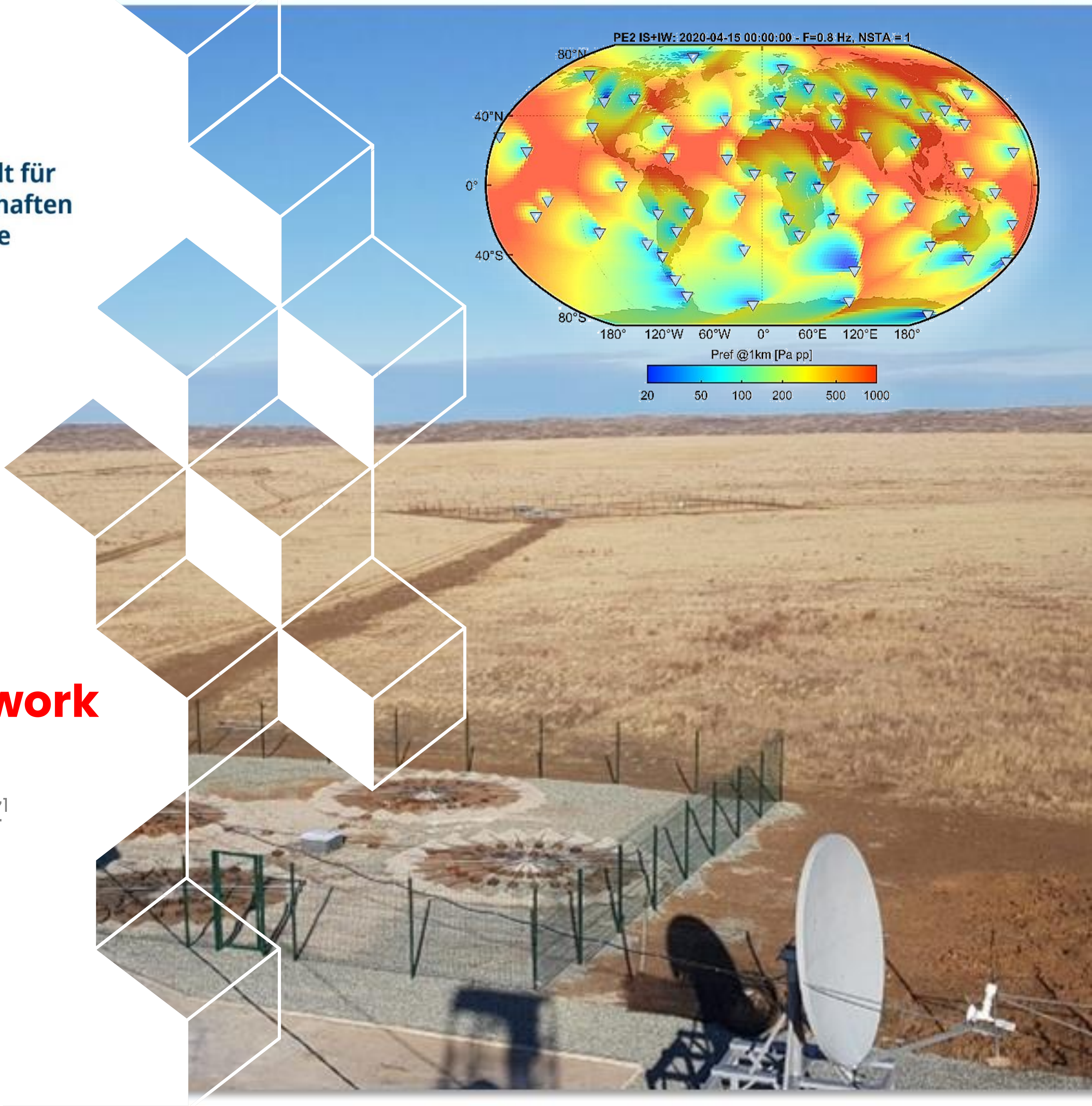


Statistical models for infrasonic propagation: application to the detection capability of the IMS network

Alexis LE PICHON[1], Constantino LISTOWSKI[1], Julien VERGOZ[1]
Patrick HUPE[2], Lars CERANNA[2]

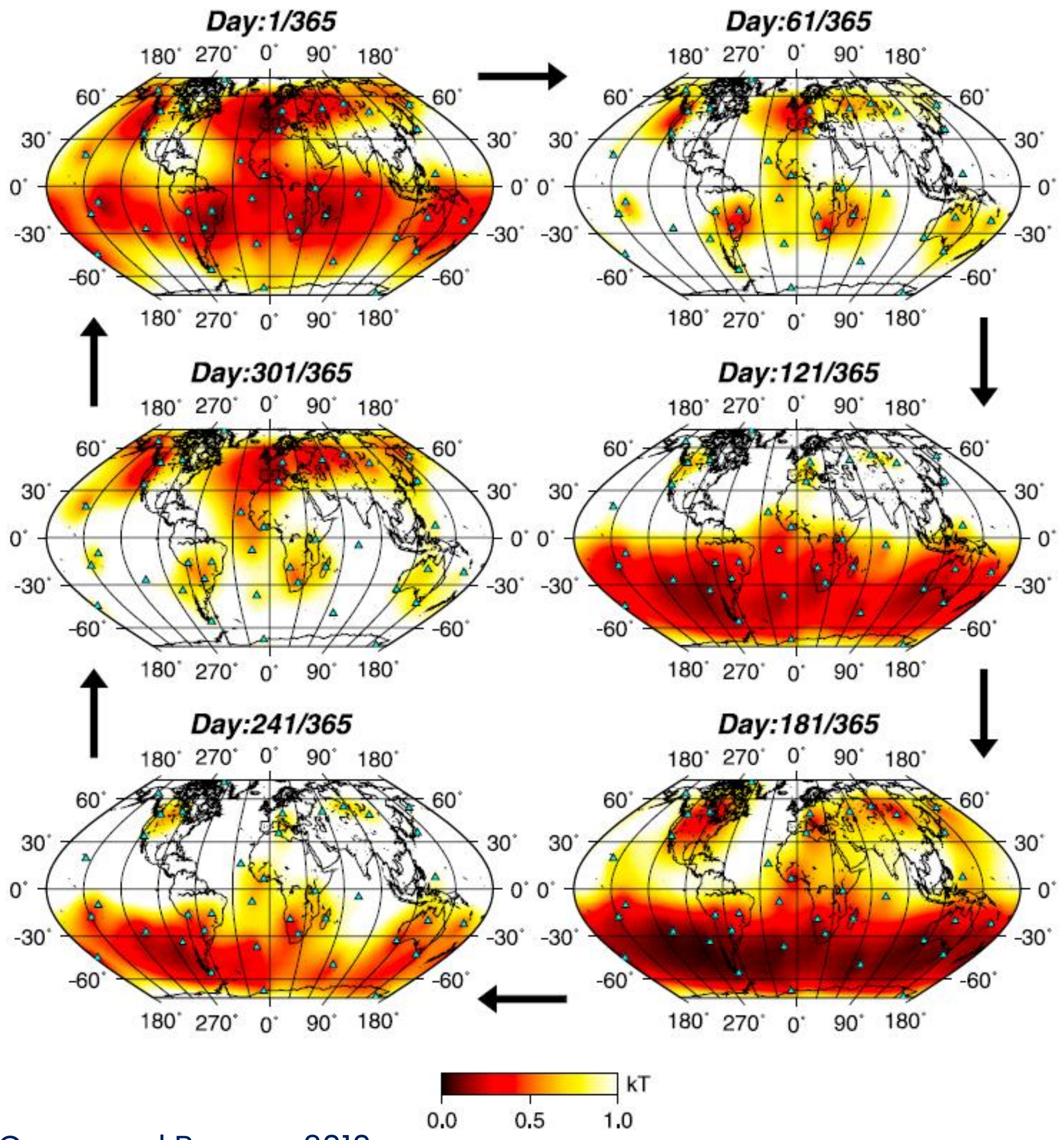
[1] CEA, DAM, DIF, F-91680, Arpajon, France
[2] BGR, B4.3, D-30655 Hannover, Germany

Infrasound Technology Workshop, November 4-8, 2024, Vienna

Objectives

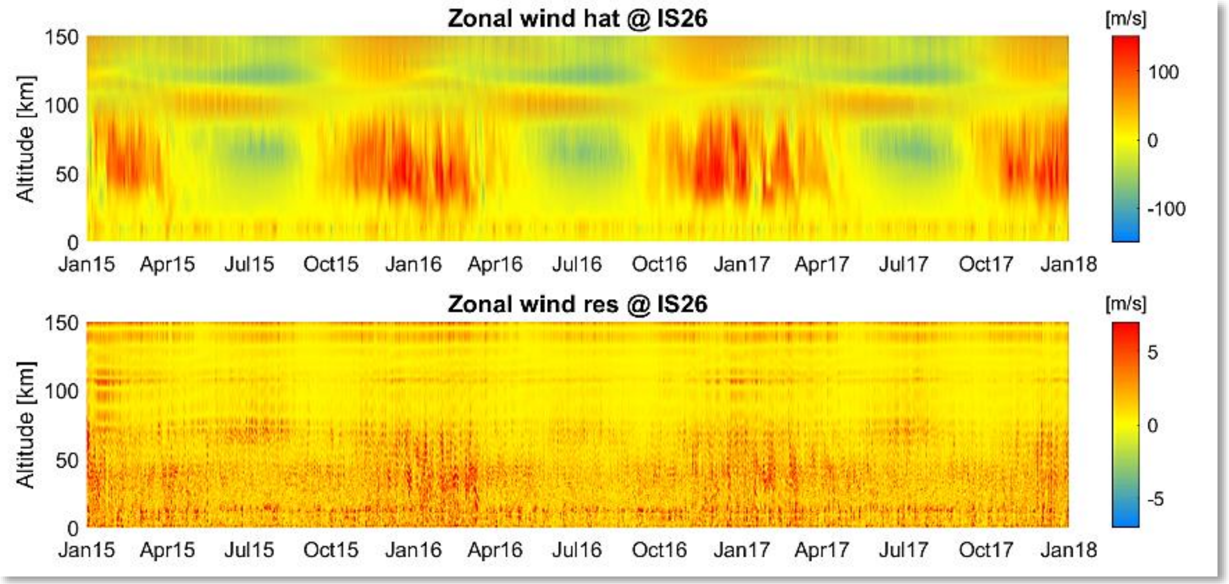
- **Context**
  - Detection capability highly variable (e.g. Green and Bowers, 2010) using AFTAC scaling relation & climatology
  - A semi-empirical attenuation relation (Le Pichon et al., 2012)
    - Massive PE simulations
    - Wide range of atmospheric scenarios BUT idealized
    - Limited range of stratospheric wind strength
    - Limited propagation range

