Fabric beats in radar data across the NEGIS ice stream

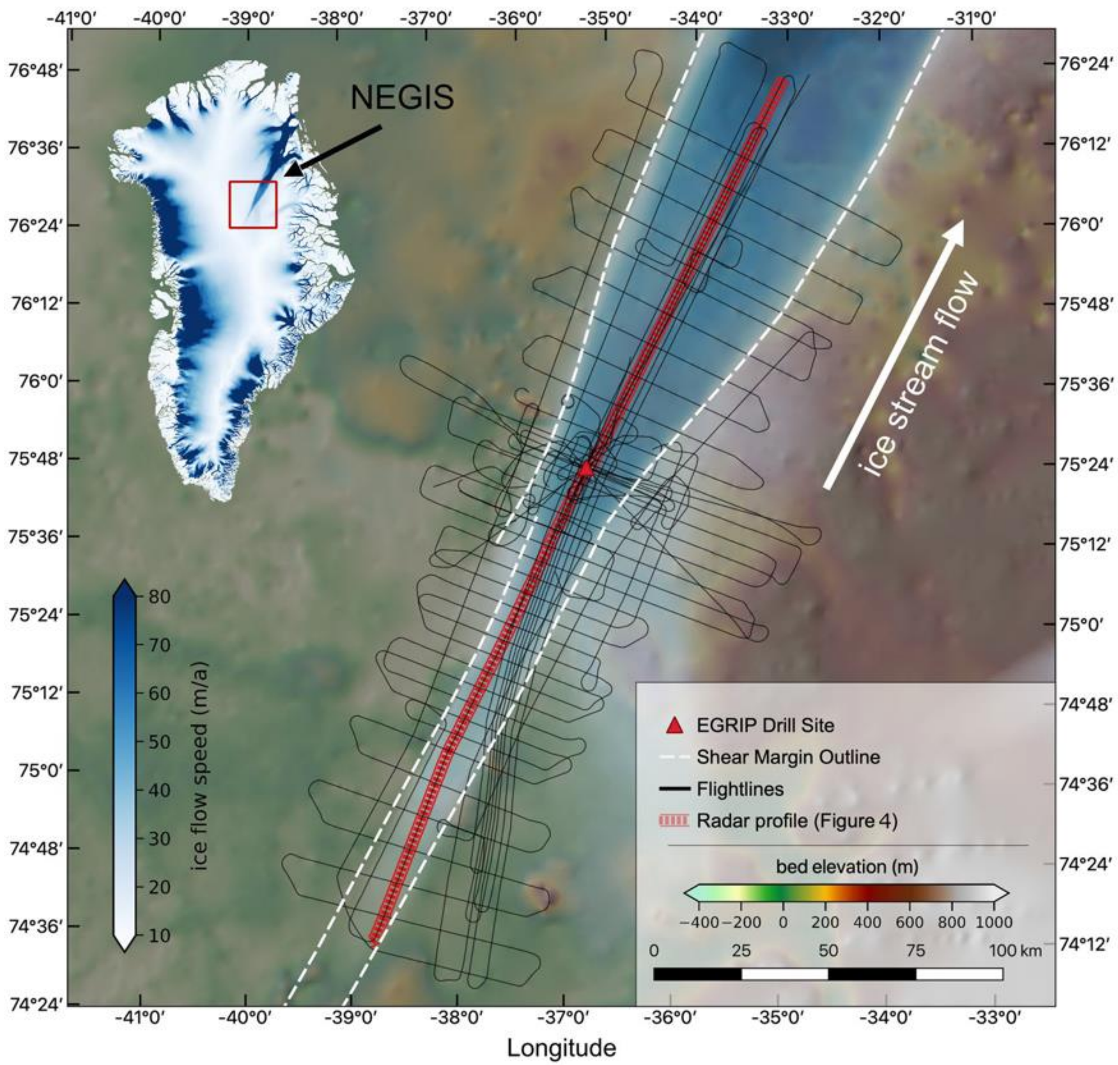
– determining horizontal anisotropy in ice from co-polarized profiling data –

O. Eisen[1], S. Franke[1], D. Jansen[1], J. Paden[2], R. Drews[3], M. R. Ershadi[3], D. Steinhage[1], V. Helm[1], D. Lilien[4], A. Grindsted[4], C. Hvidberg[4], A. Humbert[1], M. Rückamp[1], J. Yan[5], I. Weikusat[1], F. Wilhelms[1], D. Dahl-Jensen[4], H. Miller[1]

1 AWI, Bremerhaven, Germany, 2 CReSIS, Kansas, USA, 3 Uni Tübingen, Germany, 4 PICE, Uni Copenhagen, Denmark, 5 Univ Alabama, USA

#vEGU21

NEGIS ice stream & airborne survey



Survey: May 2018

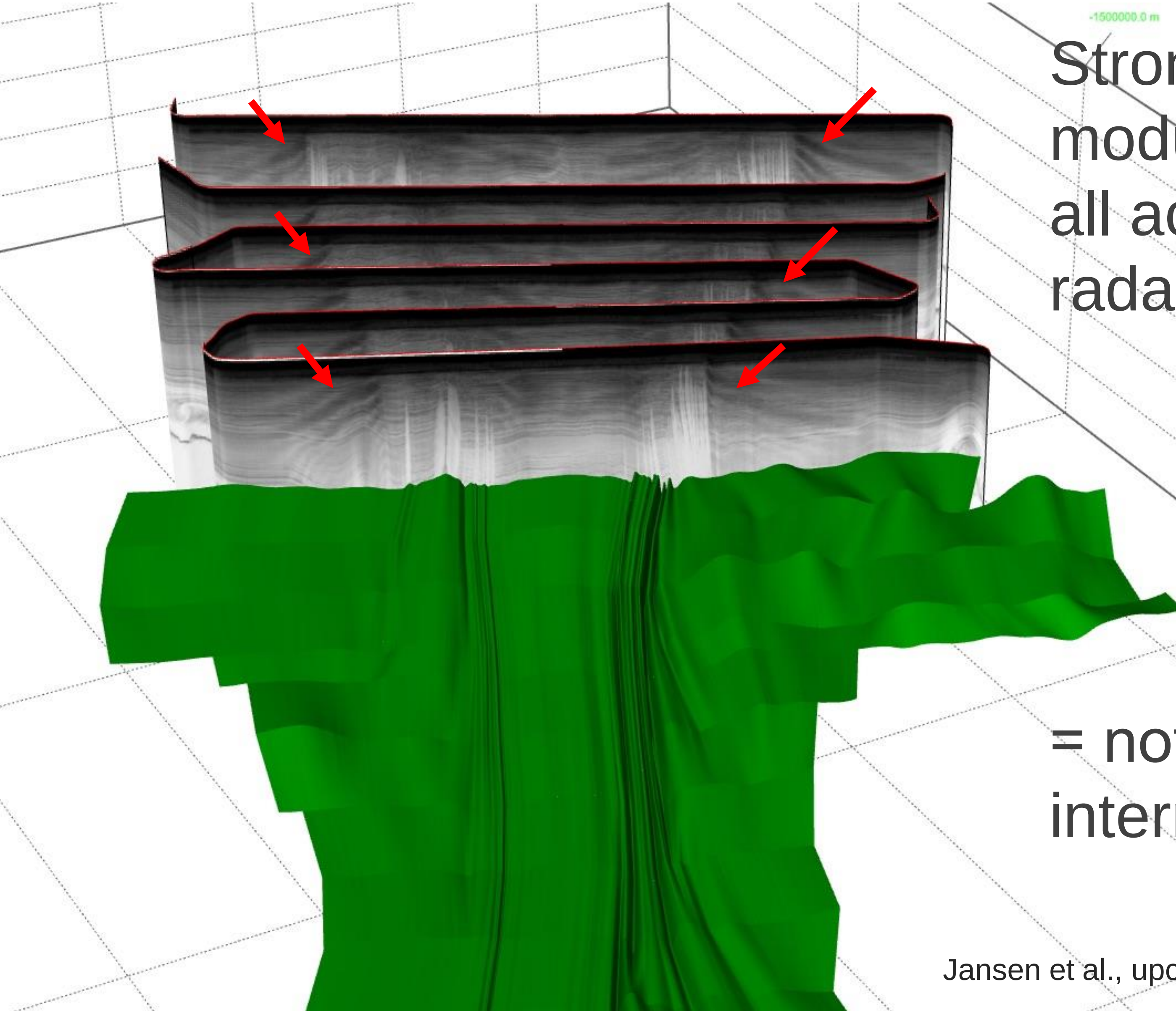
Radar: AWI UWB

MCORDS5, 8 elements

Operation in narrow band mode: 180-210 MHz

further details: [Franke et al., JGR, 2020]()

