SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

CTBTO
PREPARATORY COMMISSION

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne*, C. Groult*, B. Dando**, P. Naesholm**, T. Kværna**, Y. Cano*

O3.5-462

ORAL PRESENTATION

* Commissariat à l'énergie atomique et aux énergies alternatives, France
** Norwegian Seismic Array, Kjeller, Norway

cea NORSAR

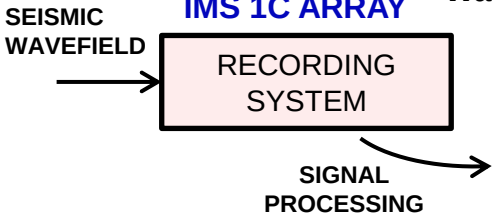
SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Pres. No.: O3.5-462

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano

CTBTO PREPARATORY COMMISSION

## INTRODUCTION

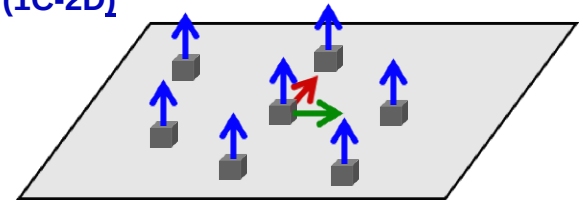


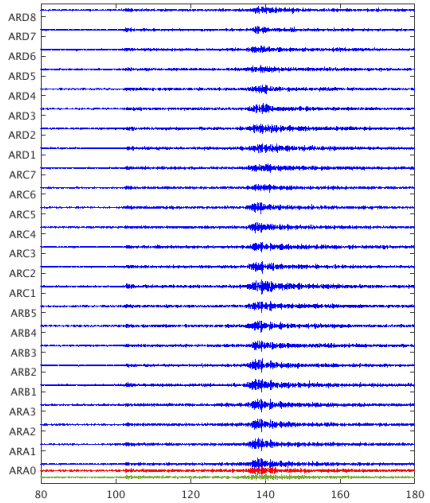

**Wave characteristics:**

- ✓ Frequency content
- ✓ Time of arrival
- ✓ Beam amplitude
  → vertical **SNR improvements**
- ✓ **Apparent propagation** (azimuth and velocity)
  → coherency of vertical components
- ✓ **Polarization** (in practice poorly used)

These estimates are important and used for **events detection and location** and for **signal identification** and **classification.**

**(1C-2D)**





SnT 2021
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
Pres. No.: O3.5-462

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano

CTBTO PREPARATORY COMMISSION

## INTRODUCTION

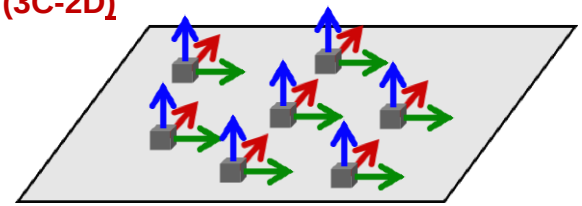
SEISMIC WAVEFIELD → RECORDING SYSTEM (3C ARRAY) → SIGNAL PROCESSING

**Wave characteristics:**

- ✓ Frequency content
- ✓ Time of arrival
- ✓ Beam amplitude
  → vertical and **horizontal** **SNR improvements**
- ✓ **Apparent propagation** (azimuth and velocity)
  → coherency of vertical and **horizontal** components
- ✓ **Polarization**

These estimates are important and used for **events detection and location** and for **signal identification** and **classification.**

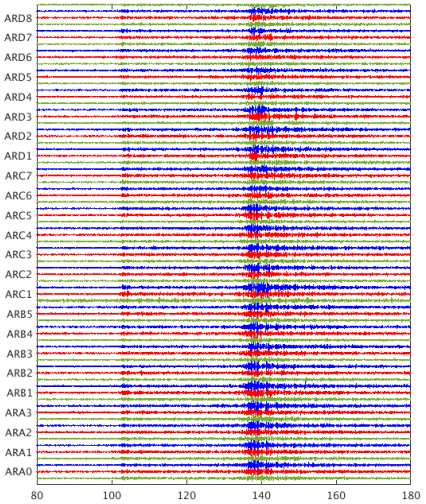
**(3C-2D)**



3C-array processing takes into account the complete wavefield instead of the vertical dimension only.

Purpose:

- Demonstrate improved events detection capabilities of using IMS 3C array
- Investigate solutions to efficiently use the coherency of the horizontal components.

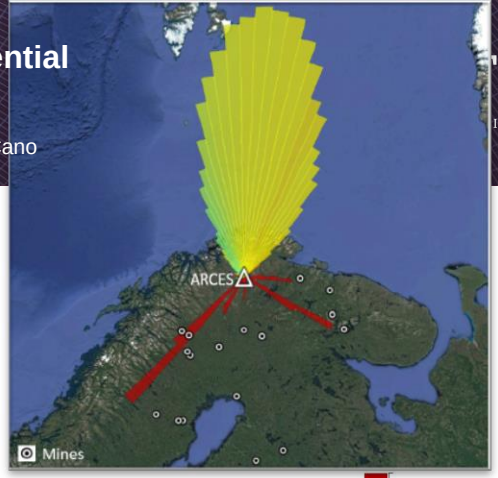


# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

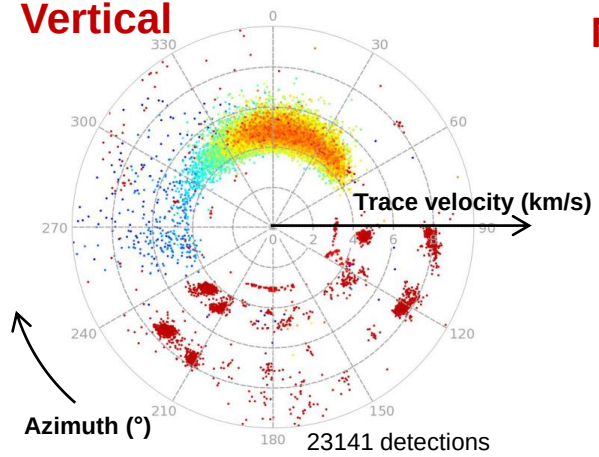
C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano

## INTRODUCTION

- **ARCES** (PS28) : IMS 3C ARRAY
- Automatic PMCC detections over one month of data
  → illustrates the complementarity of the horizontal and vertical components

