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The Multi-Channel Maximum-Likelihood (MCML) method: extension to multisource estimation and evaluation

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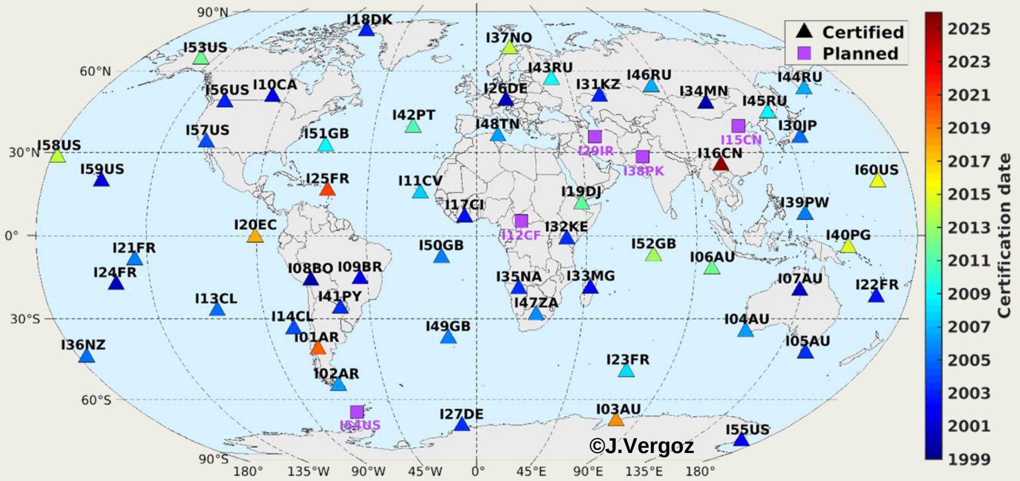
Introduction on the infrasound technology

- The international monitoring system (IMS) **is designed to detect explosion of 1 kT eq. TNT everywhere at anytime**

- Today, **90% (54/60)** of infrasound stations are **operational** on a total of 60 planned

- A **wide range** of **natural** and **anthropogenic sources** are detected

- **Detecting explosions** with low signal-to-noise ratio **from diverse sources is a key challenge**



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Overview of existing signal processing methods

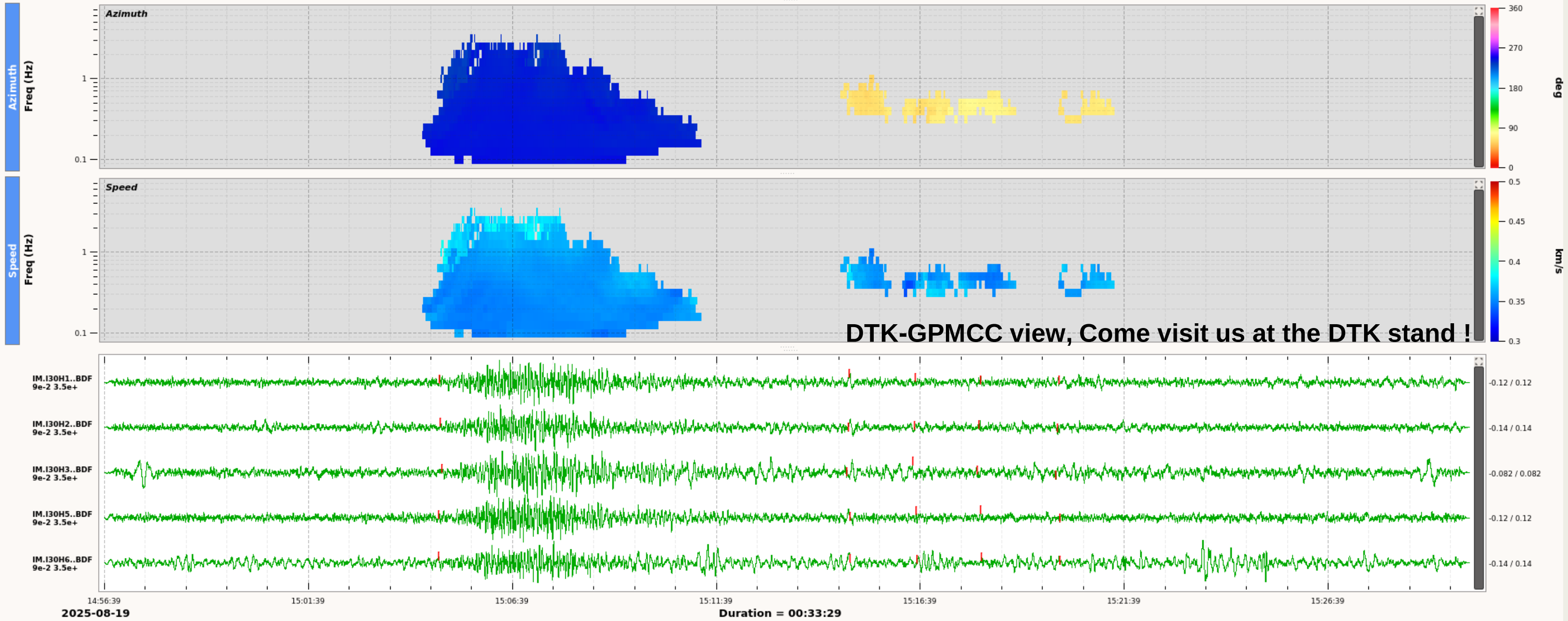
Developments over time:

