Remote sensing of rivers and lake water heights (part II)

face 2 face workshop Soil Moisture and Inland Water Monitoring with Satellite Radar

Dar es Salaam, Tanzania, 19th October 2023

Roelof Rietbroek

UNIVERSITY OF TWENTE. ITC

→ THE EUROPEAN SPACE AGENCY

SWOT worries?

Home > News > Spaceflight

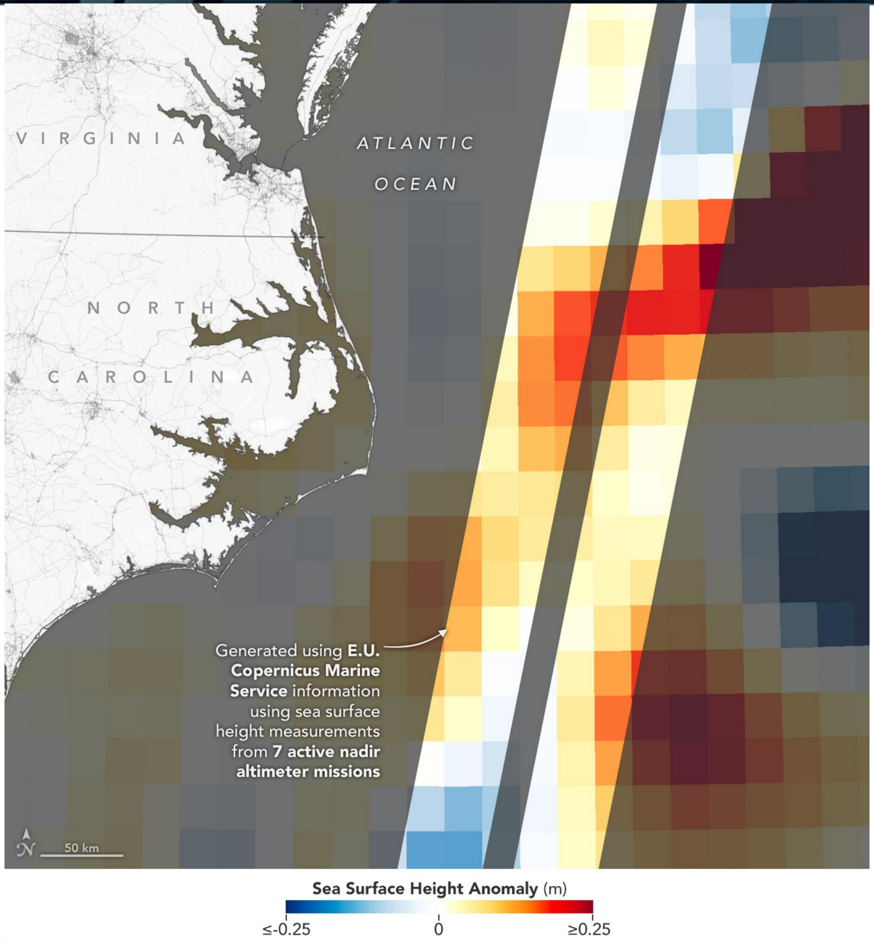
NASA's SWOT water satellite suffers instrument shutdown in orbit

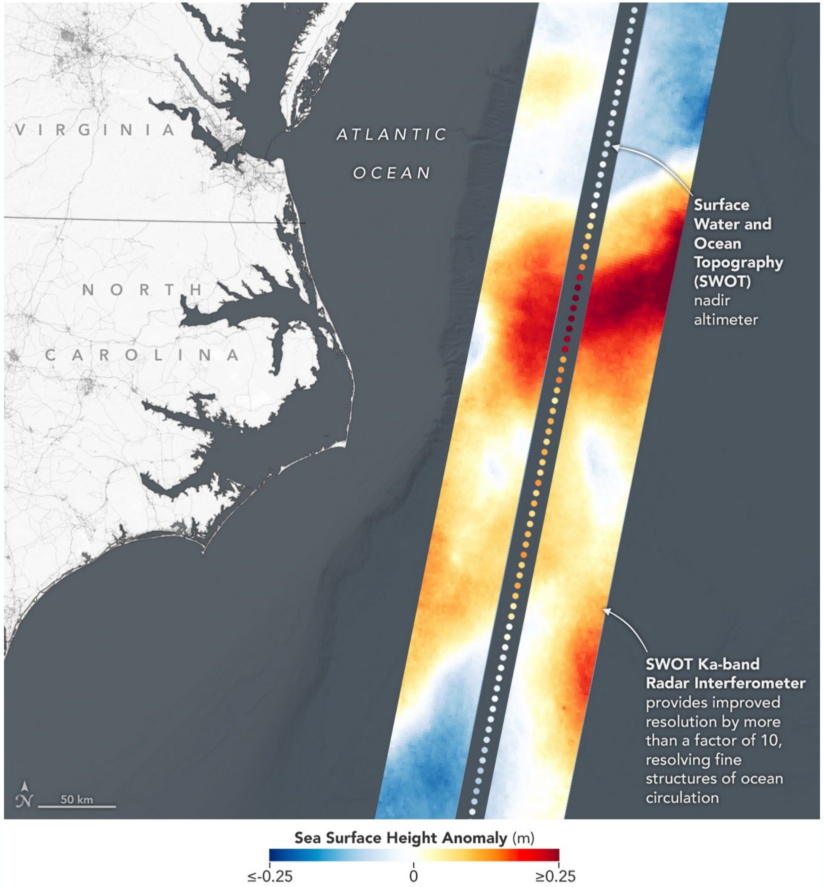
By Elizabeth Howell published 27 February 2023