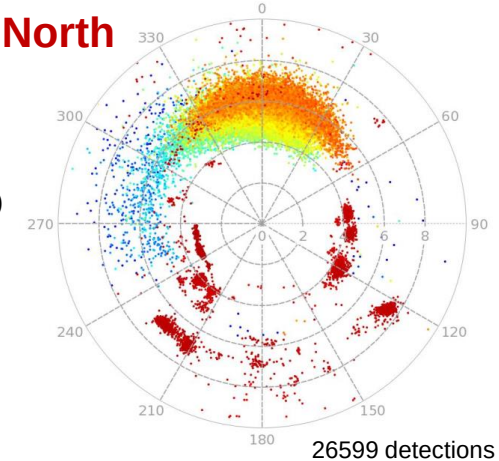



**Vertical**



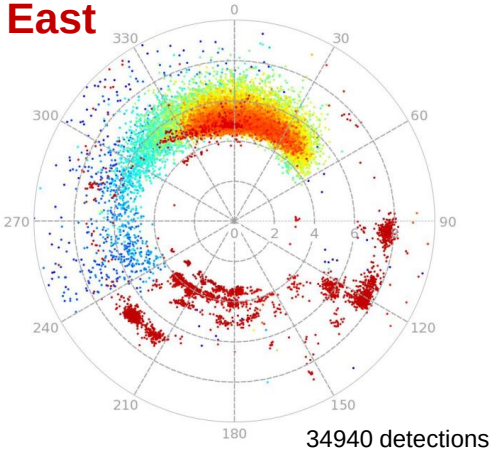

23141 detections

**North**

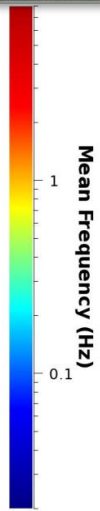


26599 detections

**East**



34940 detections




+15% of detections on North component
+51% of detections on East component

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano



## PREVIOUS WORKS

- **PMCC** (Progressive Multi-Channel Correlation) approach :

  → Influence of horizontal trace rotation on the array consistency by looking at prospective (Radial-Tranverse) rotations

  (e.g. Labonne et al. 2019, SnT)

- **F-K** (Frequency-wavenumber) approach:

  → Improvement of S-wave coherence on the transverse beams by using P-wave azimuth detection to rotate horizontal components

  (e.g. Gibbons et al., 2019, JoS)

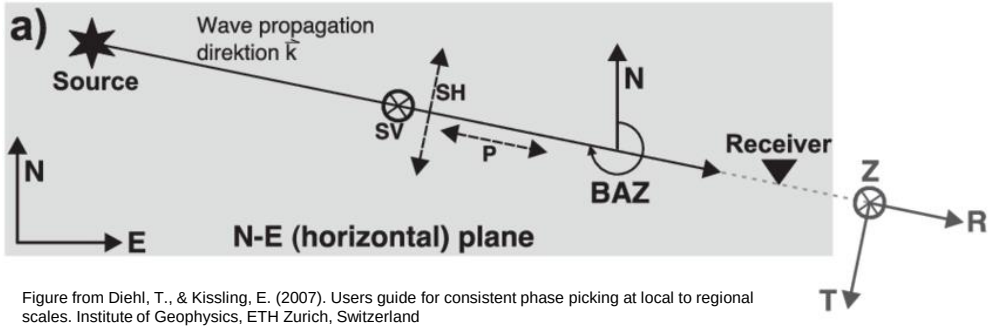



Figure from Diehl, T., & Kissling, E. (2007). Users guide for consistent phase picking at local to regional scales. Institute of Geophysics, ETH Zurich, Switzerland

**ZRT** (2D rotation)

- **Require back-azimuth (BAZ) knowledge**
- **Separation of P, SV and SH waves:**
  P and SV waves in *Z-R* components
  SH wave in T component

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano



## PREVIOUS WORKS

- **PMCC** (Progressive Multi-Channel Correlation) approach :

  → Influence of horizontal trace rotation on the array consistency by looking at prospective (Radial-Tranverse) rotations

  (e.g. Labonne et al. 2019, SnT)

- **F-K** (Frequency-wavenumber) approach:

  → Improvement of S-wave coherence on the transverse beams by using P-wave azimuth detection to rotate horizontal components

  (e.g. Gibbons et al., 2019, JoS)

## THIS STUDY

→ Perform **(3C-ZRT) PMCC** analysis over a large data set (7-months) recorded at ARCES (by using P-wave azimuth detection)

→ Comparison with the vertical-only analysis

→ Prototyping ray-coordinate **(3C-LTQ) fk-analysis** using a single Kiruna event recorded at ARCES (by looking at prospective LTQ rotations)

→ Verified using a set of phases in NORSAR's reviewed bulletin

# Multicomponent seismic arrays: demonstrating for improved event detection and charact

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm,



## (3C-ZRT) PMCC ANALYSIS

**PMCC ON Z-COMPONENT OVER 7 MONTHS OF DATA**

- **Selection of potential P-waves** (each family detection with a velocity larger than 6km/s)
- using a time window of **600s around P-arrival** (100 before and 500 after)

**ZRT ROTATION**
based on the P-wave azimuth

**PMCC ON ROTATED COMPONENTS (ZRT)**

**3C-PIXELS CONCATENATION**

**GROUPING INTO FAMILY**

**PHASE SORTING AND LABELLING**

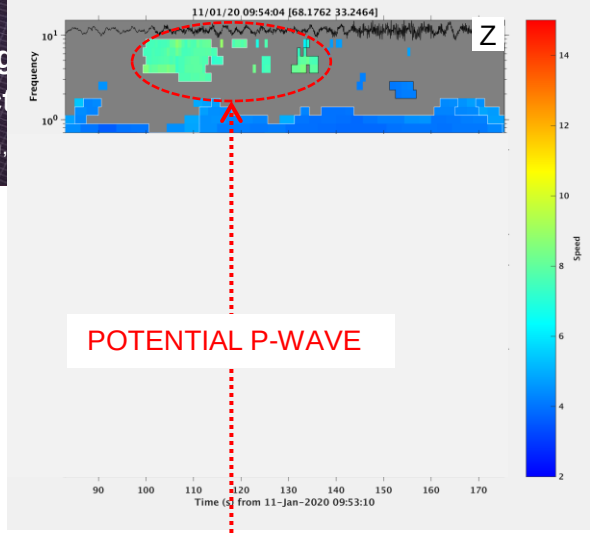
**KURTOSIS PHASE PICKER**
on radial, transverse or vertical ''beam'' waveform

**EVENT LOCALISATION**
using P- and S-wave pickings and P-wave azimuth

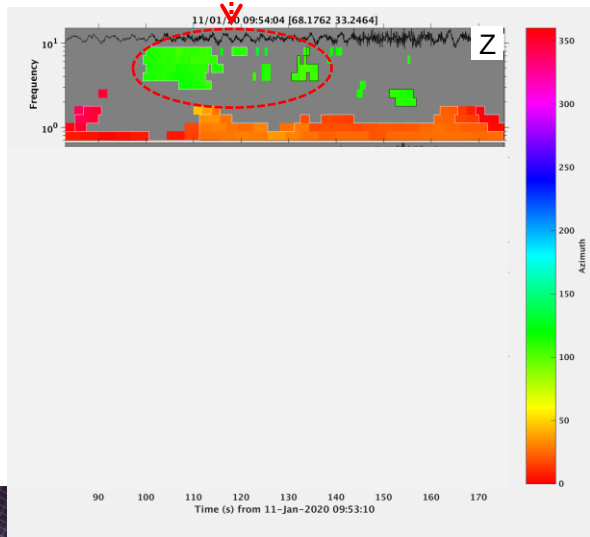
**DELETE DUPLICATED EVENTS**

**1C (Z) PROCESS**

**3C (ZRT) PROCESS**




Apparent velocity (km/s)




