TOWARDS A NEW ERA OF WAVE OBSERVATIONS FROM NADIR-LOOKING SAR ALTIMETERS: WHY SENTINEL-6 RAW DATA MATTER

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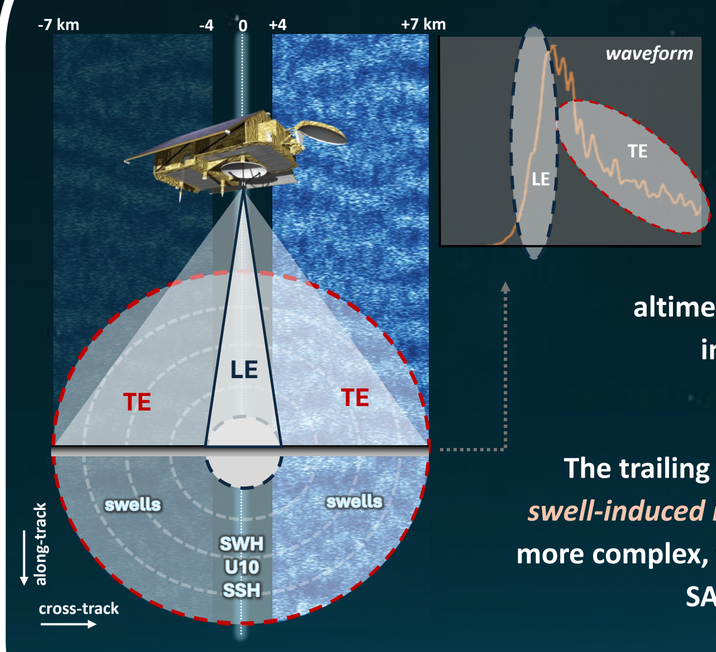
SAR ALTIMETERS AS IMAGERS



Off-nadir fully-focused SAR (FFSAR) signals enable SAR altimeters to detect long ocean waves generated by storms, known as *swells* (Figure 1). This capability can transform the altimeter from one-dimensional profiler into a two-dimensional instrument (Altiparmaki et al., 2022).

The trailing edge of FFSAR waveforms contain *swell-induced intensity modulations*, similar, but more complex, to those observed by side-looking SAR imaging systems like *Sentinel-1.*

Figure 1: Simplified schematic (not to scale) illustrating off-nadir intensity modulations induced by swells, shown as a **projected "unfolded" FFSAR waveform-tail radargram of Sentinel-6A.** Multilooked waveforms were generated using a posting rate of 680 Hz. *TE: trailing-edge, LE: leading-edge*

LIMITATIONS

While this capability introduces opportunities for developing swell wave products, its performance is affected by resolution degradation that depends significantly on sea state (Altiparmaki et al., 2024). Resolution loss is more pronounced when swells travel near the cross-track direction, where the close-to-nadir incident angle changes rapidly, altering backscatter modulations, while the ground resolution is coarse relative to typical swell wavelengths (>150 m wavelength).

Cross-track cutoff wavelength λ_{cr} (Kleinherenbrink et al., 2024) :

$$\lambda_{\mathrm{cr}} = \pi \frac{\mathrm{SWH}}{4\tan(\theta)}$$

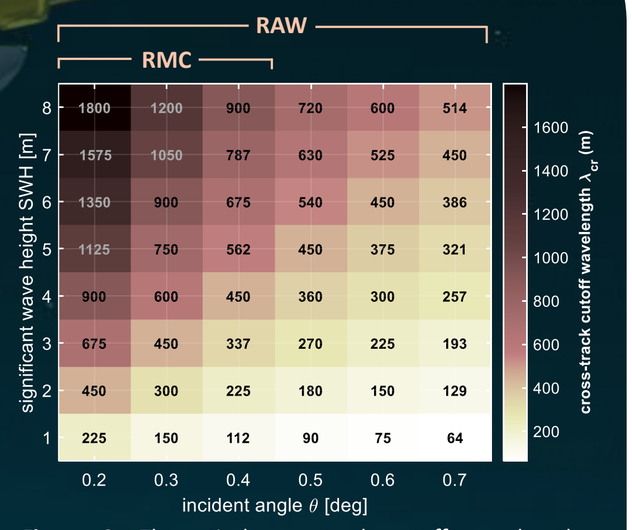
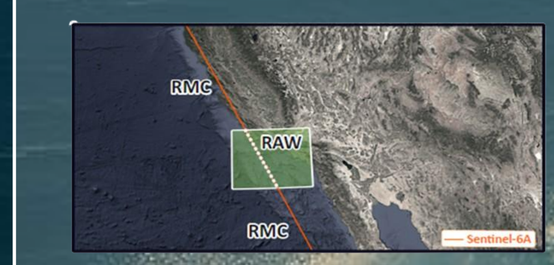


Figure 2: Theoretical cross-track cutoff wavelength λ_{cr}, which defines **the shortest swell wavelengths** that can be detected in the cross-track direction, as a function of **significant wave height** and **incident angle**. The computation assumes the Sentinel-6's Ku-band antenna beamwidth of approximately 1.28°.

