L'Aquila – 2019

Workshop on Advanced Site Characterization Methods

Making efficient use of three-component recordings in array analysis of ambient vibrations

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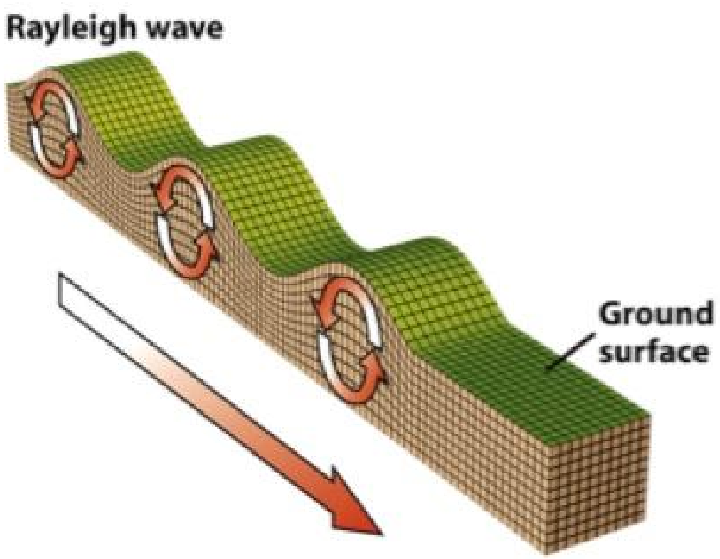
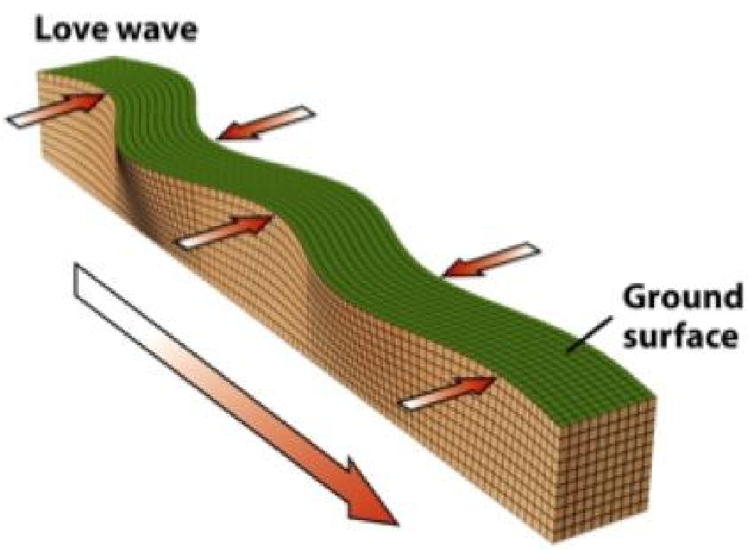
...

Surface Wave Recap

1) Rayleigh waves are polarized on a vertical plane containing the direction of propagation. Their motion can be described by a two perpendicular components (V+R).

2) Love waves are polarized on a horizontal plane containing the direction of propagation. Their motion can be described by a single component (T).

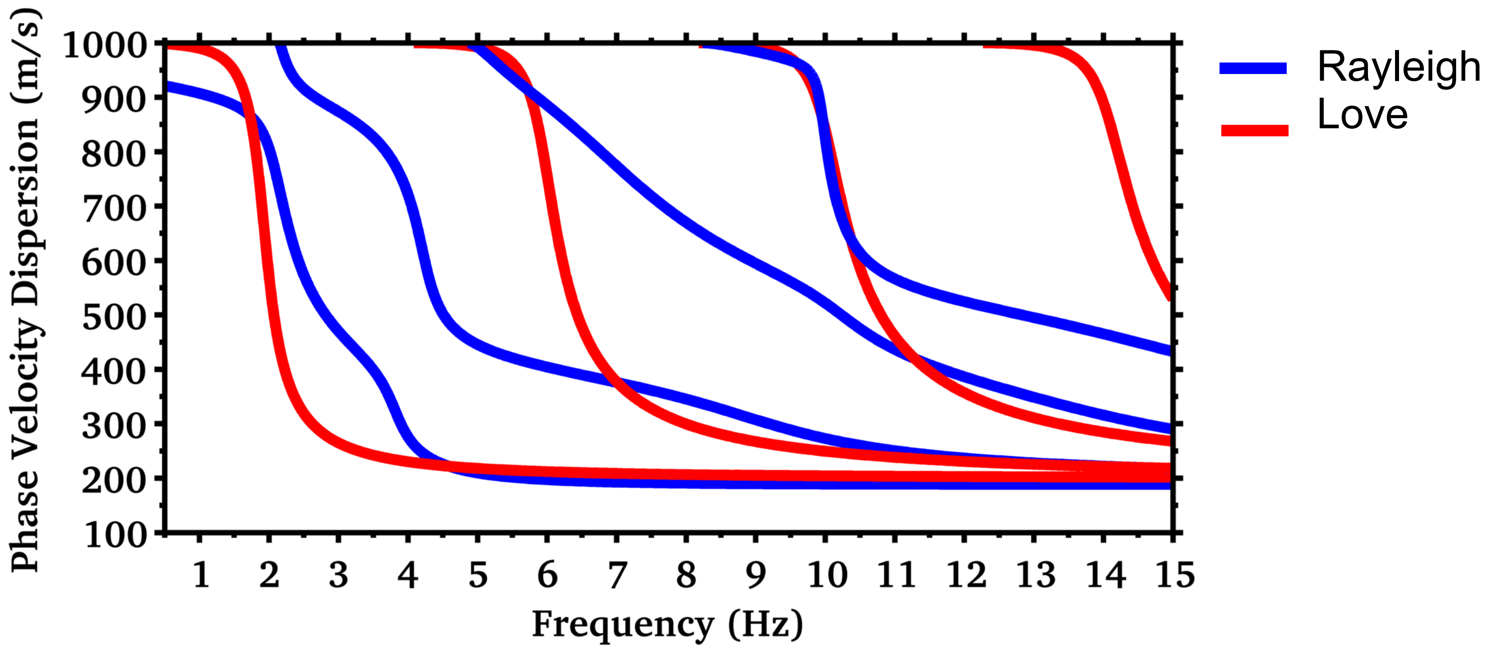




L-R Dispersion Curves

Both Rayleigh and Love waves are **dispersive in heterogenous media** (propagation velocity varies with frequency), however, dispersion pattern can be quite different for the same site.

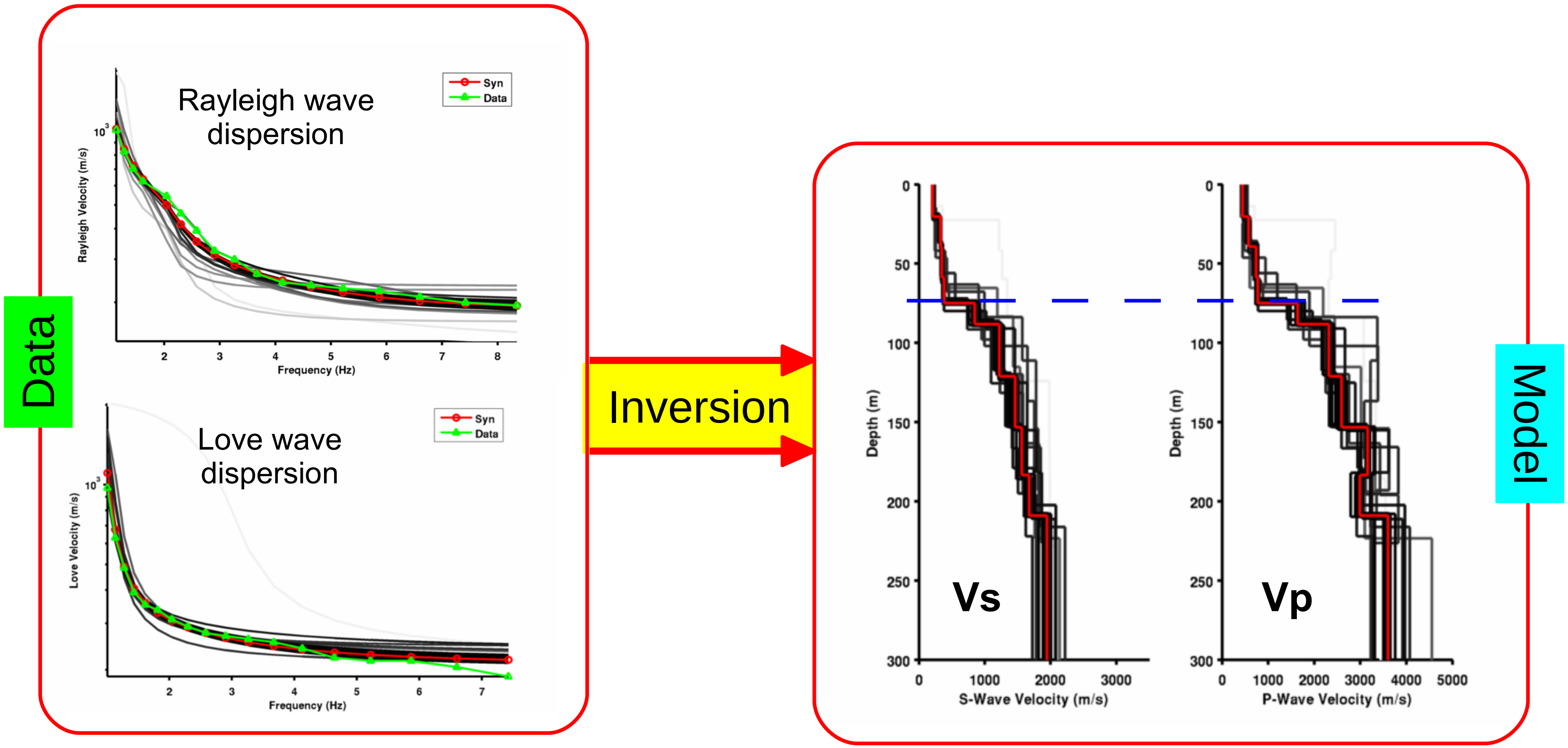
This is due to the different **mechanism of generation** of the two surface wave types (P-SV and SH interference → different dependency to Vp and Vs).