Azimuth (°)

# Multicomponent seismic arrays: demonstrating for improved event detection and charact

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm,



## (3C-ZRT) PMCC ANALYSIS

**PMCC ON Z-COMPONENT OVER 7 MONTHS OF DATA**

- **Selection of potential P-waves** (each family detection with a velocity larger than 6km/s)
- using a time window of **600s around P-arrival** (100 before and 500 after)

**ZRT ROTATION**
based on the P-wave azimuth

**PMCC ON ROTATED COMPONENTS (ZRT)**

**3C-PIXELS CONCATENATION**

**GROUPING INTO FAMILY**

**PHASE SORTING AND LABELLING**

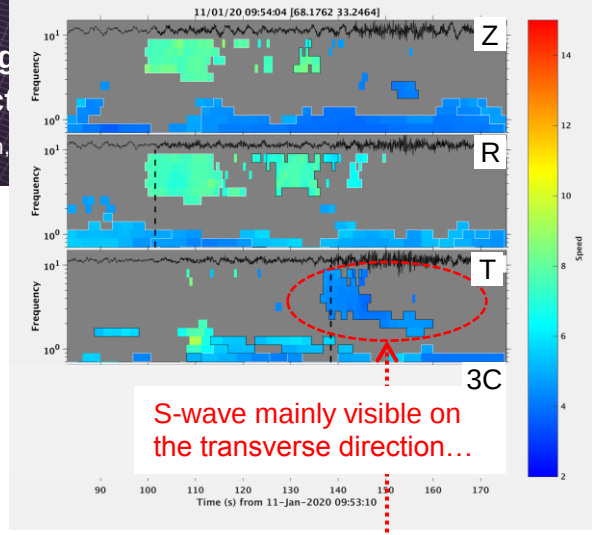
**KURTOSIS PHASE PICKER**
on radial, transverse or vertical ''beam'' waveform

**EVENT LOCALISATION**
using P- and S-wave pickings and P-wave azimuth

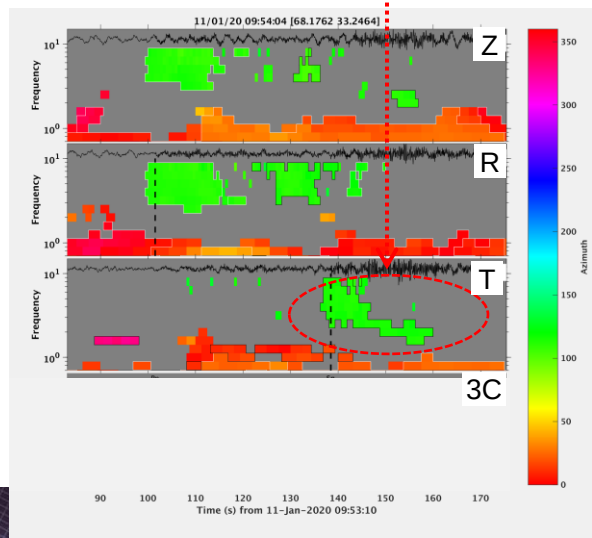
**DELETE DUPLICATED EVENTS**

**1C (Z) PROCESS**

**3C (ZRT) PROCESS**




Apparent velocity (km/s)




Azimuth (°)

# Multicomponent seismic arrays: demonstrating for improved event detection and charact

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm,



## (3C-ZRT) PMCC ANALYSIS

**PMCC ON Z-COMPONENT OVER 7 MONTHS OF DATA**

- **Selection of potential P-waves** (each family detection with a velocity larger than 6km/s)
- using a time window of **600s around P-arrival** (100 before and 500 after)

**ZRT ROTATION**
based on the P-wave azimuth

**PMCC ON ROTATED COMPONENTS (ZRT)**

**3C-PIXELS CONCATENATION**

**GROUPING INTO FAMILY**

**PHASE SORTING AND LABELLING**

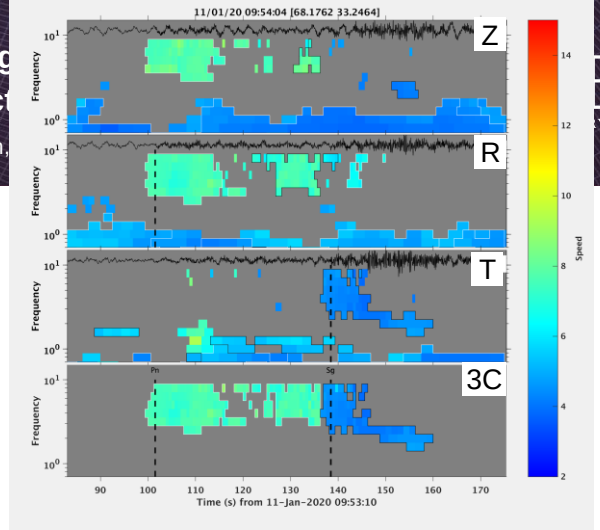
**KURTOSIS PHASE PICKER**
on radial, transverse or vertical ''beam'' waveform

**EVENT LOCALISATION**
using P- and S-wave pickings and P-wave azimuth

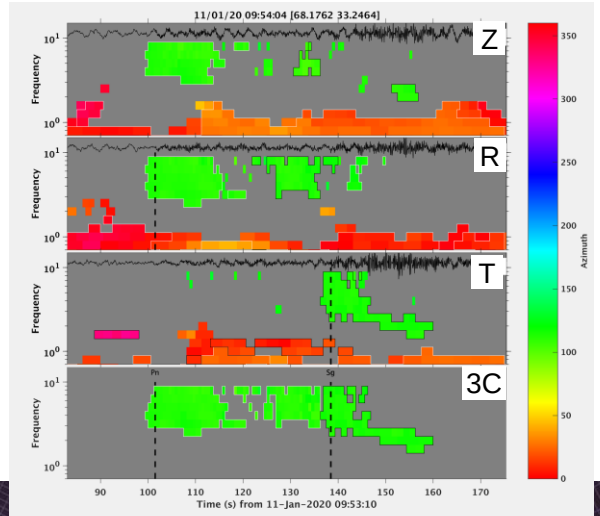
**DELETE DUPLICATED EVENTS**

**1C (Z) PROCESS**

**3C (ZRT) PROCESS**




Apparent velocity (km/s)




Azimuth (°)