- F-detector, commonly used in NDCs (e.g. Arrowsmith et al., 2009)

→ Principally used in a **single frequency band**
→ Large variety of **signals covering a wide frequency band**

- Progressive Multi-Channel Correlation (Cansi, 1995; Garcés, 2013): detector (consistency) and estimator (TDOA)

→ Used **operationally since 2000 at the IDC** and distributed to our NDC partners
→ Feedbacks: **loss of detection** and estimation errors under **unfavorable observation conditions**



Fireball above Japan in 19/08/2025, detected at I30JP

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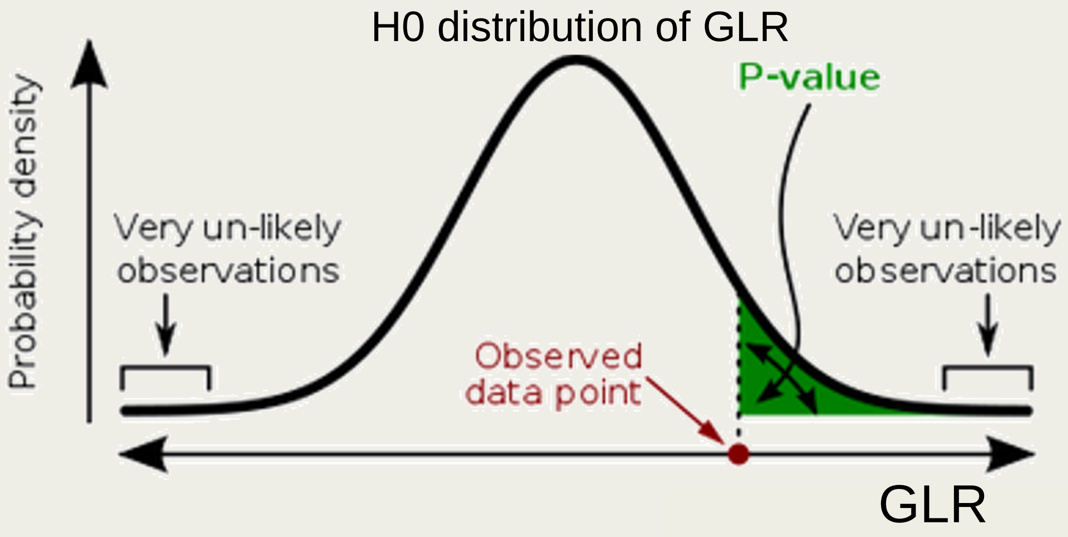
A new signal processing method: Multi-Channel Maximum Likelihood (MCML, Poste et. al (2023))

- Detection: Generalized Likelihood Ratio (GLR) (Burgess, 1994)
- Detection threshold by p-value, 1% of false positive
- Estimation: Maximization of the likelihood $\mathcal{L}(\theta, v, s^2, \sigma^2)$ (MLE)
- Able to estimate the SNR and the uncertainty of the estimation

$$GLR = 2 \max_{\theta, v}(\mathcal{L}_* - \mathcal{L}_{0*})$$

$$p - value = \int_{GLR}^{+\infty} p_{GLR|H_0}(t)\, dt \qquad \in [0, 1]$$



$$R(\theta, v) = \mathcal{T}\Gamma_0\mathcal{T} \quad \text{with} \quad \mathcal{T} = \begin{bmatrix} -v\cos(\theta) & v\sin(\theta) \\ v^2\sin(\theta) & v^2\cos(\theta) \end{bmatrix}$$

$$\Gamma_0 = \frac{3(\boldsymbol{M} \times \boldsymbol{SNR} + 1)}{8\pi^2 \times \boldsymbol{MSNR^2}((\boldsymbol{f}_{max})^3 - (\boldsymbol{f}_{min})^3)(\boldsymbol{t}_{max} - \boldsymbol{t}_{min})} (\boldsymbol{Z}^T \prod_M^{\perp} \boldsymbol{Z})^{-}$$