Surface Wave Inversion

Inversion of surface wave dispersion curves is a highly **non-linear** and **non-unique problem**, which often lead to erroneous solutions in case of insufficient data constraints.

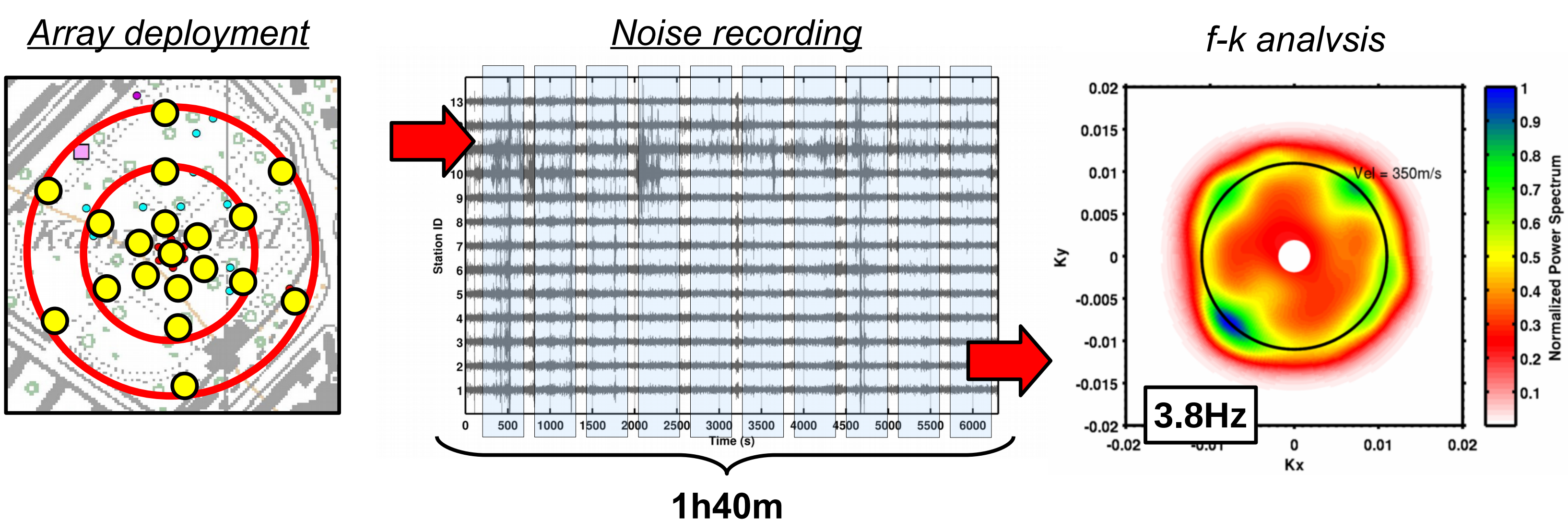
Joint (or combined) inversion of multiple datasets provides an effective way to decrease the non-uniqueness of the problem, leading to a more reliable representation of the soil structure.



Ambient Vibrations

We know that Ambient Vibrations (remember, not just noise…) are largely constitute by **surface waves**, with a minor (although not negligible) contribution of body waves.

Array analysis techniques (either F-K and/or SPAC) are nowadays the most effective mean to retrieve surface wave dispersion information from ambient vibrations.



Vertical vs. Horizontal Motion

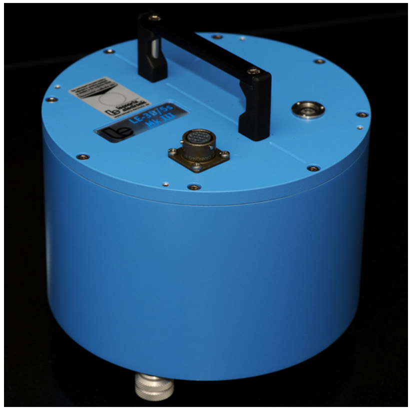
Historically, f-k surface wave dispersion analysis has been done for a long time mostly for Rayleigh waves only…

Why?

→ F-k techniques has been widely developed using equipment for shallow geophysical prospection, using array of geophones

→ the majority of "standard" geophones are just vertical sensors, because P-wave arrivals are the principal target of investigation (reflection and refraction seismic).

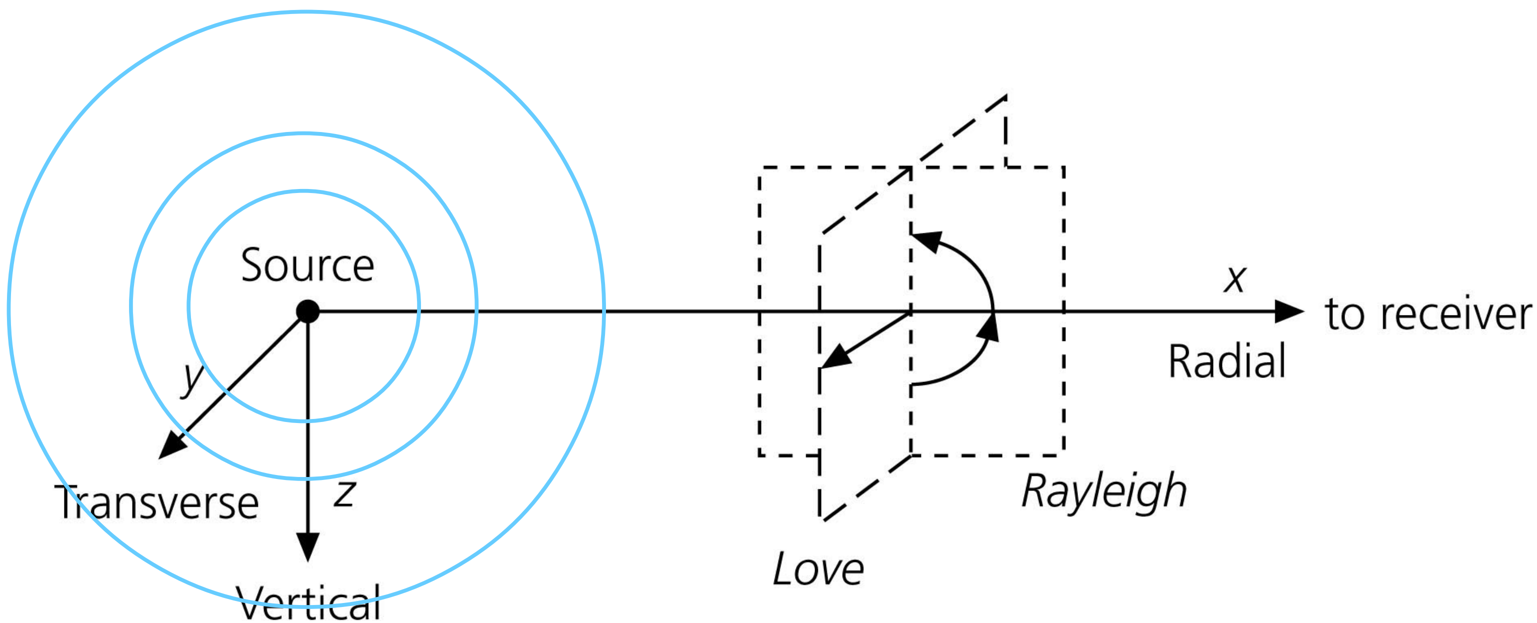
→ Practically, only few institutions had the necessary equipment to analyze and process the full three component ground motion.



Using Horizontal Components

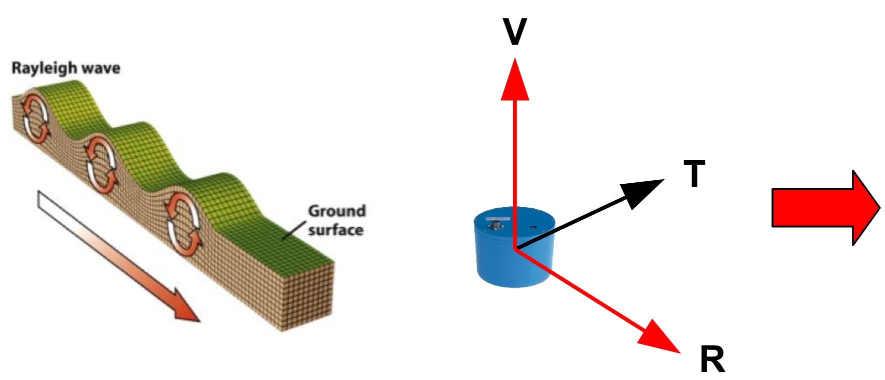
Note that processing the horizontal component of surface waves (R=radial and T=transversal) is "in principle" very simple.

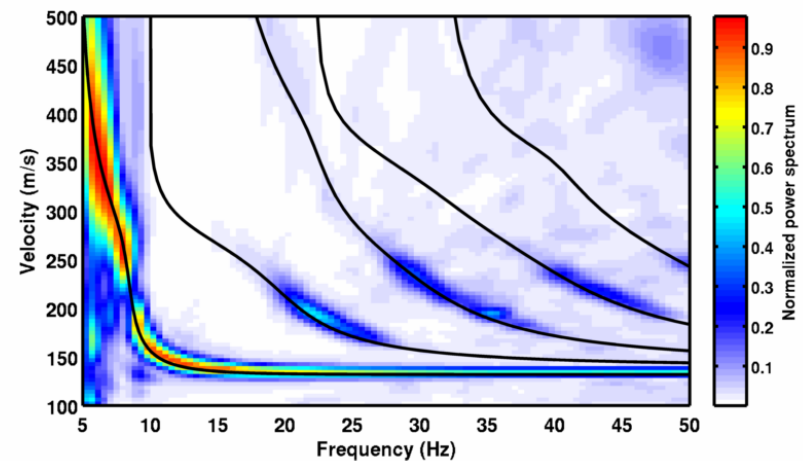
Given a specific direction of propagation, the Raleigh and Love wave contributions to the ground motion are **ideally fully separable**, as they should not interact during propagation (at least for 1d velocity profile....)



