Continuous near-surface monitoring with ambient noise collected by distributed acoustic sensing

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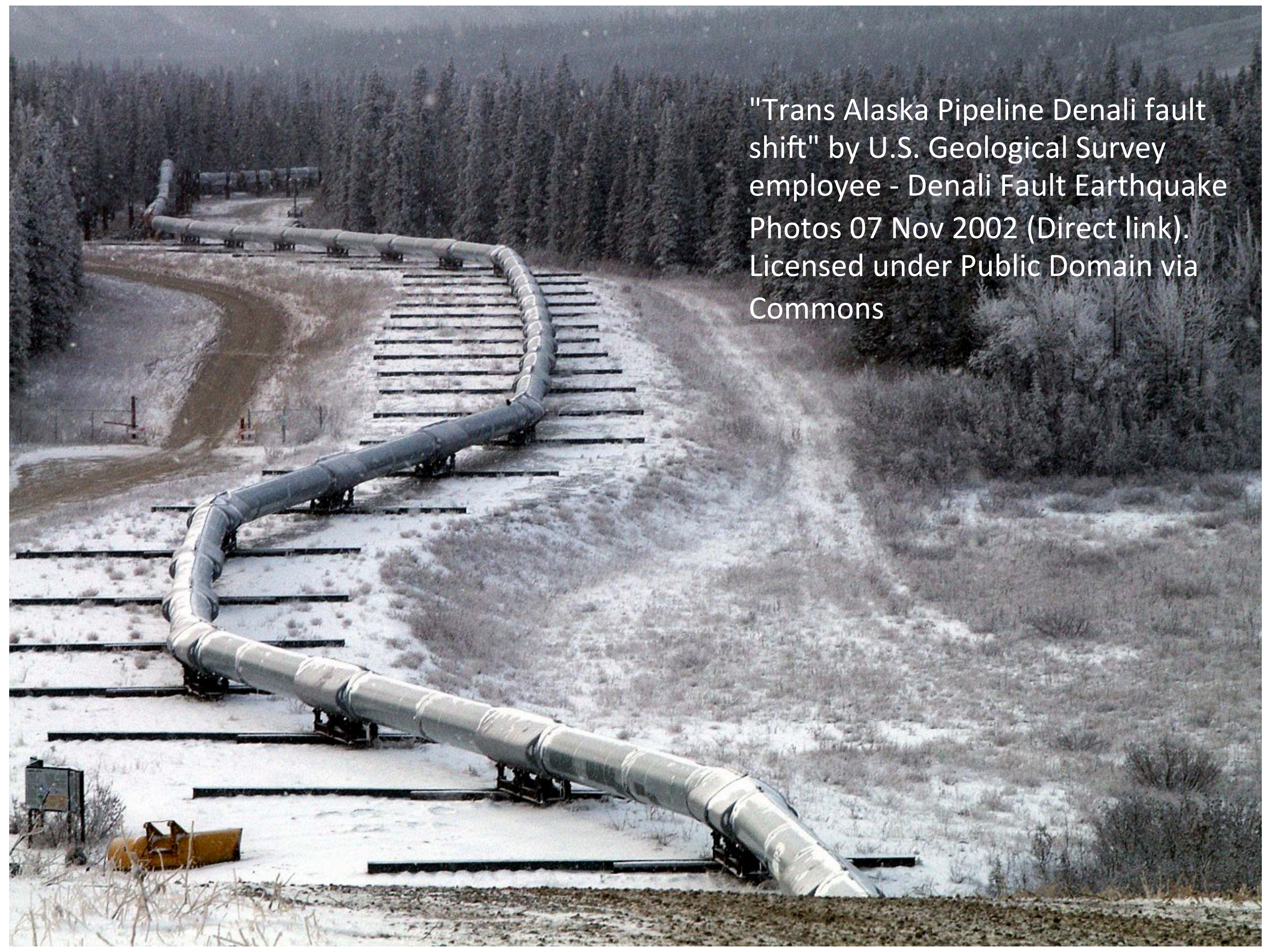
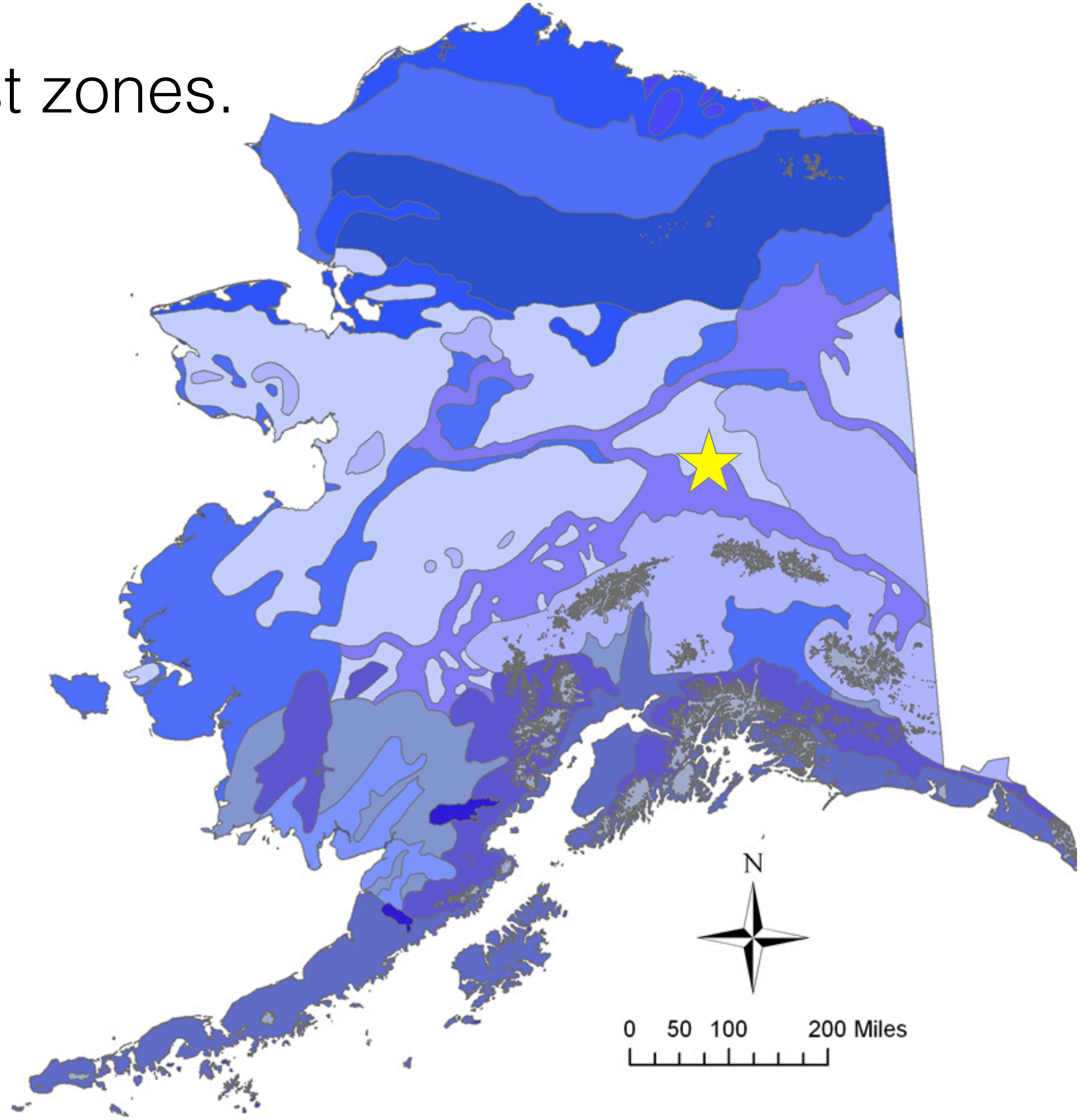
Seasonal variations in permafrost are getting more extreme.

This weakens infrastructure built on permafrost zones.

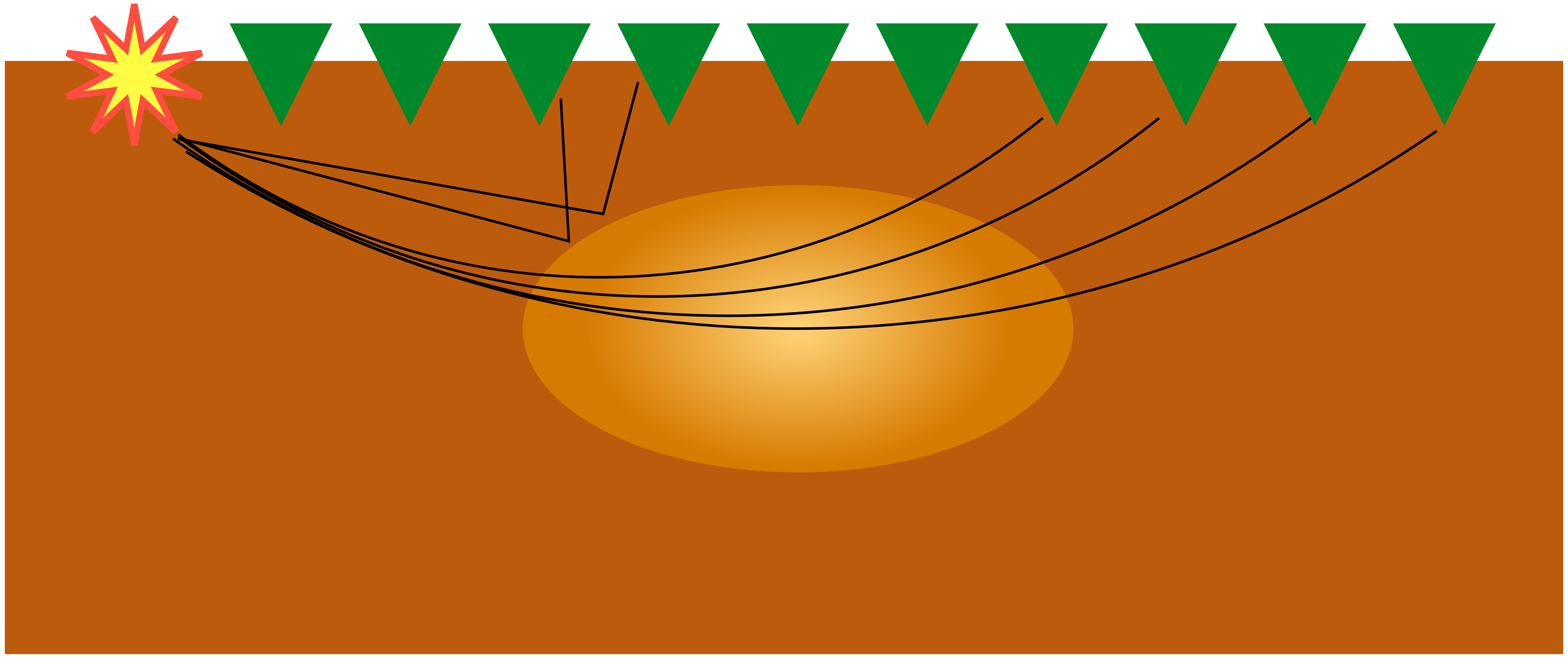
We're developing a low-cost system to frequently monitor structural stability of the ground under critical infrastructure.





Map from Alaska Public Lands Information

How a typical seismic survey works



Time for vibrations to reach sensors throughout the array indicates wave speeds in different areas.

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

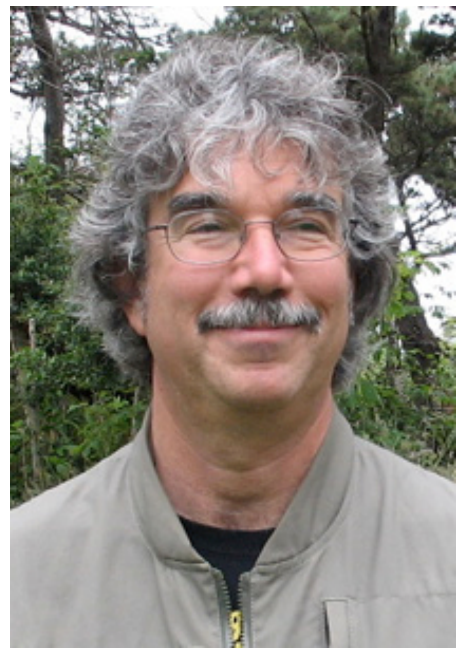
PI: Jonathan Ajo-Franklin, LBNL   Co-PI: Anna Wagner, CRREL

