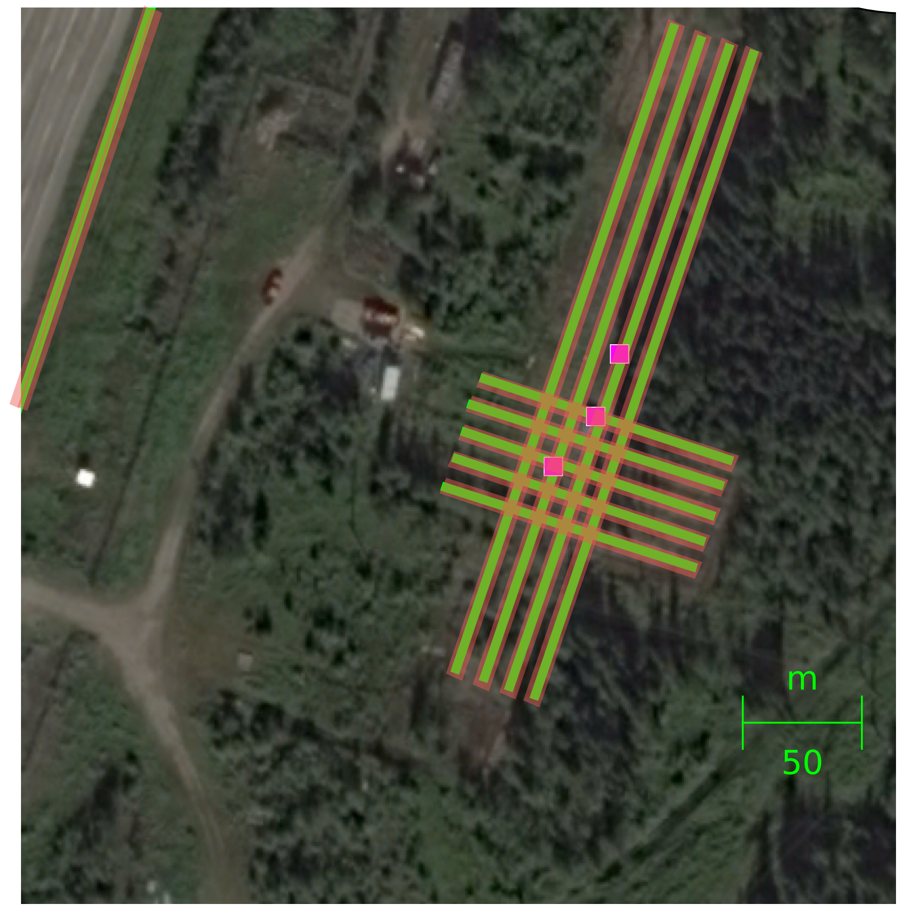
Interferometry on 2D DAS Arrays

Eileen Martin
coauthor: Biondo Biondi

Richmond Field Station (LBL, Corps of Engineers)

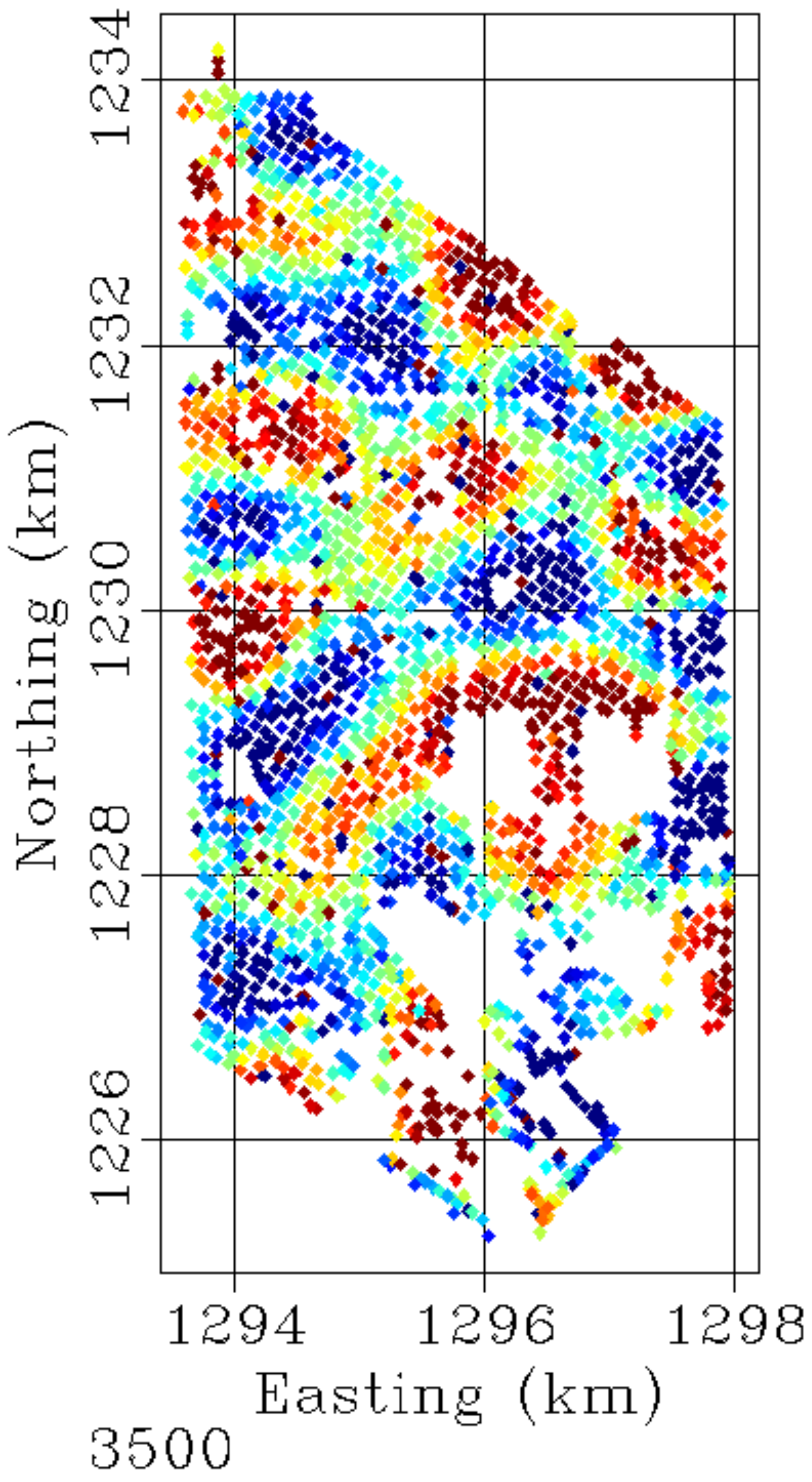
Fairbanks, AK (LBL, Corps of Engineers)



SDASA-1

Ambient noise interferometry can reduce costs

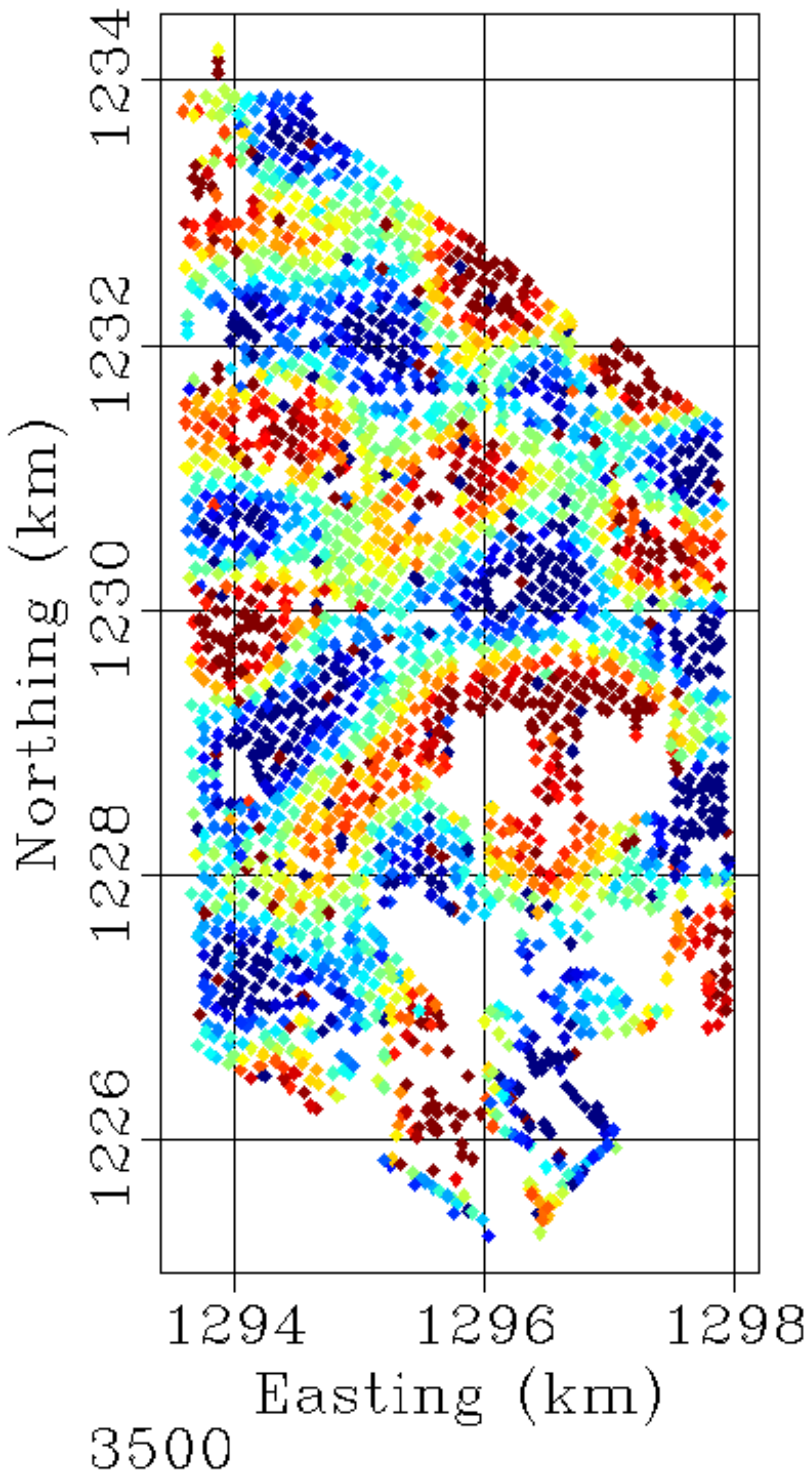
noise ~1 Hz



Example from Jason Chang (Stanford), data c/o Nodal Seismic

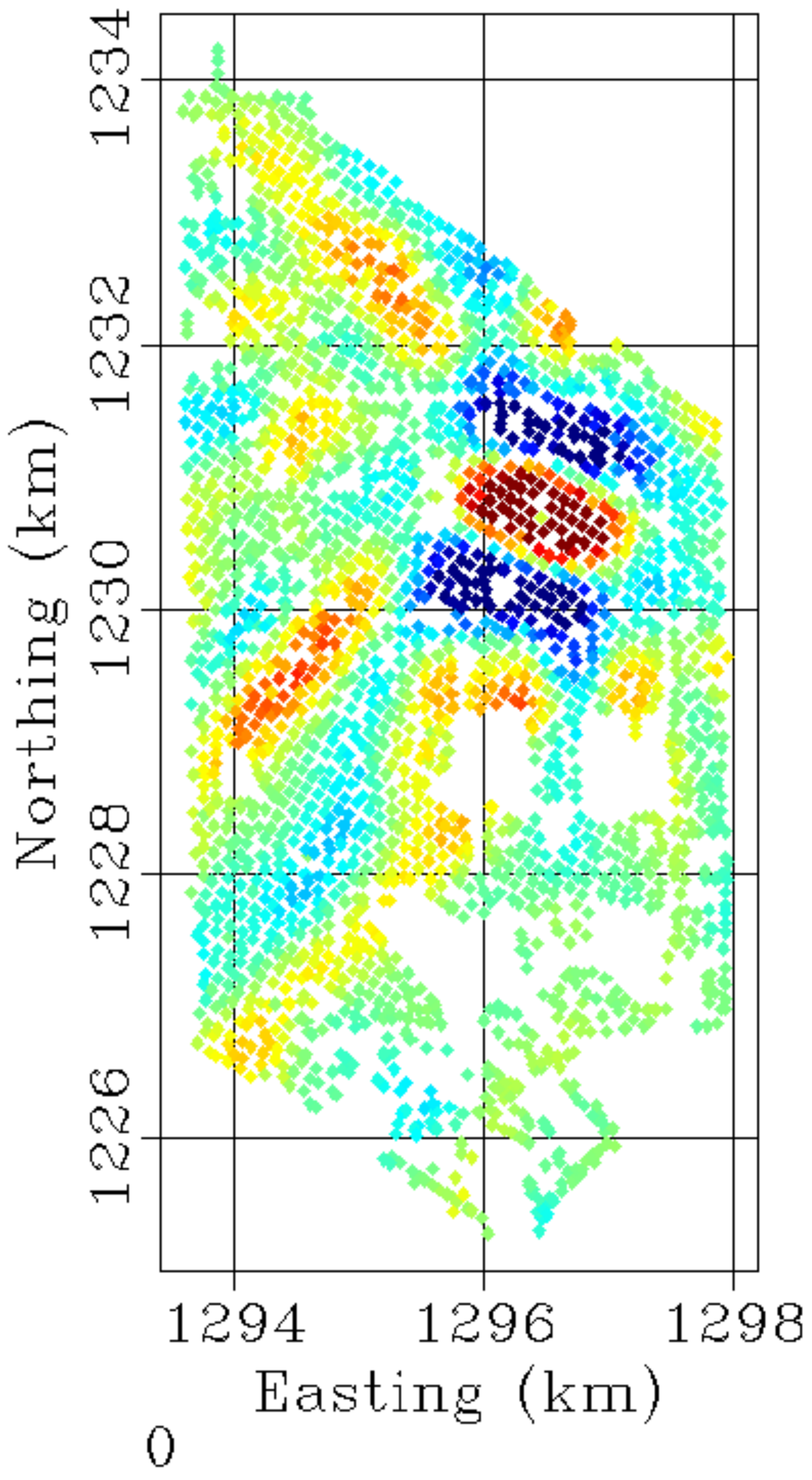
Ambient noise interferometry can reduce costs

noise ~1 Hz



correlations between windows of noise

signal mimicking active survey



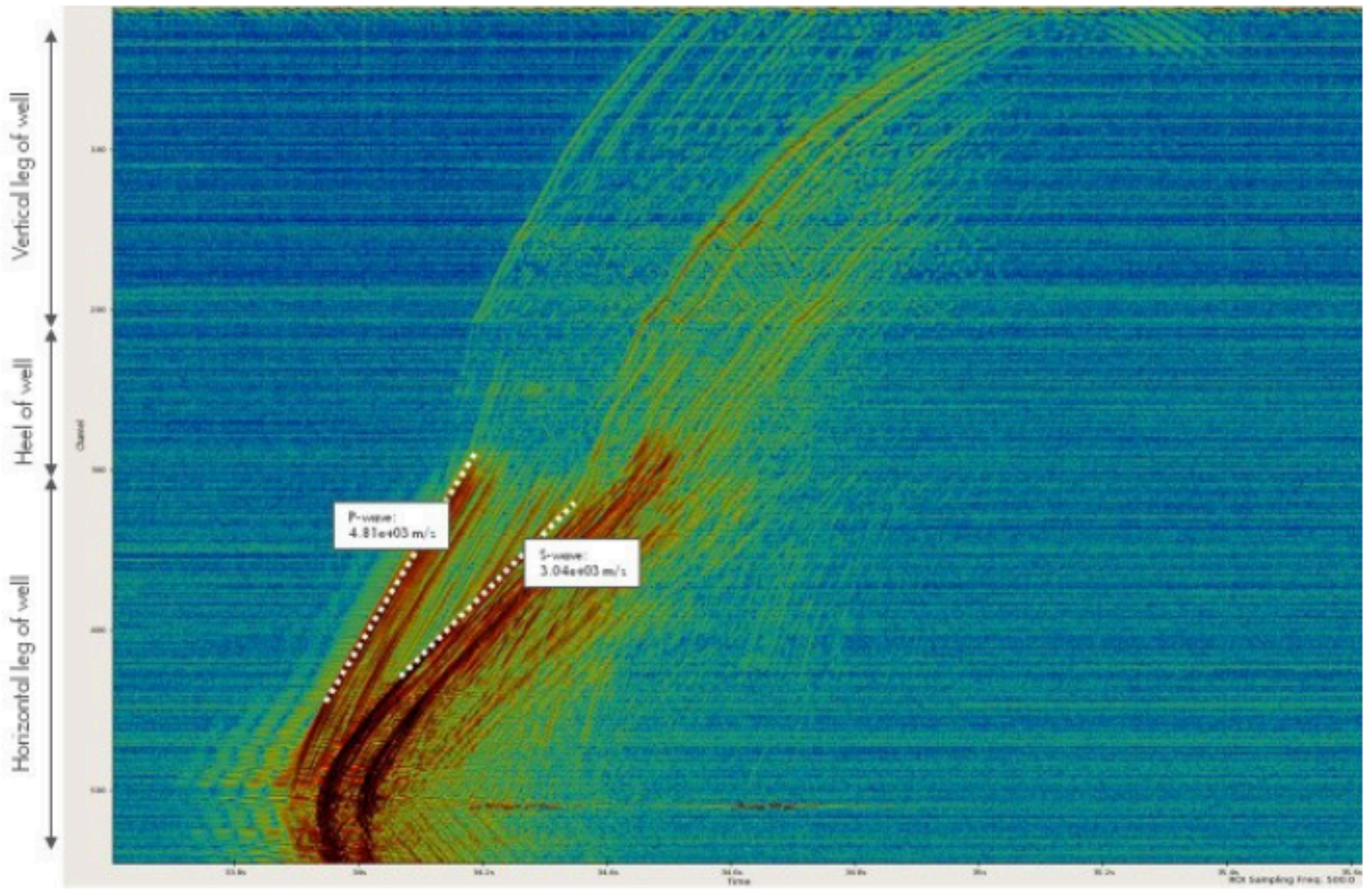
benefits:

no source crew cost

less time than waiting for earthquakes

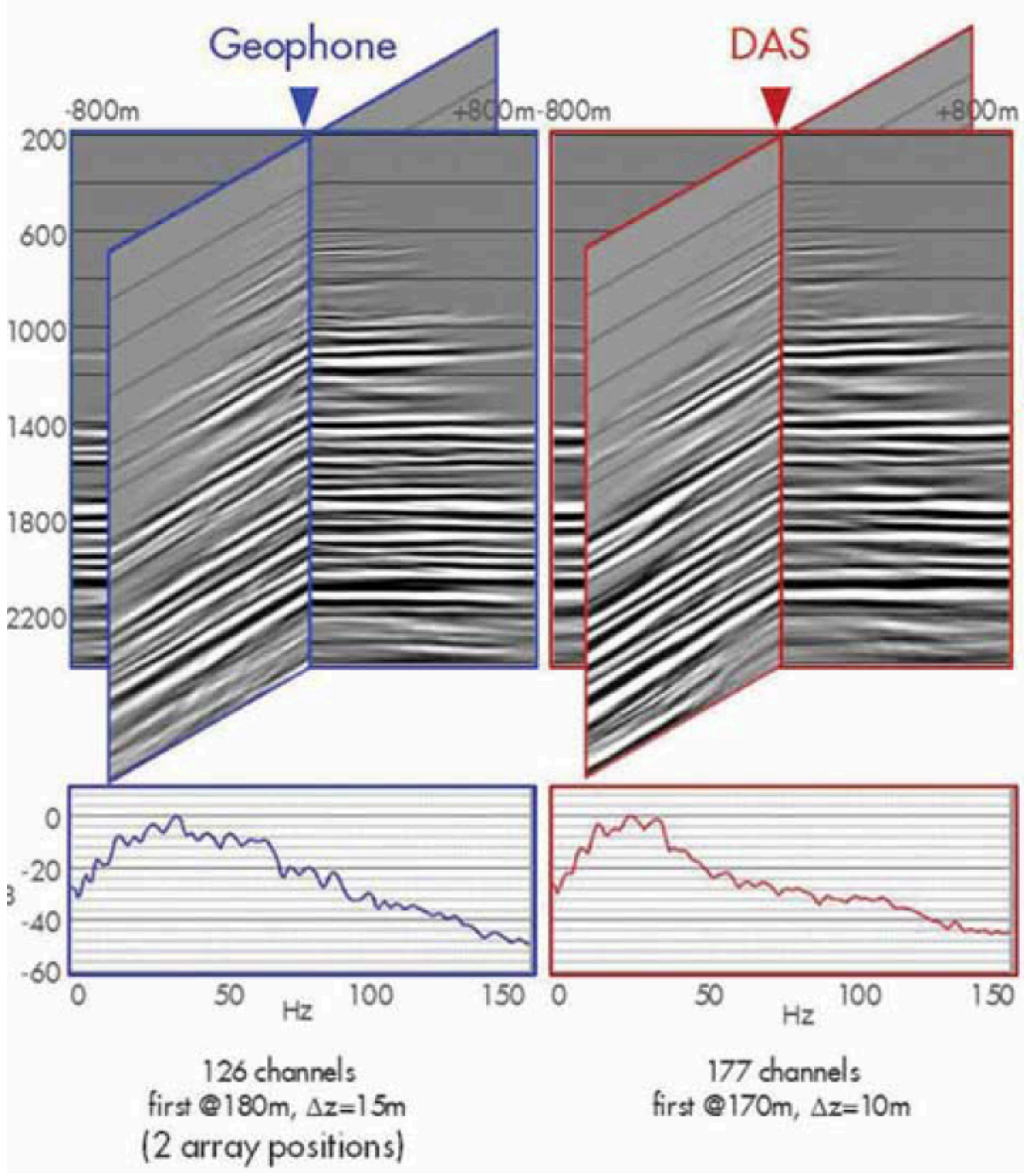
Example from Jason Chang (Stanford), data c/o Nodal Seismic

DAS is being used to lower costs in oil & gas



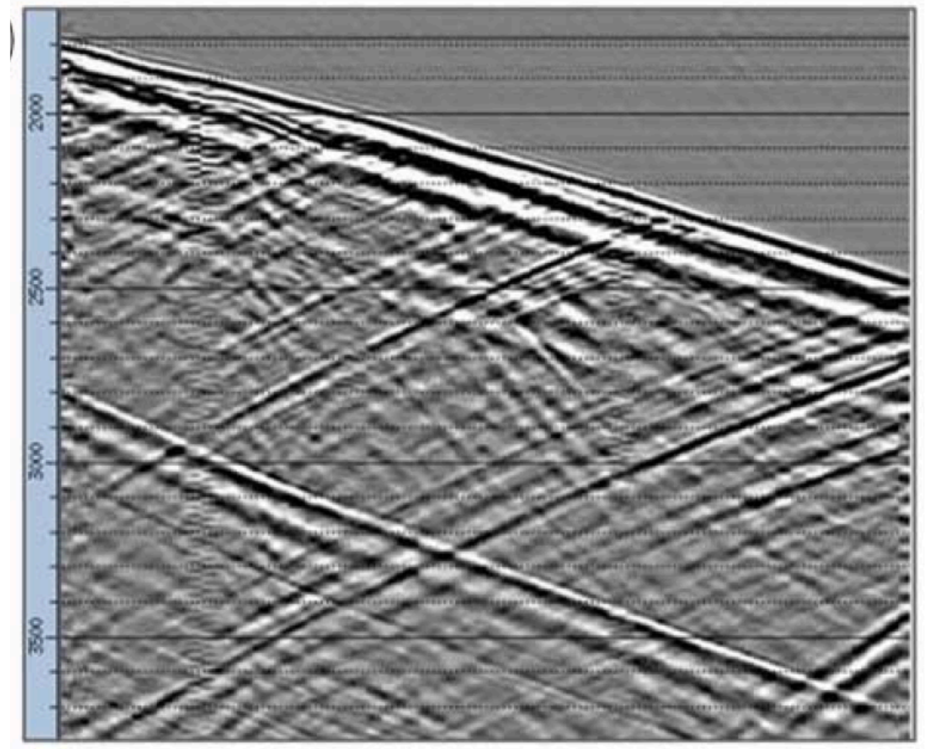
Microseismic monitoring with full well coverage

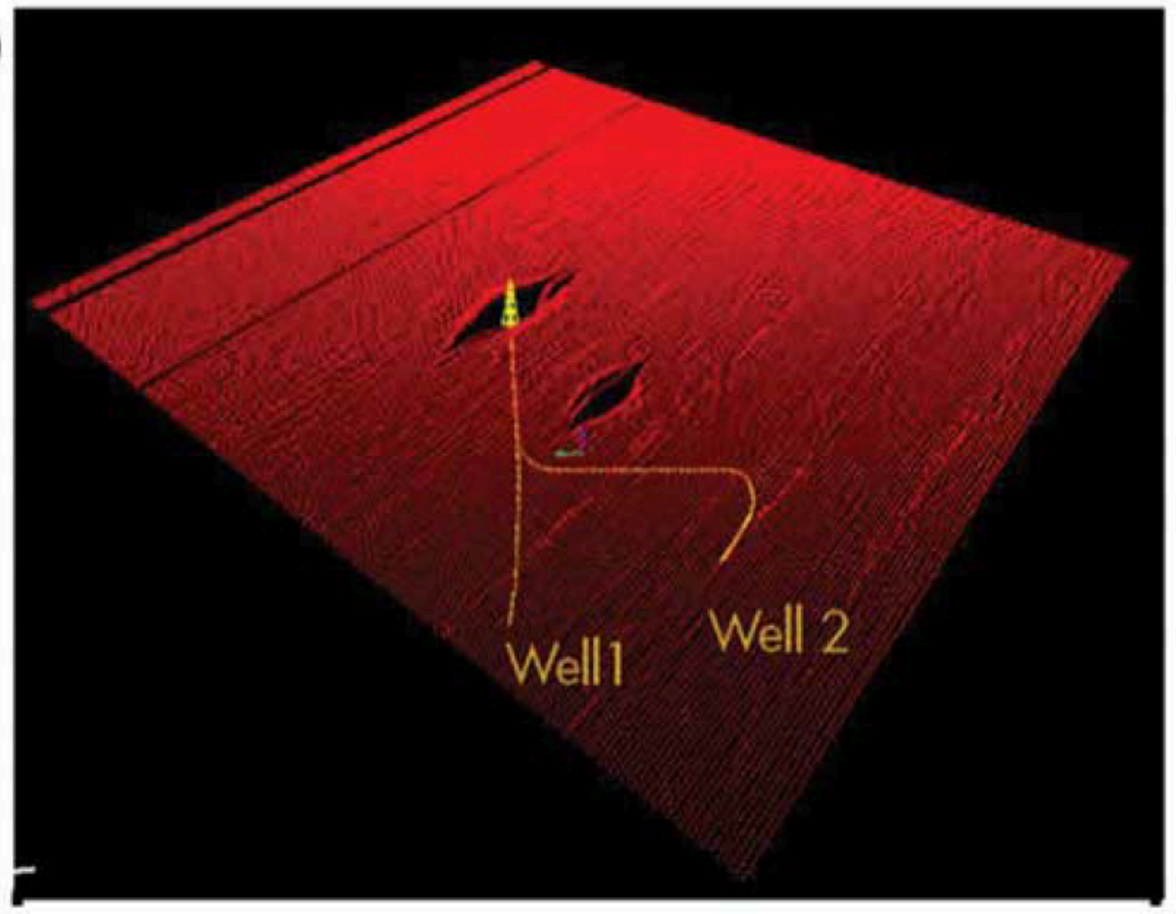
Webster et al. 2013 SEG Extended Abstracts

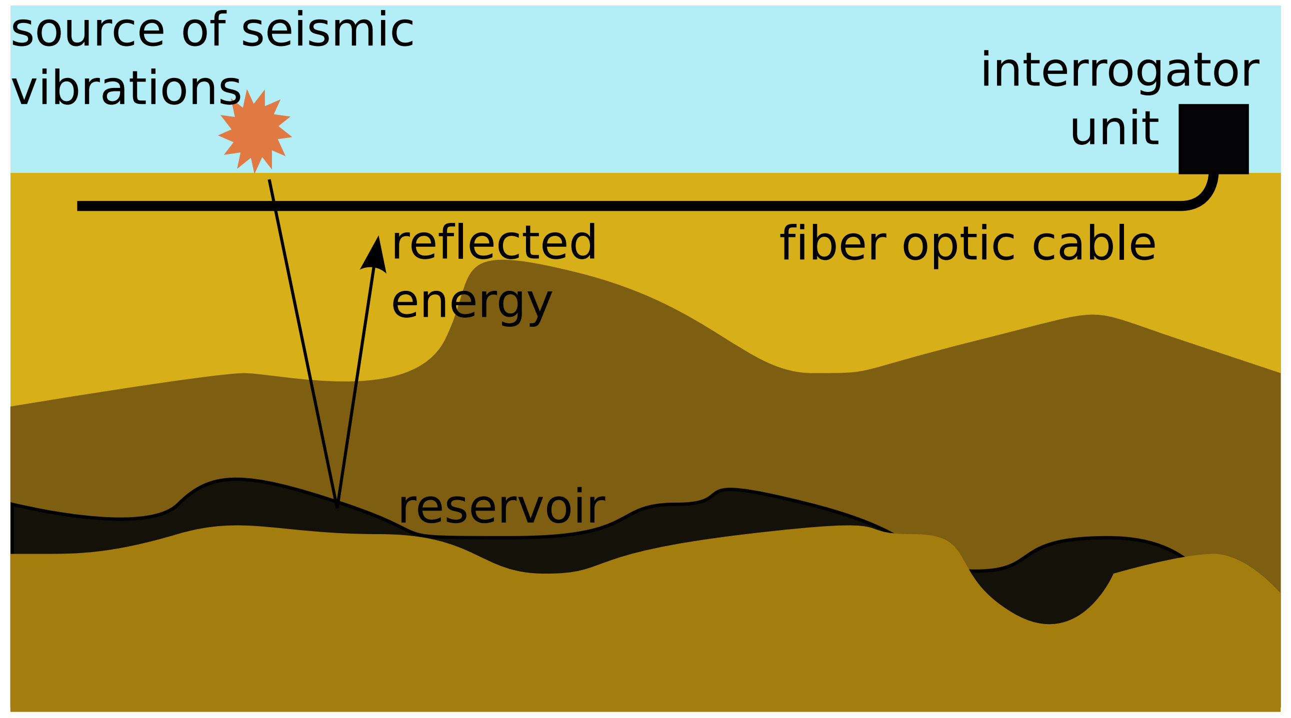


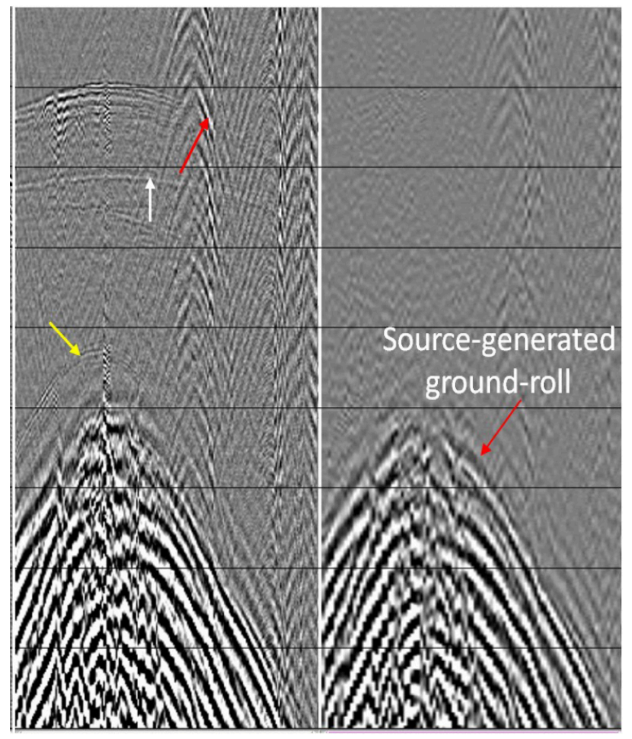
Repeatable 4D seismic offshore and onshore with fiber covering full well

Mateeva et al. 2013 The Leading Edge



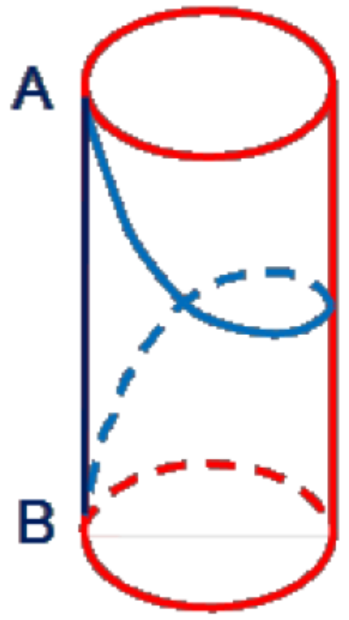




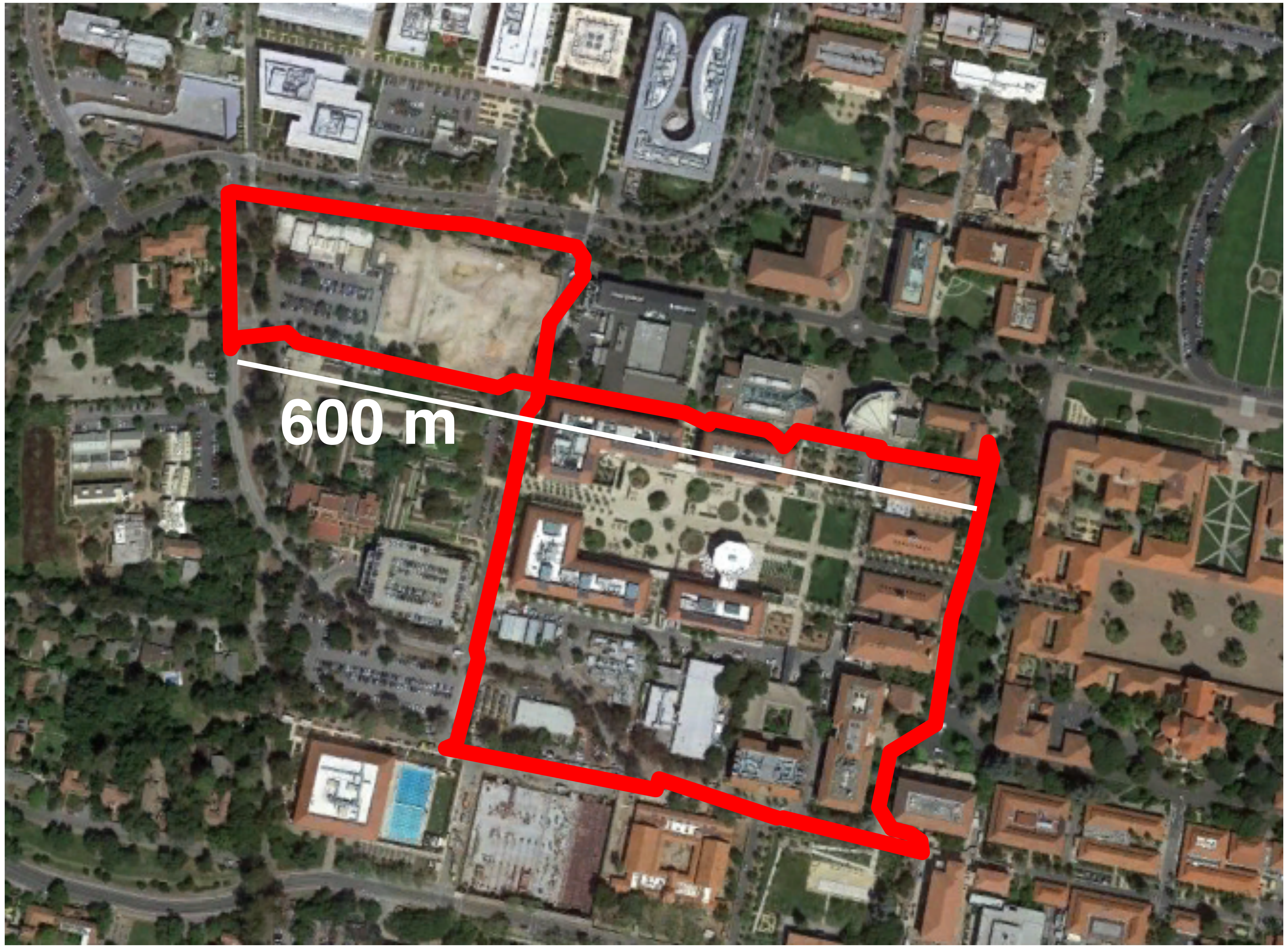


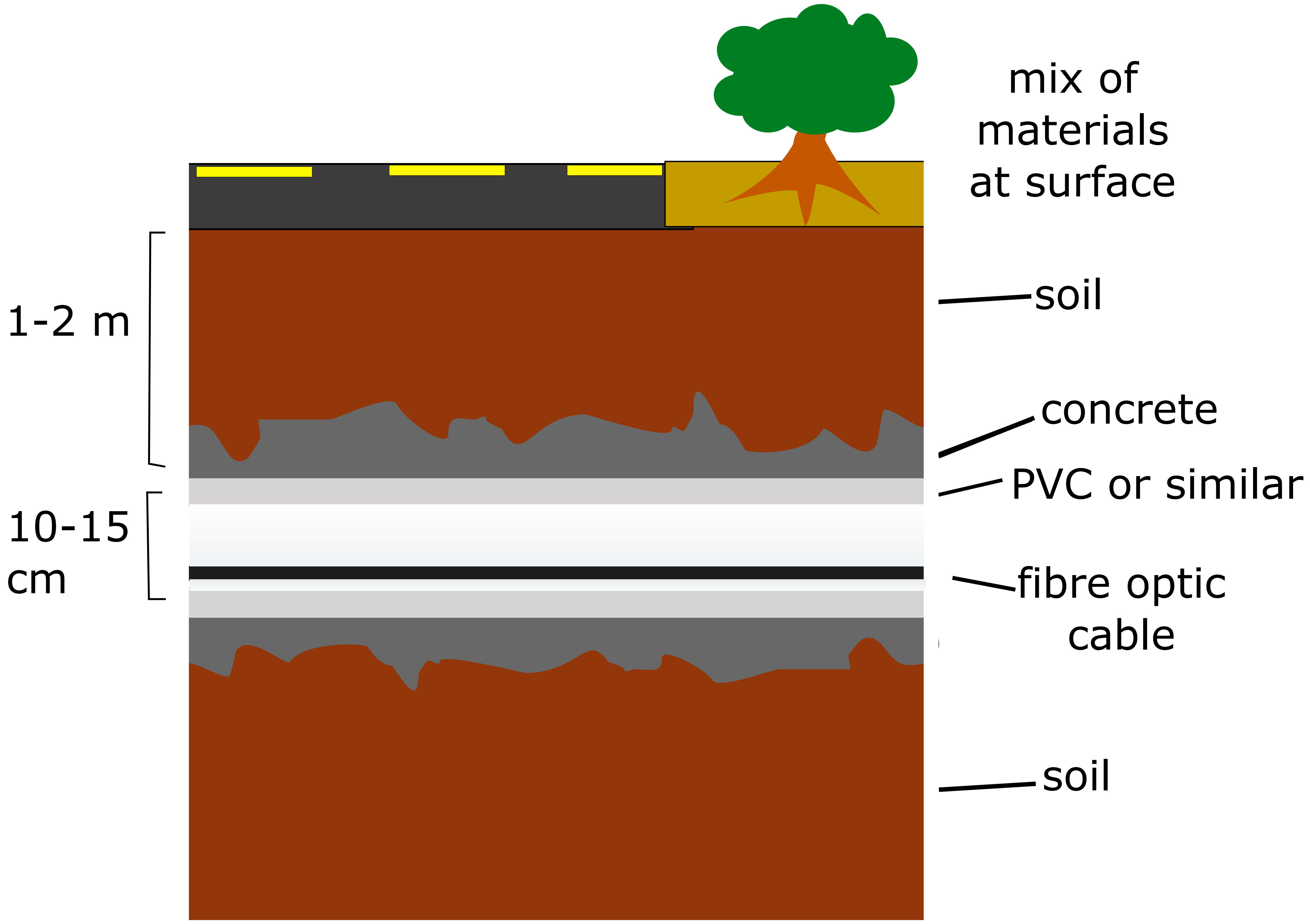
Reflection seismology with helical fibers

Hornman et al. 2013 EAGE Conference Abstracts



Stanford DAS Array-1 (SDASA-1)