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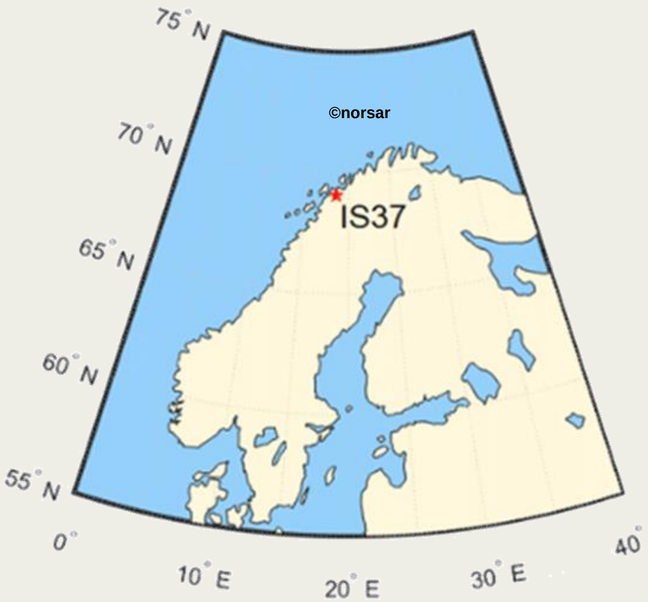
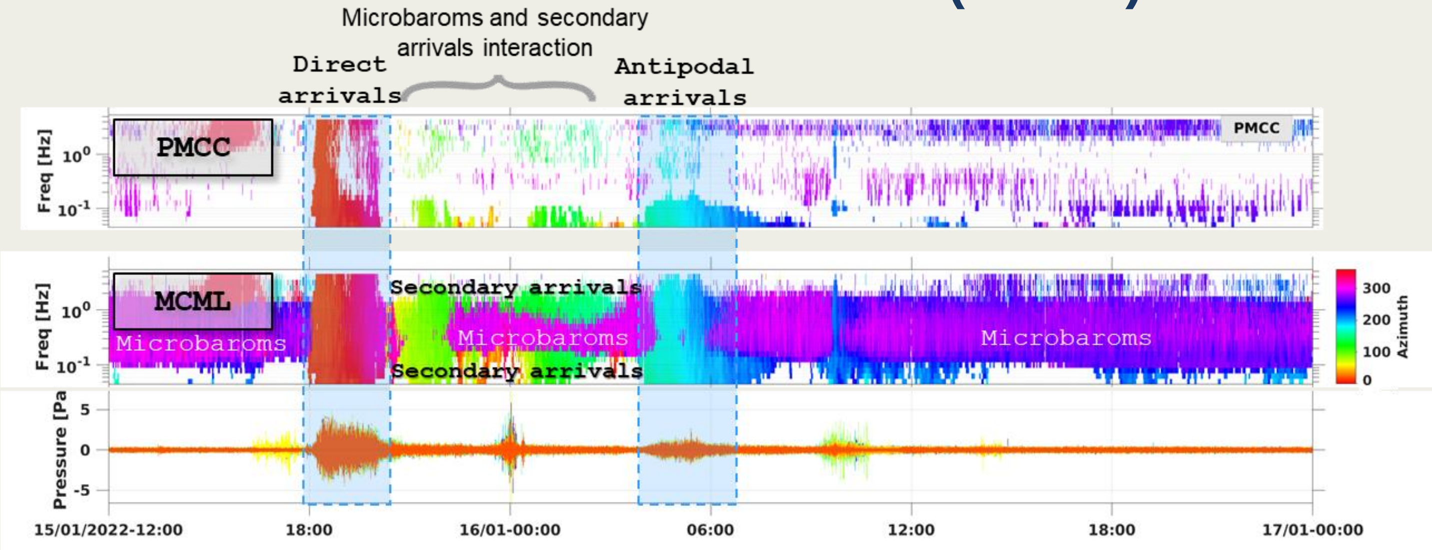
A new signal processing method : Multi-Channel Maximum Likelihood (MCML)

MCML **enhances** the **detection** of events of interest (Tonga arrivals) amid **multiple coherent sources**