SERDP DOD · EPA · DOE   Berkeley Lab   Cal   CRREL

Goal: low-cost frequent monitoring of the near surface

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


Jonathan Ajo-Franklin, LBNL

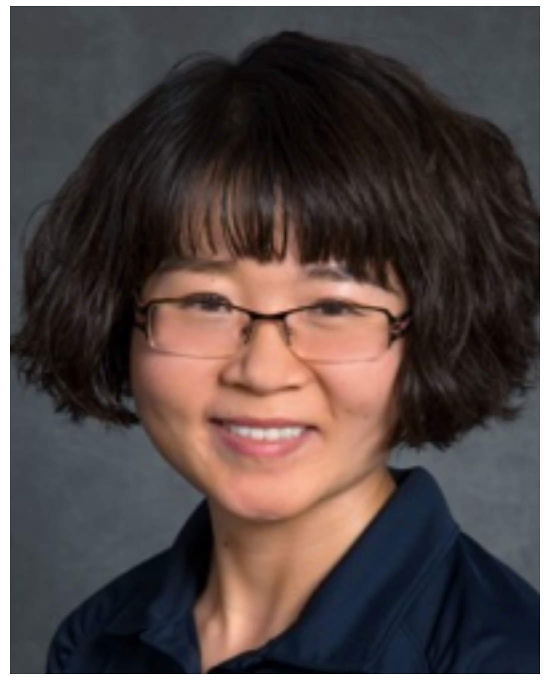

Tom Daley, LBNL


Barry Freifeld, LBNL


Michelle Robertson, LBNL


Craig Ulrich, LBNL


Nate Lindsey, UC Berkeley, LBNL

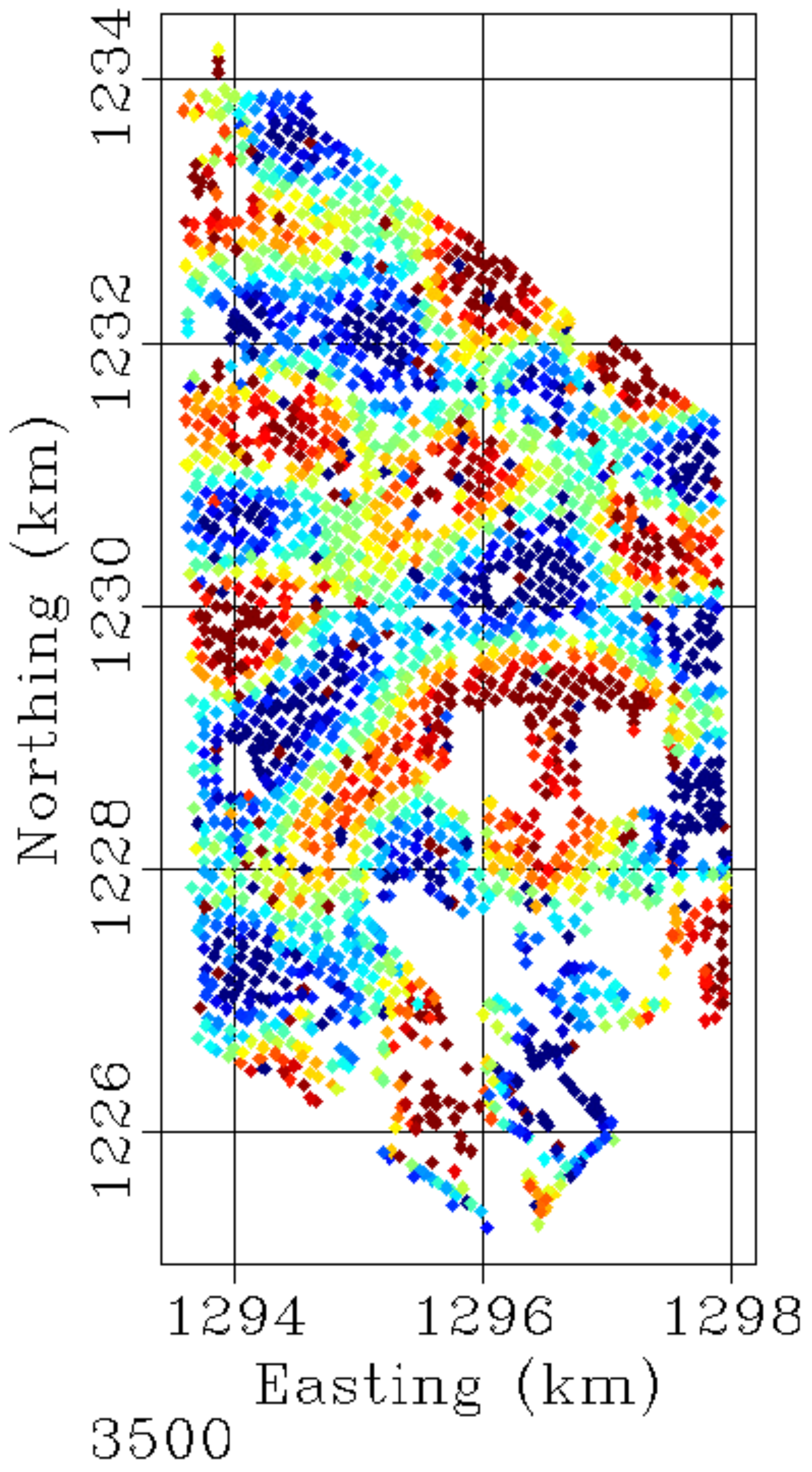

Shan Dou, LBNL


Anna Wagner

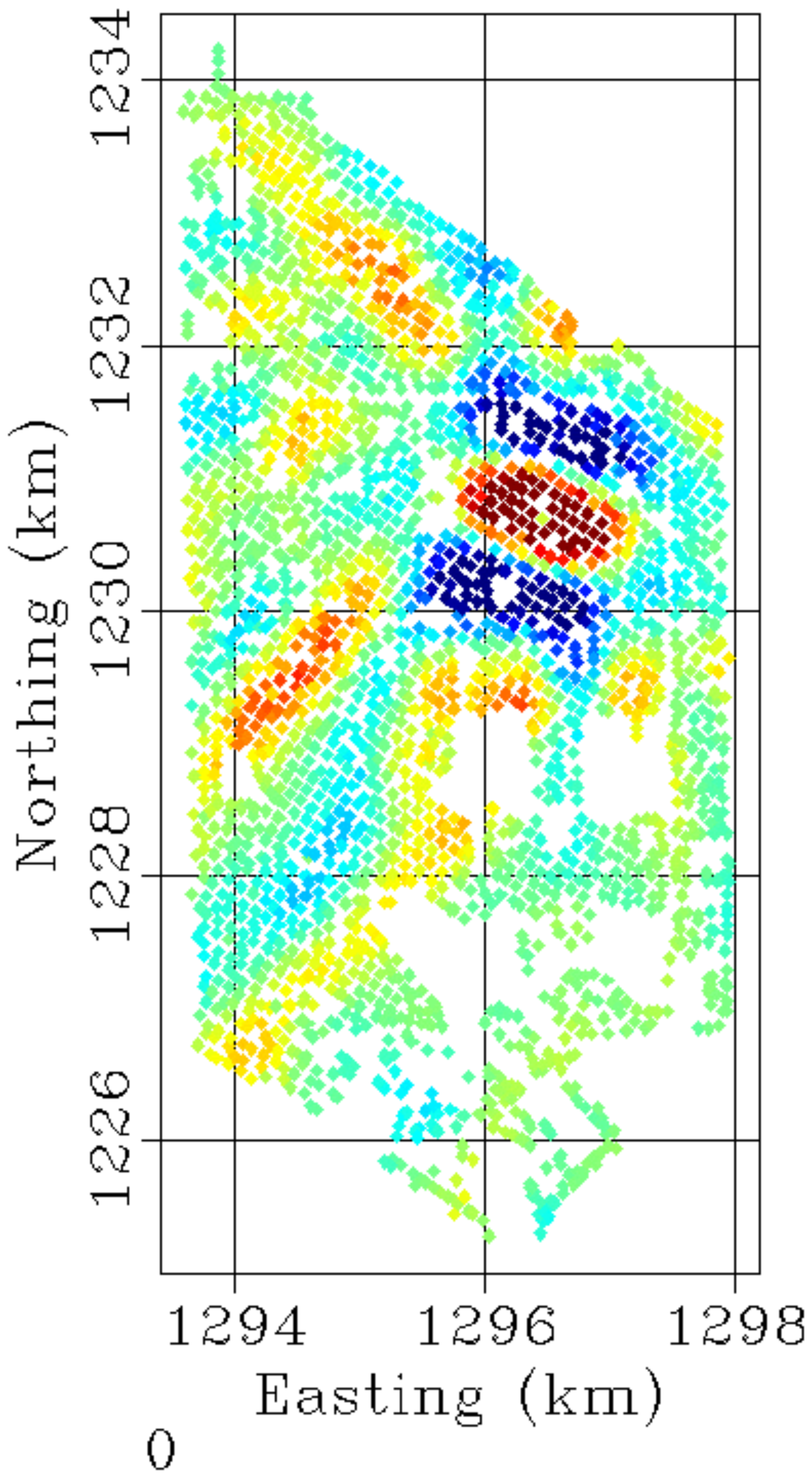

Kevin Bjella

US Army Corps of Engineers Cold Regions Research & Engineering Lab

How a passive seismic survey works

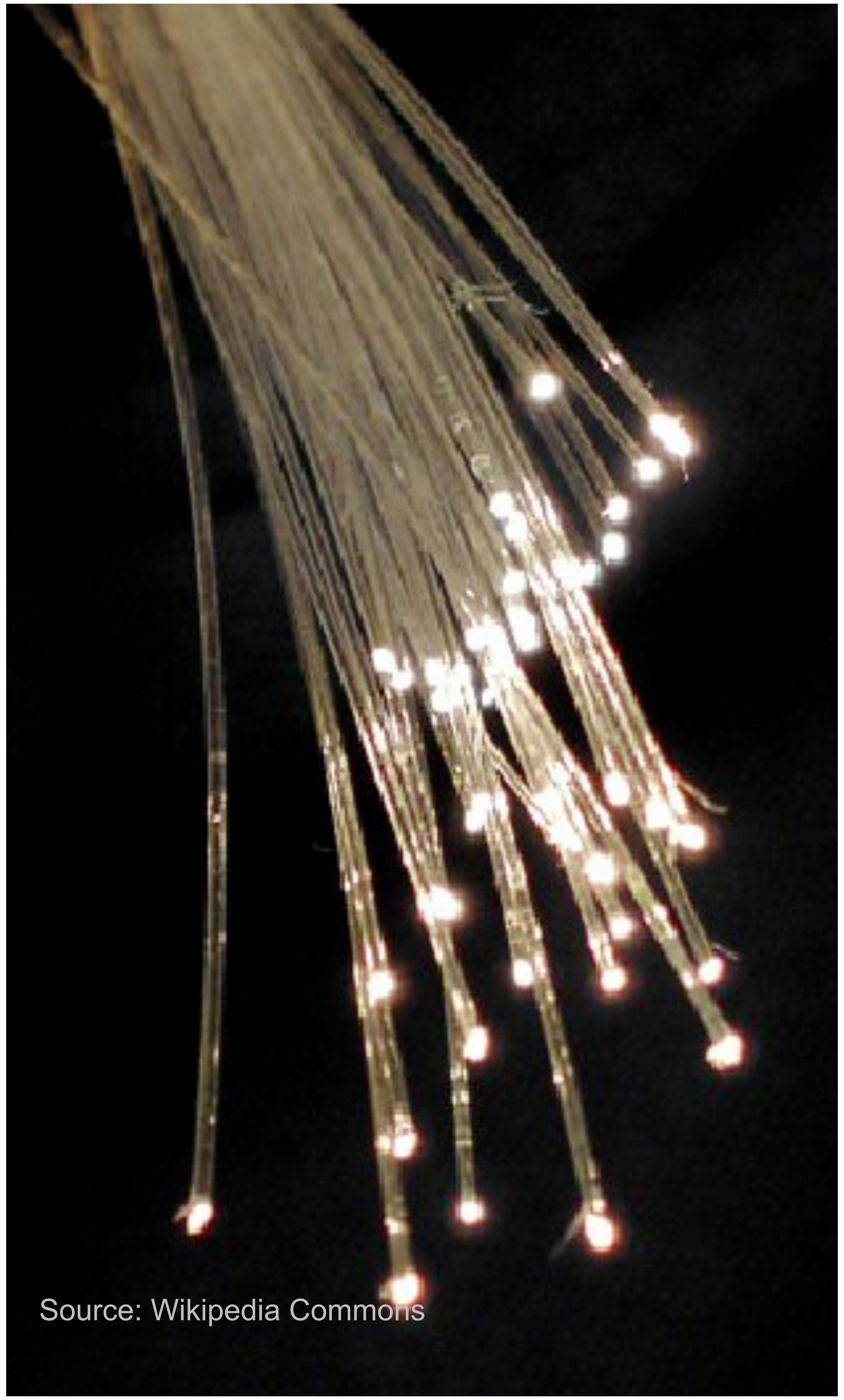


correlations
between windows
of noise



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

What is distributed acoustic sensing (DAS)?



DAS repurposes a standard fiber optic cable probed by a laser as a seismic sensor. Backscattered light is used to calculate strain rates along the fiber.

Benefits:
- Low cost per sensor
- Low energy required
- Flexible
- 10s of km covered with single laser

Downsides:
- Lower signal/noise ratio
- Lower sensitivity to waves at angles
- Large amplitude noise from phase control issues

Pilot: Richmond Field Station, Dec. ‘14

free vibration sources ambient noise

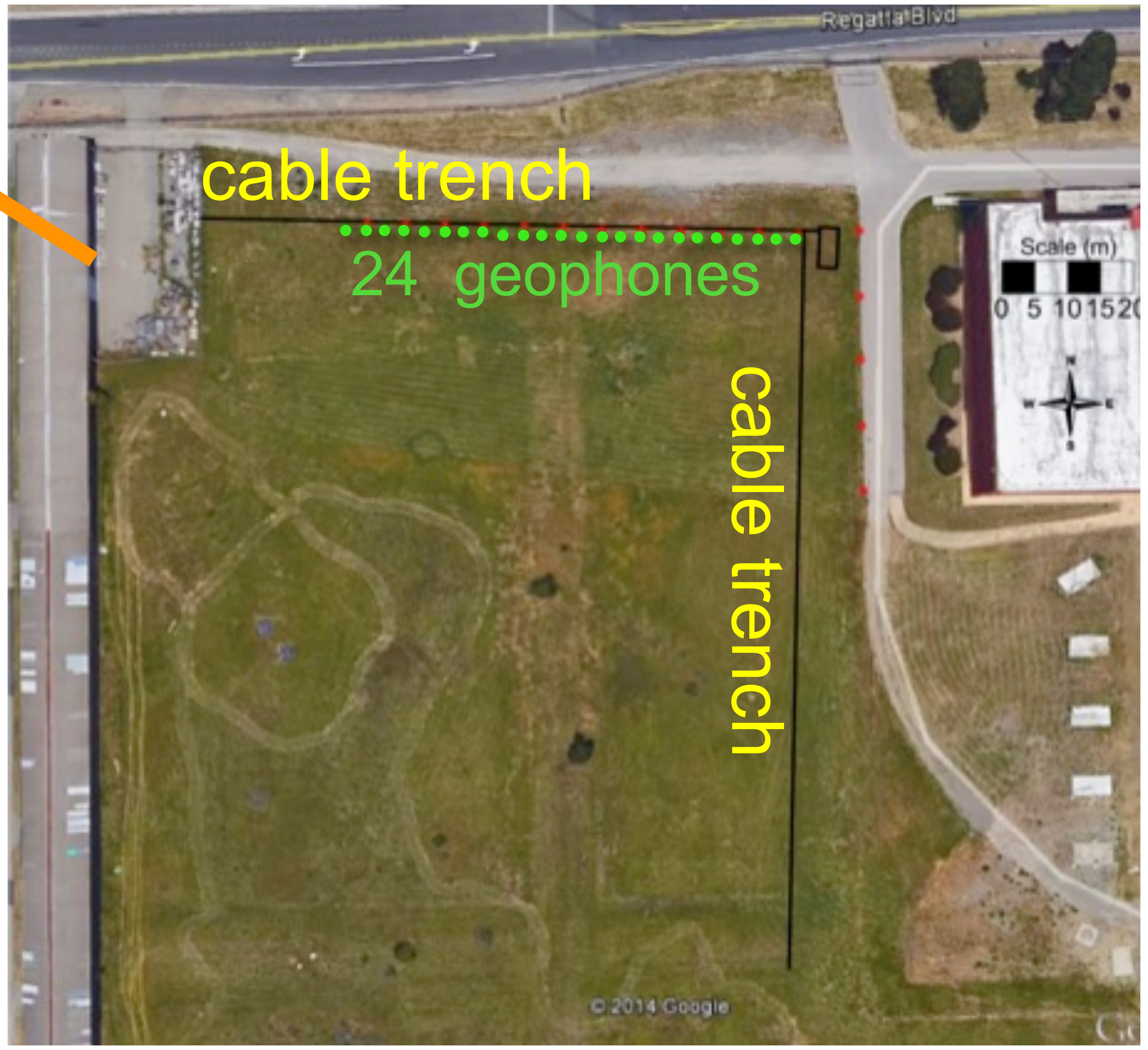
+

low-cost permanent sensors distributed acoustic sensing

=

low-cost large-scale frequent monitoring of ground stability under infrastructure on permafrost

