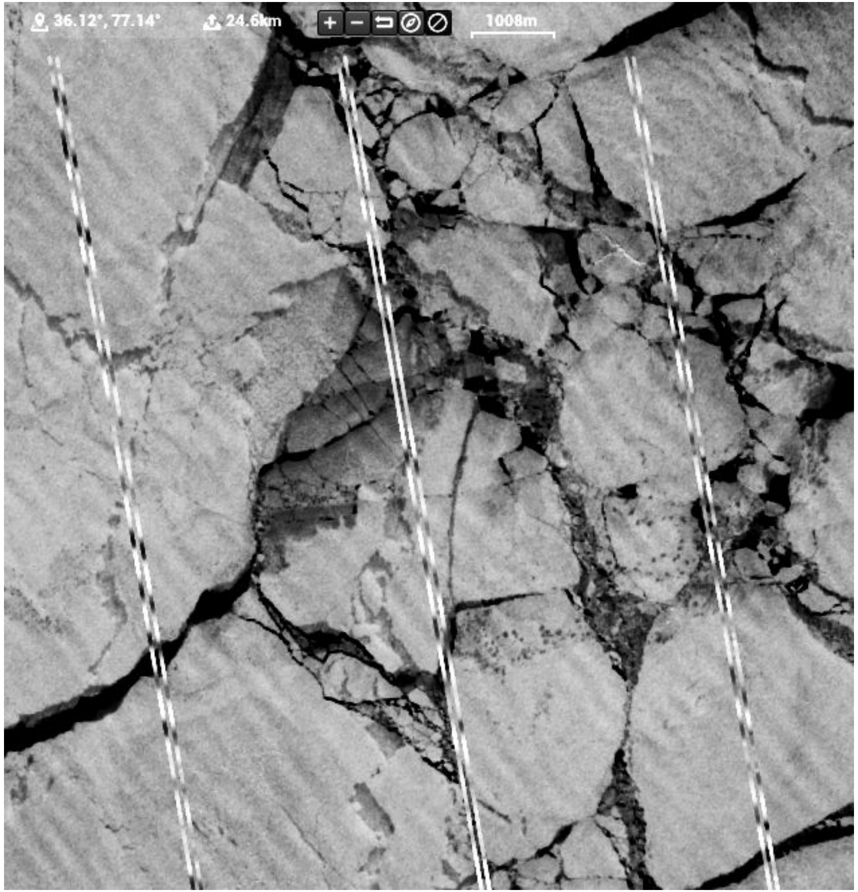
Wave propagation and attenuation under sea ice in the Arctic

Fabrice Ardhuin[1], Fabrice Collard[2],
Marcel Kleinherenbrink[3],
Louis Marié[1], Frédéric Nouguier[1]

(minor revisions with JGR-Oceans)

CFOSAT 3rd international Science Team meeting, St Malo 2022



1. Where we started

Wave-ice interactions

Pancakes and other water-ice mixtures (Rogers et al.

Effects of floe size & ice break-up on ice attenuation (Stopa et al. 2018, Ardhuin & al. 2020)

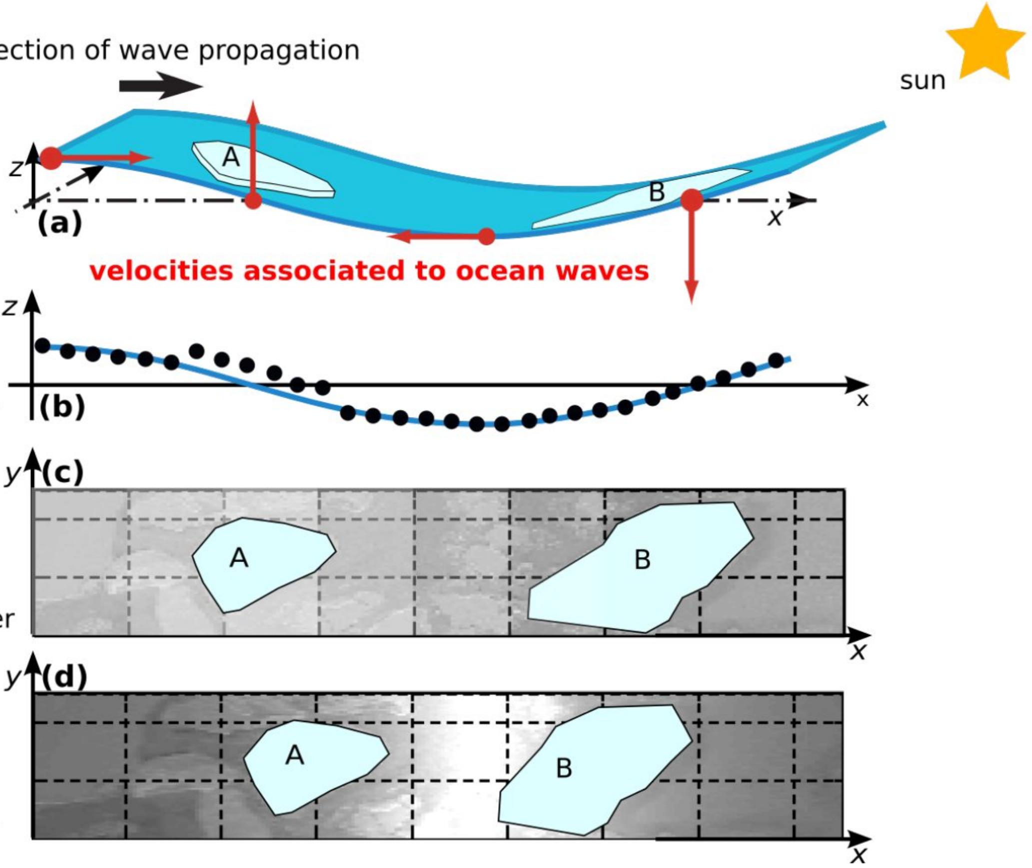
Remote sensing capabilities

SAR : Ardhuin et al. (2015, 2017 …)

IceSat-2: Horvat et al. (2020) showed evidence of waves in sea ice

2. What can be observed

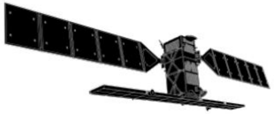
From « ice height » to vertical velocities: waves in ice show up in remote sensing data