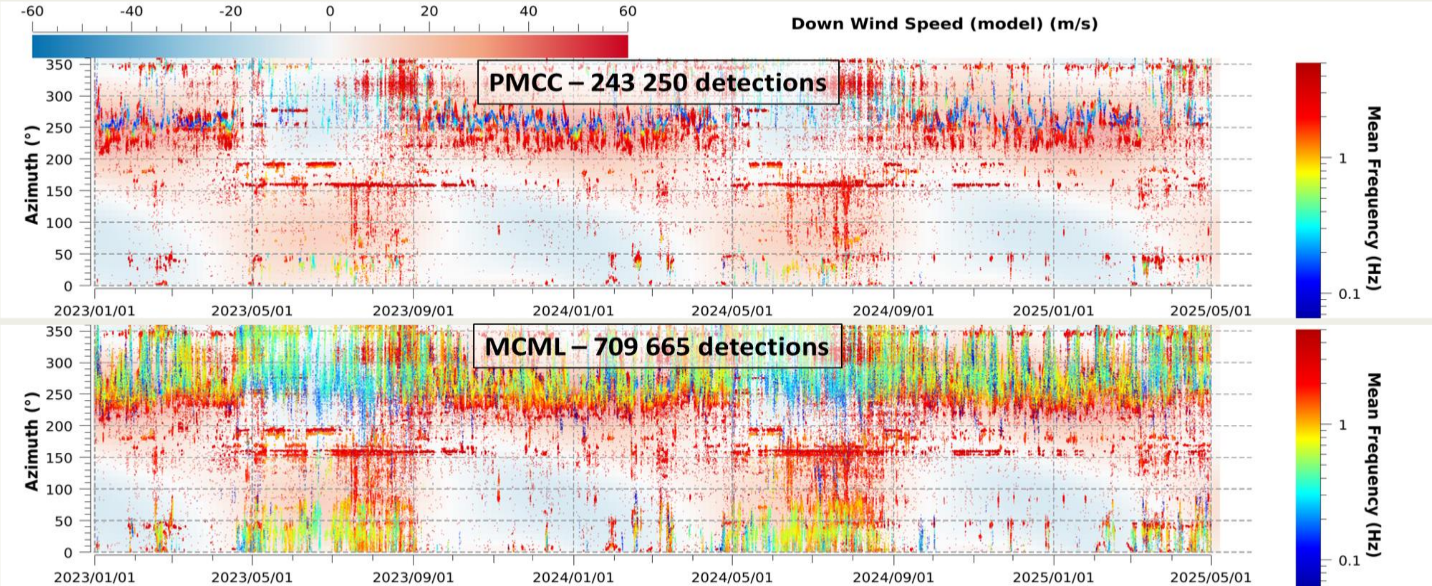
15 January 2022 Tonga eruption (IS37)





MCML enables **more numerous and continuous detections** revealing seasonal variations of stratospheric guides **under low SNR conditions**

Signal processing from 2023 to 2025 at IS37



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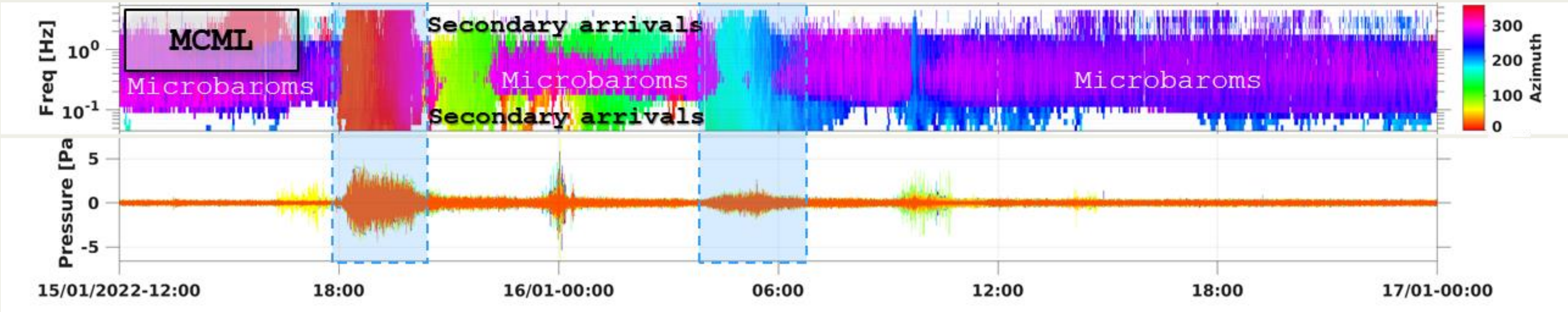
Development of MCML-based method for multisource estimation

- MCML outperforms PMCC under **unfavorable recording conditions** (SOI interferences, low SNR)
- MCML has been optimised for **real time processing** and implemented in the same time-frequency space as PMCC
- **Single source** hypothesis is **not valid in reality,** MCML detects the **dominant source**
- Several multisource algorithms exist (MUSIC, Schmidt 1986; CLEAN from: Wang et al 2004 or Den Ouden et al 2020), **need to be implemented for real time processing**

→ Towards a cost effective method: develop and evaluate multisource algorithms to the state-of-the-art



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Development of MCML-based method for multisource estimation

The signal model includes N infrasound sources recorded at a station with M sensors

$$z_m(t) = \sum_{n=1}^{N} s_n\big(t - \tau_m(\theta_n, v_n)\big) + n_m(t)$$

, $n_m(t)$ be the noise at the sensor m.