CAN RAW DATA IMPROVE SENTINEL-6's APPLICABILITY FOR SWELL DETECTION?

Sentinel-6 employs an onboard Range Migration Correction (RMC) processor that reduces data volume for operational use by truncating part of each waveform derived from the full beam-limited-footprint (RAW), effectively halving the transmitted data (Donlon et al., 2021). However, the truncated portion, available only in RAW mode for calibration and validation activities, provides higher cross-track ground resolution, leading to enhanced swell-induced intensity modulations (Figures 3 and 4).



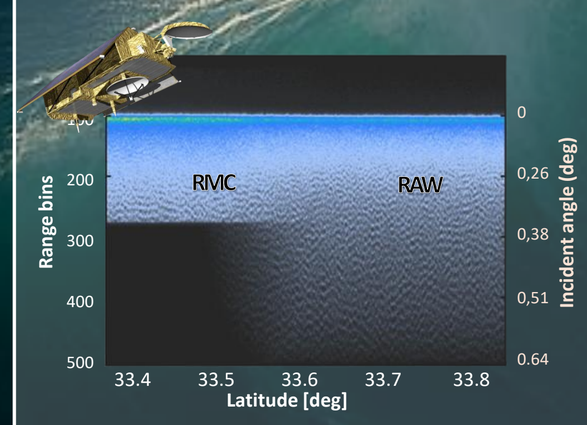


Figure 3: FFSAR radargram of Sentinel-6A over a calibration zone.

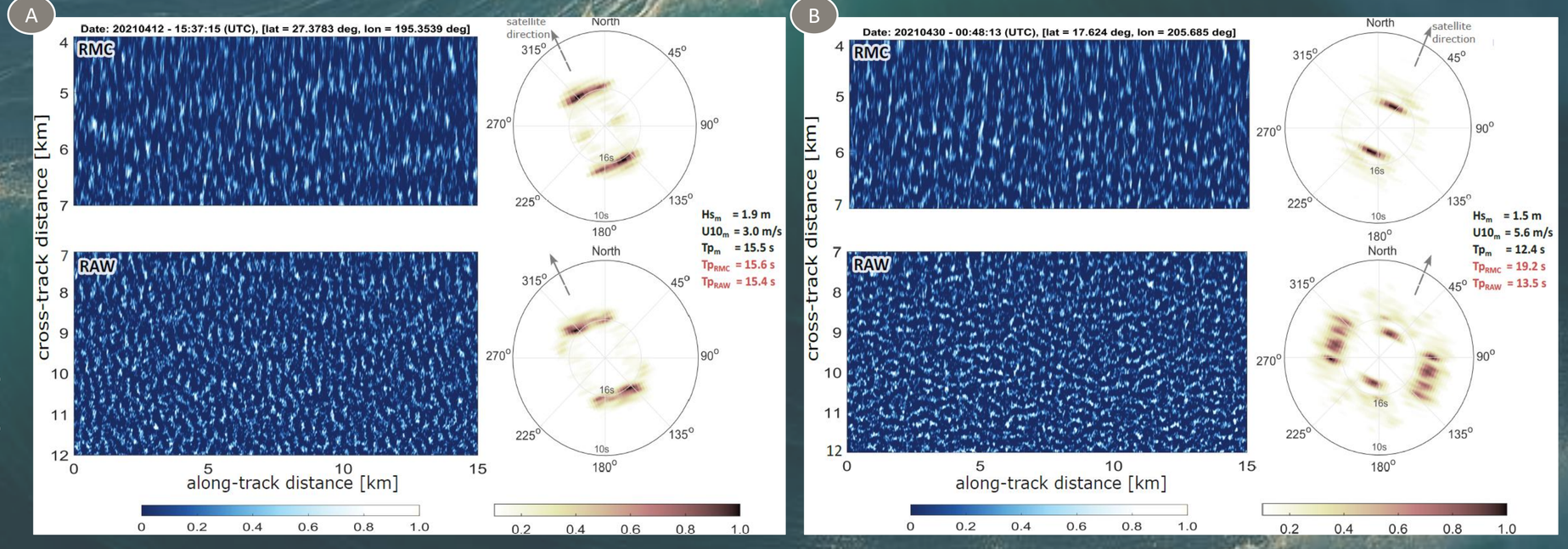


Figure 4: Sentinel-6A FFSAR RMC **(top)** and RAW **(bottom) waveform-tail radargrams** with their associated **FFSAR spectra** showing swells traveling in **(A)** along-track and **(B)** cross-track directions. Wave parameters derived from FFSAR RMC and RAW spectra are shown in light pink and those from ERA5 in black (Altiparmaki 2025).

A **Along-track swells can be retrieved from both RAW and RMC, showing comparable performance**

B **Cross-track SHORT swells are only detectable in RAW due to the higher effective cross-track ground resolution**

KEY MESSAGES

- **FFSAR altimetry enables the detection of long waves generated by storms in open oceans using off-nadir signals.**
- **Both RAW and RMC modes perform similarly for along-track swells.**
- **RAW data offer higher cross-track resolution than the operational truncated RMC products, significantly improving swell retrieval when waves travel in cross-track.**
- **Future swath altimeters will further enhance global swell monitoring.**

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