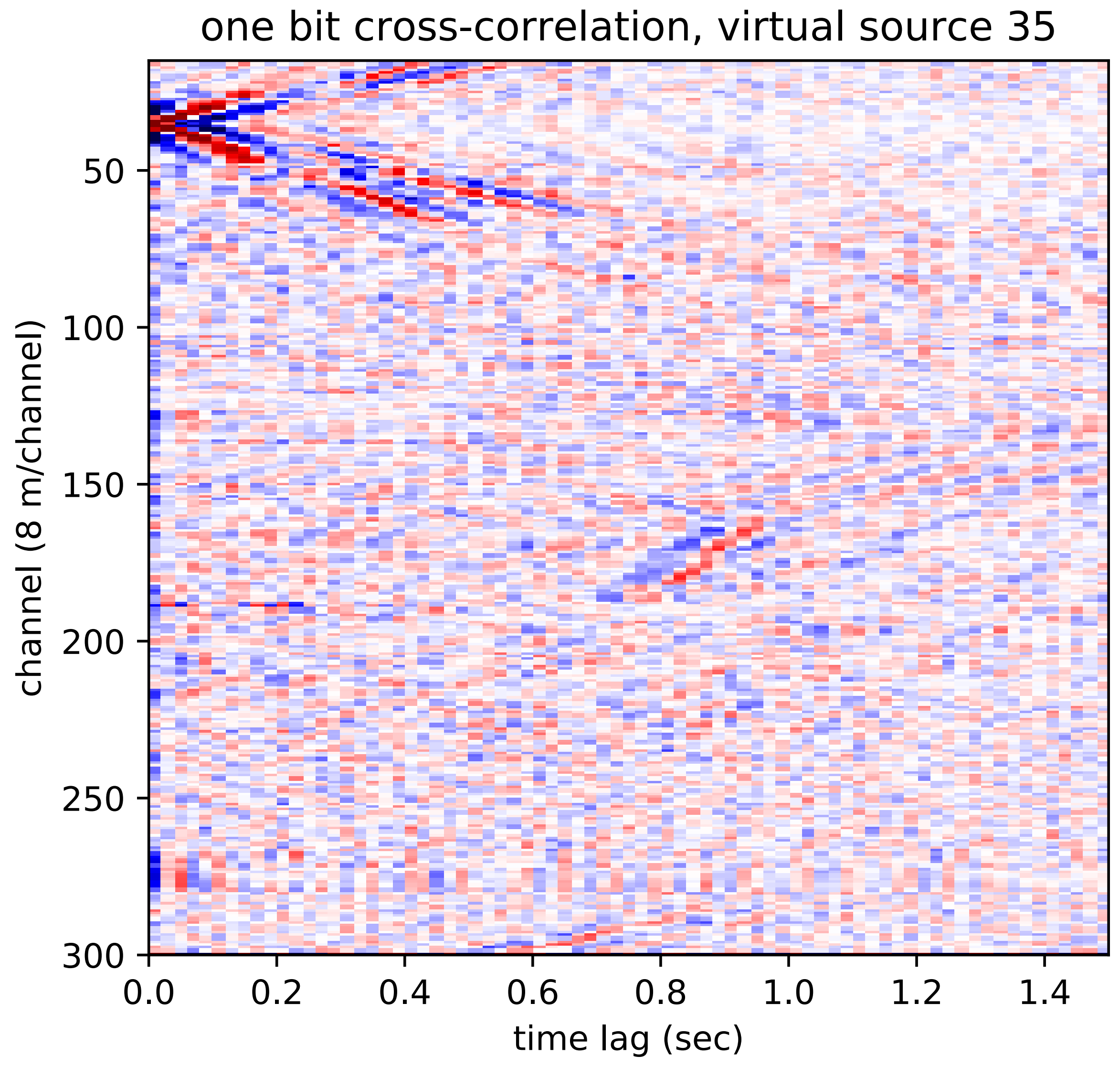


collaboration with Martin Karrenbach and Steve Cole at OptaSense®

a QinetiQ company

Objectives of SDASA-1

ambient noise tomography for near-surface imaging



Goals:

Using fiber in telecommunications conduits for:

- -Active seismic surveys
- **-Near-surface imaging with ambient noise**
- -Earthquake detection

Challenges:

-Difficult to get precise location information for fiber

-Little friction between conduit wall and fiber

-Straight fibers may be less sensitive to certain waves

-Coherent noises in urban/infrastructure environments

-Difficult to quickly decide on ambient noise pre-processing

-Only single component of strain is available

Outline

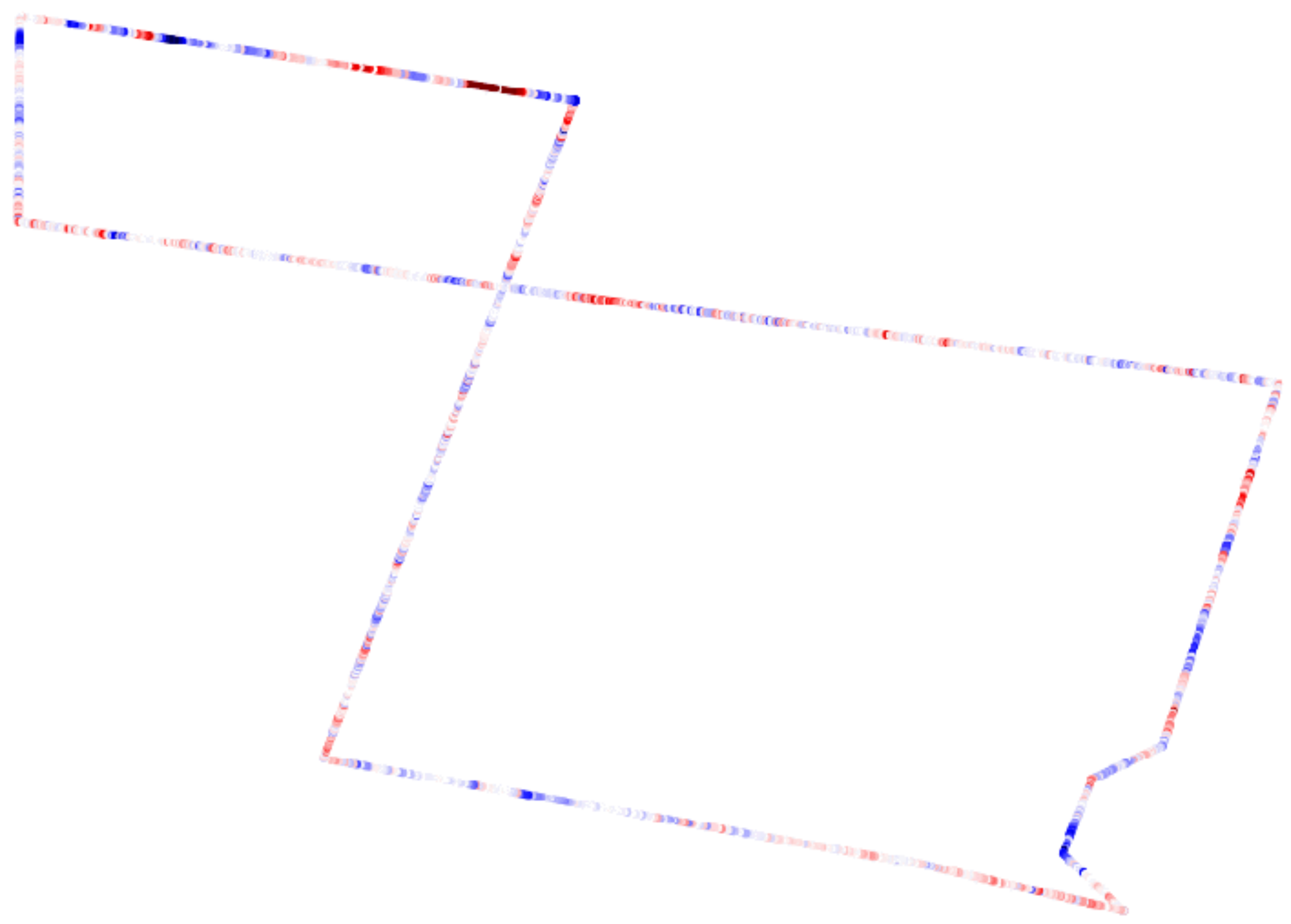
Ambient noise interferometry background

2D DAS interferometry theory

Practical challenges

2D Examples

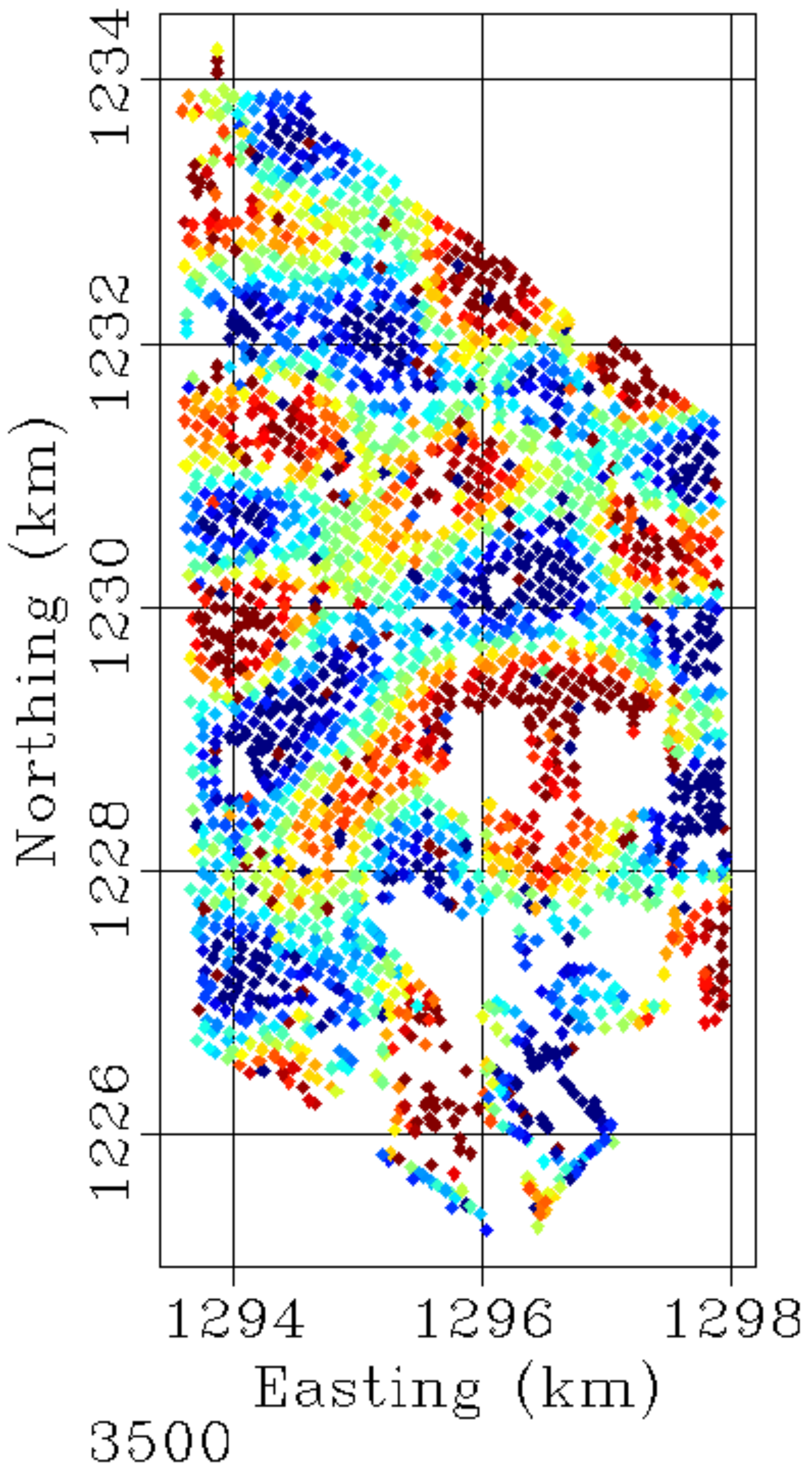
Summary and directions forward



noise at 1/10th speed

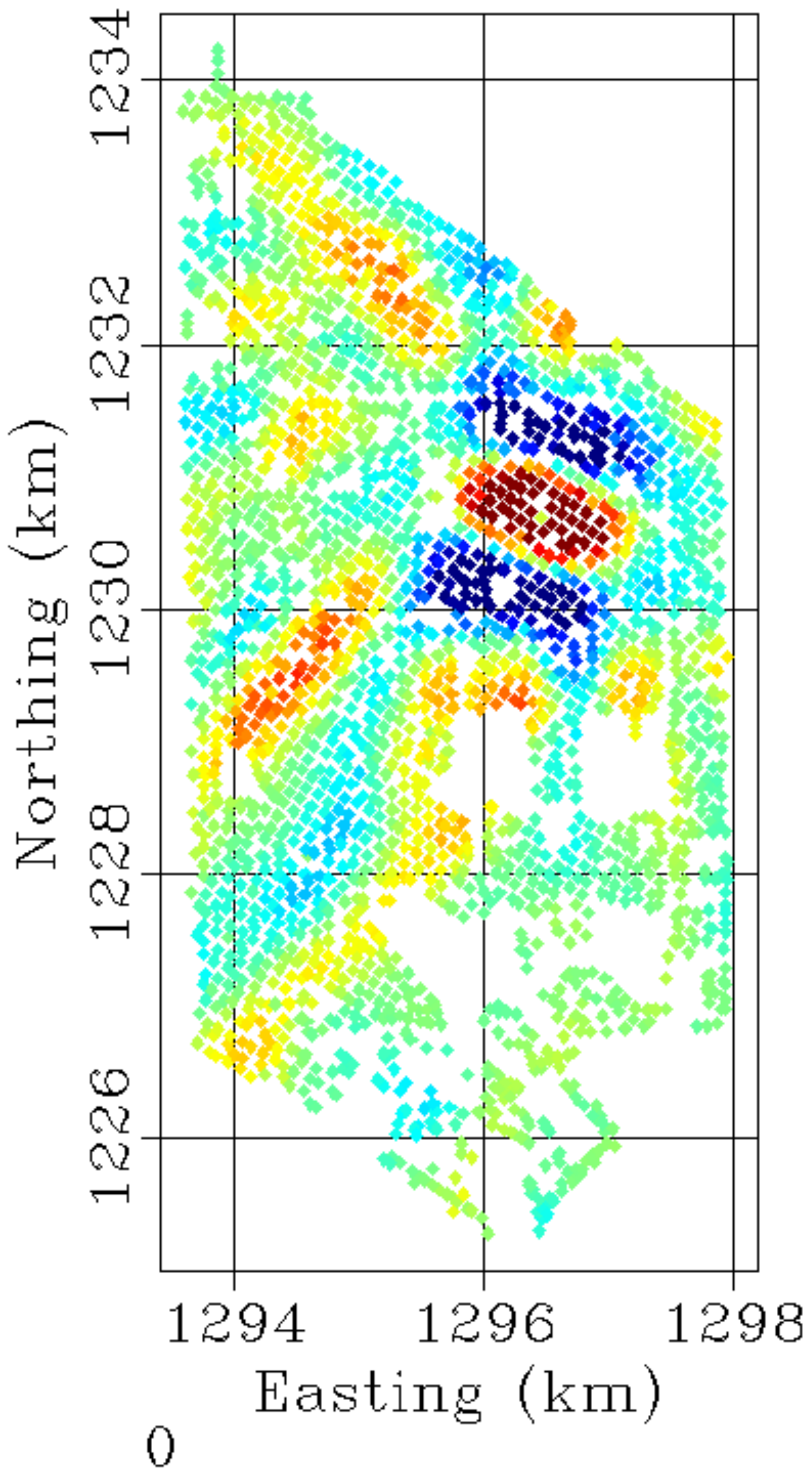
Ambient noise interferometry can reduce costs

noise ~1 Hz



correlations between windows of noise

signal mimicking active survey

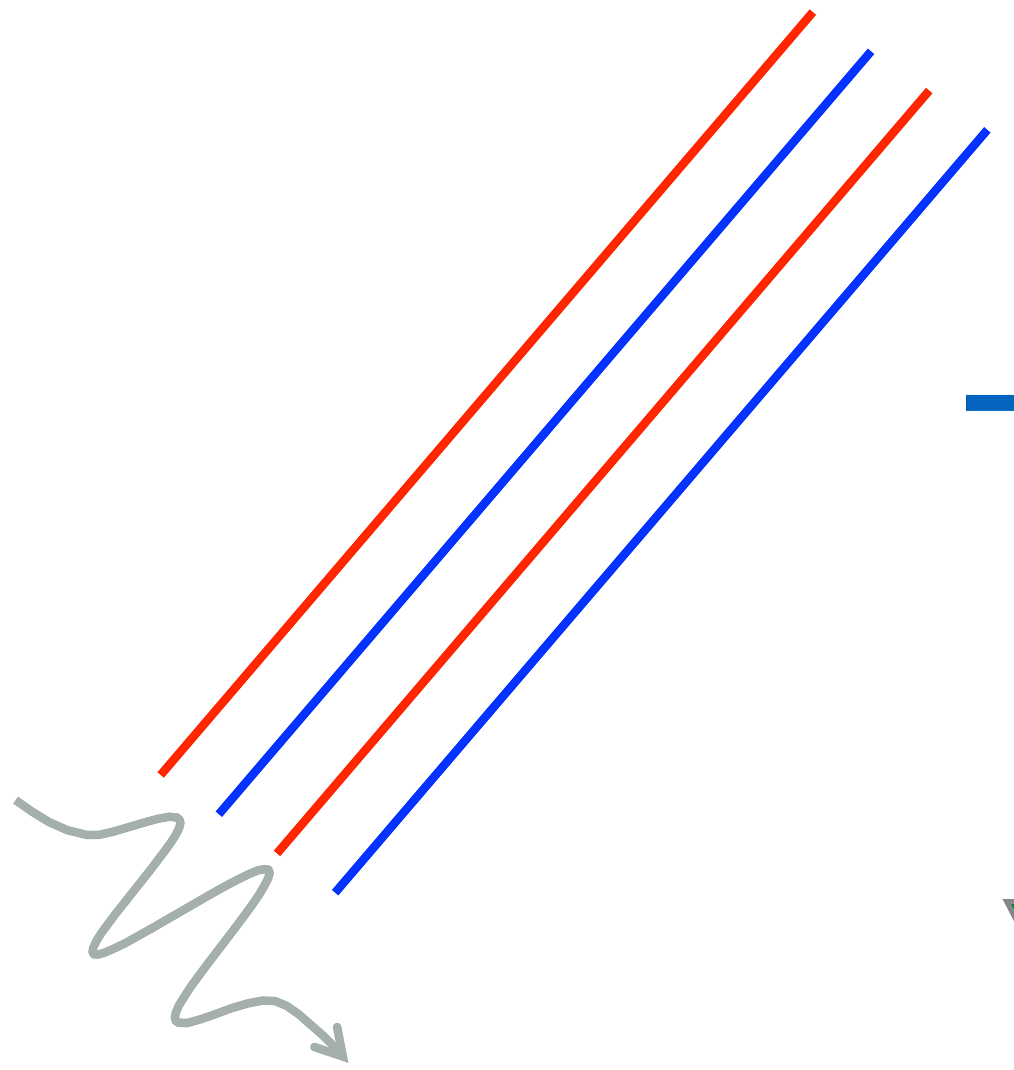


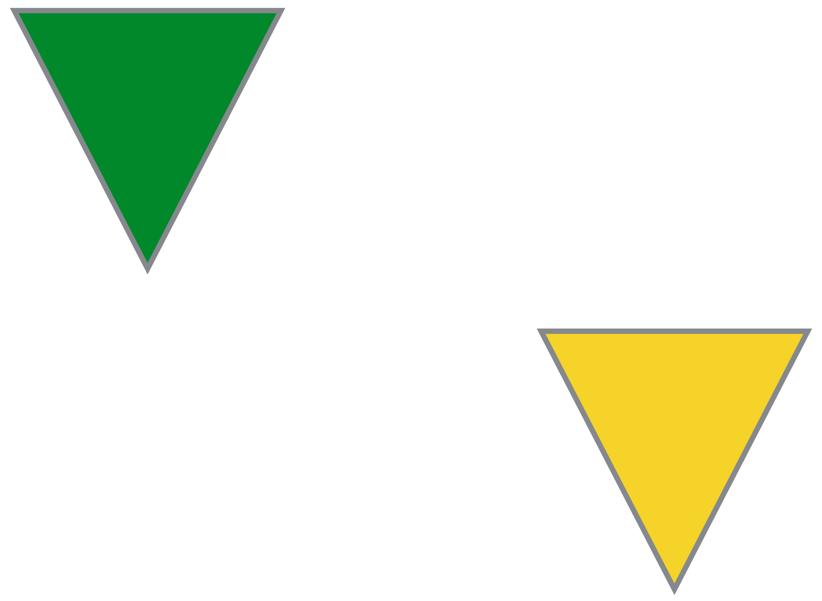
Example from Jason Chang (Stanford), data c/o Nodal Seismic

How cross-correlation works

for real time series , cross-correlation is a time-lagged dot product

$$C(\tau) = \int_{-\infty}^{\infty} d(x_r, t)\, d(x_{vs}, t+\tau)\, dt$$

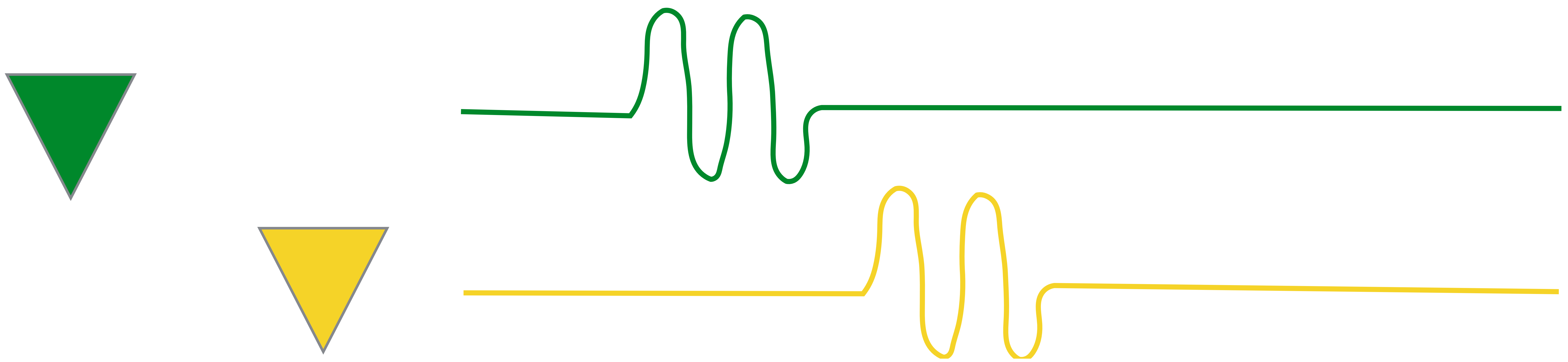




How cross-correlation works

for real time series , cross-correlation is a time-lagged dot product

$$C(\tau) = \int_{-\infty}^{\infty} d(x_r, t) d(x_{vs}, t + \tau) dt$$



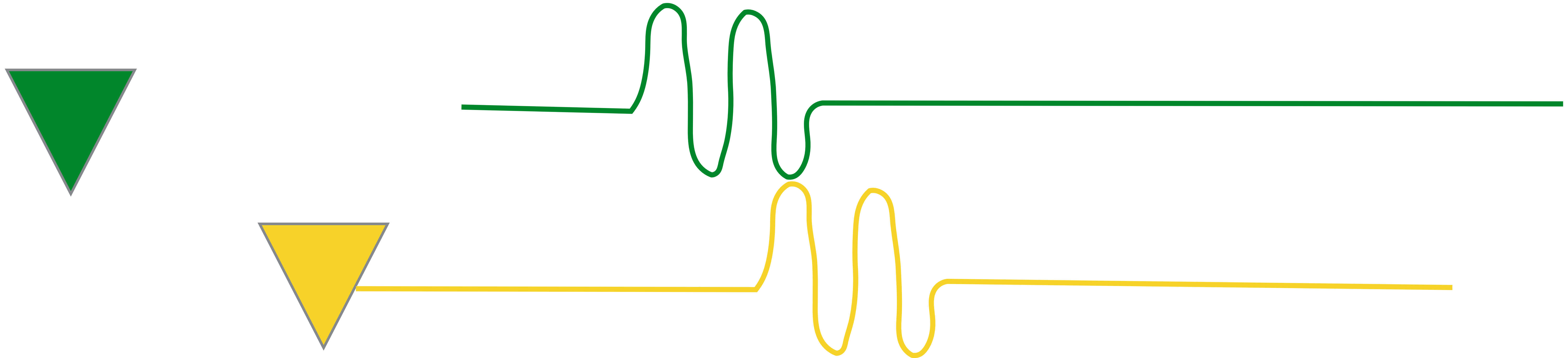
τ = 0 , C = 0

cross-correlation C =

How cross-correlation works

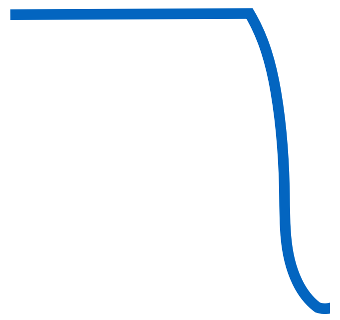
for real time series , cross-correlation is a time-lagged dot product

$$C(\tau) = \int_{-\infty}^{\infty} d(x_r, t) d(x_{vs}, t + \tau) dt$$



τ > 0, C < 0

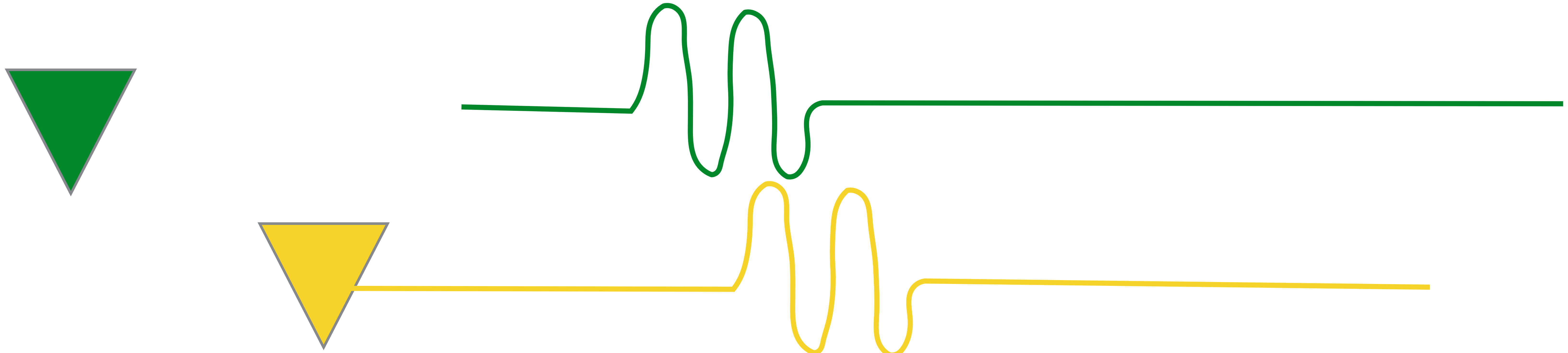
cross-correlation C =



How cross-correlation works

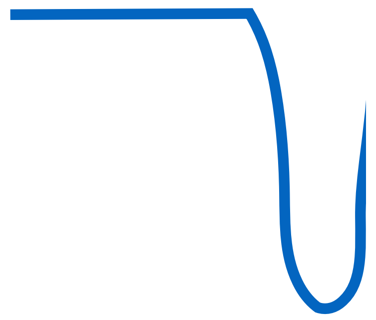
for real time series , cross-correlation is a time-lagged dot product

$$\underline{C(\tau)} = \int_{-\infty}^{\infty} \underline{d(x_r, t)}\,\underline{d(x_{vs}, t+\tau)}\,dt$$



C = 0

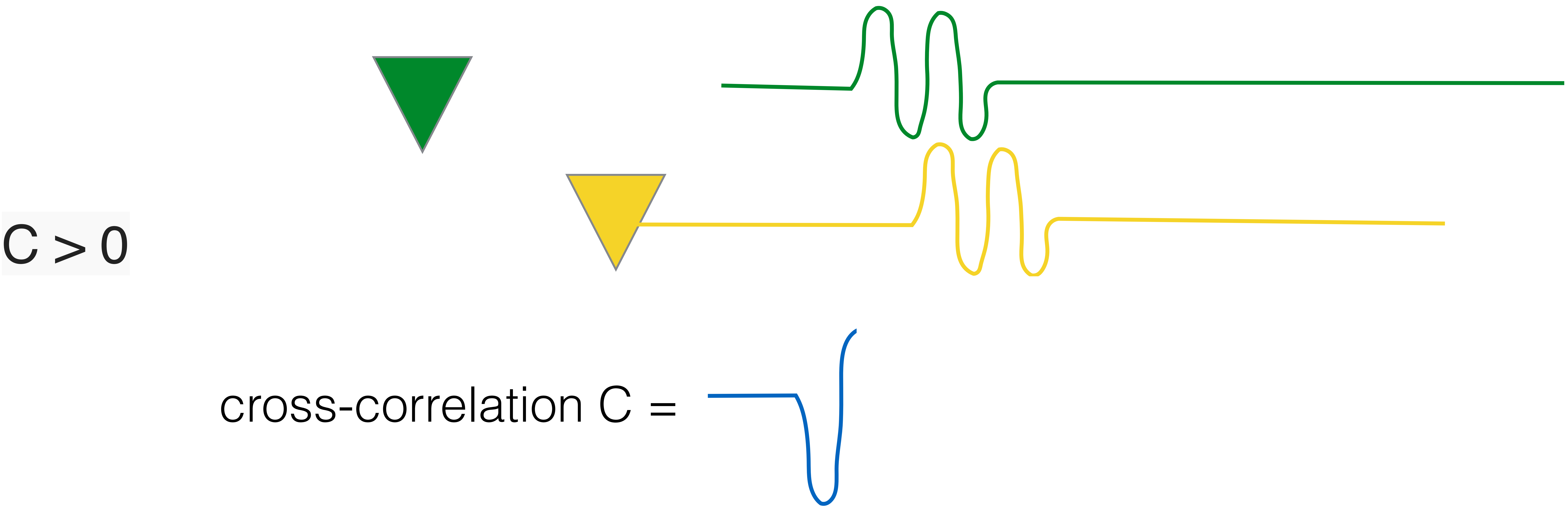
peaks and 0s line up

cross-correlation C = 

How cross-correlation works

for real time series , cross-correlation is a time-lagged dot product

$$C(\tau) = \int_{-\infty}^{\infty} d(x_r, t) d(x_{vs}, t+\tau) dt$$

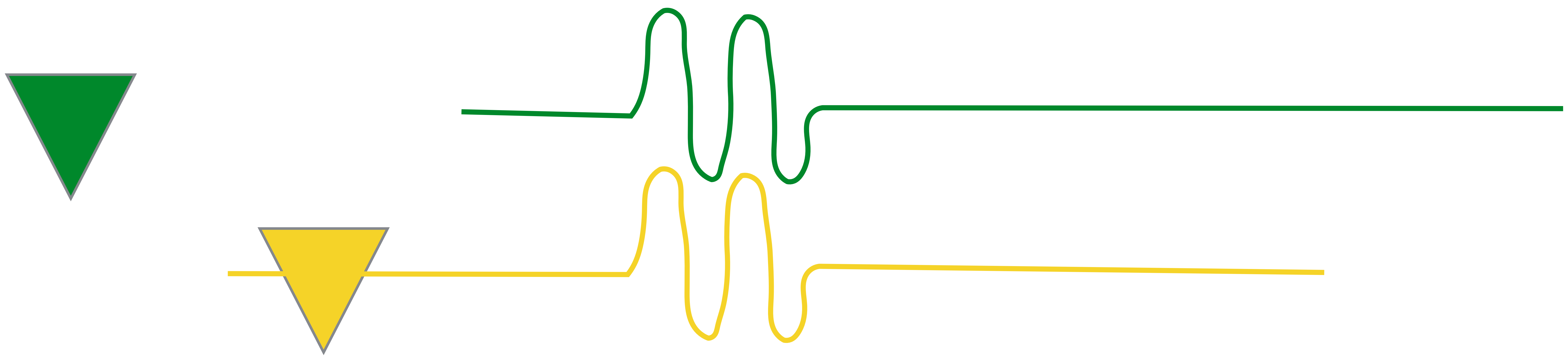


How cross-correlation works

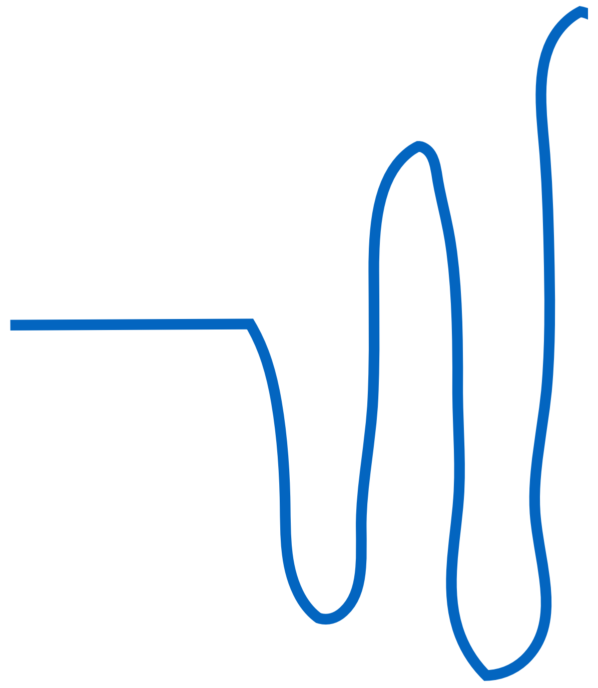
for real time series , cross-correlation is a time-lagged dot product

$$C(\tau) = \int_{-\infty}^{\infty} d(x_r, t) d(x_{vs}, t + \tau) dt$$

C >> 0



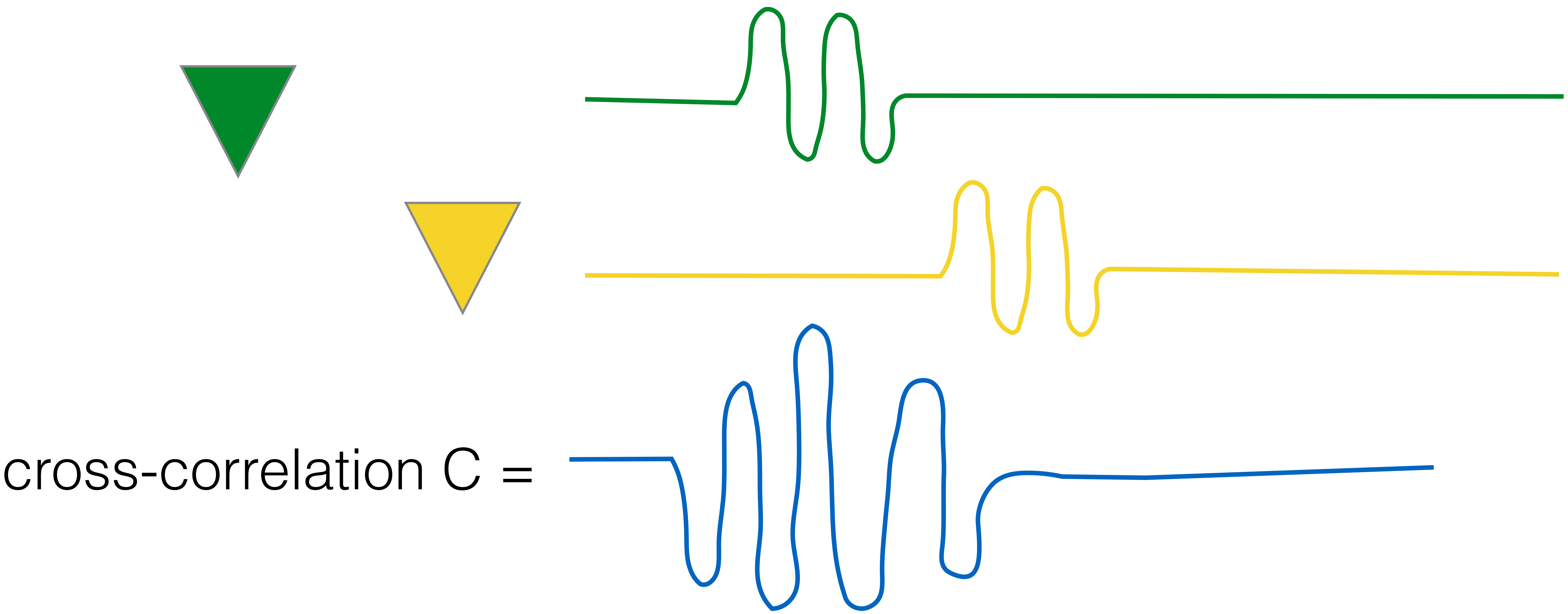
cross-correlation C =



How cross-correlation works

for real time series , cross-correlation is a time-lagged dot product

$$C(\tau) = \int_{-\infty}^{\infty} d(x_r, t) d(x_{vs}, t + \tau) dt$$

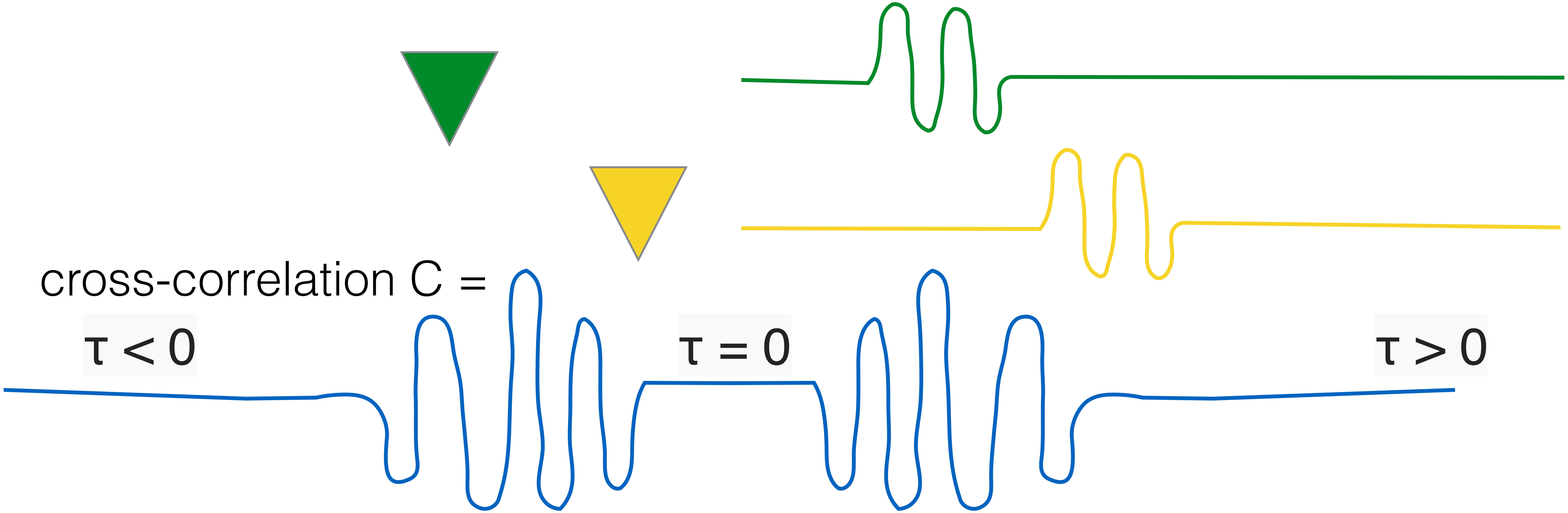


How cross-correlation works

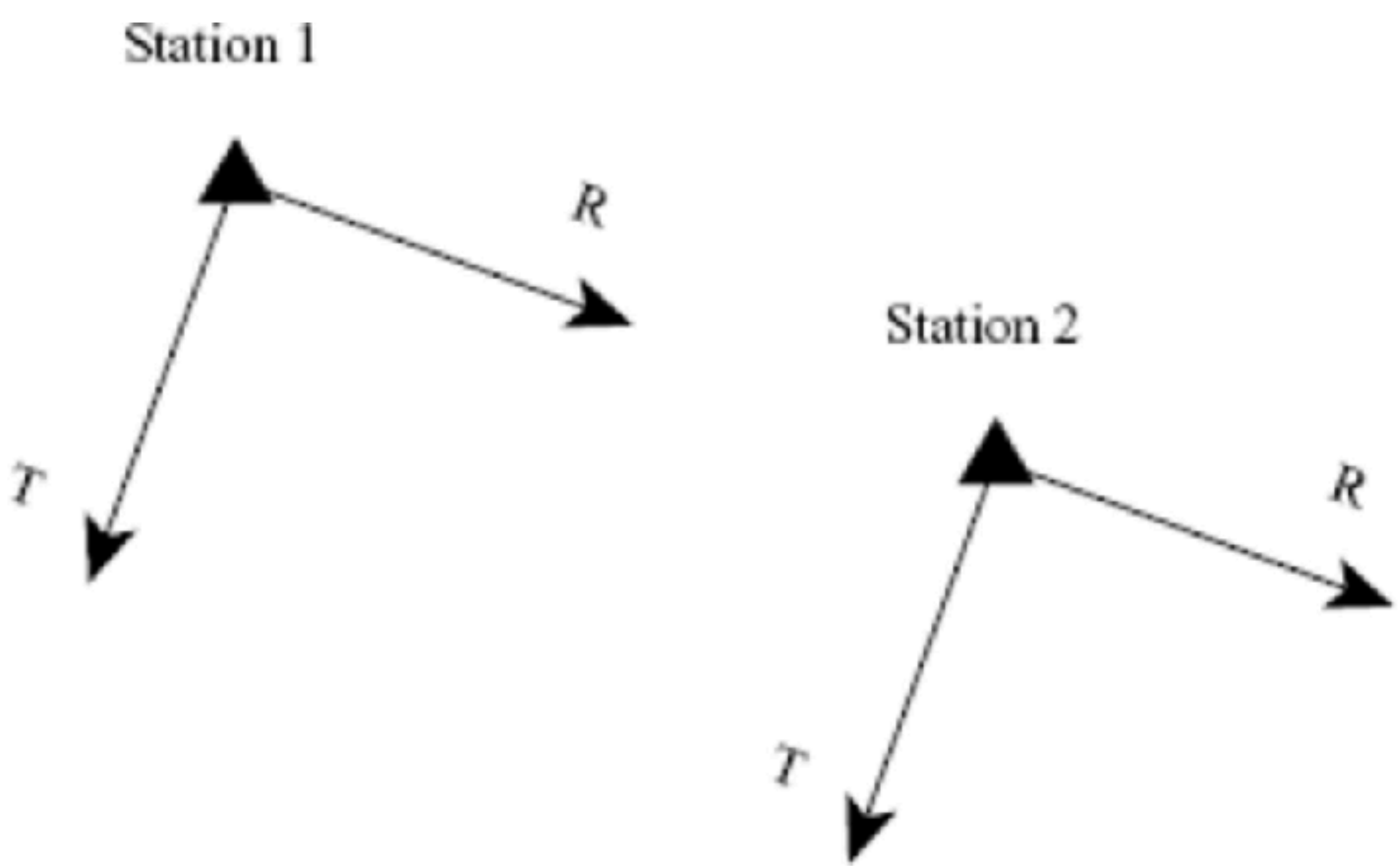
with white, **uncorrelated** spatially homogeneous noise sources on all sides