Multi peak selection method:

- Using a 2D peak finder (C.A.V. Aguilera, 2016) to **select maxima** on the **monosource** likelihood function

Iterative source signal deflation method:

- Estimation of the first source and SOI: $z_m\left(t + \tau_m\big(\widehat{\theta_1}, \widehat{v_1}\big)\right) = s_1(t) + n'_m(t)$

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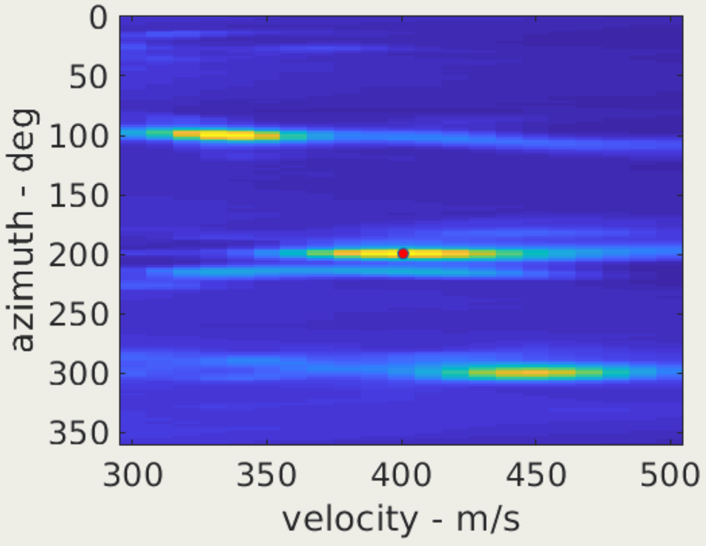
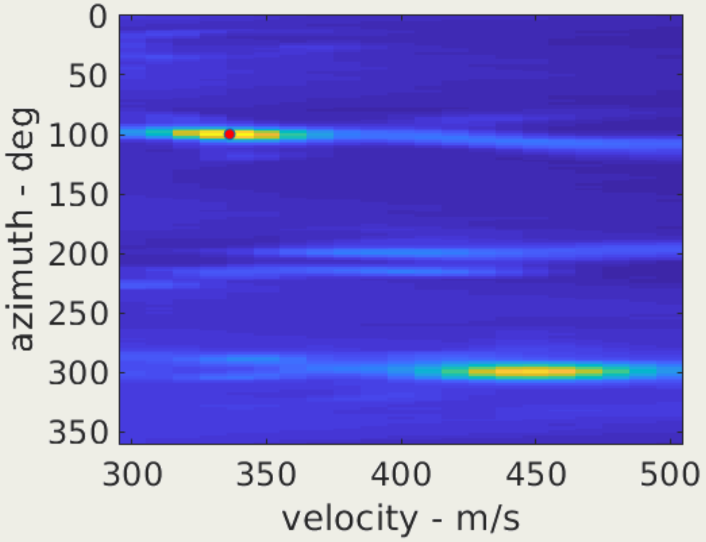
Development of MCML-based method for multisource estimation

Subtract a percentage of the SOI (i.e 25%, Wang et al. 2004) and then iterate

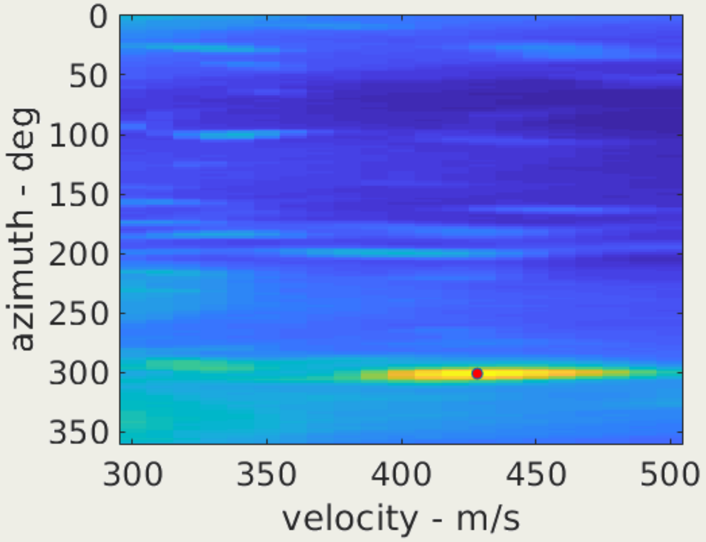
View of the likelihood function on synthetic signal (red dot represents the maximum)



