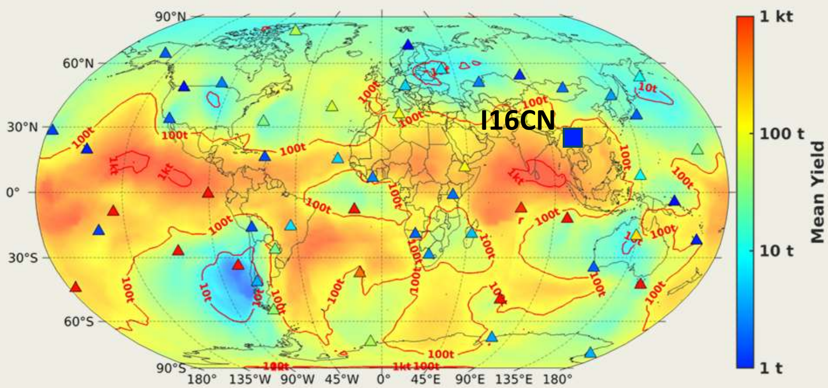
Preliminary Estimation of 3-station Detectability Gains from I16CN Certification

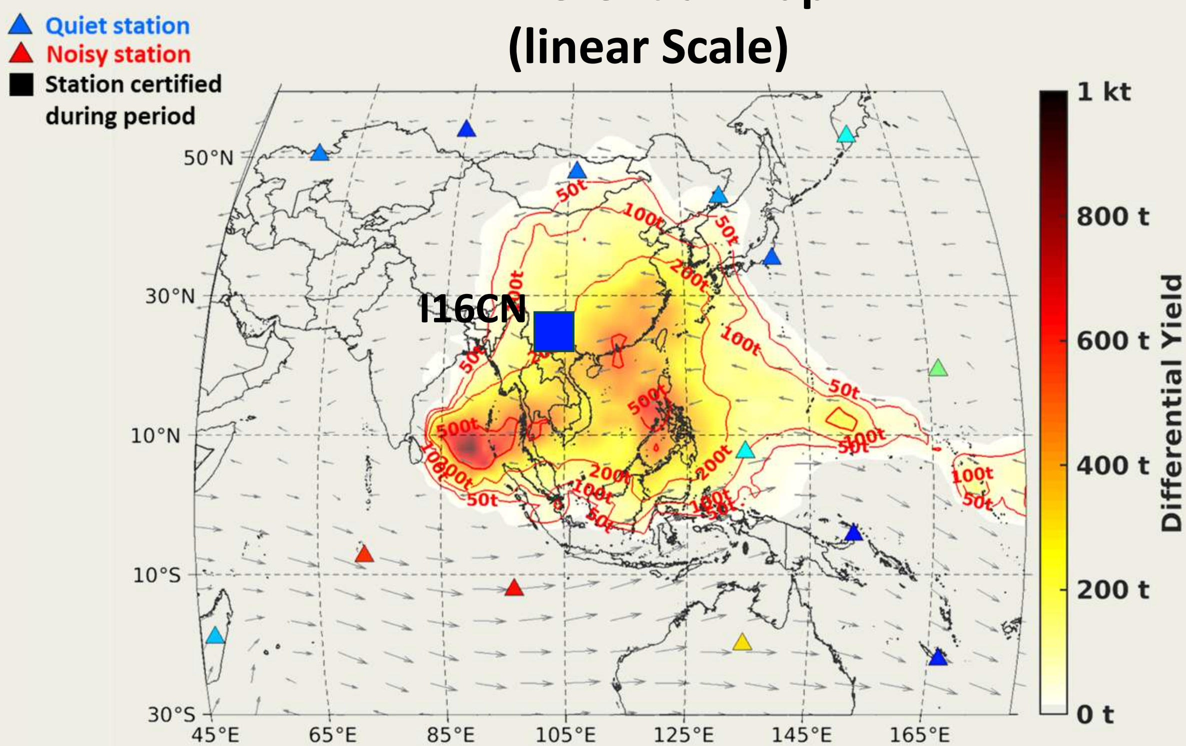
2025/08/26 – 2025/09/01
Without I16CN





2025/08/26 – 2025/09/01
With I16CN

Differential Map (linear Scale)



- **Regionally, thresholds can drop by up to 500 t**
- **Longer dataset needed** to fully assess I16CN contribution to the IMS network