ICESat-2: laser altimeter

Sentinel 2: optical imager

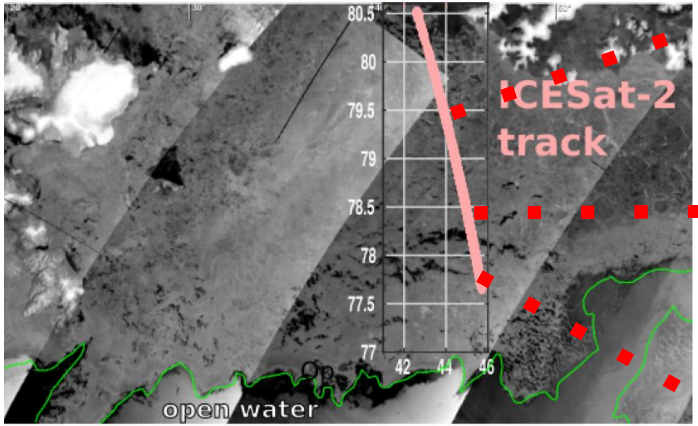
CFOSAT and

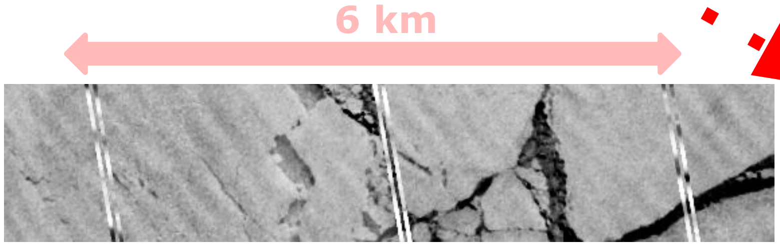


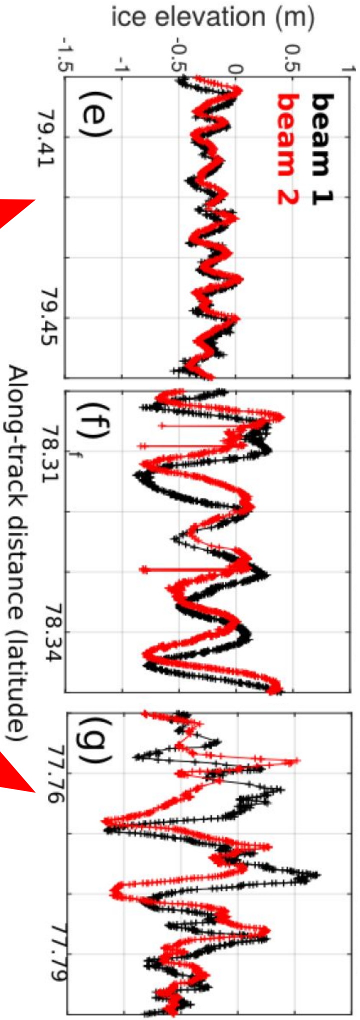
Sentinel 1: radar imager

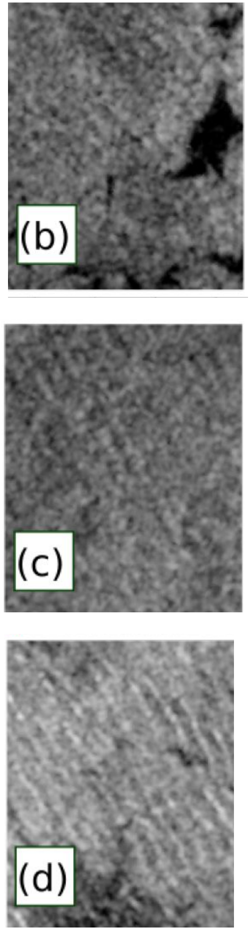
2. Wave parameters from ICESat-2

Signature in ICESat-2 lidar data
(Horvat et al. 2020)









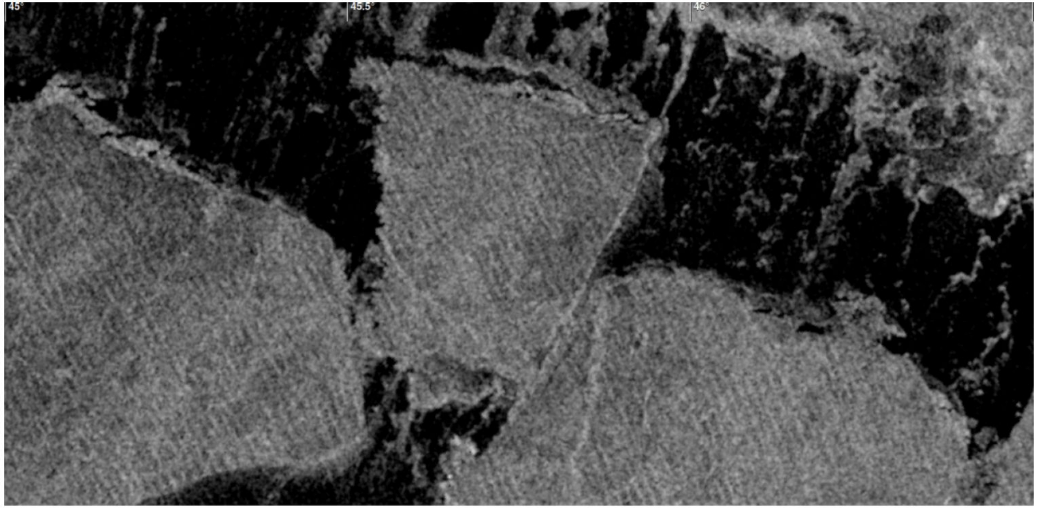
3. Wave spectra from S2

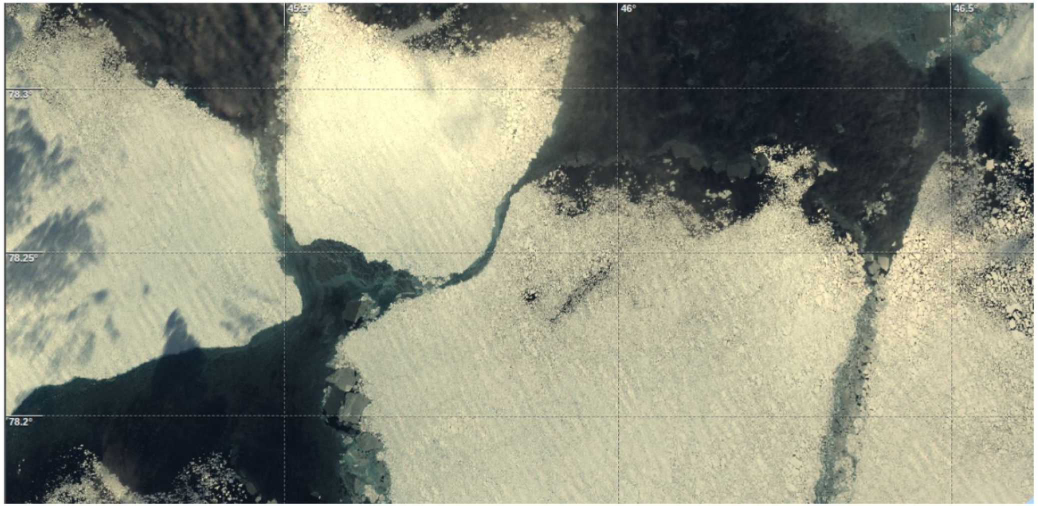
Optical imagery with grazing sun

$$\rho_{\mathrm{L1c}} = \rho_{\mathrm{true}} \frac{\cos(\theta_l)}{\cos(\theta_{\mathrm{Sun}})}$$