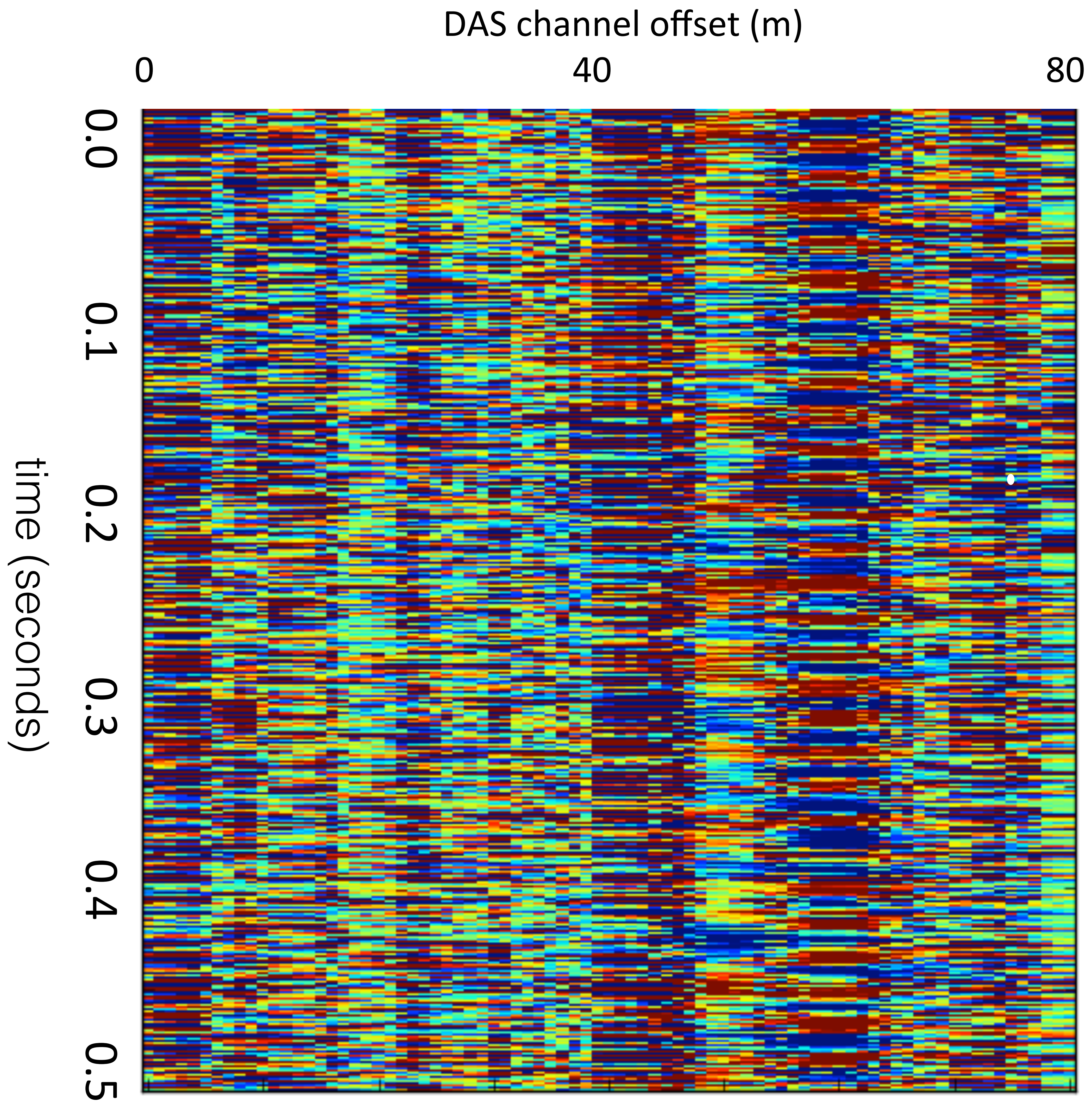
Pilot: Richmond Field Station, Dec. ‘14

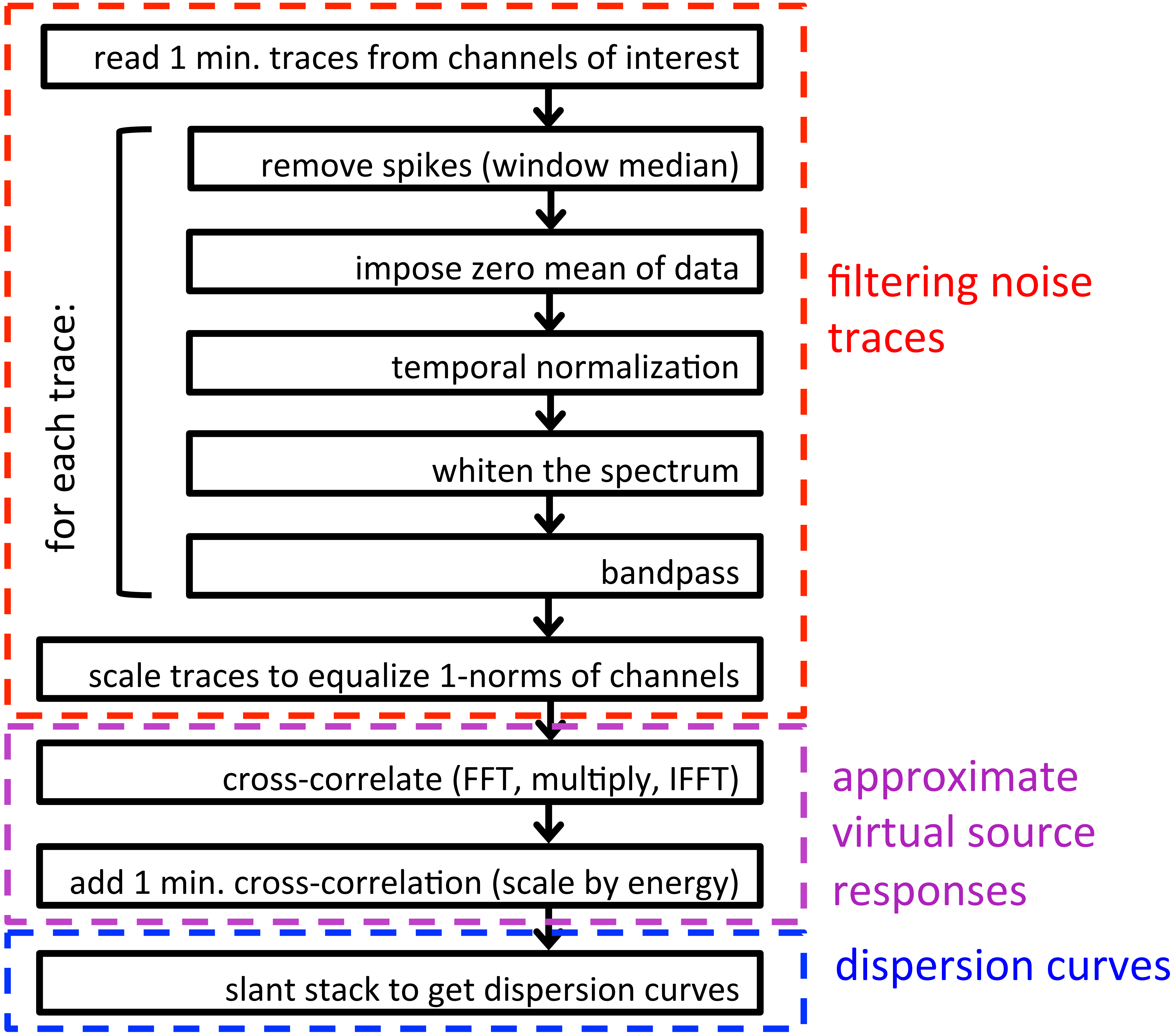


Data recorded with iDAS

SILIXA

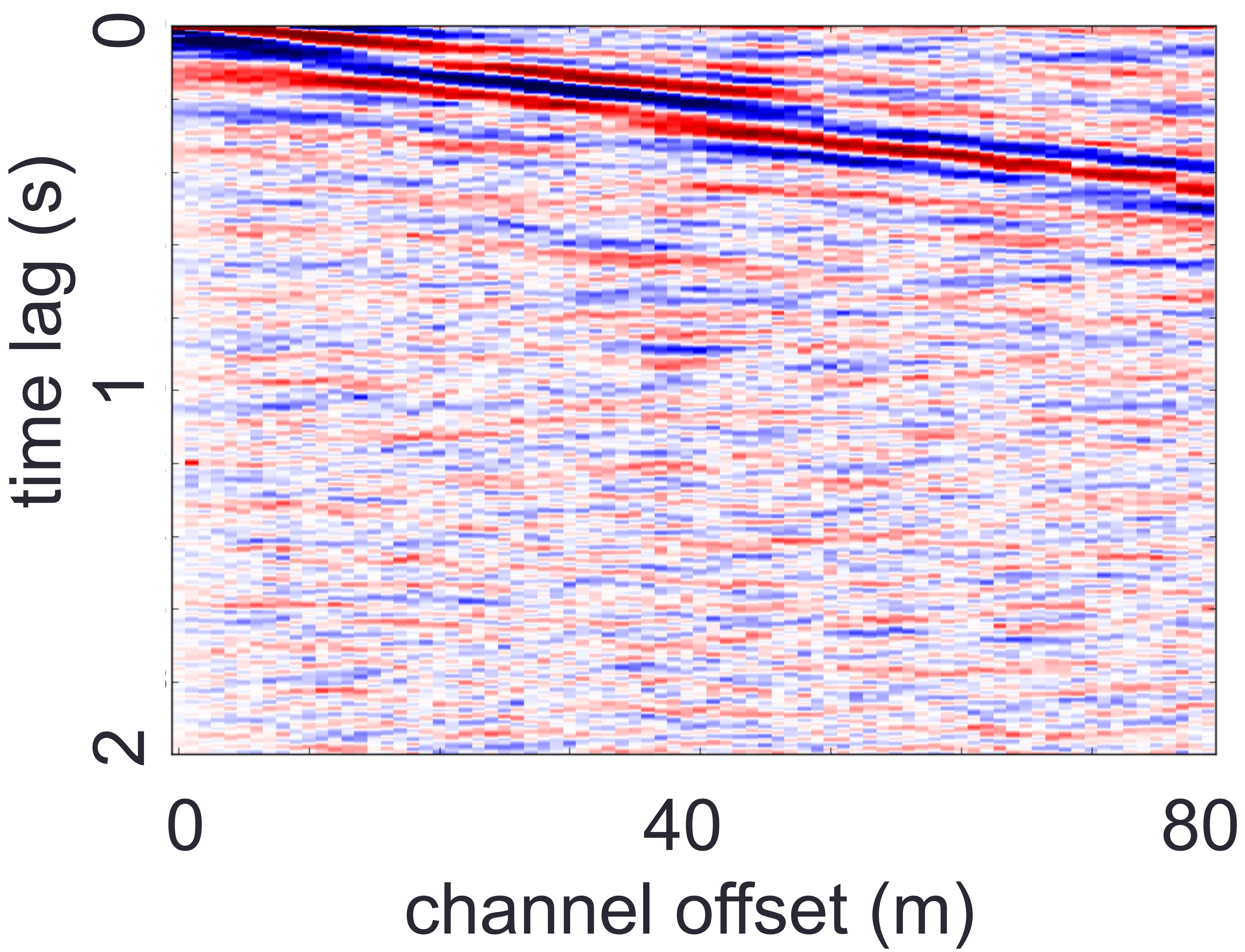
Raw data & cross-correlation processing



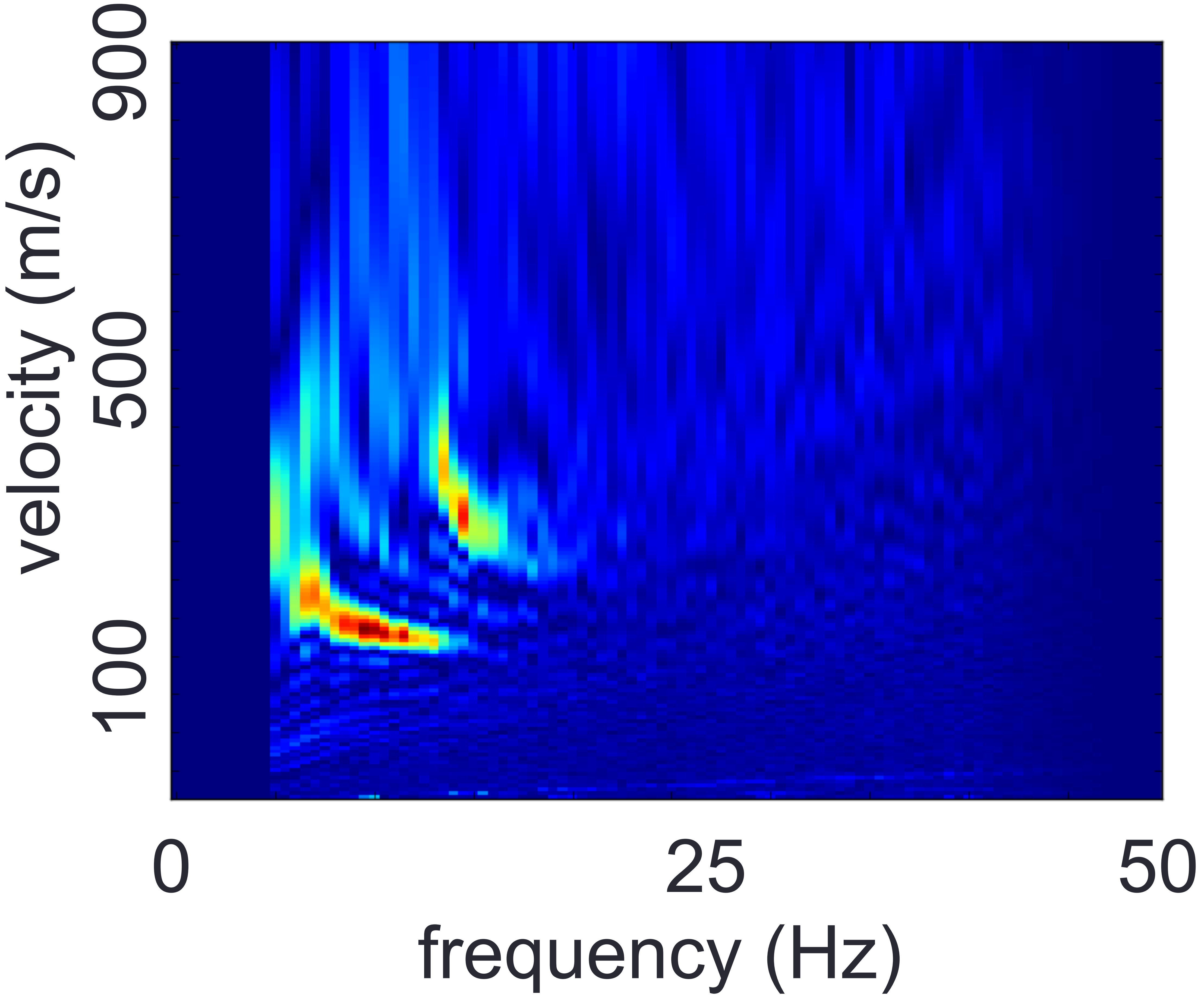


Clear response after 10 minutes

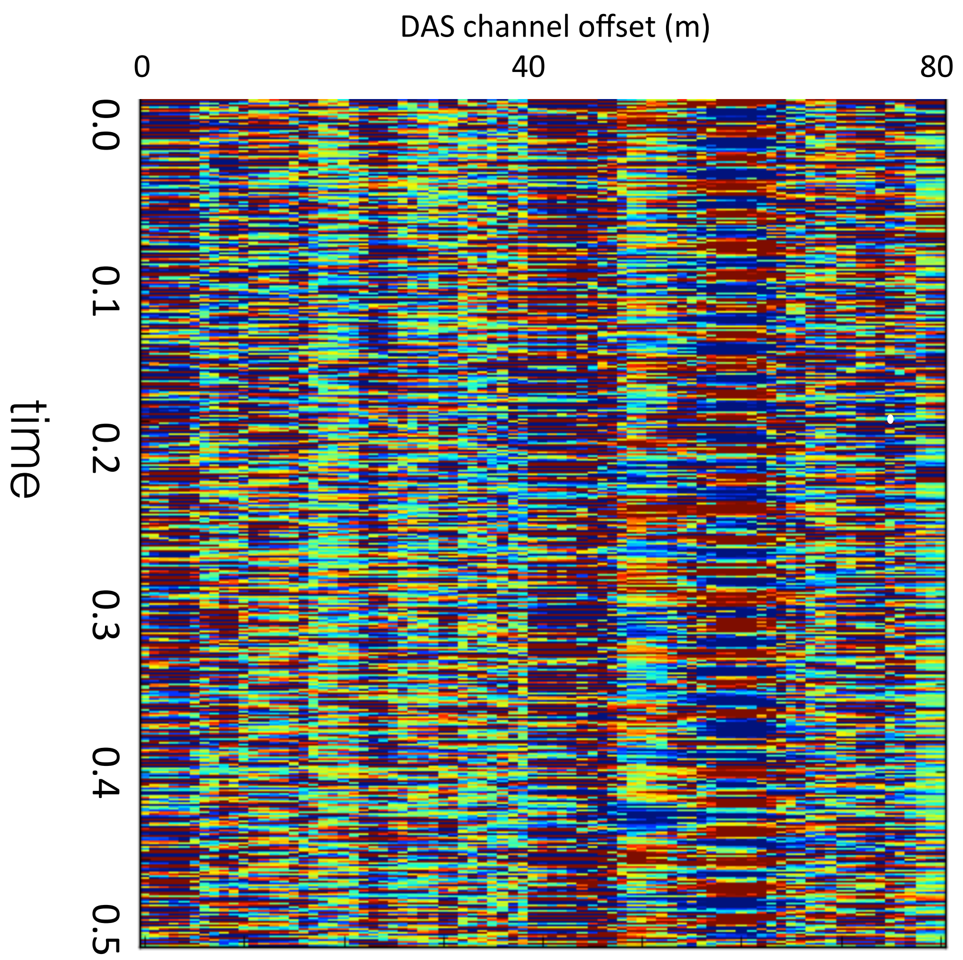
cross-correlation / virtual source response