The Surface Water and Ocean Topography (SWOT) team is troubleshooting the instrument as they seek to have the spacecraft ready for operations in June.

Comments (0)

SWOT first results of Karin instrument



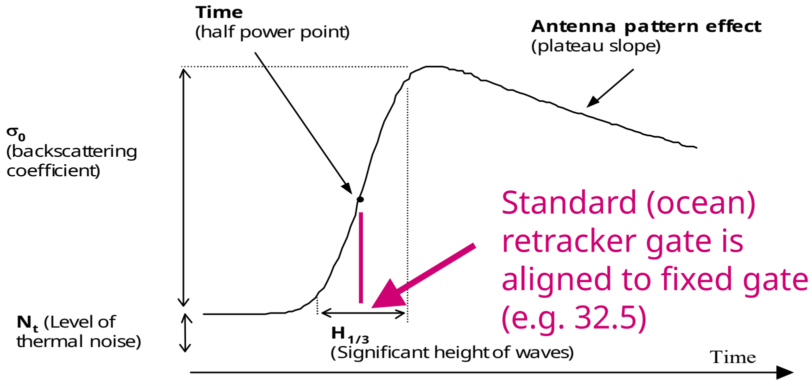


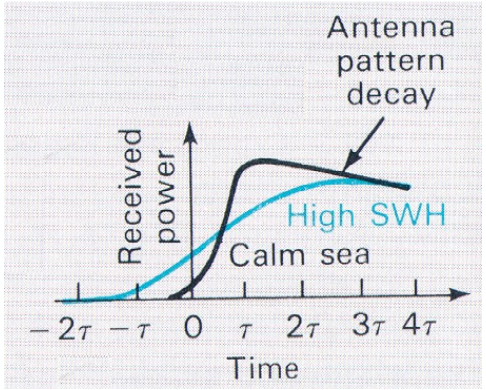
~~Today (& tomorrow~~ → today)

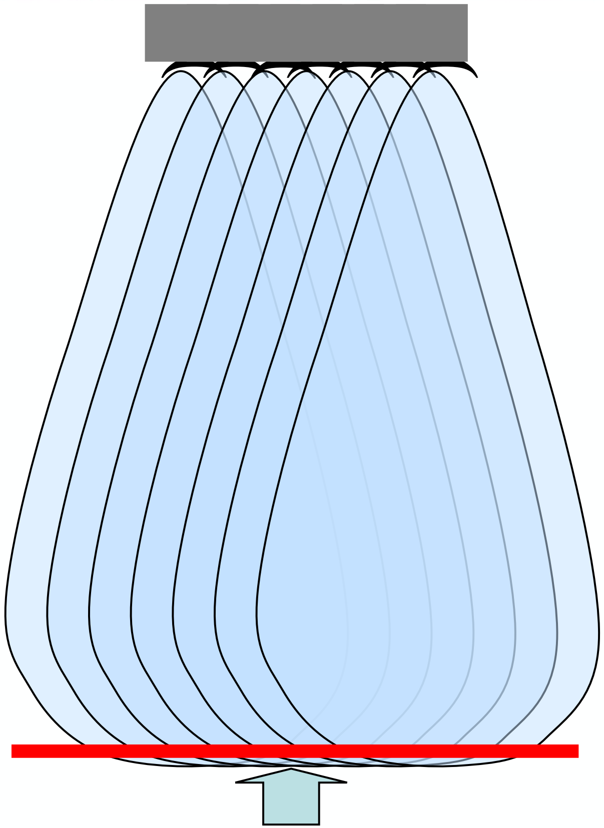
- Motivation of measuring lake and river heights from space
- Principles of radar altimetry
  - “conventional” radar altimetry (pulse limited)
  - “modern” radar altimetry (beam limited)
  - Geophysical corrections

Recap: building a waveform

- Pulse repetition frequency ~ 2 kHz
  - Collect over an integration time (20Hz)
- X-axis: Chirps are deramped and binned according to their delta t (range gates)
- Y-axis: Average the received pulses (power) in 20 Hz blocks (y-axis)
- **Pulse-limited**: Chirp bandwidth (B) determines range resolution:
  - Dr =c/(2B). So B=320Mhz resolves to 0.468m (3 nanosec) range resolution
  - When a waveform has 128 gates, how large is the "range window"?
- Over the ocean: the waveform can be modelled wit an analytical 'Brown model´