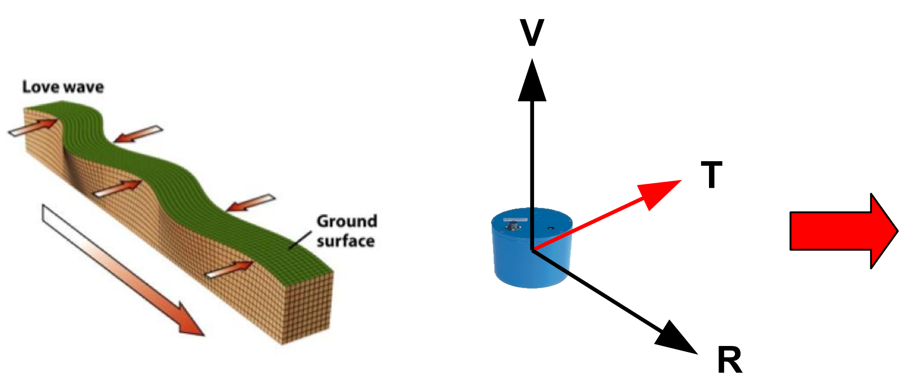
Component-Wise Analysis

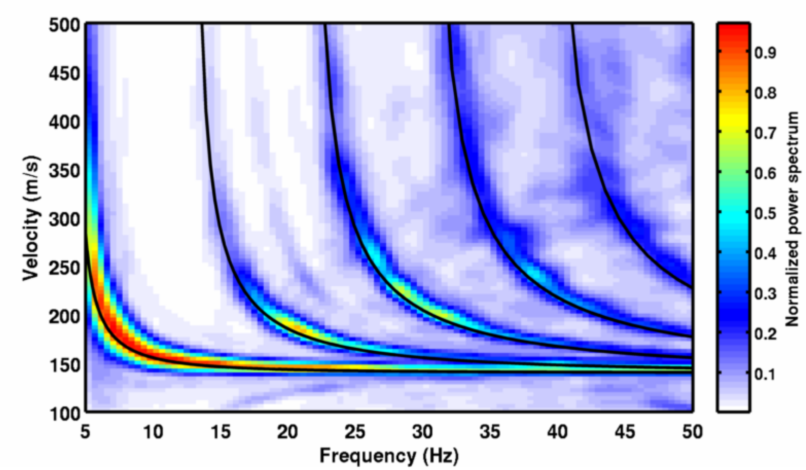
If the direction of propagation is known (e.g. in active seismic, earthquakes), f-k analysis can be performed separately for Rayleigh and Love waves by simple rotation of the horizontal components to the direction of propagation (**DoP**).





Rayleigh wave dispersion





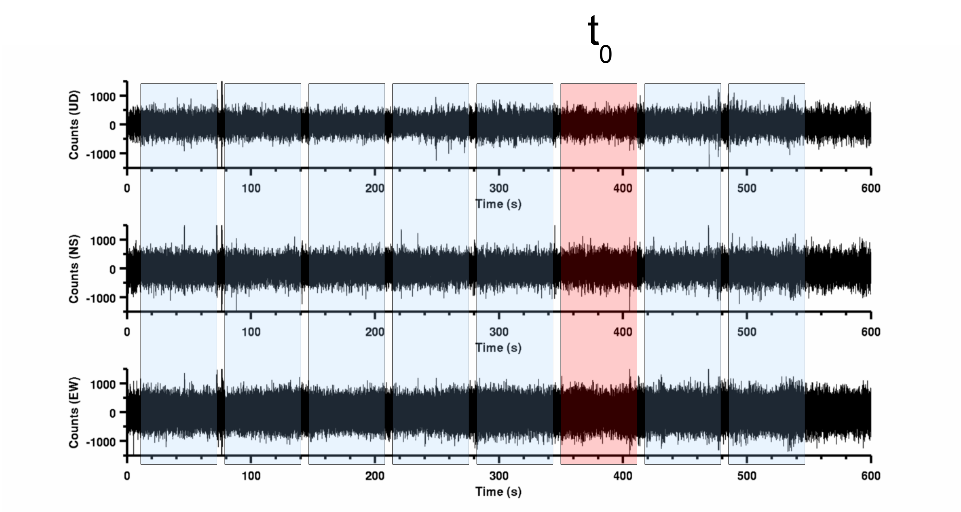
Love wave dispersion

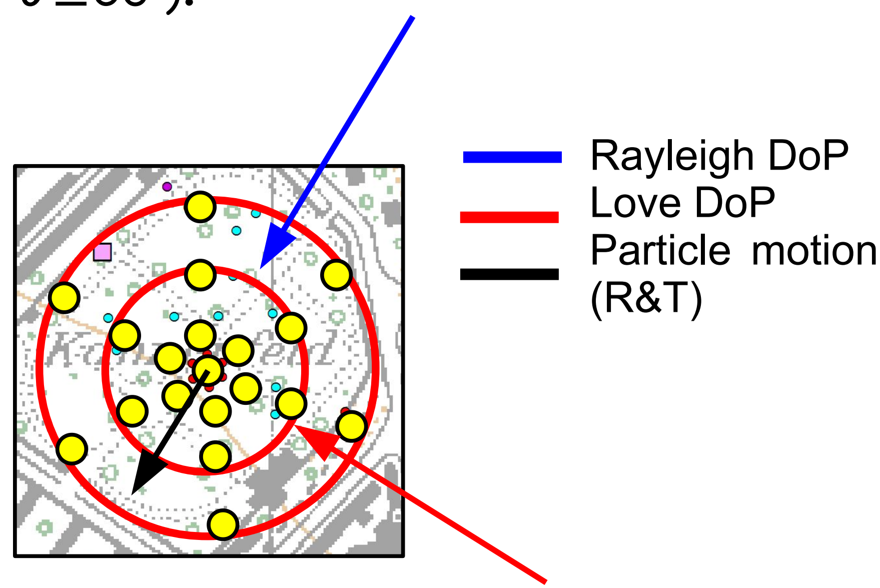
The Ambiguity Problem

However, what happens in case of ambient vibrations? Is the direction of propagation known a priori? ...unfortunately not!

The ambient vibration wavefield is assumed to be a "stochastically uniform" process, mainly composed of surface waves (R+L) impinging from different directions (azimuth) at unknown origin time.

Therefore, at any instant (t_0) there might be an ambiguity on the horizontal motion, which can be generated either by Rayleigh (from azimuth ϑ) or Love waves (from azimuth $\vartheta \pm 90°$).



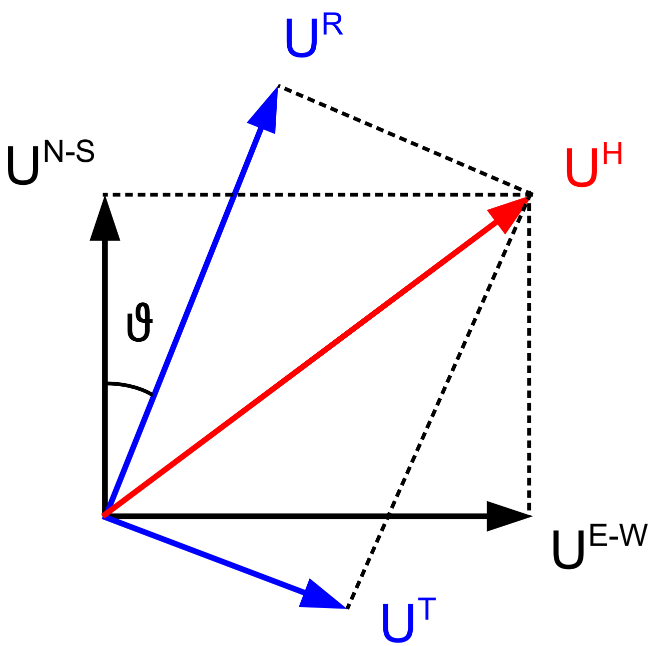


Radial/Transversal Decomposition

This ambiguity can be solved by array analysis using vector composition of the horizontal wave-field:

Radial direction (Rayleigh) → $U^R = U^{N-S} \cdot \cos(\vartheta) + U^{E-W} \cdot \sin(\vartheta)$
Transversal direction (Love) → $U^T = U^{N-S} \cdot \cos(\vartheta + \pi/2) + U^{E-W} \cdot \sin(\vartheta + \pi/2)$

This is also equivalent to a rotation of the reference system to the DoP.