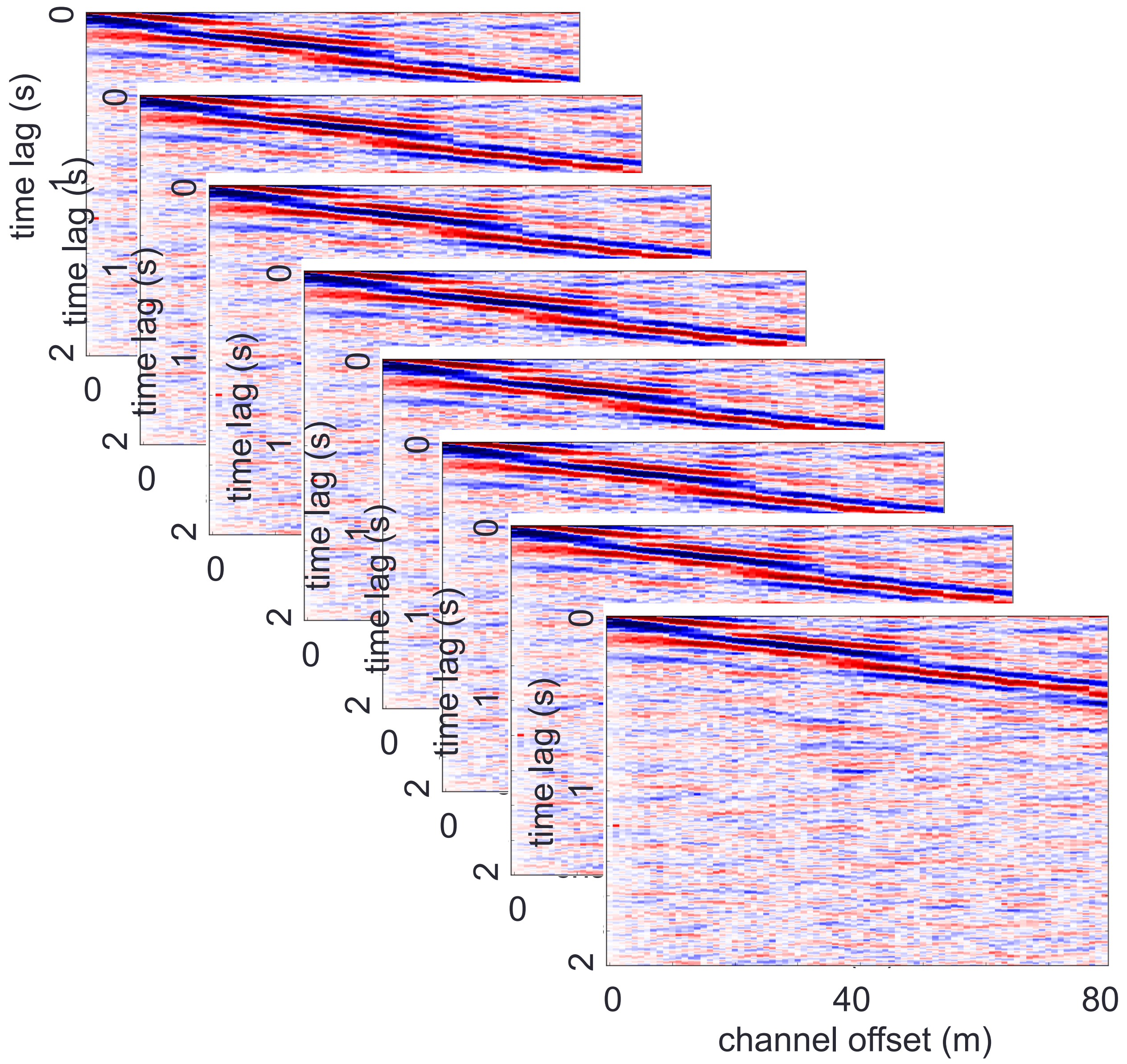
dispersion image



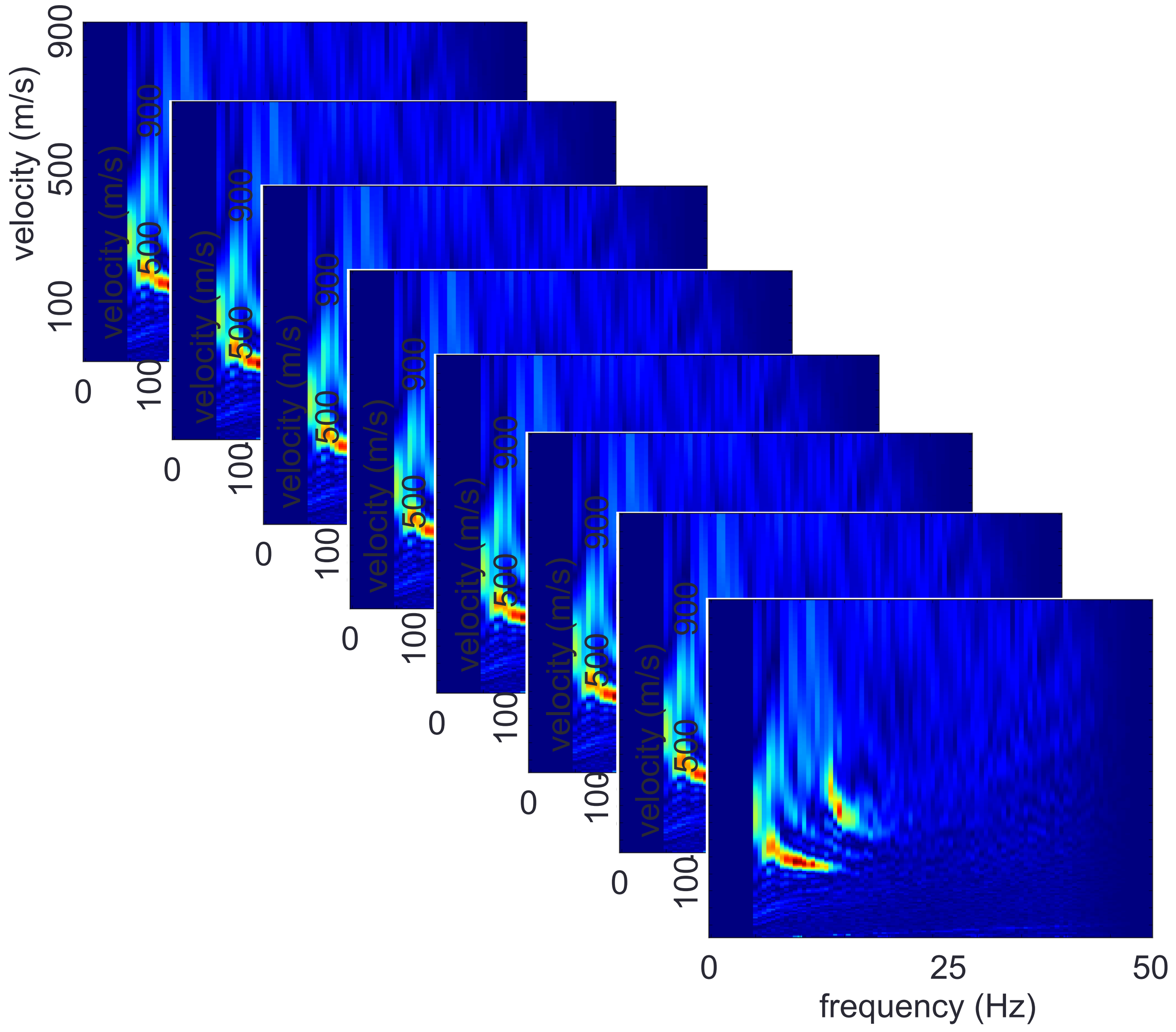
Typical workflow is $O(n^2)$…



raw data
n sensors



n virtual source response estimates
via **n^2 cross-correlations**



n dispersion images with energy at set of (frq,vel) combinations from each virtual source response estimate

input to dispersion domain surface wave inversion*

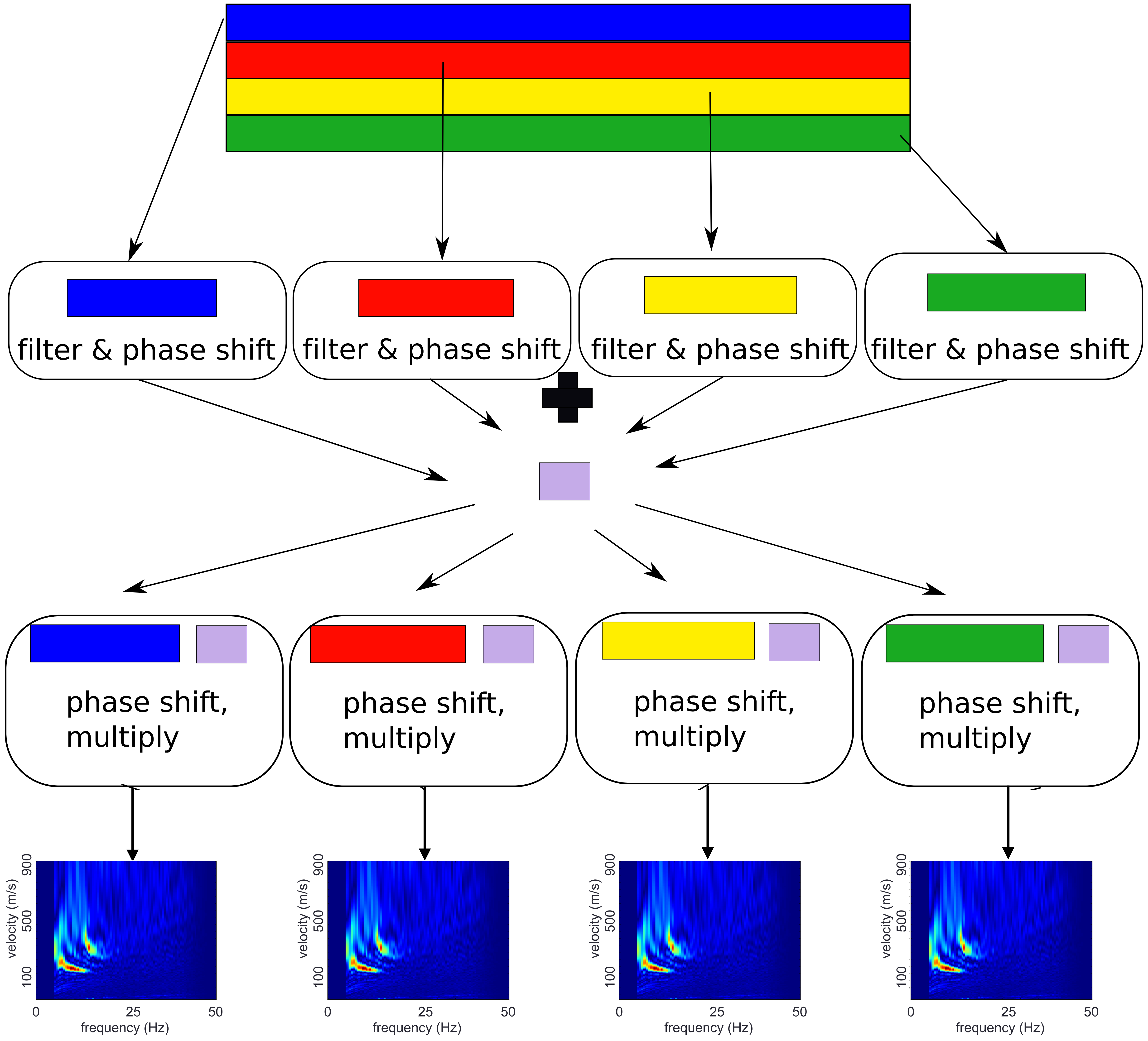
*Dou, S. and J. Ajo-Franklin, 2014, Geophysics, 79.

…or we can get dispersion images in O(n) serial time with an embarrassingly parallel algorithm:

dispersion image for virtual source s, velocity v, frequency omega

$$
\begin{aligned}
I_s(\mathbf{v},\omega) &= \mathcal{F}_t\left[\sum_{r=1}^{n} u_s\left(\mathbf{x}_r, t+(1/v_x,1/v_y)\cdot(\mathbf{x}_r-\mathbf{x}_s)\right)\right] \\
&= \sum_{r=1}^{n} \mathcal{F}_t\left[u_s\left(\mathbf{x}_r, t+(1/v_x,1/v_y)\cdot(\mathbf{x}_r-\mathbf{x}_s)\right)\right] \\
&= \sum_{r=1}^{n} \mathcal{F}_t u_s(\mathbf{x}_r,\omega) e^{2\pi i(1/v_x,1/v_y)\cdot(\mathbf{x}_r-\mathbf{x}_s)\omega} \\
&= \sum_{r=1}^{n} \hat{d}^*(\mathbf{x}_s,\omega)\hat{d}(\mathbf{x}_r,\omega) e^{2\pi i(1/v_x,1/v_y)\cdot(\mathbf{x}_r-\mathbf{x}_s)\omega} \\
&= \hat{d}^*(\mathbf{x}_s,\omega) e^{-2\pi i(1/v_x,1/v_y)\cdot\mathbf{x}_s} \sum_{r=1}^{n} \hat{d}(\mathbf{x}_r,\omega) e^{2\pi i\omega(1/v_x,1/v_y)\cdot\mathbf{x}_r} \\
&= \hat{d}^*(\mathbf{x}_s,\omega) e^{-2\pi i(1/v_x,1/v_y)\cdot\mathbf{x}_s} \sigma(\mathbf{v},\omega)
\end{aligned}
$$

factor common to all dispersion images



Scaling up: Fairbanks, AK, Aug. ‘15

free vibration sources ambient noise

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low-cost permanent sensors distributed acoustic sensing

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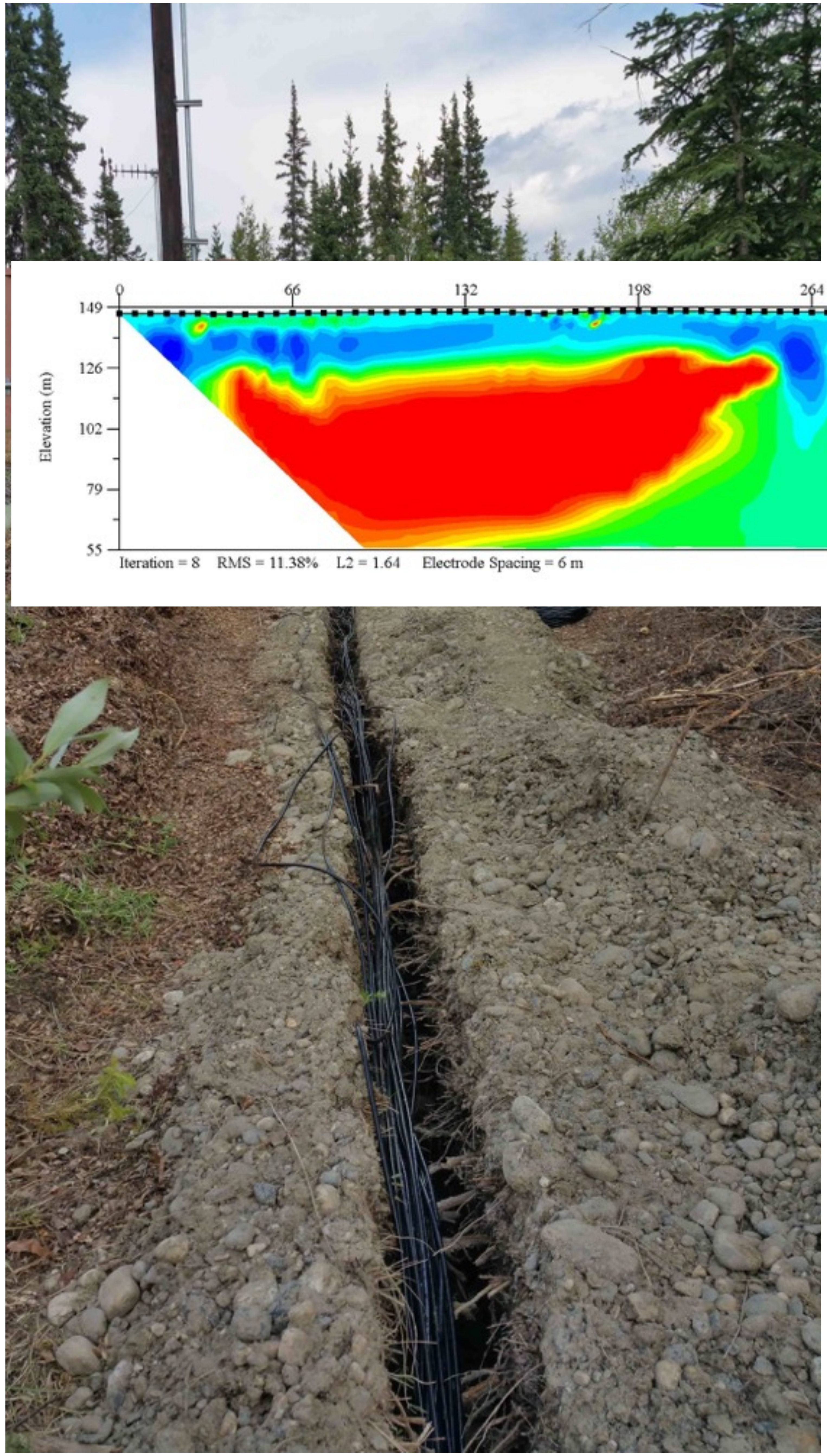
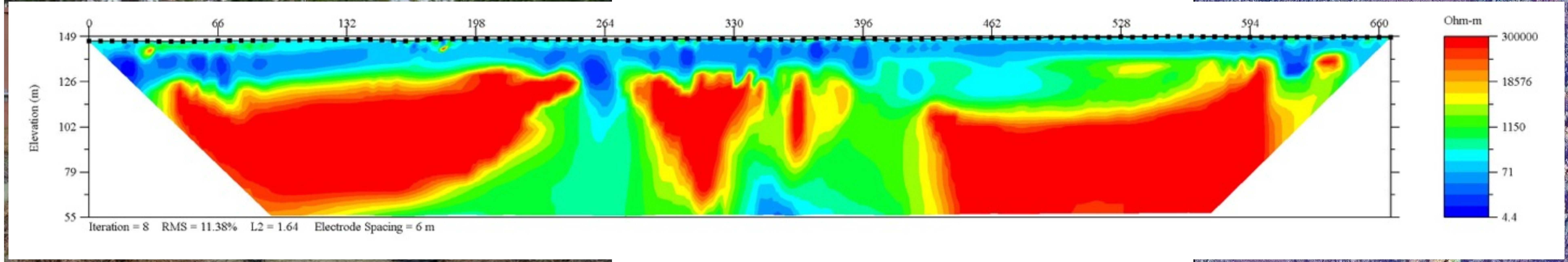
low-cost larger-scale frequent monitoring of ground stability under infrastructure on permafrost