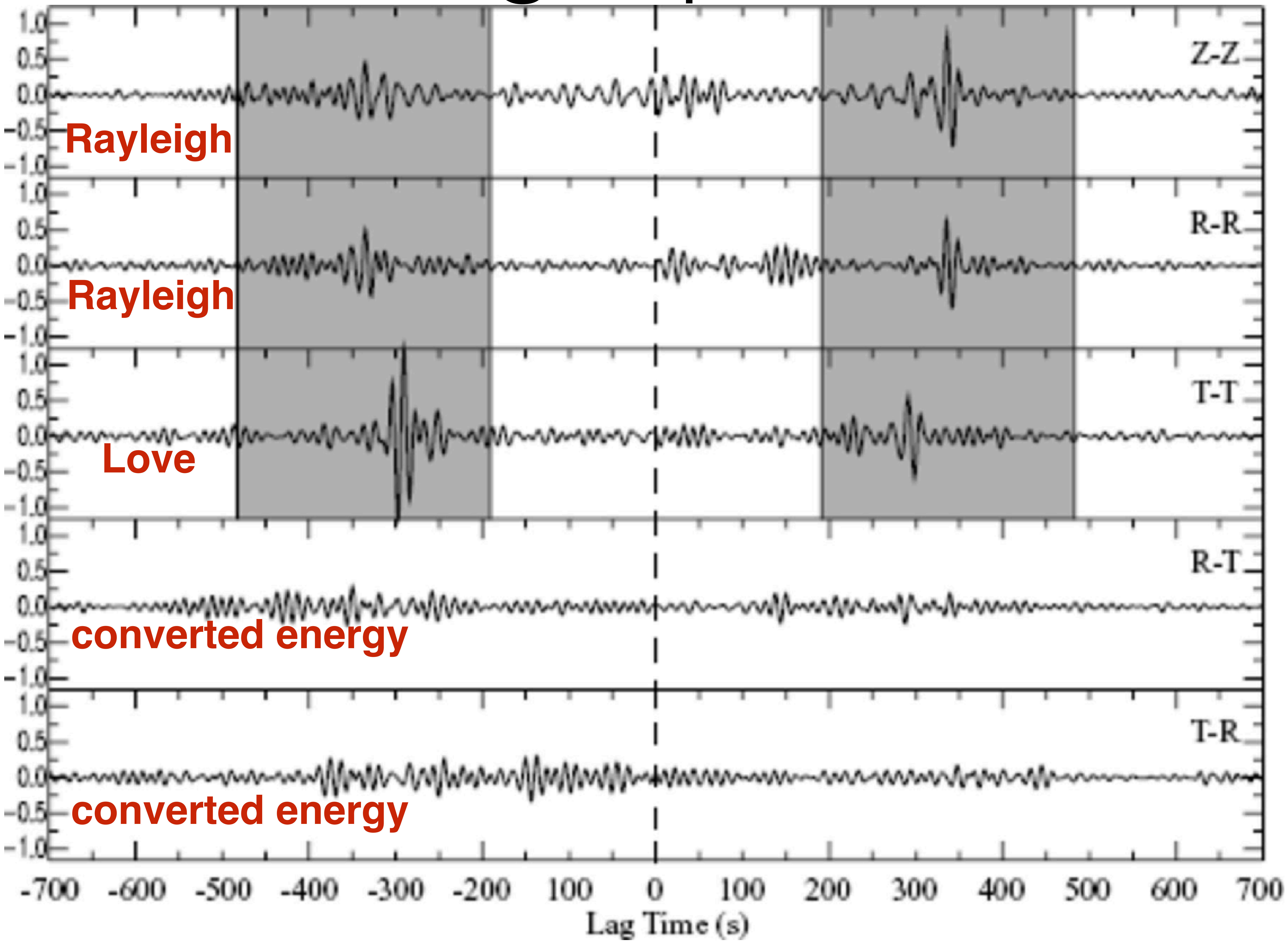
for real time series , cross-correlation is a time-lagged dot product

$$C(\tau) = \int_{-\infty}^{\infty} d(x_r, t)\, d(x_{vs}, t+\tau)\, dt$$



Ambient noise with 3C geophones





figures from Lin et al. 2008, GJI

Collinear Channel Cross-Correlations

$$m(x,t) = d(x+g,t) - d(x,t)$$

measurement difference of in-line point sensor data

cross-correlation

strains measured

$$C(\tau) = \int m(x_r,t)\, m(x_{vs}, t+\tau)\, dt$$

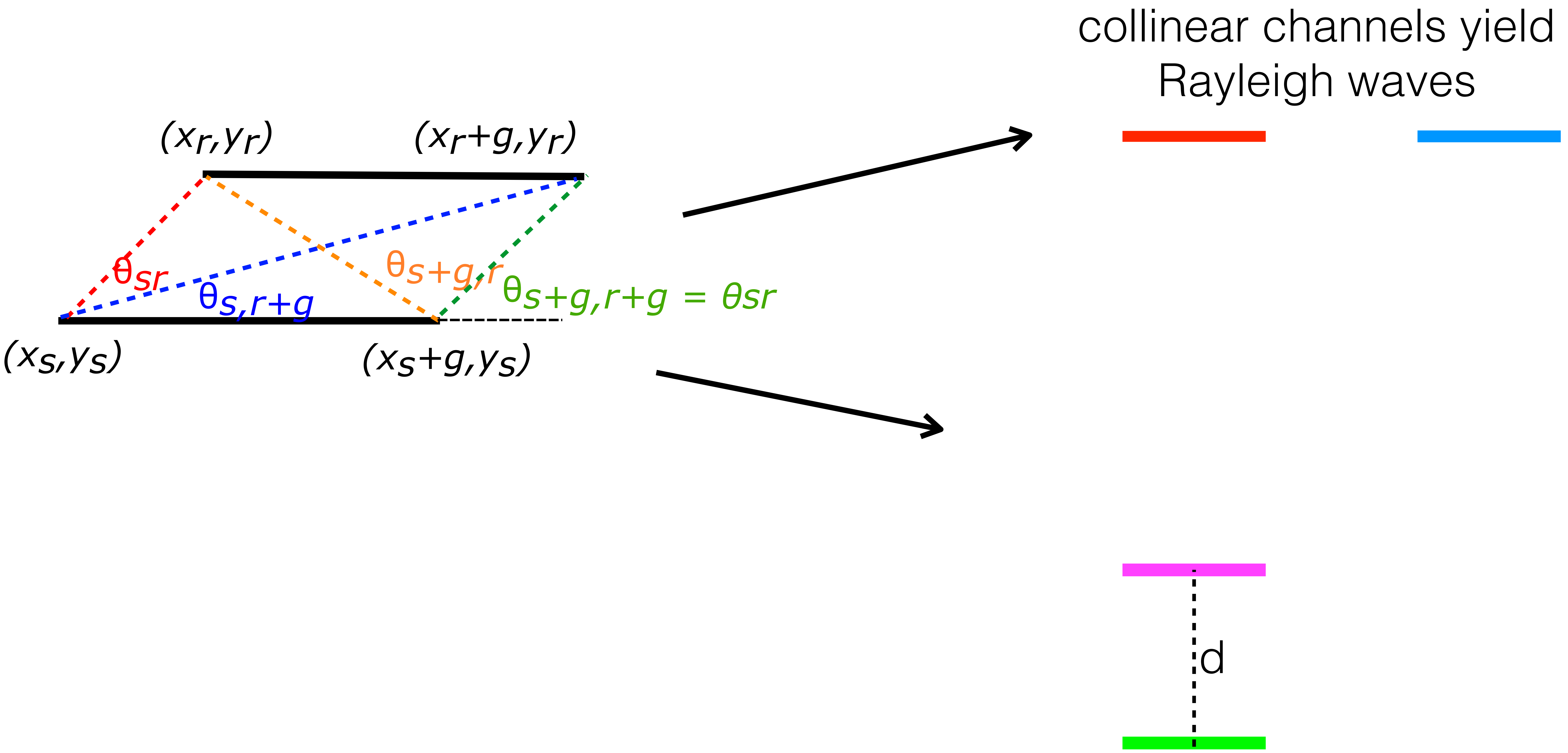
point displacements

$$= \int d(x_r+g,t)\, d(x_{vs}+g, t+\tau)\, dt - \int d(x_r+g,t)\, d(x_{vs}, t+\tau)\, dt$$

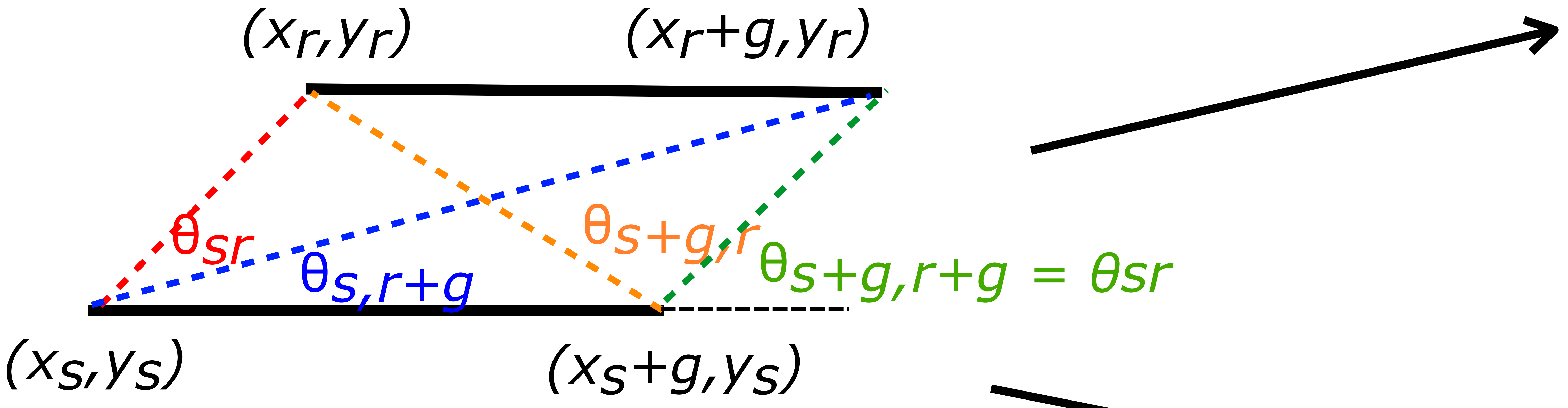
$$- \int d(x_r,t)\, d(x_{vs}+g, t+\tau)\, dt + \int d(x_r,t)\, d(x_{vs}, t+\tau)\, dt$$

$$= C_{r+g,vs+g}(\tau) - C_{r+g,vs}(\tau) - C_{r,vs+g}(\tau) + C_{r,vs}(\tau)$$

Parallel Fibers are Simple Case

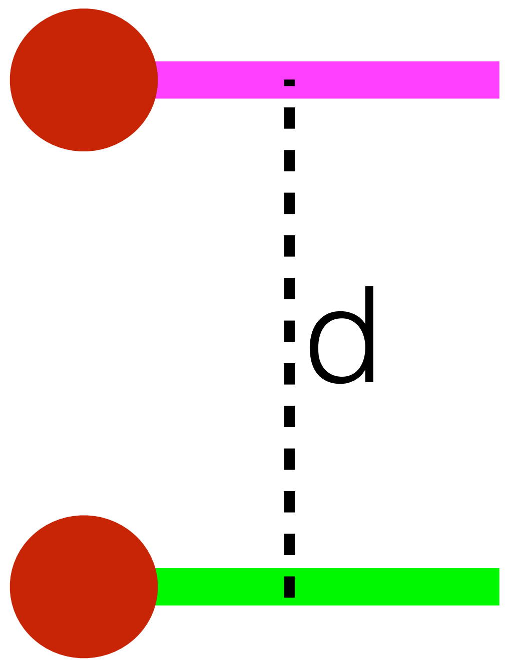


Parallel Fibers are Simple Case

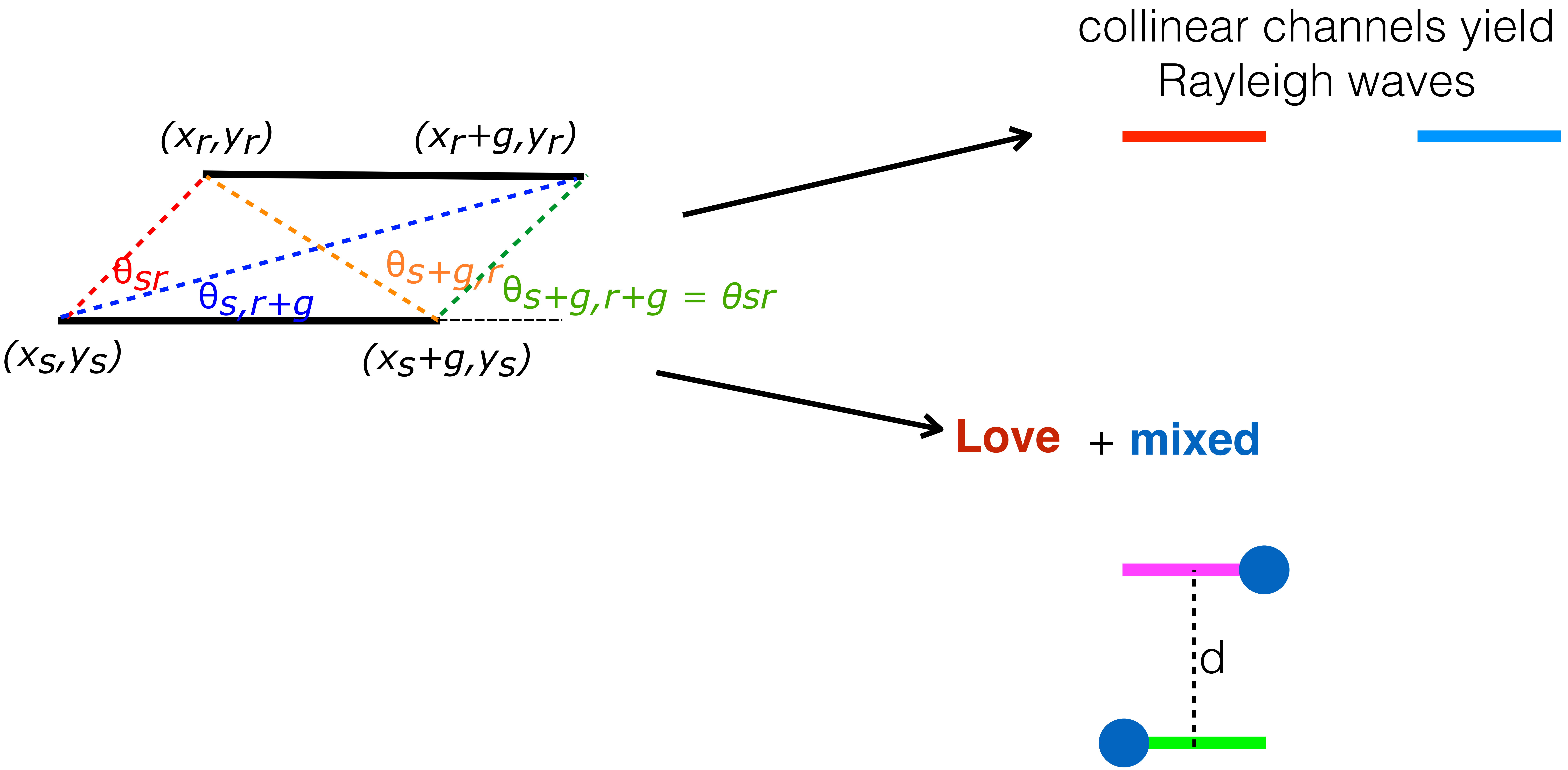


collinear channels yield Rayleigh waves

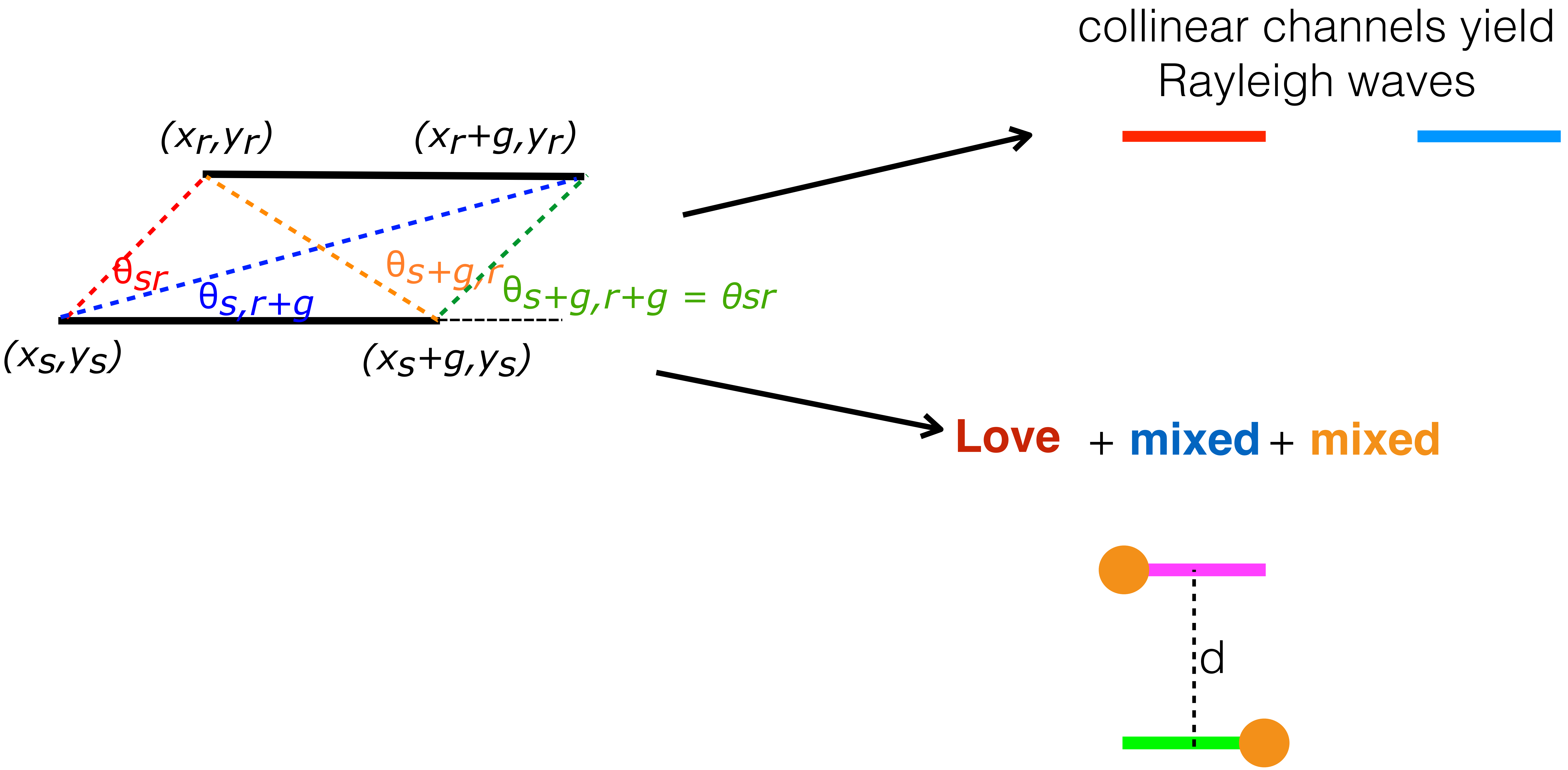
Love



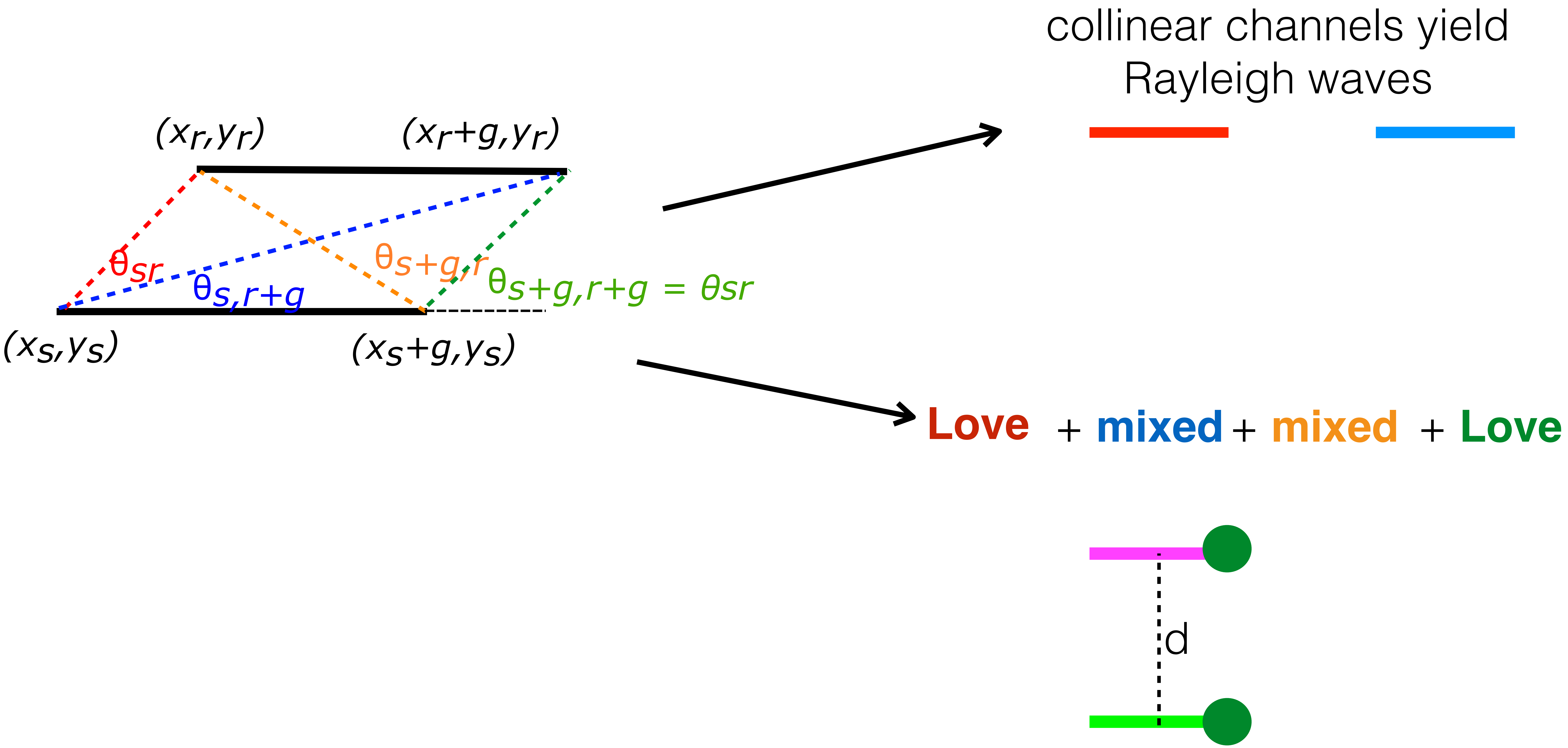
Parallel Fibers are Simple Case



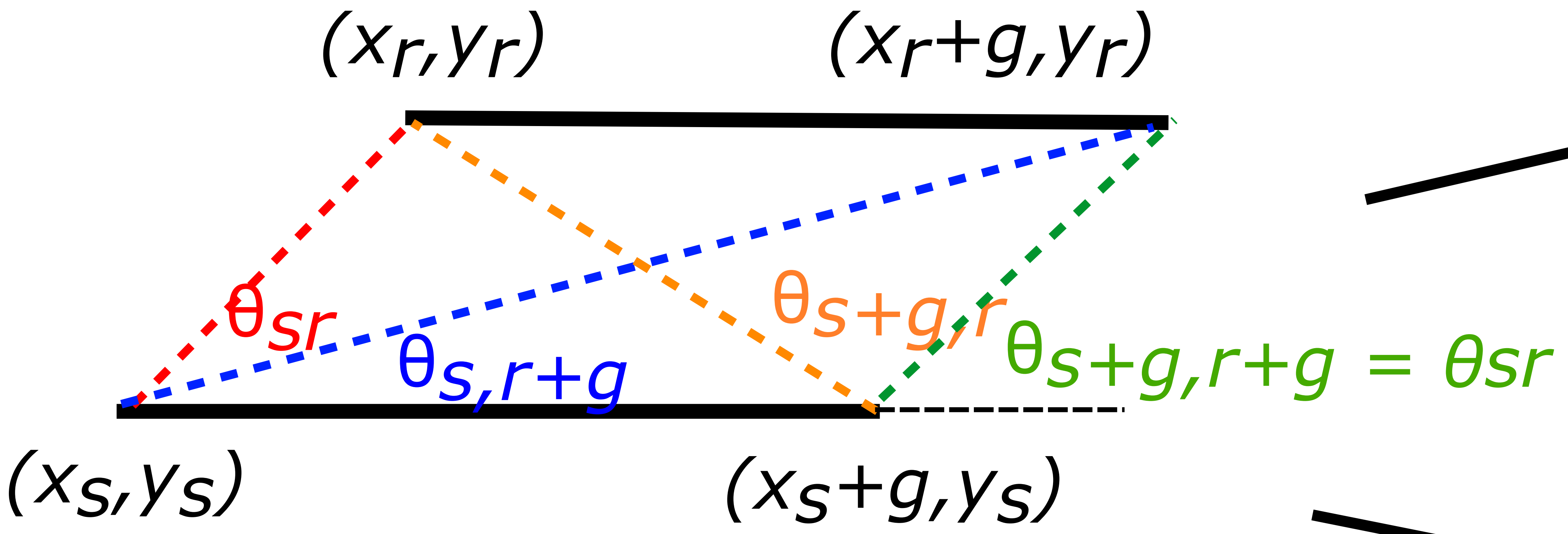
Parallel Fibers are Simple Case

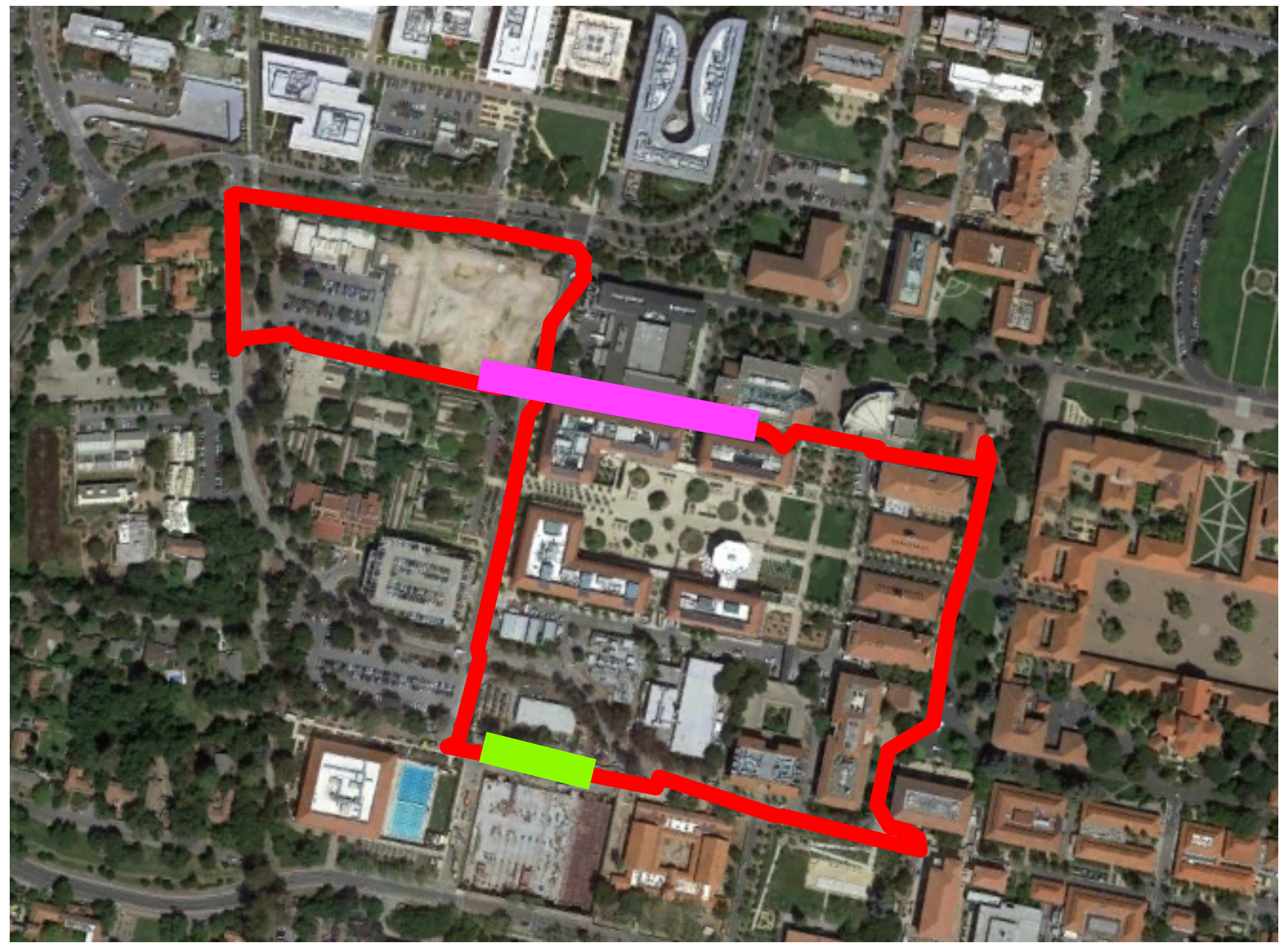


Parallel Fibers are Simple Case



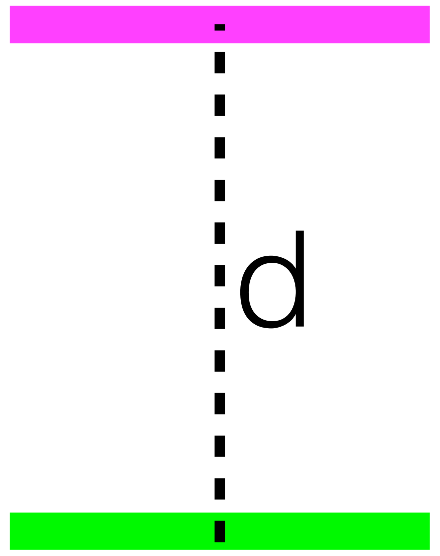
Parallel Fibers are Simple Case



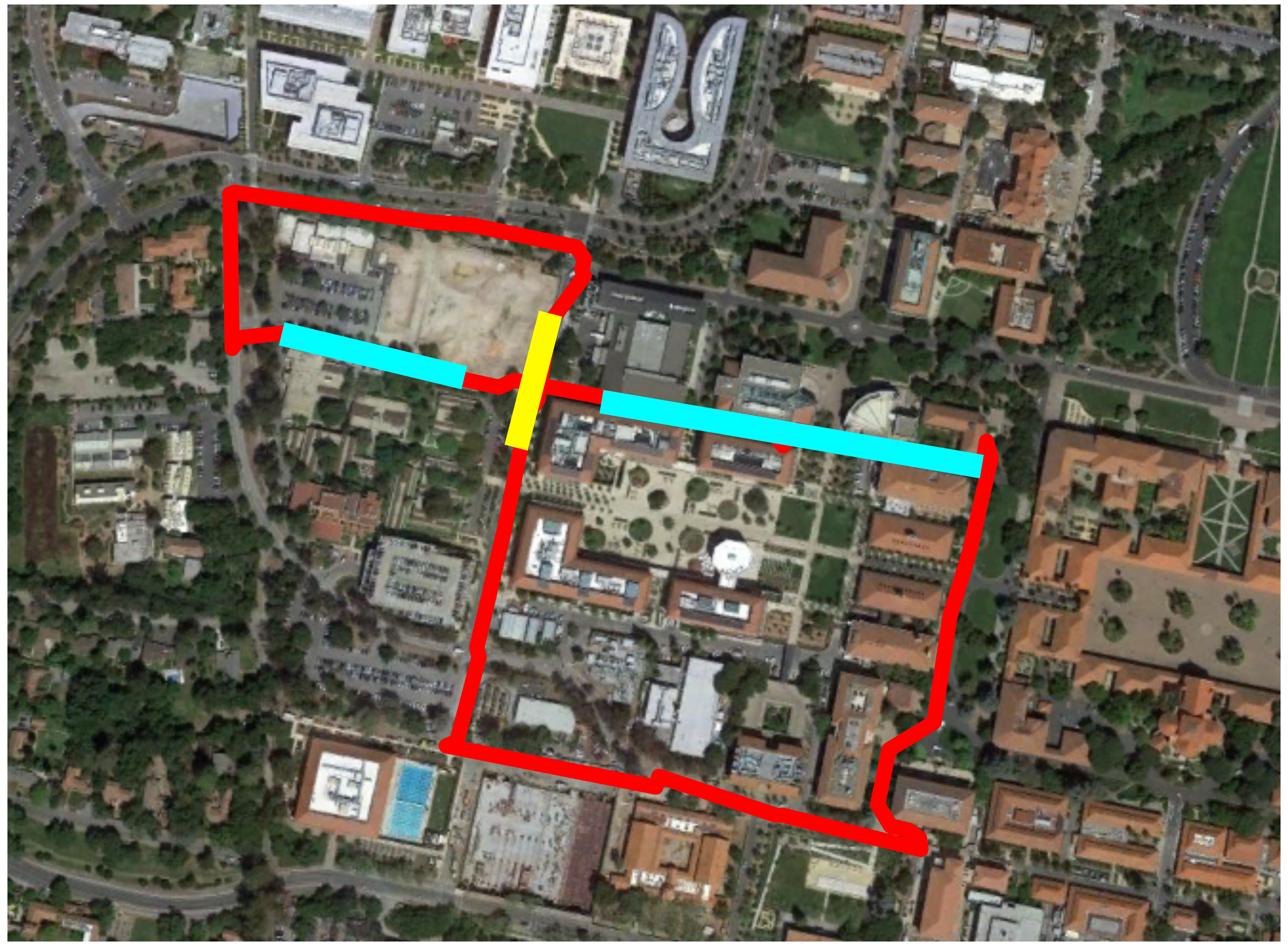


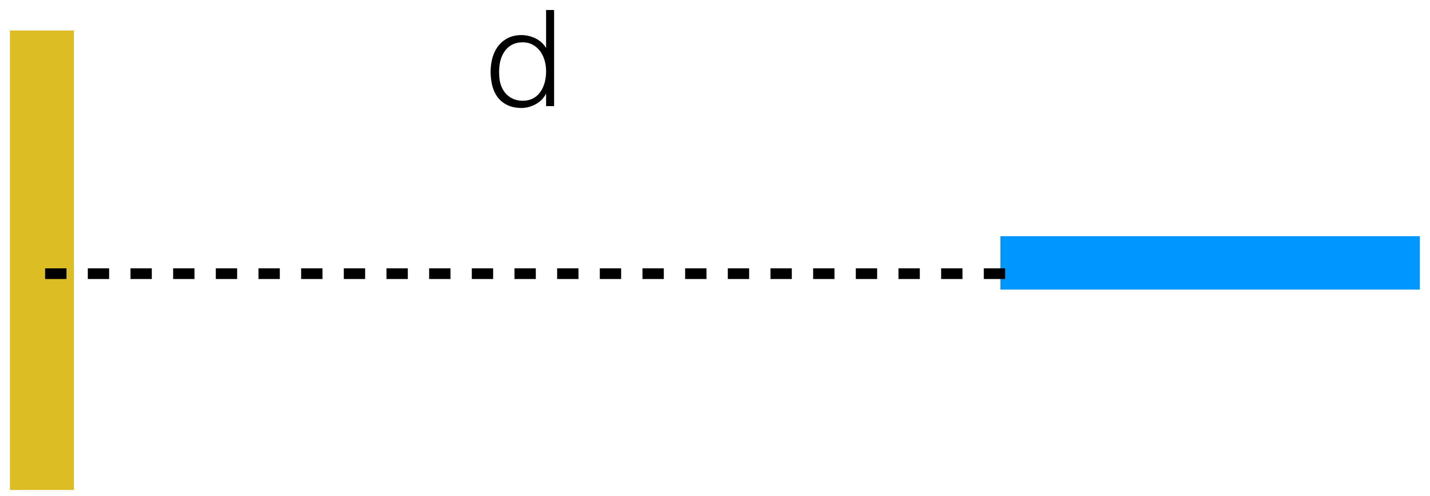
collinear channels yield
Rayleigh waves

directly across channels yield
Love waves as d grows



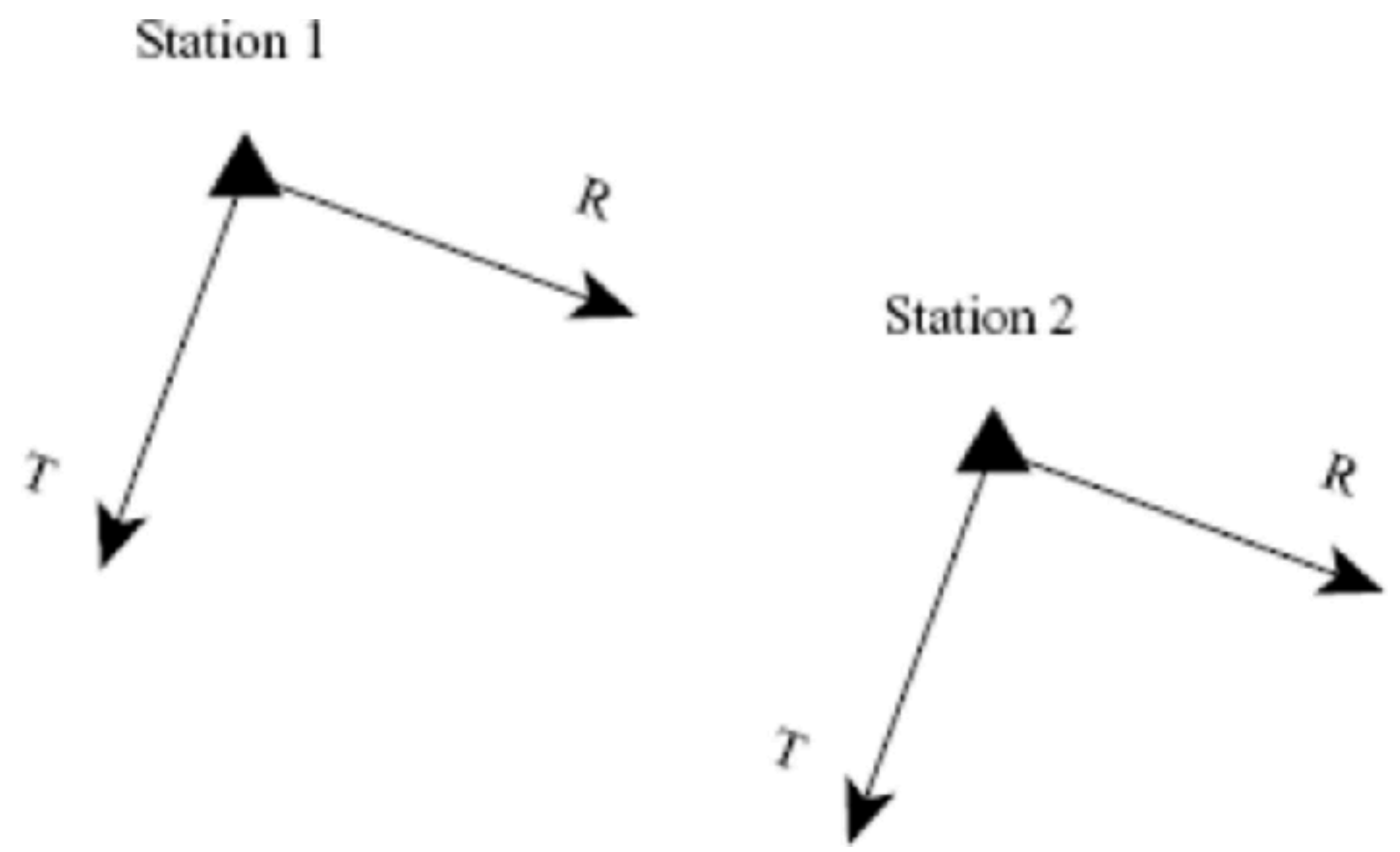
Orthogonal In-Line Fibers are Another Simple Case