- **Objectives**
  - Extend transmission loss (TL) predictions up to 4,000 km
  - Incorporate realistic atmospheric specifications
  - Account for the multiple waveguides (stratospheric + MLT ducted waves)
  - Assess the spatio-temporal variability of the IMS network performance using a Bayesian framework

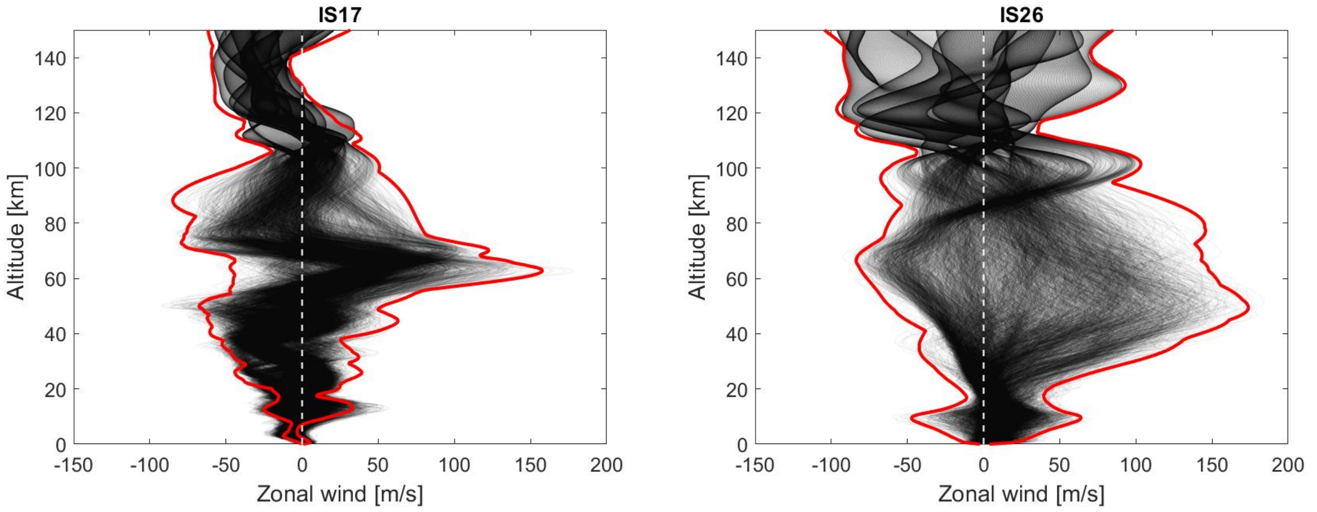


Green and Bowers, 2010

Atmospheric dataset



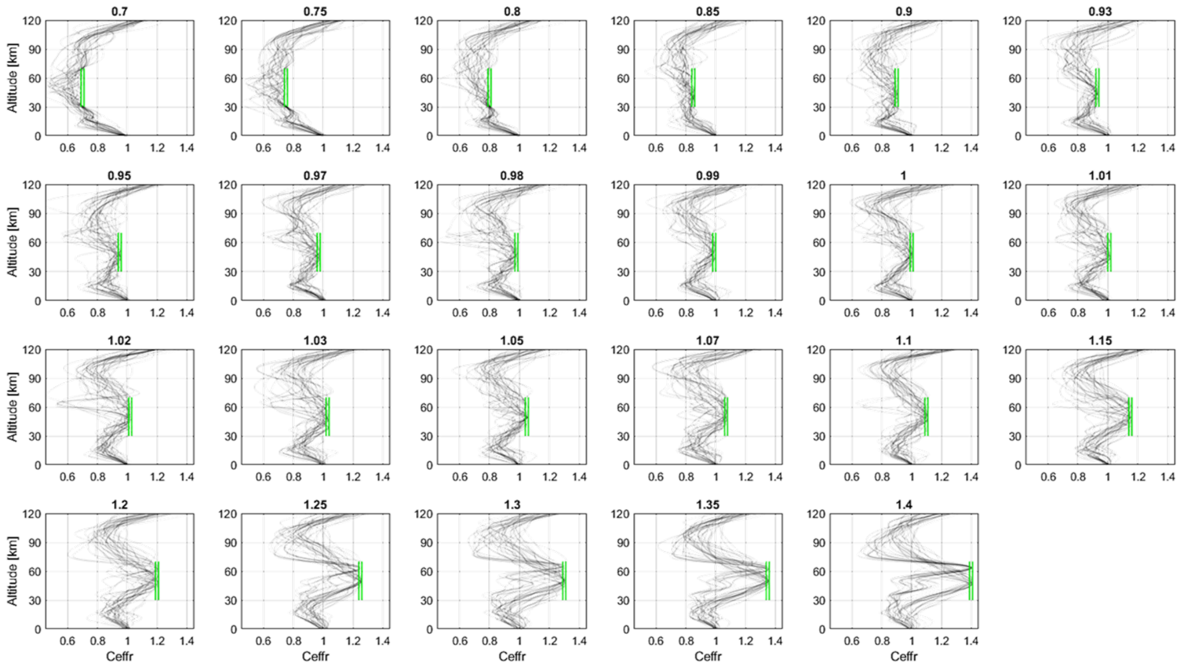
- Generate statistics of the atmosphere using historical NWP models
- Vertical temperature / zonal / meridional winds extracted with WACCM specifications (Whole Atmosphere Community Climate Model)
- Quantify atmospheric perturbation statistics: database parameterized using Empirical Orthogonal Function (EOF) decomposition (Assink, 2014)
- Probability distribution functions are obtained using the first 10 EOF coefficients



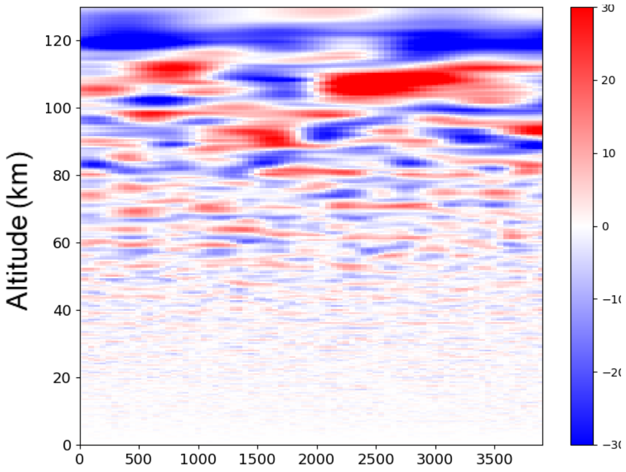
Atmospheric dataset

- Build multi-year database of temperature and wind models at IMS stations (2003-2020, 53 stations)
  - z ∈ [0; 120] km altitude
- Construct different classes of effective sound speed (ceff) ratios representing the variability of the stratospheric ducts (30-70 km)
- For each sample: incorporate 2D range dependent spectral model of wind perturbations (Gardner, 1993)
- PE* propagation modeling at: 0.1 - 3.2 Hz

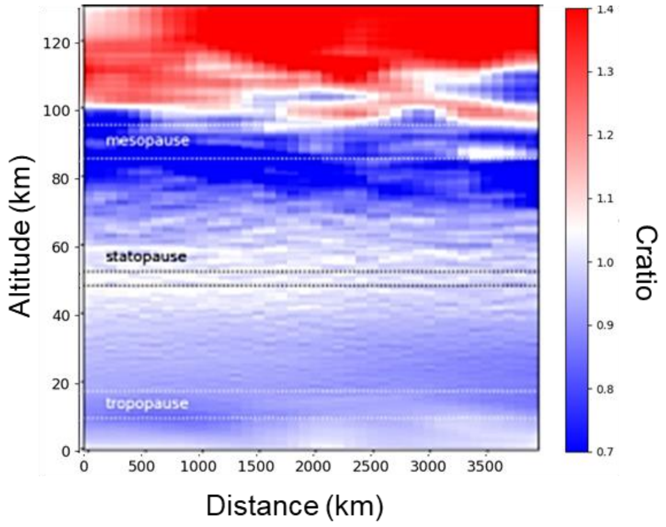
➔ 23 ceff x 100 samples x 10 GW x 10 frequencies = 230,000



Wind perturbation (m/s)



Perturbed ceff



*ePape parabolic equation numerical solver
National Center for Physical Acoustics (*Assink and Waxler, 2019*)

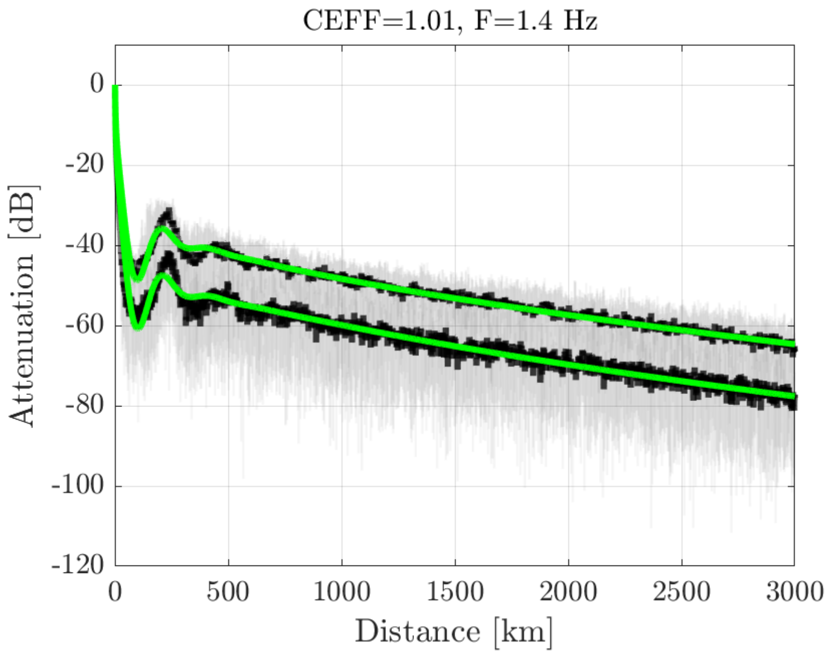
Multi-dimensional curve-fitting

- Non-linear curve-fitting of simulated TLs [ceff x f] (Coleman, 1996)
- Physical approach: attenuation relation accounting for geometrical spreading, dissipation and scattering (Lay and Wallace, 1995)
- Tabulated parameters: $\alpha, a_s, d_s, R_s, \beta$ vs. effective sound speed ratio and frequency