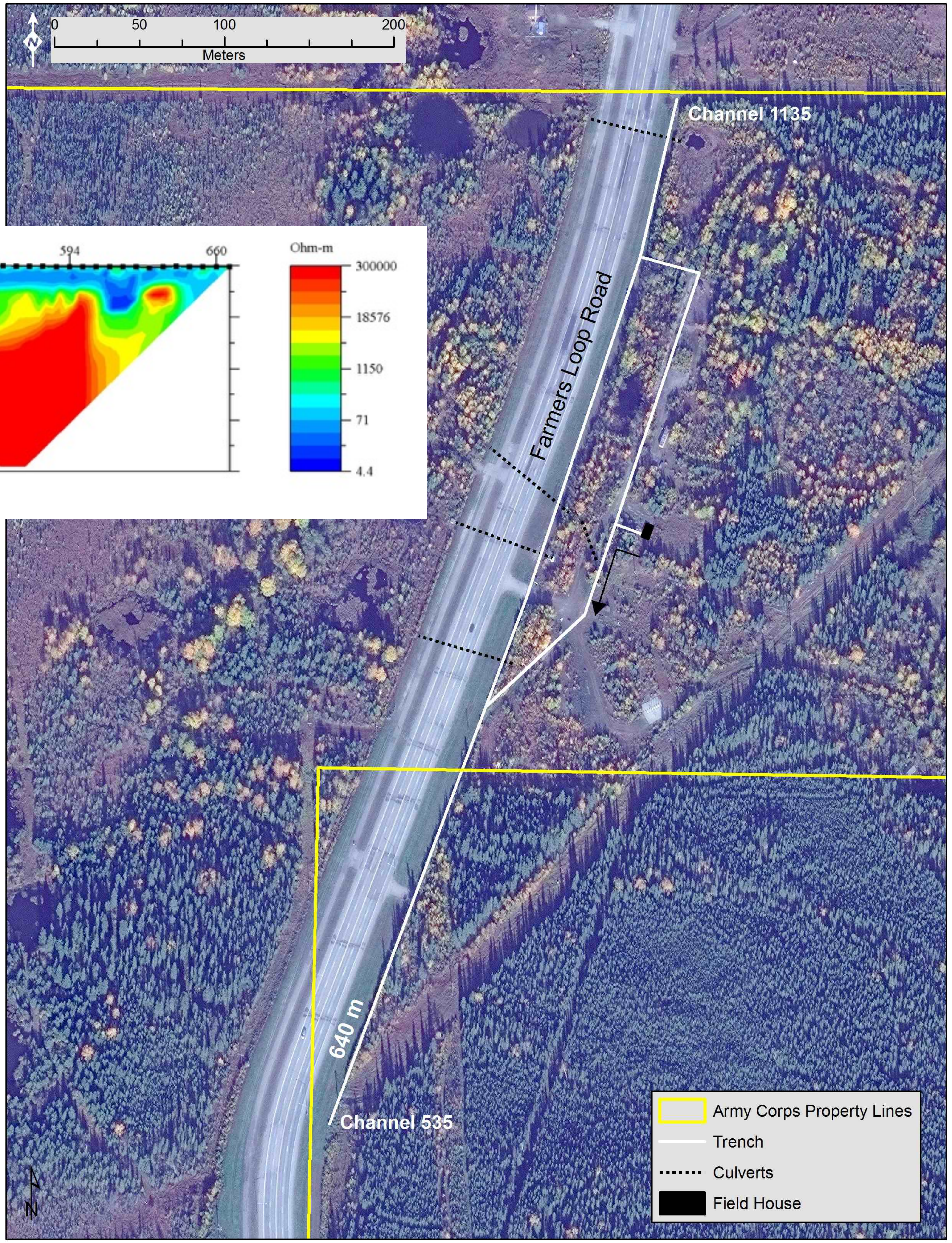
Site



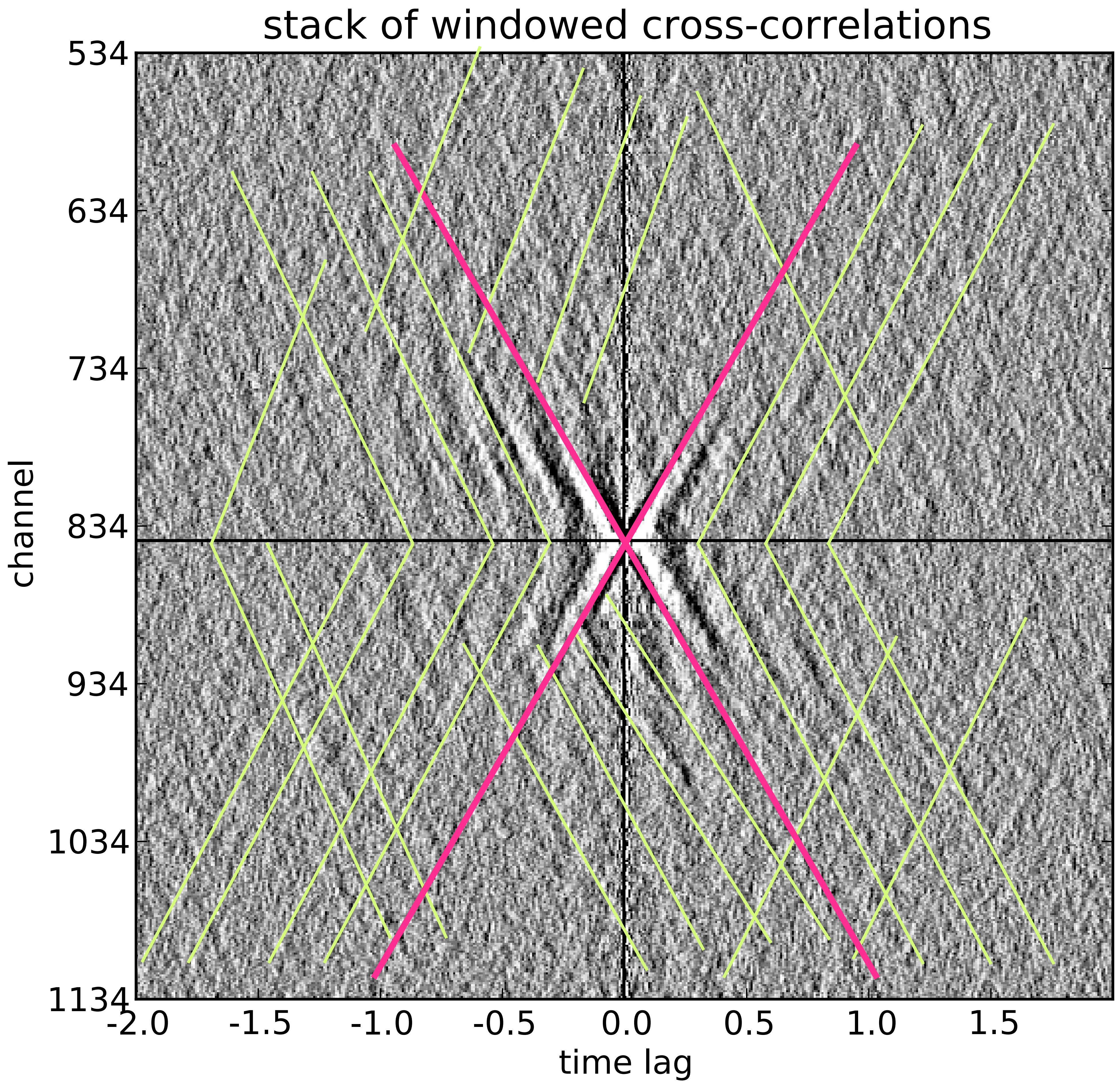


patchy permafrost
wooded area
1 mi north of Fairbanks
highway 400 m east

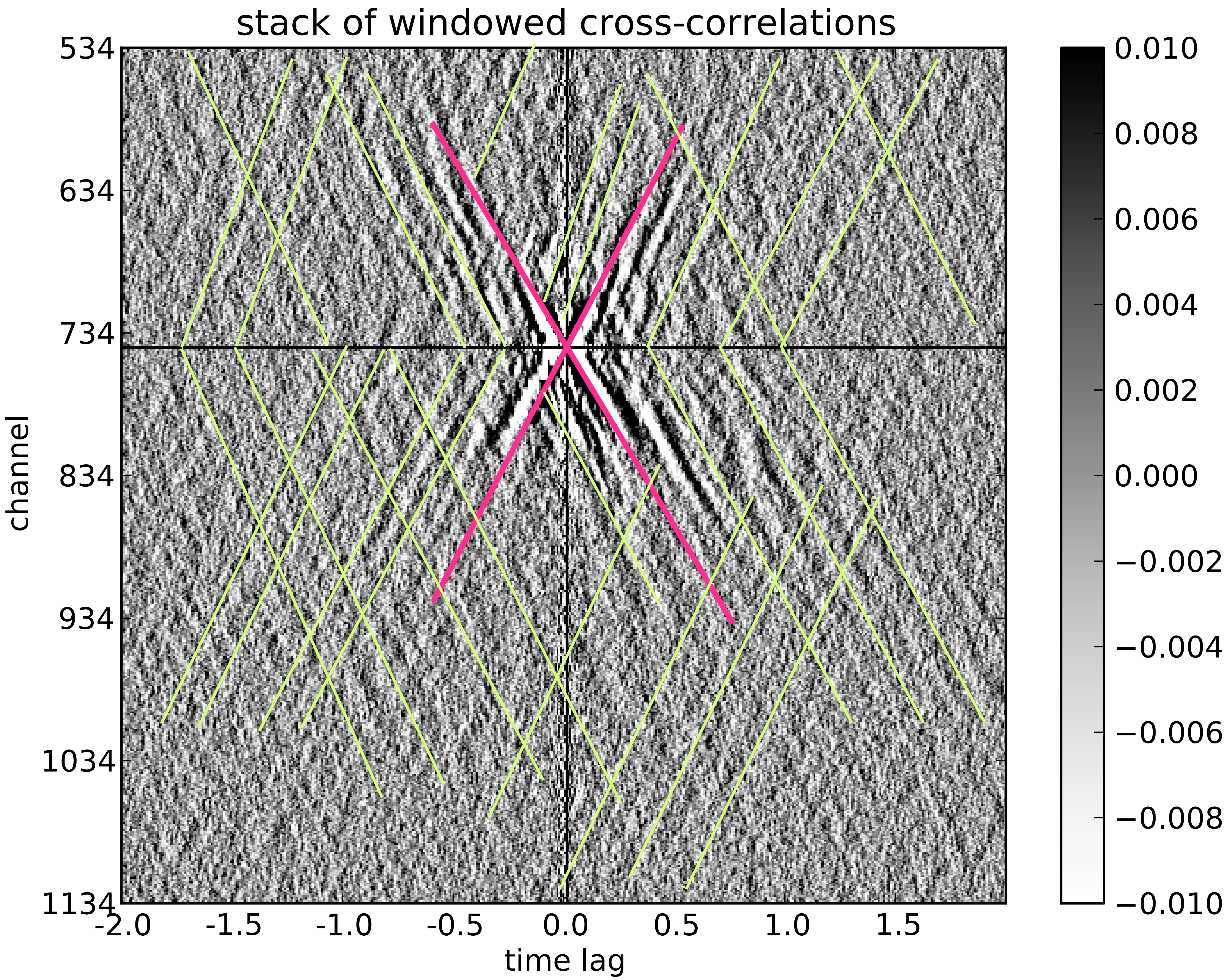
passive recording
SILIXA iDAS
1 m channel spacing
10 m gauge length
1 kHz recording