gives a MTF,

$$M = k \tan \theta_{\mathrm{Sun}} \cos(\phi_{\mathrm{Sun}} - \phi_w)$$





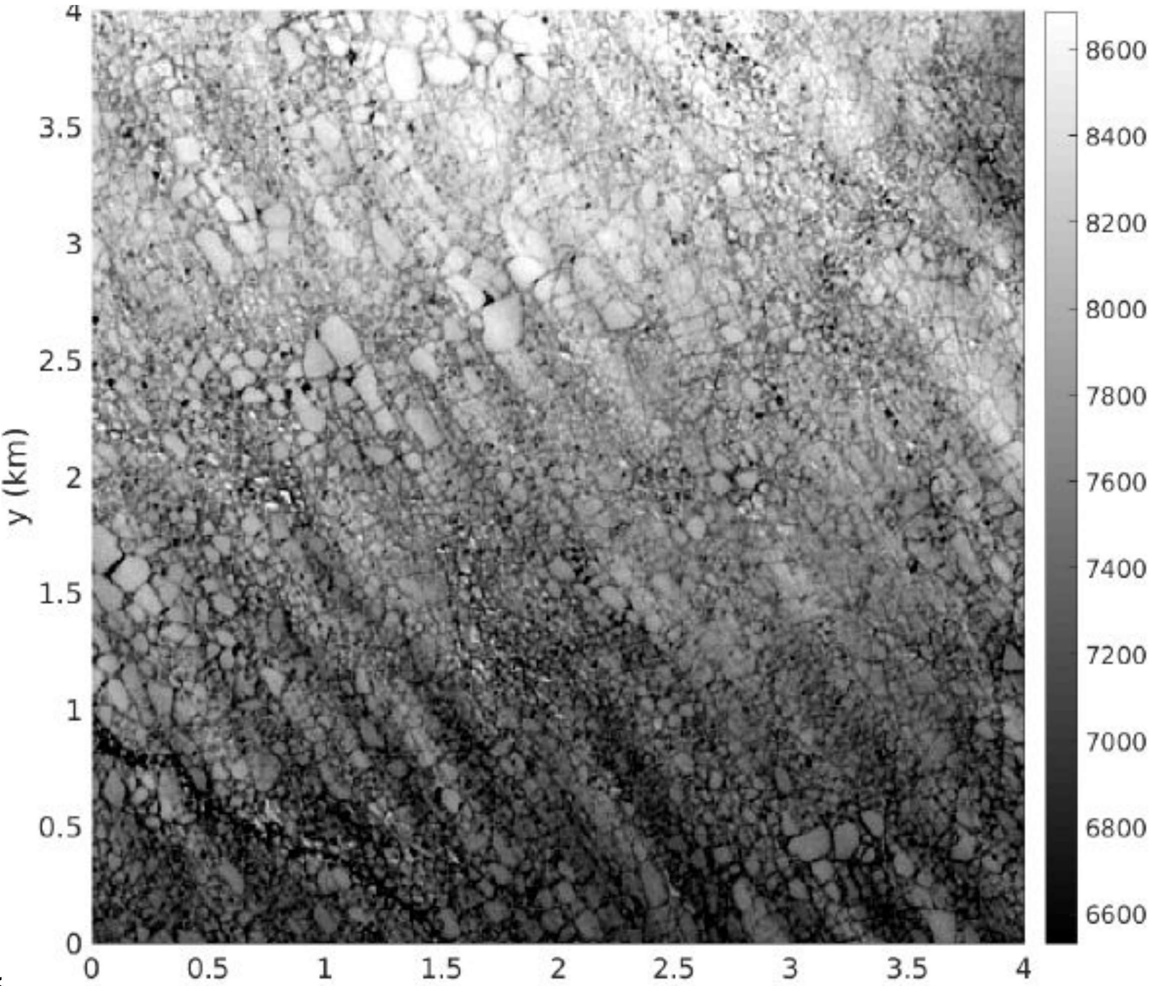
3. Wave spectra from S2

One minor issue:
water-ice edges (floes, leads) …

Here: 10 m resolution

NB: next generation S2 will
Have 5 m pixels!

we should correct MTF
for water fraction
(defined using threshold …)



3. Wave spectra from S2

Optical imagery with grazing sun

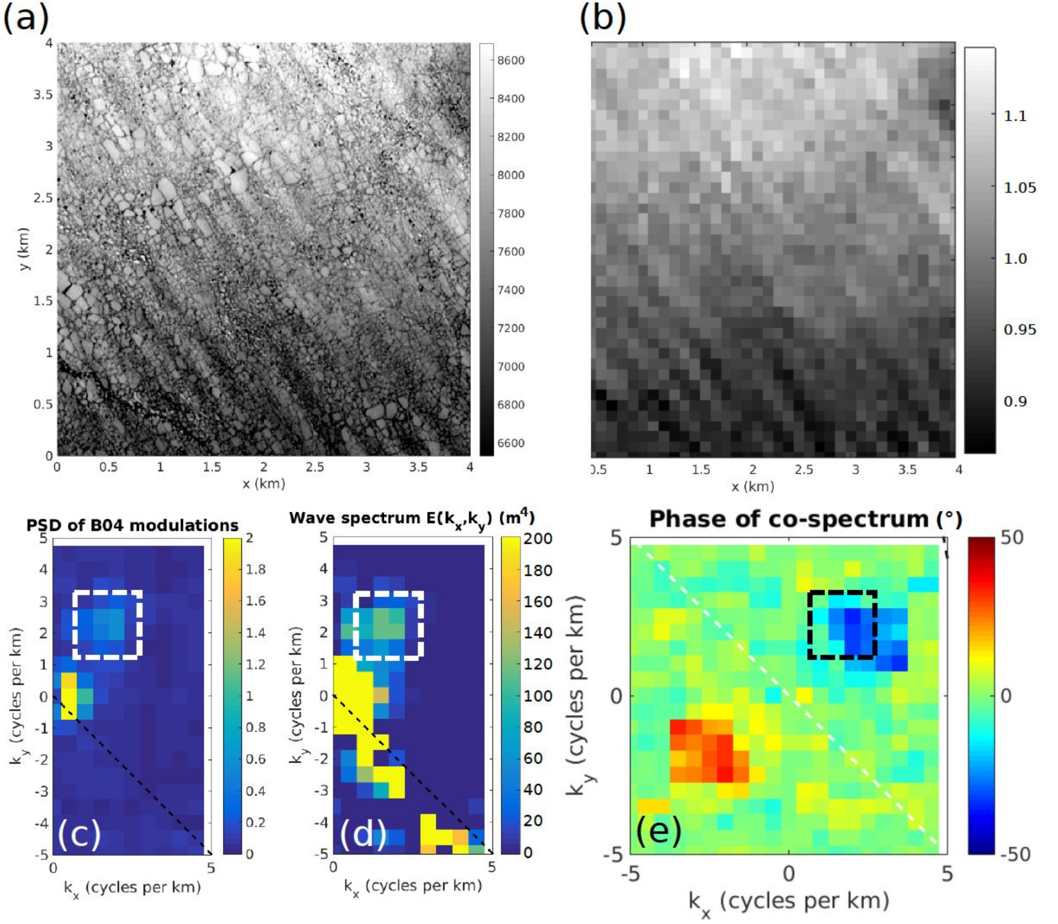
$$\rho_{\mathrm{L1c}} = \rho_{\mathrm{true}} \frac{\cos(\theta_l)}{\cos(\theta_{\mathrm{Sun}})}$$

gives a MTF,

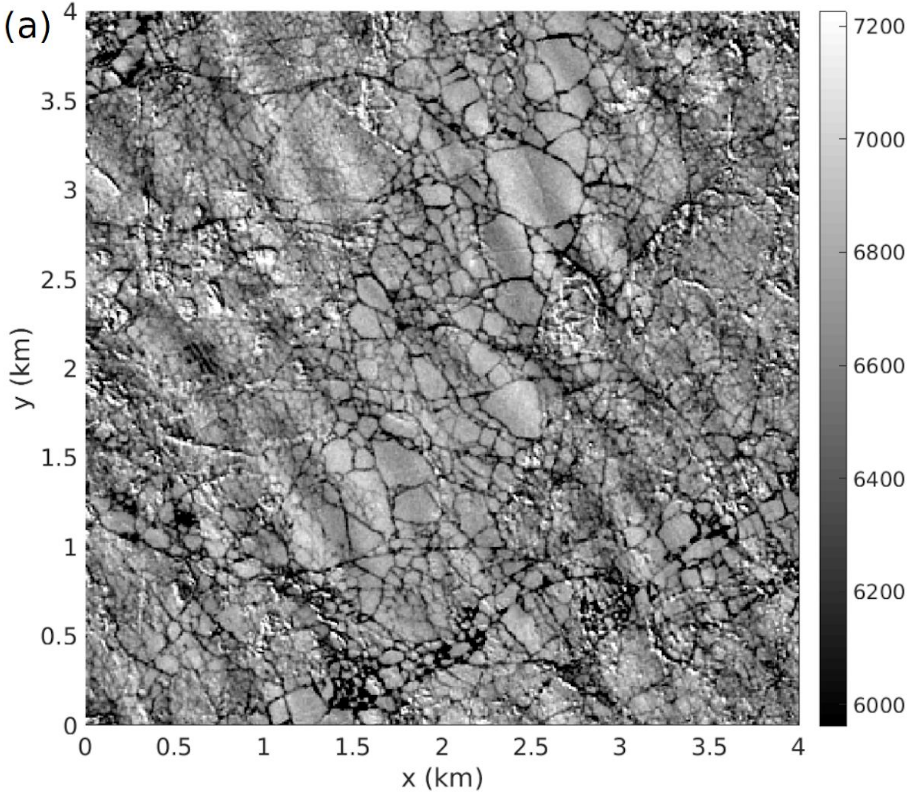
$$M = k \tan\theta_{\mathrm{Sun}} \cos(\phi_{\mathrm{Sun}} - \phi_w)$$