Conclusion and perspectives

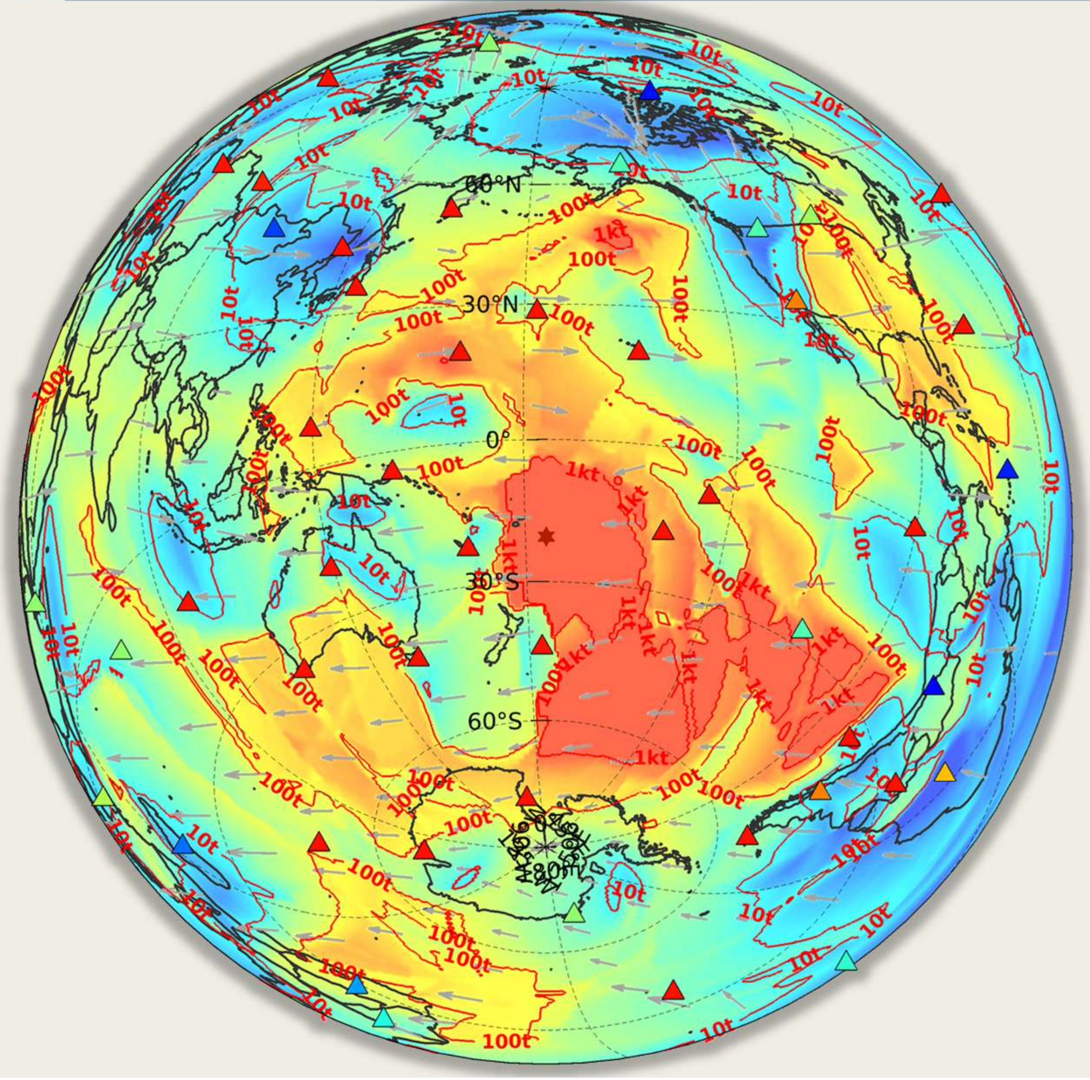
Conclusion

- **Statistical framework applied to two decades of IMS infrasound data to assess detection capability and uncertainties with more realistic precision**
- **Highly variable thresholds**: **from seasonal to hourly scales** (90% detection probability, 95% global coverage)
  - 2-station: **80 t – 600 t**
  - 3-station: 100 t – 2 kt (95% coverage) / 70 t – 1 kt (90% coverage)
- With **53 stations** delivering **high-quality data**, a **1 kt explosion** is **already globally detectable**, though with **temporal and regional gaps** that are most pronounced at the solstices
- **Improved performance expected from the full network**, already evident with I16CN certification

Perspectives

- Next step: near-real-time assessment of the IMS network performance at the French NDC
  → **Useful for civil applications** (eg. Beyrout explosion, Hunga-Tonga eruption, …)
- **Incorporate new approaches based on ML techniques to calculate transmission losses** (e.g. Cameijo et al., JGR, 2025)
- Account for **station-dependent detector performance** (Poste et al., 2023)
- Perform **sensitivity studies on middle-atmospheric fine structures** (Vorobeva et al., 2023; Listowski et al., 2024)

cea



Thank you!

LP25 : Transmission loss statistics
Le Pichon et al. 2025 (under review)

- Physical approach: attenuation relation accounting for geometrical spreading, dissipation and scattering (Lay and Wallace, 1995)

Geometrical spreading — Attenuation and scattering

$$\mu_{TL}(f,r,ceff) = R^{-\alpha\left(1+a_s\left(1-\cos\left(2\pi\frac{r}{d_s}\right)\right)\right)e^{-\frac{r}{R_S}}} \times e^{-\beta r}$$

Geometrical shadow zones

- Non-linear curve-fitting of simulated TLs [ceff x f] (Coleman, 1996)
- Tabulated parameters: $\alpha, a_s, d_s, R_s, \beta$ vs. effective sound speed ratio and frequency
- For [f x r x ceff]: μ_{TL} and σ_{TL}