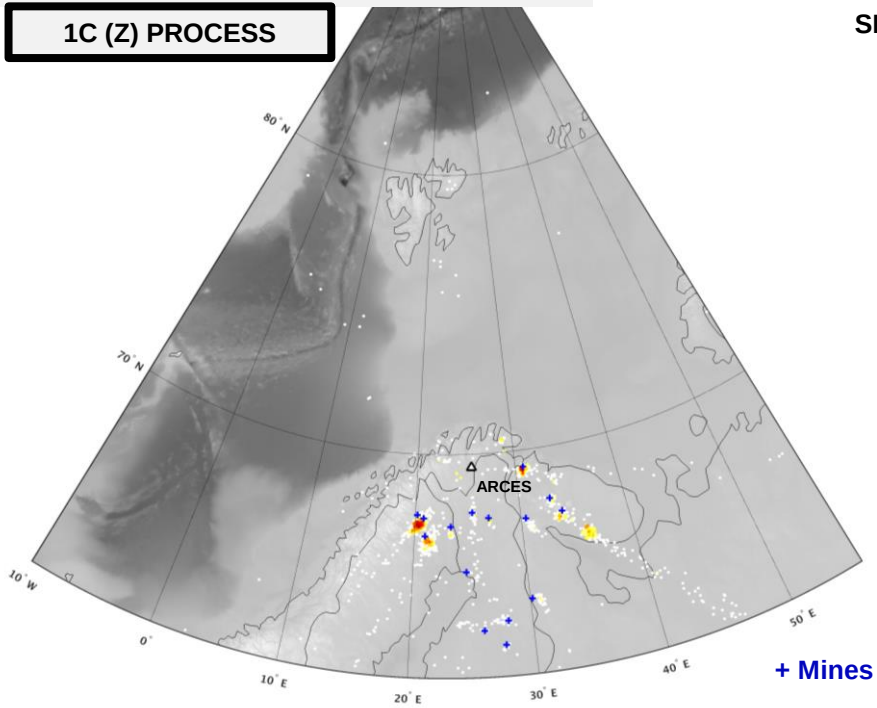
# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano

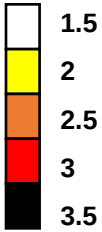
CTBTO PREPARATORY COMMISSION

## (3C-ZRT) PMCC RESULTS

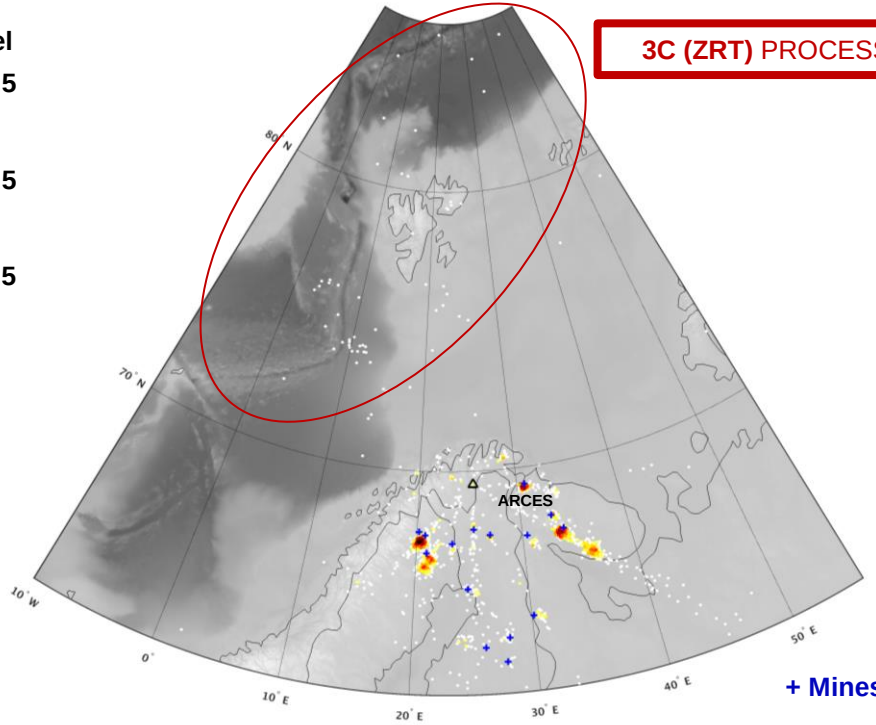
**1C (Z) PROCESS**




**SNR level**




**3C (ZRT) PROCESS**



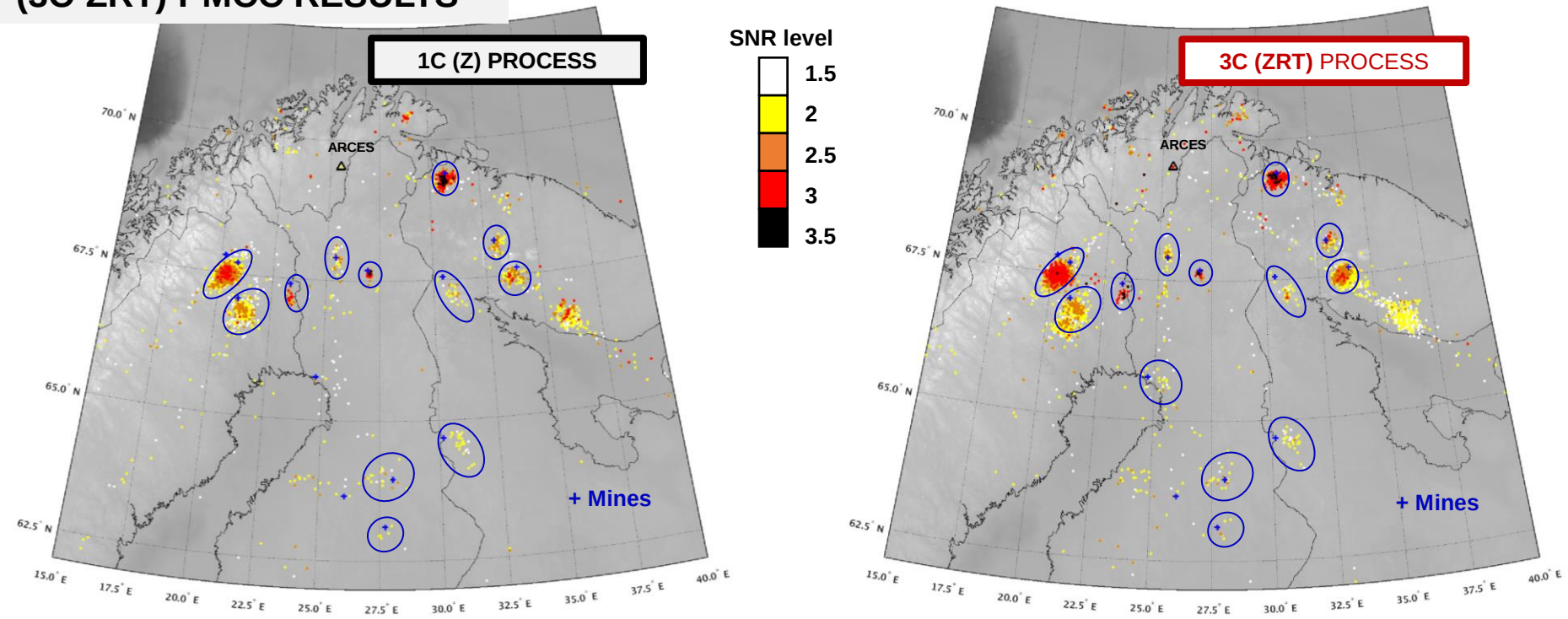

Automatic event localisation using a single array (ARCES) over 7 months of data ( january – july 2020)