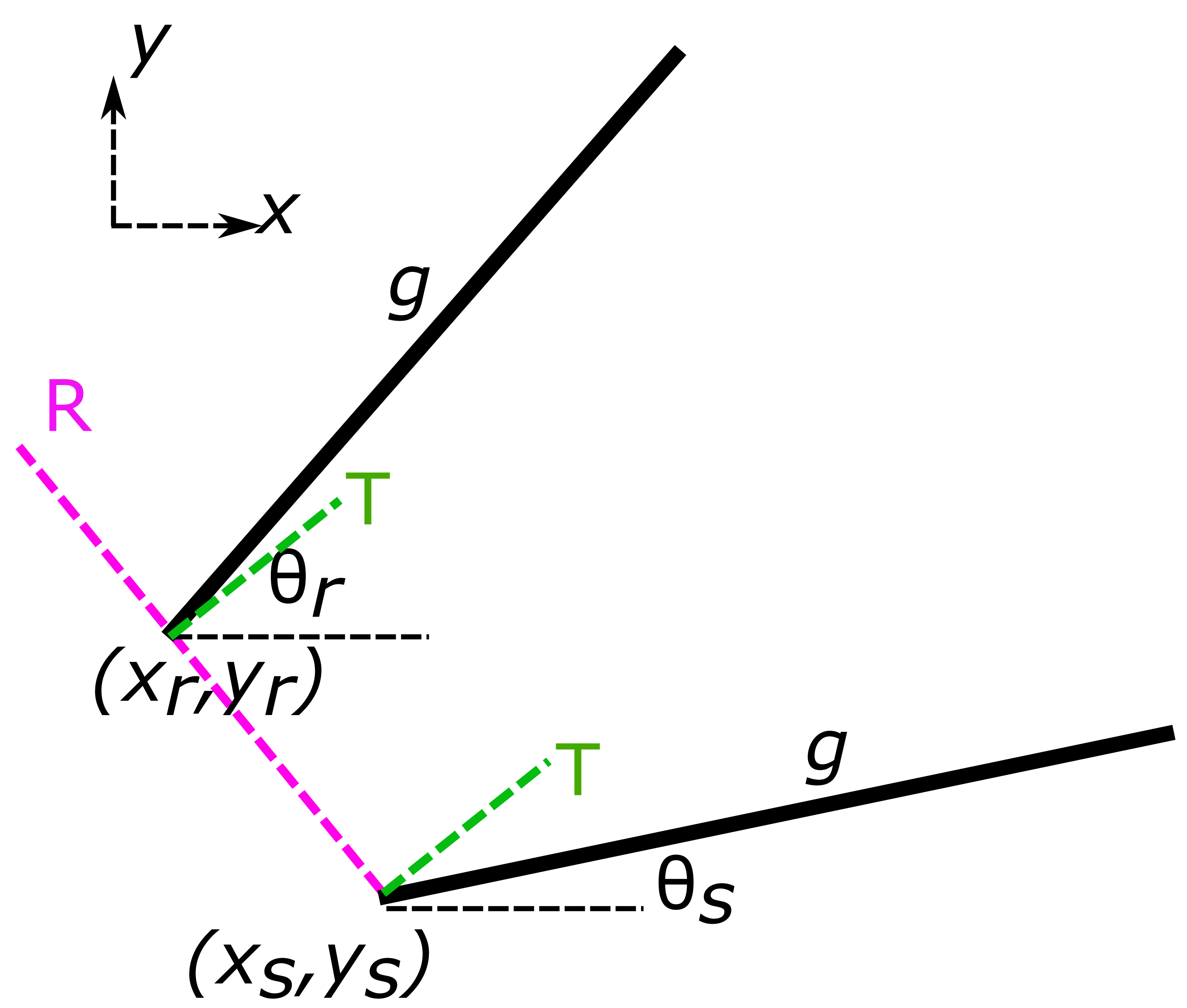




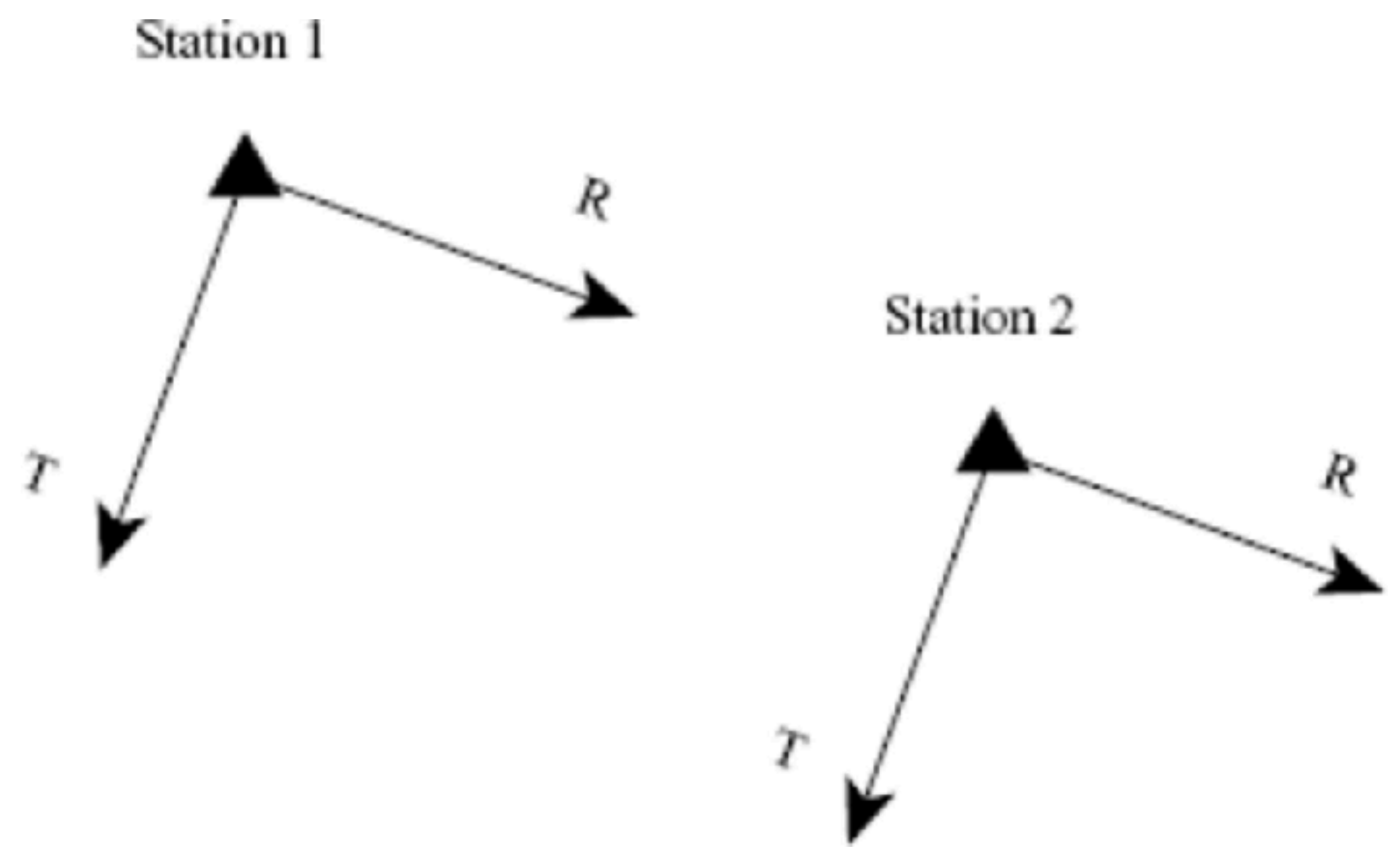
converted Rayleigh/Love
waves as d grows

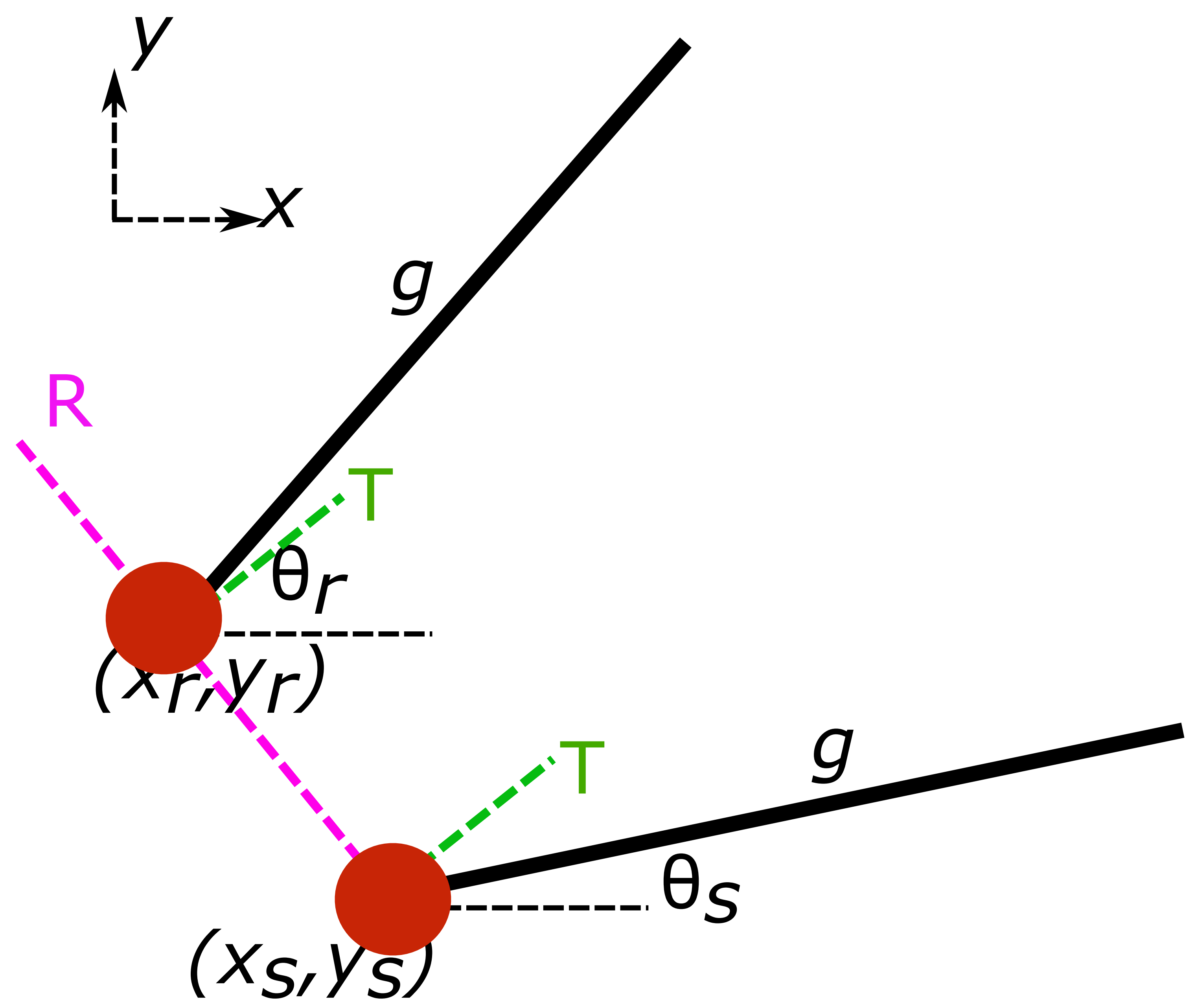
More generally, DAS cross-correlations are linear combinations of cross-correlations of improperly rotated geophones.



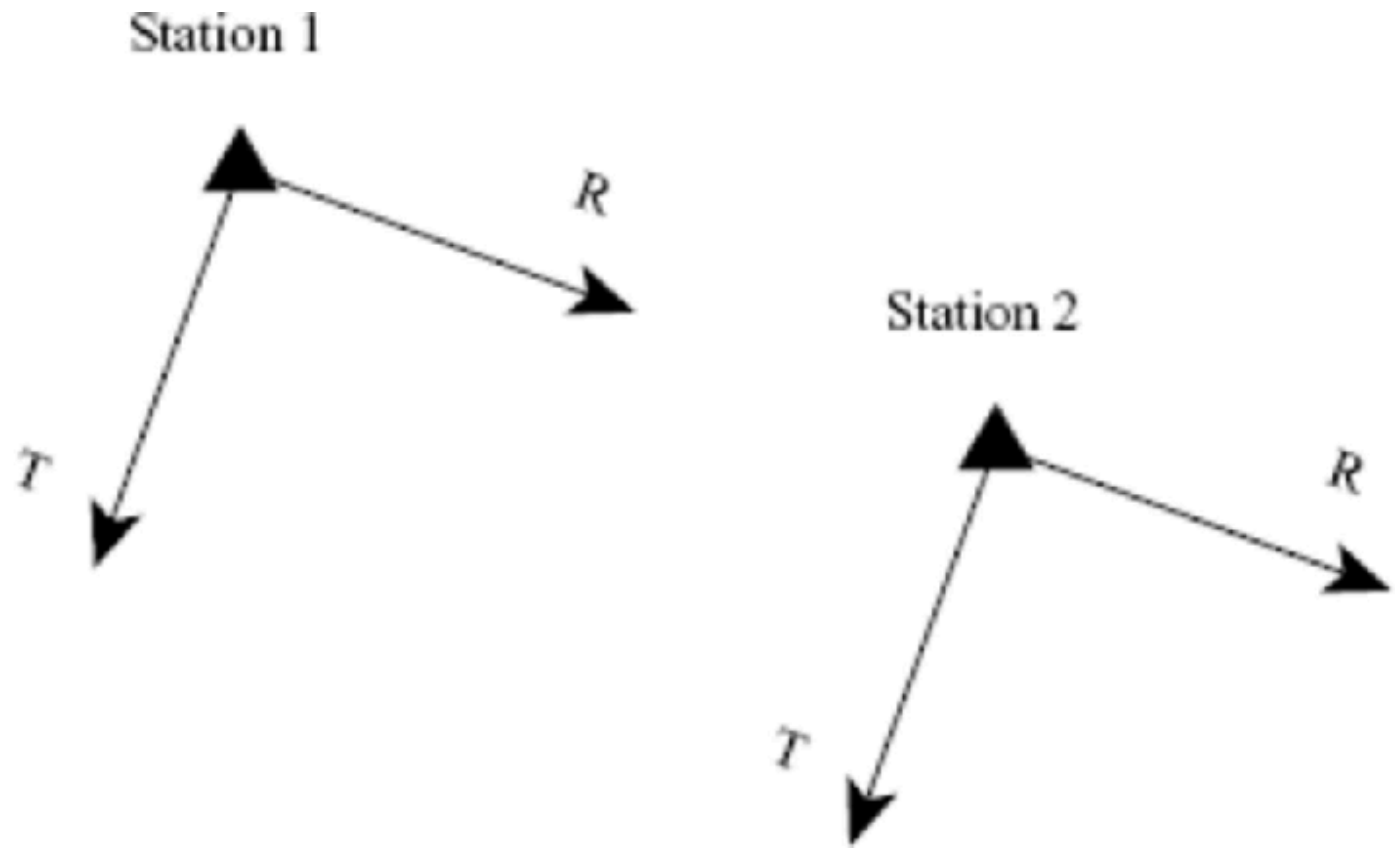


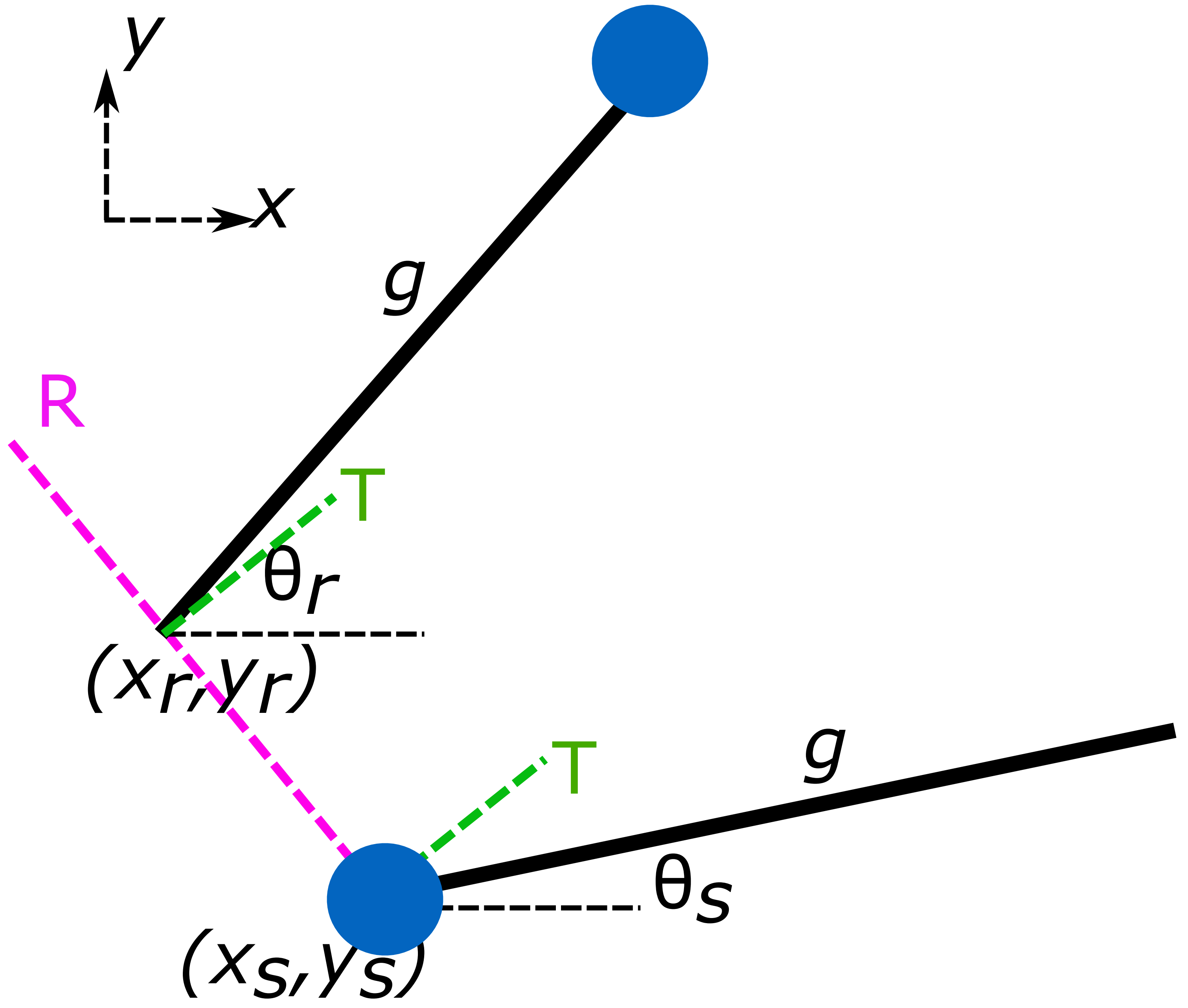
More generally, DAS cross-correlations are linear combinations of cross-correlations of improperly rotated geophones.



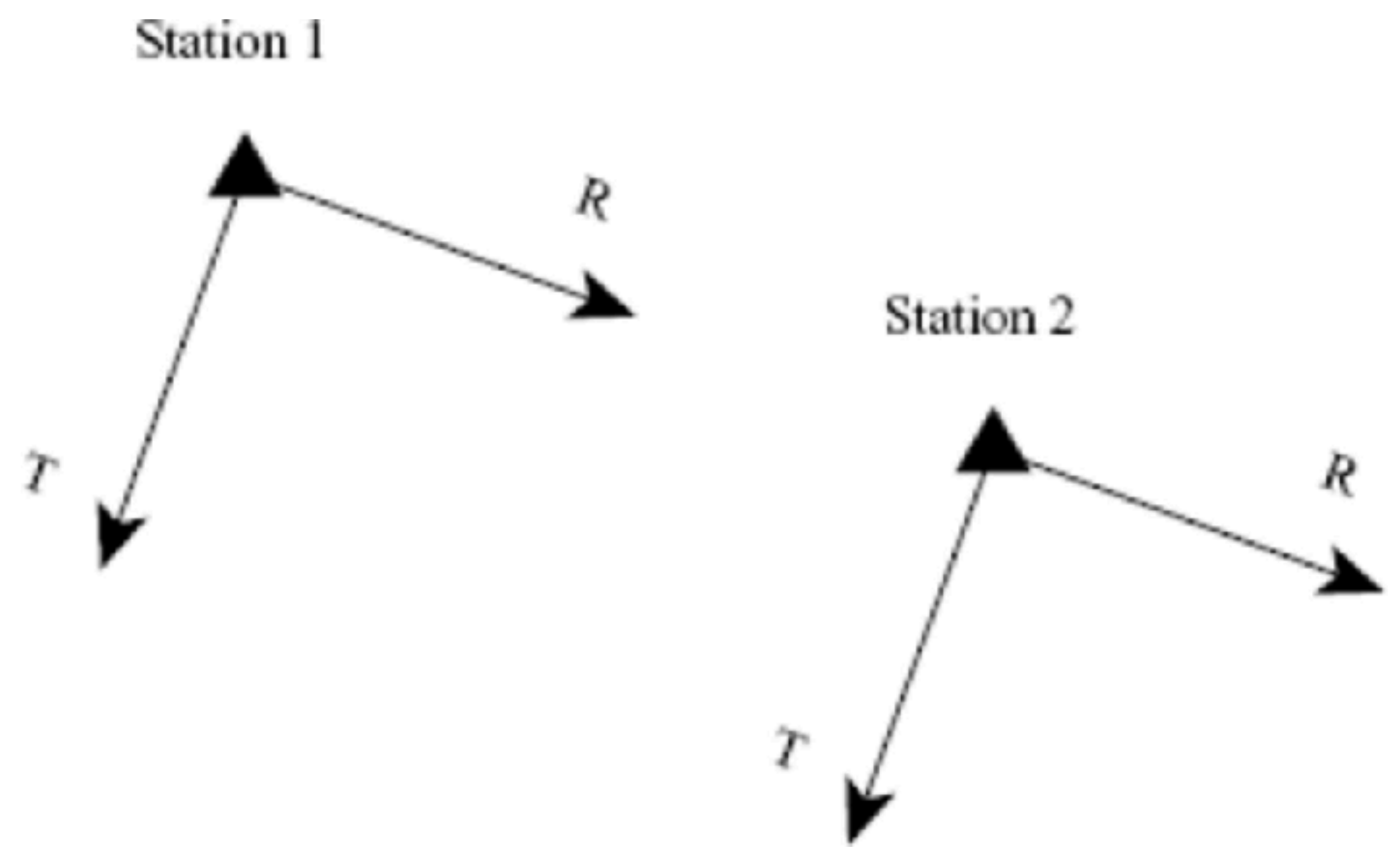


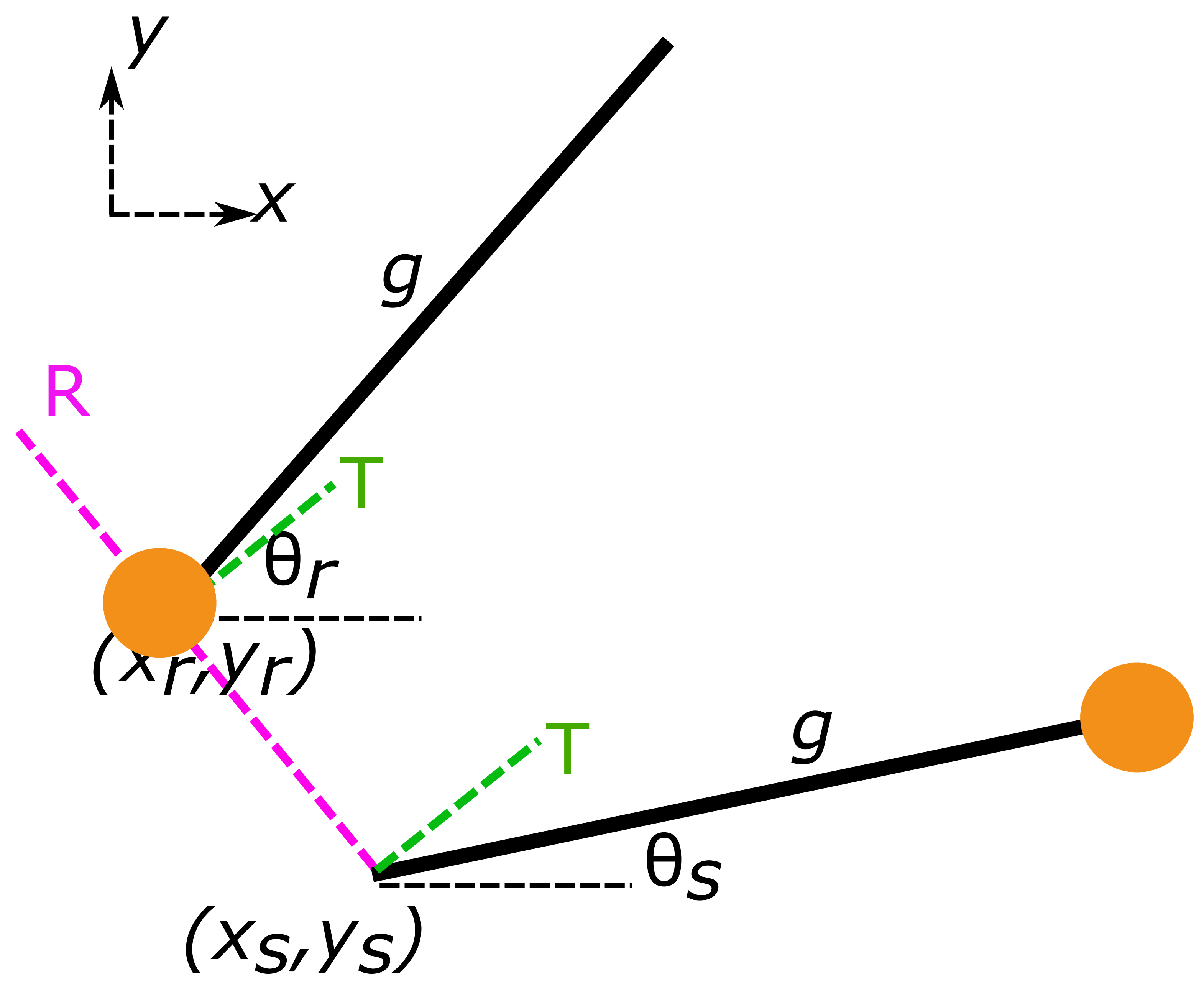
More generally, DAS cross-correlations are linear combinations of cross-correlations of improperly rotated geophones.



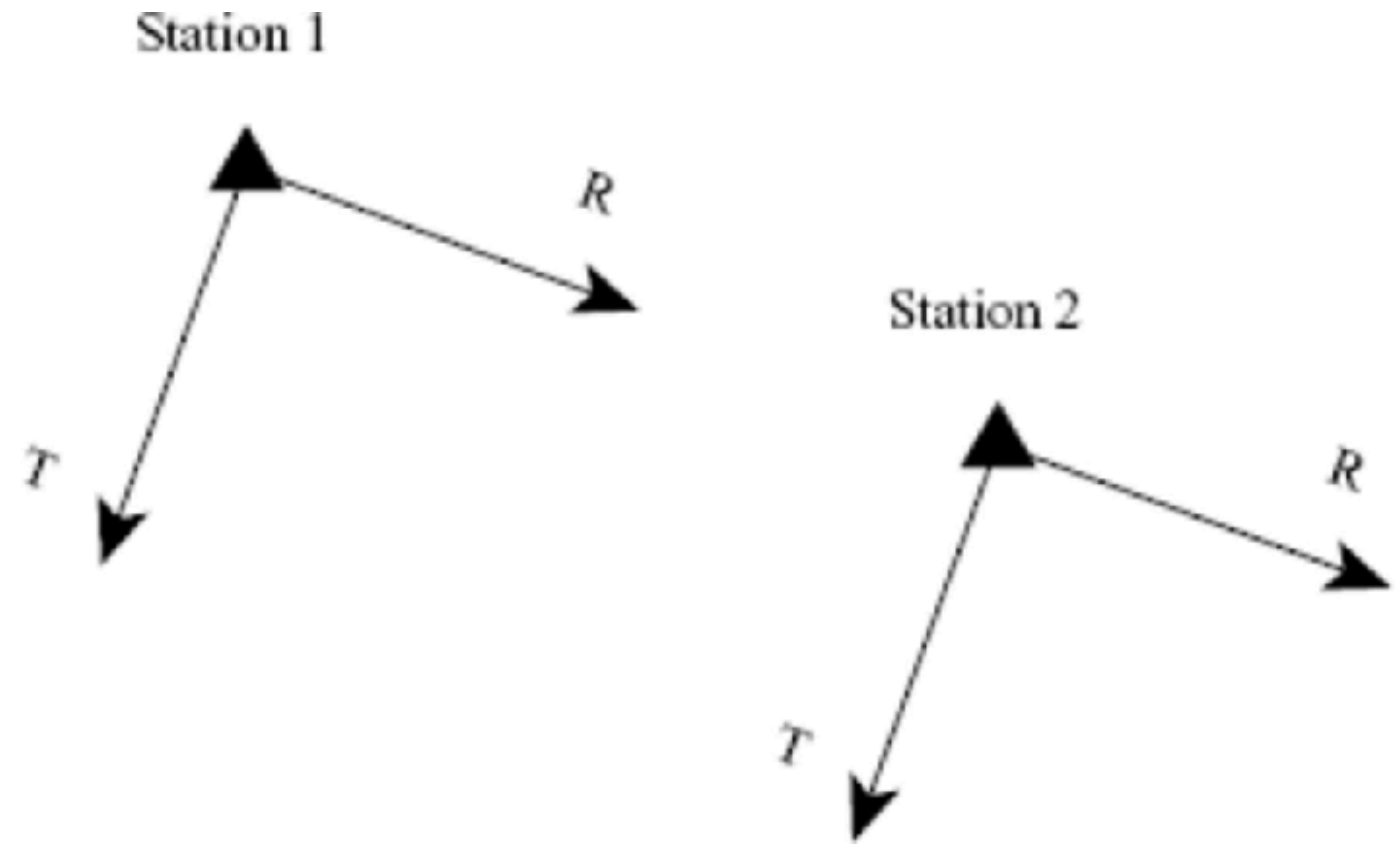


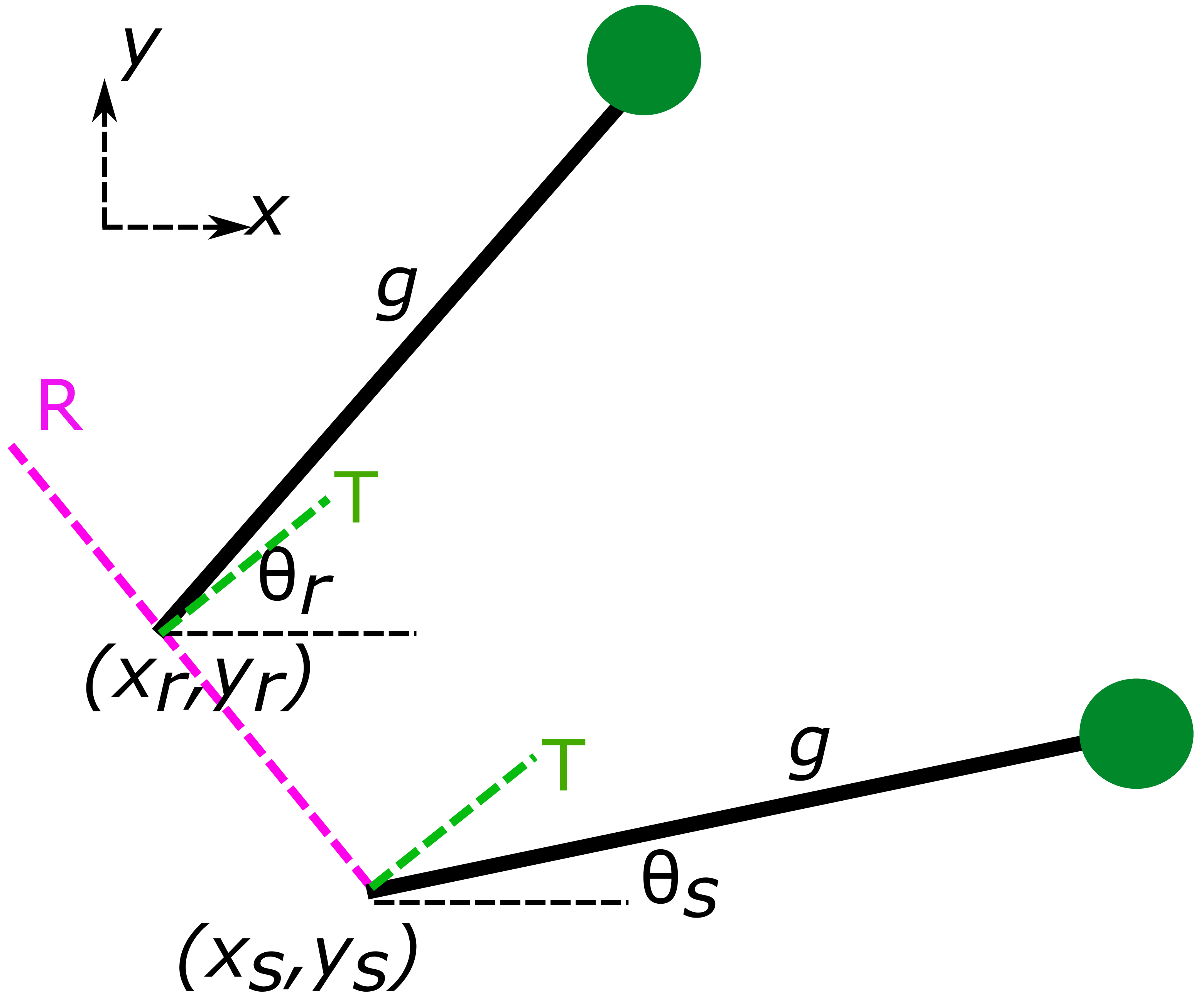
More generally, DAS cross-correlations are linear combinations of cross-correlations of improperly rotated geophones.





More generally, DAS cross-correlations are linear combinations of cross-correlations of improperly rotated geophones.





Outline

Ambient noise interferometry background

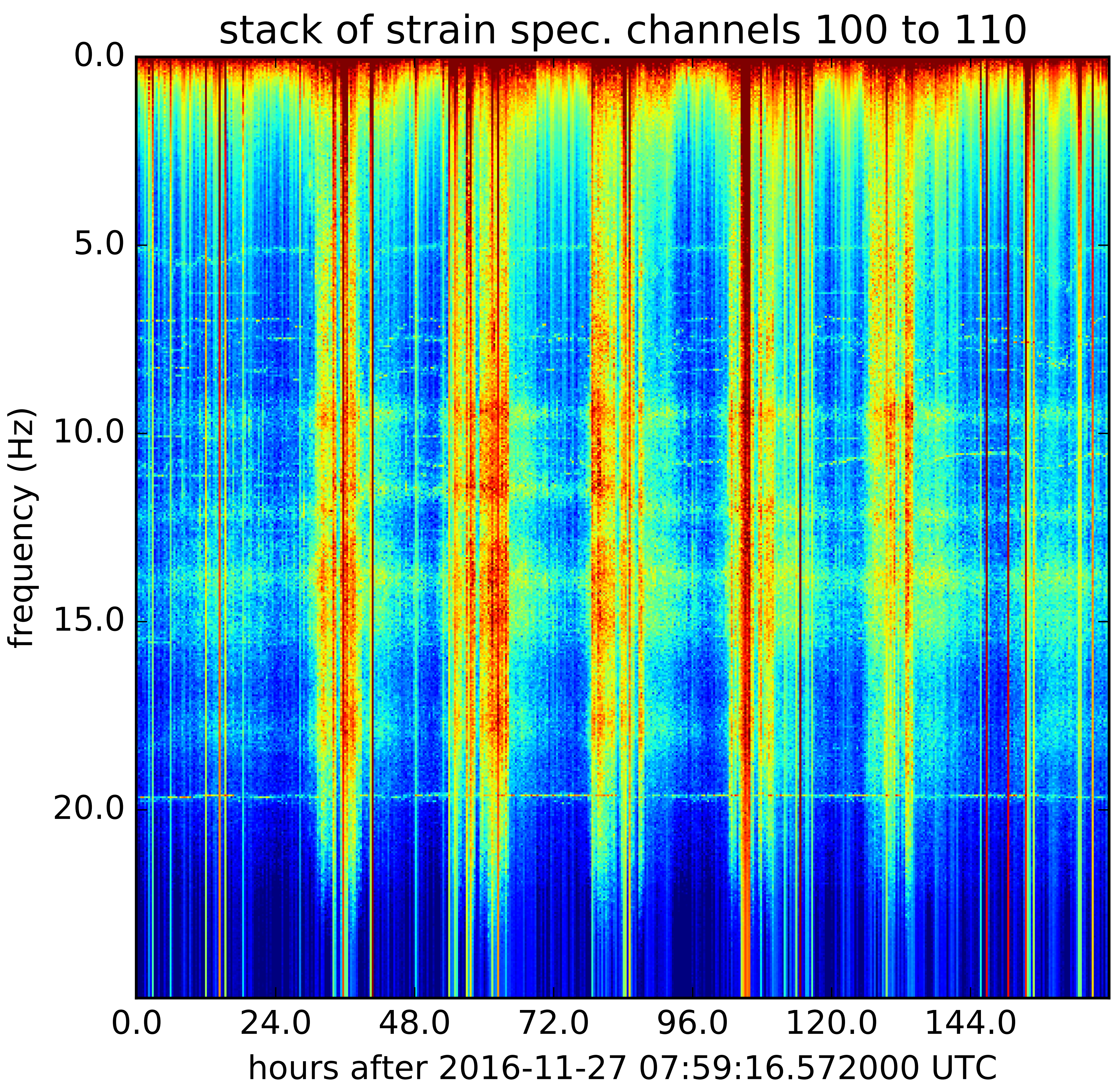
2D DAS interferometry theory

Practical challenges

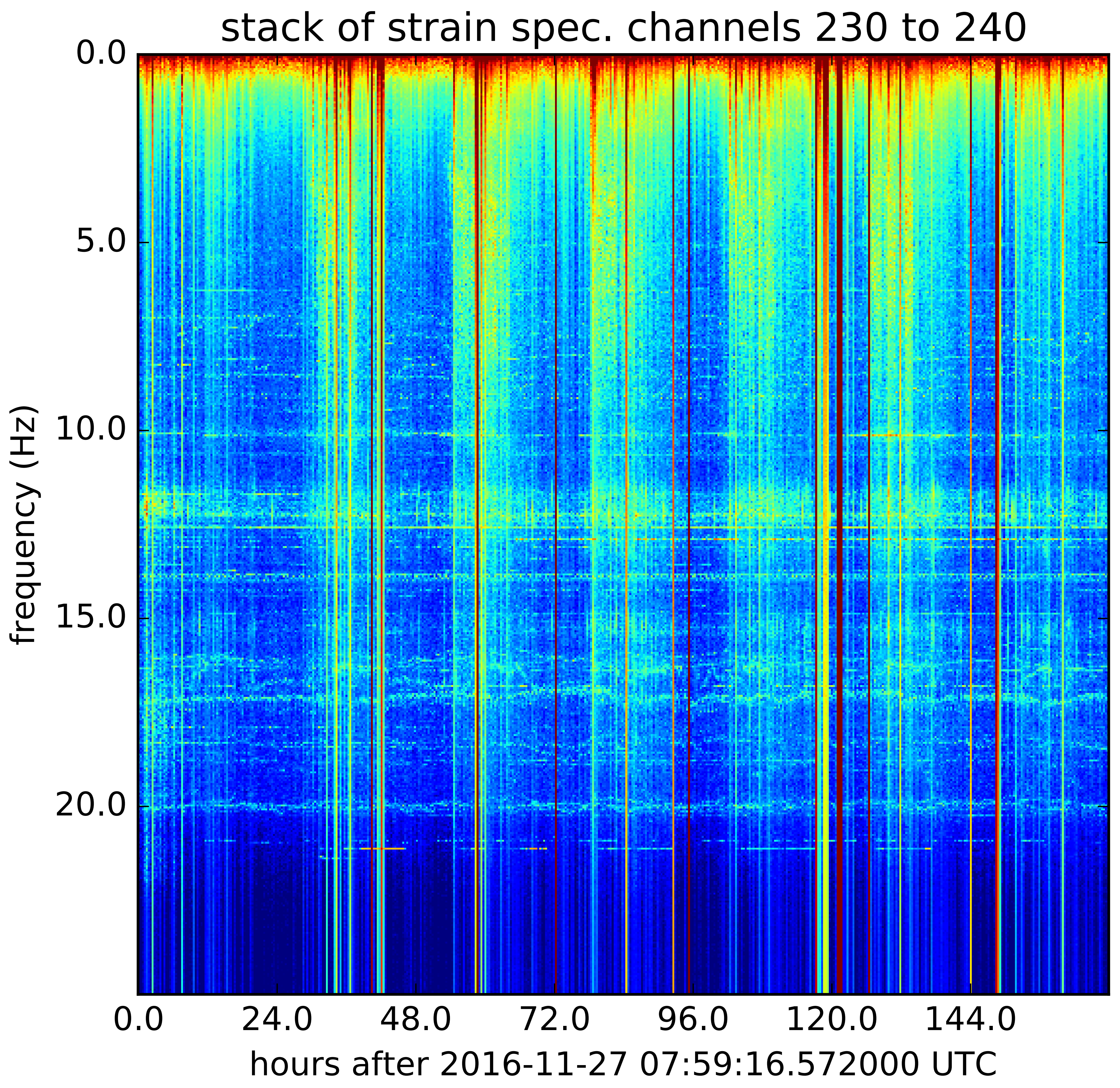
2D Examples

Summary and directions forward

Traffic, Localized Noise Sources

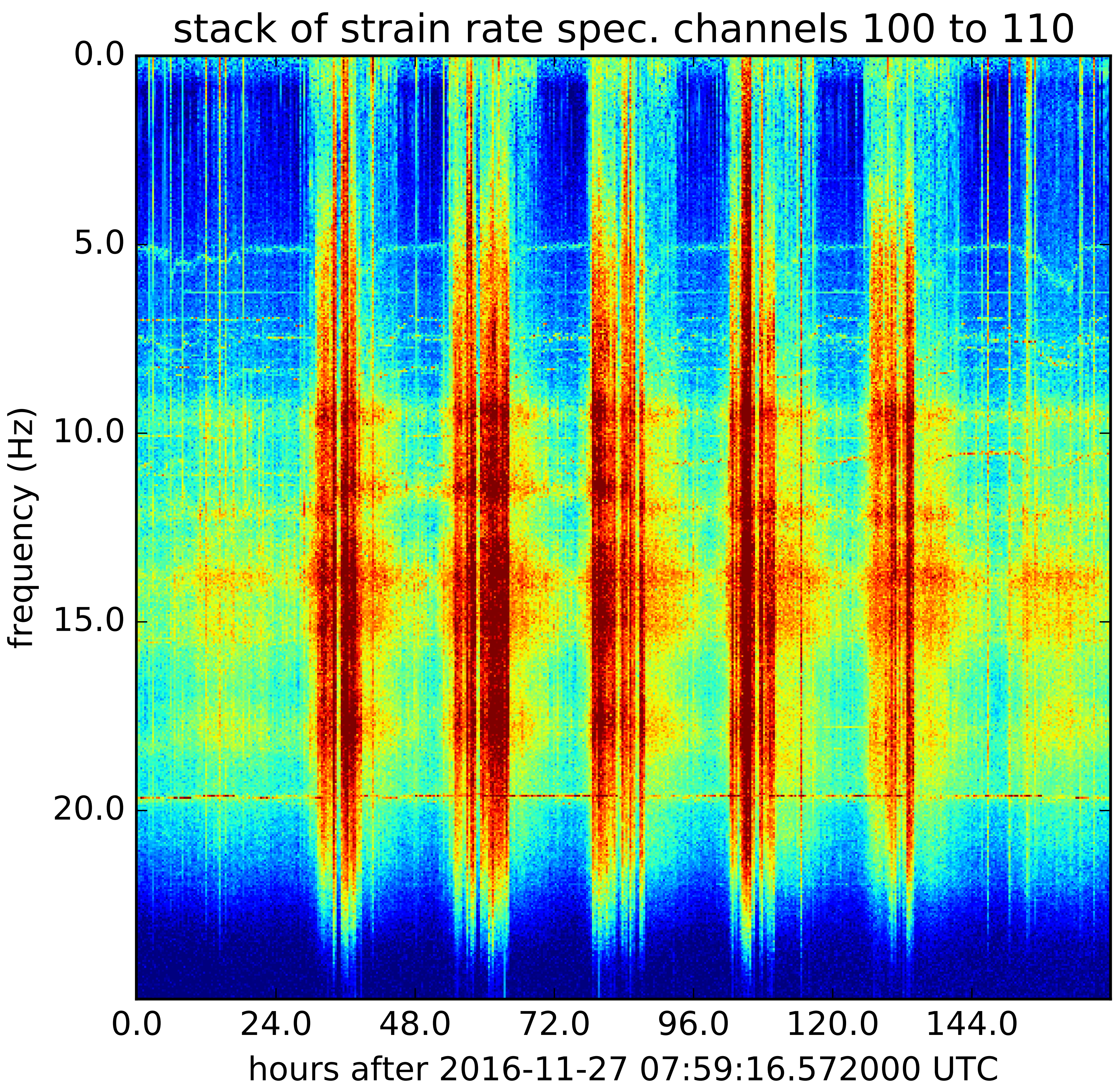


along Campus Dr.