Geometrical spreading — Attenuation and scattering

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

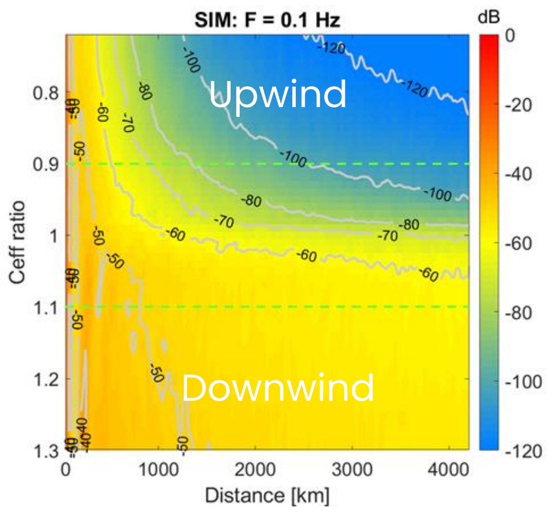
Geometrical shadow zones



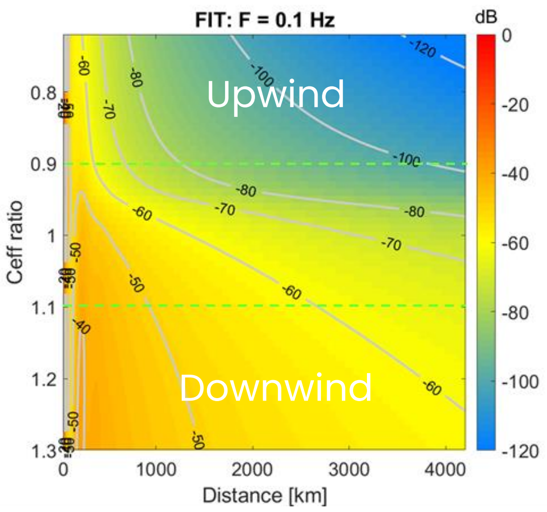
- **For [ceff x f x r]:** μ_{TL} **and** σ_{TL}