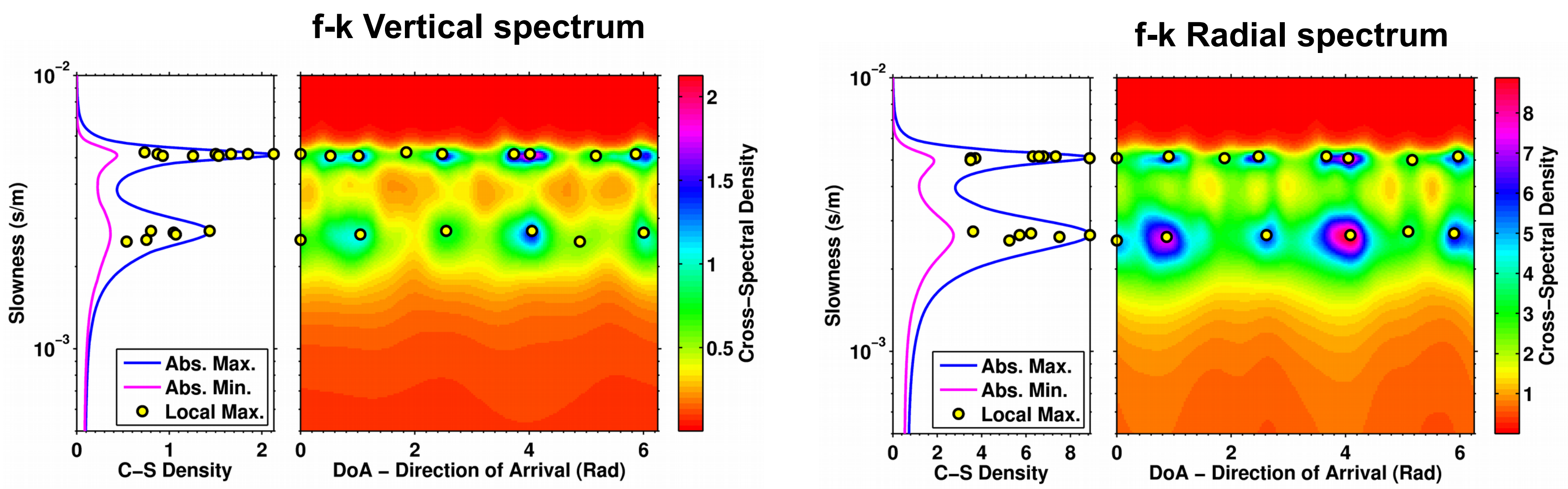


U^H = Actual horizontal motion
U^{N-S},U^{E-W} = Recorded motion on N–S and E–W
U^R,U^T = Radial and Transversal motion (on the rotated system)
ϑ = Assumed direction of propagation (azimuth)

Radial/Transversal Decomposition

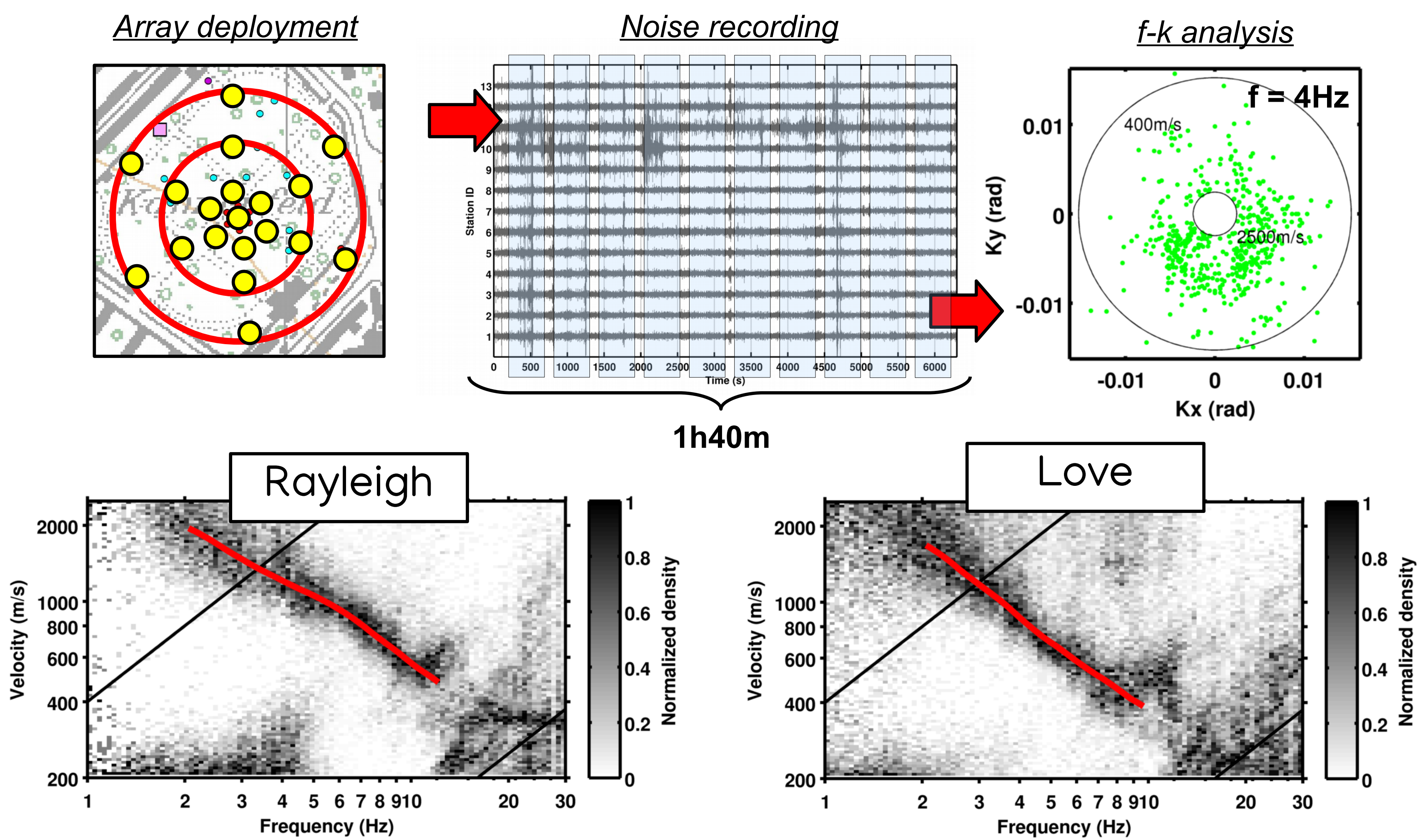
In other words, the observed ground motion is projected to a new ROTATED reference system which is consistent with the assumed direction of propagation.

Since this direction of propagation is unknown a-priori, the rotation is performed for any possible azimuth ϑ where the f-k power spectrum is calculated till a coherency maximum is found.



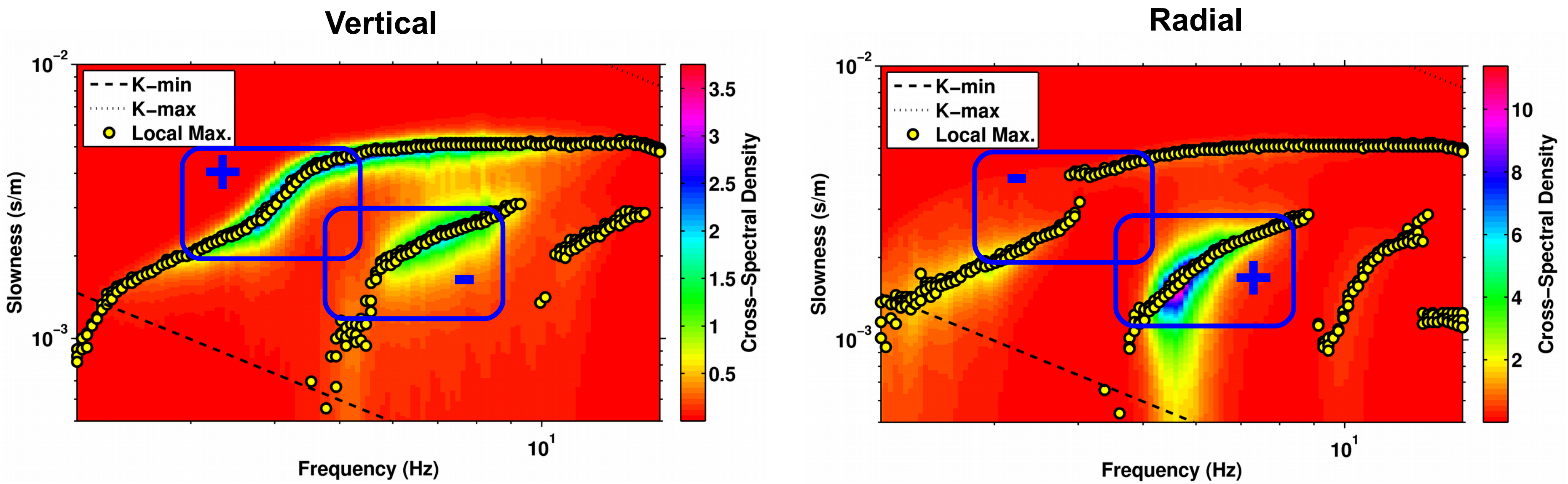
Three-Component f-k

The same procedure is repeated for consecutive time windows, and all the f-k maxima are then collected and statistically analyzed using histogram representation.



Advantages of 3C

1) Combined analysis of the (horizontal-)radial and vertical direction of motion allows to extract the Rayleigh velocity dispersion curves when energy is transferred from one component to the other



2) Love waves provide an unique constraint to invert the Vs velocity profile.

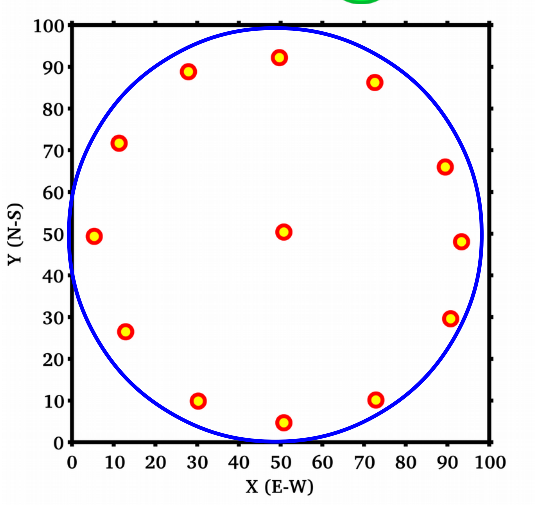
Requirements (1)

To properly perform 3C f-k analysis we need few additional requirements

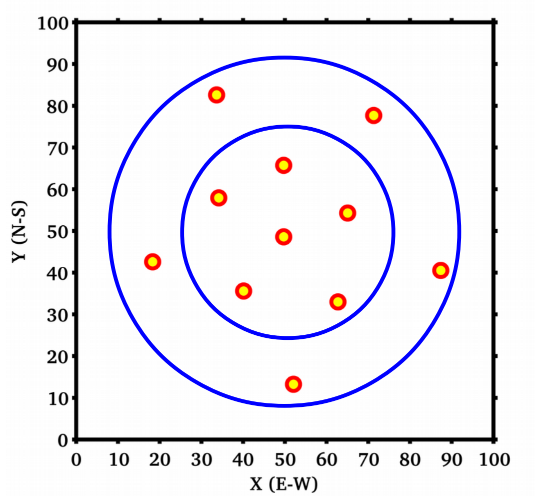
1) Weak requirement

A good azimuthal coverage by using regular array geometries (circular, concentric…). This is generally also suggested for standard f-k, but could be more problematic with 3C where direction of arrivals matters.