Across flow radargrams NEGIS



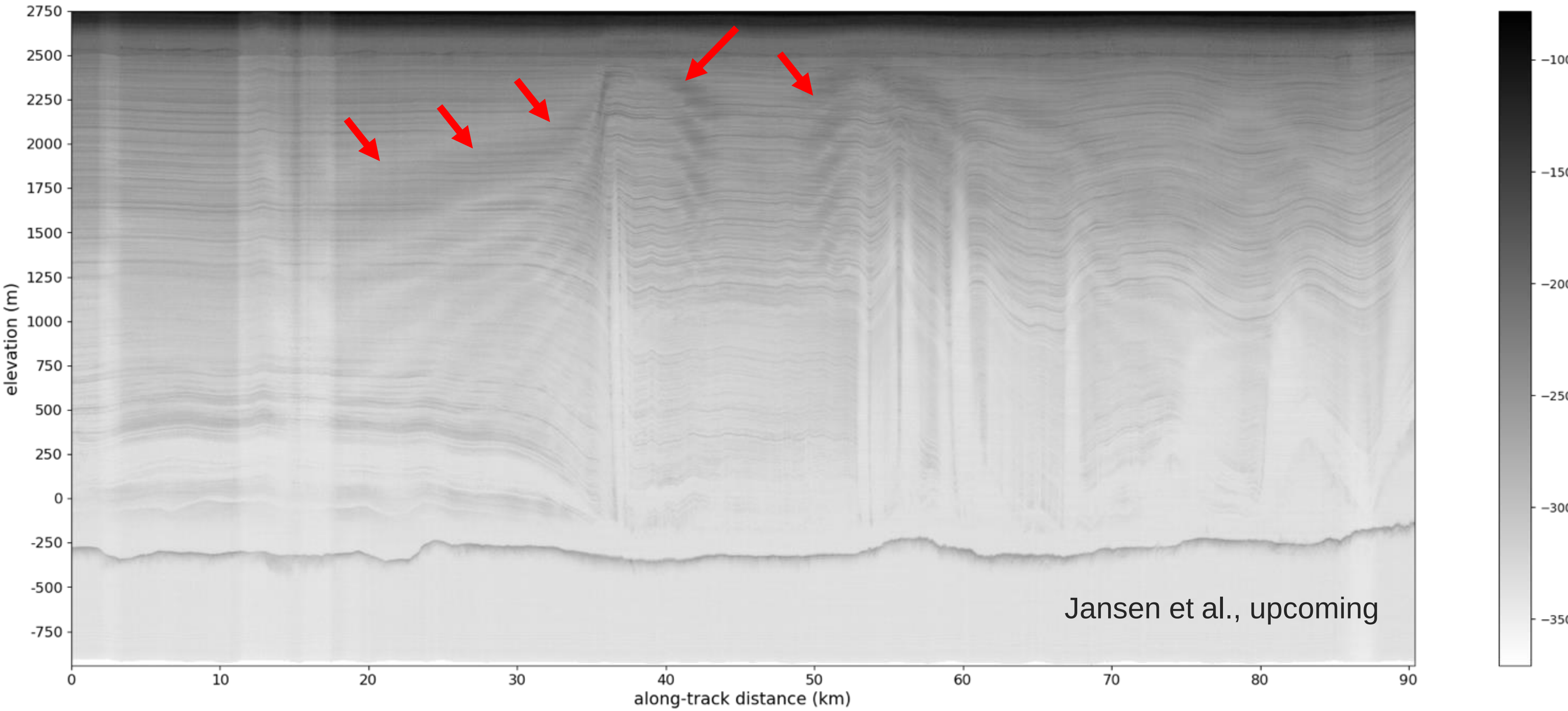
Strong amplitude modulations in all across-flow radargrams

= not „normal" internal layers!

Jansen et al., upcoming

Across flow radargram NEGIS

amplitude modulation – origin?



Presentation overview (=)

Part 1: Physics

- Where are the modulations coming from?
- What do they tell us?

Part 2: Analysis

- From observations to horizontal anisotropy

Part 3: Implications

- What can we learn about ice stream dynamics?

Part 1: Physics – a birefringent medium

ice 1h: anisotropic crystal, effects on

- rheology ("softness" of ice)
- radar velocity:

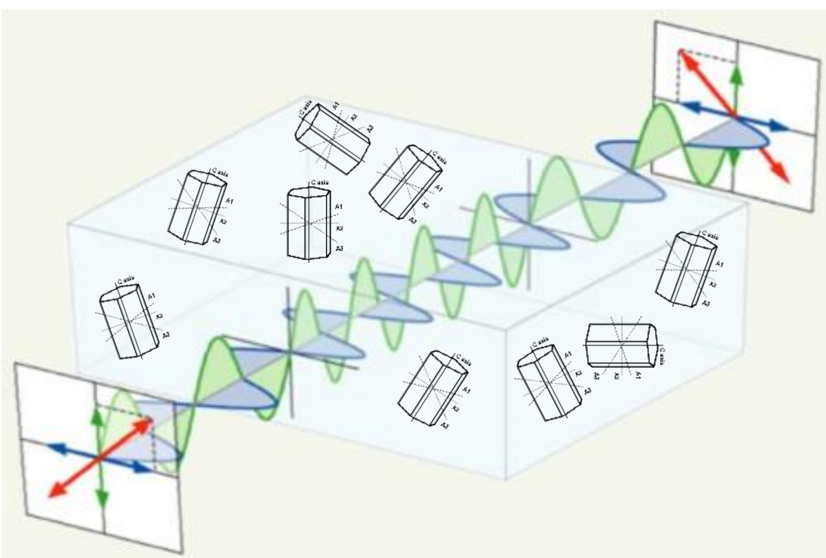
$$c = \frac{c_0}{\sqrt{\varepsilon'}}$$

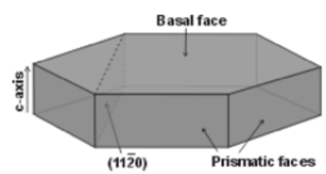
$$\varepsilon'_{||} - \varepsilon'_{\perp} \approx 1\%\varepsilon', \qquad \varepsilon' \approx 3.1 - 3.2$$

- seismic velocity:

$$v^s_{||} - v^s_{\perp} \approx 100\ \mathrm{ms}^{-1} \approx 5\% v^s, \qquad v^s \approx 1900\ \mathrm{ms}^{-1}$$

$$v^p_{||} - v^p_{\perp} \approx 100\ \mathrm{ms}^{-1} \approx 3\% v^p, \qquad v^p \approx 3900\ \mathrm{ms}^{-1}$$

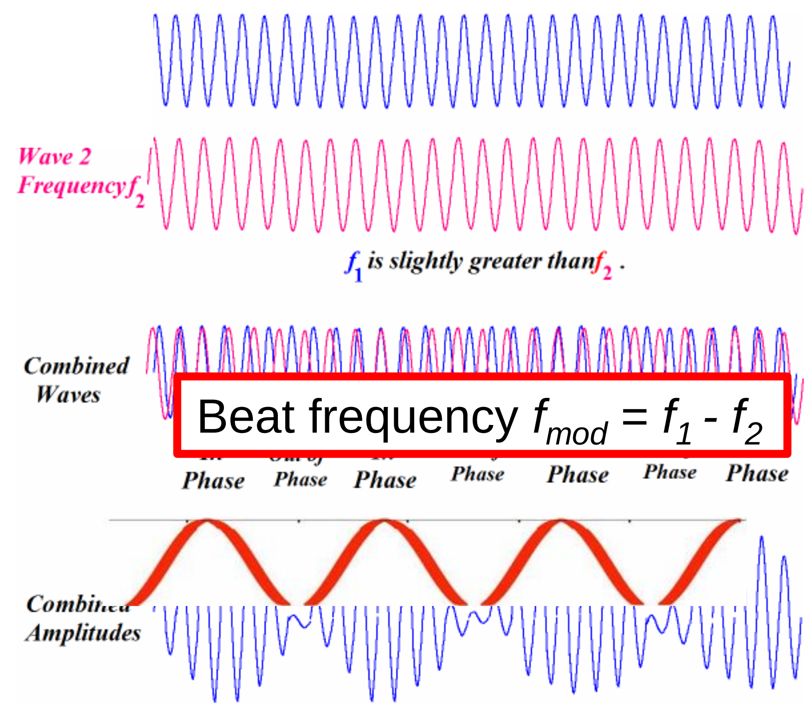




Interference of radar waves travelling with slightly different **velocities**:

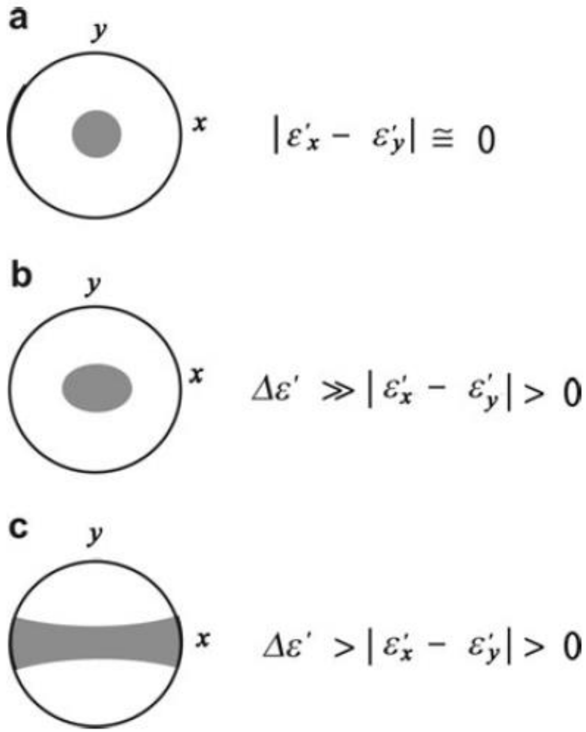
$$\Delta\varepsilon' = \varepsilon'_{||} - \varepsilon'_{\perp} = 0.034$$

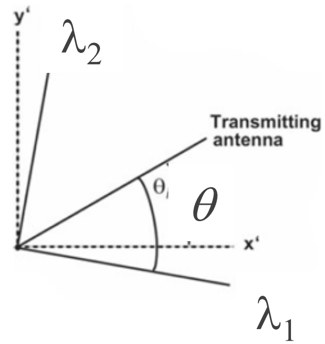
$$\Delta c = (1.6995 - 1.6903)\ 10^8\ \mathrm{m/s} = 0.54\%\ c_0$$