MLE classic



2nd iteration



3rd iteration

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Development of MCML-based method for multisource estimation

- The **spectral matrix model** of the monosource estimator is

$$C_1(f_i) = a(f_i, \theta_1, v_1)\sigma_{s1}^2 a^H(f_i, \theta_1, v_1) + \sigma_b^2 I_M$$

where σ_{s1}^2 the power of the first source, σ_b^2 the power of the noise, I_M the identity matrix

- **Given the estimated parameters ($\boldsymbol{\theta_1, v_1}$) from MCML**, the spectral matrix is generalised as

$$C(f_i) = \sum_{n=1}^{N} \sigma_{sn}^2 a_n(f_i, \theta_n) a_n^H(f_i, \theta_n) + \sigma_b^2 I_M$$

- We use iteratively the **Whittle Likelihood as an estimator**

$$\mathcal{L}(\theta, v) = \sum_{f=f_{min}}^{f_{max}} \log\det C(f_i)^{-1} + Z^H(f_i) C(f_i)^{-1} Z(f_i)$$

where $Z(f_i)$ is the DFT of the received signal

- Also implemented with approximations to **reduce computational cost** (theorically calculated)

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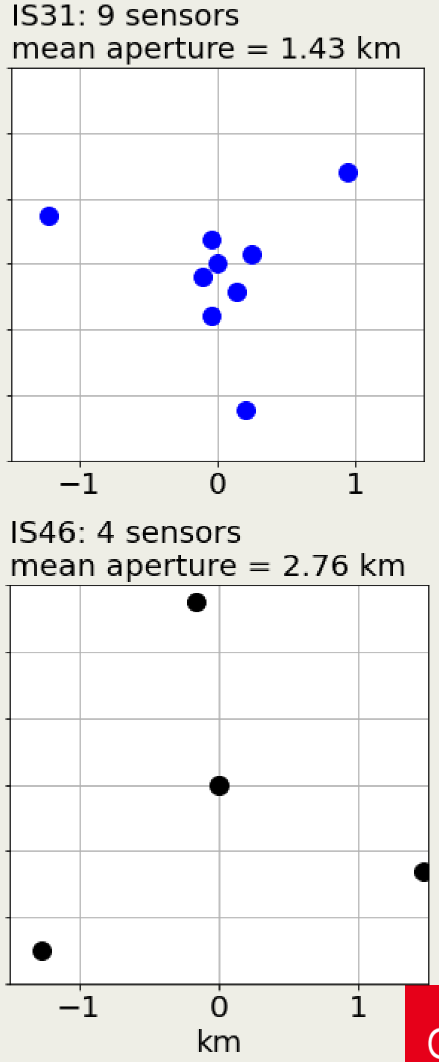
Comparison and selection of a cost effective multisource estimator

Protocol:

- 3 sources in one signal with random azimuthal and velocity distribution
- Known number of sources
- Different frequency bands: [0.1 – 0.12] Hz, [0.5 – 0.65] Hz, [3.2 – 4] Hz
- Different geometries: IS31, IS46
- Different SNR between the sources: 5, 0, -5 dB
- A false estimation rate is determined by identifying the fraction of azimuth and trace velocity errors larger than the two-sigma theoretical uncertainty of MLE
- 1000 simulations for statistics significance