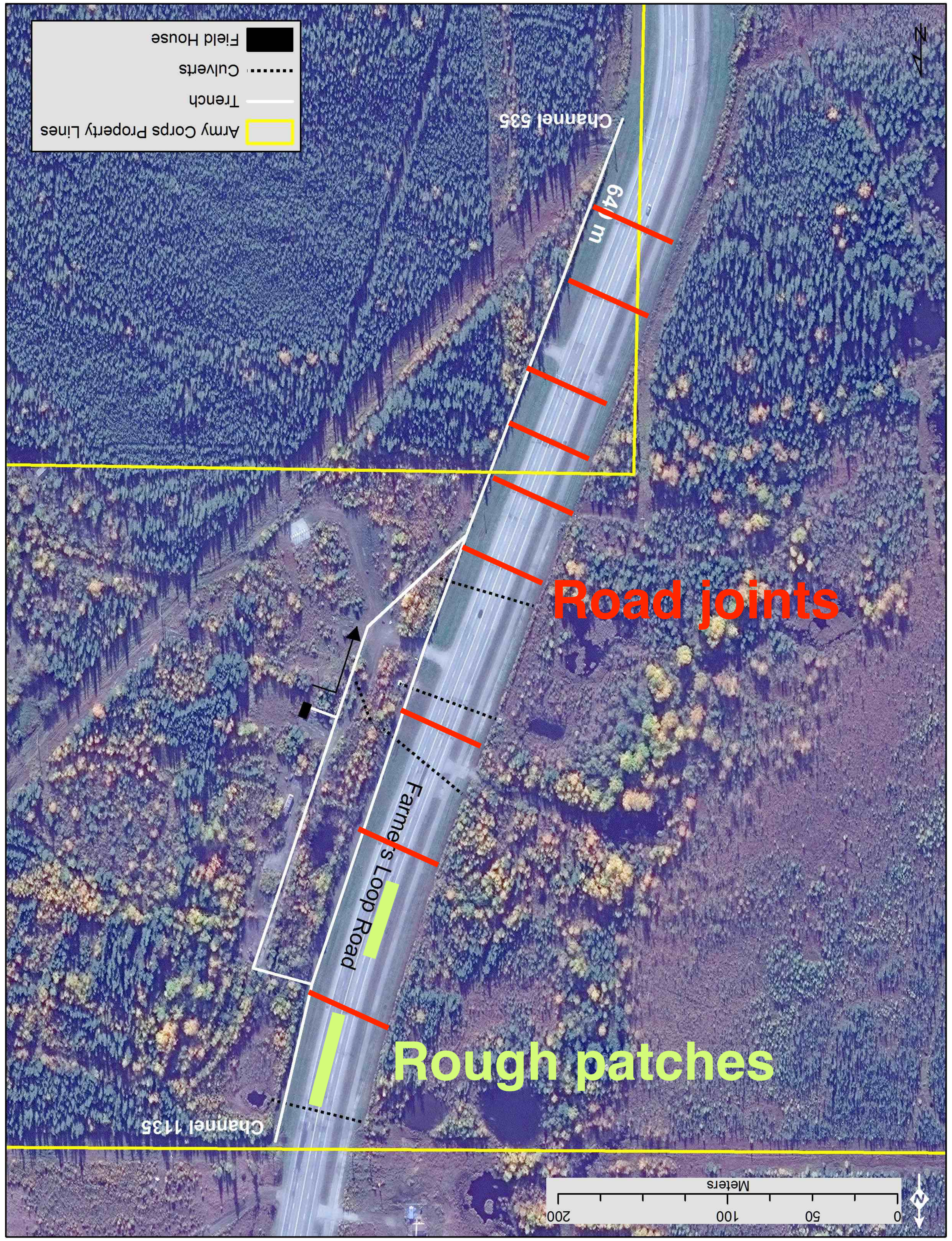
Cross-correlations

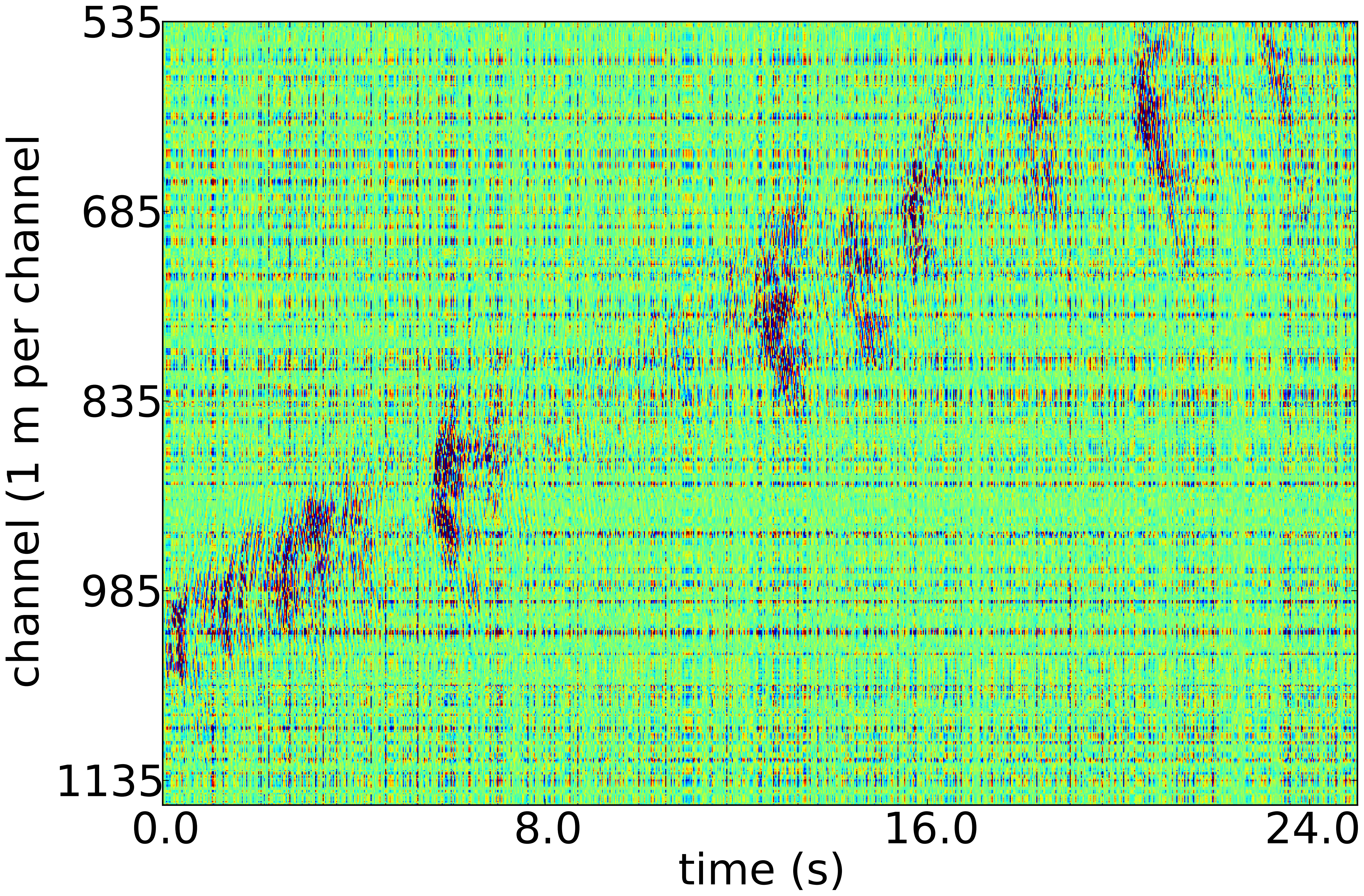


Channel 844

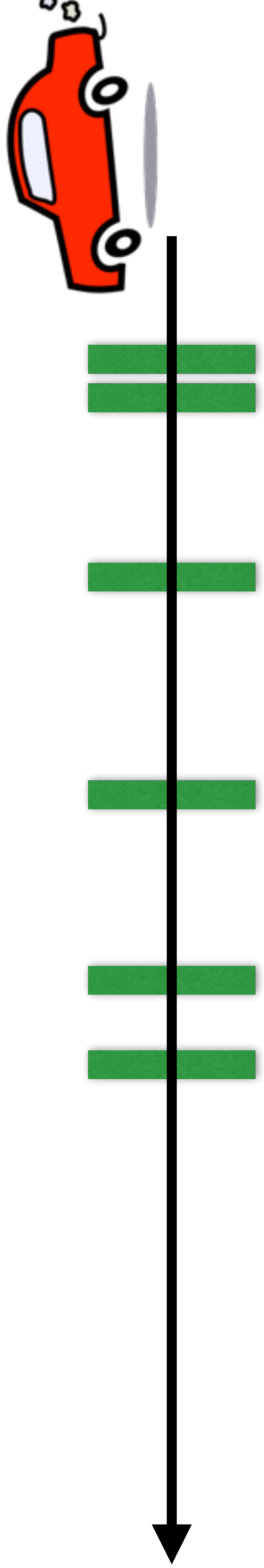


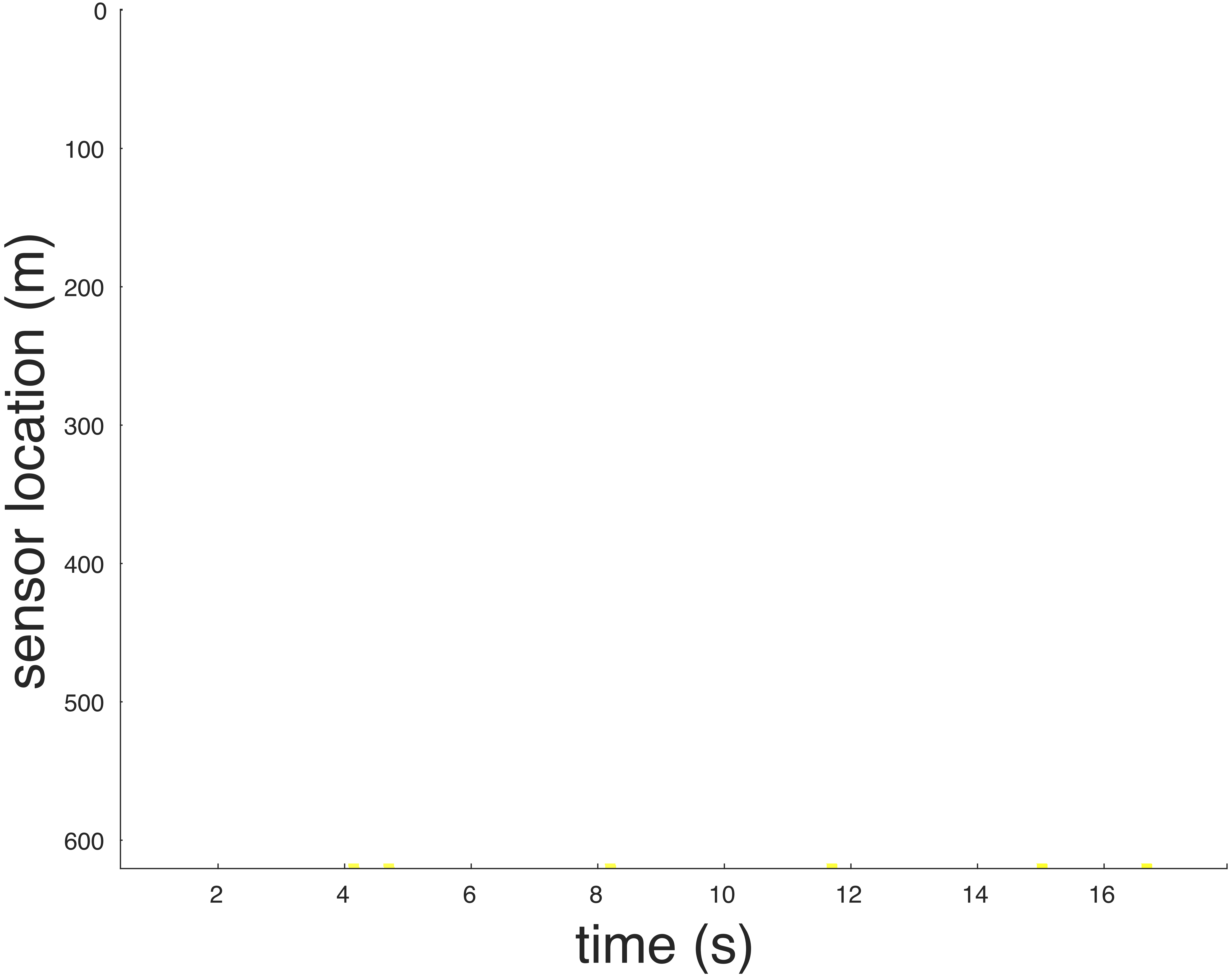
Channel 745


Field House
Culverts
Trench
Army Corps Property Lines
Channel 535
Road joints
Farmers Loop Road
Rough patches
Channel 1135
Meters
0
50
100
200

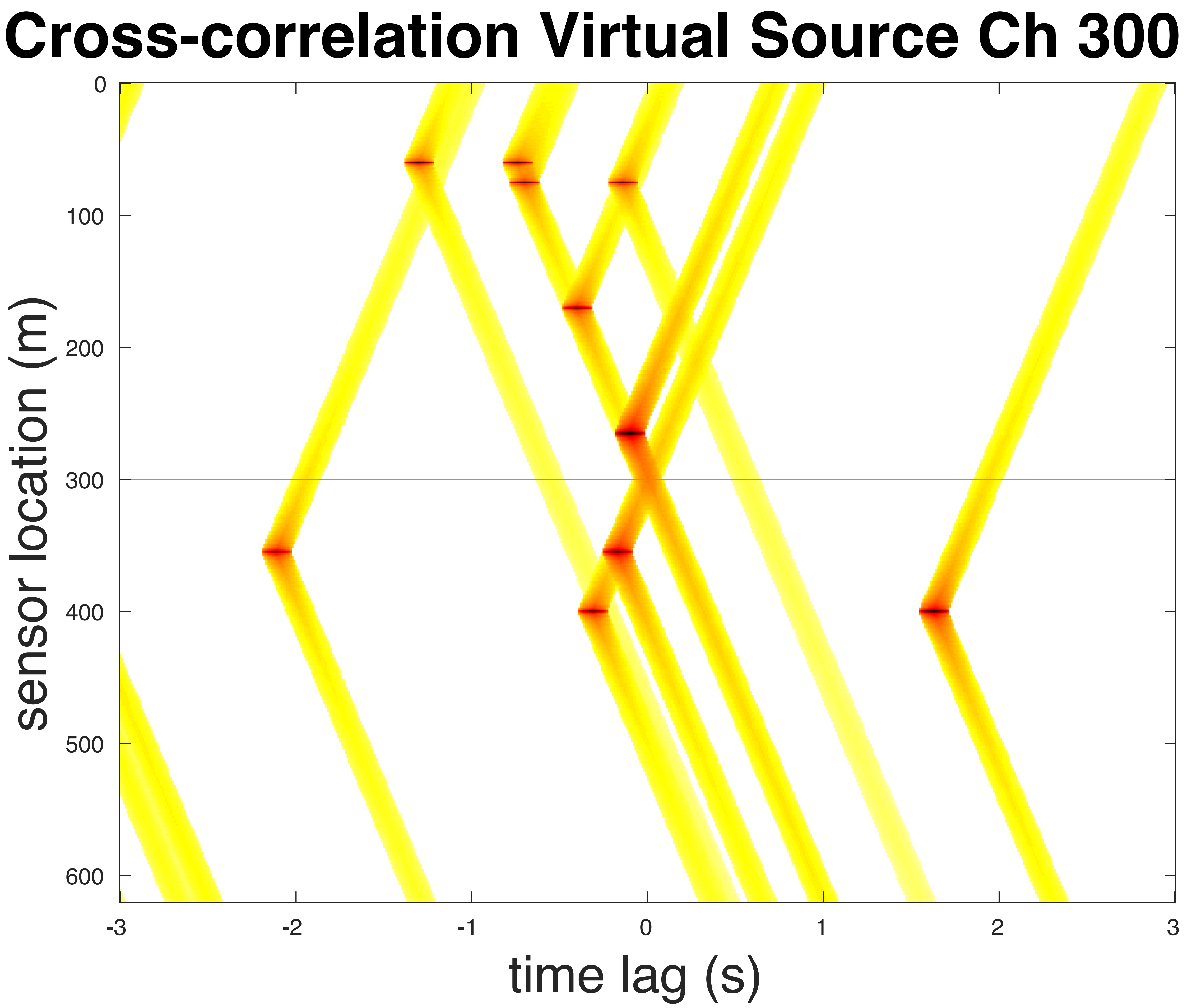

535
685
835
985
1135
channel (1 m per channel
0.0
8.0
16.0
24.0
time (s)