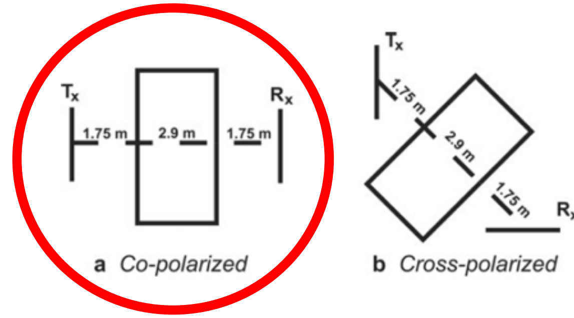


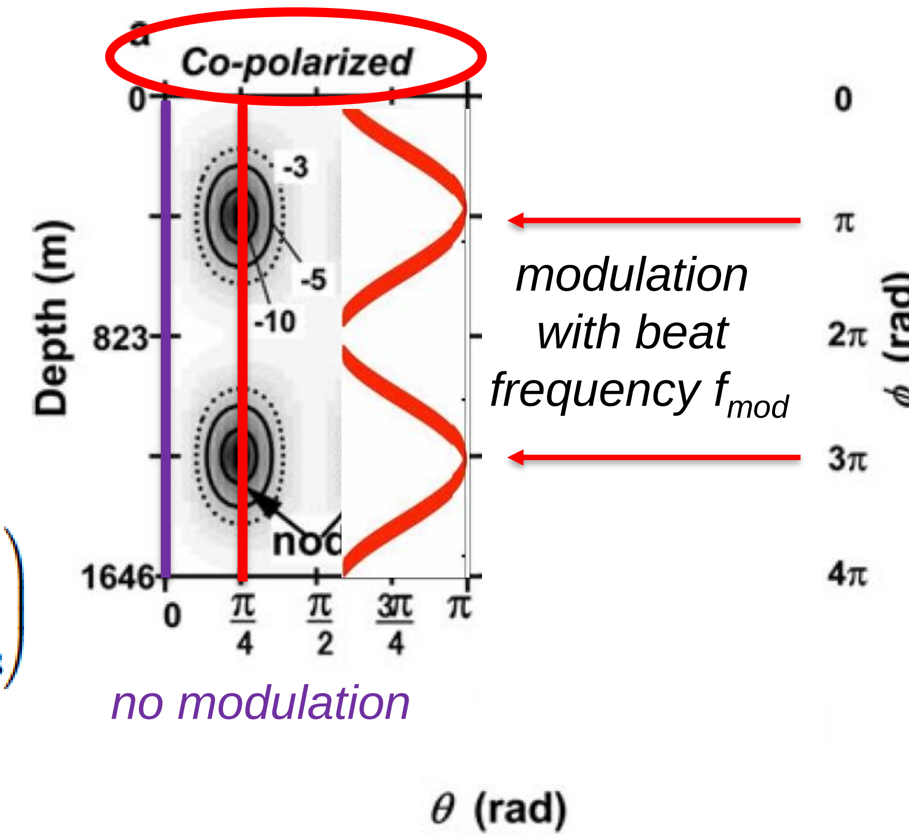
Theory: [Fujita et al. (2006)]() (on ice)

Bulk properties of polycrystals:









Bulk properties related to single crystals:

$$\epsilon'(z) = \begin{pmatrix}\epsilon'_x & 0 & 0\\ 0 & \epsilon'_y & 0\\ 0 & 0 & \epsilon'_z\end{pmatrix} = \begin{pmatrix}\epsilon'_\perp + \Delta\epsilon'\lambda1 & 0 & 0\\ 0 & \epsilon'_\perp + \Delta\epsilon'\lambda2 & 0\\ 0 & 0 & \epsilon'_\perp + \Delta\epsilon'\lambda3\end{pmatrix}$$

$\Delta\varepsilon' = \varepsilon'_{||} - \varepsilon'_\perp = 0.034$ (for a single crystal)

Relating modulation to anisotropy

Phase difference ϕ of ordinary and extraordinary wave cause modulation (Fujita et al., 2006)

$$\phi = \frac{4\pi f}{c_0} \int_z^0 (\sqrt{\epsilon'_x} - \sqrt{\epsilon'_y}) dz + (\Delta\phi_x + \Delta\phi_y),$$

$$= \frac{4\pi f}{c_0} \int_z^0 \frac{\Delta\epsilon(z)}{2\sqrt{\bar{\epsilon}}} dz$$

Taylor expansion (e.g. Jordan et al., 2019)

$$= const \cdot \Delta\lambda\, z$$

assuming vertically constant fabric

$$= 0.078\, \Delta\lambda\, z$$

for f = 195 MHz

(bulk properties of polycrystals)

$$\Delta\epsilon = \epsilon_y - \epsilon_x = \Delta\epsilon'(\lambda_2 - \lambda_1),$$

$$= 0.034\Delta\lambda$$

$$\Sigma_i \lambda_i = 1$$

$$\lambda_3 = 1 - 2\lambda_1 - \Delta\lambda$$

$\Delta\lambda$: horizontal anisotropy

Nodes from destructive interference

- modulation $A \sim A_0 \cos(\phi)$: minimum for $\phi = (2n\text{-}1)\pi$
- wave number: $k = 2\pi\,/$ wavelength $= 2\pi f_{mod}/c$

forward simulation:

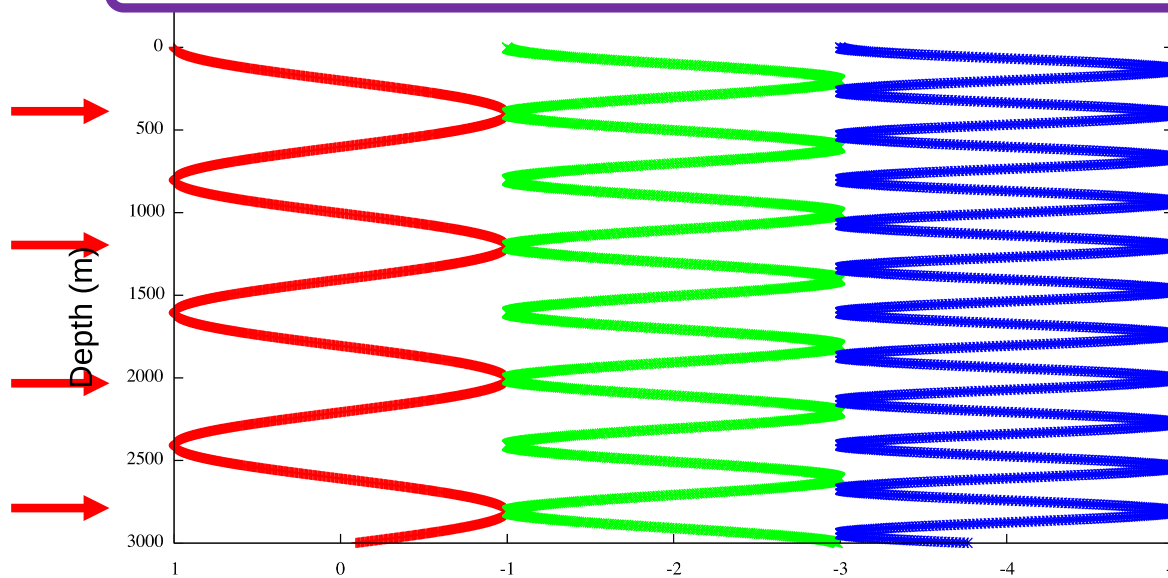
$\phi = kz = 0.078\Delta\lambda z$

$\Downarrow$

$\Delta\lambda = 4.8 \cdot 10^{-7} f_{mod}$

$\Delta\lambda \sim k \sim f_{mod}$

$\Delta\lambda = 0.1$	$\Delta\lambda = 0.2$	$\Delta\lambda = 0.3$



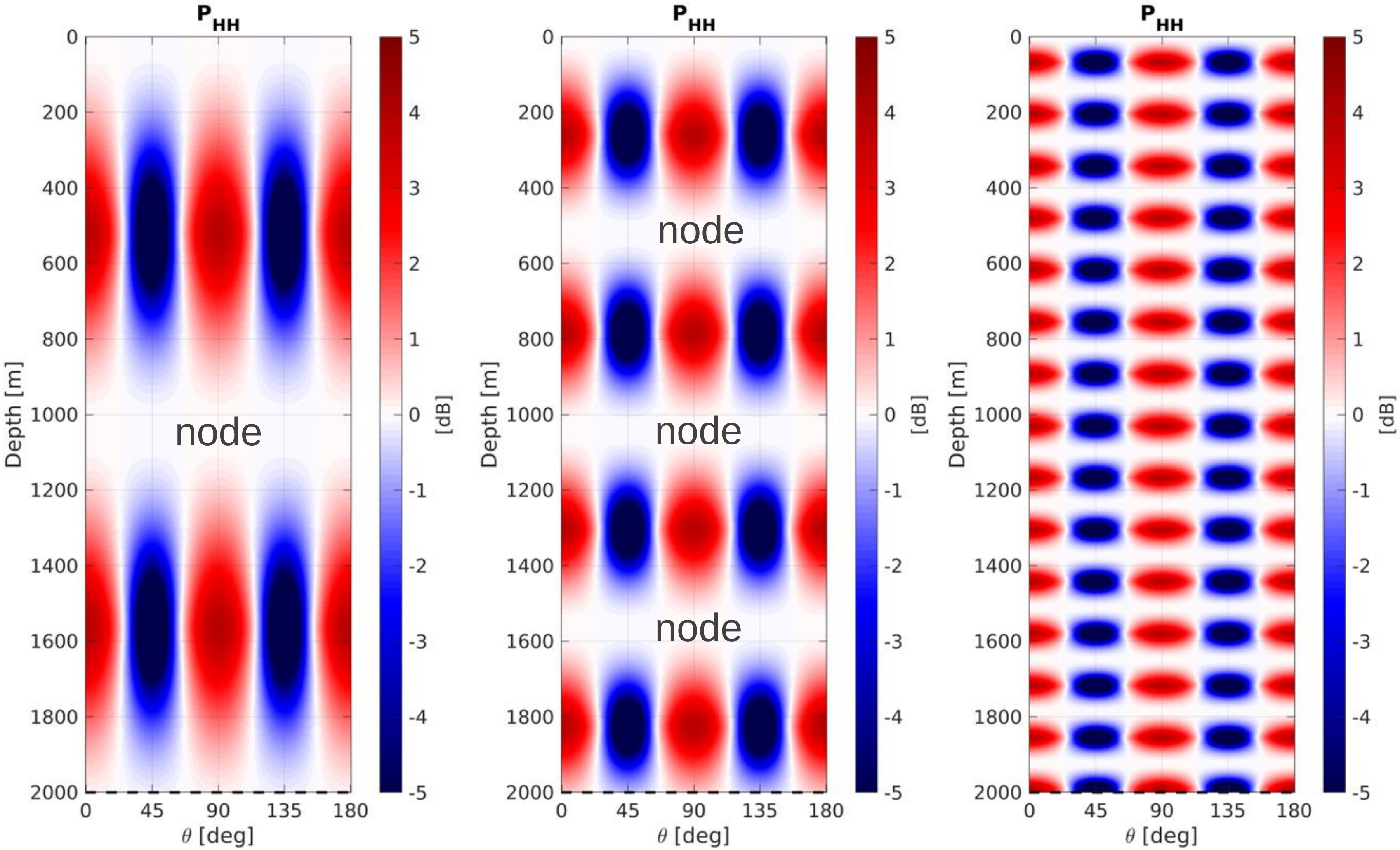
$k\,/\,2\pi = 3.75/3000$ m $= 7.5/3000$ m $= 11/3000$ m