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano



## (3C-ZRT) PMCC RESULTS




Automatic event localisation using a single array (ARCES) over 7 months of data ( january – july 2020)

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano

CTBTO PREPARATORY COMMISSION

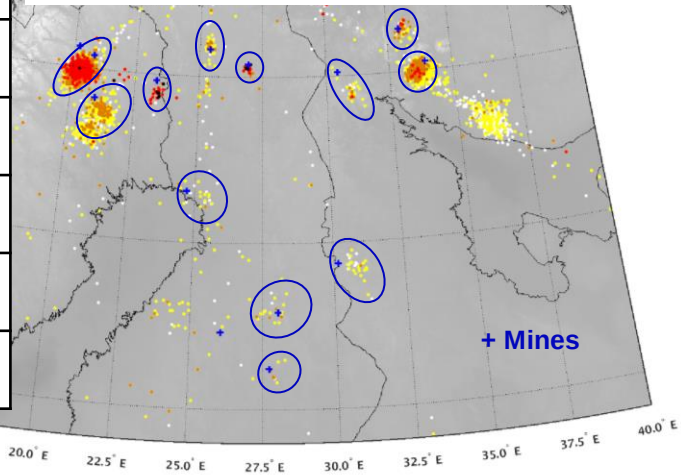
## (3C-ZRT) PMCC RESULTS

SNR level

| SNR LEVEL | Number of detected events over 7 months | | % of increase |
|---|---|---|---|
| | 1C (Z) PROCESS | 3C (ZRT) PROCESS | |
| ALL EVENTS | 3438 | 5272 | +53% |
| 1.5 | 3388 | 5175 | +53% |
| 2 | 2832 | 4402 | +55% |
| 2.5 | 1451 | 2740 | +88% |
| 3 | 404 | 1027 | +154% |
| 3.5 | 29 | 37 | +28% |

**3C (ZRT)** PROCESS

→ Detection capabilities improvement
- Higher number of detections
- Higher SNR level



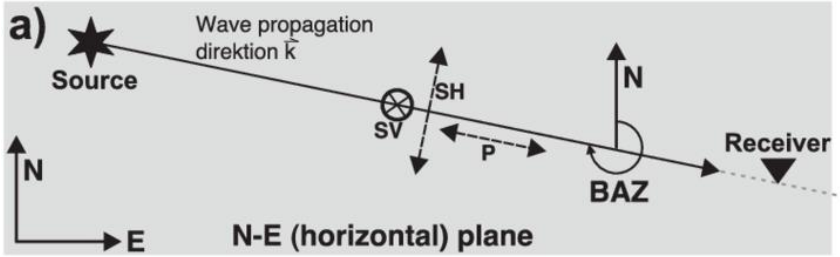

Automatic event localisation using a single array (ARCES) over 7 months of data ( january – july 2020)

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano

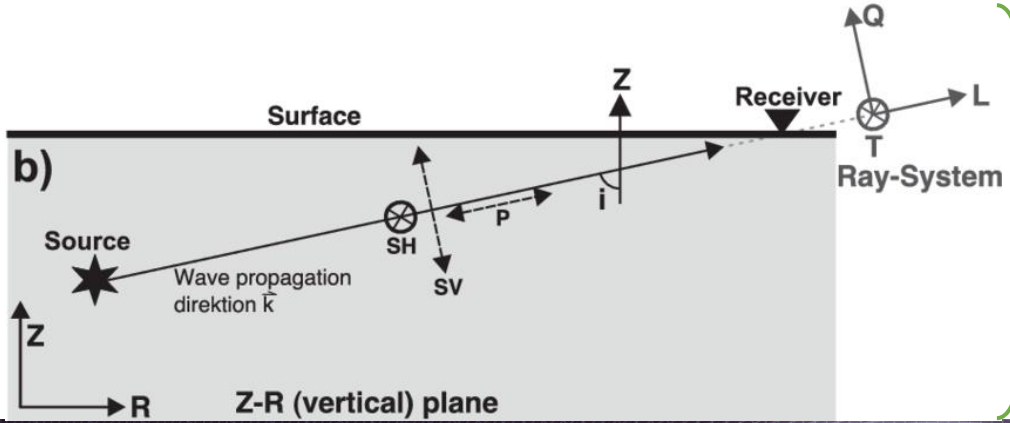


## RAY-COORDINATE SYSTEM (LTQ)




**ZRT** (2D rotation)

- **Require back-azimuth (BAZ) knowledge**
- **Separation of P, SV and SH waves:**
  P and SV waves in *Z-R* components
  SH wave in T component




**LTQ** (3D rotation)

- **Require BAZ and incidence (i) knowledge**
- **Full separation of P, SV and SH waves :**
  *L* – Aligned in direction of P wave
  *Q* – Aligned in direction of SV phase
  *T* – Aligned in direction of SH phase

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

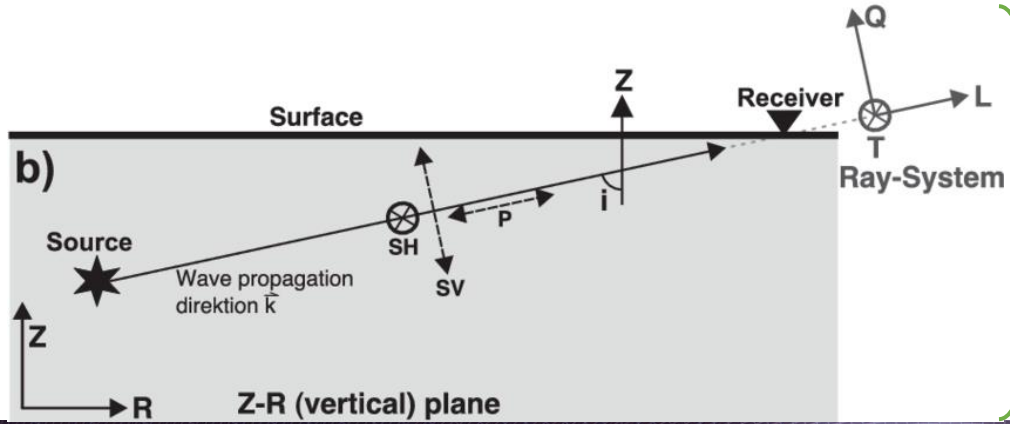
C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano