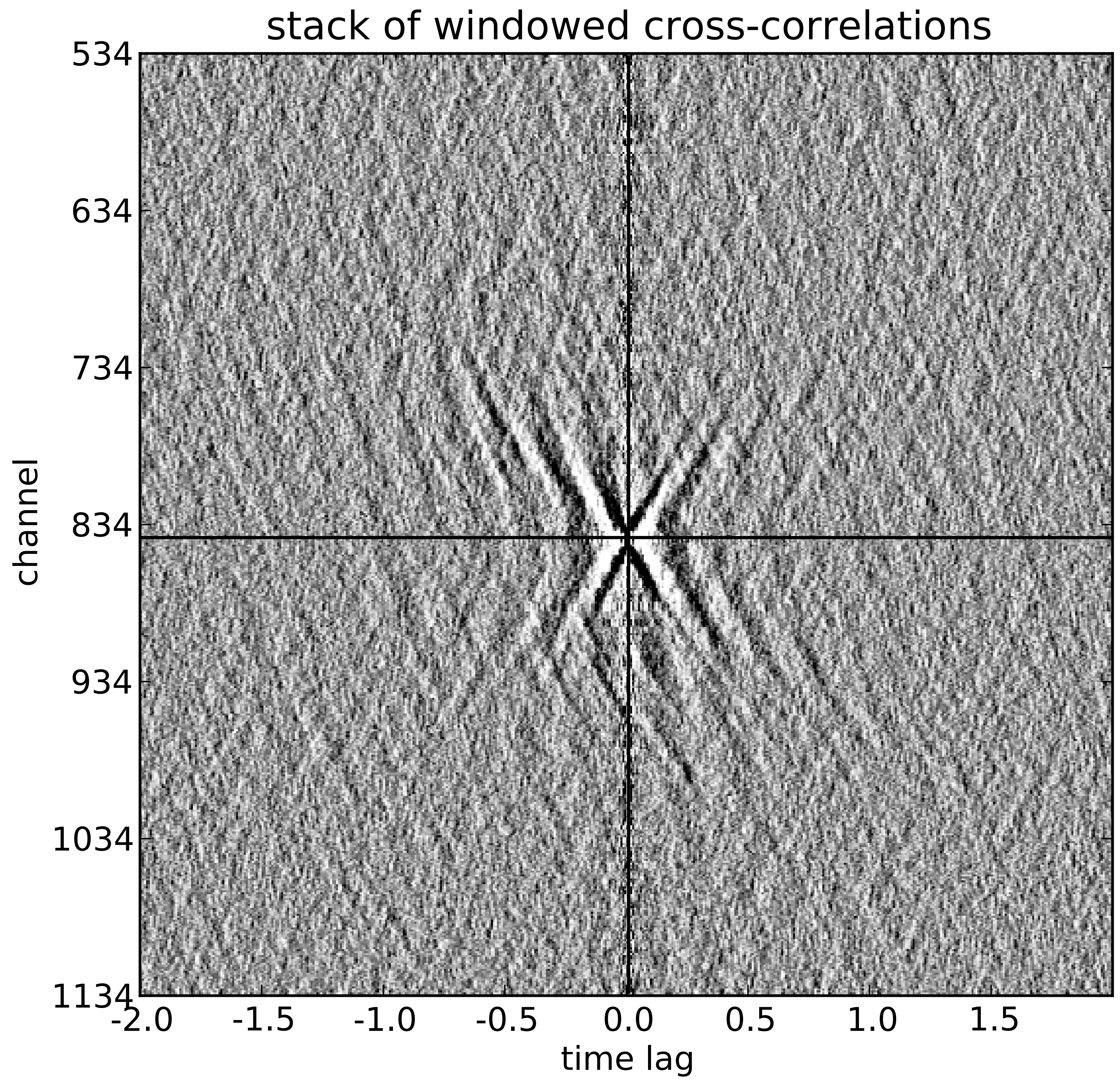
Time records





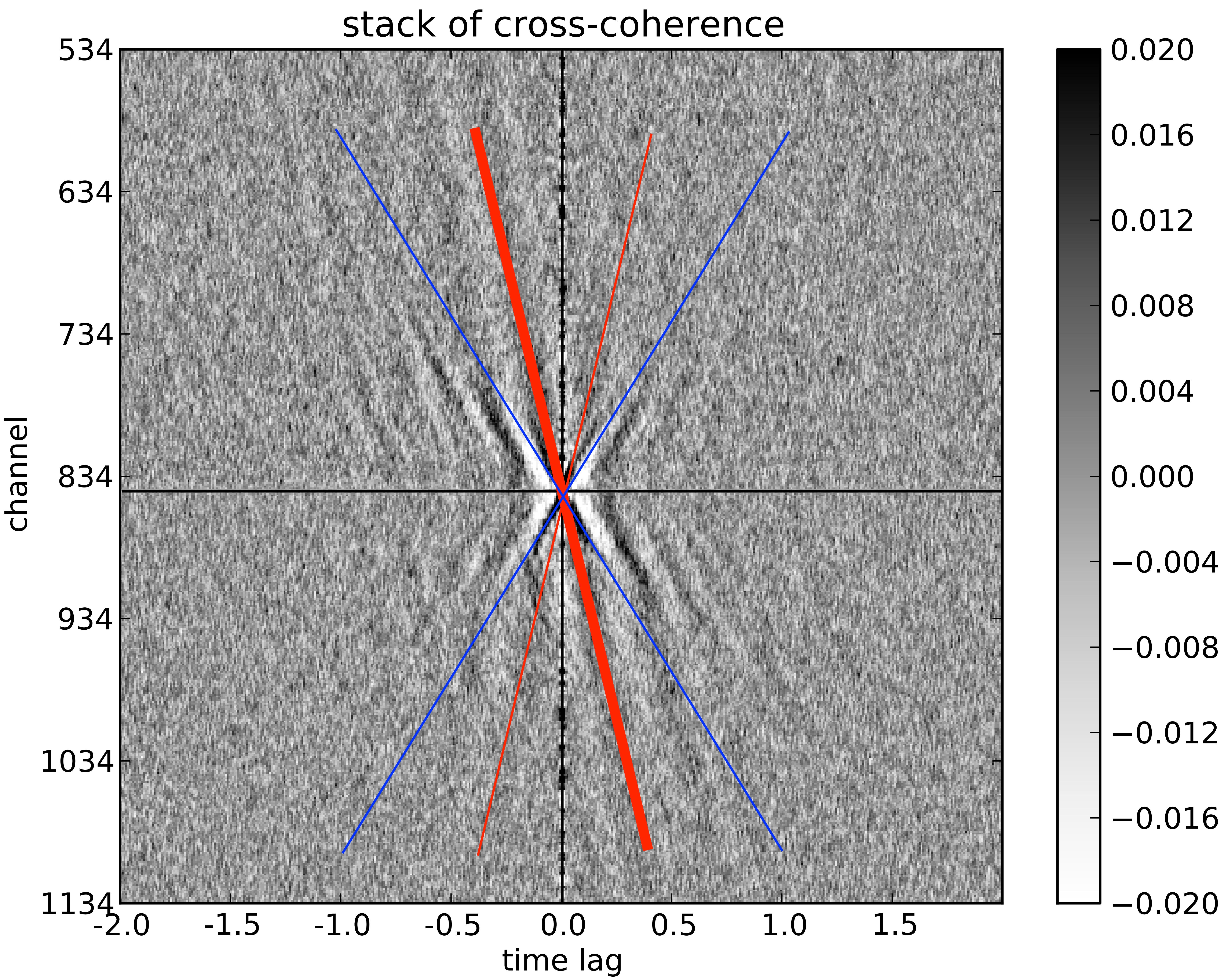
Bumps were probably the cause of artifacts in cross-correlations