Multi-dimensional curve-fitting

PE simulations

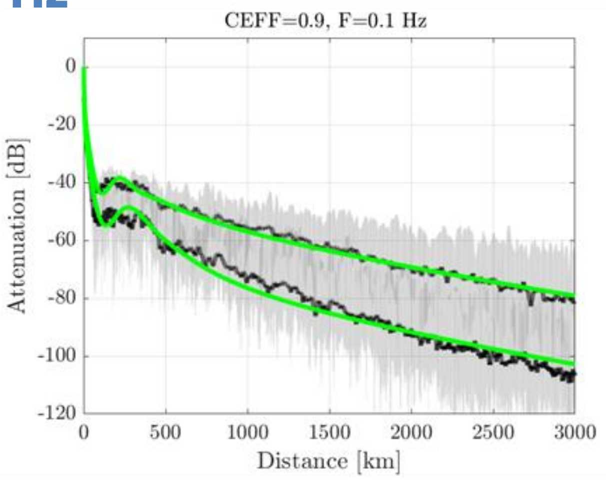


Predictions

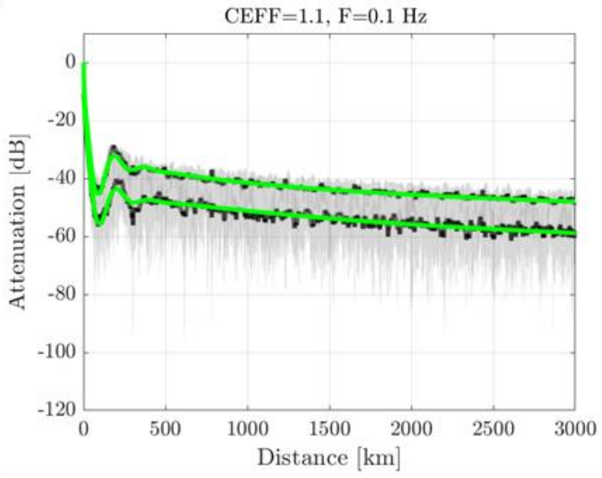


0.1 Hz

Upwind

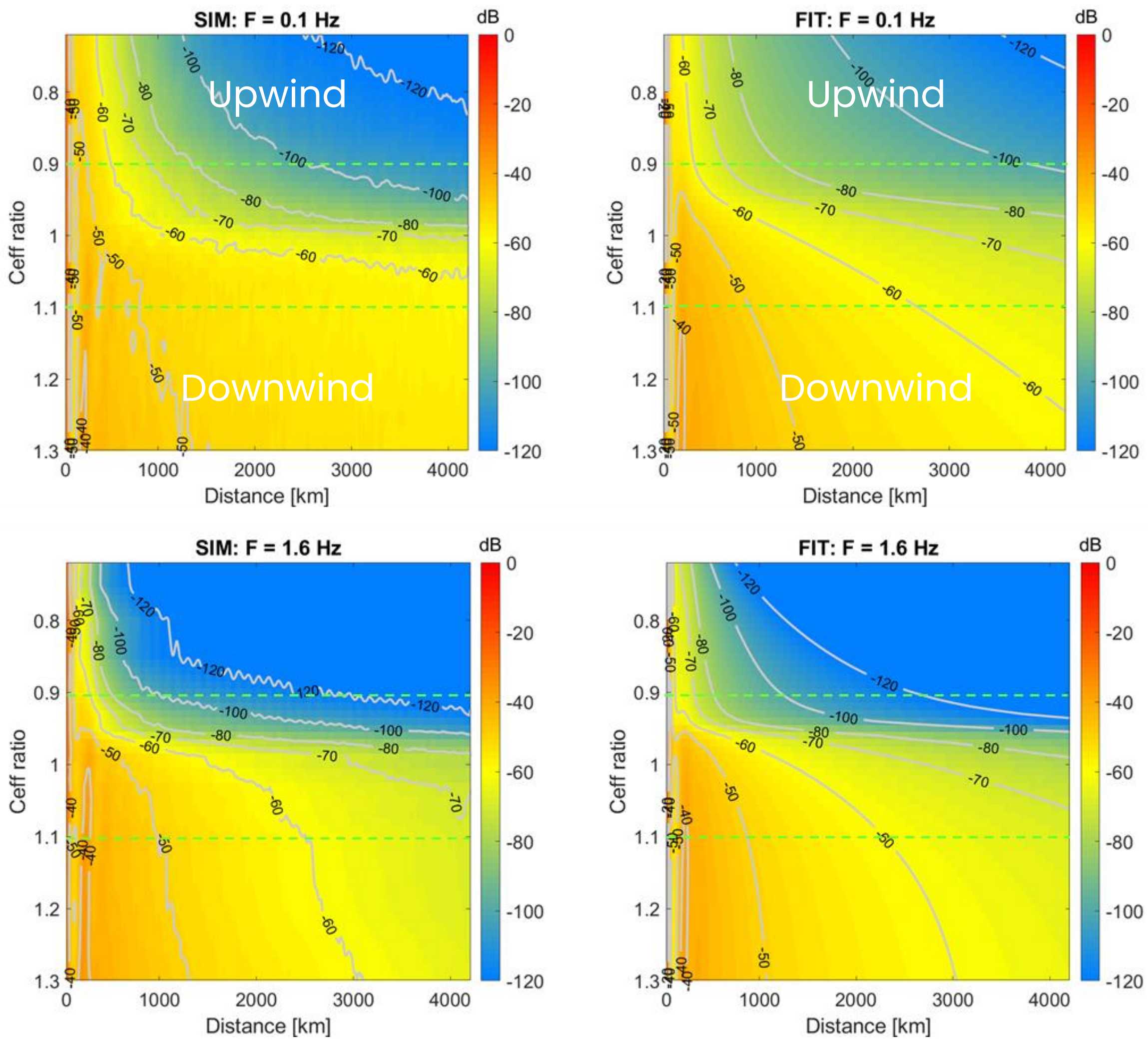


Downwind



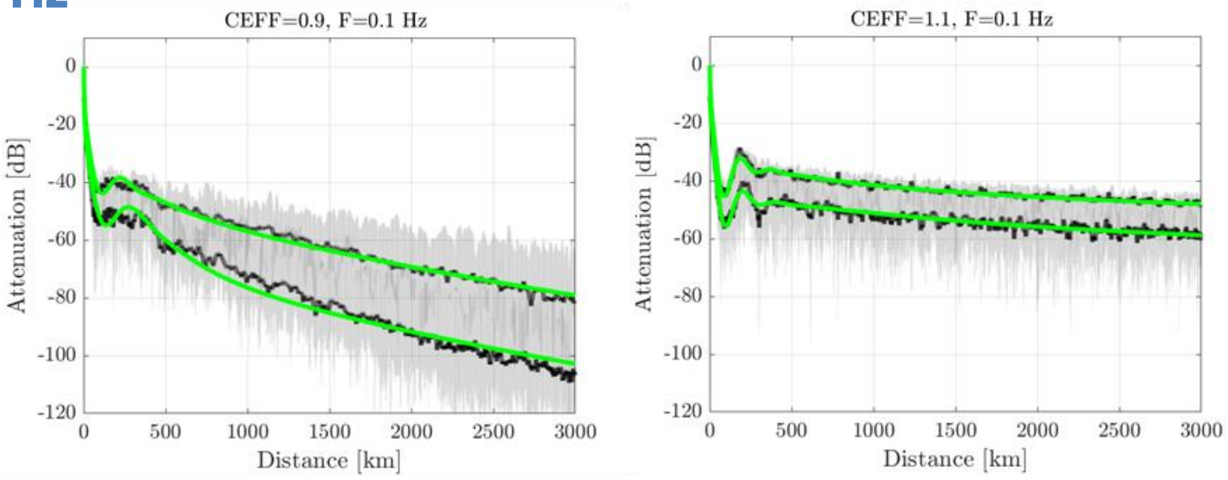
Multi-dimensional curve-fitting

PE simulations | Predictions

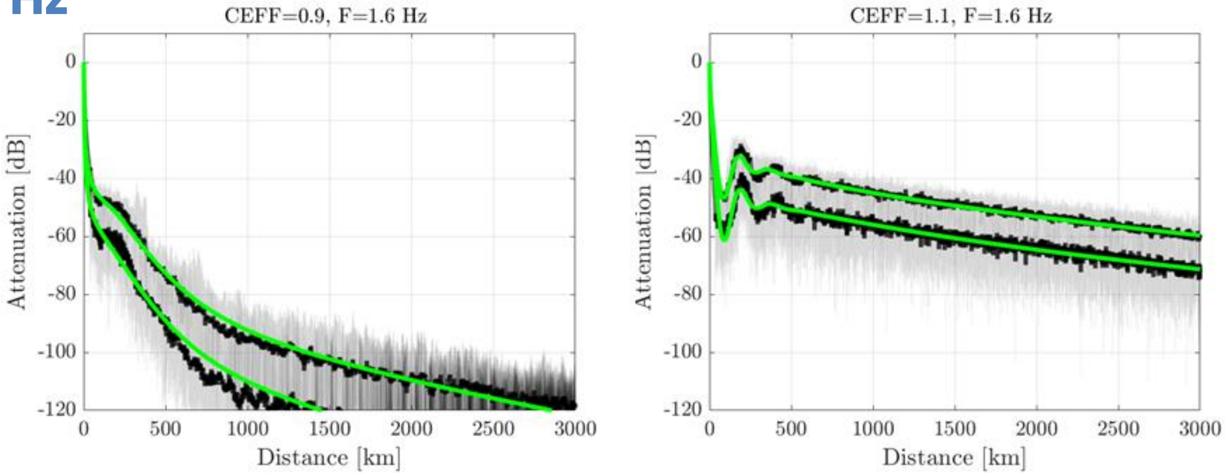


Upwind | Downwind

0.1 Hz



1.6 Hz



- Curve fitting provides TL estimates with errors lower than ~10 dB downwind and ~20 dB upwind

Network performance simulation
A Bayesian framework (Blom et al., 2023)

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

$$P_{KG\_dB}(W_J, f, r)$$

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

$$\rho_{arr}(W_J, f, r, c_{effr}) = \frac{1}{\sigma_{TL}(f, r, c_{effr})\sqrt{2\pi}} \times e^{-\frac{1}{2}\left(\frac{P - P_{KG_{dB}}(W_J, f, r) - \mu_{TL}(f, r, c_{effr})}{\sigma_{TL}(f, r, c_{effr})}\right)^2}$$

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

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

- Cumulative distribution of the noise statistics

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

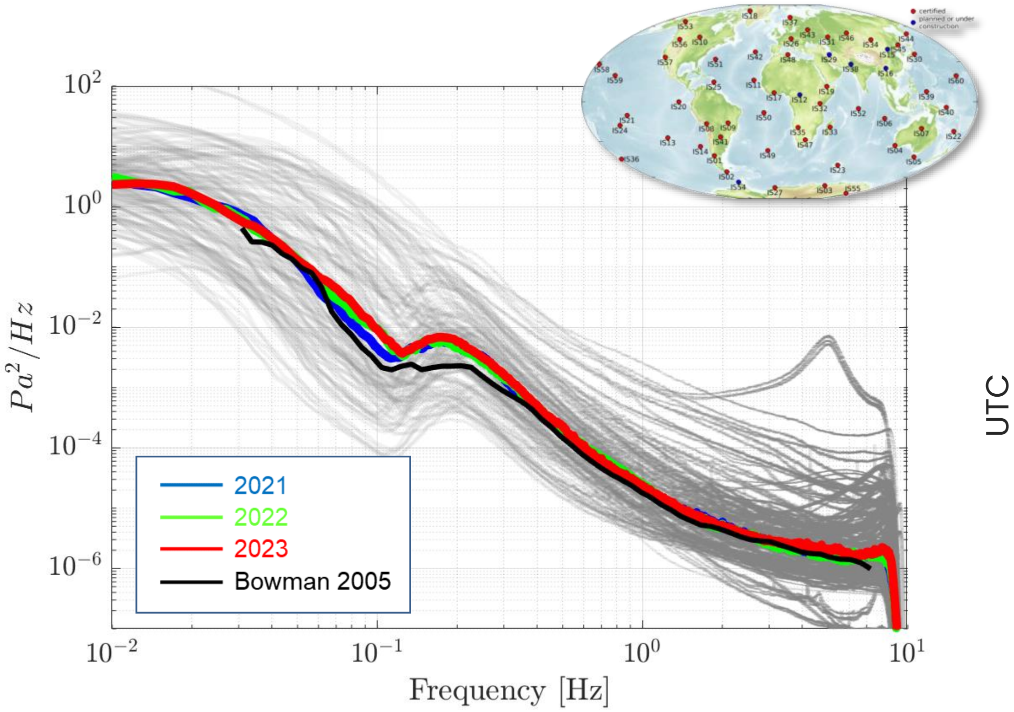
- Probability distribution of the effective noise (Pa/Hz)

$$\rho_{ns}(f, r, N)$$

➔ Calculate the 90% probability for detecting explosive yield

Noise statistics

- PSDs calculated on continuous IMS records
- 53 certified stations
- 2021, 2022, 2023
- Hourly basis
- Hanning, 300 s window length
- μ_{PSD} and σ_{PSD} derived from PSDs at **all array elements**



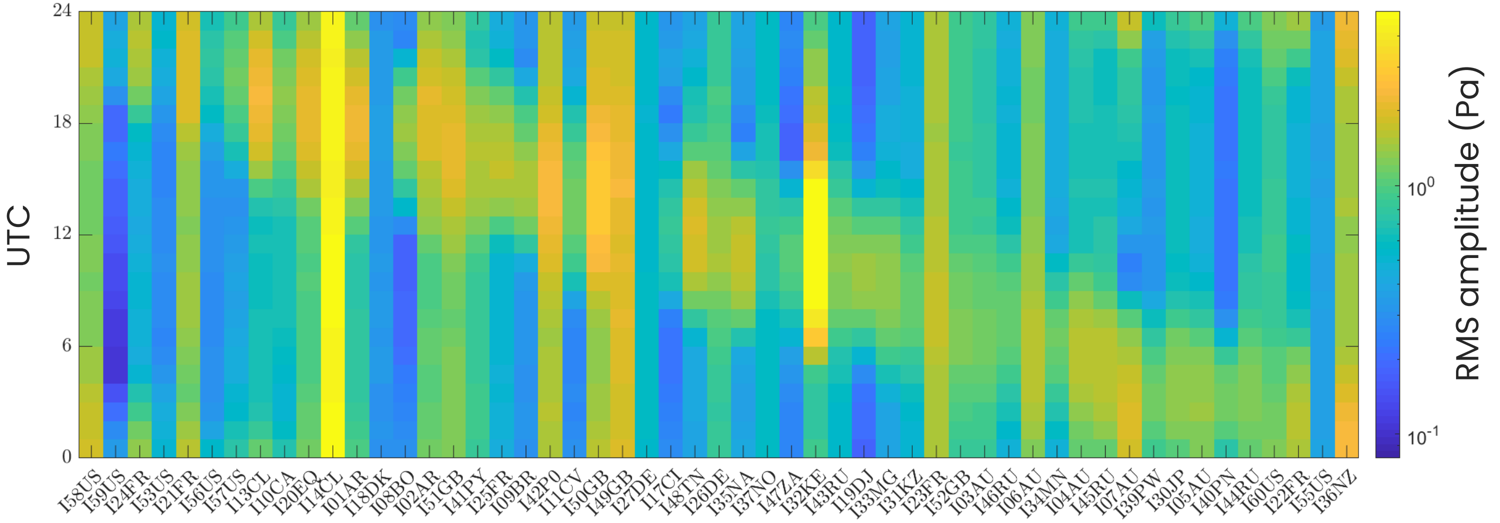
Probability distribution of the effective noise

$$\rho_{ns}(f,r,N) = \frac{1}{\sigma_{PSD}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{P-\mu_{PSD}(f,r,N)}{\sigma_{PSD}(f,r,N)}\right)^2}$$

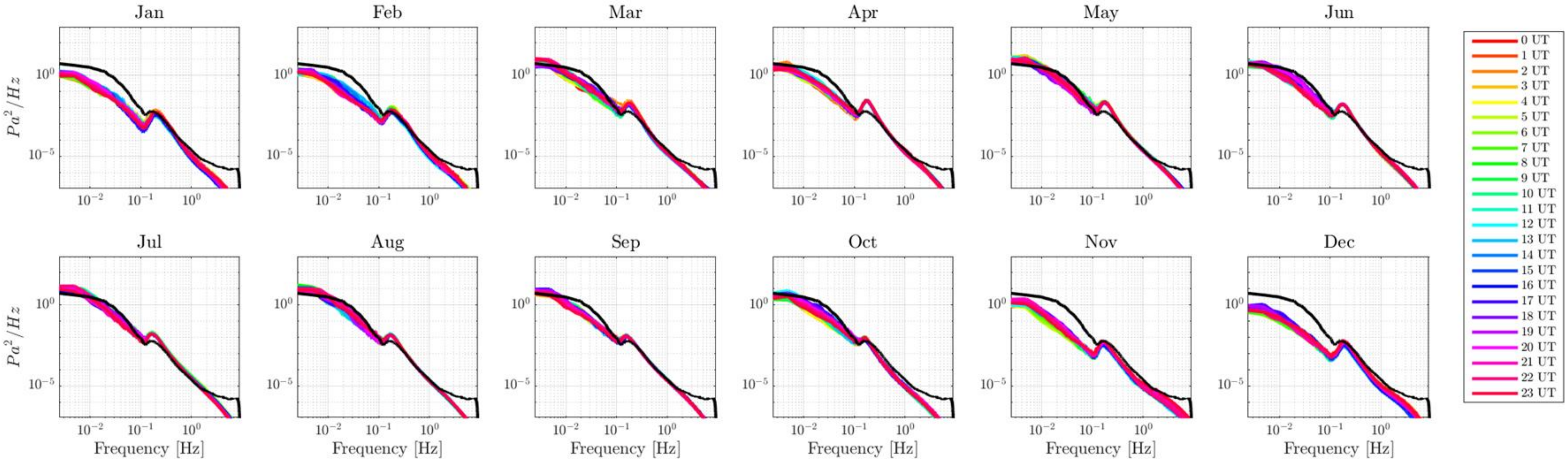
$$\mu_{PSD}(f,r,N) = \sqrt{PSD(f)\frac{\tau(r)}{N}}$$