=> $k = 0.0078$ m^{-1} $= 0.015$ m^{-1} $= 0.023$ m^{-1}

$\Delta\lambda = 0.099$	$= 0.192$	$= 0.294$

What would theory produce?

increasing $\Delta\lambda$ ($\sim k \sim f_{mod}$) → more node(line)s



Polarimetric plots (e.g. Ershadi et al., 2021)

Part 2: Analysis

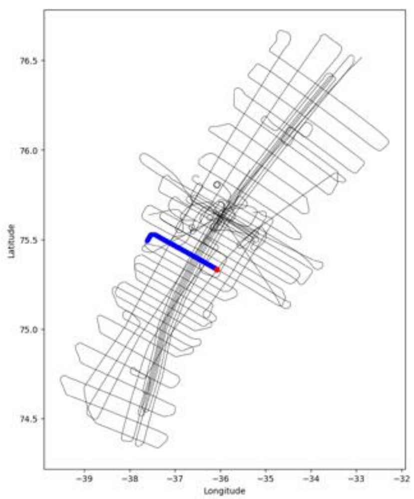
Processing flow:

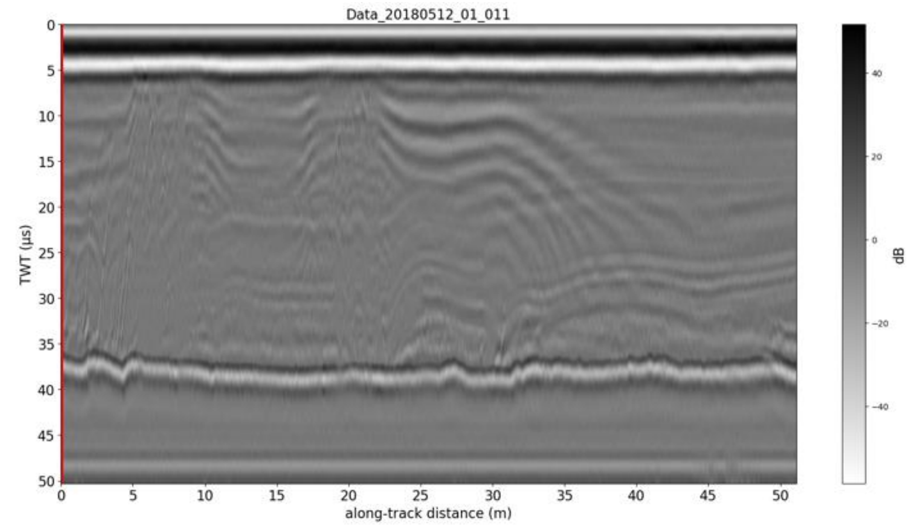
- pre-processing of radargrams
  (remove features which would cause artefacts)
- (semi-)automatic extraction of f_{mod} from radargrams
  (low-pass filtering & spectrogram analysis)
- mapping of $\Delta\lambda$ along all profiles

Removing layers to visualize nodes

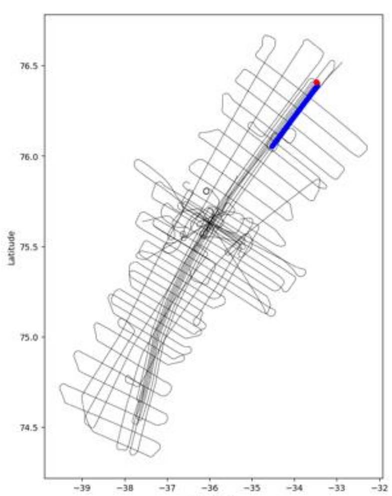
Bandpass filtering (f_{mod} = 100 – 600 kHz ≈̂ Δλ = 0.03 – 0.16)

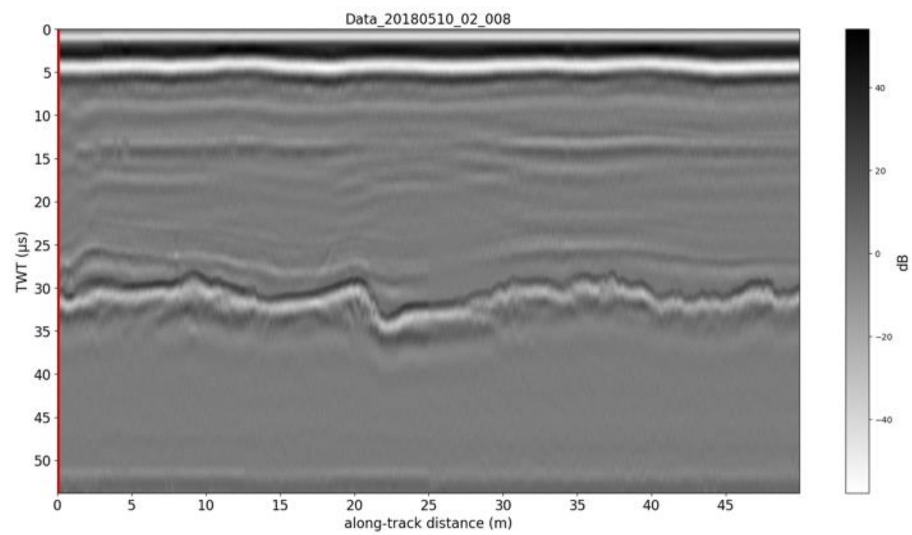
Across:





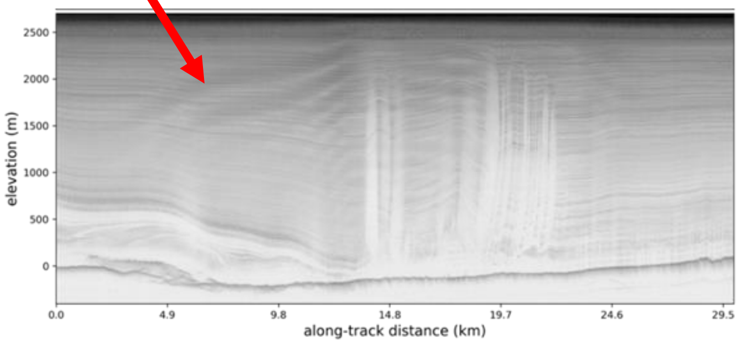
Along:

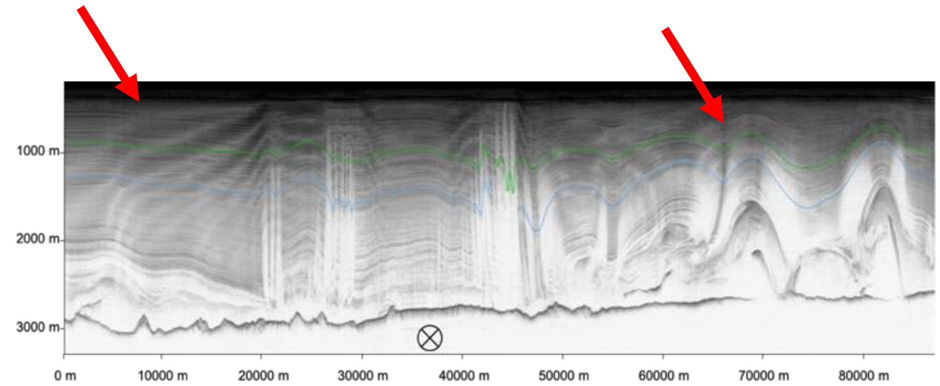




Presence: everywhere

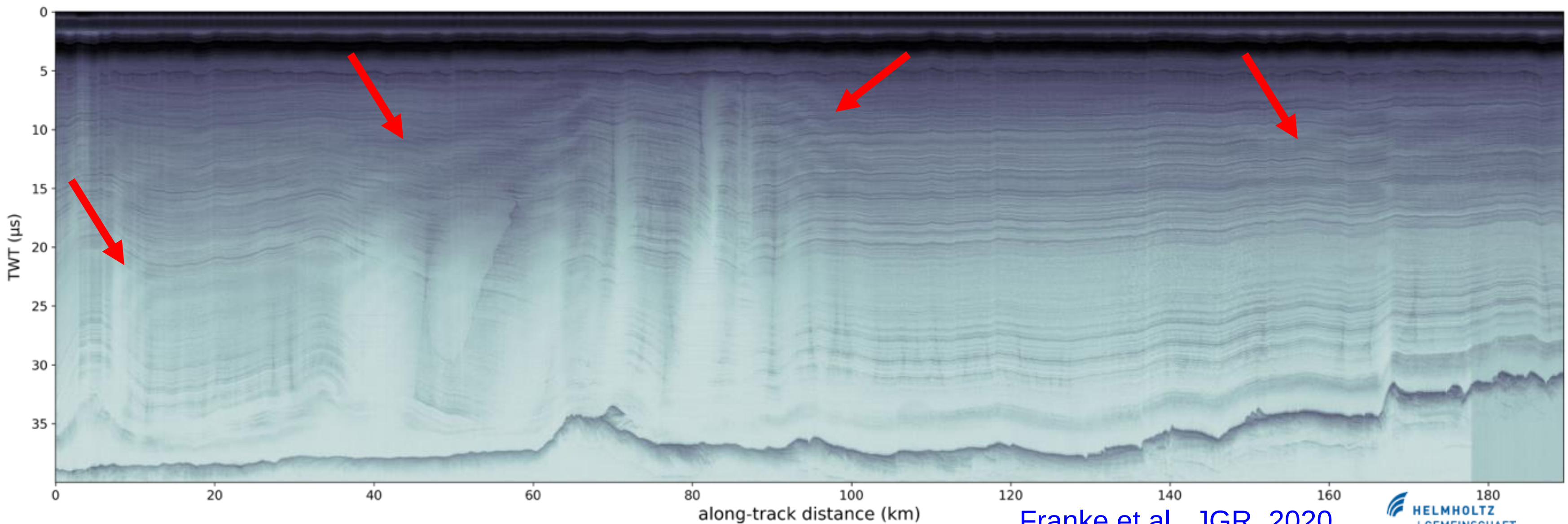
across flow





Jansen et al., upcoming

along flow

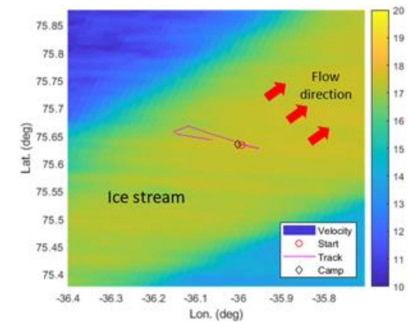


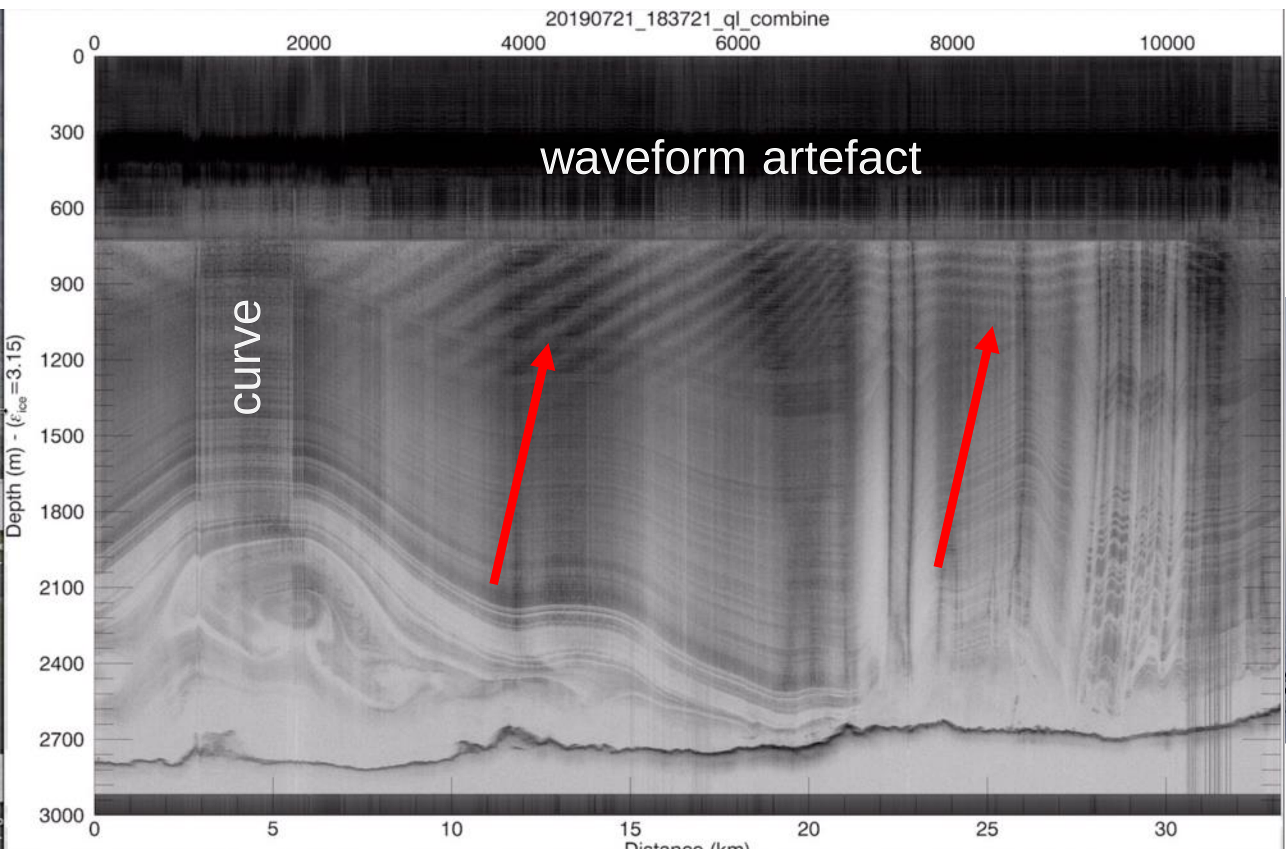
Franke et al., JGR, 2020

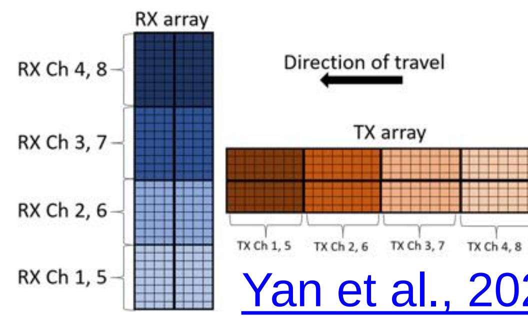
Test: visible in different radar system?

- Ground-based survey 2019
- Mills-T UHF radar, f = 600-900 MHz

=> same features, higher f_{mod} (because of f)







[Yan et al., 2020]

Still not convinced?

Comparable approach:

T. J. Young et al.

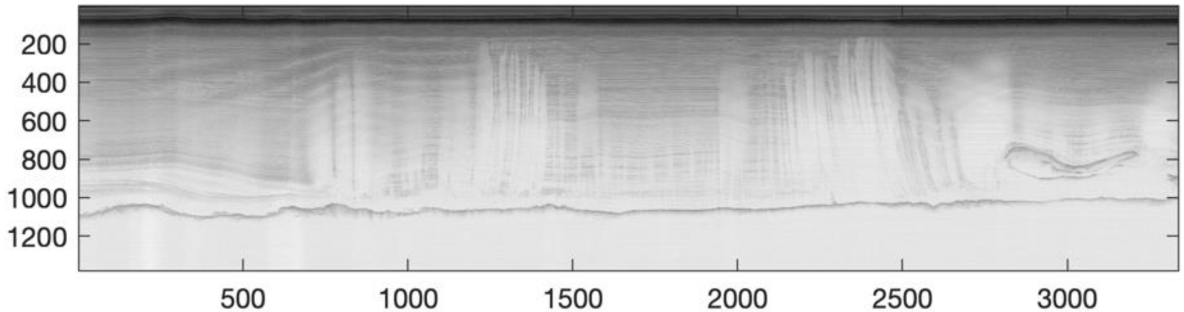
Polarimetric radar-sounding to infer and quantify shear margin ice fabric anisotropy

EGU21-2107

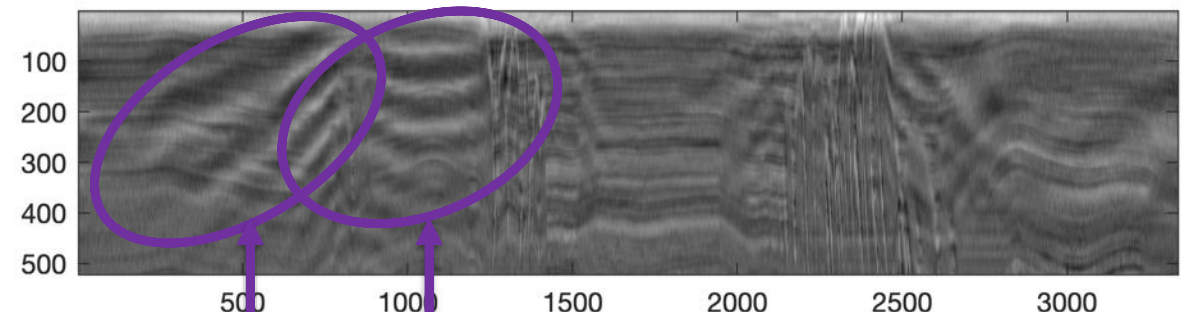
(Thwaites Glacier eastern shear margin)

Getting formal: f_{mod} as f(**r**)

Spectrogram along radar profile

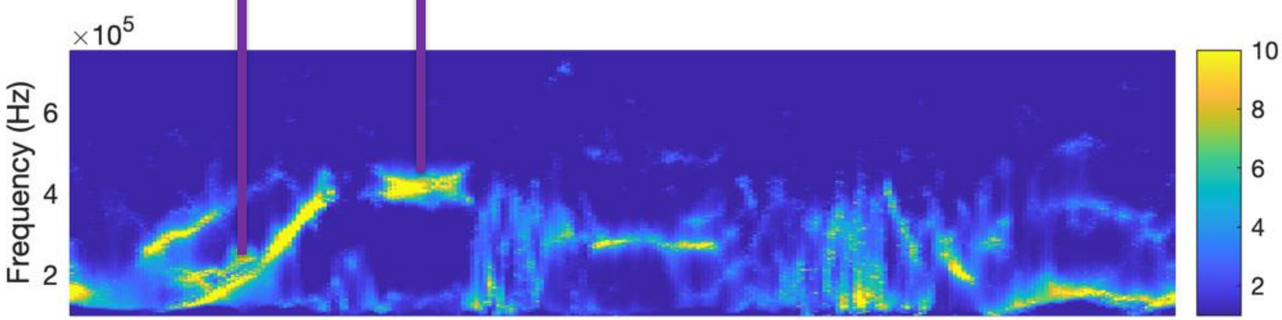


original data



Processing:

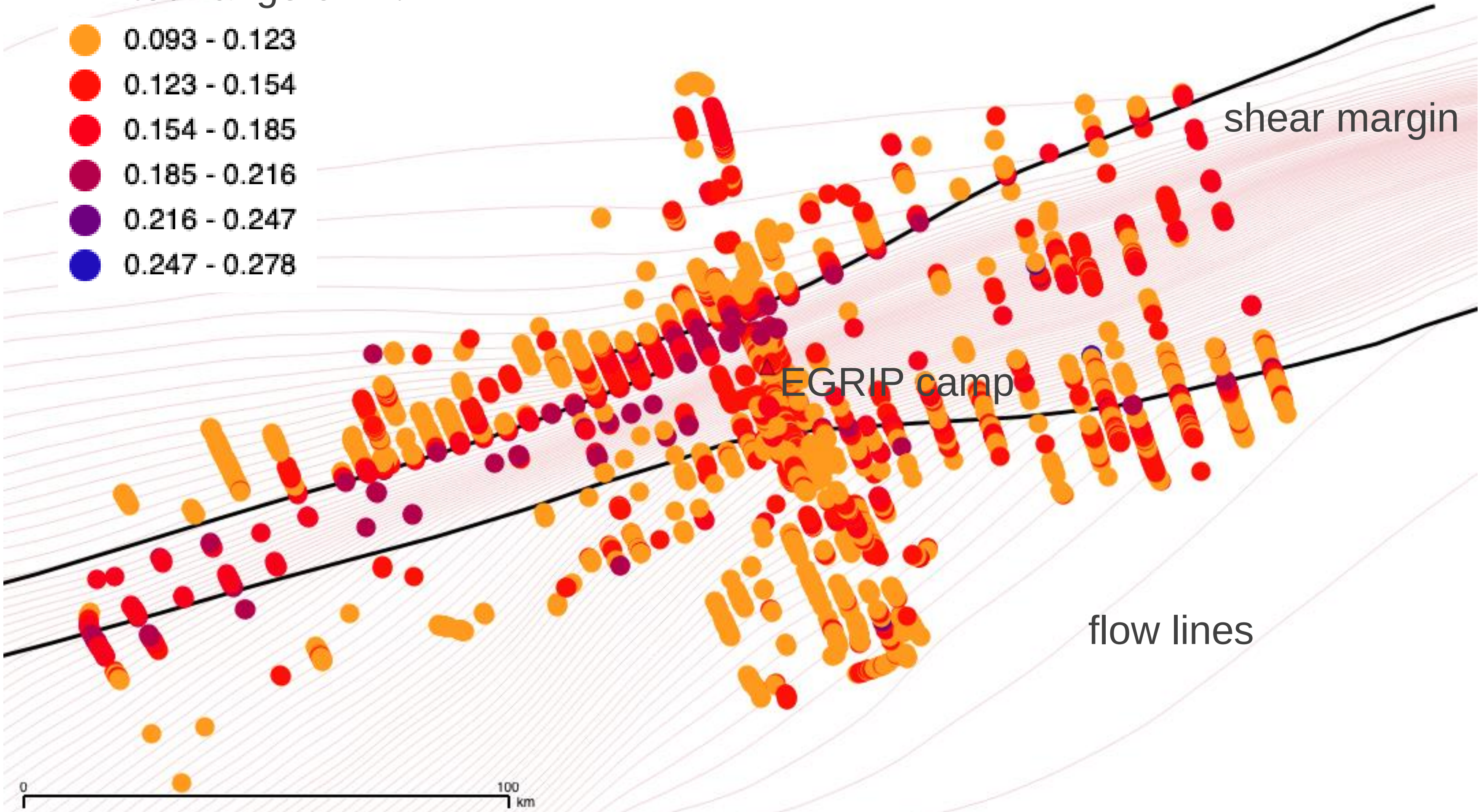
- bandpass filter
- time cut
- bandpass filter



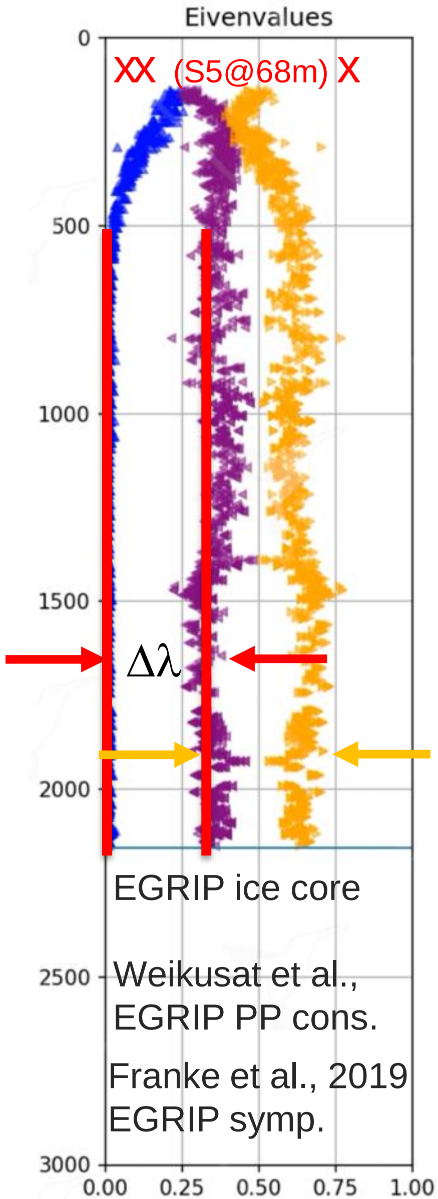
spectrogram
=> f_{mod}

Mapping Δλ

- displayed: only profiles across flow
- limited range of Δλ



Plausible ranges of $\Delta\lambda$ (f = 195 MHz for AWI UWB)



$$\Sigma_i \lambda_i = 1$$

$$\lambda_3 = 1 - 2\lambda_1 - \Delta\lambda$$

- EGRIP: $\Delta\lambda = 0.3$ for z > 500 m

- Assuming wide-spread simple shear (girdle)

λ_1 H 0
0.5 ~ λ_2 ~ 0.05
0.5 } λ_3 } 0.95

$\Delta\lambda = 0.05 - 0.5 \approx f_{mod} =$ 190 kHz – 1.9 MHz

- Visible range (radar data analysis):
  $\Delta\lambda = 0.03 - 0.16 \approx f_{mod} =$ 100 kHz – 600 kHz

- Resolution:
  $\Delta\lambda = 0.02 - 0.4 \approx f_{mod} =$ 75 kHz – 1.5 MHz

Part 3: Implications

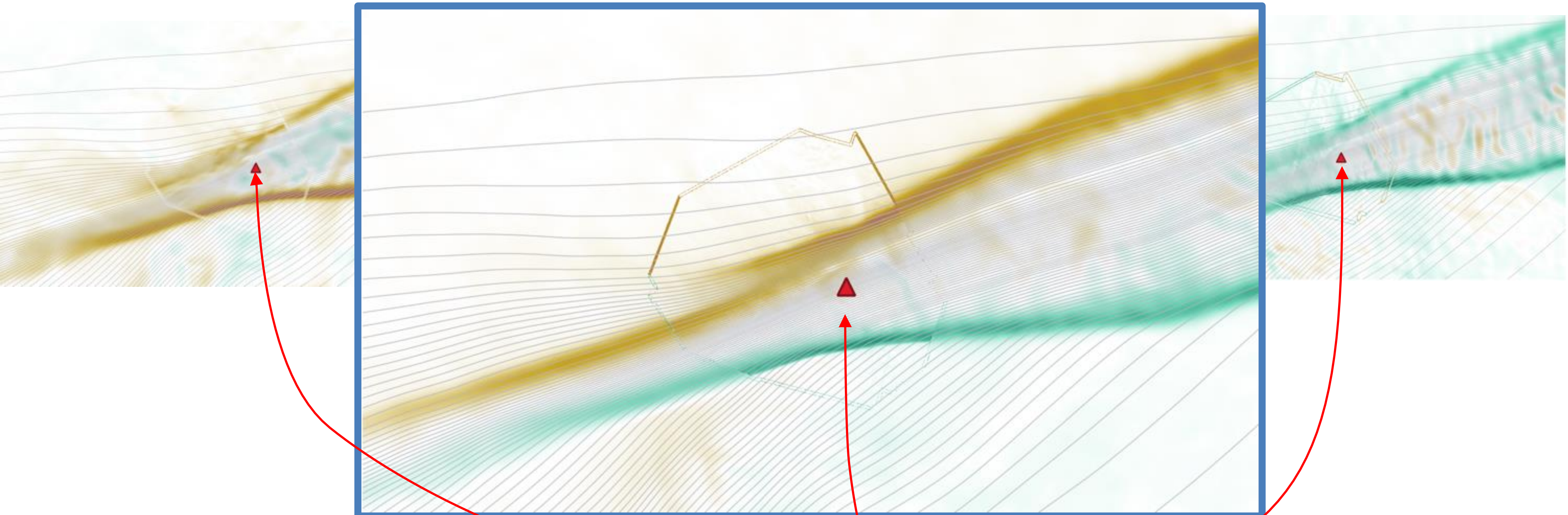
Questions:

- What can we actually detect?
- Where do we see horizontal anisotropy?
- How does it change spatially?
- What does it mean for ice dynamics?