## (3C-LTQ) F-K ANALYSIS

- **Grid search** over angle of incidence (i) and back-azimuth (BAZ)

for a given (i/BAZ) → **LTQ ROTATION (ray-coordinate system)** → **FK-ANALYSIS FOR EACH ROTATED COMPONENT (LTQ)** → **SEMBLANCE ESTIMATION (normalized measure of the coherence)** → (back to grid search)




**LTQ** (3D rotation)

- **Require BAZ and incidence (i) knowledge**
- **Full separation of P, SV and SH waves :**
  - *L* – Aligned in direction of P wave
  - *Q* – Aligned in direction of SV phase
  - *T* – Aligned in direction of SH phase

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano

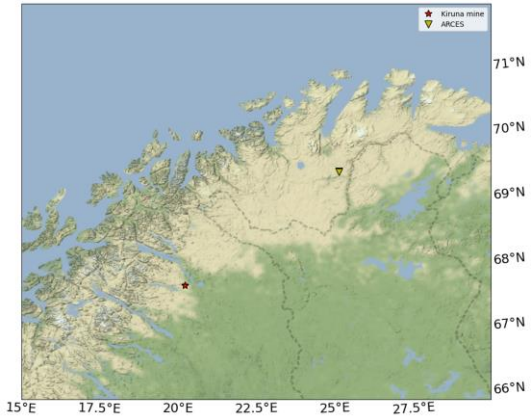


## (3C-LTQ) F-K ANALYSIS

- **Grid search** over angle of incidence (i) and back-azimuth (BAZ)

for a given (i/BAZ) → **LTQ ROTATION (ray-coordinate system)** → **FK-ANALYSIS FOR EACH ROTATED COMPONENT (LTQ)** → **SEMBLANCE ESTIMATION (normalized measure of the coherence)** → (back to grid search)

- First prototype made using an event from Kiruna mine recorded at ARCES: 2017-04-22T00:18:30 (epicentral distance: 2.56 degrees ~ 285 km)



# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

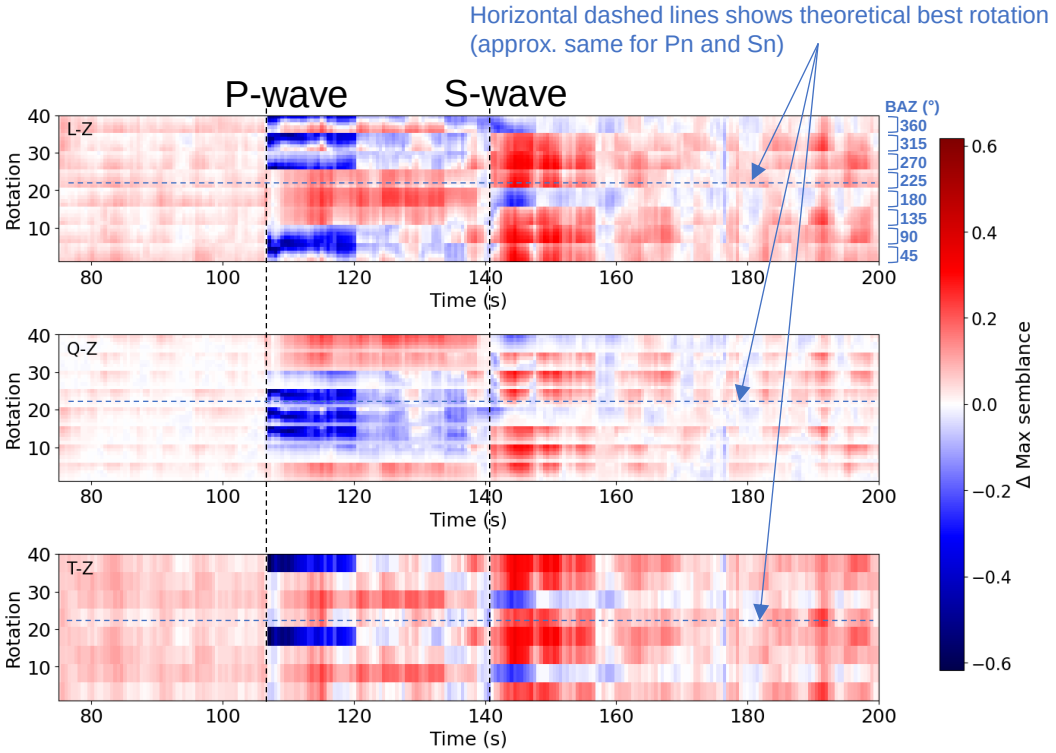
C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano



## (3C-LTQ) F-K RESULTS

**Semblance improvement** relative to vertical component (Z) processing for the different rotations:

- One line corresponds to processing for a given (BAZ/i)
- Any semblance improvement (where there is an arrival) means the rotations are worthwhile
- L-Z shows we do get a benefit to the P-wave
- T-Z shows we get a significant improvement to the S-wave




Event from Kiruna mine recorded at ARCES: 2017-04-22T00:18:30
Theoretical (BAZ,i) = (231°,45°)

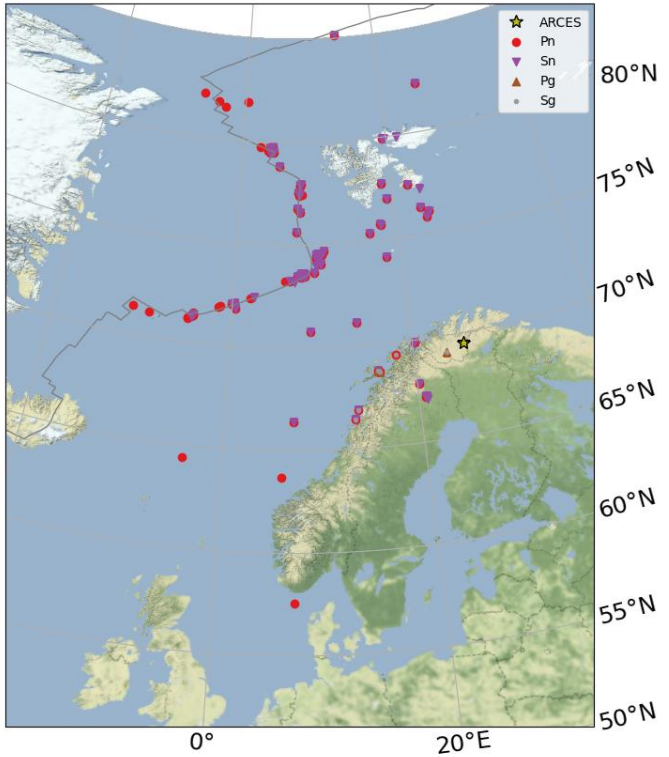
# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano