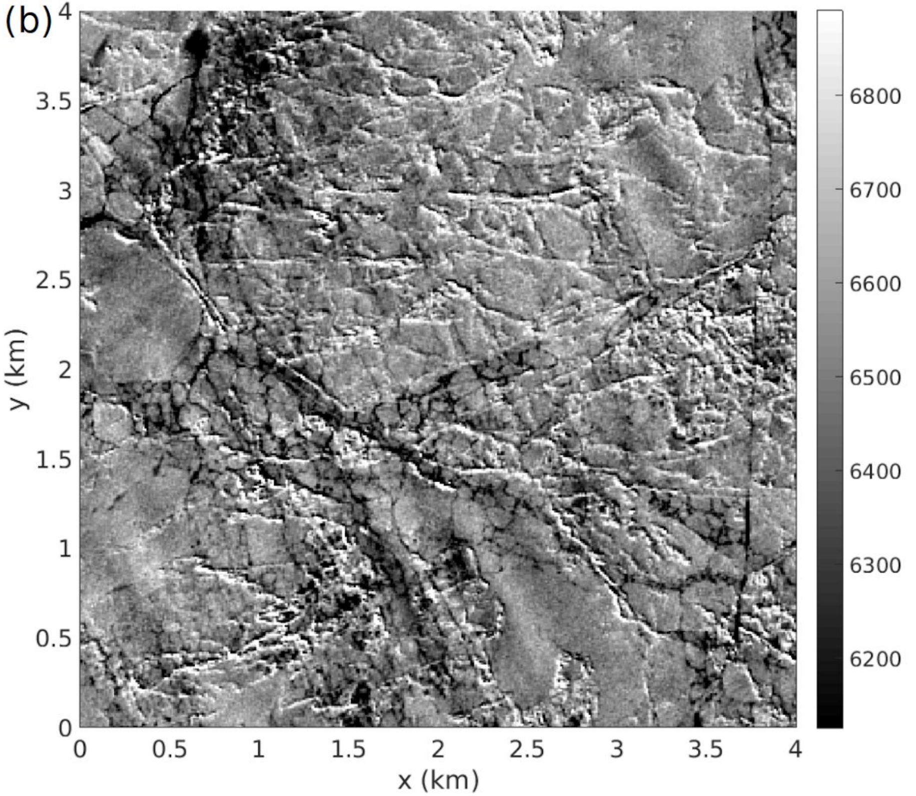
Which can be inverted to get
The wave spectrum E(kx,ky)

(NB: no 180° ambiguity thanks to co-spectra of multiple bands, here B04-B02)