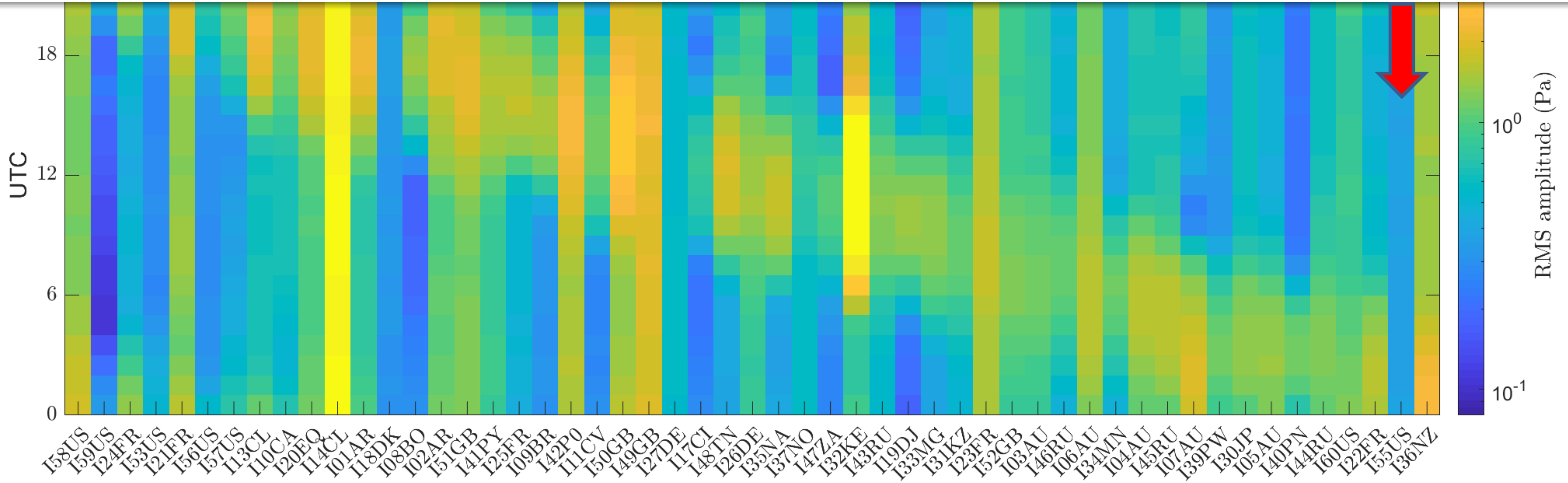
Green and Nippress, 2019

- $\tau(r)$: wavetrain duration
- N: number of array elements

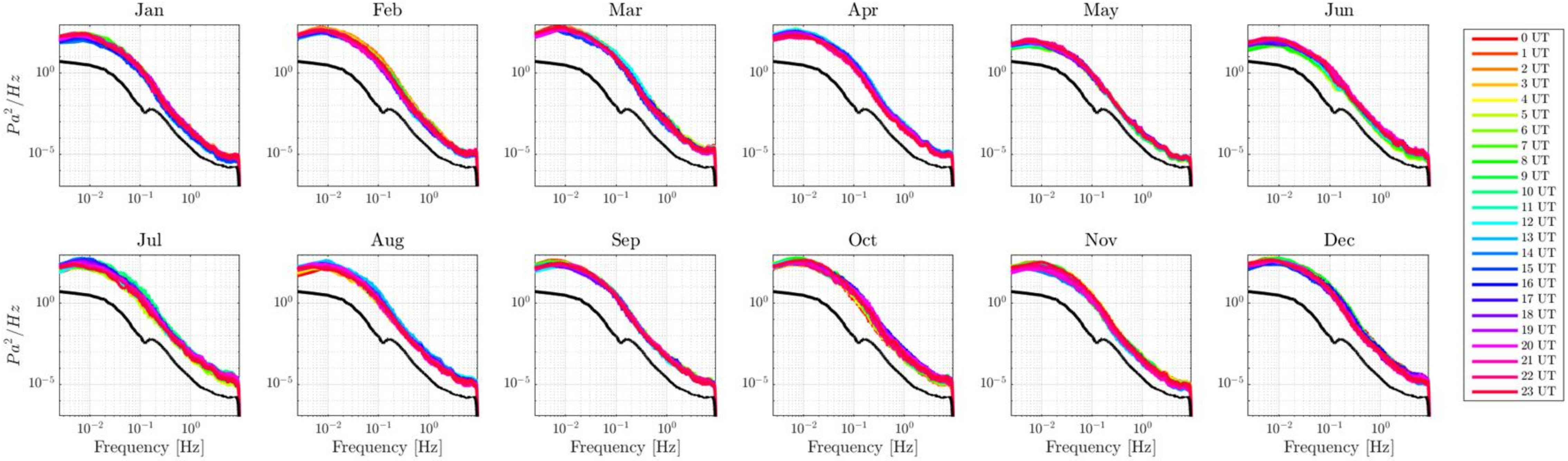


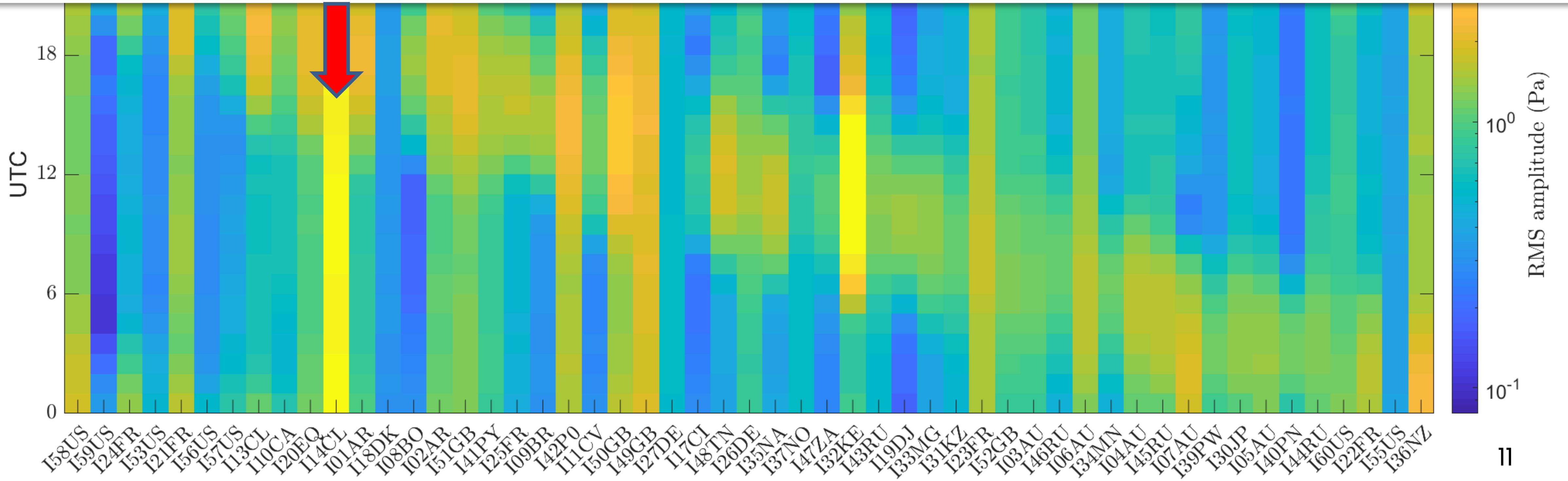
I55US


Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Pa^2/Hz
10^0
10^{-5}
10^{-2}
10^{-1}
10^0
Frequency [Hz]
0 UT
1 UT
2 UT
3 UT
4 UT
5 UT
6 UT
7 UT
8 UT
9 UT
10 UT
11 UT
12 UT
13 UT
14 UT
15 UT
16 UT
17 UT
18 UT
19 UT
20 UT
21 UT
22 UT
23 UT