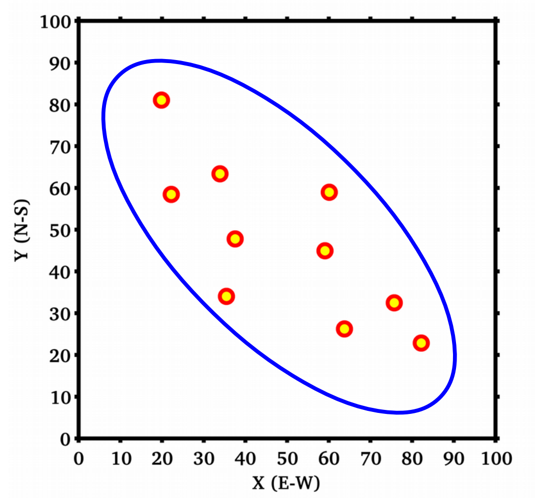
Circular



Concentric



Irregular

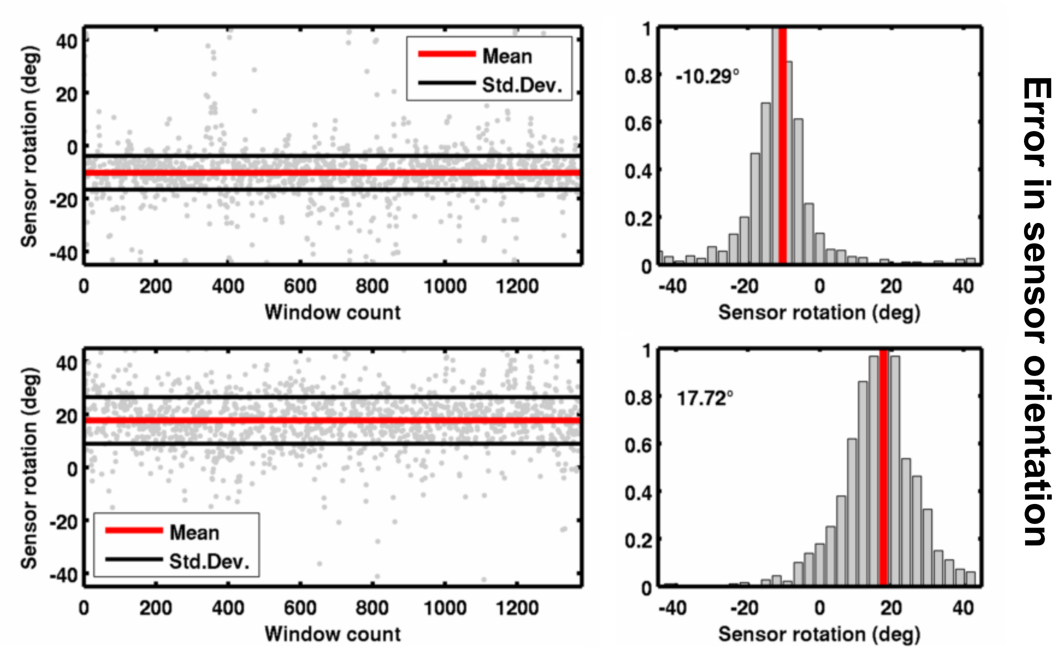


Requirements (2)

2) Strong requirements

– Uniform and precise alignment of the sensors to a common horizontal reference direction (e.g. the magnetic North)

– Precise knowledge of the reference direction with respect of the f-k coordinate system (less problematic with DPGS, critical with manual position measurements)



Breaking the Assumptions

In reality, not all the assumptions needed for 3C f-k are always fulfilled.

Some problems might be caused by:

1) spherical (close) wave-fronts, which implies a not-full separation between R and T components (critical for nearby anthropogenic sources)

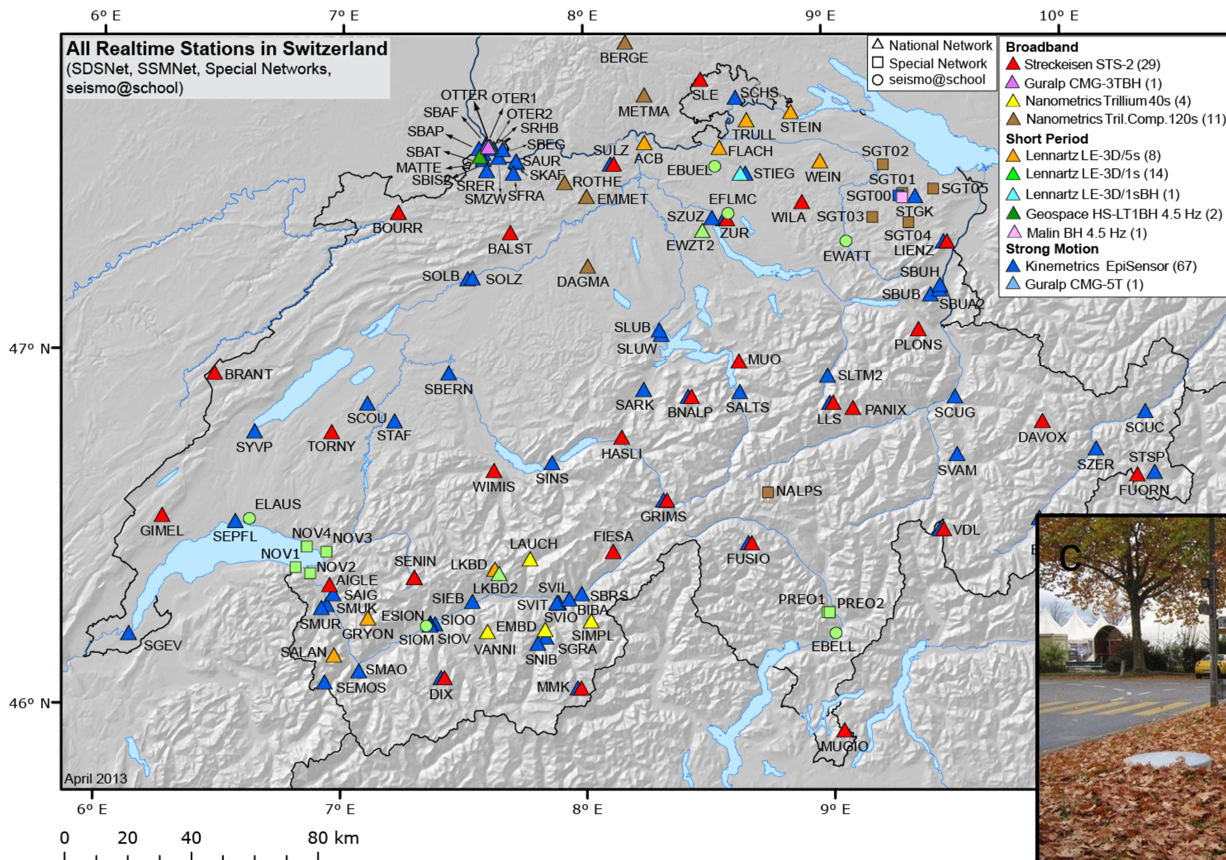
2) non-1D soil structure (assumption also needed for standard f-k)

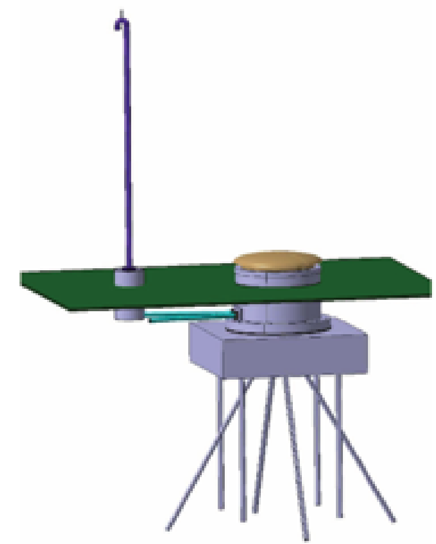
3) anisotropy of the soil properties (not really a problem, also an advantage!)

These problems must be verified during the interpretation phase, to avoid misinterpretation of the modal pattern and biasing of the inverted velocity profiles.

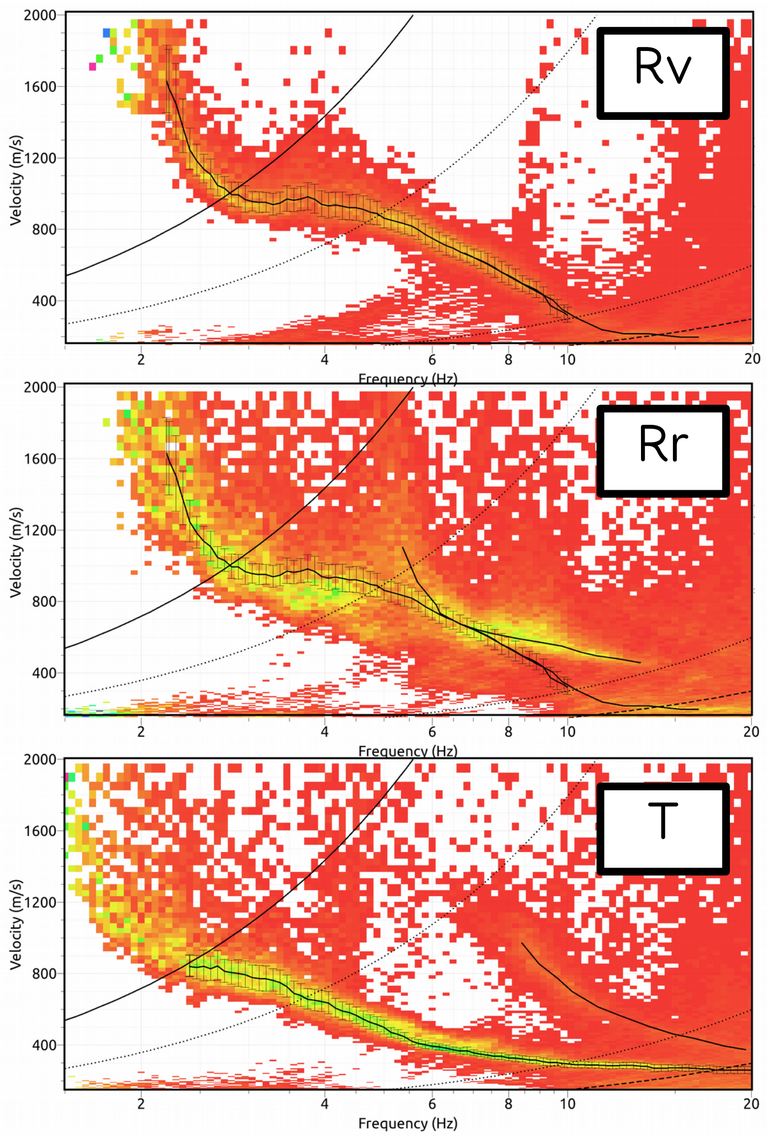
Swiss Networks Characterization

The presented technique has been used for the characterization of many sites of the **Swiss Strong Motion Network** (SSMNet) and the **Swiss Digital Network** (SDSNet), covering a variety of geological conditions, from very hard rock sites to low-velocity sedimentary valleys.