Large-scale flow field

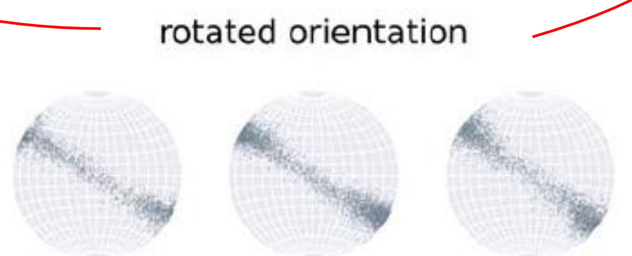
Strain rates from surface velocities:

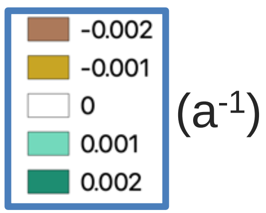
across flow strain | in-flow shear | in-flow strain



Jansen (strain rates from Neckel & Measures)

- laterally compressive
- accelerating flow
- small-scale variations
- considerable shear

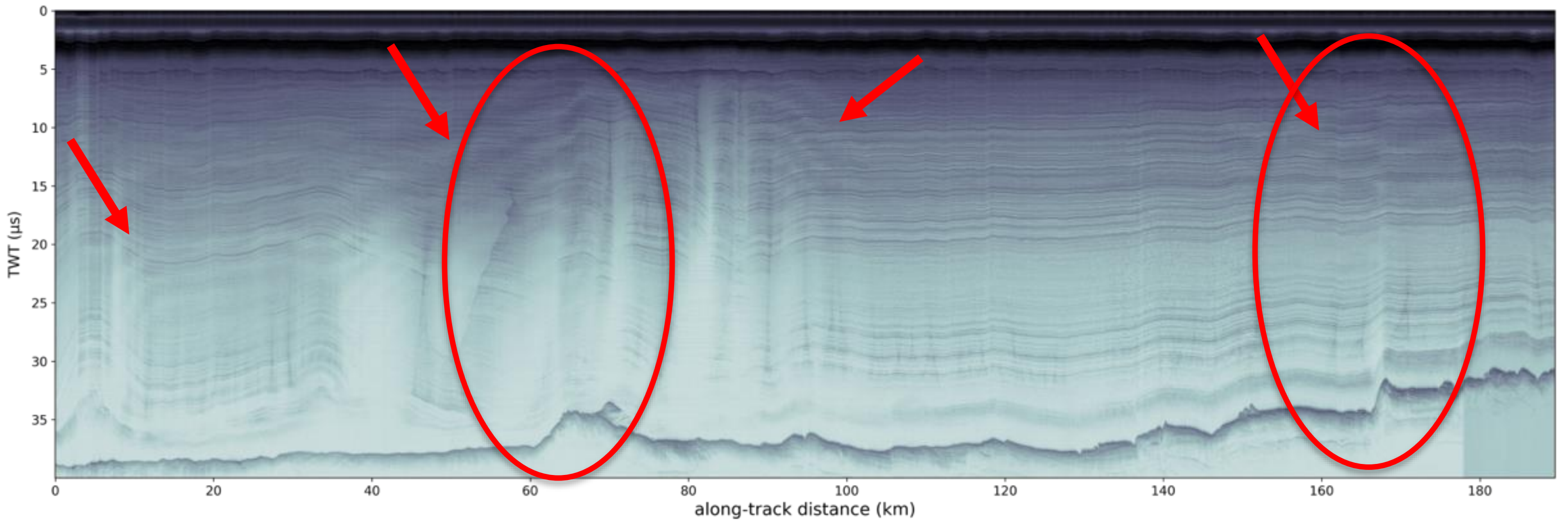




Westhoff et al., 2020

Dynamics: when does fabric change?

Along-flow signatures of changing fabric anisotropy:



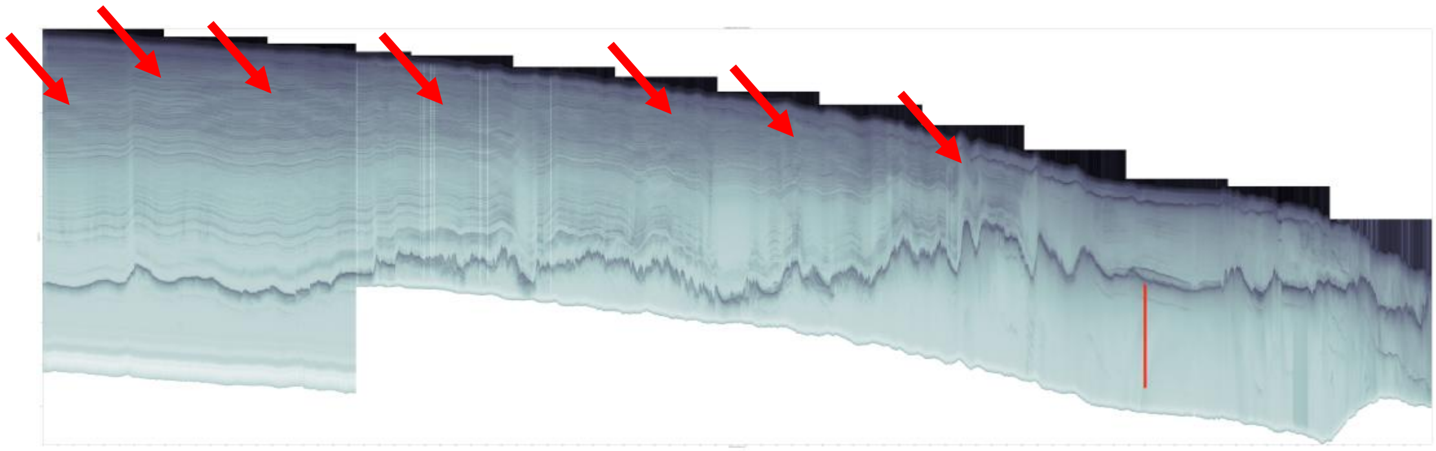
[Franke et al., JGR, 2020]

- Horizontal anisotropy seems to change when ice thickness changes
  => Indication of internal deformation?