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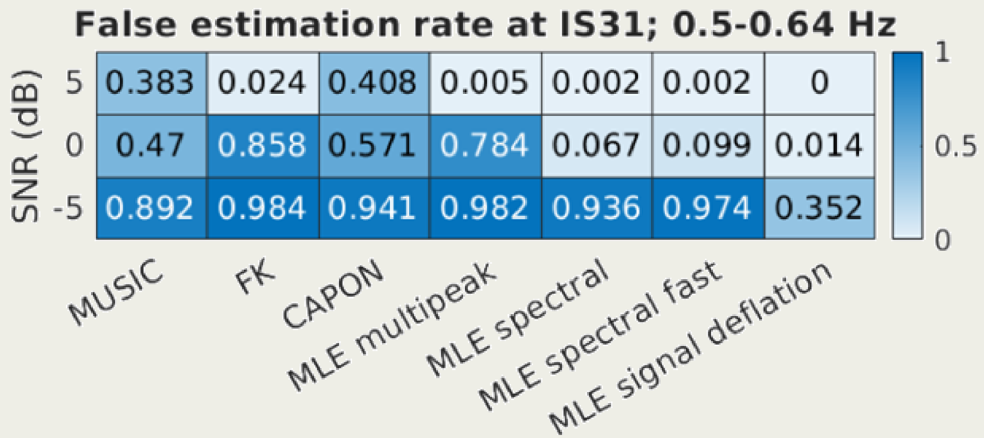
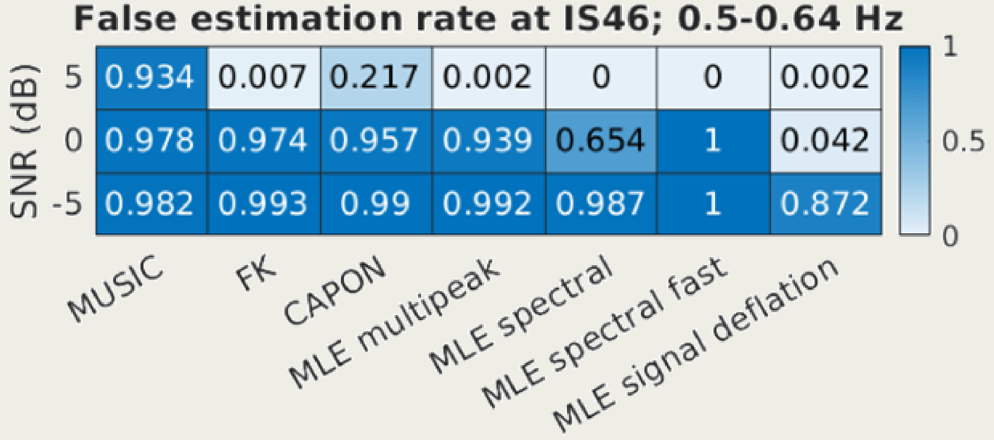
Comparison and selection of a cost effective multisource estimator

- False estimation rate in function of the SNR of sources and different algorithms for IS31 and IS46
- MLE **signal deflation** with **lowest false estimation rate**
- **Lower** false estimation rate with **increasing number of sensors**
- **MUSIC struggles with poor number of sensor**
- Other results: **Lower** false estimation rate with **increasing frequency**





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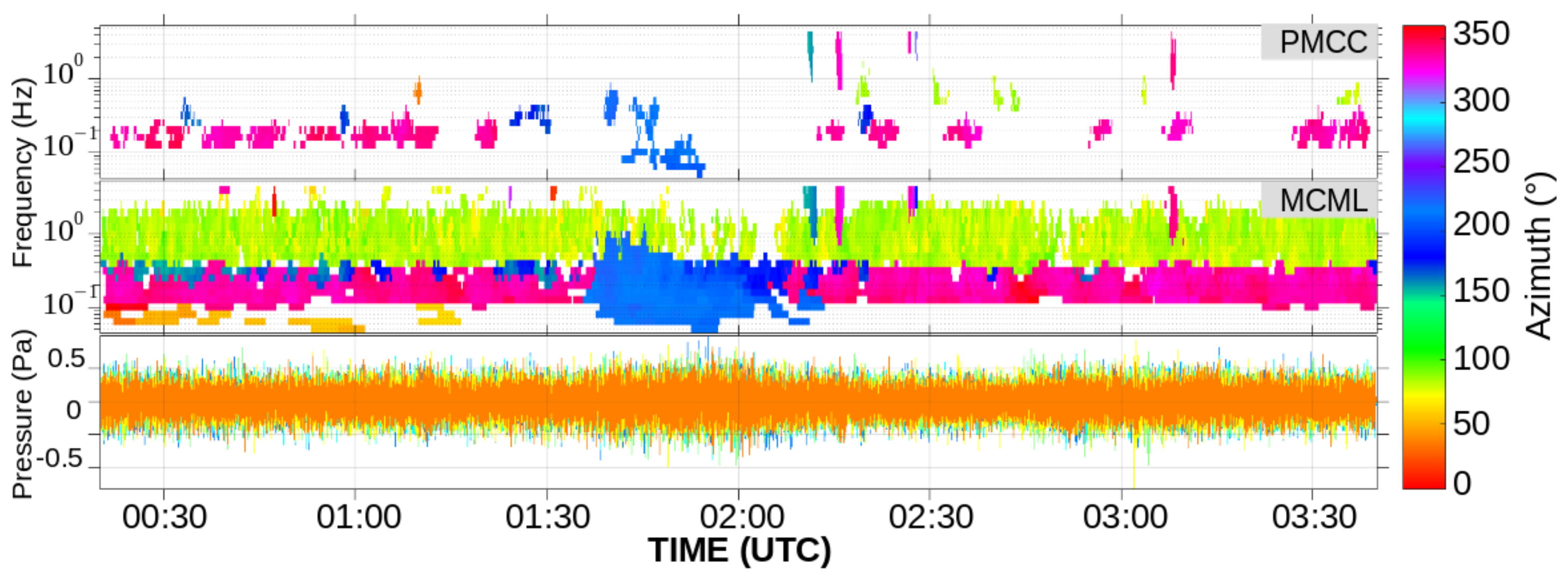