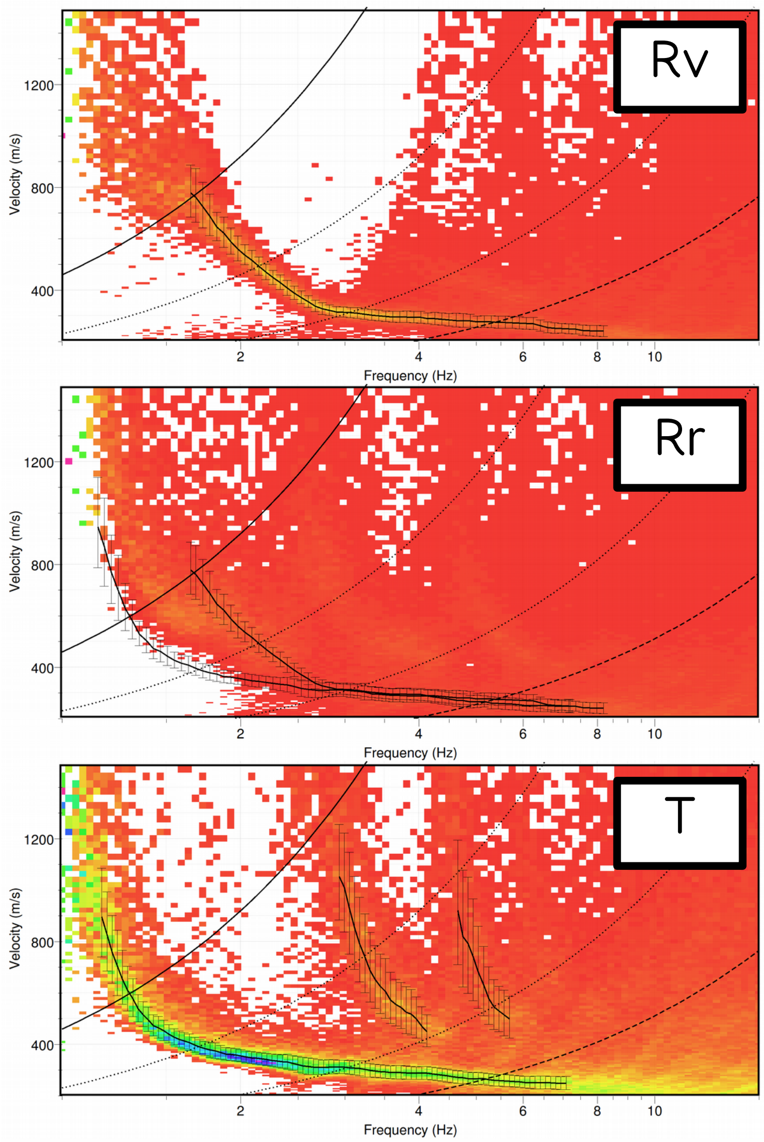
Same Example



Brigue

- Rayleigh wave modal jump (around 7Hz), not clearly identifiable by processing the only vertical component.
- Clear Love wave dispersion pattern with higher mode.

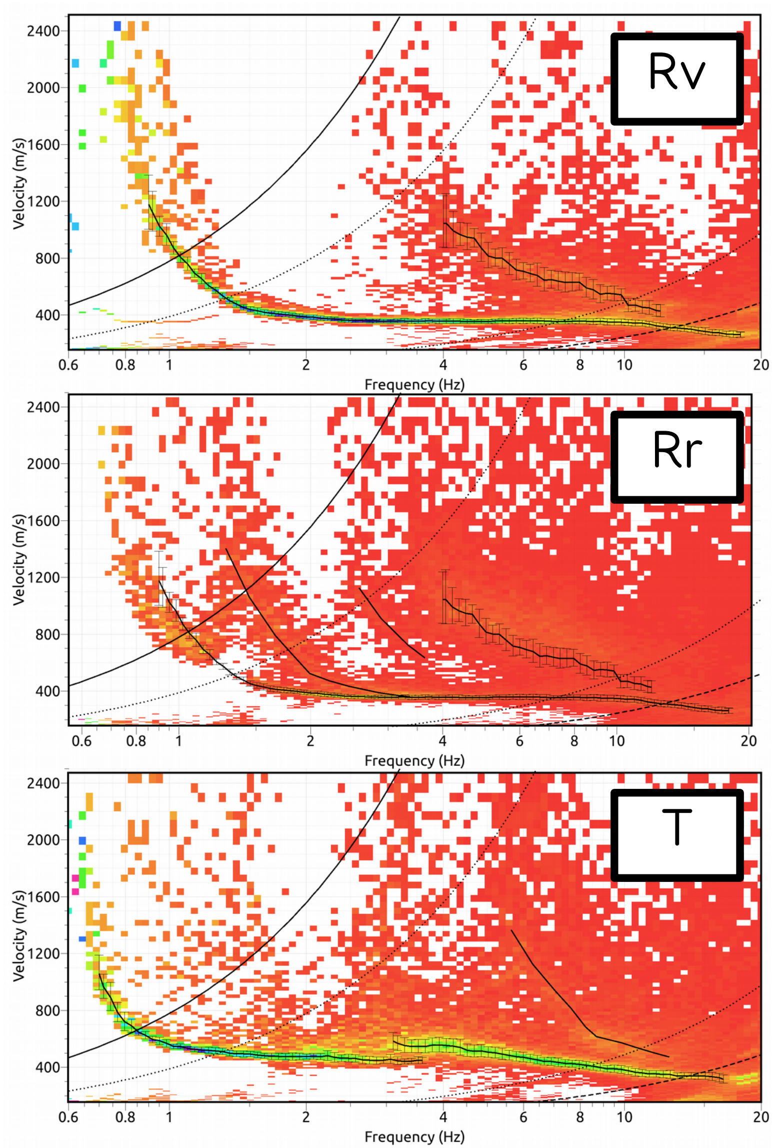
Some Example



Yverdon

- Multimodal dispersion pattern of Love waves
- Rayleigh wave weakly energetic
- Radial component of difficult interpretation (because of Love wave dominance)

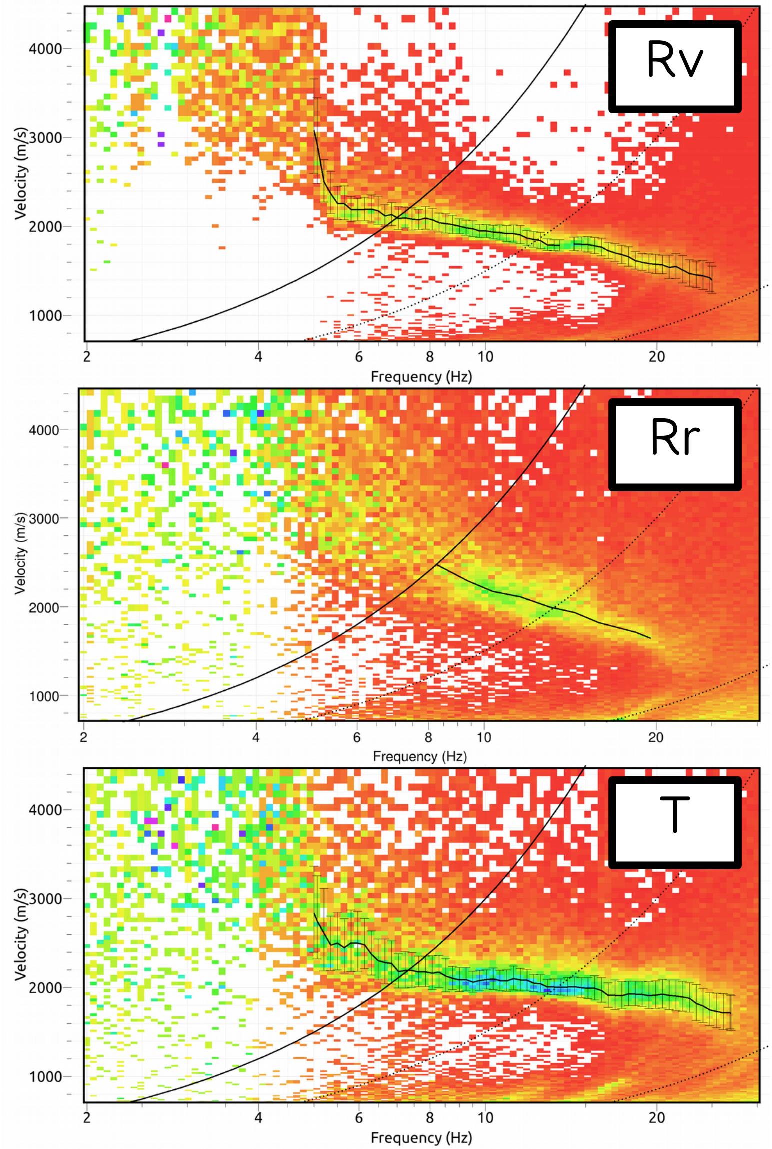
Same Example



Buchs

- Multimodal dispersion pattern of Rayleigh and Love waves.
- Energy exchange between vertical and radial direction of Rayleigh waves.