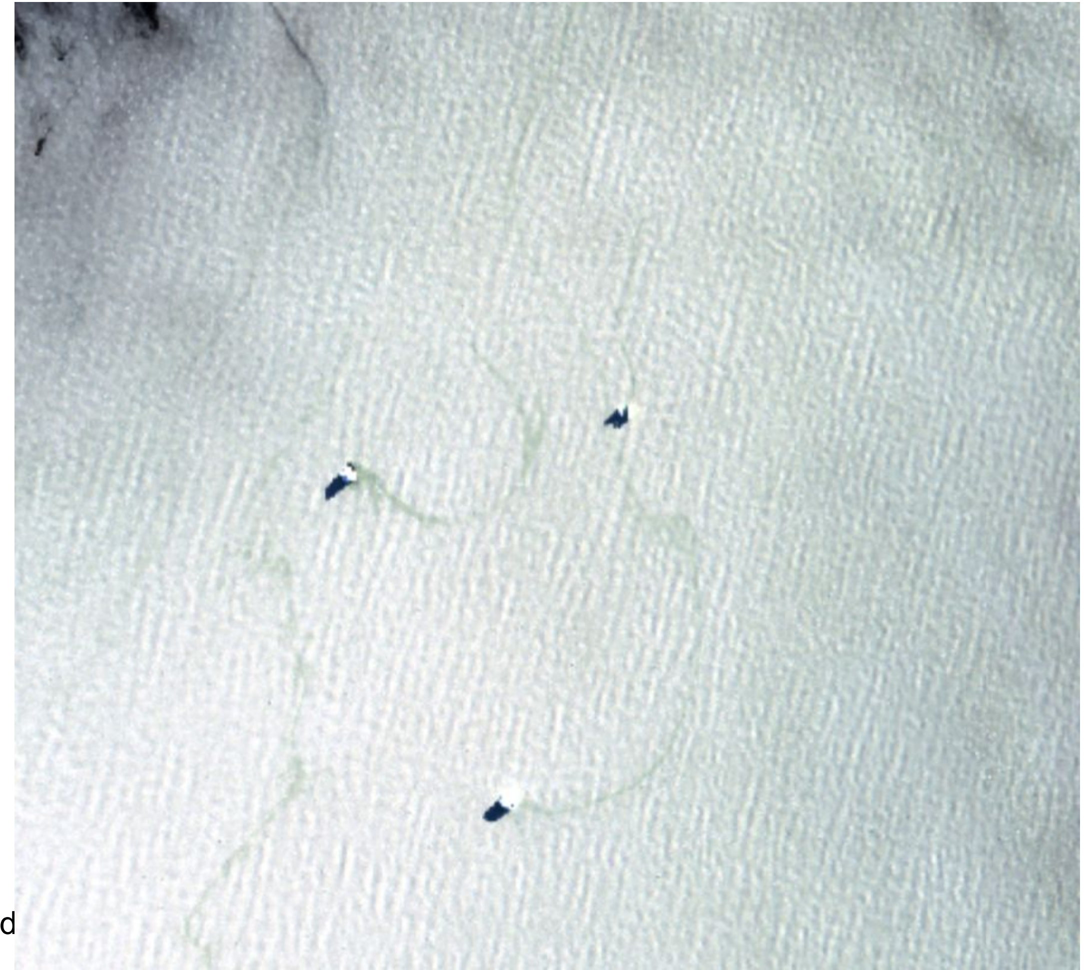
3. Wave spectra from S2 Other examples





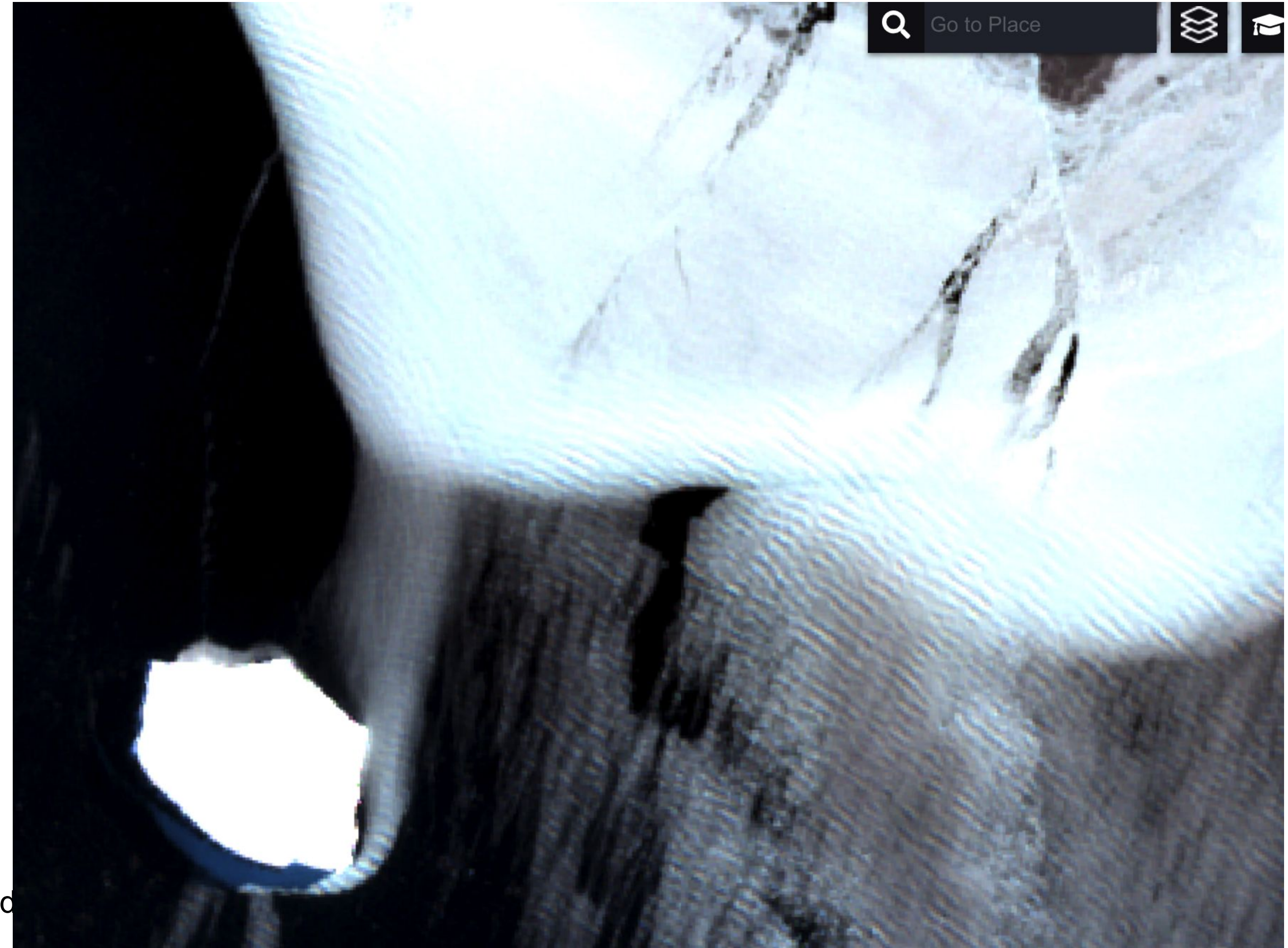
3. Wave spectra from S2

Other examples



3. Wave spectra from S2

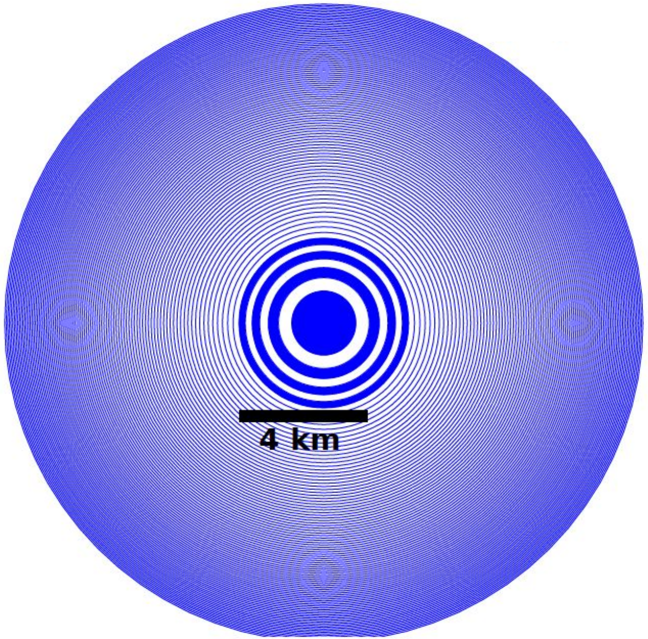
Other examples

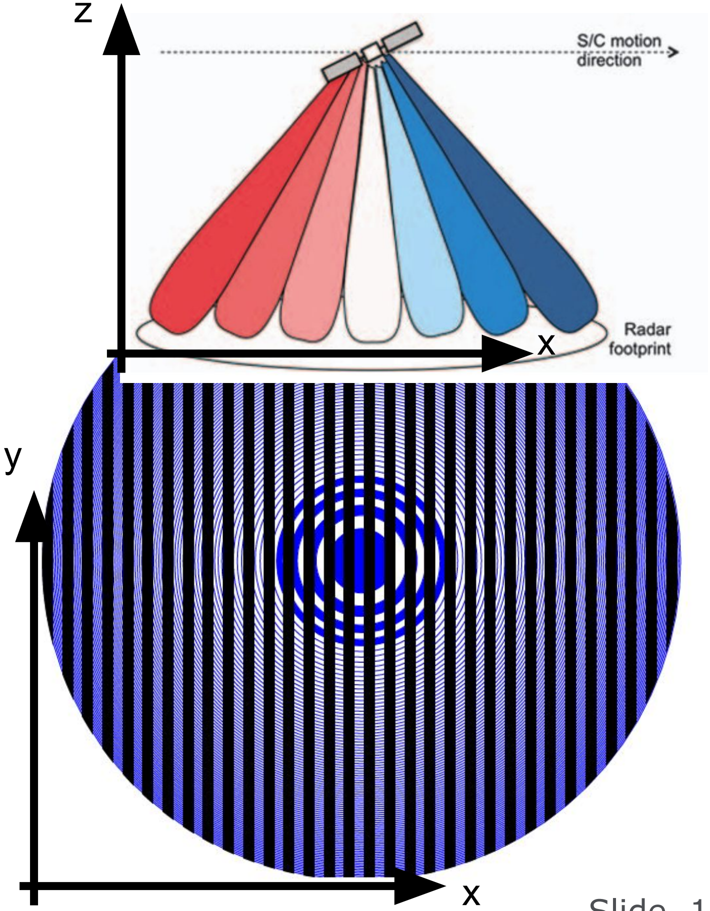


4. Wave signatures in S3 - FFSAR

Sentinel 3 L1b data: O(300 m) along-track res. dx

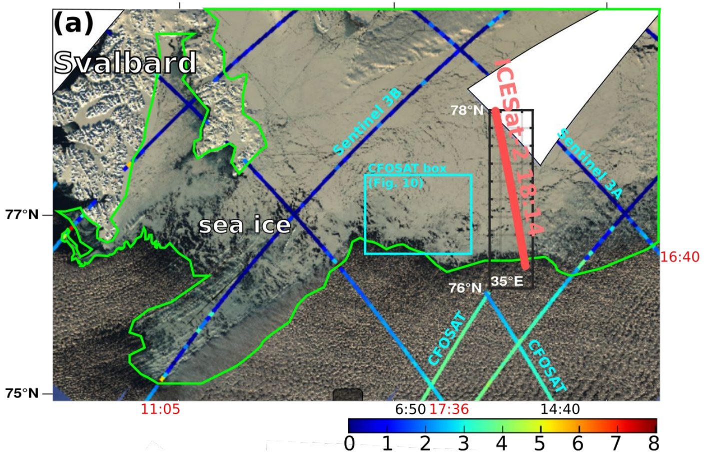
Going back to L1a: can do any dx !