## REVIEWED BULLETIN COMPARISON

- Reprocess all phases from the NORSAR reviewed bulletin from 01/01/2021 to 20/05/2021 by looking at the direction (called *D*) yielding the maximum semblance over all possible directions in 3D (expected to match the ray direction $\rightarrow D \sim L$ for P-wave, $\rightarrow D \perp L$ for S-wave)
- 169 phases (Pn: 83, Sn: 77, Pg: 3, Sg: 7)
- Processing using the same frequency band as used in the review
- Single window used around each phase (3-3.5 seconds long)




Events from the NORSAR reviewed event bulletin between 01/01/2021 and 20/05/2021

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Grout, B. Dando, P. Naesholm, T. Kværna, Y. Cano

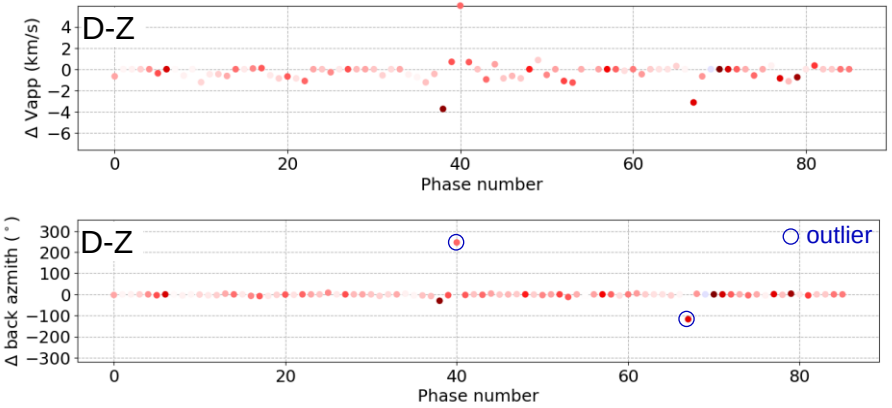


## REVIEWED BULLETIN COMPARISON RESULTS

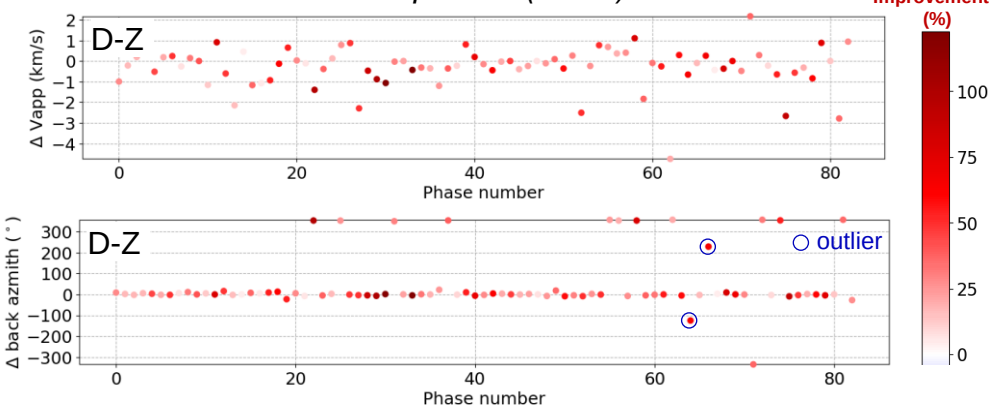
**Semblance improvement**:

- *D*: direction yielding the maximum semblance over all possible directions in 3D
- Back-azimuth and velocity largely consistent for all reviewed phases (4 outliers need investigating)
- D-Z showing significant improvements in semblance for all P- and all S-phases

*P-phases (D ~ L)*




*S-phases (D ⊥ L)*



# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano



## SUMMARY ► ONGOING WORK

- We demonstre the **benefits** of using all 3-components for array processing through two approaches:
  - (3C-ZRT) PMCC automatic events detection and localisation using a single array
    → Higher number of detections (+53%)
    → Higher SNR level
  - Prototyped a continuous (3C-LTQ) F-K detector that uses a grid search for different prospective LQT rotations…
    → verified using a set of phases in NORSAR's reviewed bulletin
- Clear detection **SNR improvements** for **both P-wave and S-wave** using horizontal components

► Comparison with IDCX bulletin and the NORSAR's reviewed bulletin

► Toward an (3C-LTQ) PMCC using **polarization** of P-wave (to estimate the incidence angle)

**!!** Azimuth of polarisation and azimuth of propagation can be different **!!** (e.g. Labonne et al, IUGG 2019)

Refinement of the processing still needed but proof of concept is good…

► Effect of window length and frequency band needs further investigation

► Iterating over finer increments of back azimuth and angle of incidence needs testing

► Apply 3C array processing analysis on **smaller aperture array** (such as SPITS)

**Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation**

C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano



# Thank you for your attention

**References**

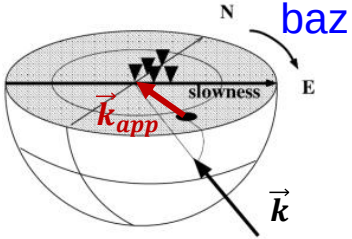

- Labonne C., Cano Y., Sèbe O., Gaffet S. (2019) Improvements of phase detection and identification using 3C array processing, CTBT Science and Technology Conference. (Poster)
- Gibbons, S. J., Schweitzer, J., Kværna, T., & Roth, M. (2019). Enhanced detection and estimation of regional S-phases using the 3-component ARCES array. *Journal of Seismology*, *23*(2), 341-355.
- Labonne C, Cano Y., Gaffet, S., Improvements of phase detection and identification using 3C array processing, 27th IUGG General Assembly, July 2019. (Oral)

# Multicomponent seismic arrays: demonstrating their potential for improved event detection and characterisation

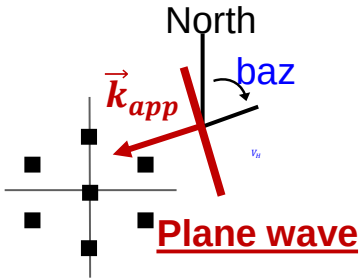
C. Labonne (claire.labonne@cea.fr), C. Groult, B. Dando, P. Naesholm, T. Kværna, Y. Cano

CTBTO PREPARATORY COMMISSION

## FK/PMCC ARRAY PROCESSING PRINCIPLE

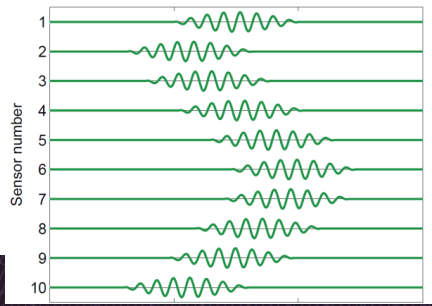


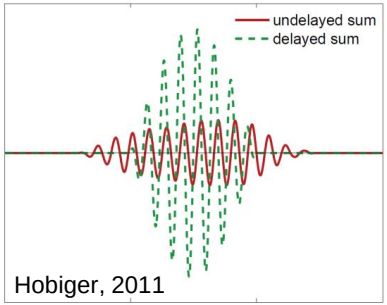

- → Planar wave front propagation
- → Recovering propagation parameters horizontal velocity ($V_H$) and direction (baz) ⇨ $\vec{k}_{app}$
- → Well adapted with time-fequency decomposition ⇨(t-f- $\vec{k}_{app}$)