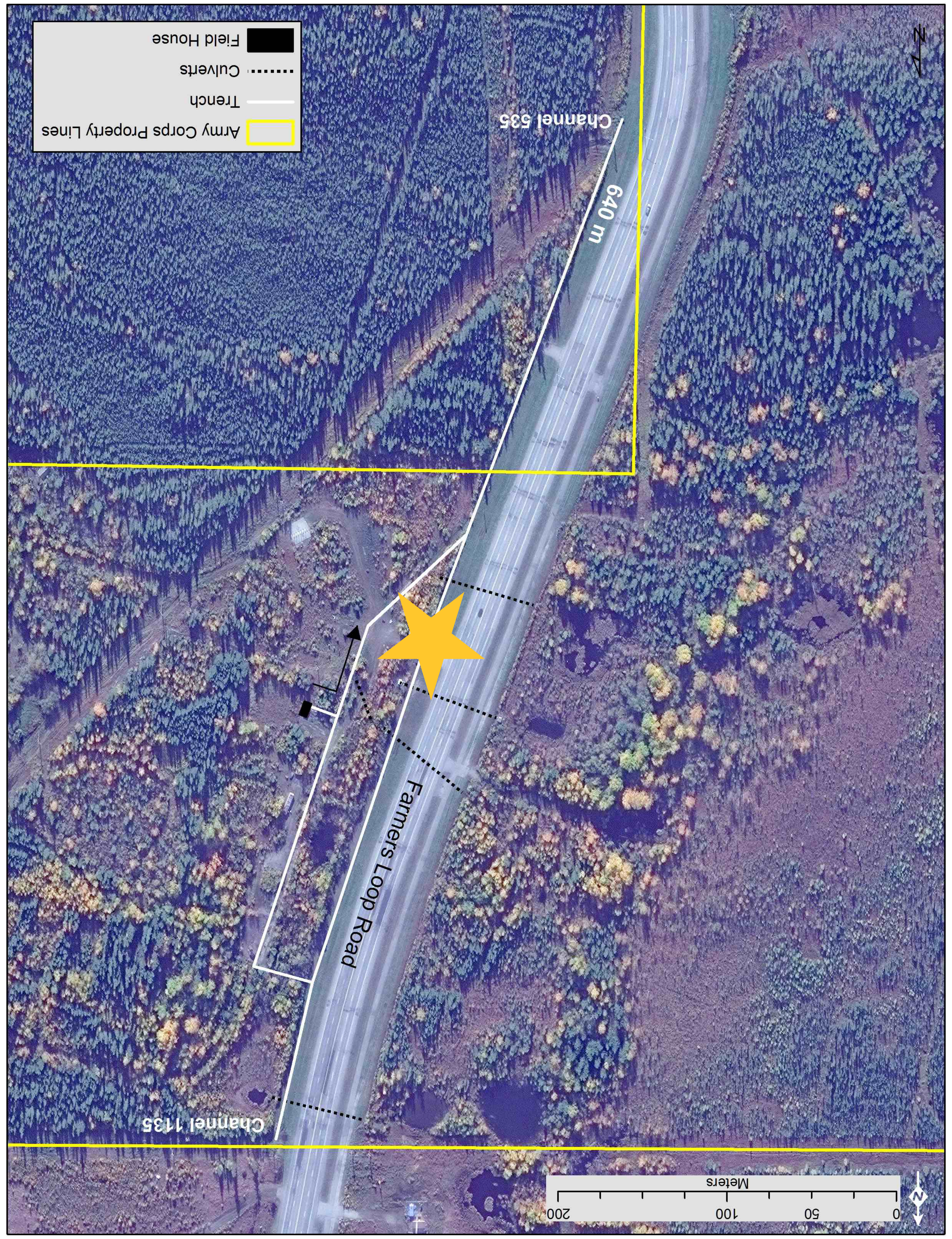




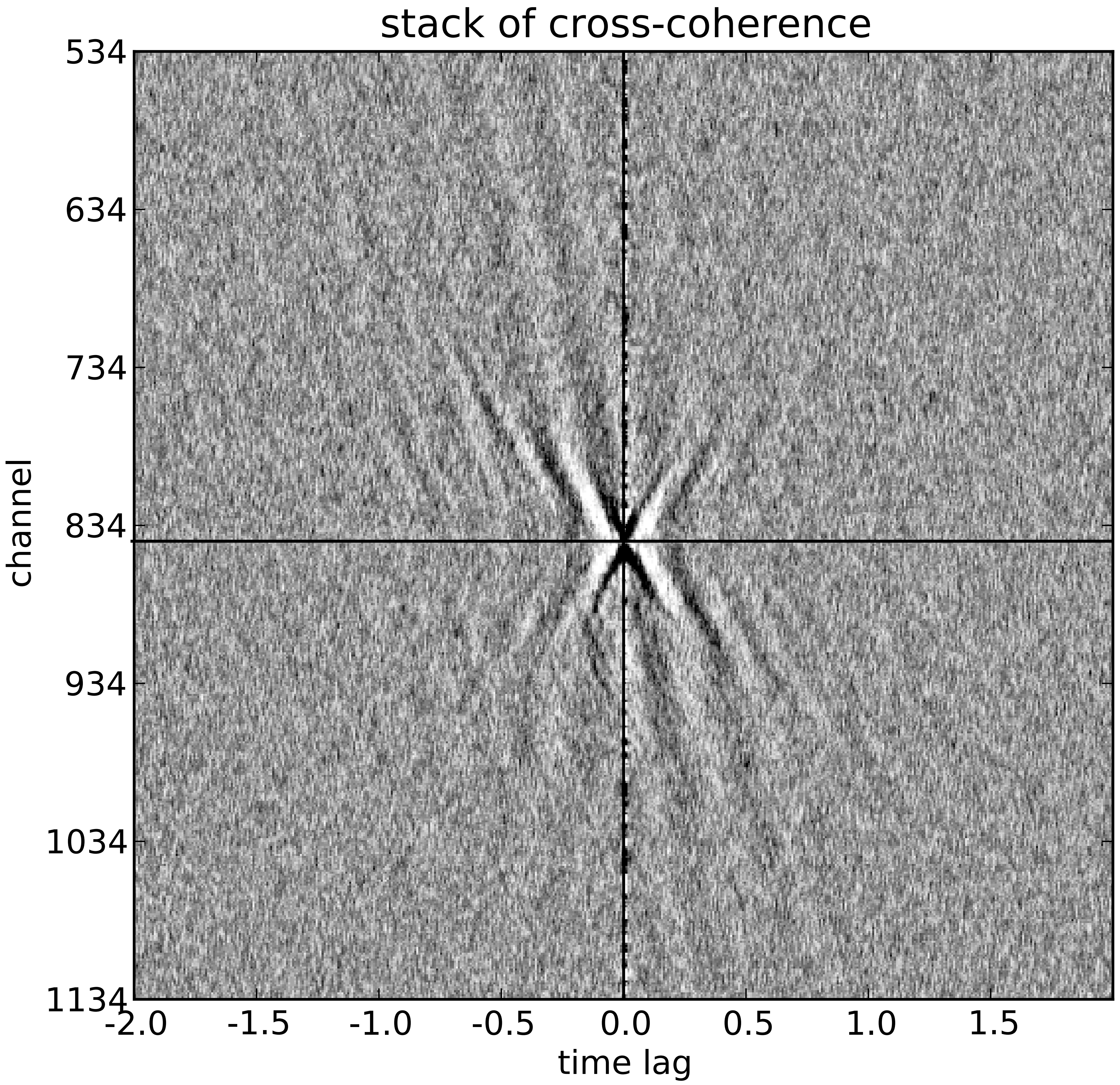
Cross-coherence

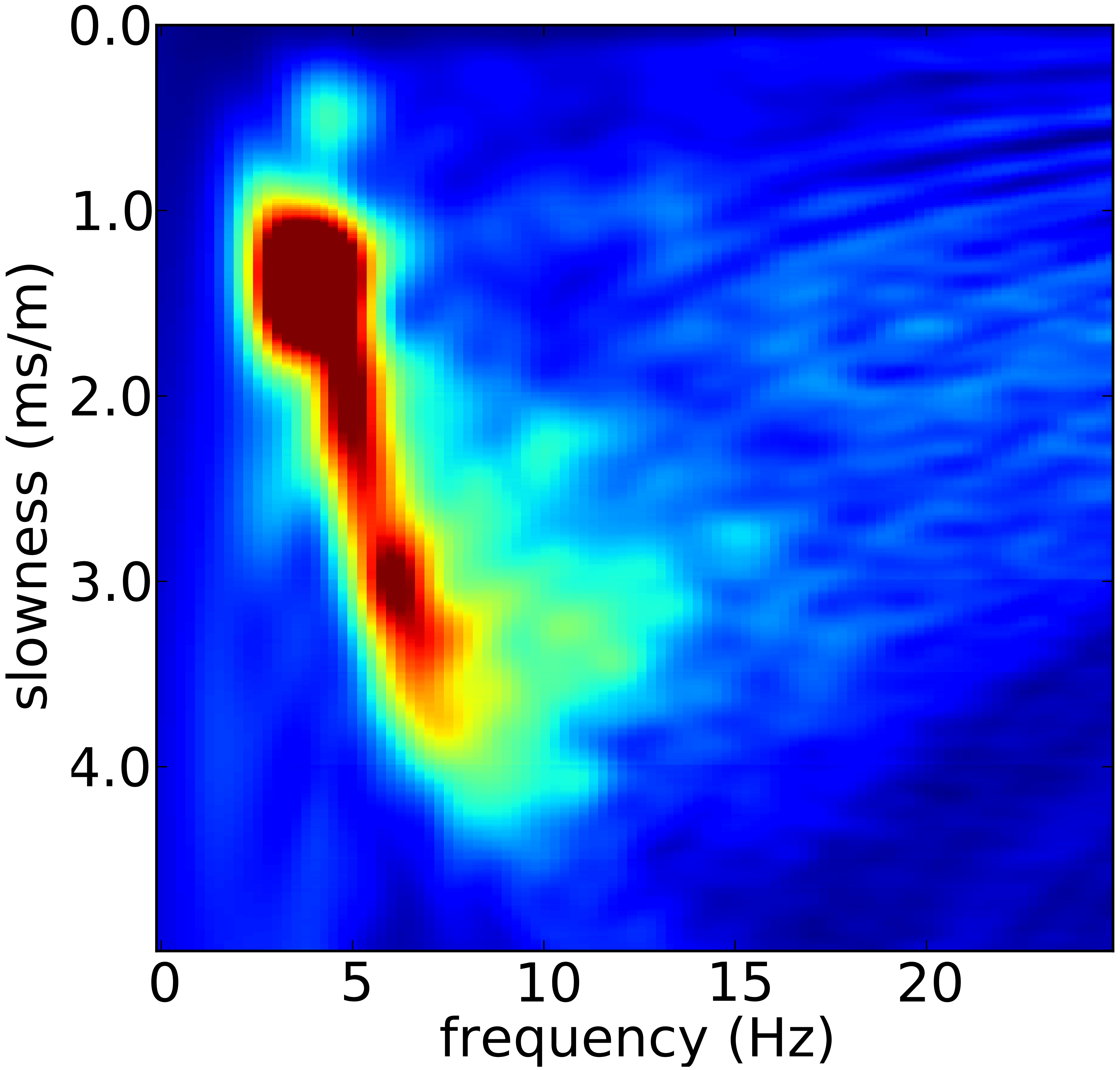
No filtering applied



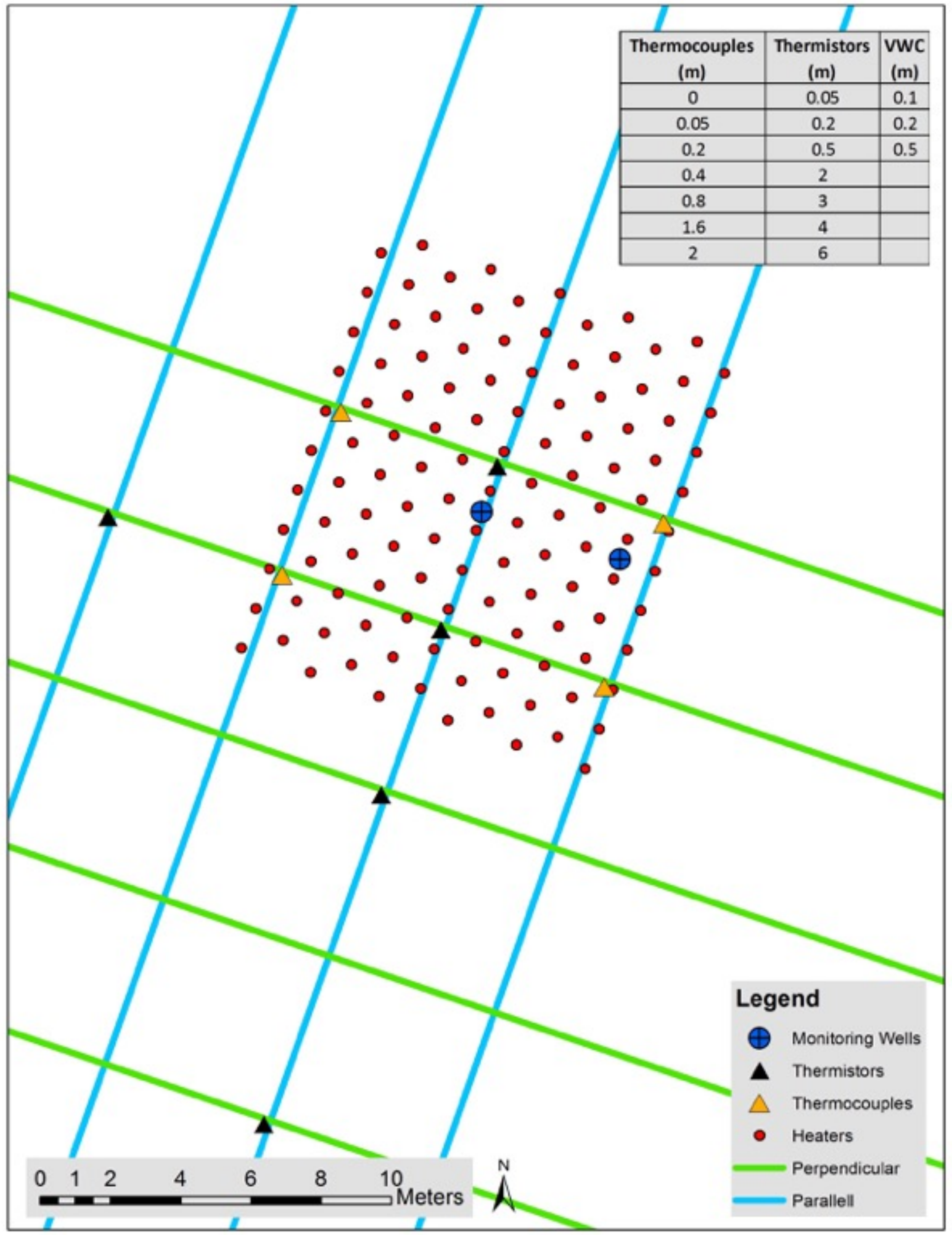


Dispersion image





Controlled thaw: Fairbanks, AK, now



Thermocouples (m)	Thermistors (m)	VWC (m)
0	0.05	0.1
0.05	0.2	0.2
0.2	0.5	0.5
0.4	2	
0.8	3	
1.6	4	
2	6	

free vibration sources ambient noise

+

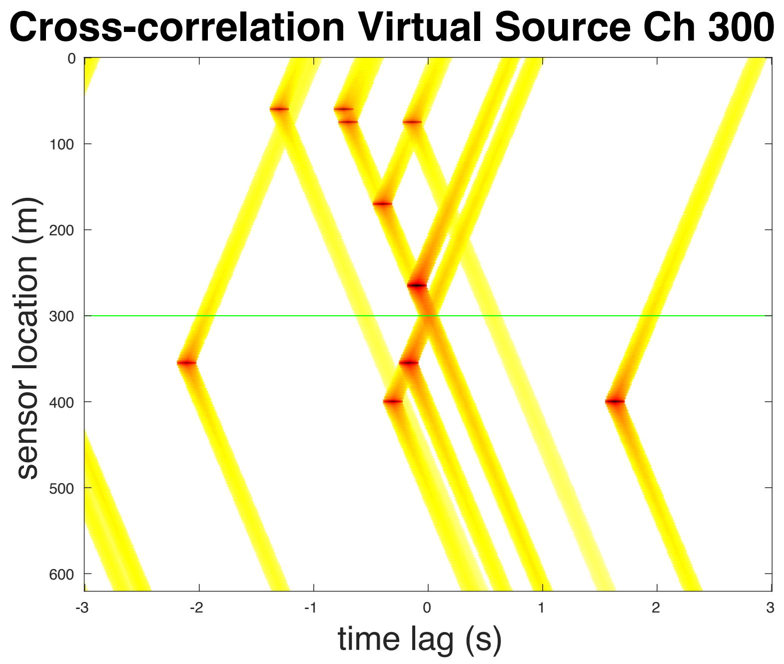
low-cost permanent sensors

distributed acoustic sensing

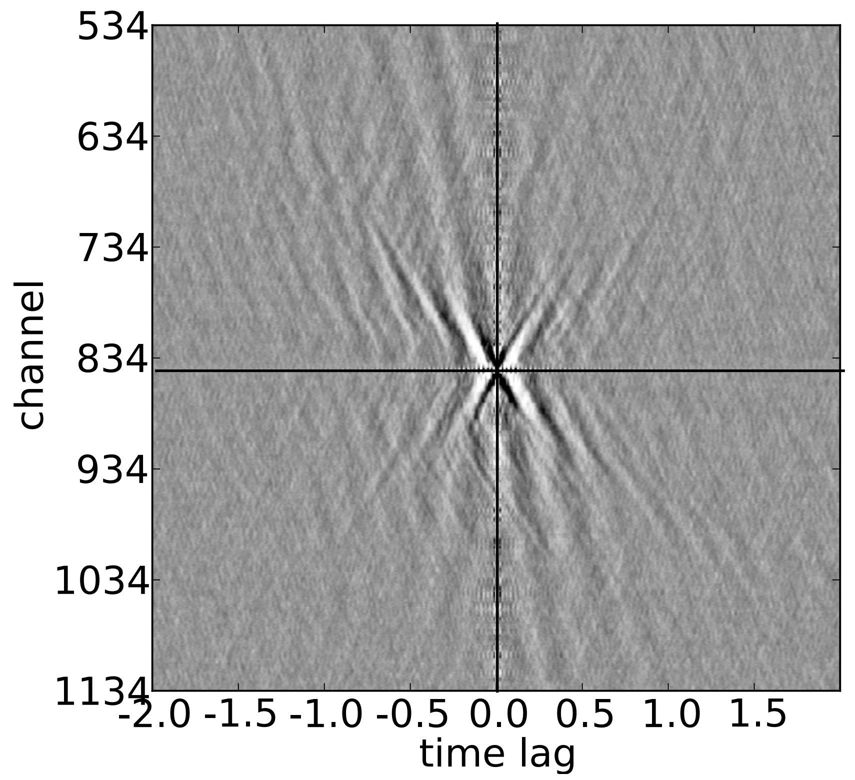
=

low-cost large-scale frequent monitoring of ground stability under infrastructure on permafrost

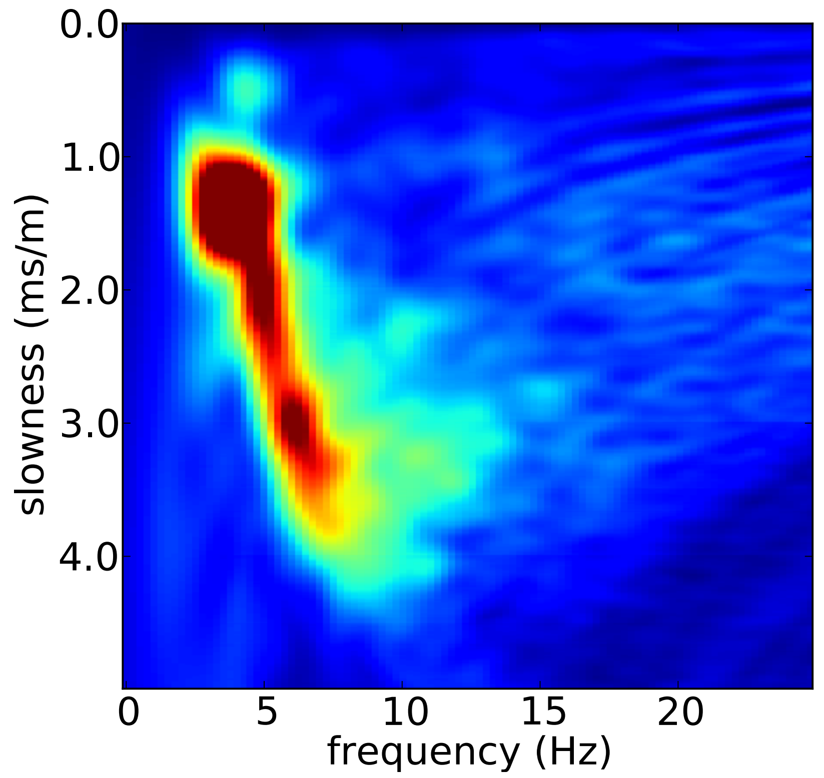
Conclusions



Despite low signal-to-noise-ratio and directional sensitivity issues, DAS is a feasible option for further lowering the cost of ambient seismic noise studies.



Such studies require huge amounts of data to be handled in a streaming context, so we have developed new algorithms suitable to these data.

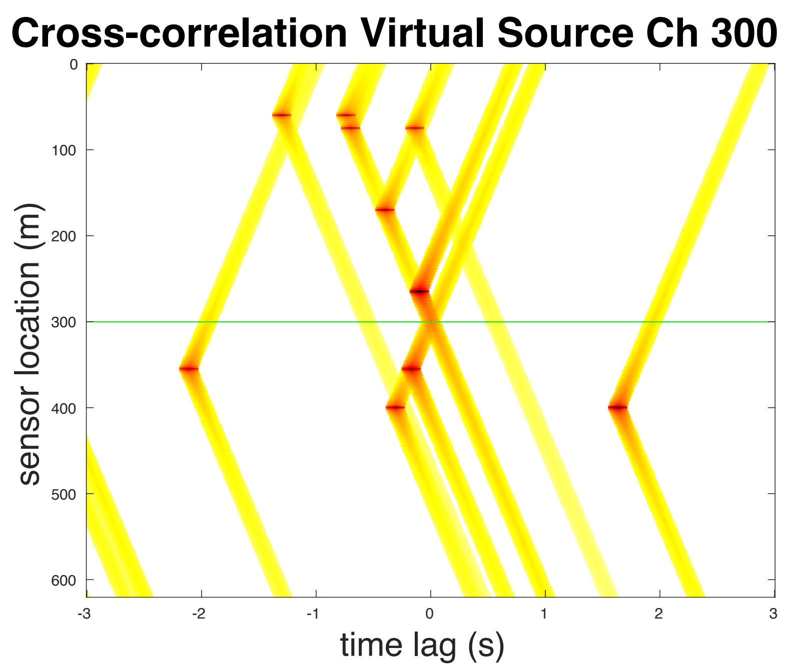


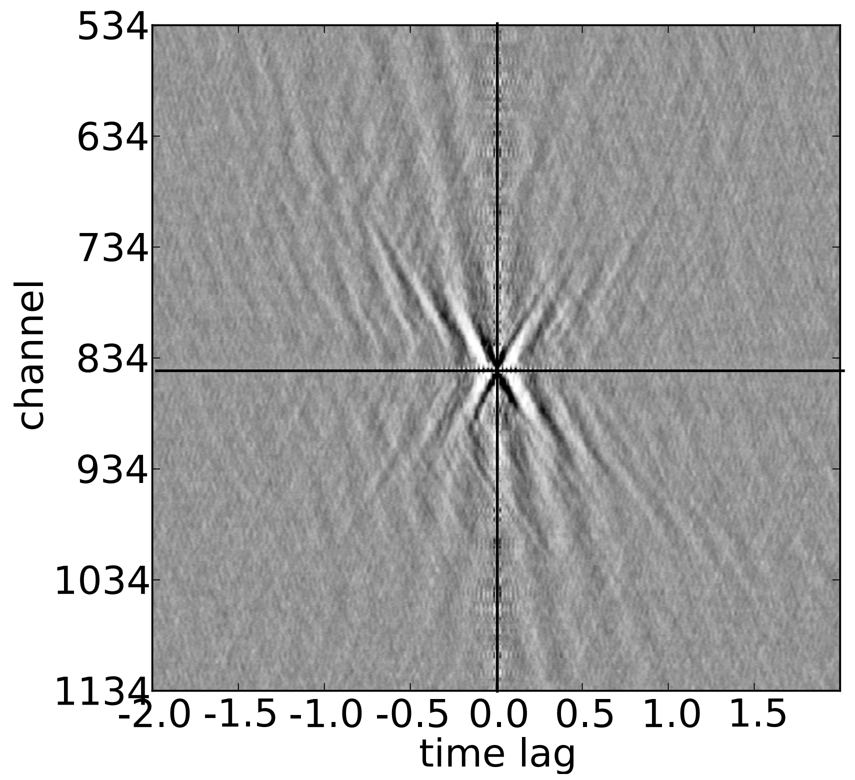
We continue to develop methods for automatic detection and removal of the effects of non-ideal noise sources.

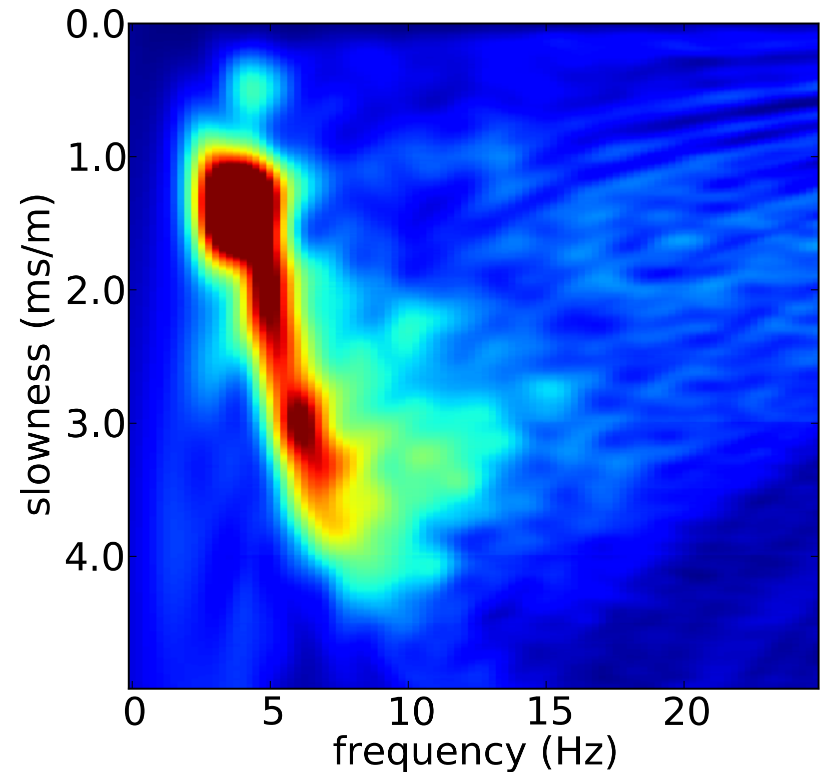
Acknowledgements

- Field experiments and some authors supported by US Dept of Defense, SERDP grant RC-2437
- Work at LBNL funded by US Dept of Energy contract DE-AC02-05CH11231
- I'm supported by US Dept of Energy grant DE-FG02-97ER25308
- Staff at CRREL for field work support
- Thanks to Stanford/SEP colleagues for useful discussions, especially Jason Chang, Nori Nakata, Sjoerd de Ridder, Biondo Biondi, Bob Clapp and Stewart Levin

For more details…







Richmond deployment:
JAF, NL, TD, BF, EM, MR, CU, AW, *A field test of distributed acoustic sensing for ambient noise recording*, SEG extended abstracts 2015.

DAS interferometry at Richmond:
EM, JAF, SD, NL, TD, BF, MR, AW, CU, *Interferometry of ambient noise from a trenched distributed acoustic sensing array*, SEG extended abstracts 2015.

Fast dispersion images:
E. Martin, *Fast dispersion curves from ambient noise*, SEP report 158, 2015. (paper in preparation, report available)

DAS interferometry and noise at Fairbanks:
EM, NL, SD, JAF, AW, KB, TD, BF, MR, CU, *Interferometry of a roadside DAS array in Fairbanks, AK*, SEG extended abstract 2016 (to appear).