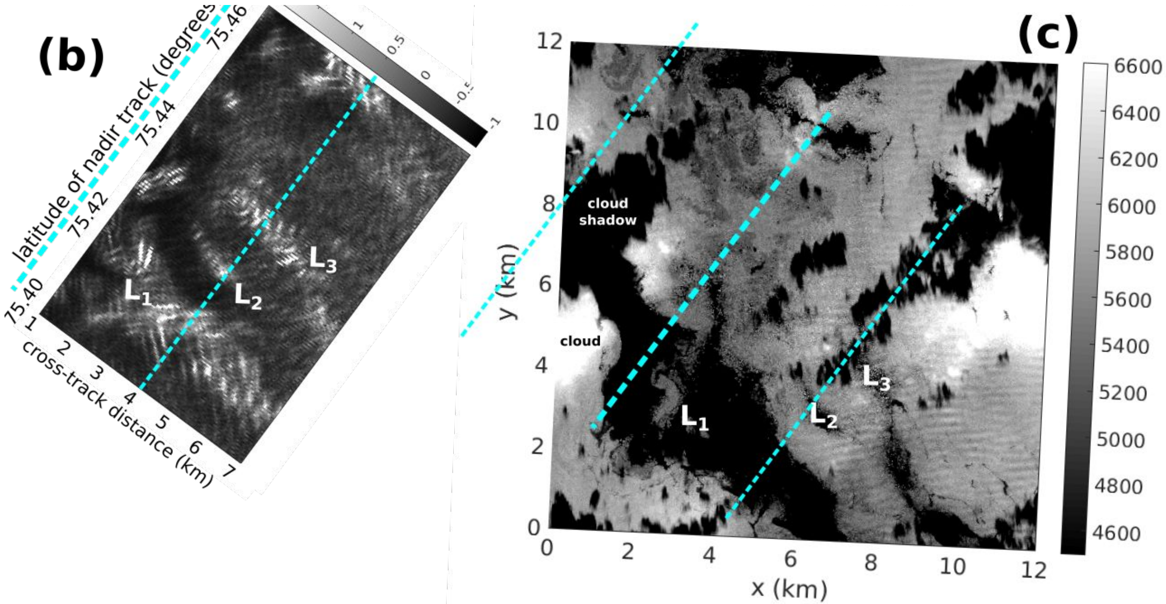
4. Wave signatures in S3 - FFSAR

The same swell-in-ice event …



Sentinel 3–FFSAR

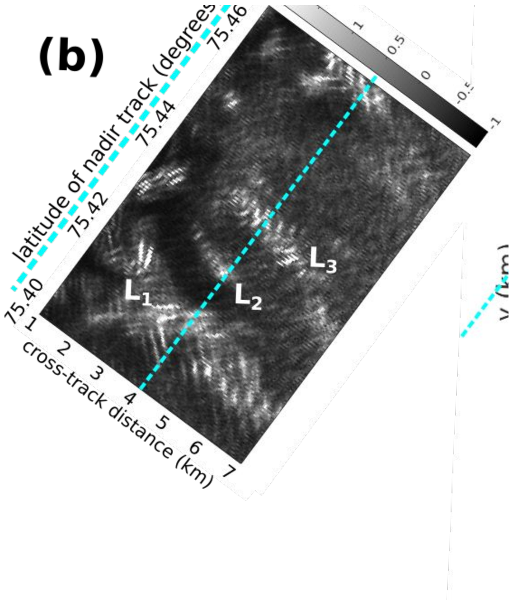
Sentinel 2

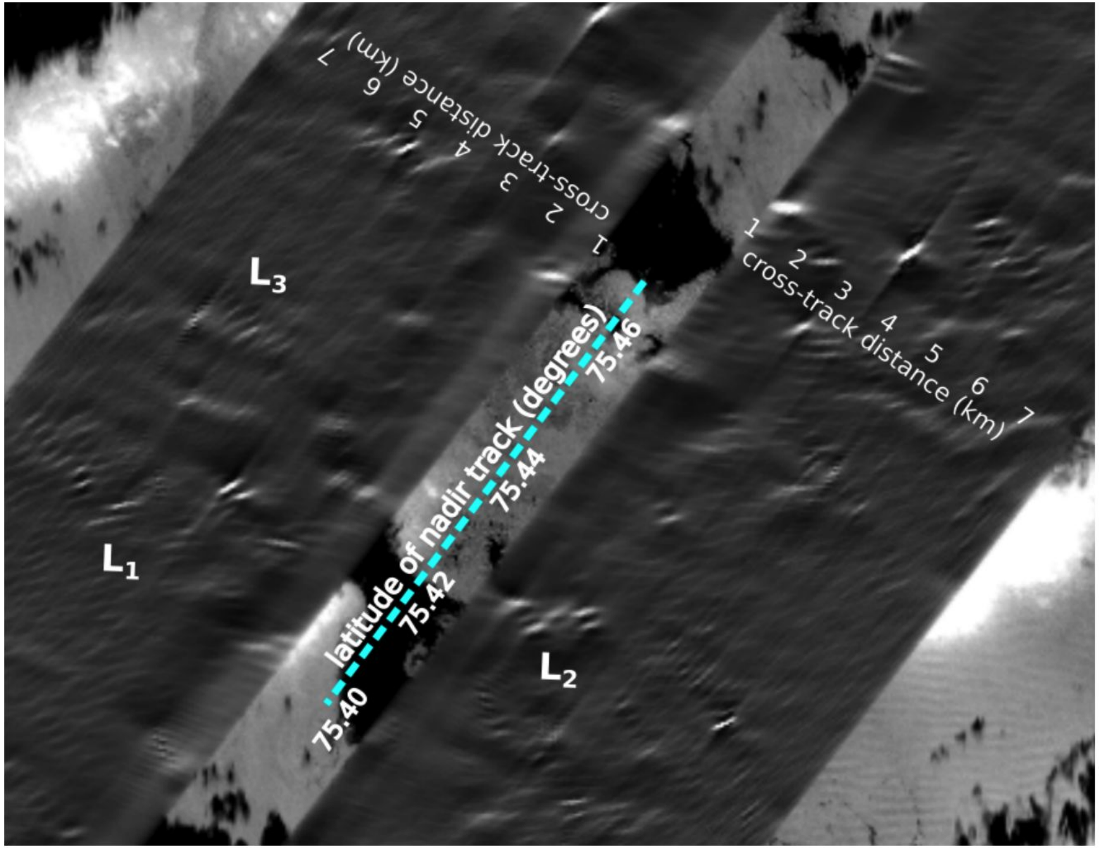


4. Wave signatures in S3 - FFSAR

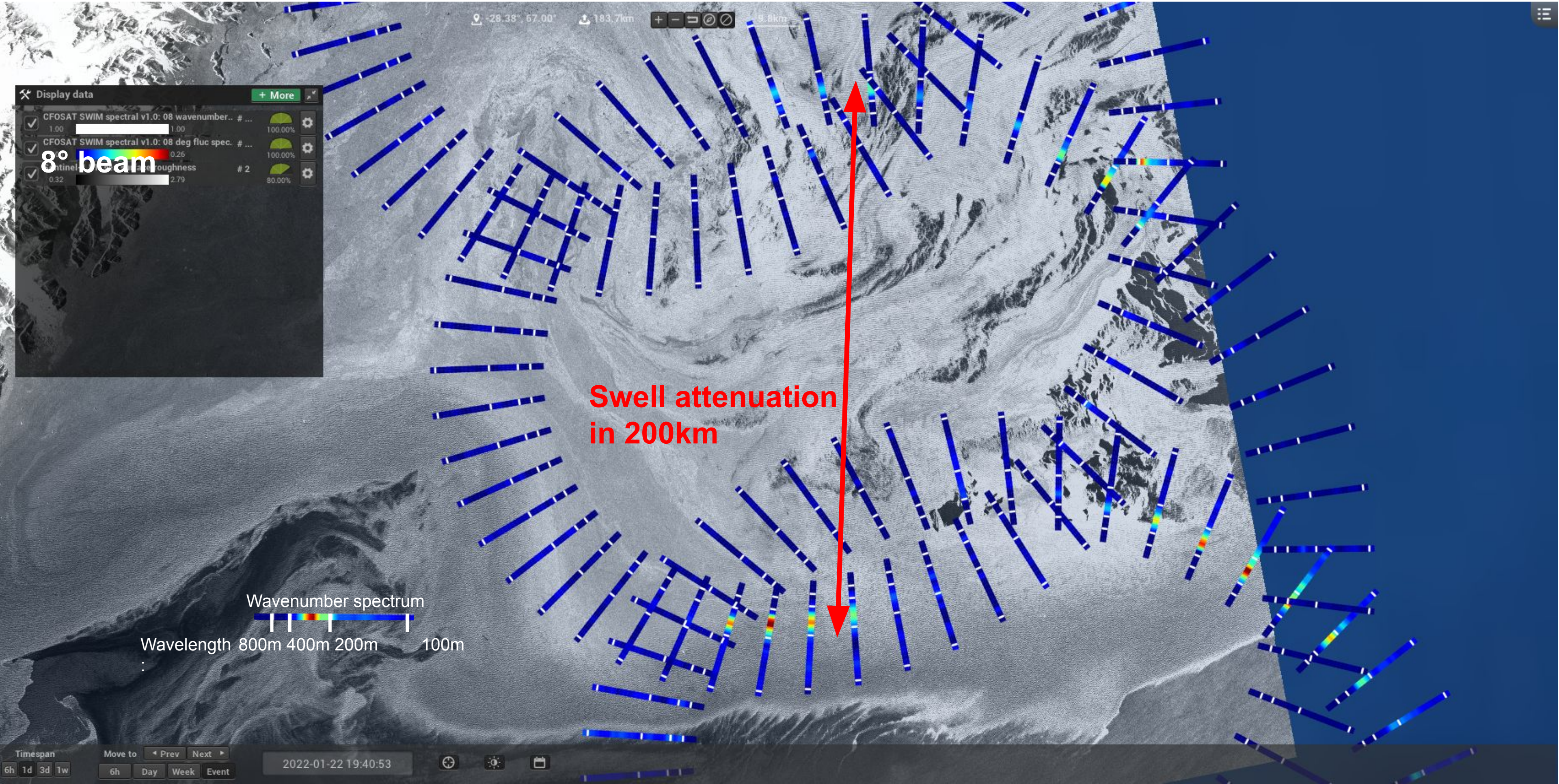
Tsame swell-in-ice event …

Sentinel 3–FFSAR -> unfolding ->





5. Last sensor: CFOSAT's SWIM instrument



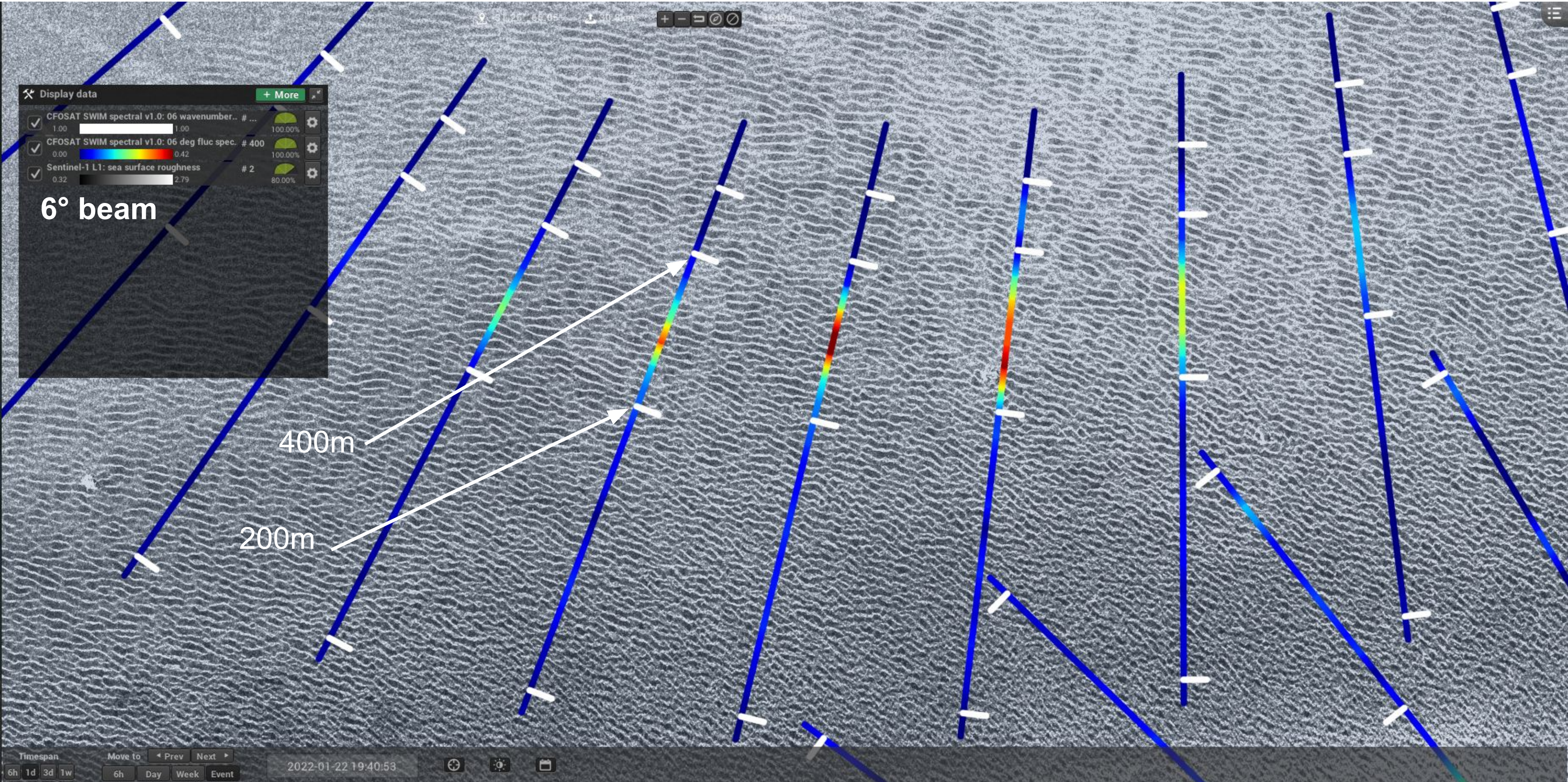
8° beam

Swell attenuation in 200km

Wavenumber spectrum

Wavelength 800m 400m 200m 100m