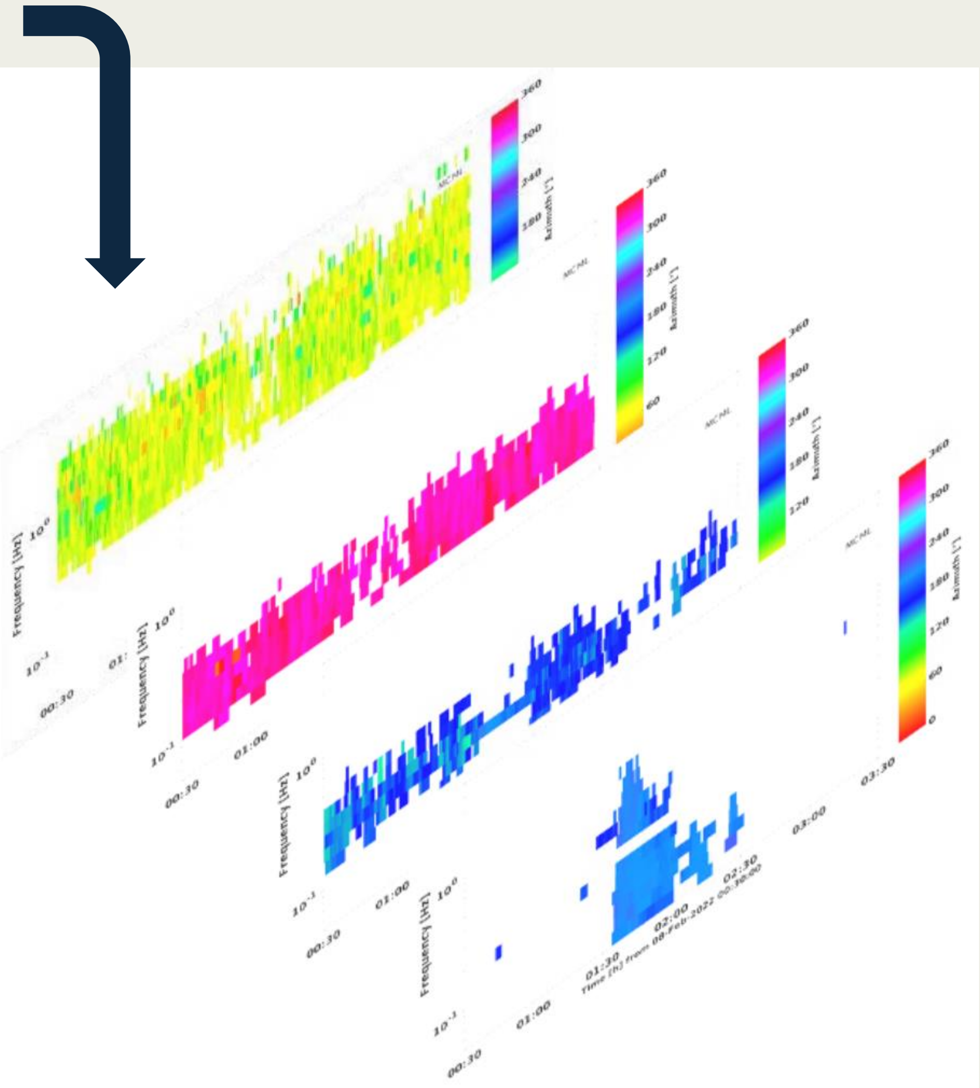

- Detection of the fragmentation of a meteor 500 km off the Namibia coast (February, 7th 2022) at IS19 (Djibouti)
- Removing **2 defective sensors** allows PMCC to detect
- Several sources interfering **detected continuously**: microbaroms (Atlantic & **Indian now detected**), surf noise and the meteor

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Conclusion

- **MCML outperforms PMCC**, especially at **low SNR** and amid **multiple interfering SOIs**
- Currently undergoing operational testing at the French NDC
- MCML is slated for **implementation in DTK tools** in 2026-2027 becoming the new operational detector
- This improvement leads to the development of multiple sources estimators
- **MCML with iterative signal deflation** offers a cost-effective solution for **real time processing**
- Optimise the proportion α of subtracted signal in MCML multisource
- More **systematic evaluations are needed** on reference events
- **Need of a robust post-processing method** (pixel clustering) to build event

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Thanks for listening !

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