Some Example

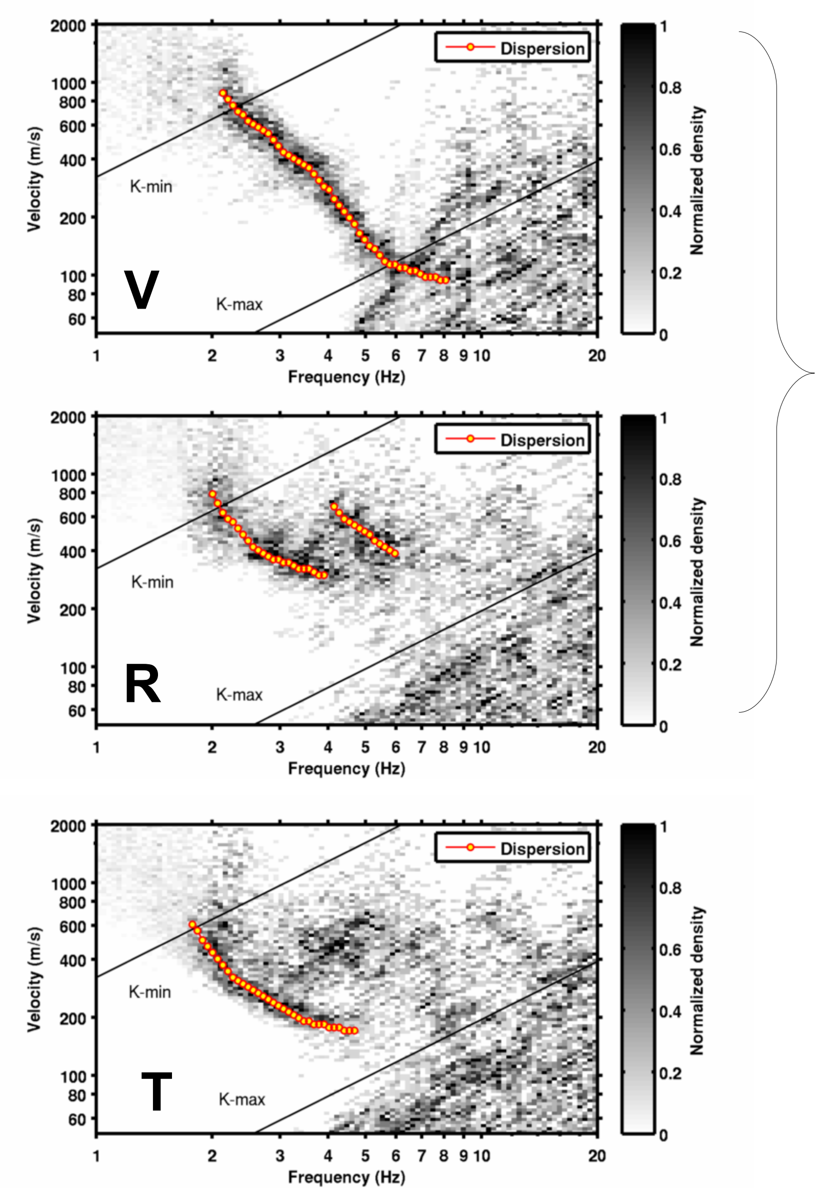


Slub (Lucerne)

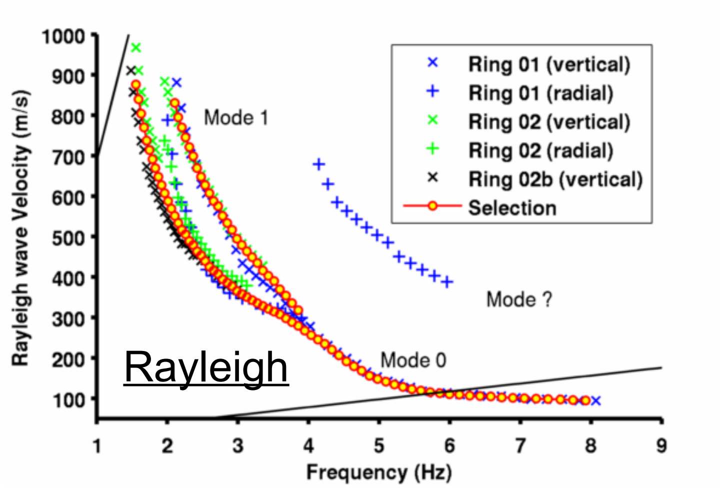
- Rock site example

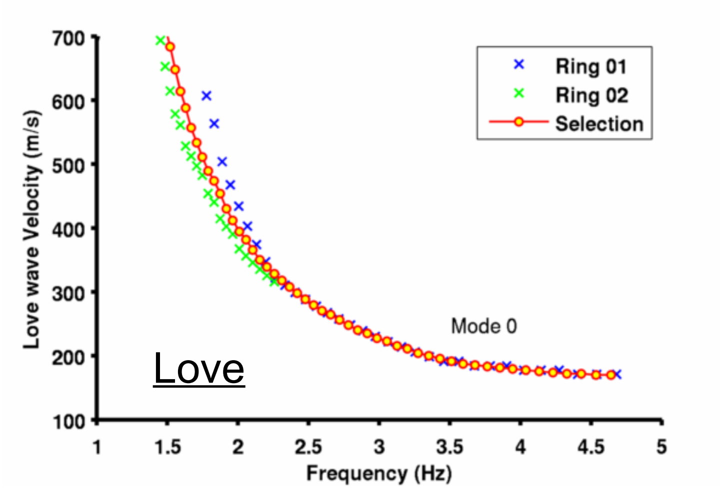
- Radial component of difficult interpretation: higher mode or vertical anisotropy?

Same Example

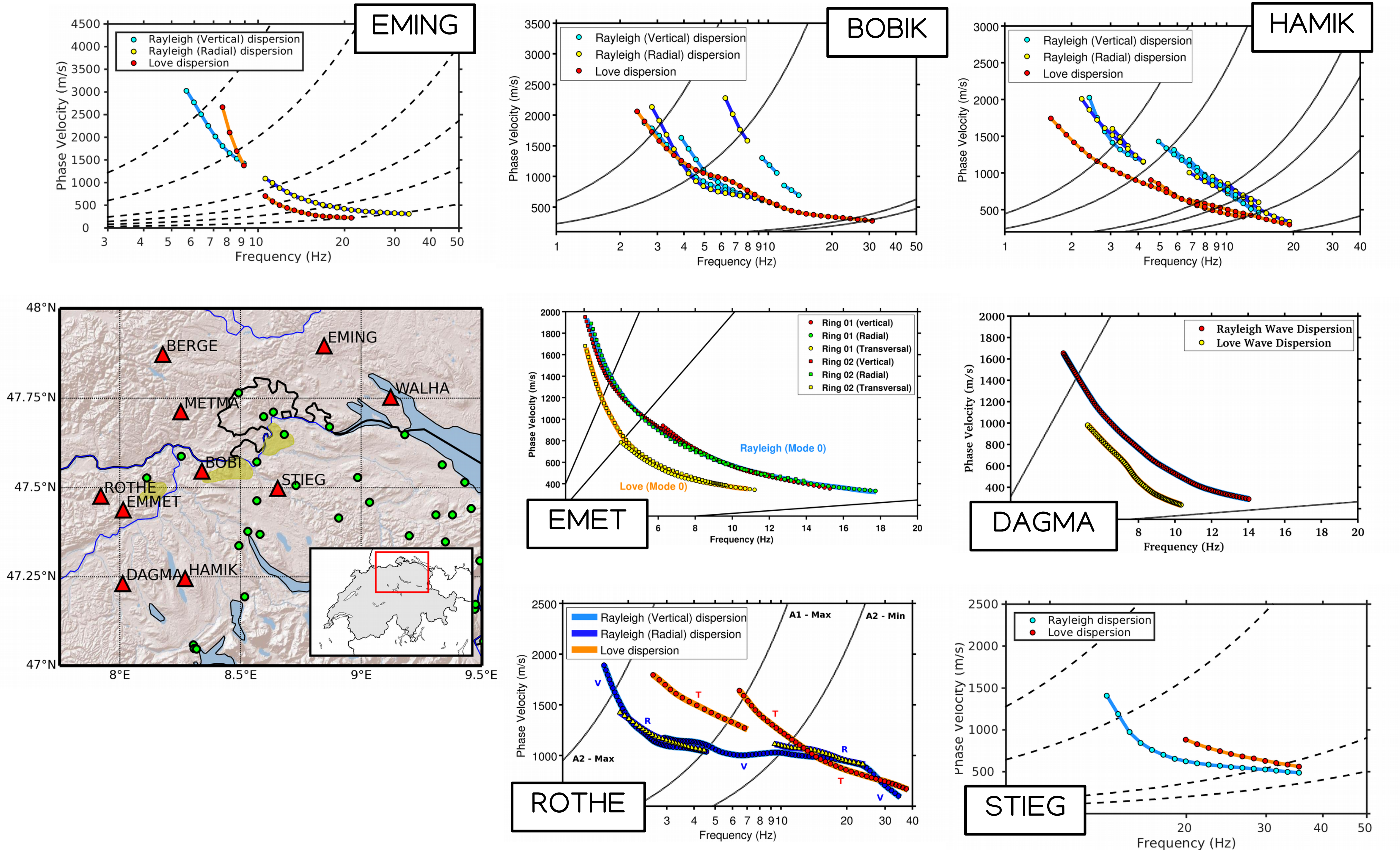


Lucerne (basin)