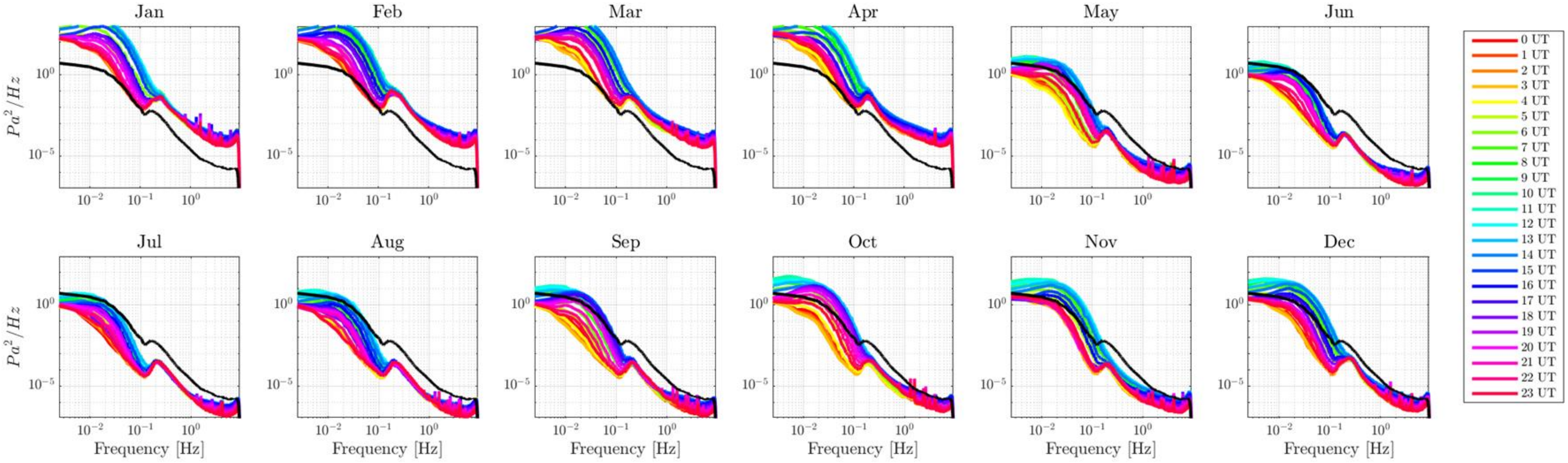

UTC
0
6
12
18
RMS amplitude (Pa)
10^0
10^{-1}
I58US
I59US
I24FR
I53US
I21FR
I56US
I57US
I13CL
I10CA
I20EQ
I14CL
I01AR
I18DK
I08BO
I02AR
I51GB
I41PY
I25FR
I09BR
I42PO
I11CV
I50GB
I49GB
I27DE
I17CI
I48TN
I26DE
I35NA
I37NO
I47ZA
I32KE
I43RU
I19DJ
I33MG
I31KZ
I23FR
I52GB
I03AU
I46RU
I06AU
I34MN
I04AU
I45RU
I07AU
I39PW
I30JP
I05AU
I40PN
I44RU
I60US
I22FR
I55US
I36NZ

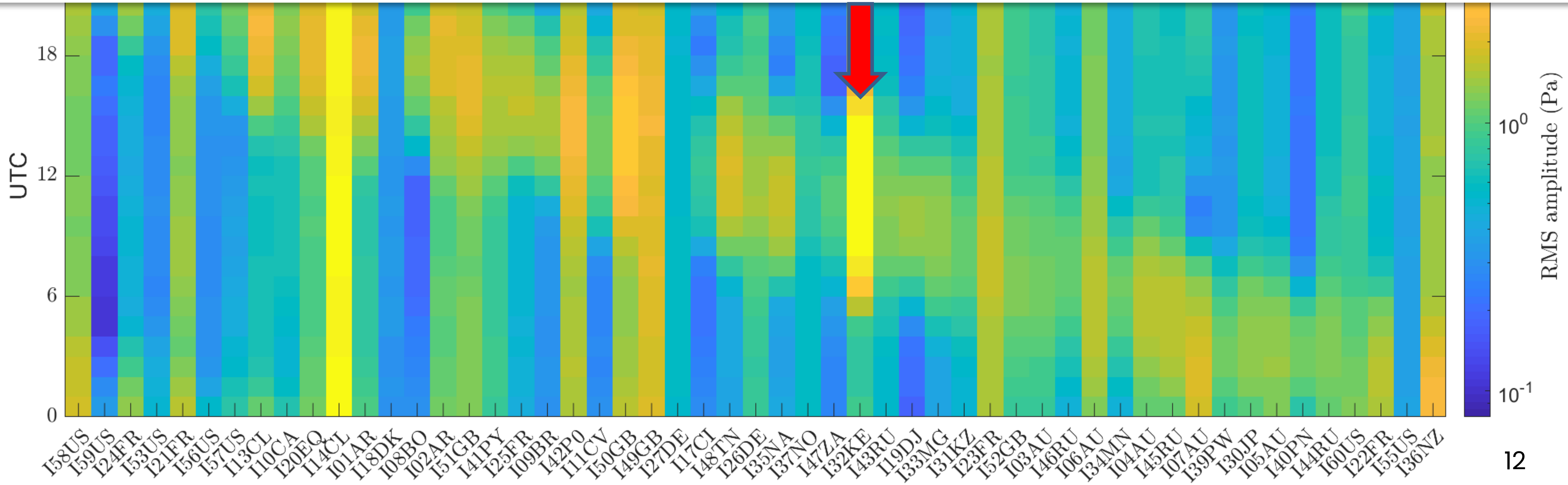
I14CL


Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Pa^2/Hz
10^0
10^{-5}
10^{-2} 10^{-1} 10^0
Frequency [Hz]
0 UT
1 UT
2 UT
3 UT
4 UT
5 UT
6 UT
7 UT
8 UT
9 UT
10 UT
11 UT
12 UT
13 UT
14 UT
15 UT
16 UT
17 UT
18 UT
19 UT
20 UT
21 UT
22 UT
23 UT

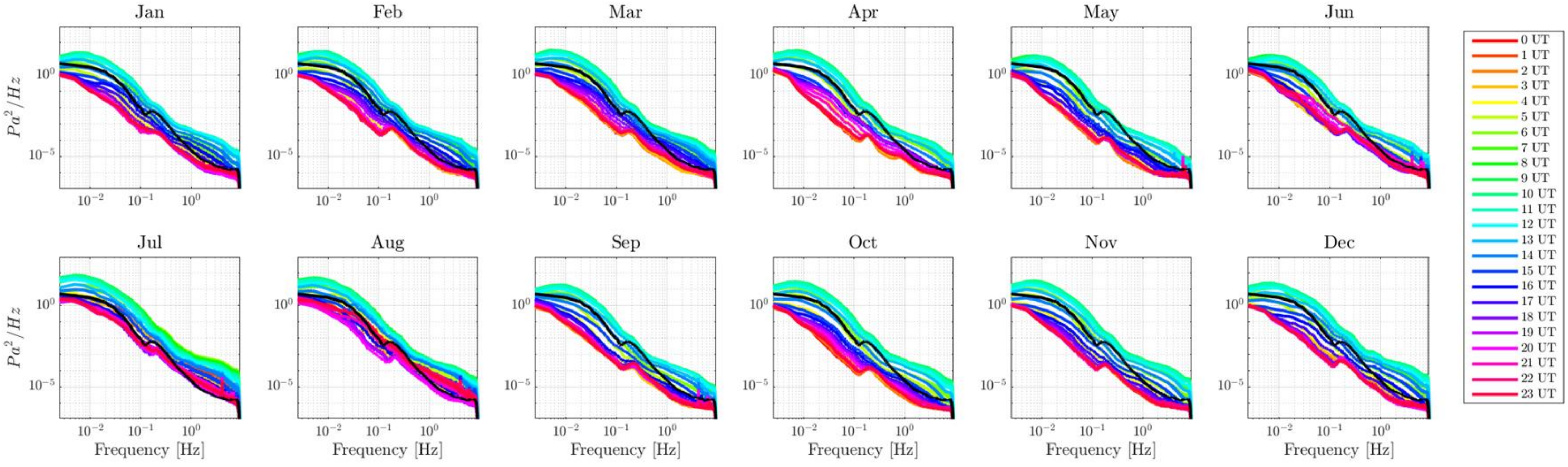

UTC
0
6
12
18
I58US I59US I24FR I53US I21FR I56US I57US I13CL I10CA I20EQ I14CL I01AR I18DK I08BO I02AR I51GB I41PY I25FR I09BR I42PT I11CV I50GB I49GB I27DE I17CI I48TN I26DE I35NA I37NO I47ZA I32KE I43RU I19DJ I33MG I31KZ I23FR I52GB I03AU I46RU I06AU I34MN I04AU I45RU I07AU I39PW I30JP I05AU I40PN I44RU I60US I22FR I55US I36NZ
RMS amplitude (Pa)
10^0
10^{-1}

I32KE

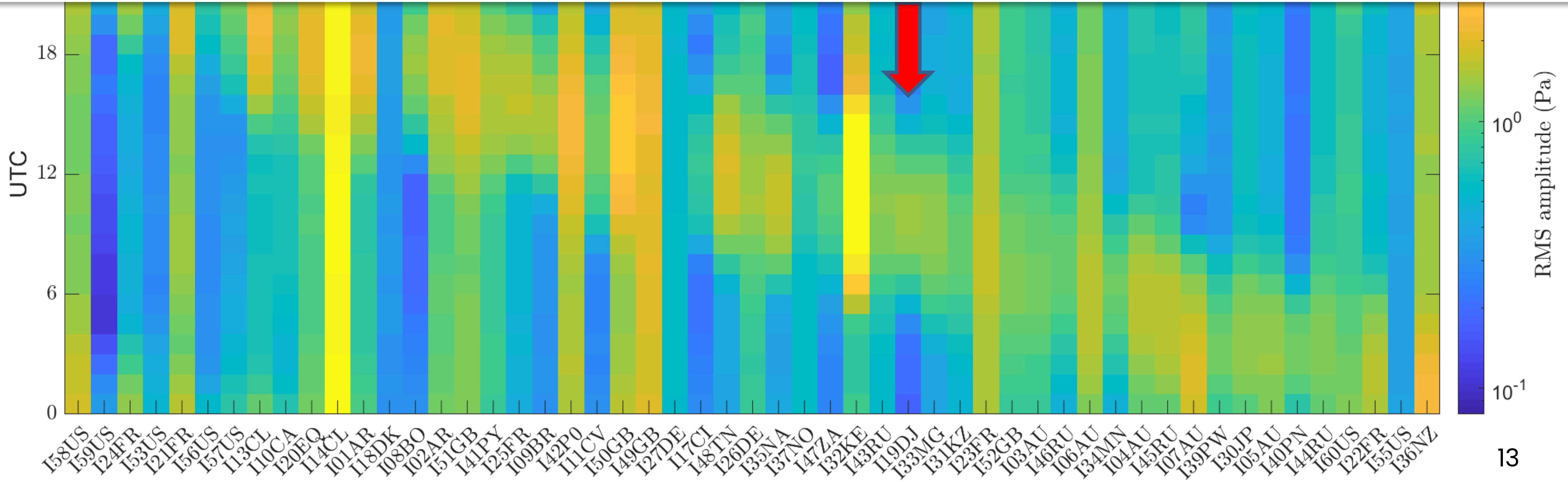

Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Pa^2/Hz
Frequency [Hz]
0 UT
1 UT
2 UT
3 UT
4 UT
5 UT
6 UT
7 UT
8 UT
9 UT
10 UT
11 UT
12 UT
13 UT
14 UT
15 UT
16 UT
17 UT
18 UT
19 UT
20 UT
21 UT
22 UT
23 UT