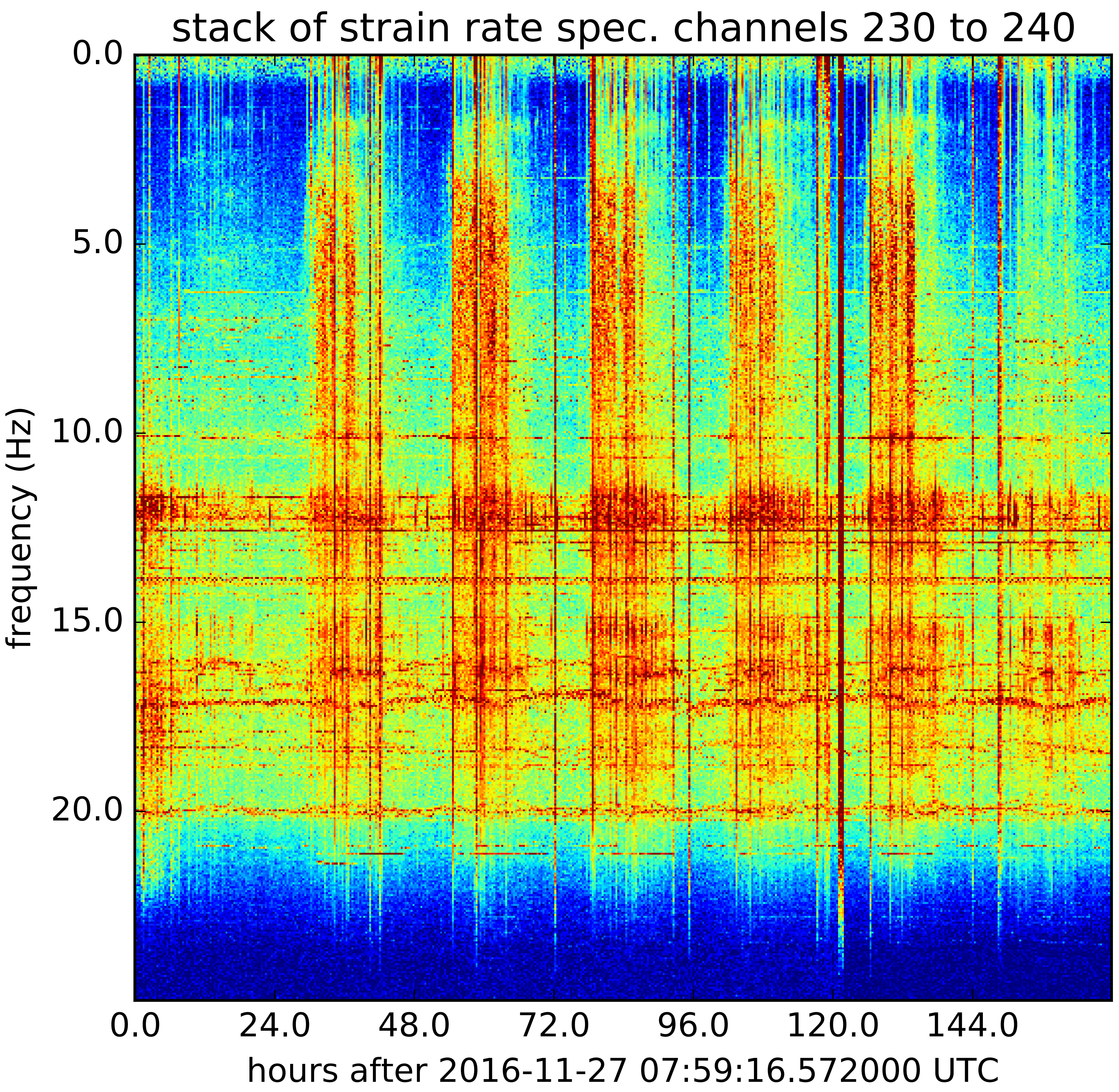


along Via Pueblo

Traffic, Localized Noise Sources

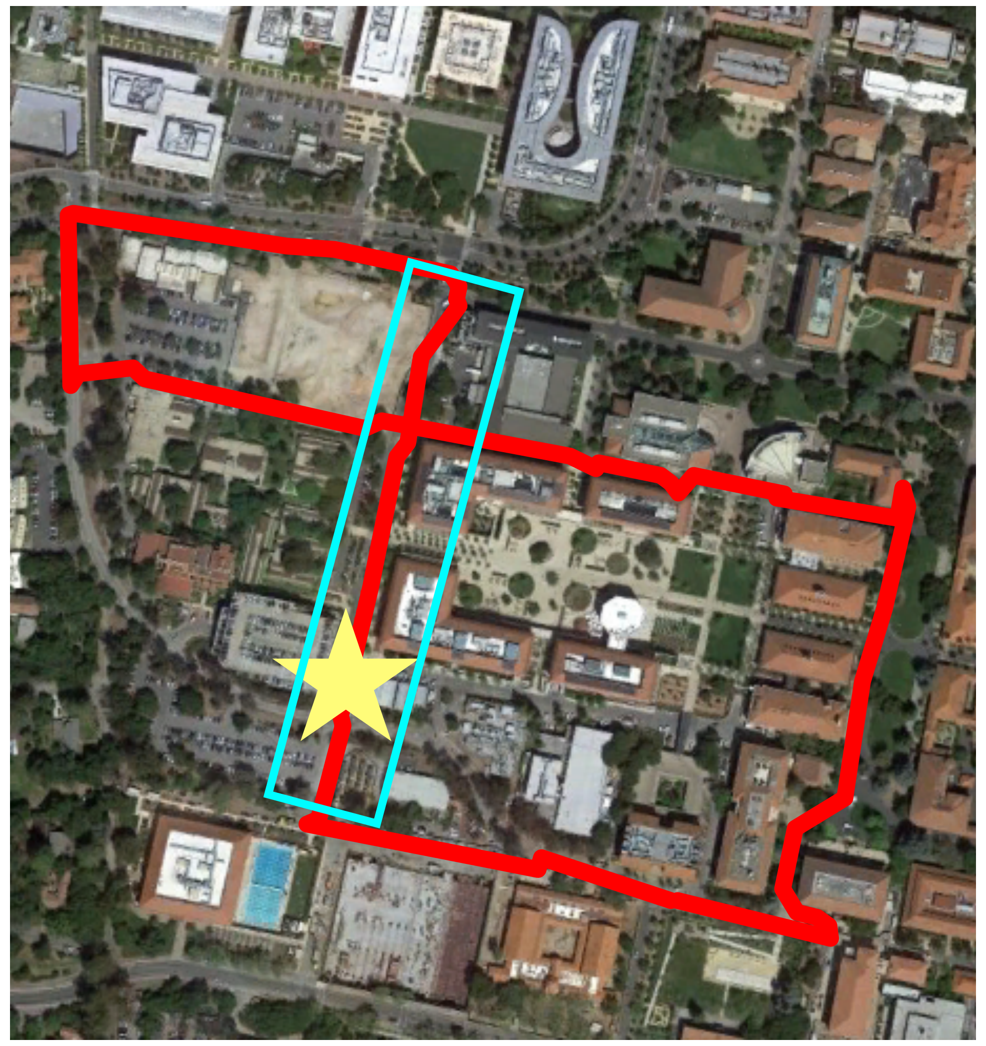


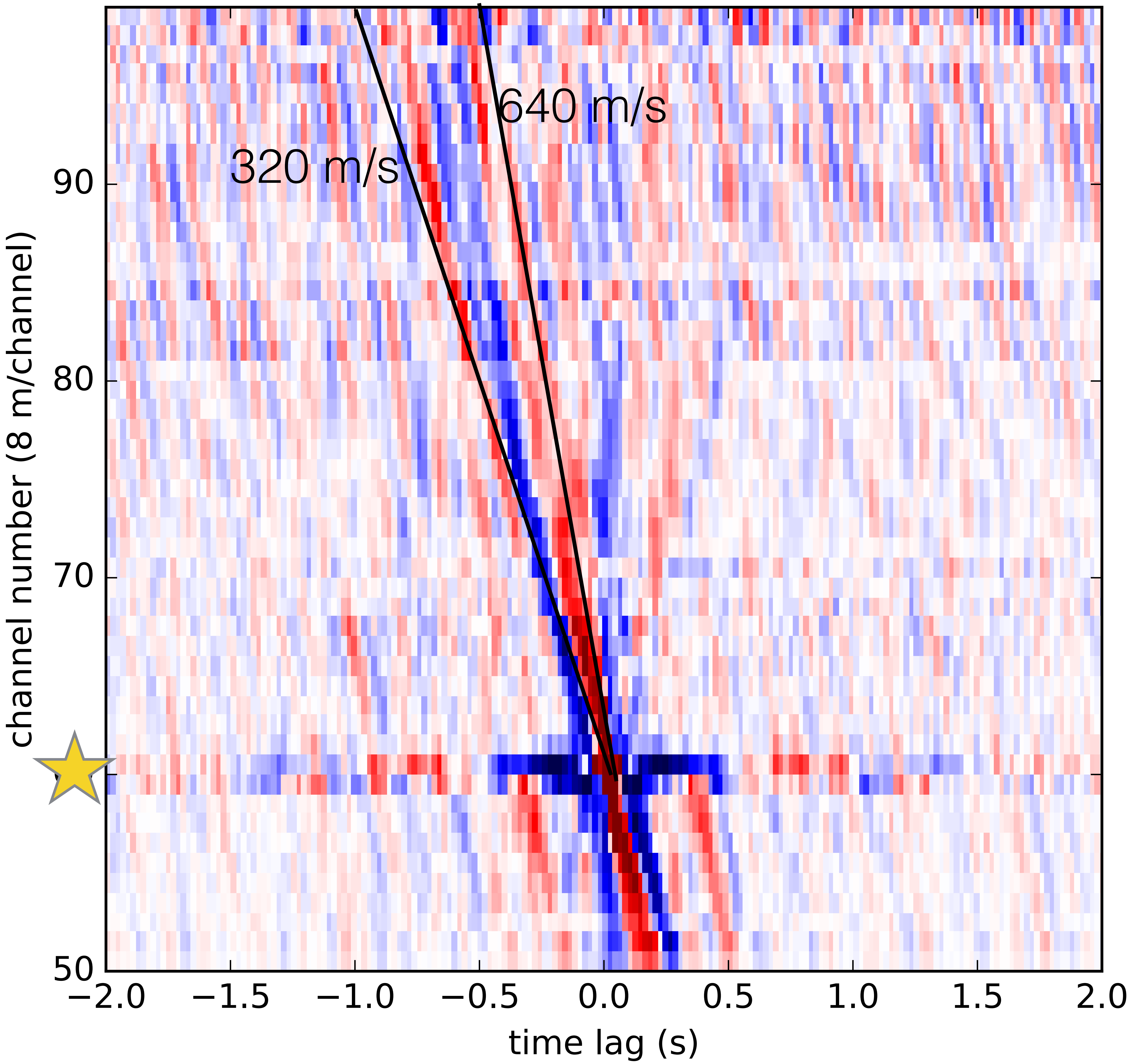
along Campus Dr.



along Via Pueblo

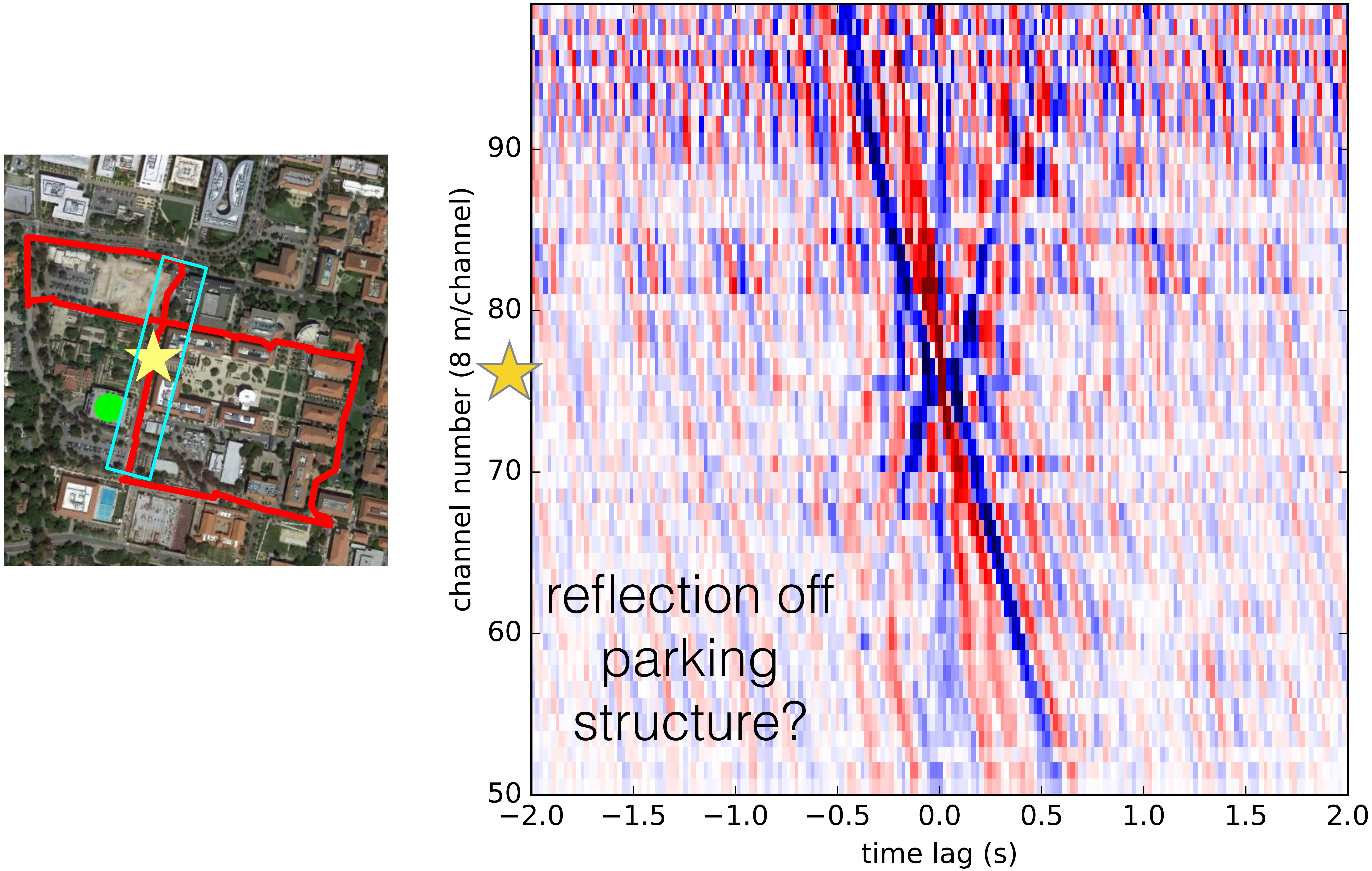
Virtual Source Channel 60



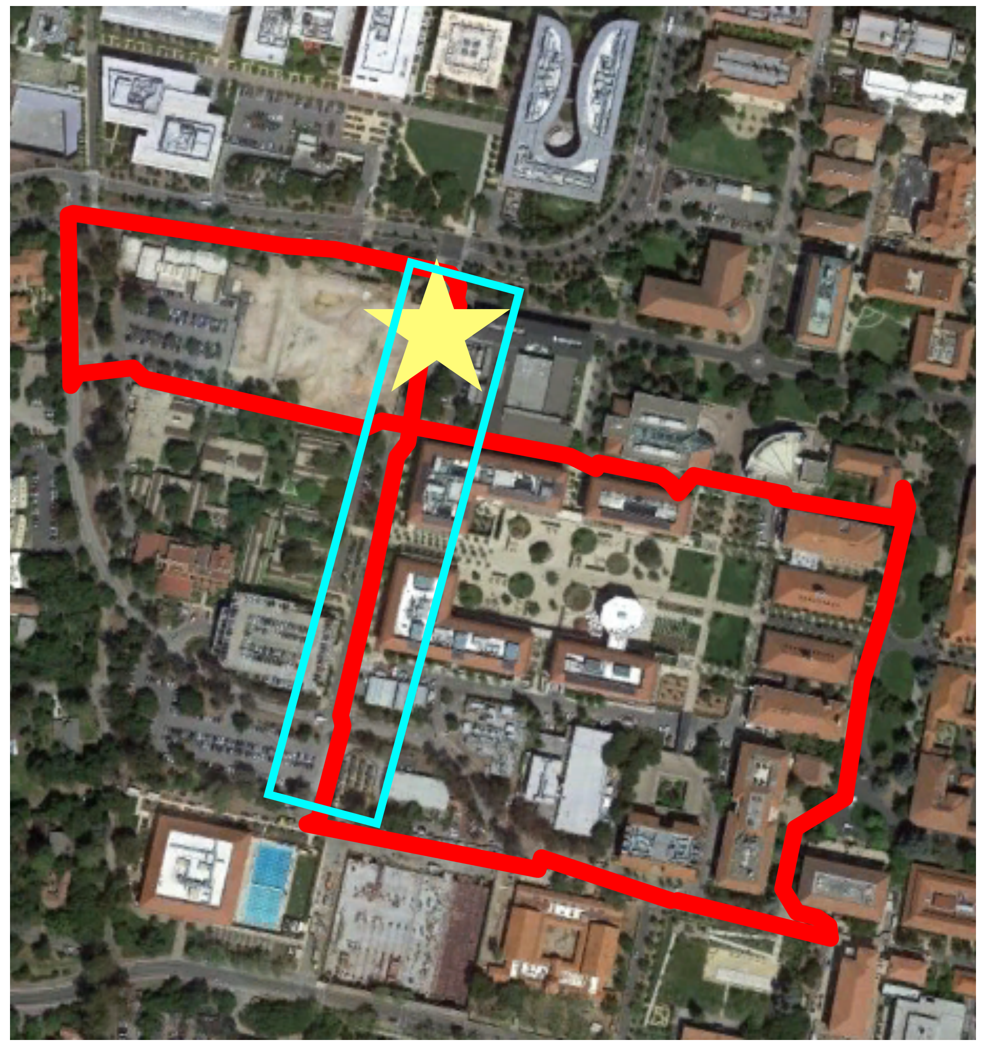


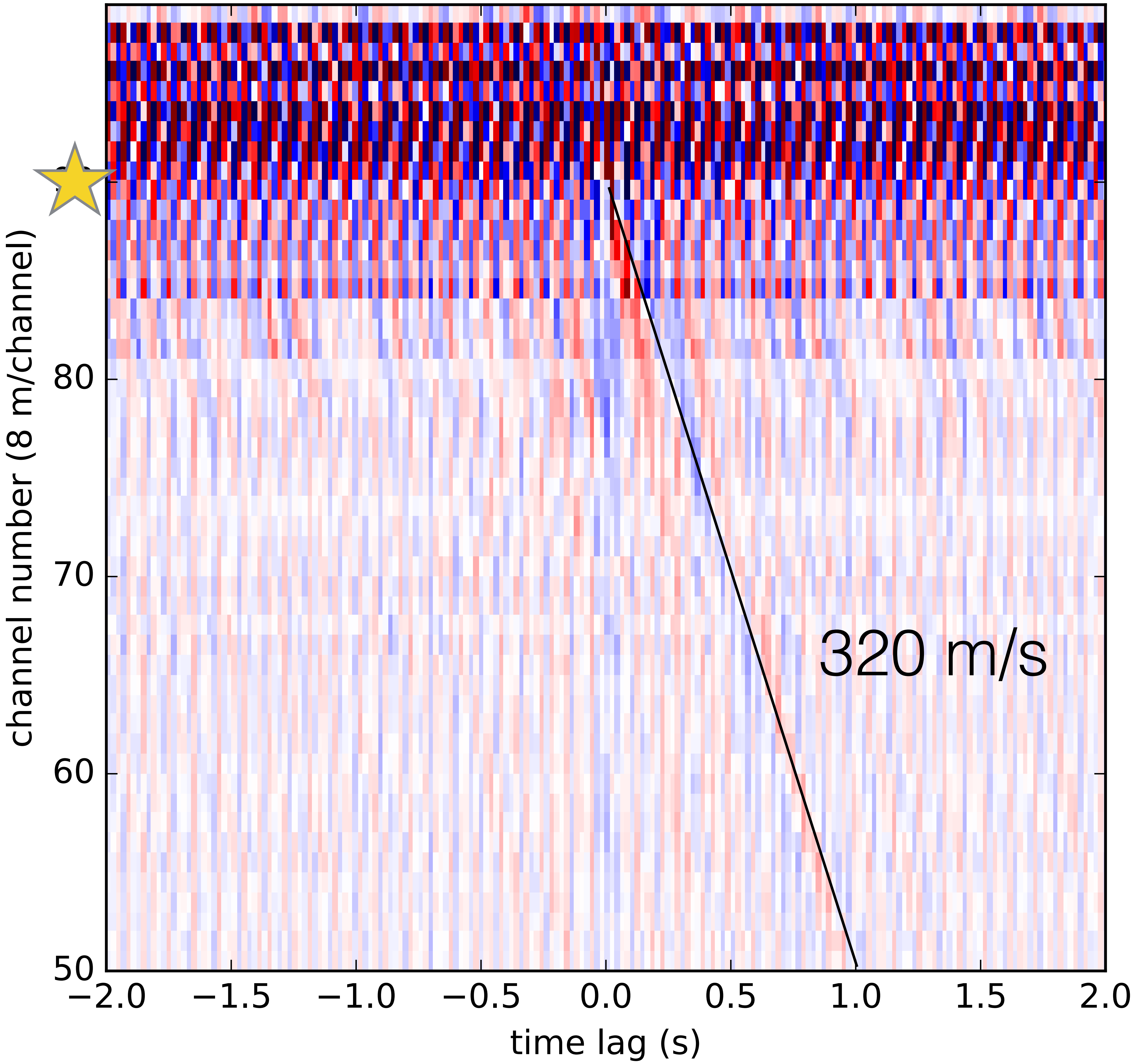
1 to 24 Hz

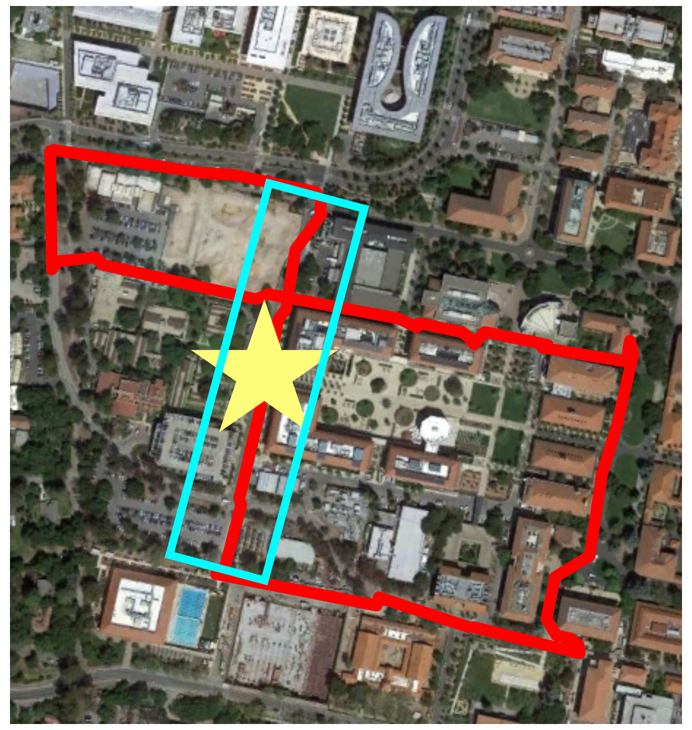
Virtual Source Channel 75



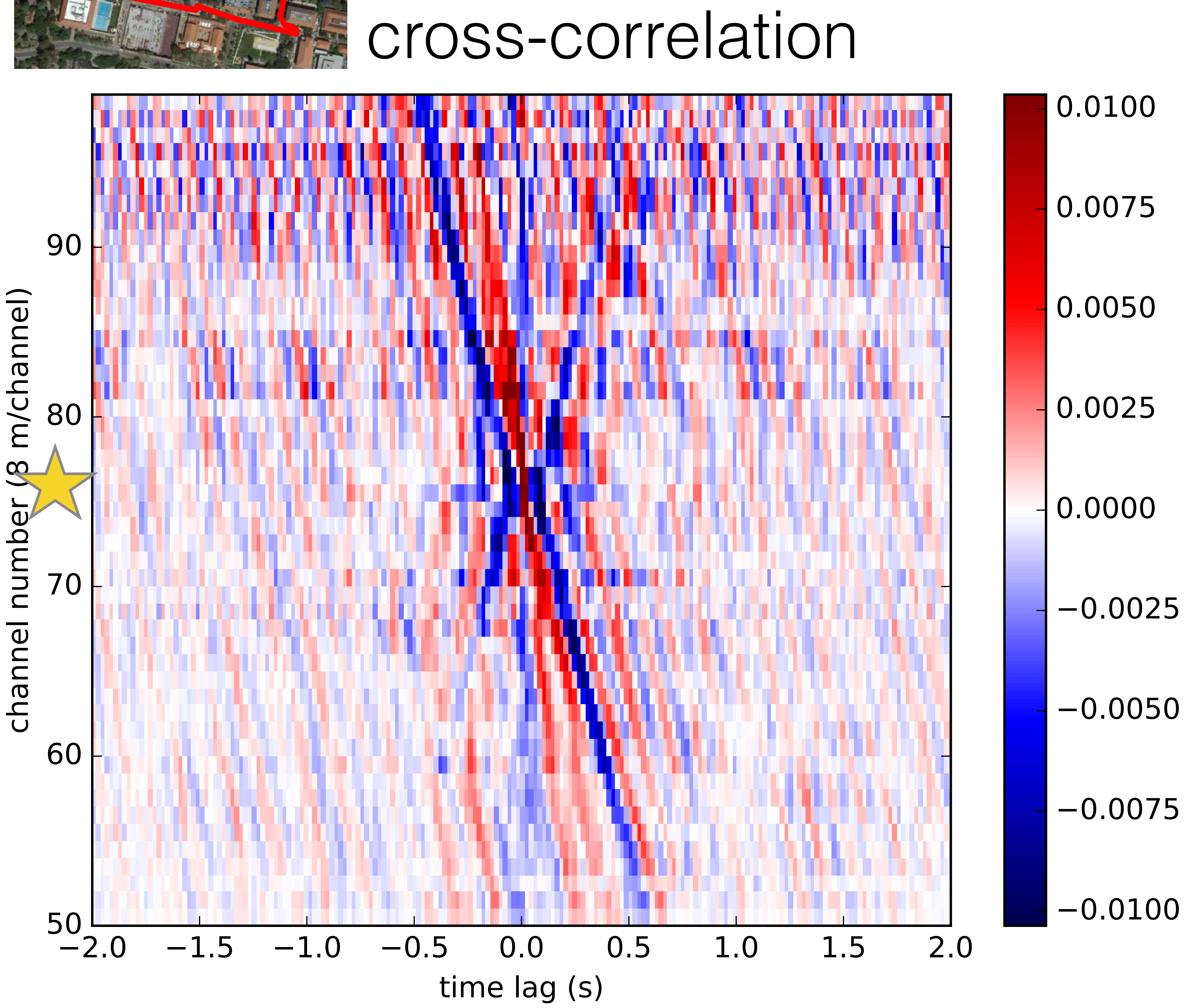
Virtual Source Channel 90

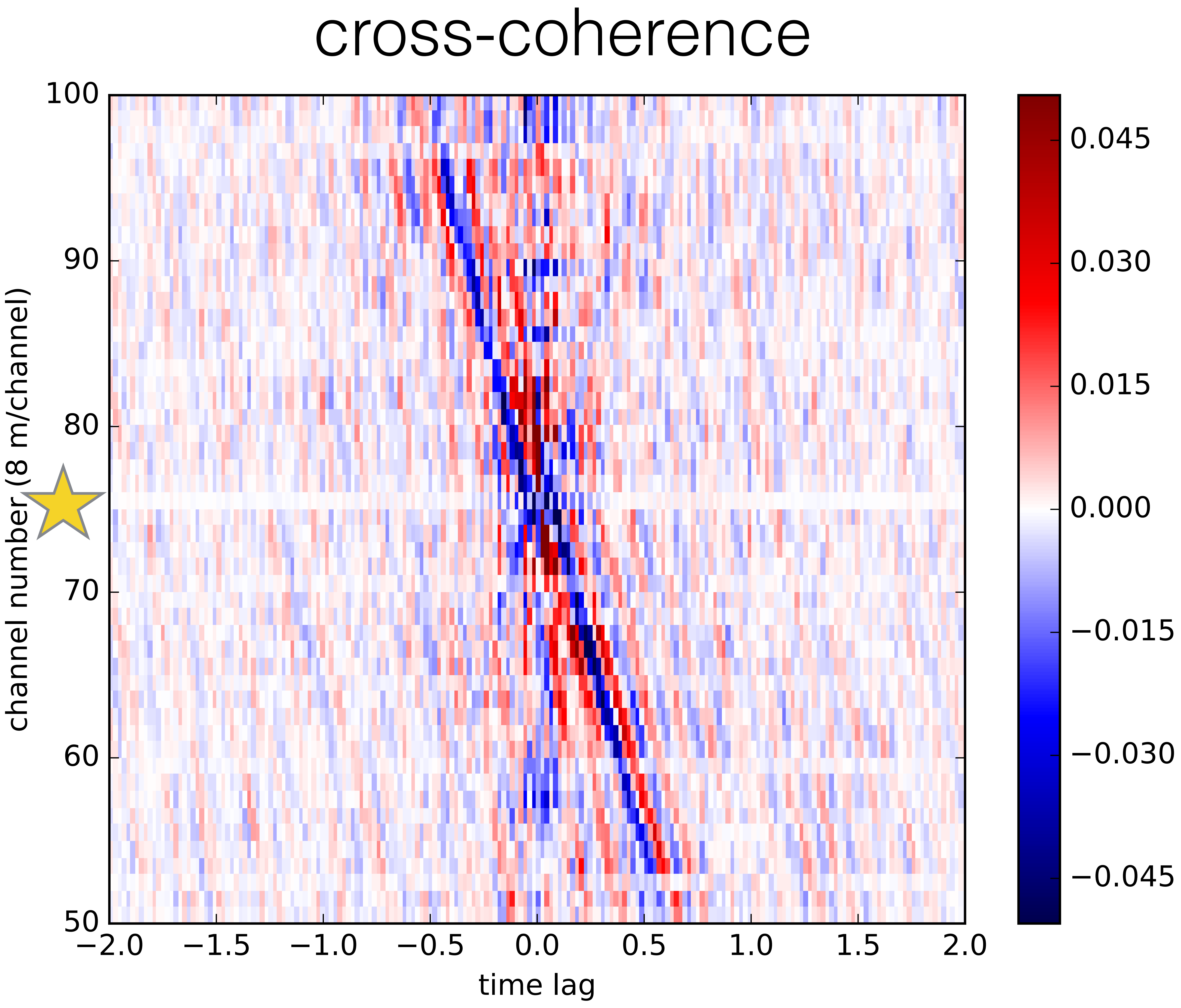






Cross-Correlation or Coherence?





Outline

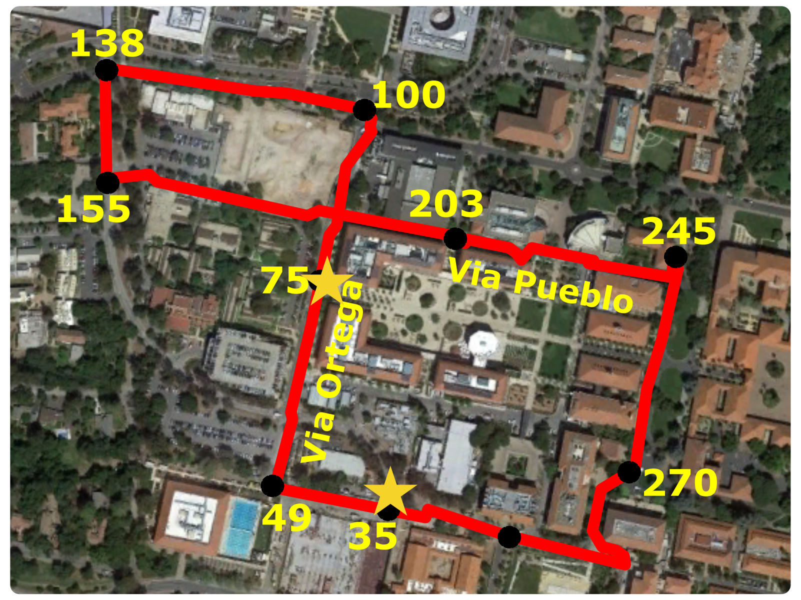
Ambient noise interferometry background

2D DAS interferometry theory

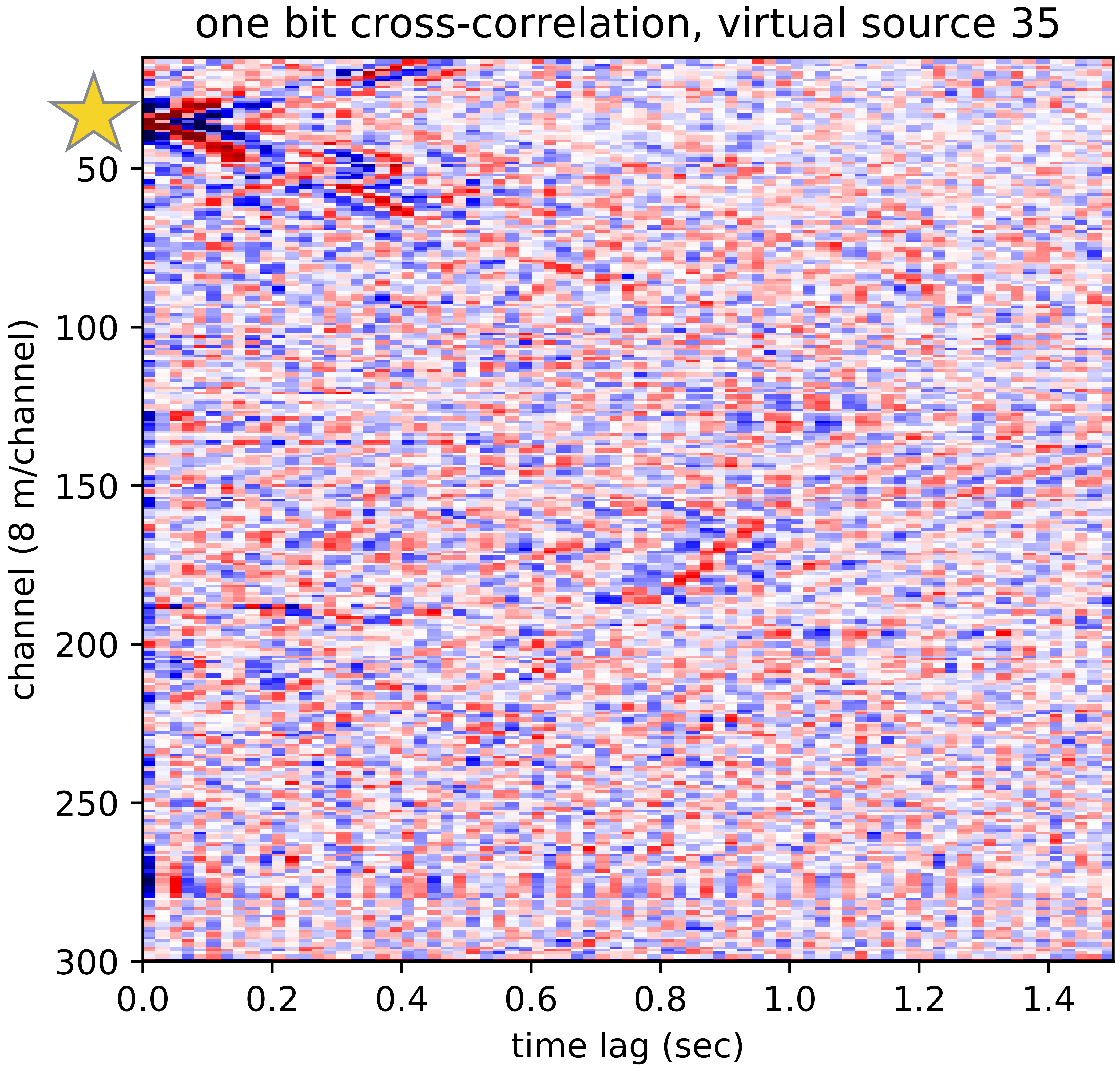
Practical challenges

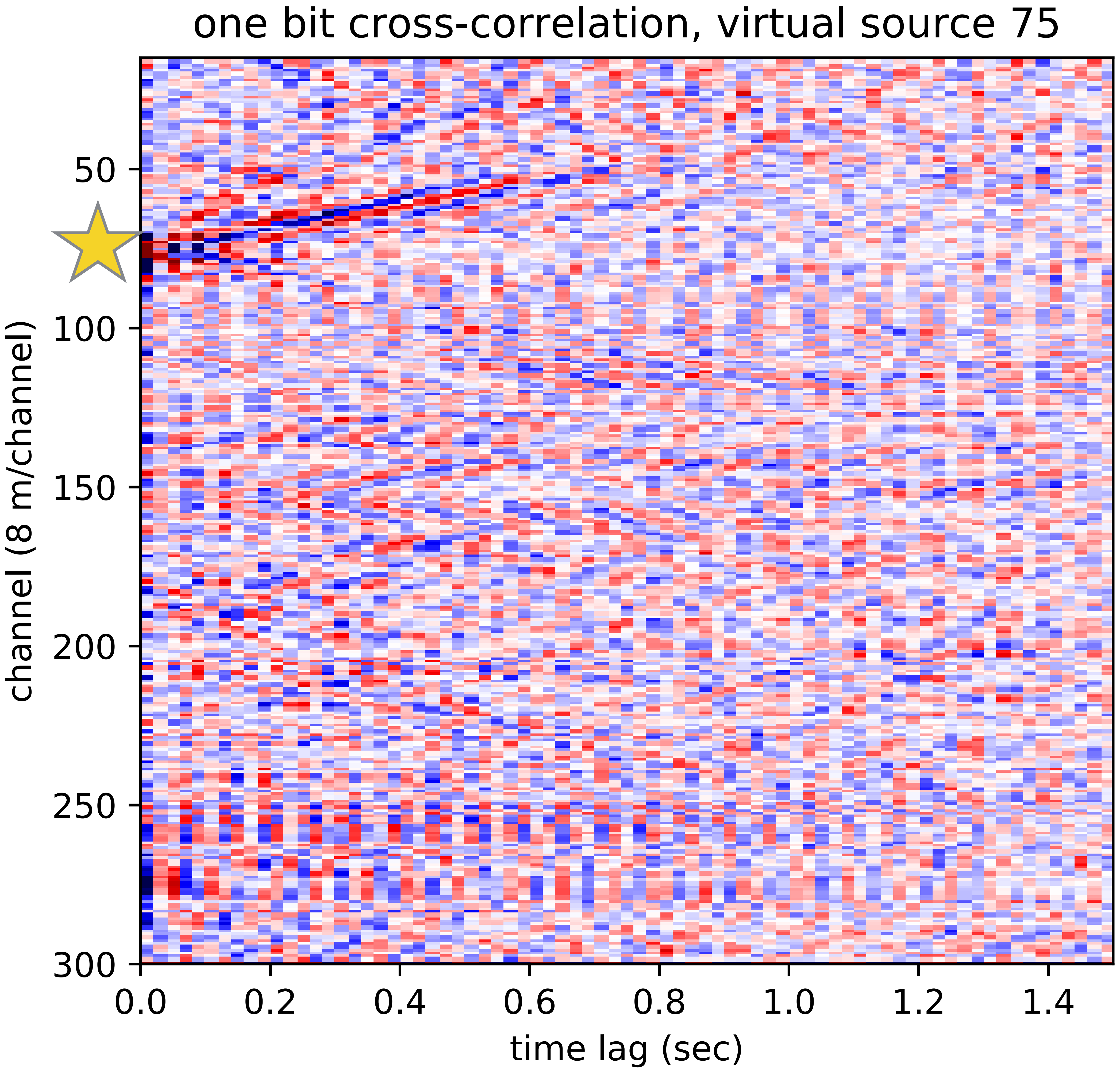
2D Examples

Summary and directions forward

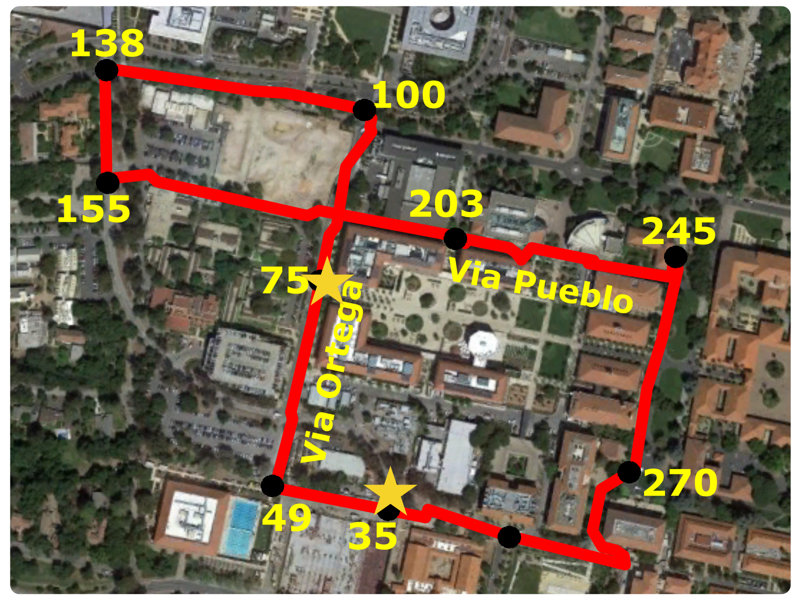


1-bit cross-correlation, 1 day



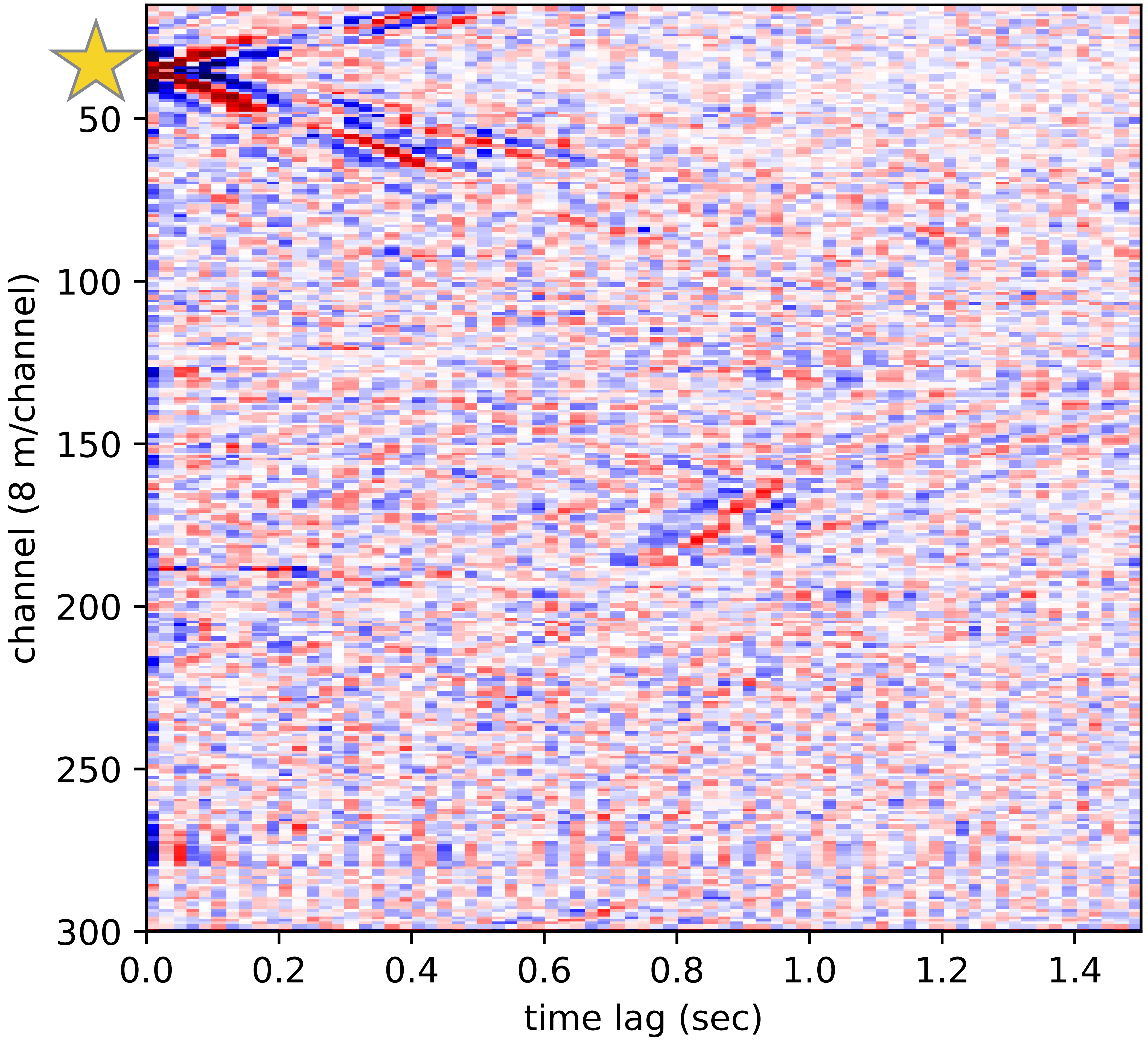


E. Martin and B. Biondi, “Ambient noise interferometry across two-dimensional DAS arrays,” submitted to SEG annual meeting.