5. Last sensor: CFOSAT’s SWIM instrument



Display data

☑ CFOSAT SWIM spectral v1.0: 06 wavenumber.. # ... 1.00 1.00 100.00%

☑ CFOSAT SWIM spectral v1.0: 06 deg fluc spec. # 400 0.00 0.42 100.00%

☑ Sentinel-1 L1: sea surface roughness # 2 0.32 2.79 80.00%

2022-01-22 19:40:53

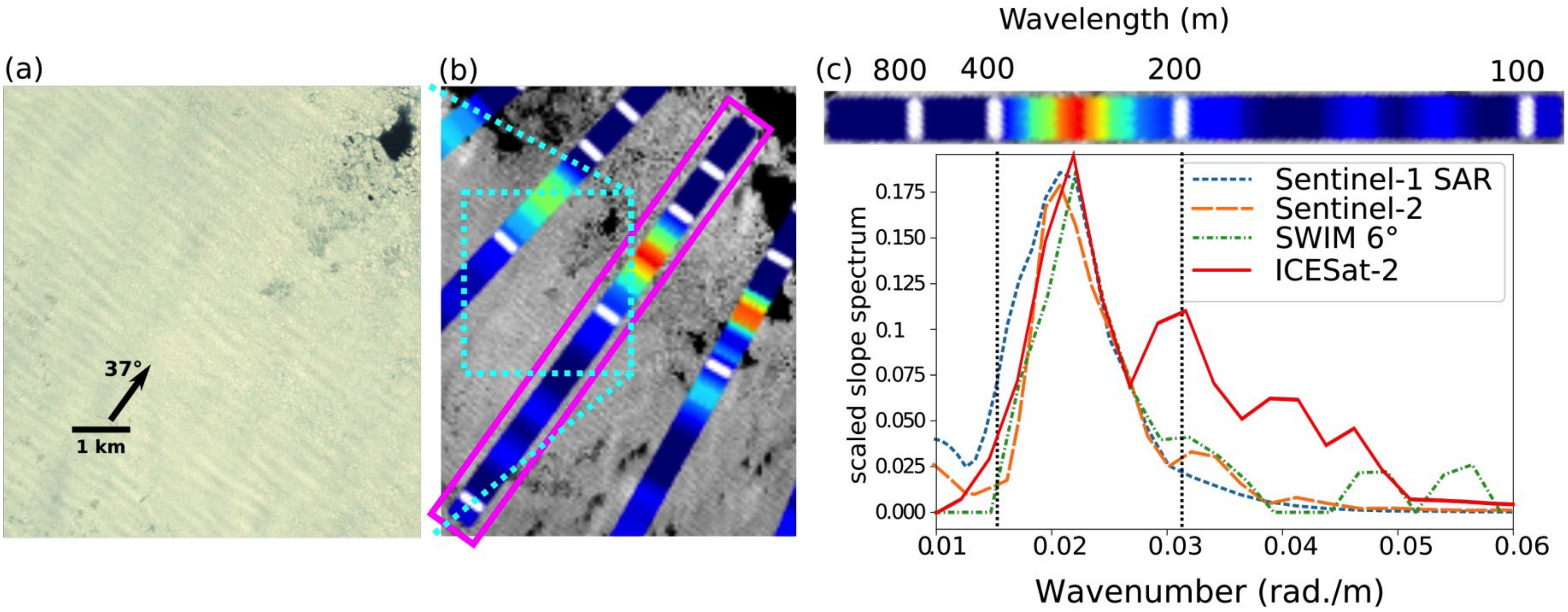
6° beam

400m

200m

5. Last sensor: CFOSAT’s SWIM instrument

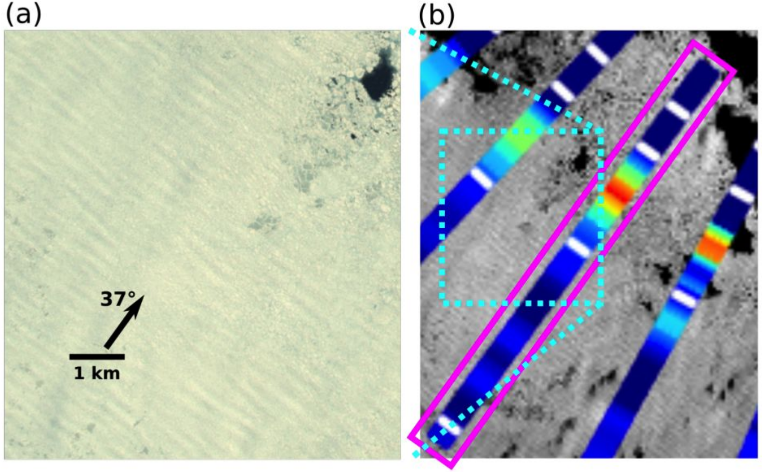
In this case modulations are averaged over O(20 km)

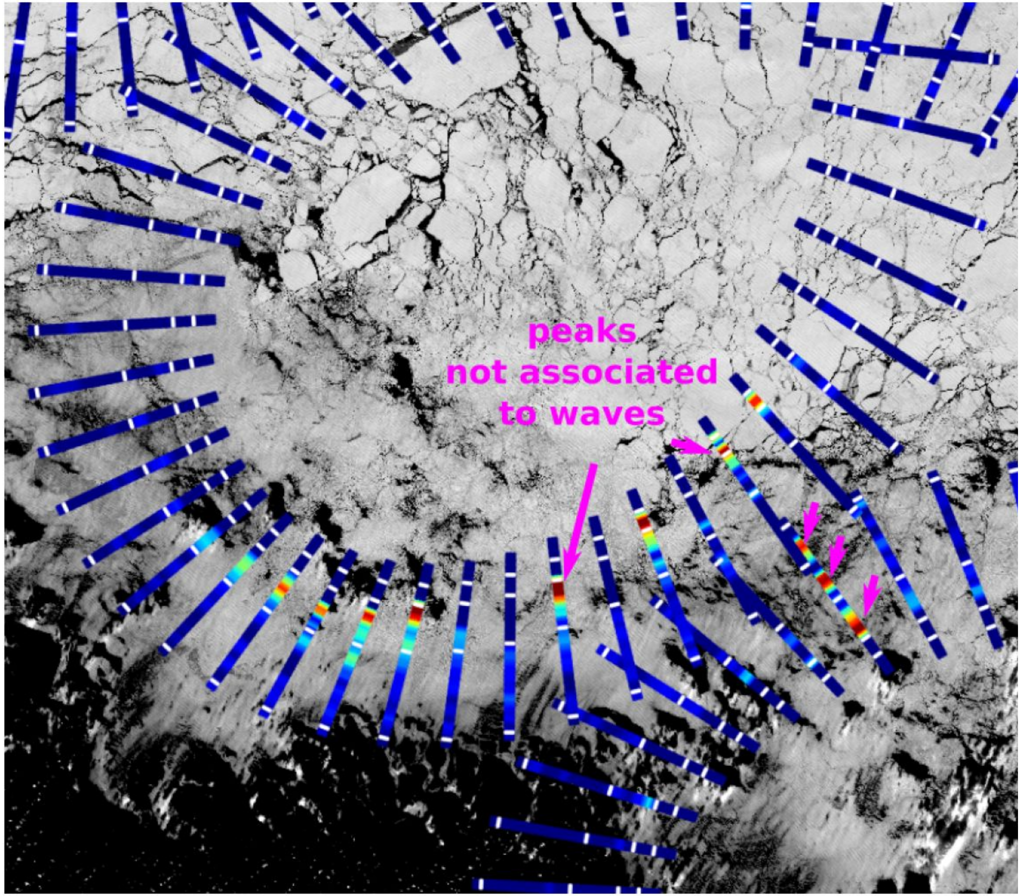


5. Last sensor: CFOSAT’s SWIM instrument

But … Ice features can also give modulations!

Hard to discriminate without a real image of the surface …




peaks
not associated
to waves

Conclusions

All radar and optical systems that can resolve them see waves in sea ice but,

- Imaging mecanism often non-linear
- Ice features lead to errors in wave parameter retrievals
- errors are more easily detected in high resolution imagery
- Optical imagery at res. < 10 m can also provide floe size information, which is critical for wave dissipation (e.g. Ardhuin et al. GRL 2020)