UTC
RMS amplitude (Pa)
I58US
I59US
I24FR
I53US
I21FR
I56US
I57US
I13CL
I10CA
I20EQ
I14CL
I01AR
I18DK
I08BO
I02AR
I51GB
I41PY
I25FR
I09BR
I42PO
I11CV
I50GB
I49GB
I27DE
I17CI
I48TN
I26DE
I35NA
I37NO
I47ZA
I32KE
I43RU
I19DJ
I33MG
I31KZ
I23FR
I52GB
I03AU
I46RU
I06AU
I34MN
I04AU
I45RU
I07AU
I39PW
I30JP
I05AU
I40PN
I44RU
I60US
I22FR
I55US
I36NZ

I19DJ

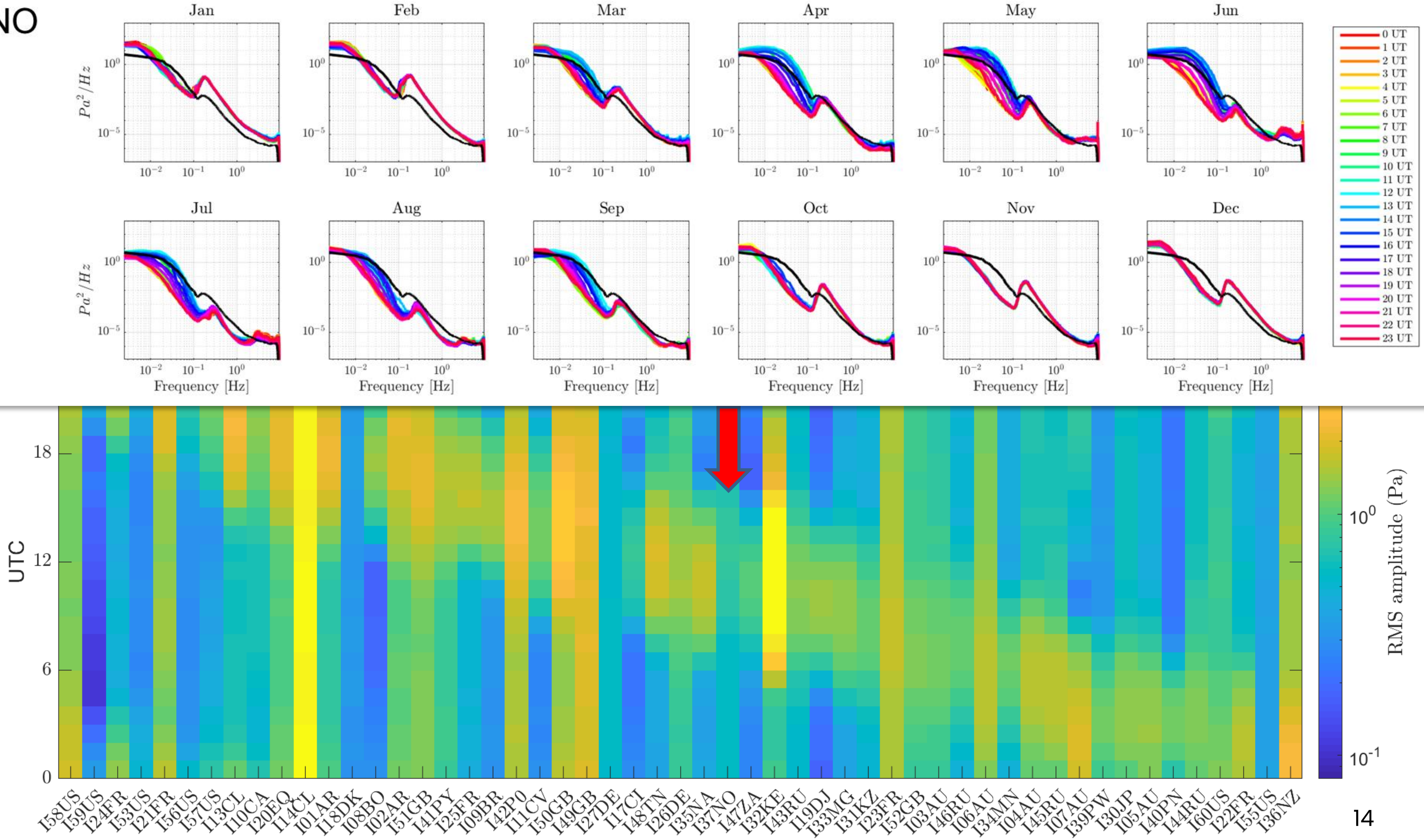


Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Pa^2/Hz
10^0
10^{-5}
10^{-2} 10^{-1} 10^0
Frequency [Hz]
0 UT
1 UT
2 UT
3 UT
4 UT
5 UT
6 UT
7 UT
8 UT
9 UT
10 UT
11 UT
12 UT
13 UT
14 UT
15 UT
16 UT
17 UT
18 UT
19 UT
20 UT
21 UT
22 UT
23 UT



UTC
18
12
6
0
I58US I59US I24FR I53US I21FR I56US I57US I13CL I10CA I20EQ I14CL I01AR I18DK I08BO I02AR I51GB I41PY I25FR I09BR I42PO I11CV I50GB I49GB I27DE I17CI I48TN I26DE I35NA I37NO I47ZA I32KE I43RU I19DJ I33MG I31KZ I23FR I52GB I03AU I46RU I06AU I34MN I04AU I45RU I07AU I39PW I30JP I05AU I40PN I44RU I60US I22FR I55US I36NZ
RMS amplitude (Pa)
10^0
10^{-1}

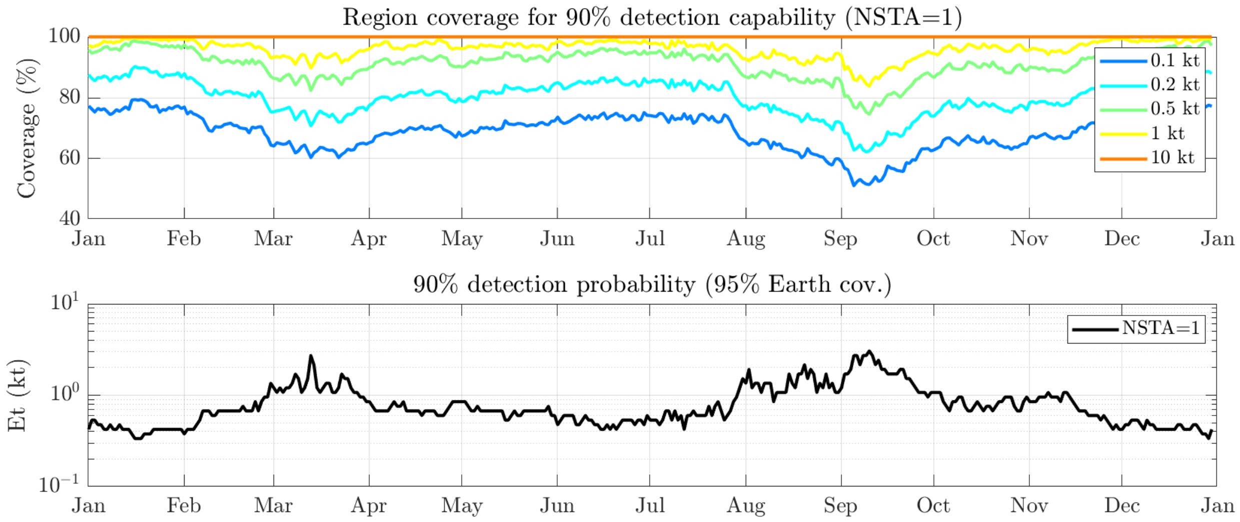
I37NO


Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Pa^2/Hz
Frequency [Hz]
0 UT
1 UT
2 UT
3 UT
4 UT
5 UT
6 UT
7 UT
8 UT
9 UT
10 UT
11 UT
12 UT
13 UT
14 UT
15 UT
16 UT
17 UT
18 UT
19 UT
20 UT
21 UT
22 UT
23 UT
UTC
RMS amplitude (Pa)
I58US I59US I24FR I53US I21FR I56US I57US I13CL I10CA I20EQ I14CL I01AR I18DK I08BO I02AR I51GB I41PY I25FR I09BR I42PO I11CV I50GB I49GB I27DE I17CI I48TN I26DE I35NA I37NO I47ZA I32KE I43RU I19DJ I33MG I31KZ I23FR I52GB I03AU I46RU I06AU I34MN I04AU I45RU I07AU I39PW I30JP I05AU I40PN I44RU I60US I22FR I55US I36NZ

Global simulations (WACCM 3h)

(90% probability, 95% coverage)