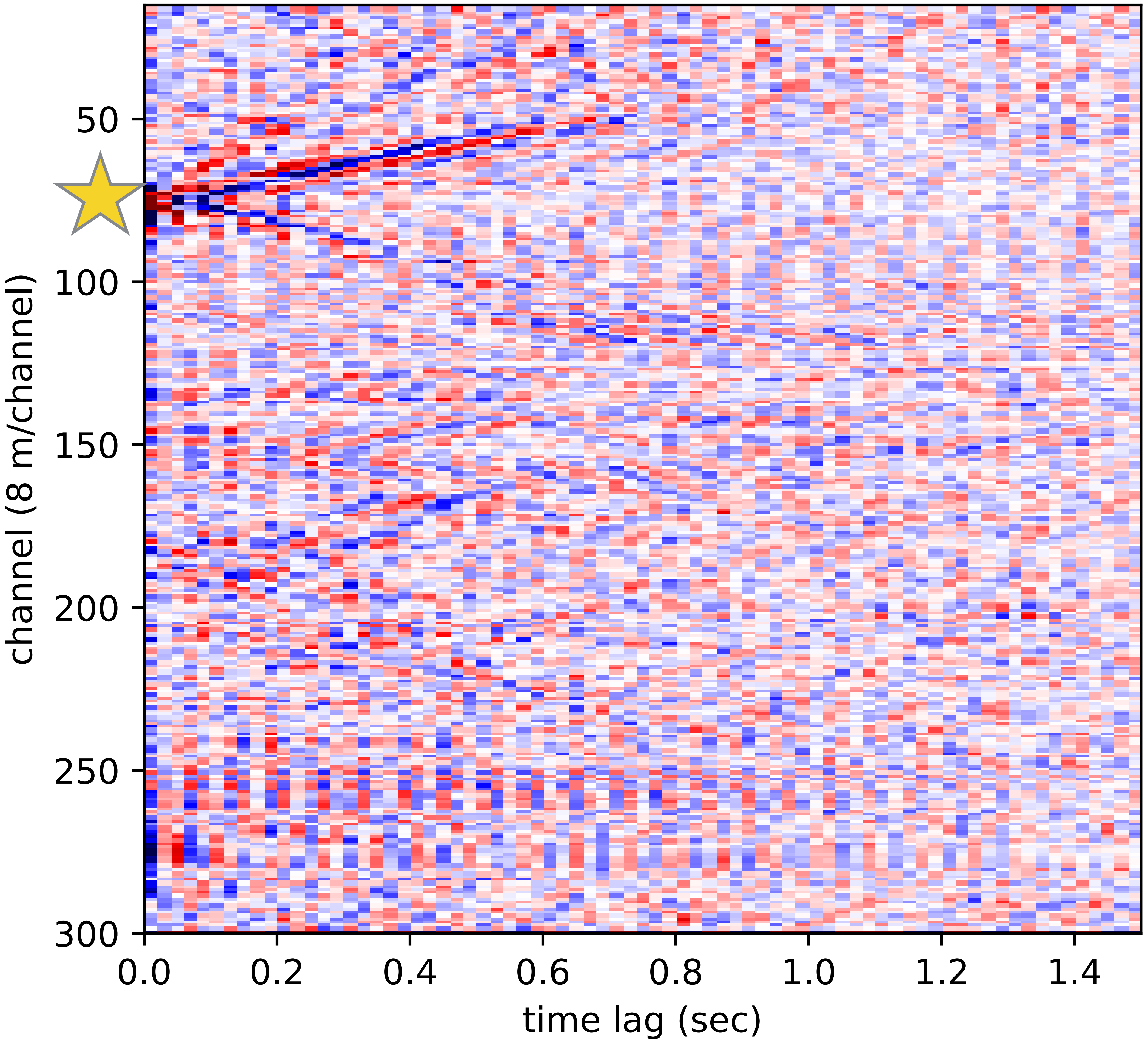


1-bit cross-correlation, 3 day

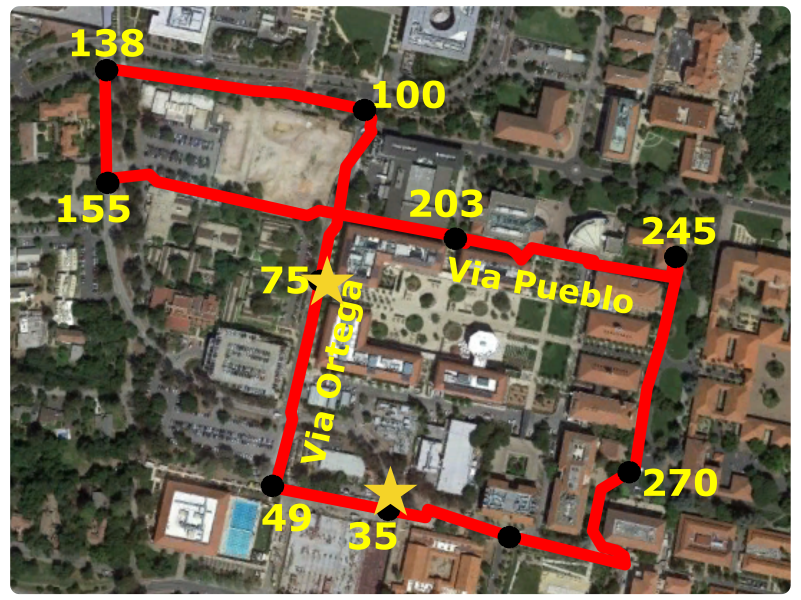
one bit cross-correlation, virtual source 35



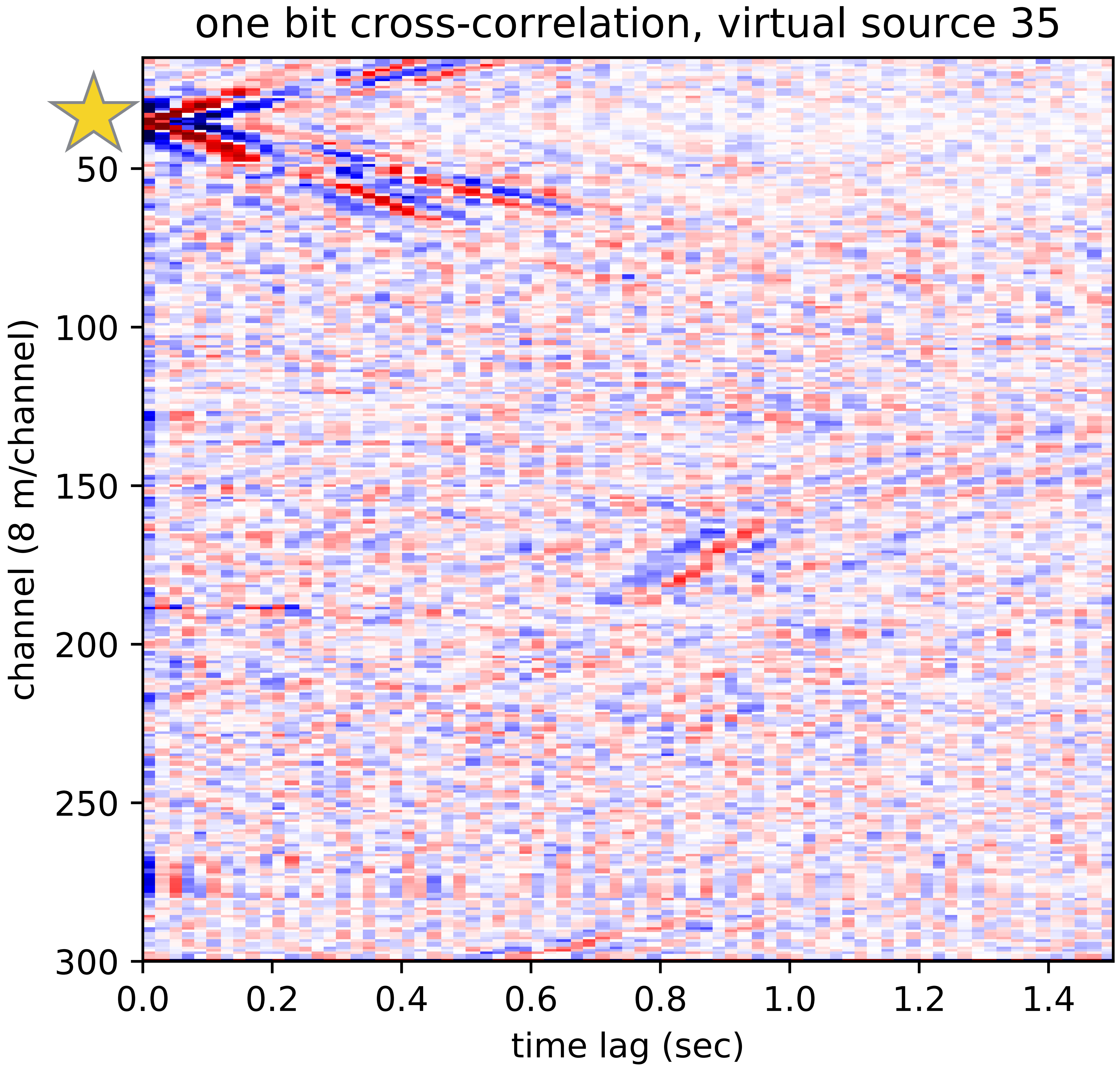
one bit cross-correlation, virtual source 75

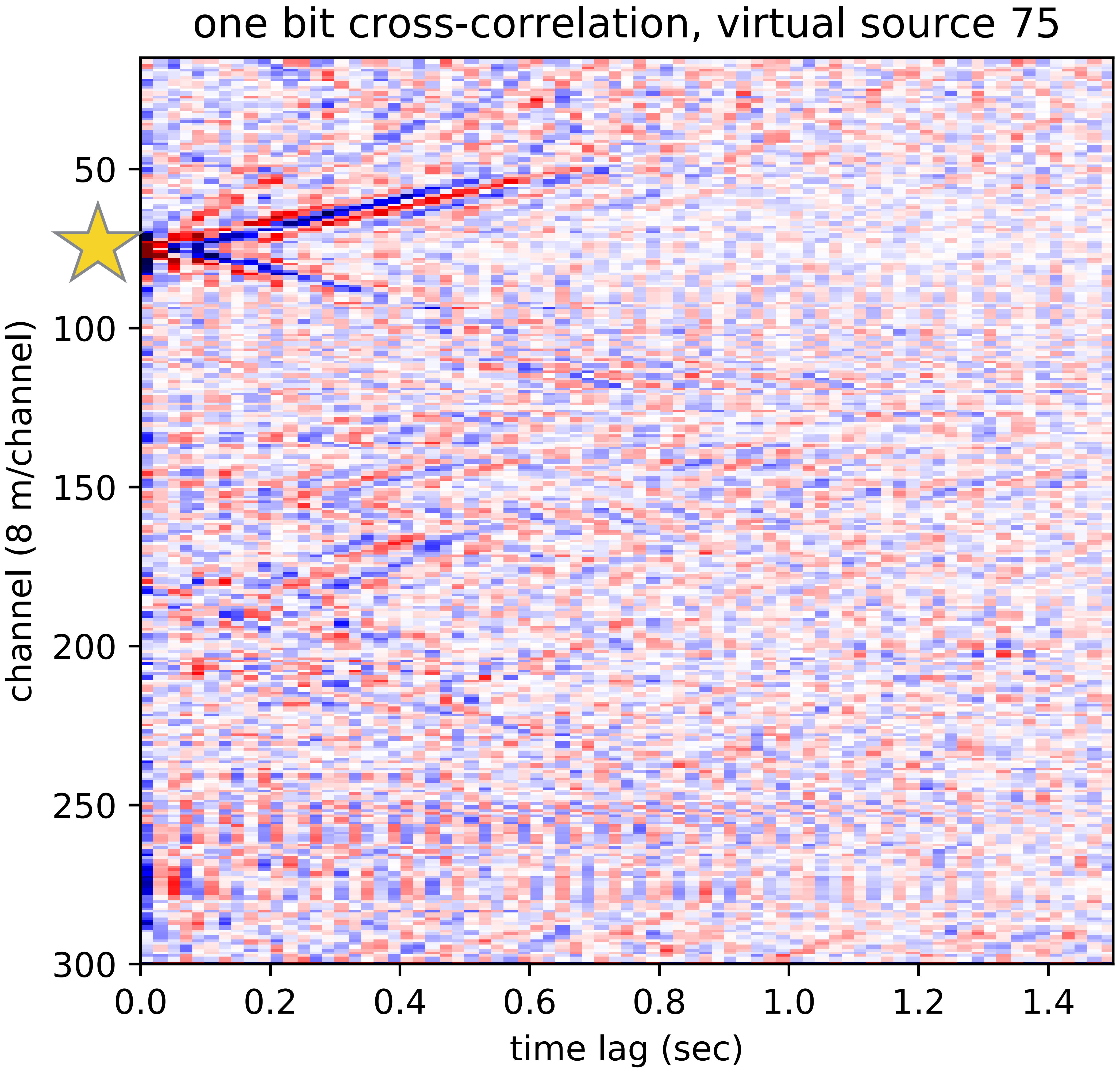


E. Martin and B. Biondi, "Ambient noise interferometry across two-dimensional DAS arrays," submitted to SEG annual meeting.

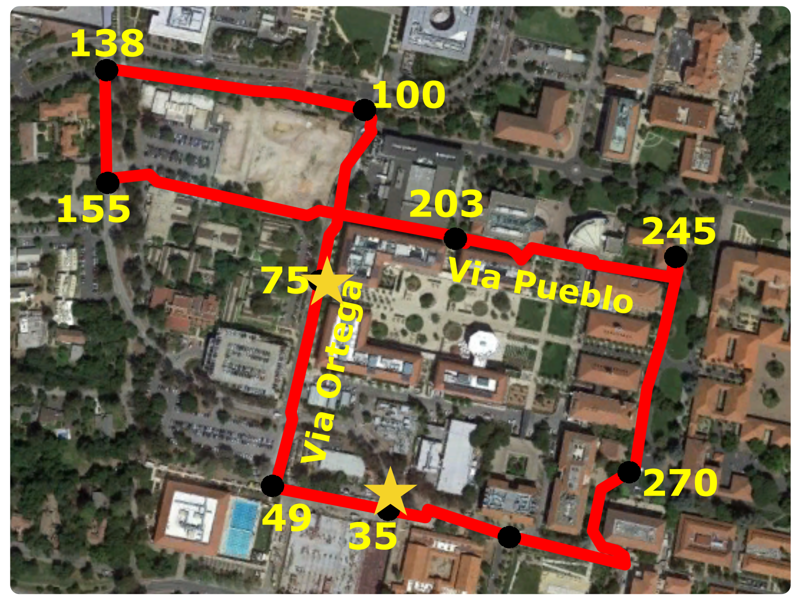


1-bit cross-correlation, 5 day

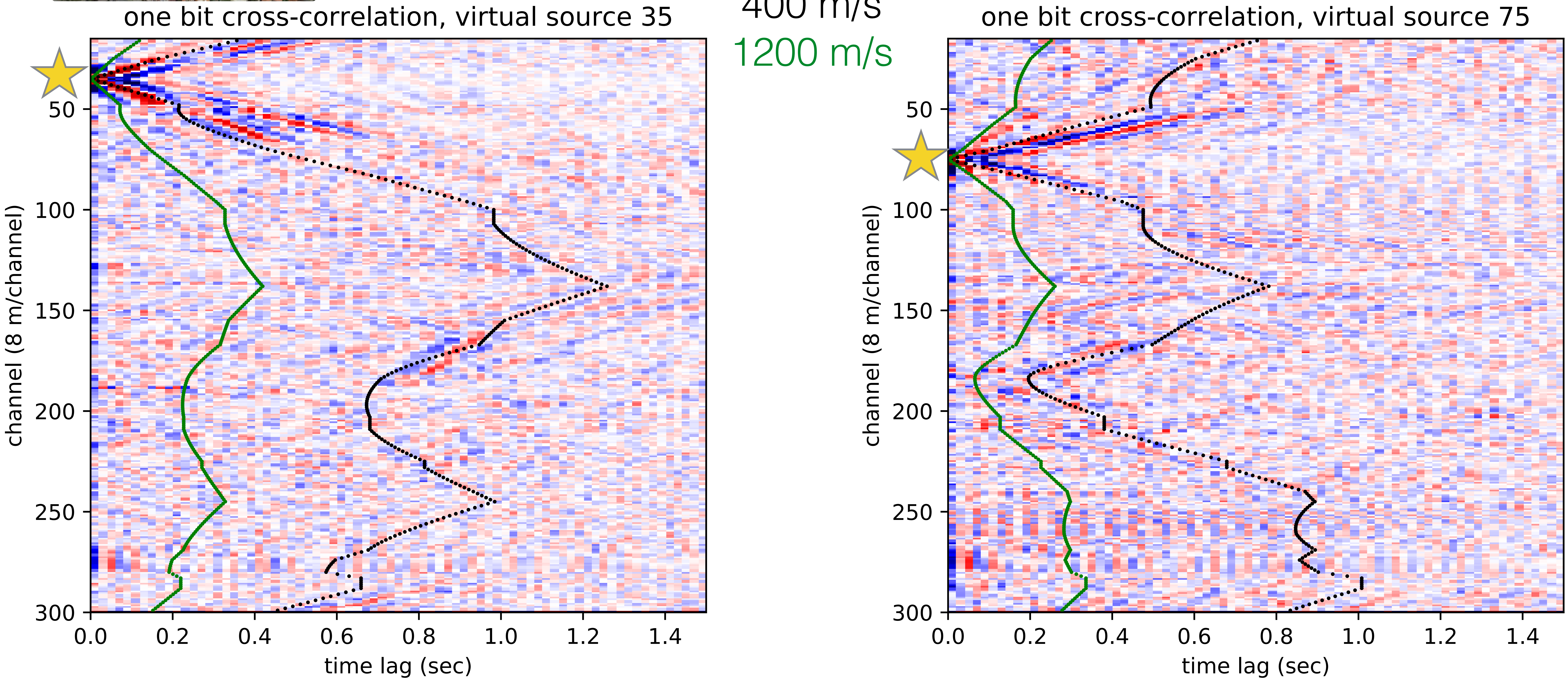




E. Martin and B. Biondi, “Ambient noise interferometry across two-dimensional DAS arrays,” submitted to SEG annual meeting.

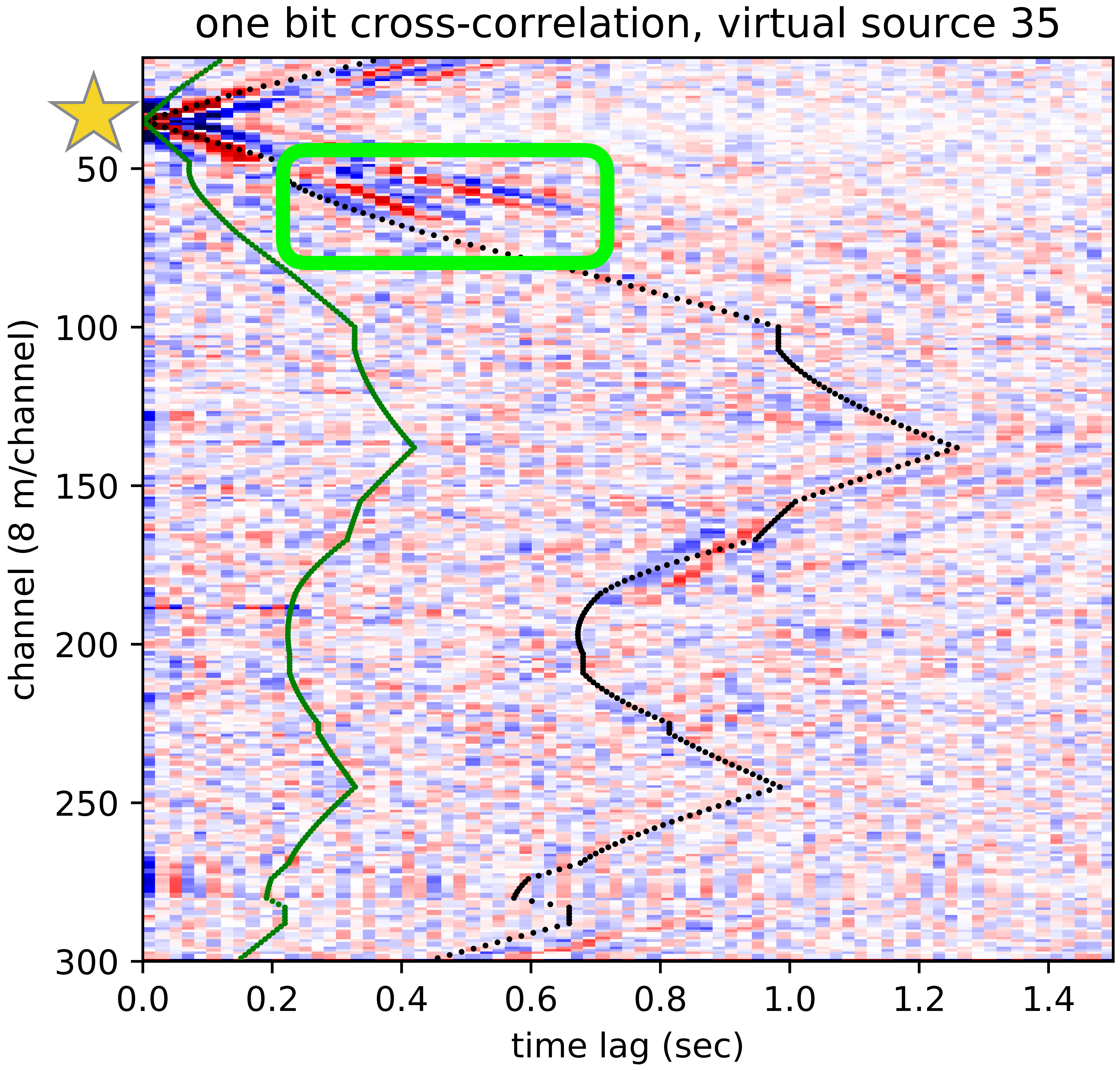


1-bit cross-correlation, 5 day



E. Martin and B. Biondi, "Ambient noise interferometry across two-dimensional DAS arrays," submitted to SEG annual meeting.

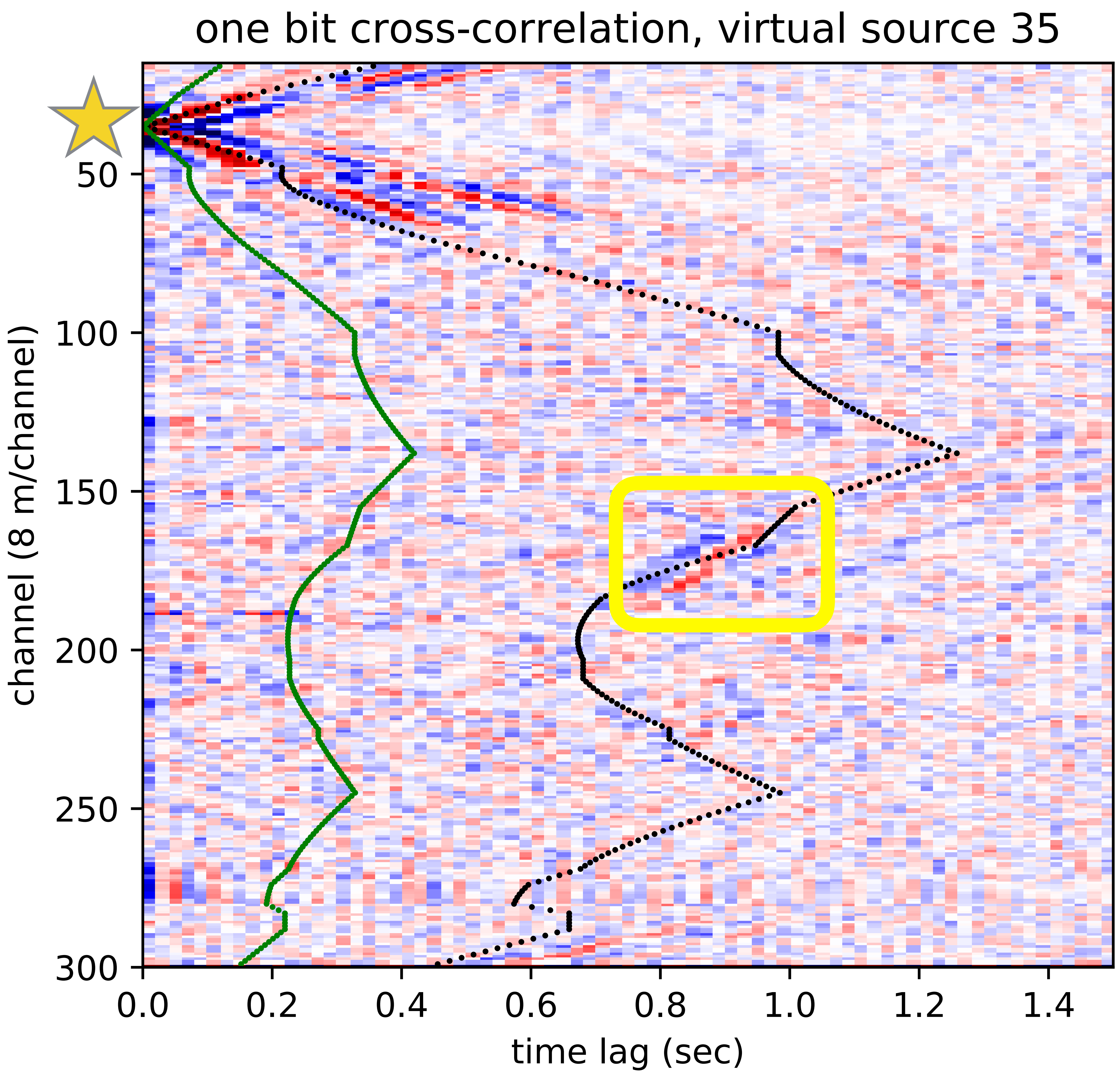
1-bit cross-correlation, 5 day



400 m/s
1200 m/s

E. Martin and B. Biondi, "Ambient noise interferometry across two-dimensional DAS arrays," submitted to SEG annual meeting.

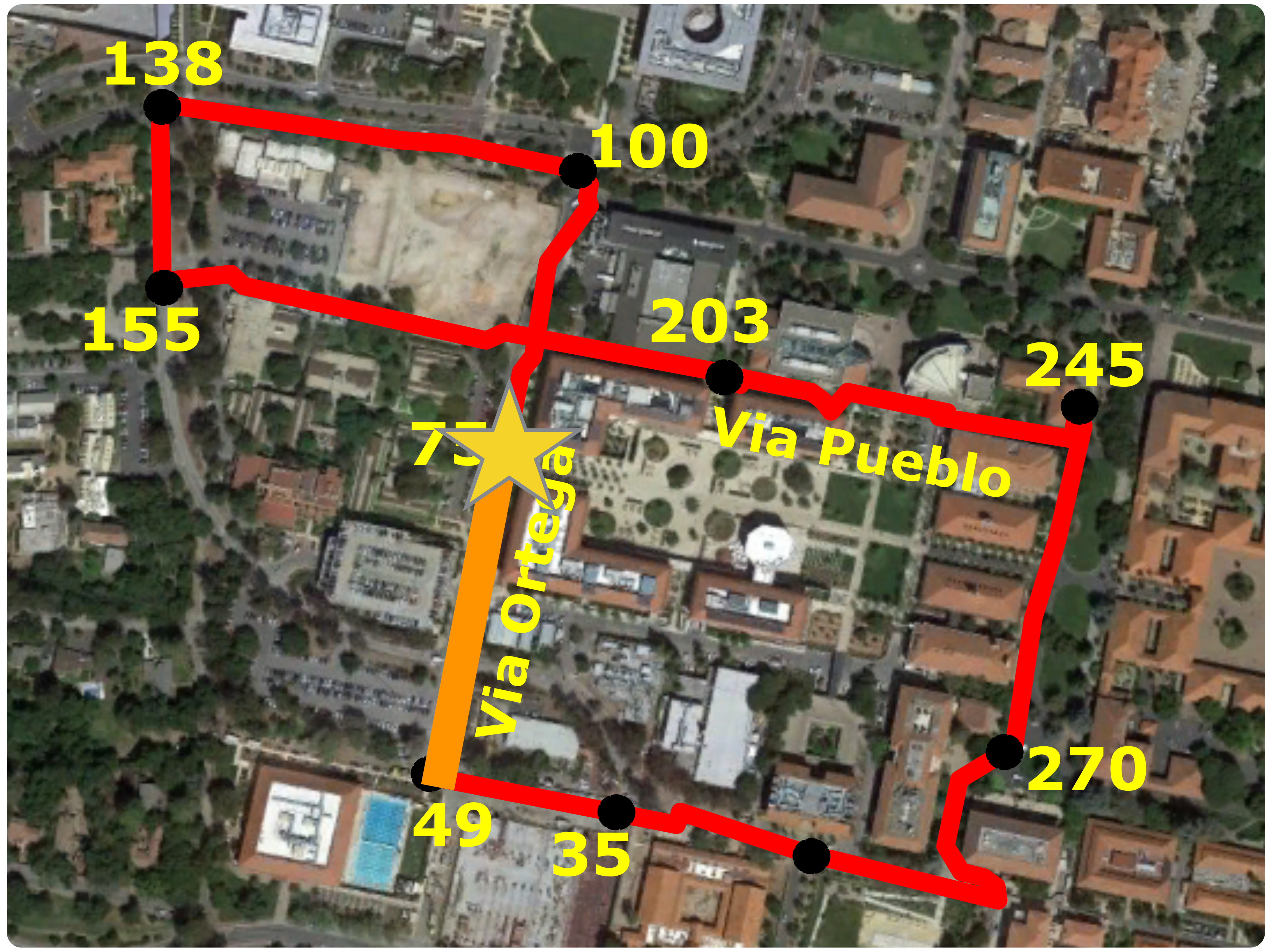
1-bit cross-correlation, 5 day

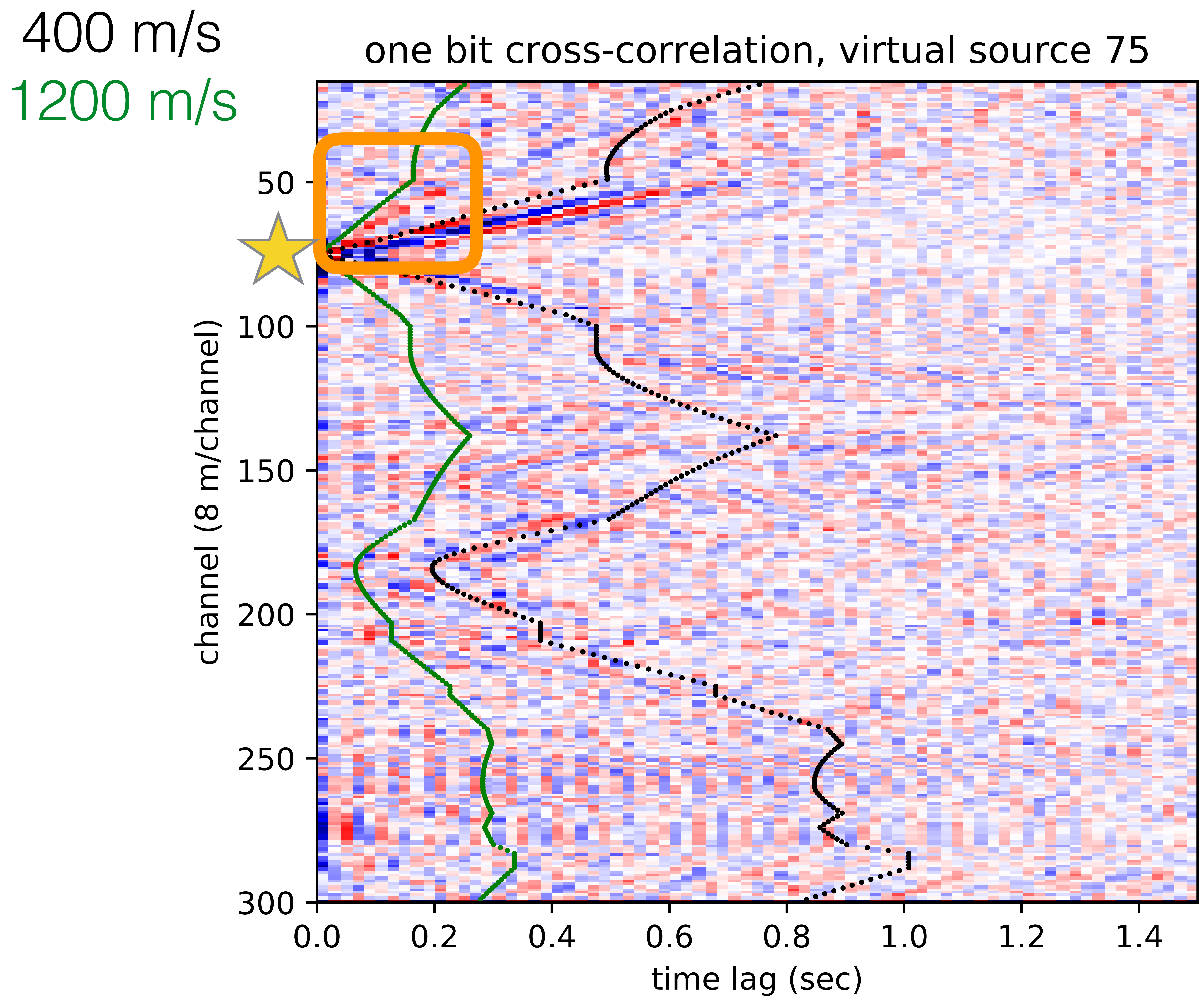


400 m/s
1200 m/s

E. Martin and B. Biondi, "Ambient noise interferometry across two-dimensional DAS arrays," submitted to SEG annual meeting.