- Not yet investigated: lateral effects

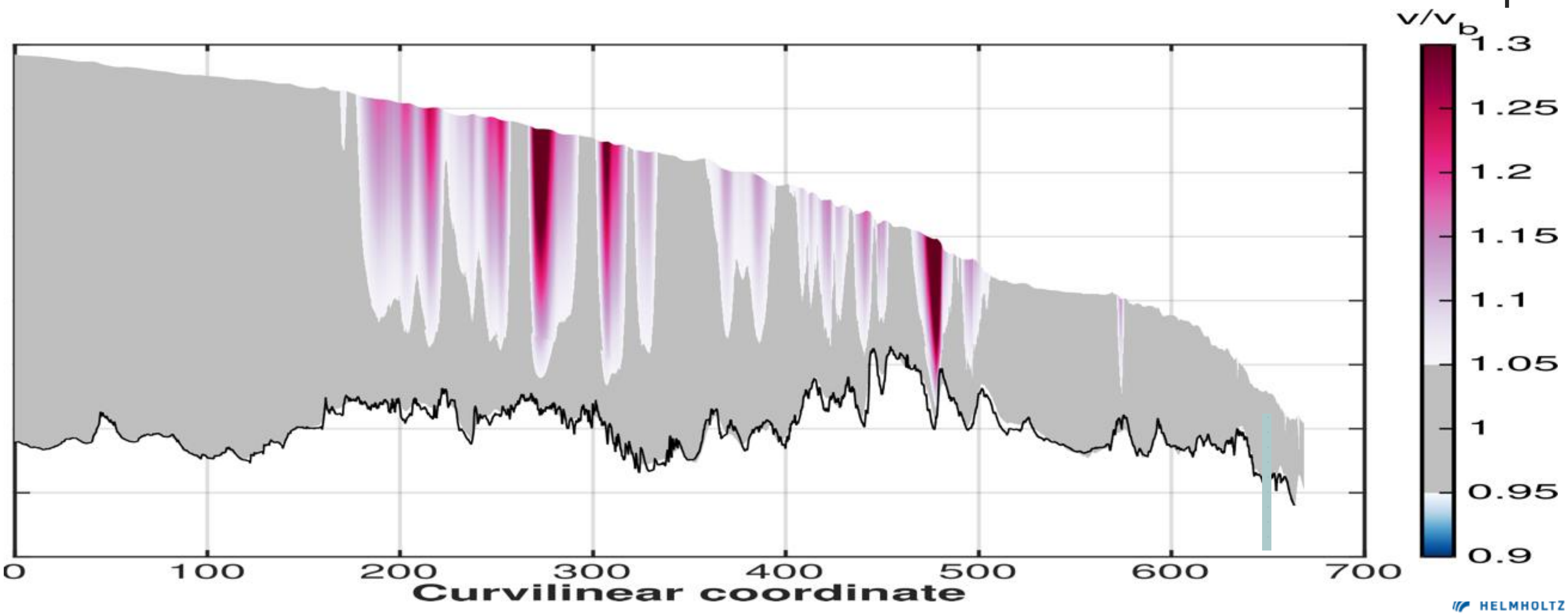
NEGIS along-flow profile

Modelled contribution to flow from internal deformation

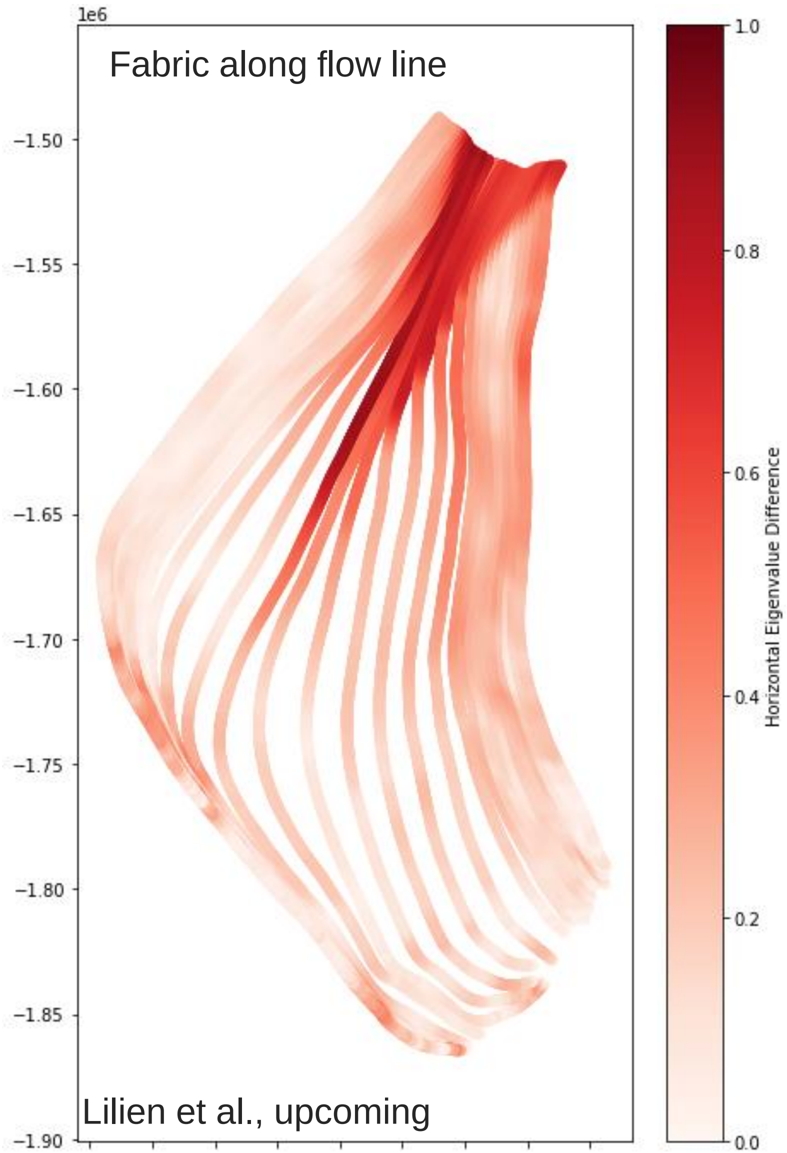


ISSM
v: velocity
v_b: basal velocity

Rückamp/Humbert



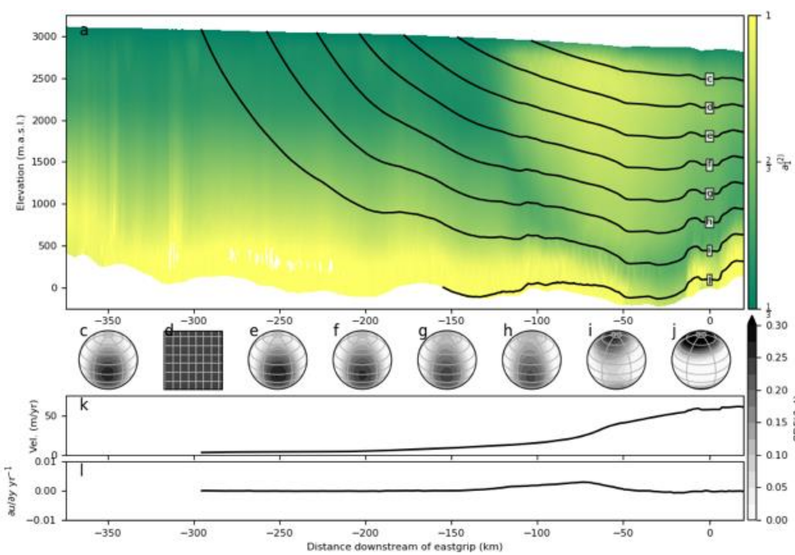
Anisotropic ice-flow model



PRELIMINARY!

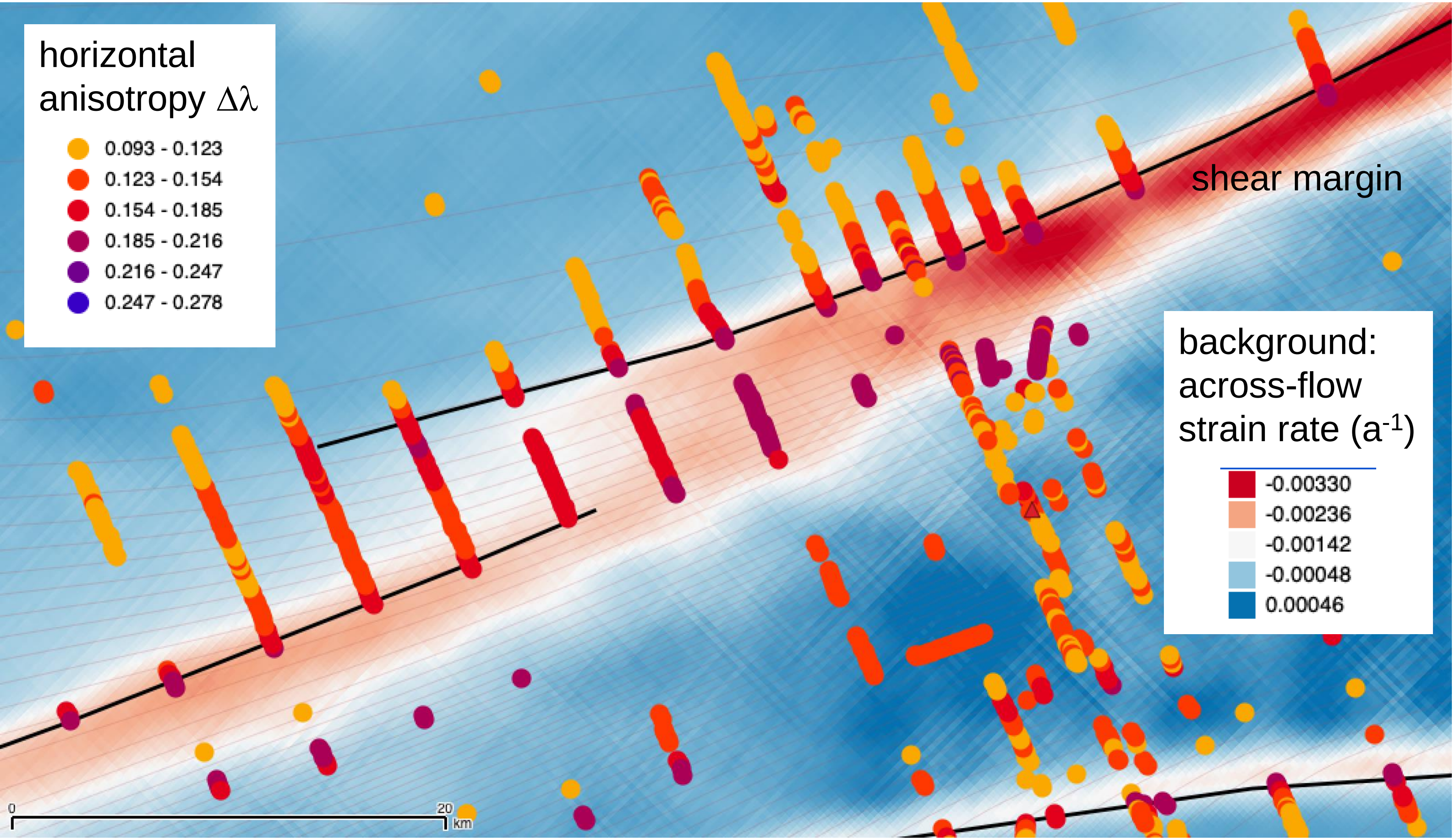
ELMER/ICE

- Bed topography: BedMachine (400 m interpol)
- Anisotropy: GOLF (Gillet-Chaulet et al., 2006)
- No subglacial hydrology
- Basal sliding: linear Weertman



HELMHOLTZ GEMEINSCHAFT

Close-up on northern shear margin



Conclusions I: Methodology

What do we get from beat frequency?

- strength of horizontal anisotropy $\Delta\lambda = \lambda_2 - \lambda_1$
- as function of position (consistent with ice core)

Disappearing modulation (amplitude ~ 0):

- orientation of eigenvector || radar profile
- or $\Delta\lambda = 0$

Several beat frequencies in spectrogram:

- potentially vertically changing $\Delta\lambda$

Problems:

- beat signals lost in shear margin (low SNR from folding)
- artefacts in automatic analysis => manual correction

Conclusions II: Ice-stream dynamics

Spatial pattern of $\Delta\lambda$: across flow

- increases towards margin (from outside)
- decreases slightly in ice stream

Spatial pattern of $\Delta\lambda$: along flow (preliminary)

- $\Delta\lambda$ increases around bedrock undulation

Process interpretation:

- Strong correlation with shear strain rate
- qualitative agreement with anisotropic flow model
- but: mangitude of $\Delta\lambda$ does not match (yet)

Open question:

- how to constrain $\lambda_3 = 1 - 2\lambda_1 - \Delta\lambda$ to get absolute values from co-pol measurements only?

  => non-nadir geometries, other options?

Acknowledgements

EastGRIP is directed and organized by the Centre for Ice and Climate at the Niels Bohr Institute, University of Copenhagen. It is supported by funding agencies and institutions in Denmark (A. P. Möller Foundation, University of Copenhagen), USA (US National Science Foundation, Office of Polar Programs), Germany (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research), Japan (National Institute of Polar Research and Arctic Challenge for Sustainability), Norway (University of Bergen and Bergen Research Foundation), Switzerland (Swiss National Science Foundation), France (French Polar Institute Paul-Emile Victor, Institute for Geosciences and Environmental research) and China (Chinese Academy of Sciences and Beijing Normal University).

Tobias Binder and the Polar6 crew for data acquisition. Fernando Valero (AWI) for the assisstence regarding automatic processing.