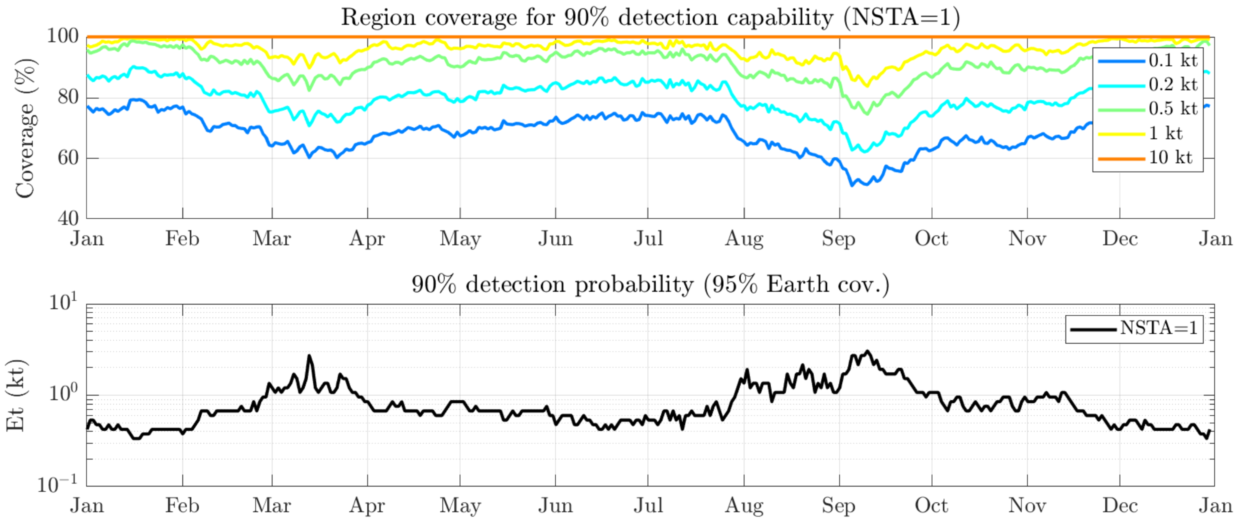
Median PSD



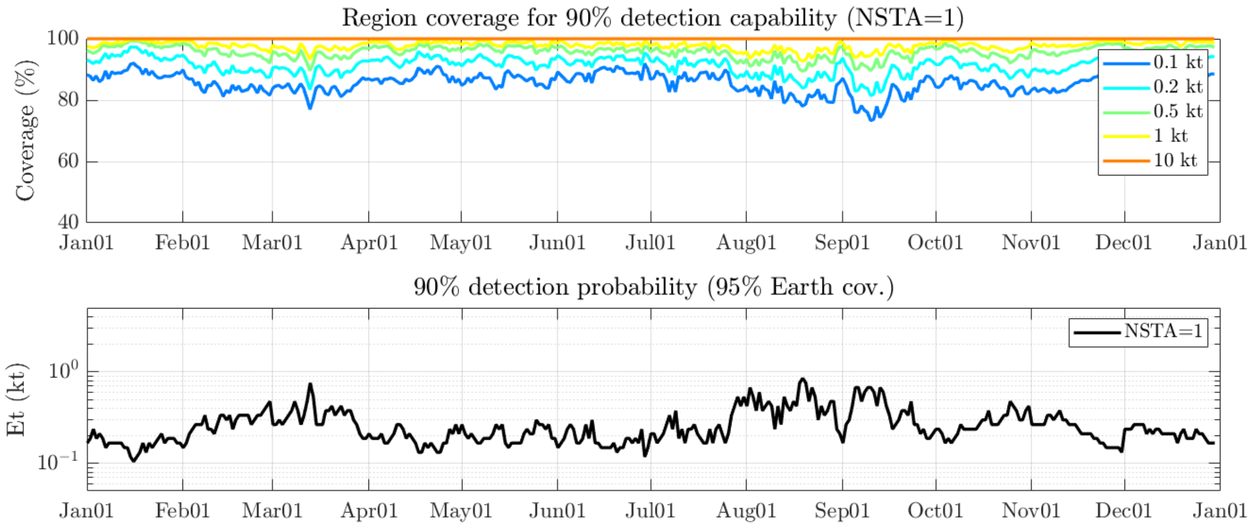
Global simulations (WACCM 3h)

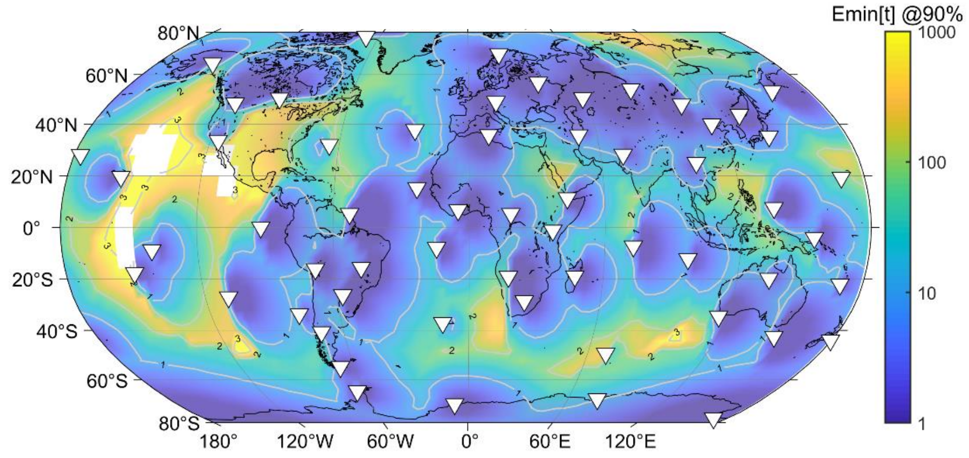
(90% probability, 95% coverage)

Median PSD



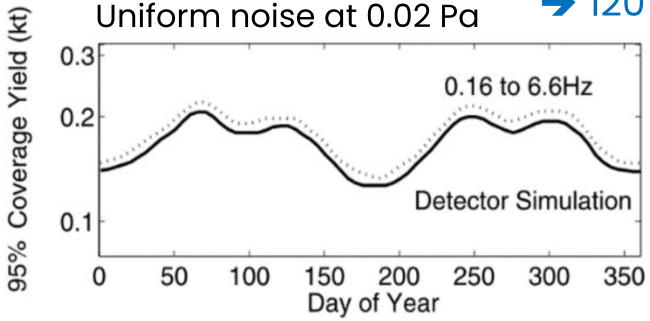
Hourly PSD





Green and Bower, 2010
Uniform noise at 0.02 Pa

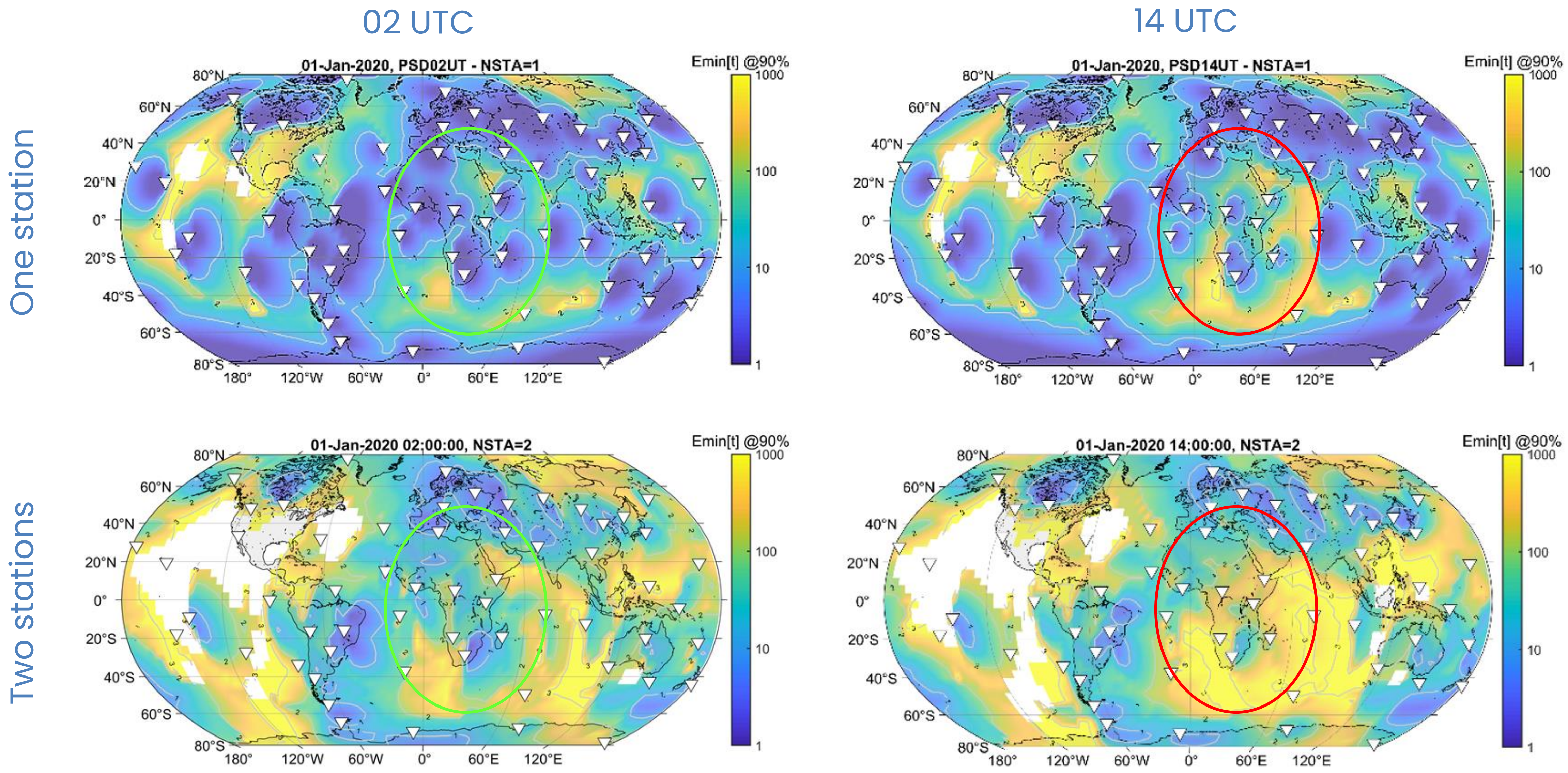
➔ 120 – 210 t



- **Global simulation with real noise**
  - One station coverage: 100 – 800 t TNT
  - 100 t threshold is achieved for 75% earth coverage
  - (Sub-)seasonal variations: one order of magnitude

Global simulations at 2 and 14 UTC

(90% probability, 95% coverage)



Summary / perspectives

- **Results**
  - A Bayesian framemork: from the source to the receiver
  - Updated attenuation relation; station noise measures
  - Highly variable thresholds: from season to hourly scales
  - One station coverage: 100 – 800 t TNT
  - Applications: near-real time assessment of the spatio-temporal variability of the IMS network performance; MA diagnostics using GT, civil applications (e.g. volcanoes)

- **Perspectives**
  - Perform sensitivity studies on middle-atmospheric fine structures (Drob et al., 2013; Vorobeva et al., 2023)
  - Validation through comparisons with observations
  - New approaches based on ML techniques are being explored (Brissaud et al. 2022; Cameijo, ITW24)