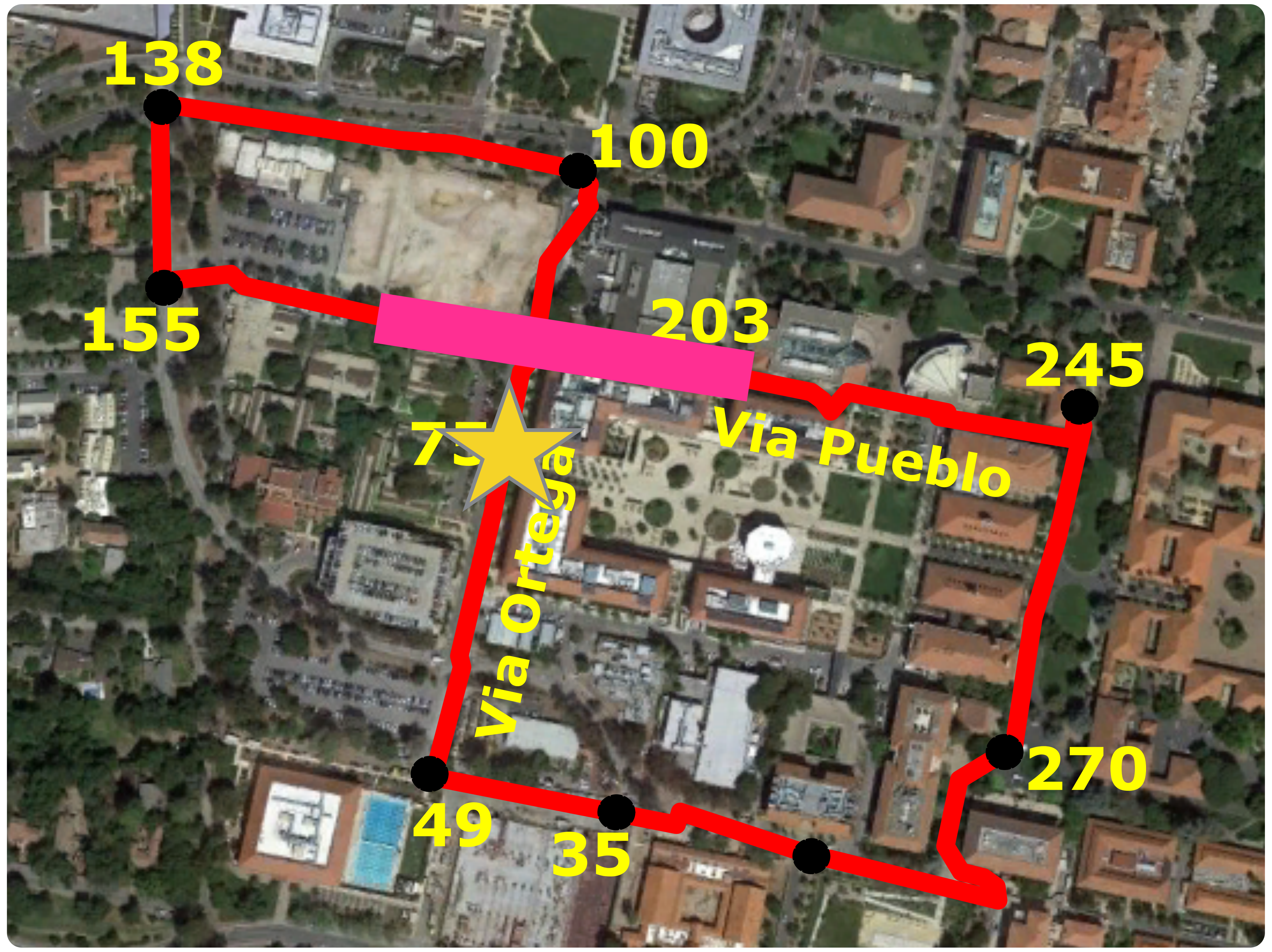
1-bit cross-correlation, 5 day

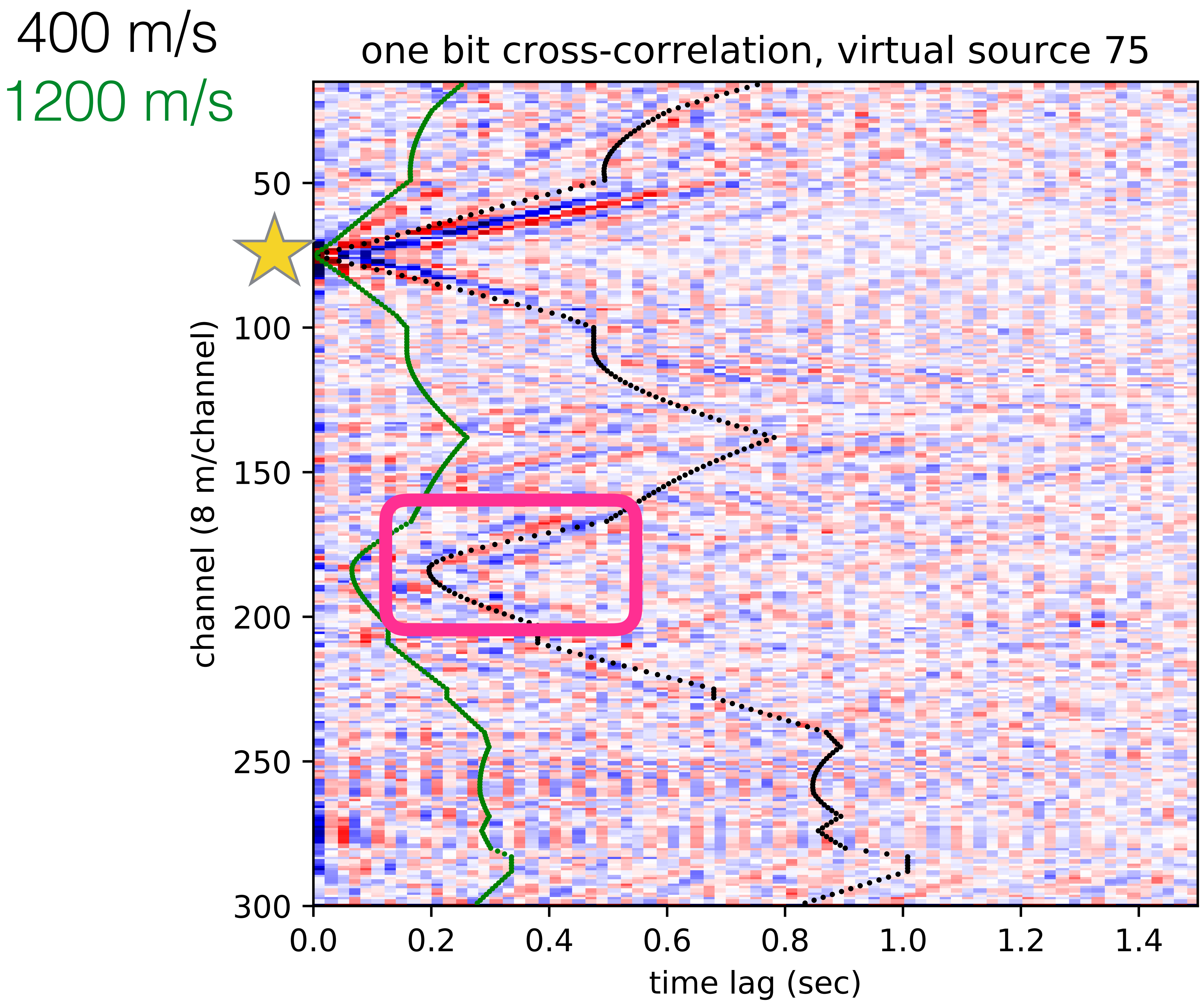




E. Martin and B. Biondi, “Ambient noise interferometry across two-dimensional DAS arrays,” submitted to SEG annual meeting.

1-bit cross-correlation, 5 day





E. Martin and B. Biondi, "Ambient noise interferometry across two-dimensional DAS arrays," submitted to SEG annual meeting.

Summary:

We can extract virtual source responses throughout 2D DAS arrays, greatly increasing the usable ray path coverage of passive DAS arrays.

The extracted responses show some features predicted by theory.

We are working towards a more automated, unified workflow.

Open questions:

How do we reliably select Rayleigh and Love waves from mixed outputs?
Does this work at other sites (Fairbanks, AK or Richmond, CA)?
How can we use the R-T and T-R components for near surface imaging?

Acknowledgements

Advice and useful discussions:

Bob Clapp, Jason Chang, George Papanicolaou, Jonathan Ajo-Franklin (LBL), Nate Lindsey (Cal), Shan Dou (LBL)

Calibration field work:

Carson Laing (OptaSense)
Martin Karrenbach
Stewart Levin
Chris Castillo
Ethan Williams
Shanna Chu
Jon Claerbout

Financial:

DOE CSGF under grant DE-FG02-97ER25308 (E. Martin)
Schlumberger Innovation Fellowship (E. Martin)
Stanford Exploration Project Sponsors (E. Martin and SDASA-1 tests)
SERDP grant RC-2437 (permafrost thaw tests, LBL and Corps of Engineers)

Computing, Equipment, and Resources:

Stanford Center for Computational Earth and Environmental Science
Stanford IT (fiber team)
Stanford SEEES IT
OptaSense (ODH-3 Interrogator Unit)
Subsea Systems (GPS trigger timing)

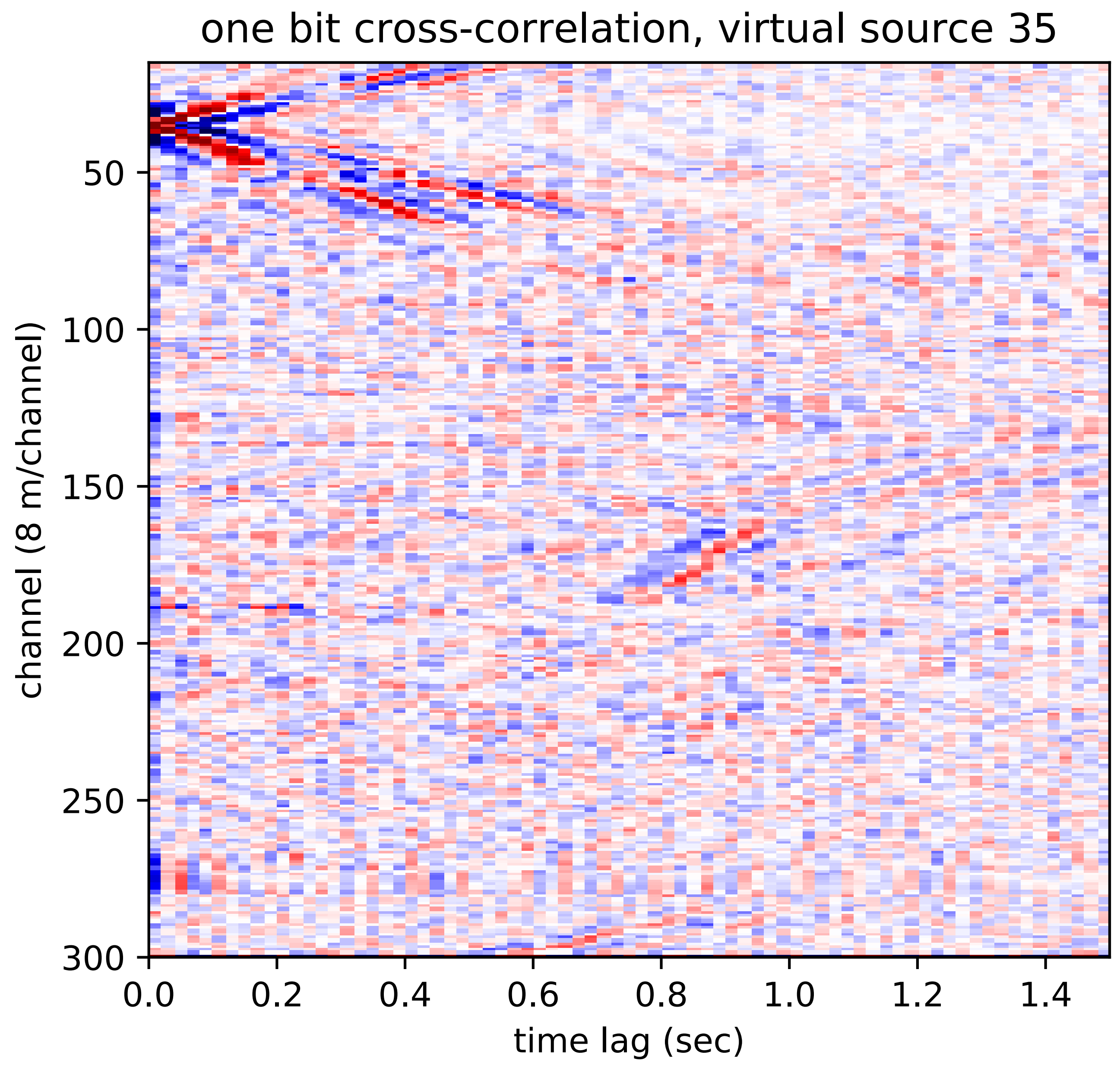
Summary:

We can extract virtual source responses throughout 2D DAS arrays, greatly increasing the usable ray path coverage of passive DAS arrays.

The extracted responses show some features predicted by theory.

We are working towards a more automated, unified workflow.

Questions?

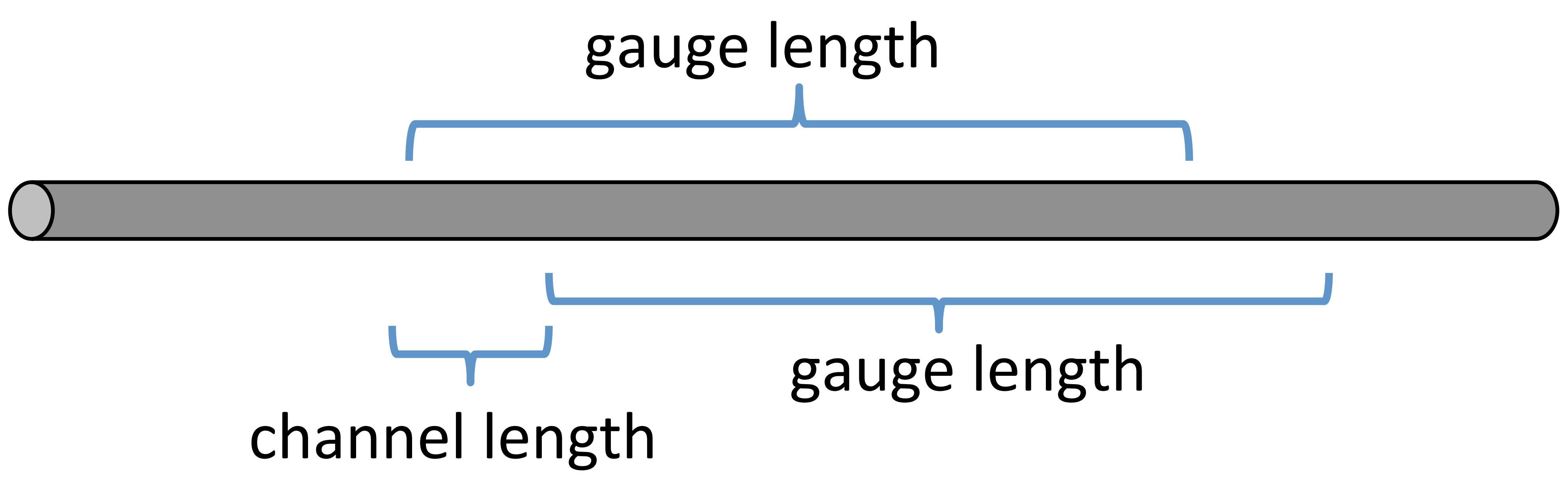


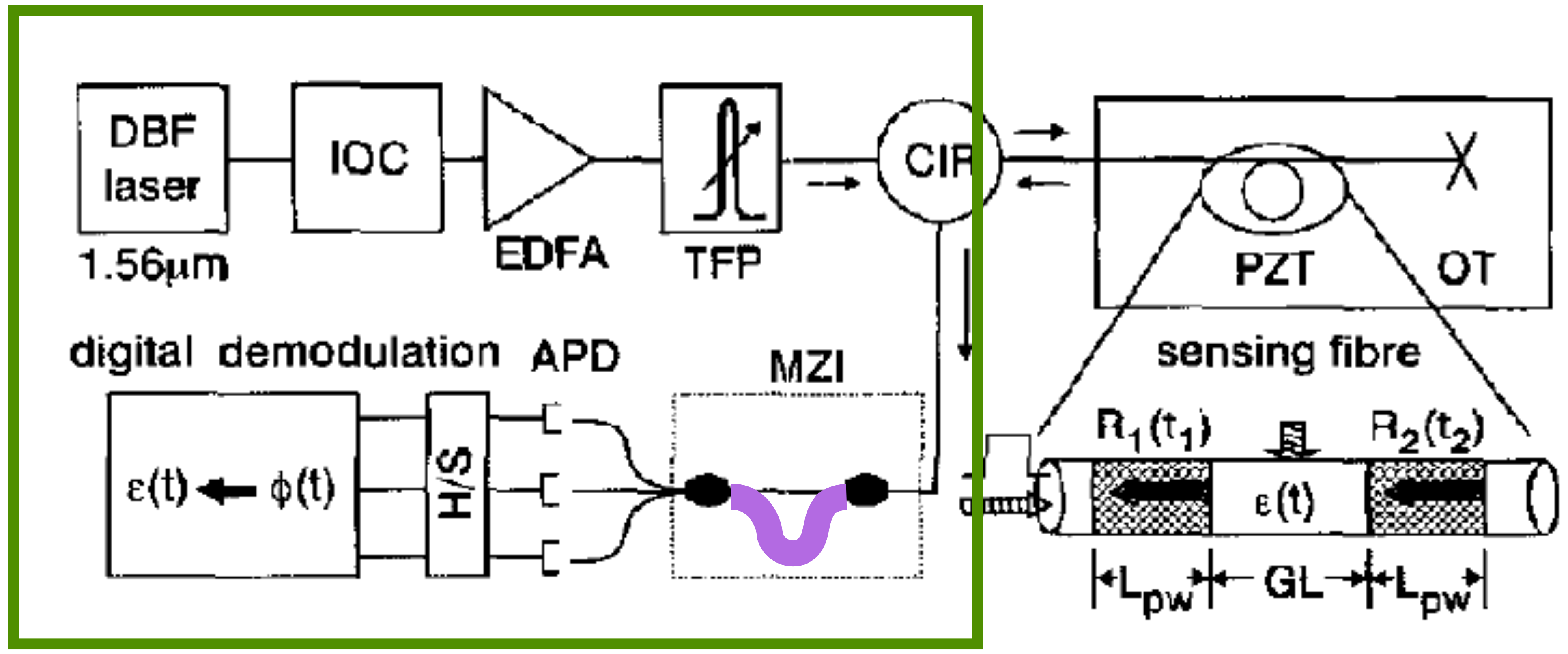
Extra information

- Benefits/drawbacks of DAS
- Earthquake recordings and sensitivity
- More on permafrost thaw tests
- Infrastructure related artifacts

benefits and drawbacks of DAS

Lower cost per sensor
High repeatability of sensor locations
Cover large range (not moving subsets)
Flexible sensors
High density that can be changed





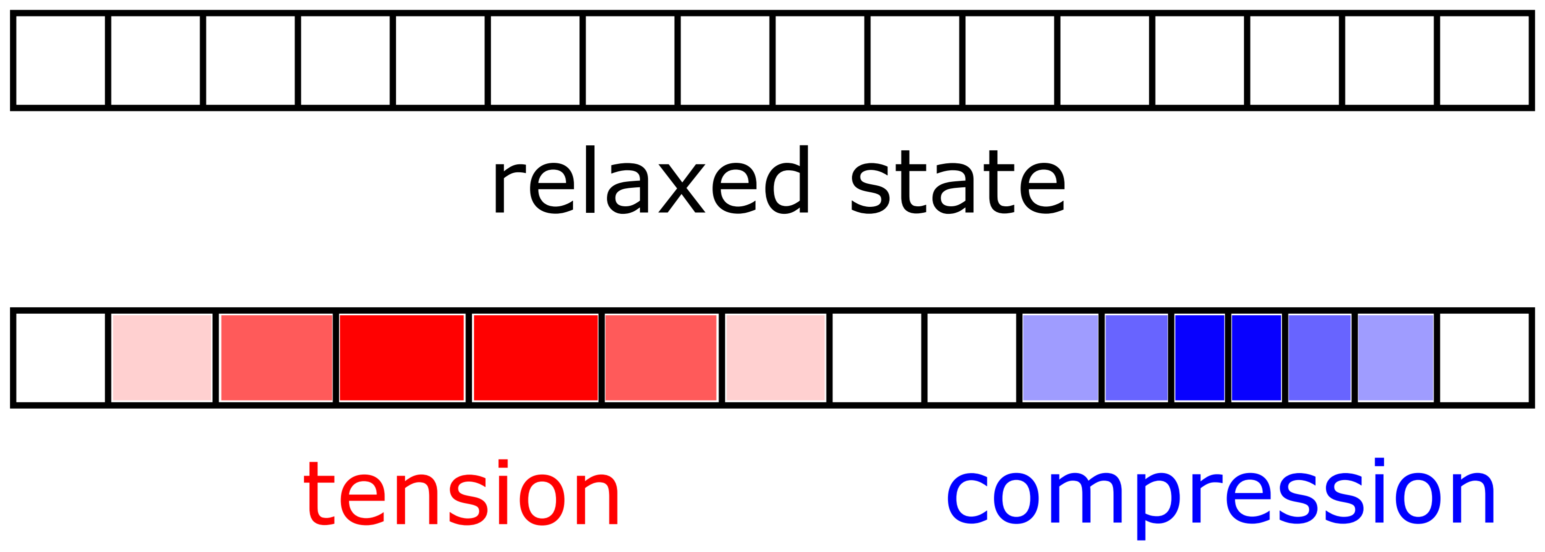
interrogator unit

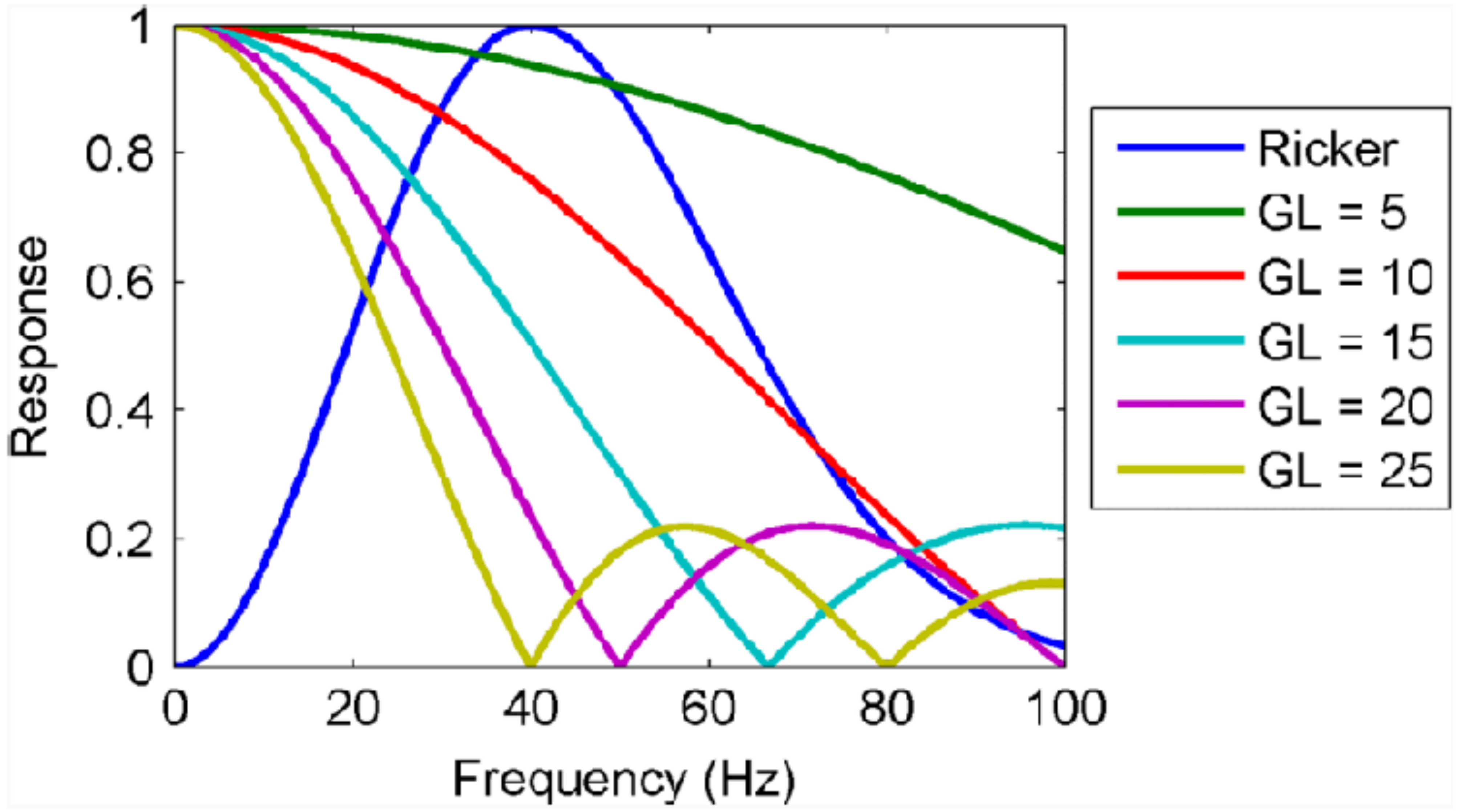
Lower sensitivity to broadside waves
Blind to certain frequencies
Some laser drift noise

Posey et al. 2000

Limitations of DAS

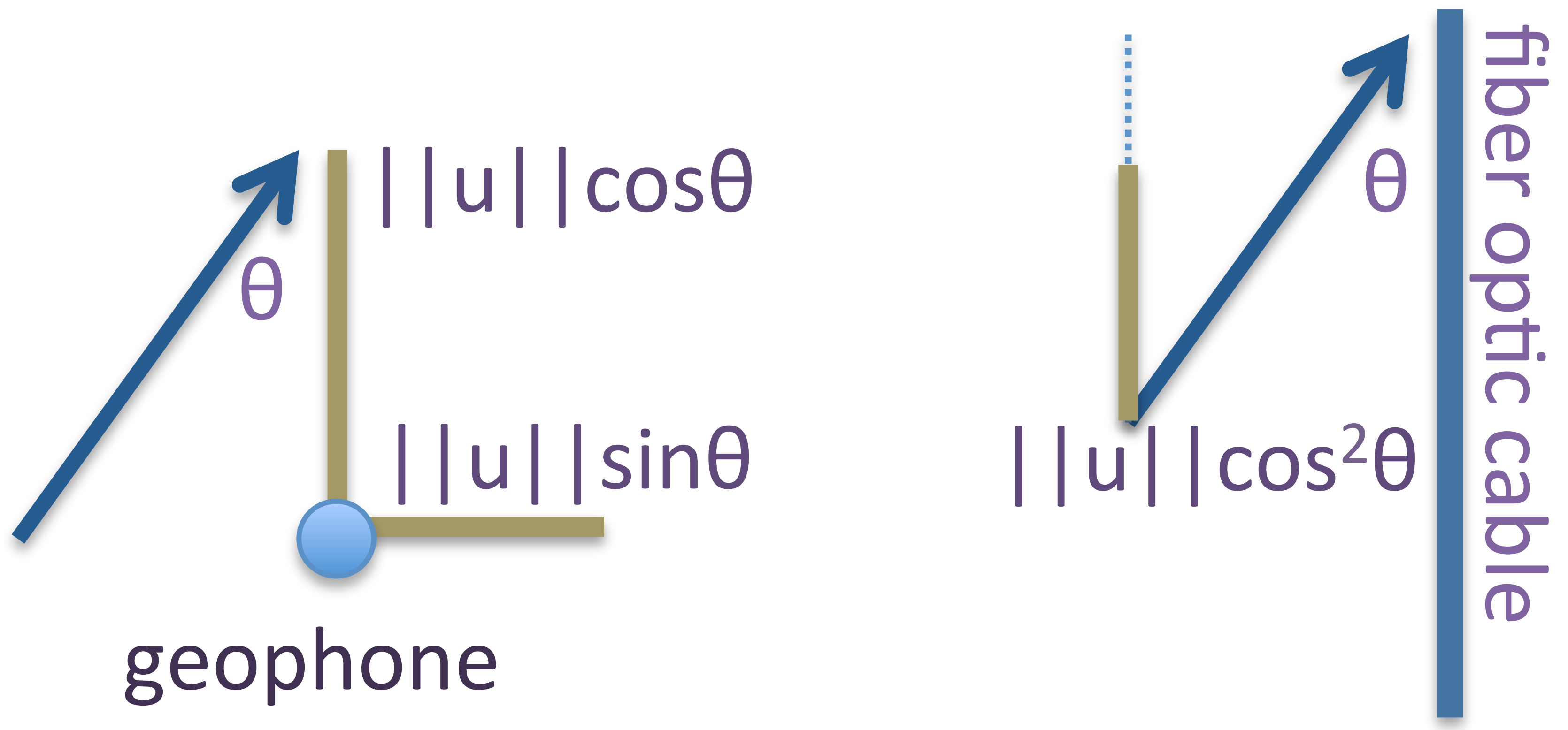
Blind frequencies





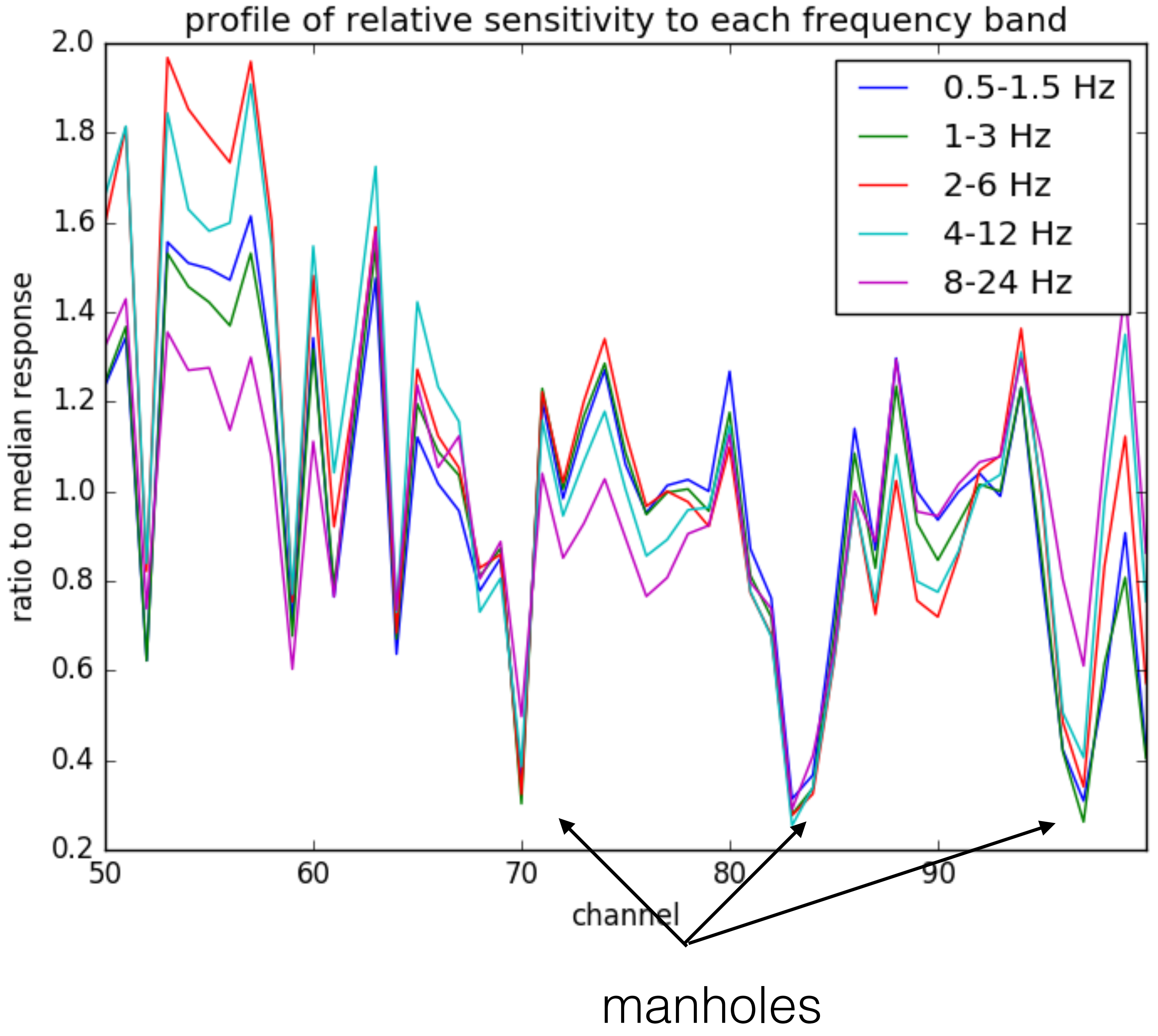
Dean et al. 2016 Geophysical Prospecting

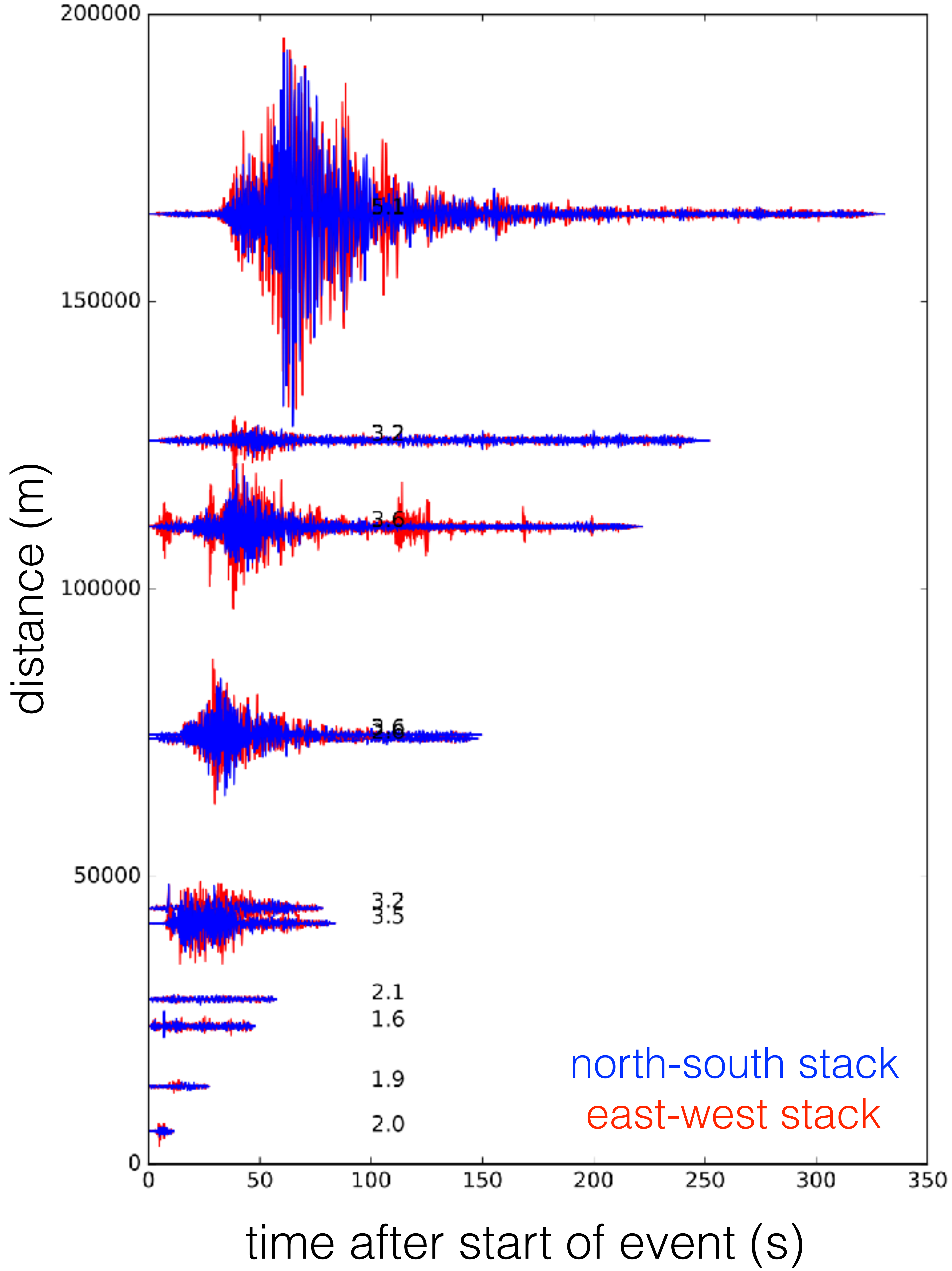
Lowered sensitivity to waves coming at an angle (cos^2 vs cos)



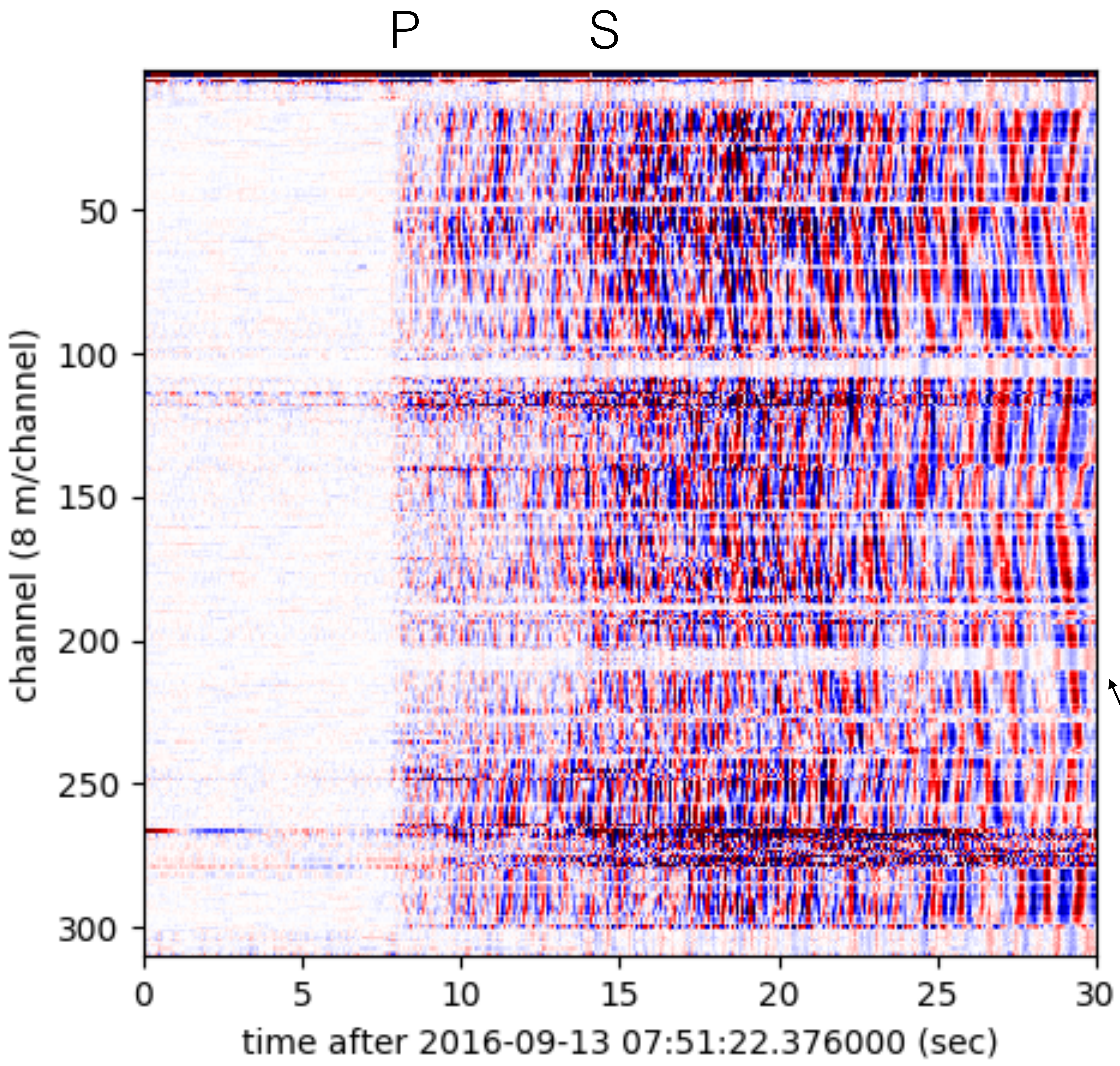
Nearby Earthquakes

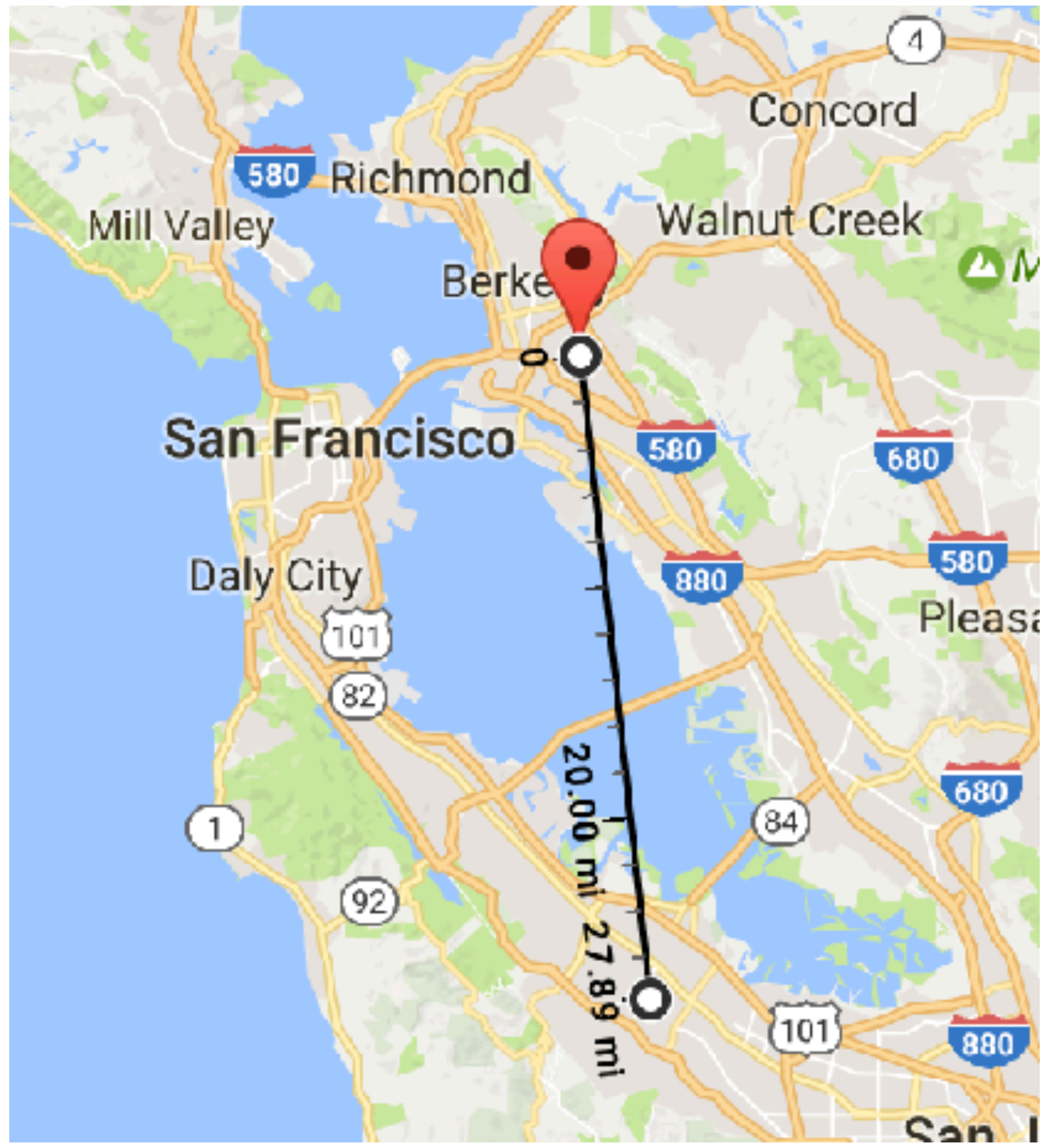
heterogeneous response





Piedmont
M 3.5

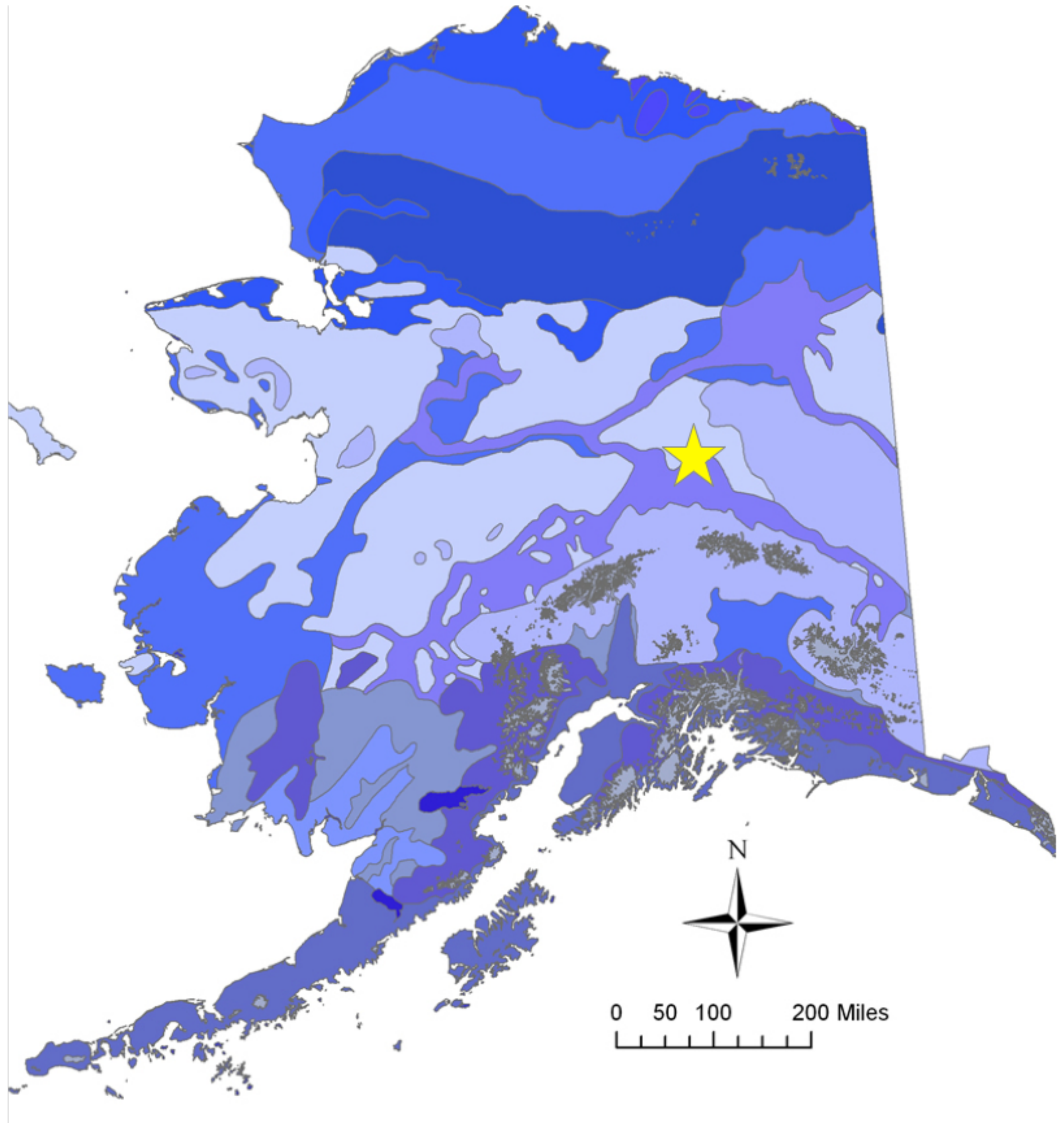




150 ft fiber loops
in manholes

Developing Smart Infrastructure for a Changing Arctic Environment Using Distributed Fiber-Optic Sensing Methods