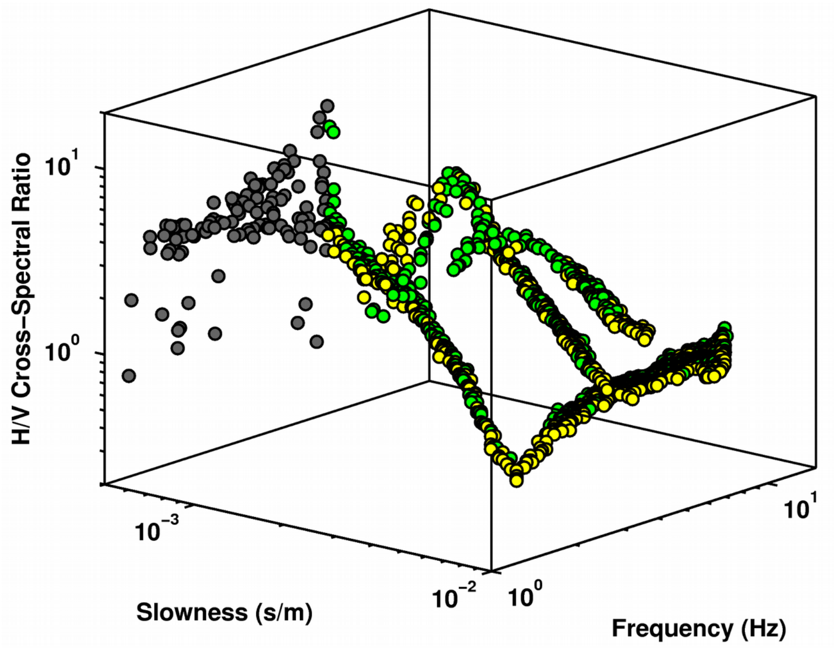
NAGRA Network



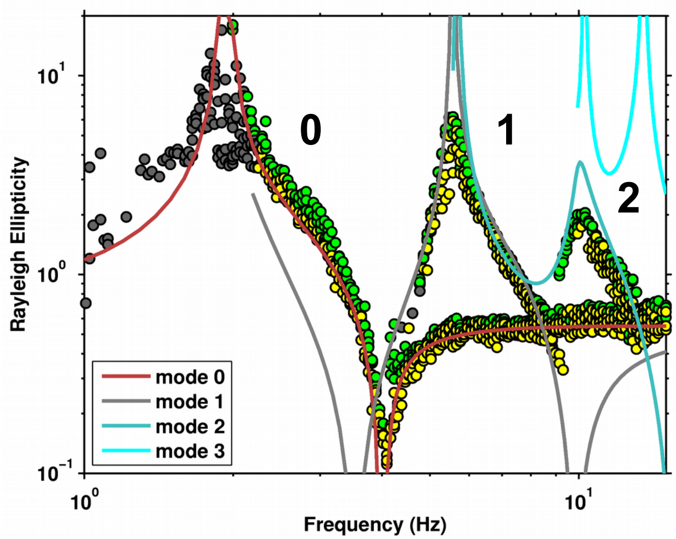
Cross-Spectral H/V Ratio

If a Rayleigh wave mode is identified on the f-k planes, the **amplitude ratio between the horizontal-radial and the vertical f-k power-spectra** will represent its **ellipticity**.

Thus, if several modes of propagation are identified in the f-k planes, then the Rayleigh ellipticity function can be extracted *for each mode separately*



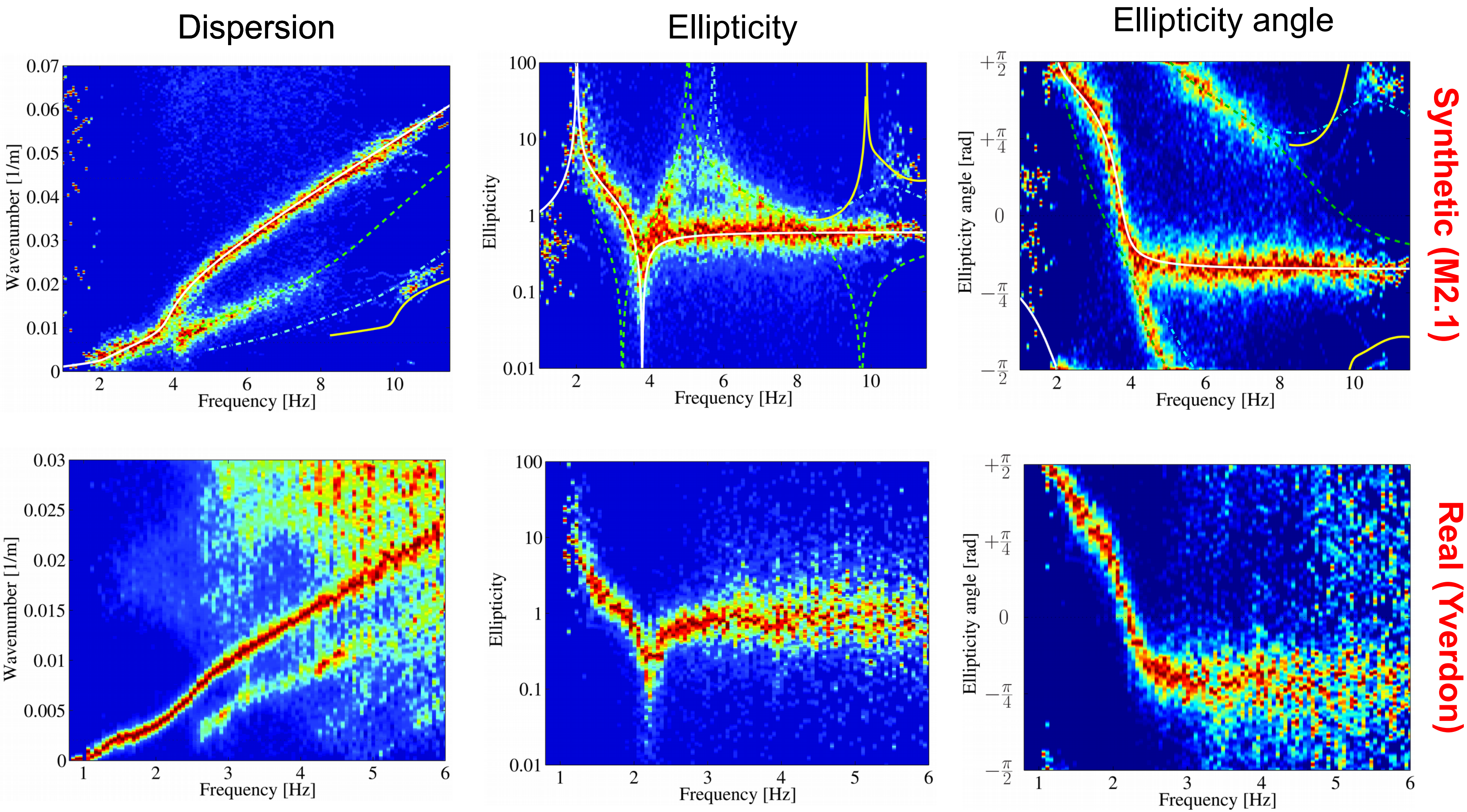
SESAME Dataset M2.1



- *Picking from vertical component*
- *Picking from radial component*
- *Outside resolution limits*

Advanced 3C Techniques

Factor-graph decomposition of ambient vibration wave-field
(Maranò et al. 2012)



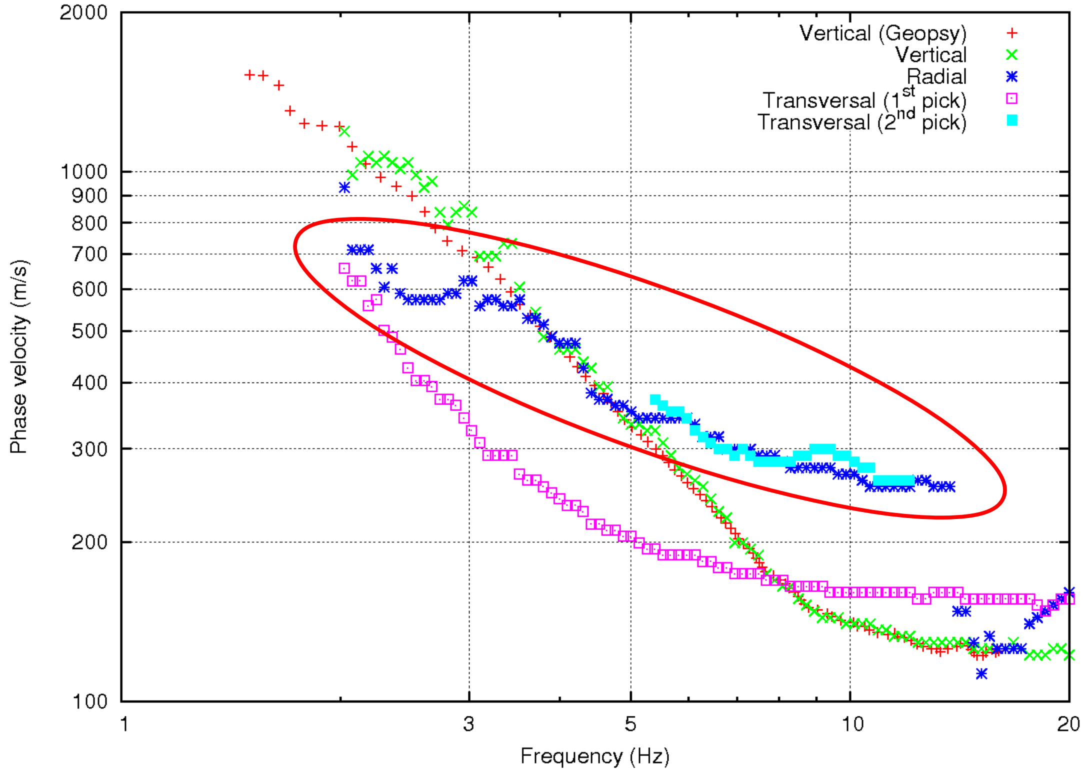
Conclusions

Thank you!

Title

Text

Some Example



Visp

– Smearing of Horizontal components

– Modal jump