### FK (frequency-wavenumber)

- Time delays estimated for different given $\vec{k}_{app}$ using a plane wave propagation model
- Find the best delay times ( $\vec{k}_{app}$ ) to get the largest delayed sum of signals amplitude → Grid search



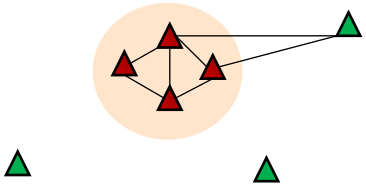




### PMCC (Progressive Multi-Channel Cross-Correlation)

- Time delays for each couple of stations ($\Delta t_{ij}$) by cross-correlation
- Detection criterion: CONSISTENSY

$$\Delta t_{ij} + \Delta t_{jk} + \Delta t_{ki} = 0$$

- IF DETECTION: compute propagation parameters using a plane wave propagation model
- Progressivity:



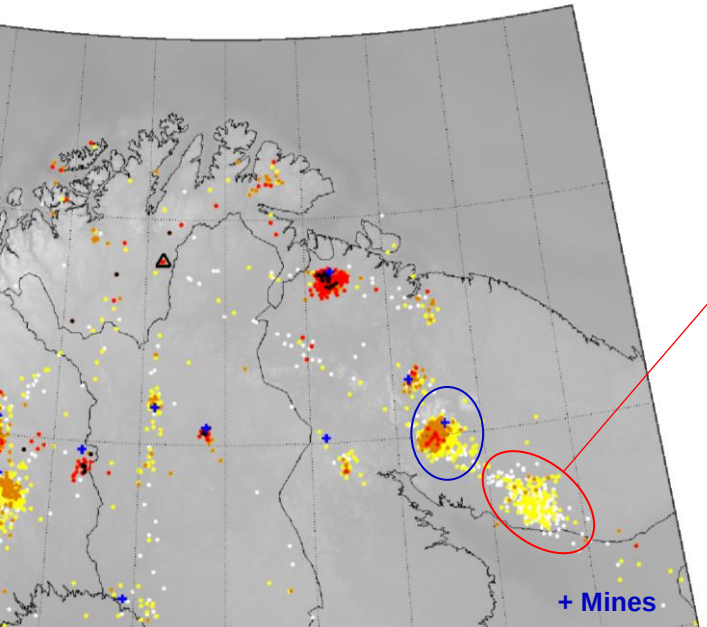
Cansi, 1995

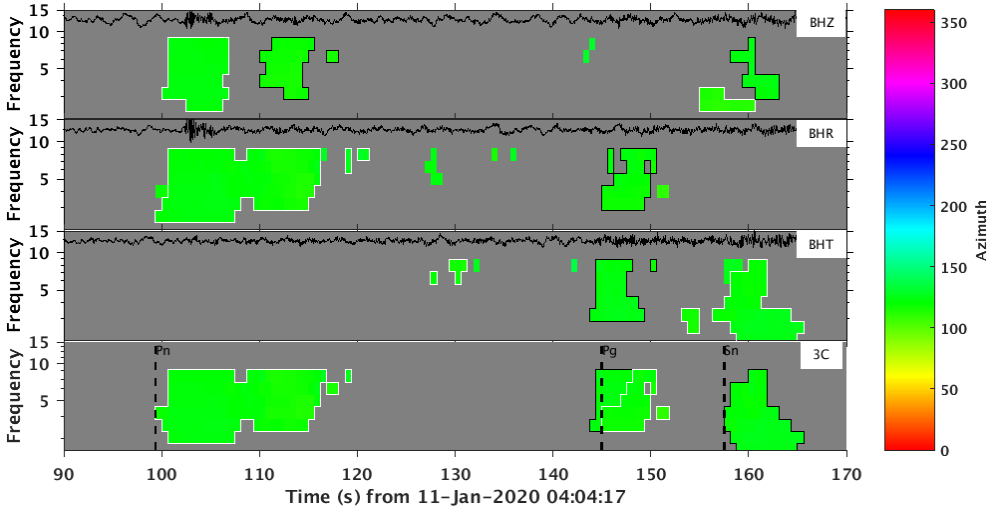
Multicomponent seismic array
for improved event dete

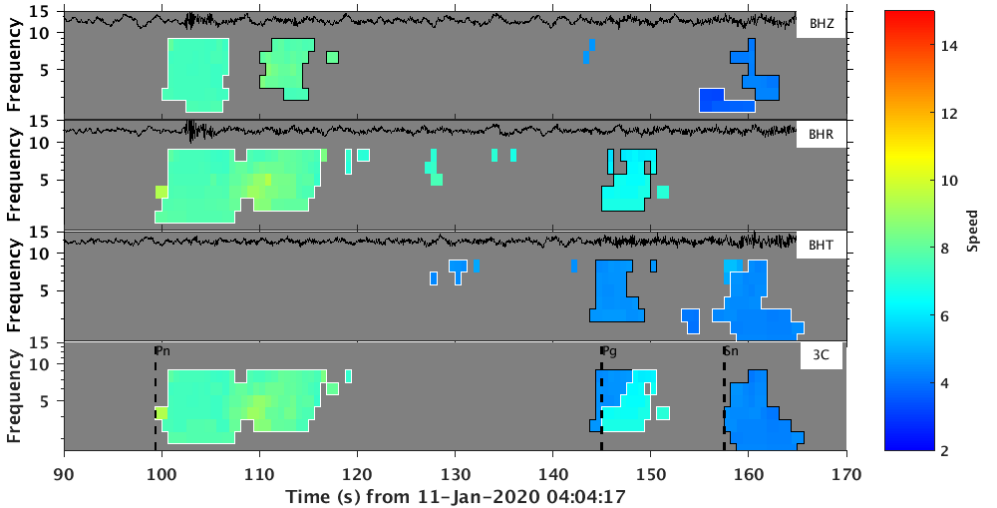
C. Labonne (claire.labonne@cea.fr), C. Gro

# S-PHASE AUTOMATIC MISIDENTIFICATION

→ double cluster in the direction of some mines



# (3C-LTQ) F-K RESULTS

Event from Kiruna mine recorded at ARCES: 2017-04-22T00:18:30
Theoretical BAZ = 231°
Theoretical incidence:
- Pn: 45°
- Sn: 50° (SV) or 0° (SH)