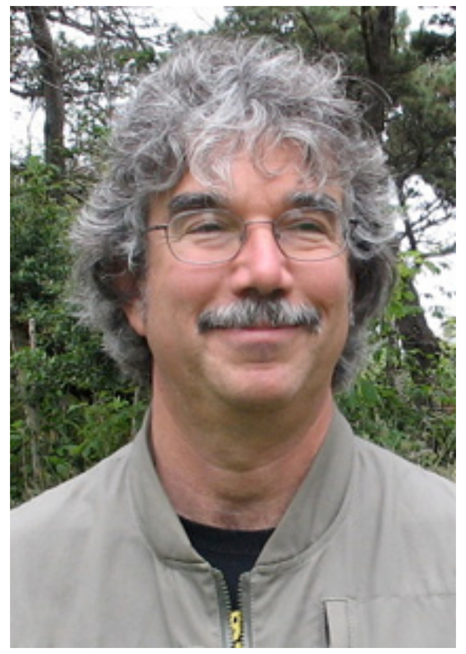
PI: Jonathan Ajo-Franklin, LBNL Co-PI: Anna Wagner, CRREL



Map from Alaska Public Lands Information

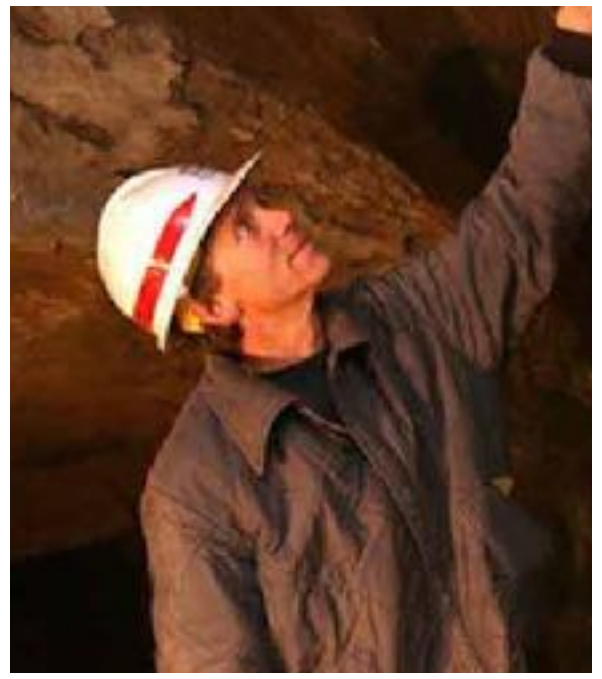
Goal: low-cost frequent monitoring of the near surface

Method: passive seismic collected by trenched fiber optics with low-cost per sensor





Jonathan Ajo-Franklin, LBNL

Tom Daley, LBNL

Barry Freifeld, LBNL

Michelle Robertson, LBNL

Craig Ulrich, LBNL

Nate Lindsey, UC Berkeley, LBNL

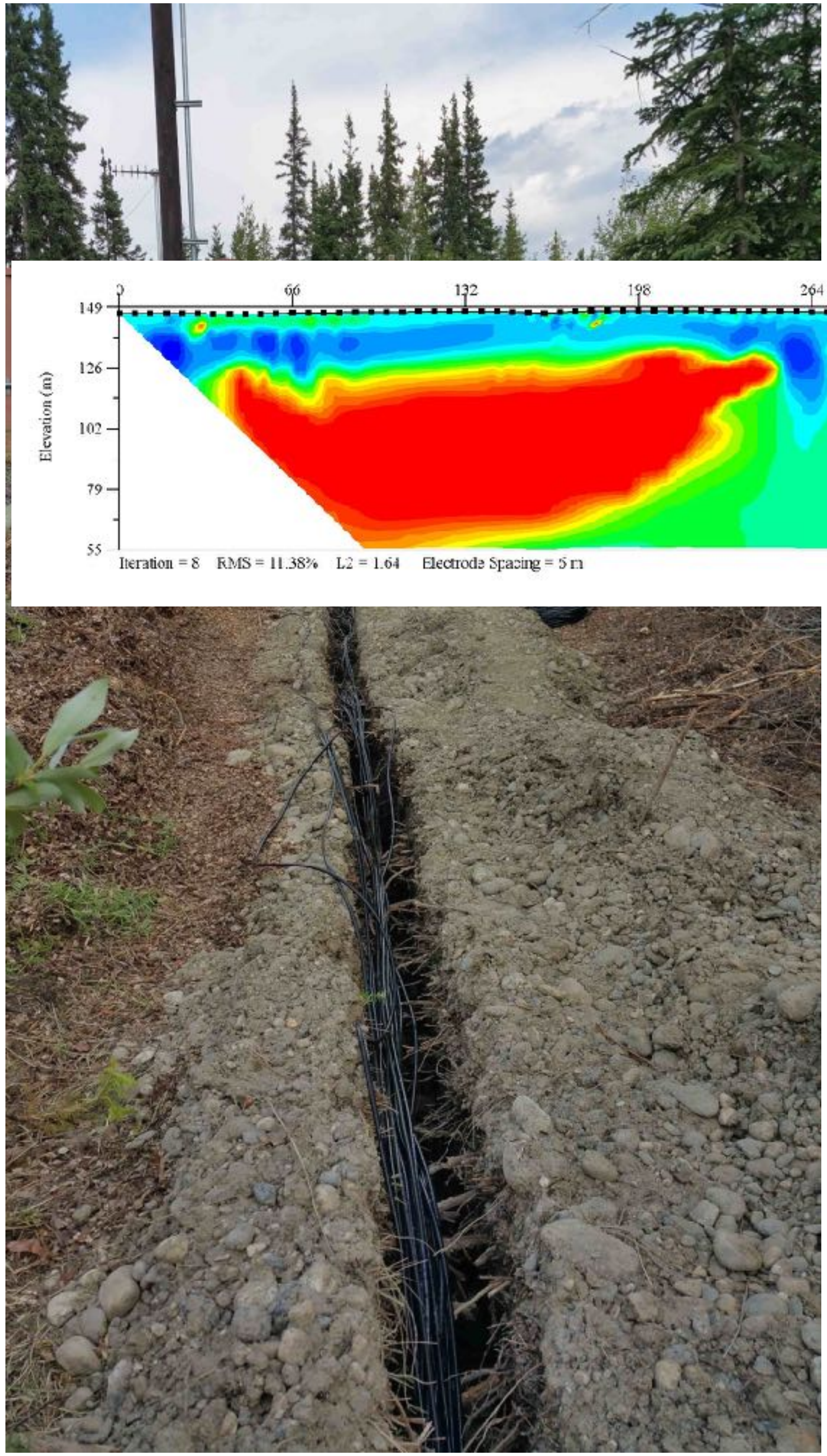
Shan Dou, LBNL

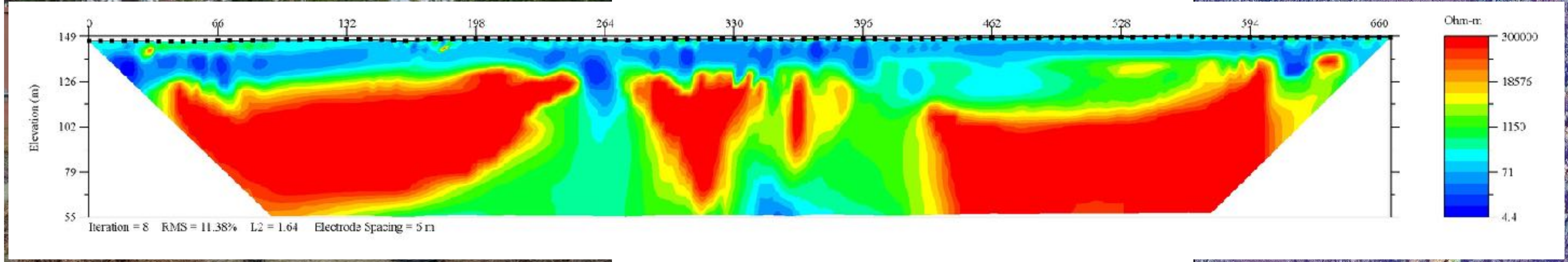
Anna Wagner

Kevin Bjella

US Army Corps of Engineers Cold Regions Research & Engineering Lab

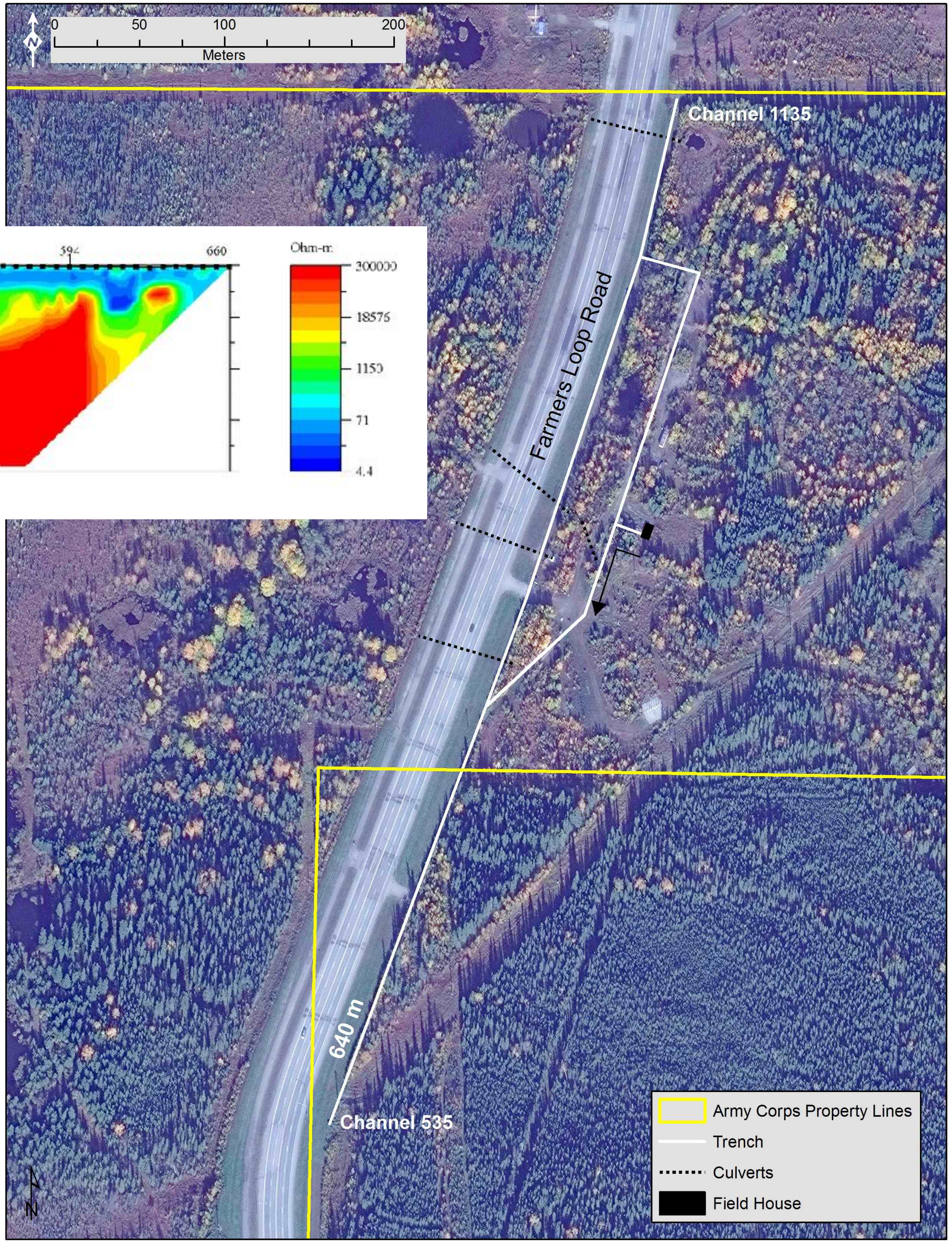
Site



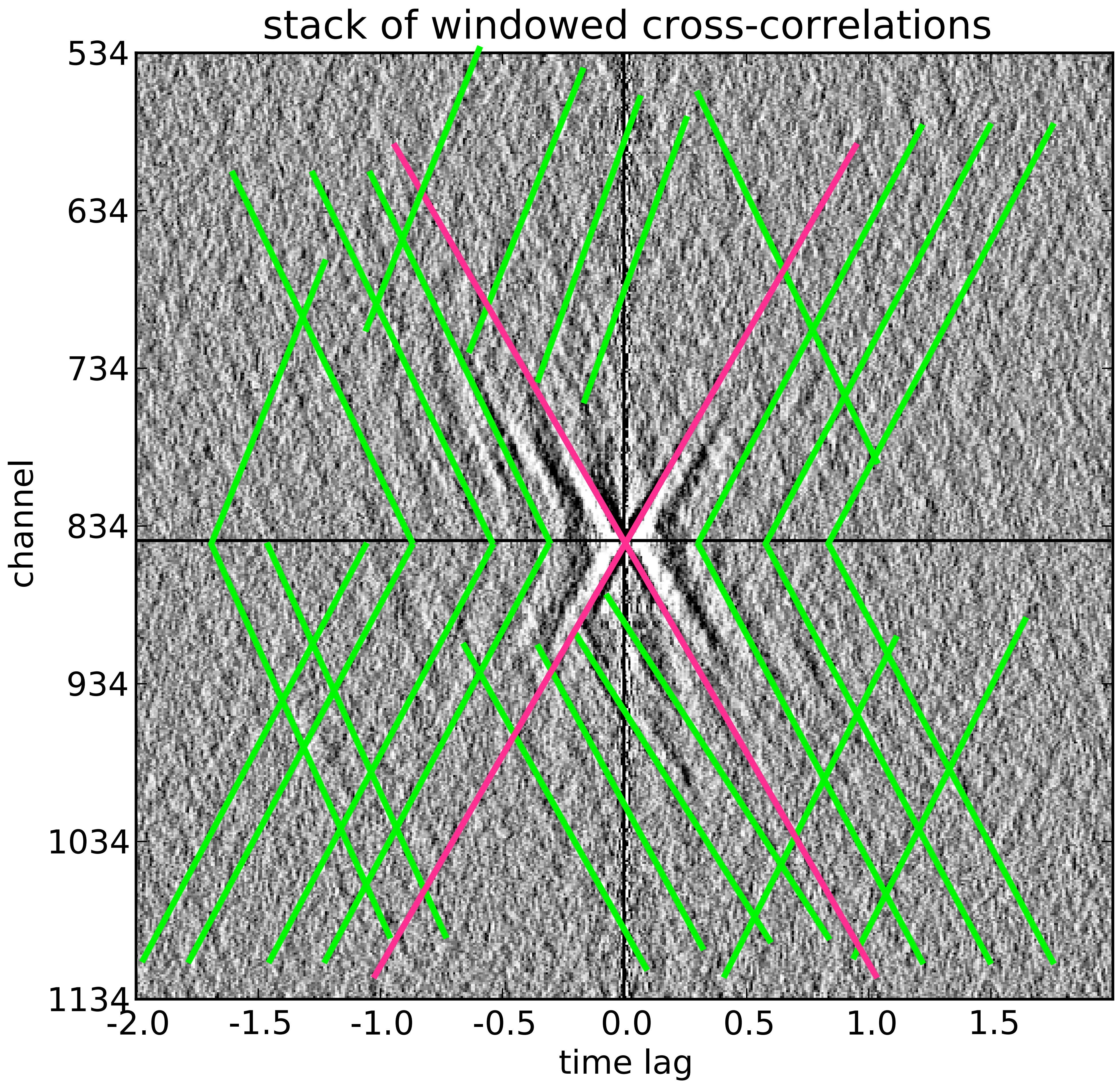


patchy permafrost
wooded area
1 mi north of Fairbanks
highway 400 m east

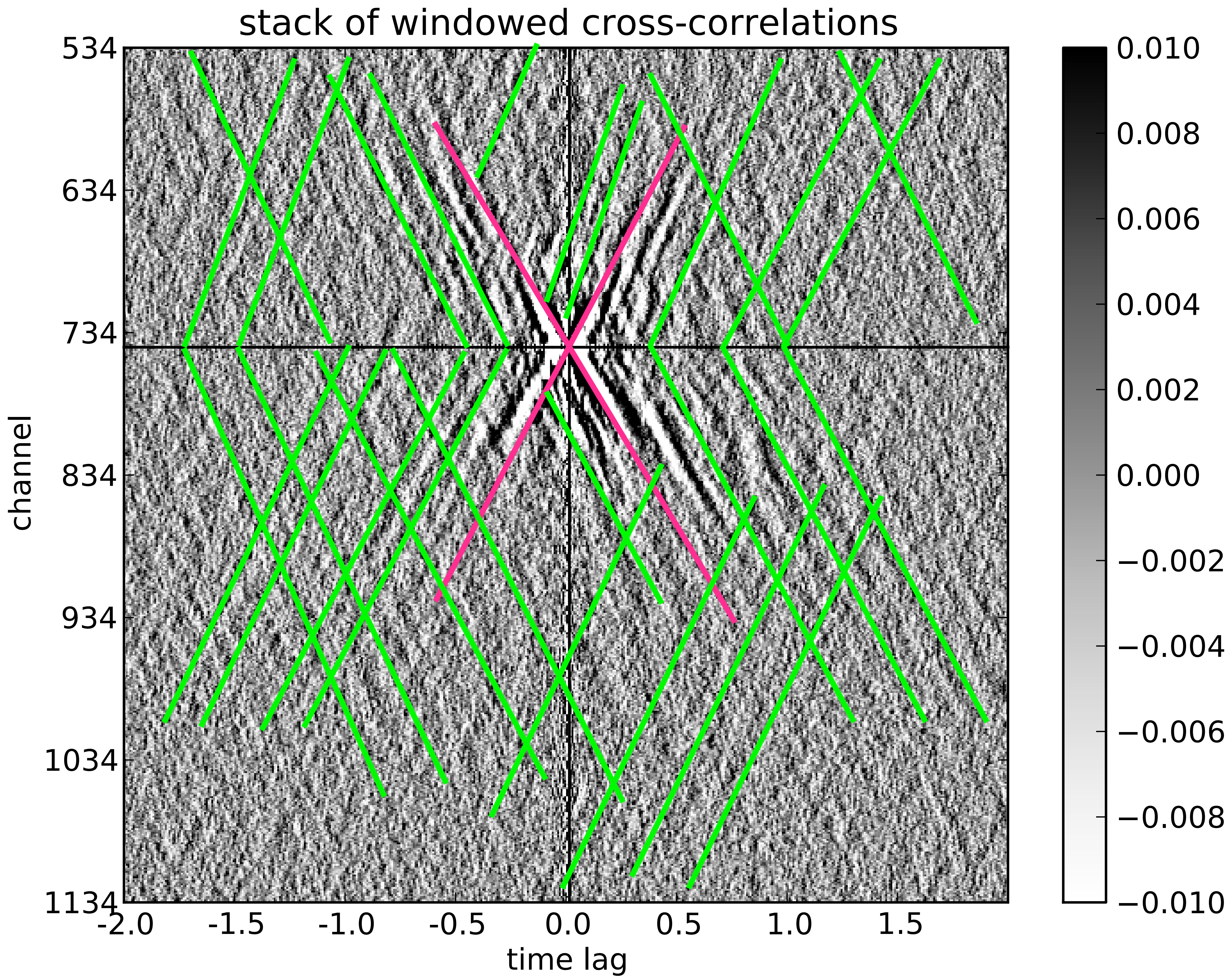
passive recording
SILIXA iDAS
1 m channel spacing
10 m gauge length
1 kHz recording



Cross-correlations

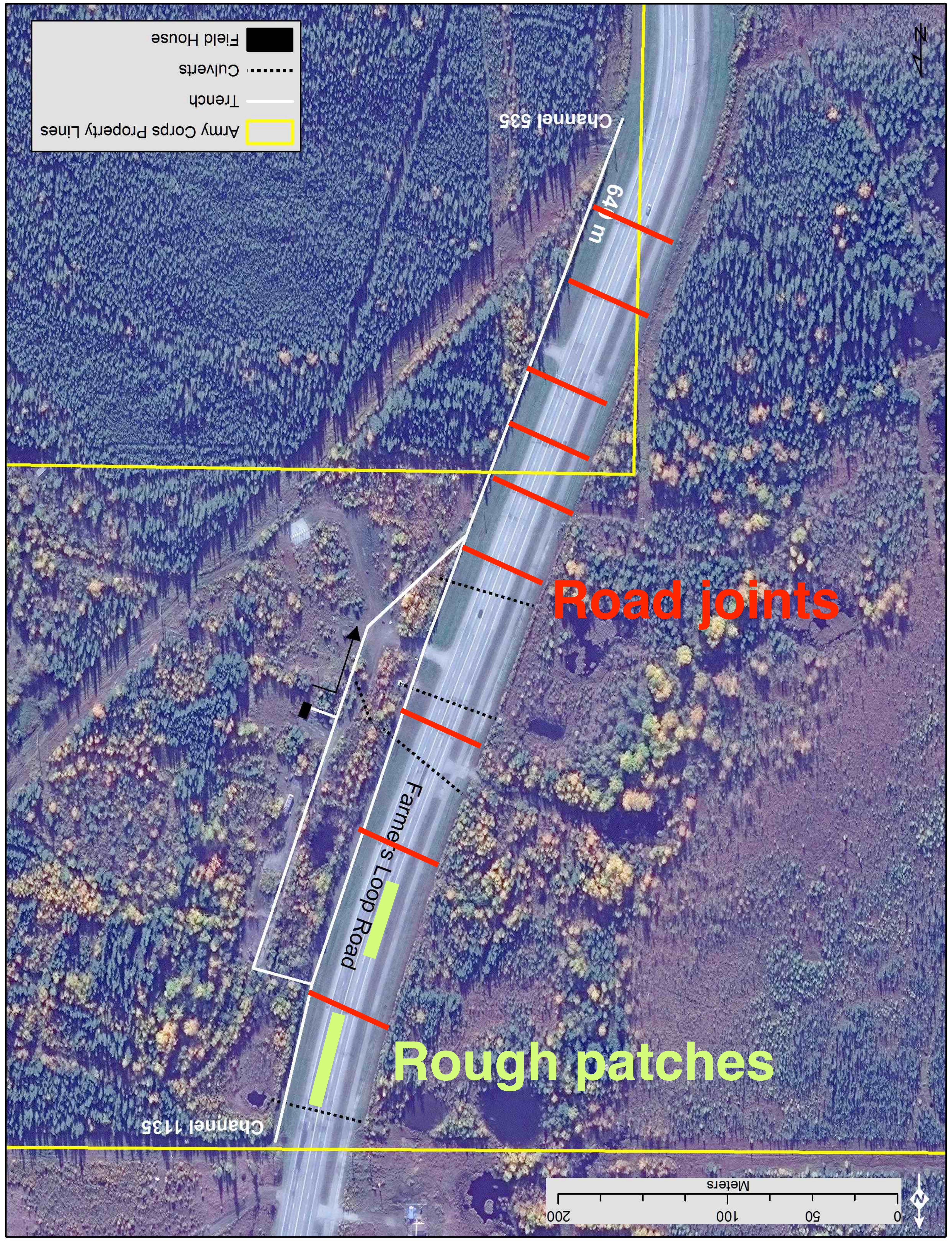


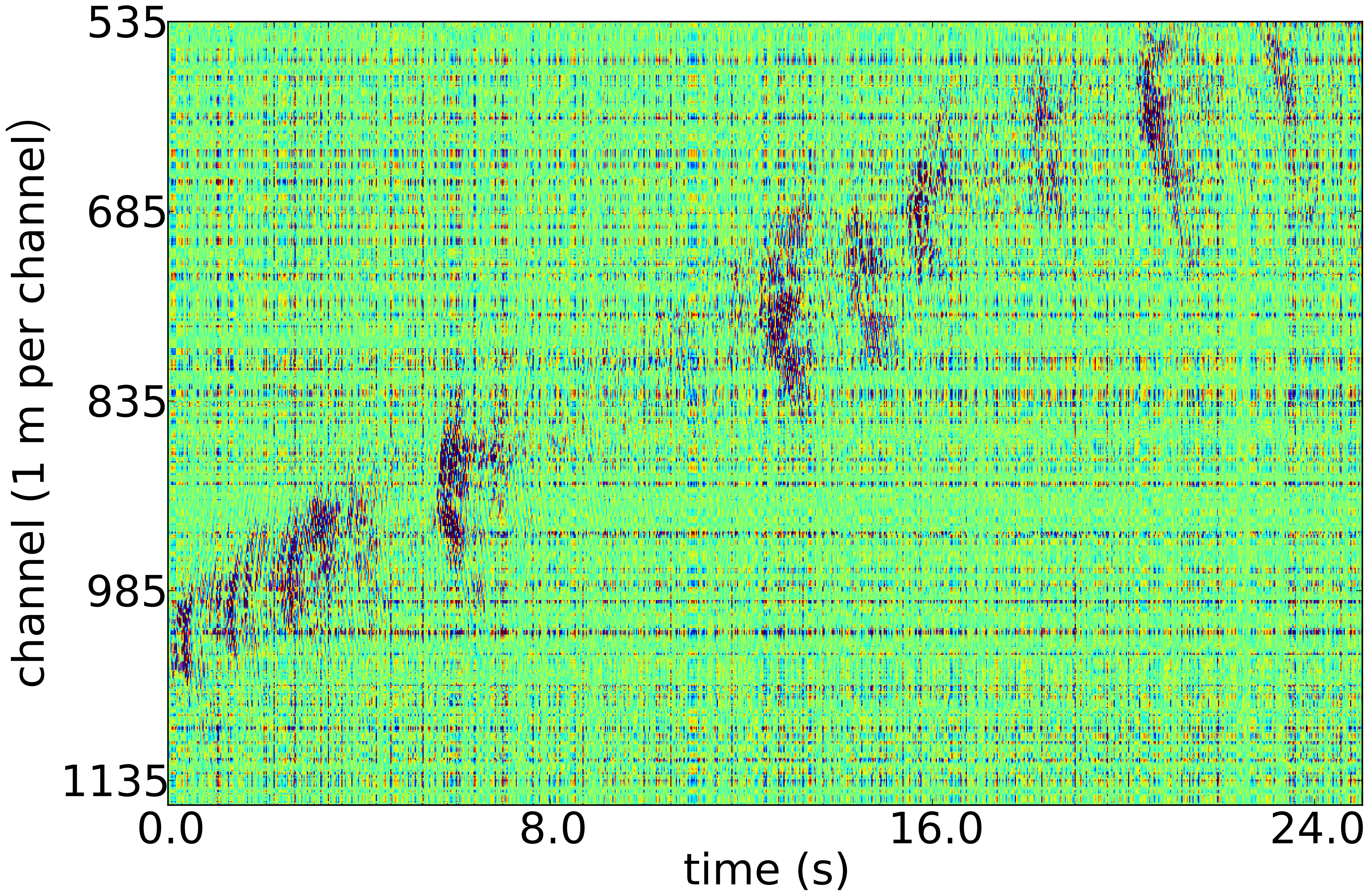
Channel 844



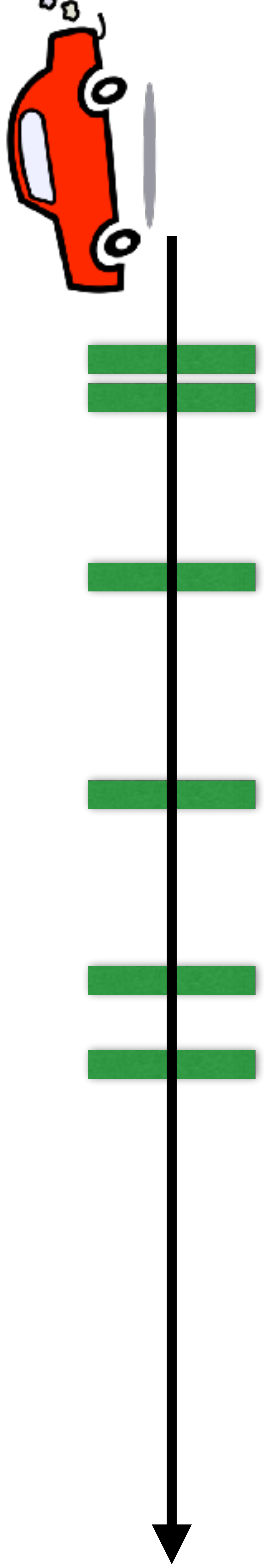
Channel 745

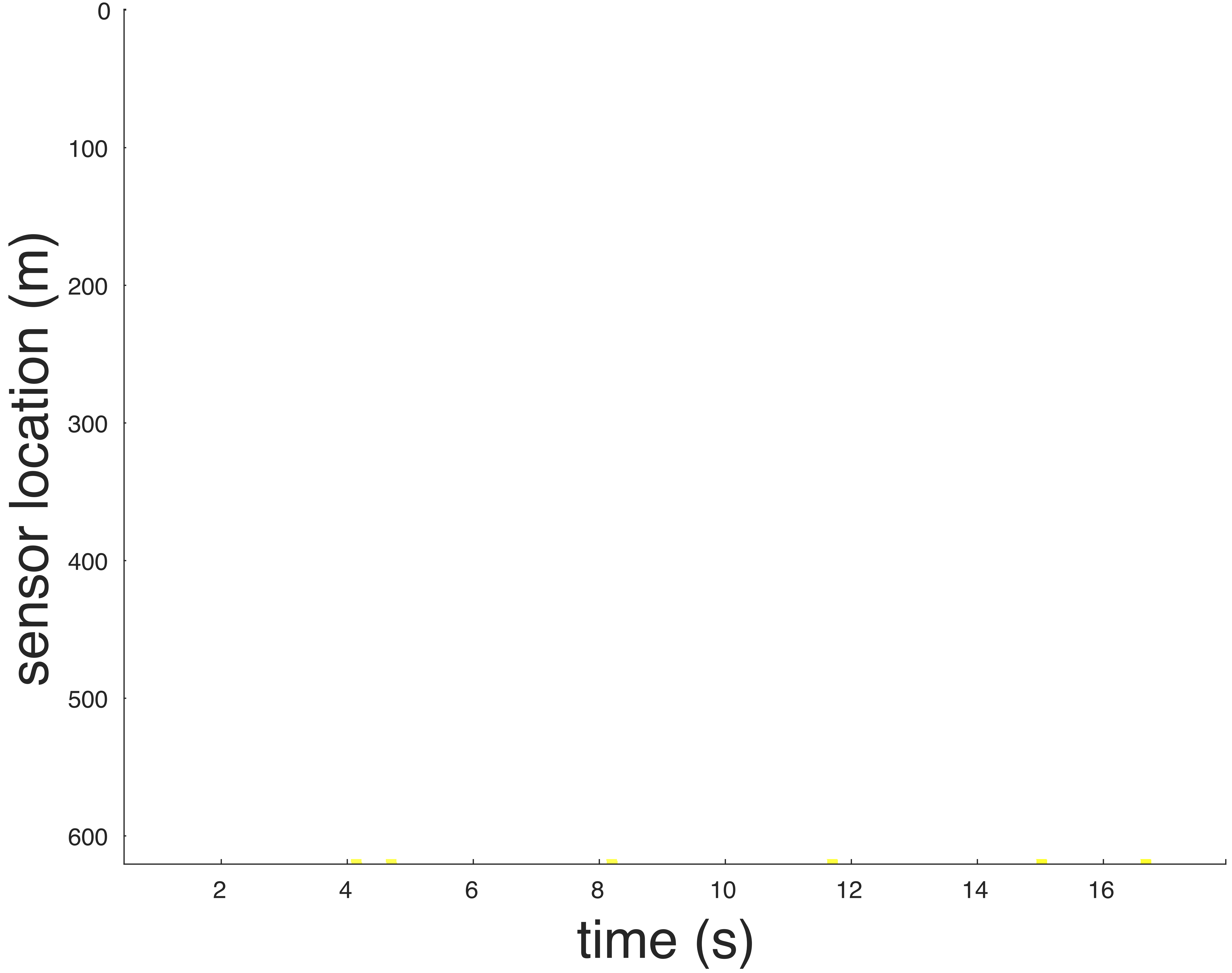
Issue: Theory of ambient noise assumes uncorrelated noise sources.



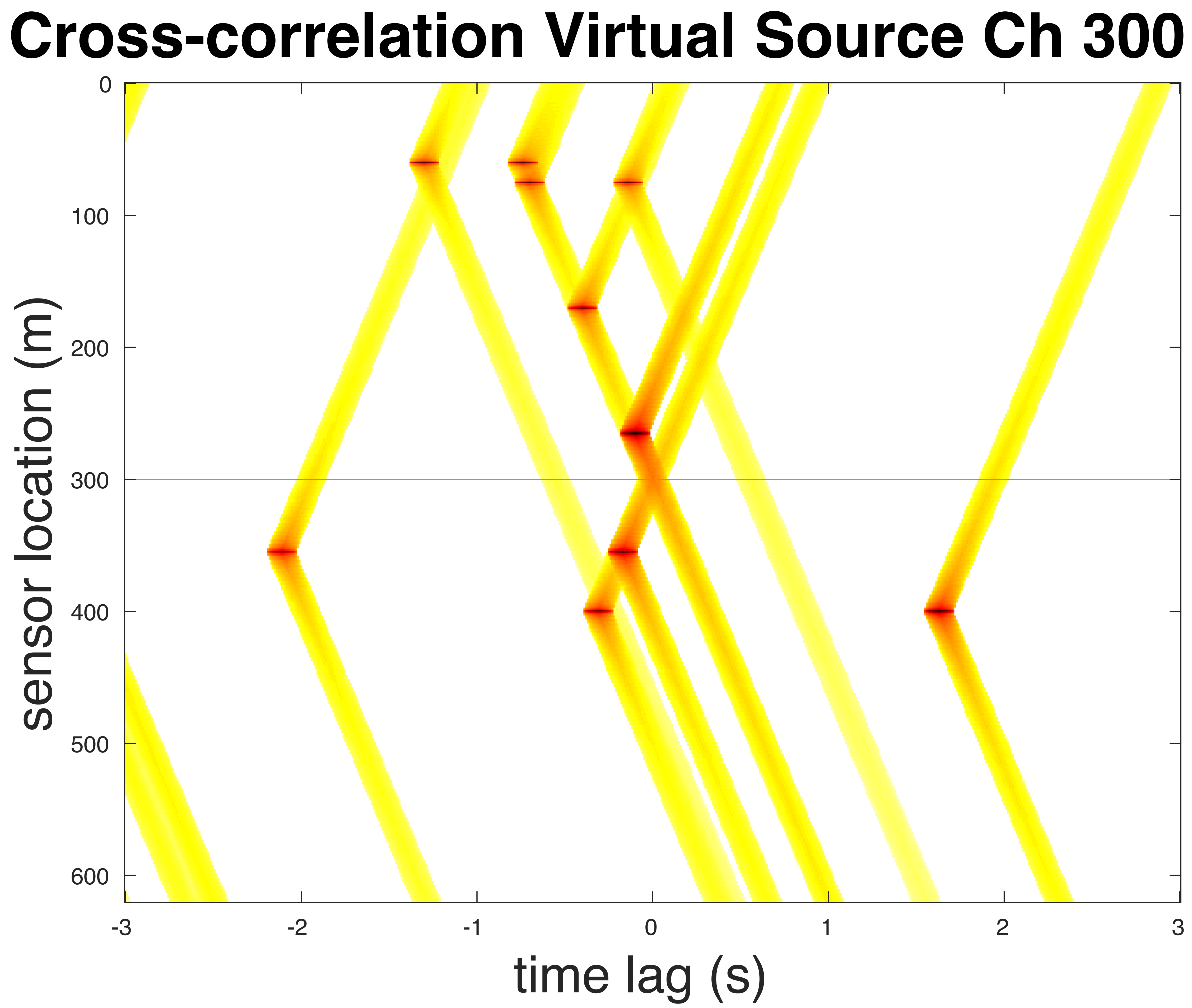


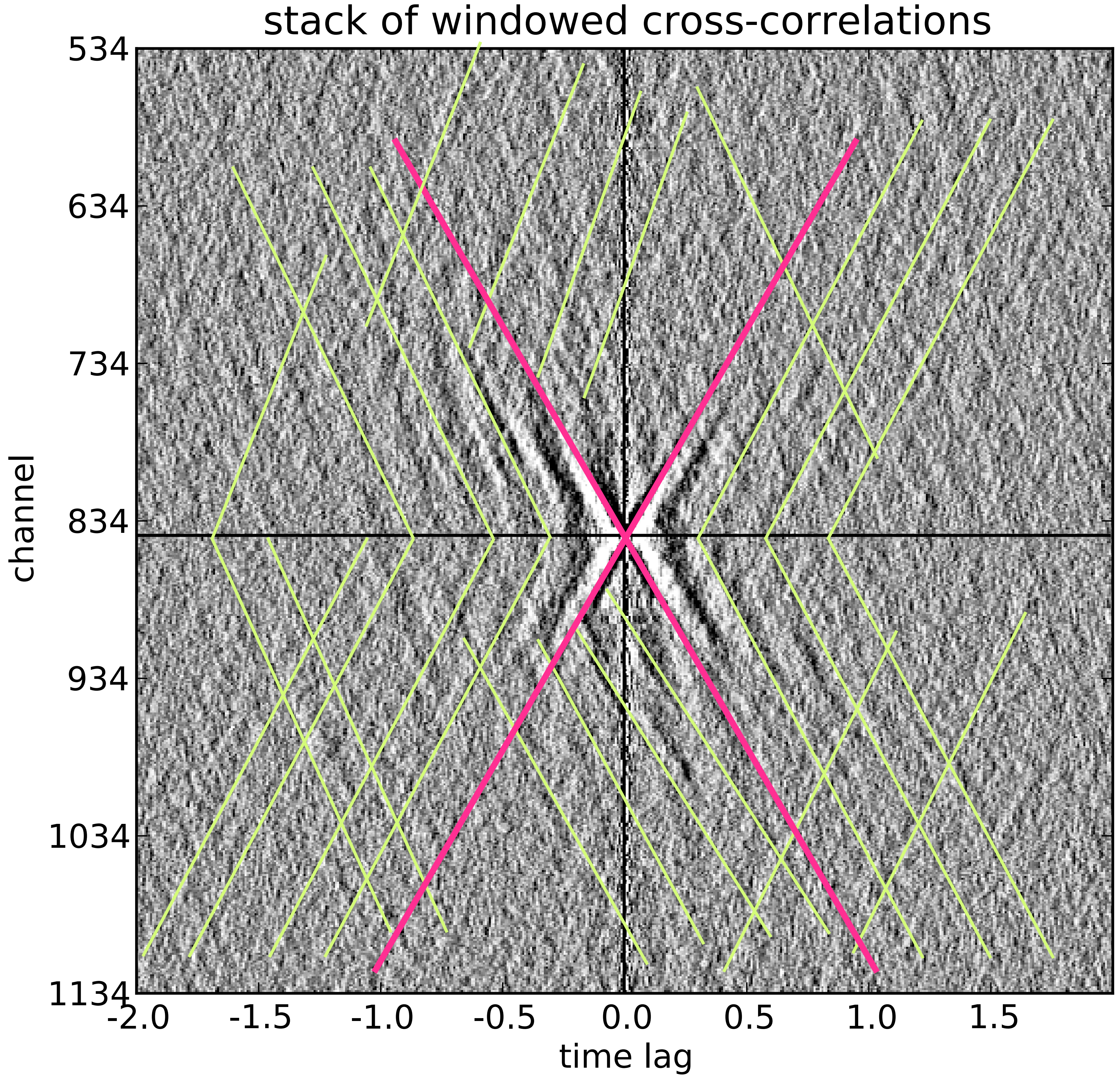
Time records





Bumps were probably the cause of artifacts in cross-correlations





Channel 844