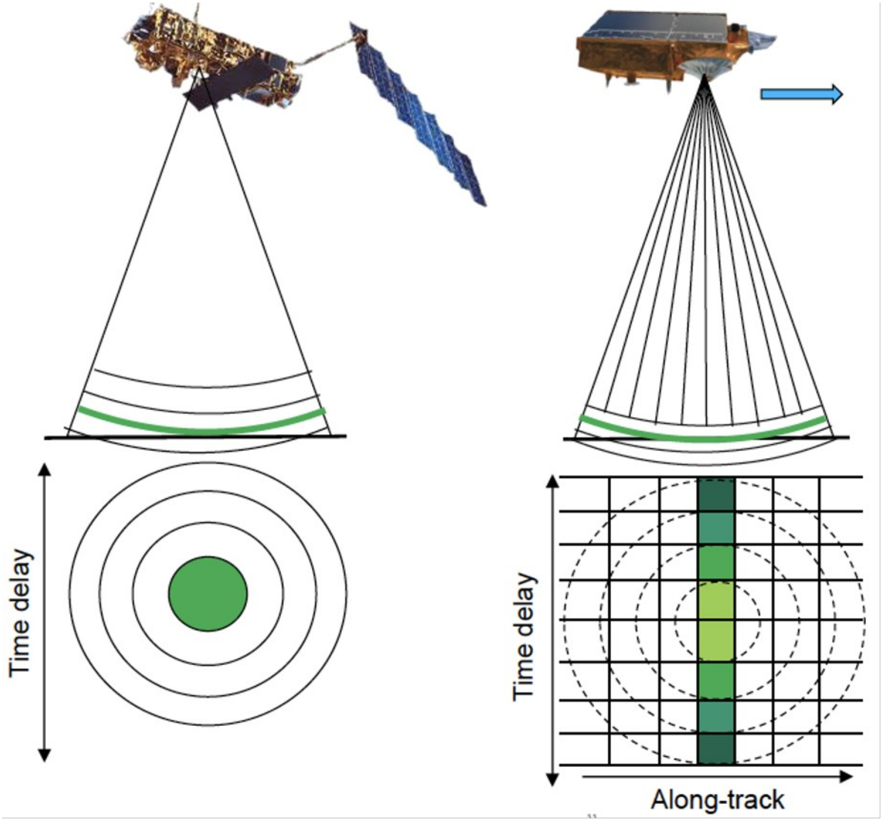




Ground resolution cell (3-5 km)
Image Credit Keith Raney

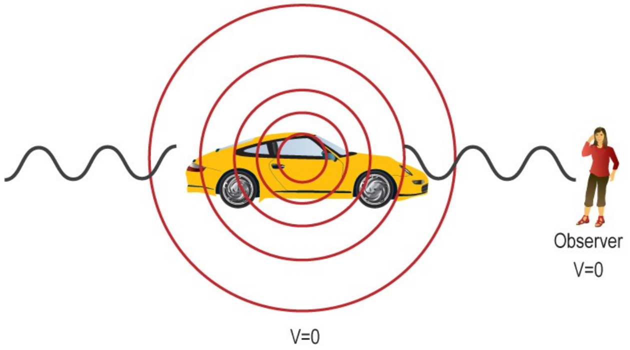
Conventional versus SAR altimetry

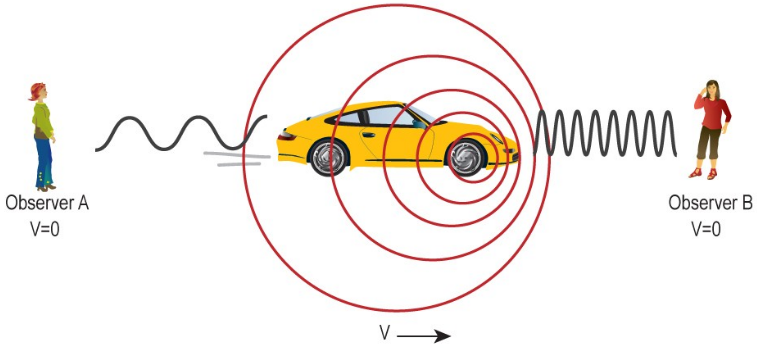
- Conventional (or Low resolution mode): pulse limited
- SAR (or delayed doppler): pulse limited cross-track but beam limited along track
- How can we assign reflections to alongtrack bins???



Measuring the Doppler shift

- Frequency shift of a electromagnetic wave depends on relative velocity
- How would this be noticeable in the reflected chirps?





SAR altimetry (delay doppler altimetry)

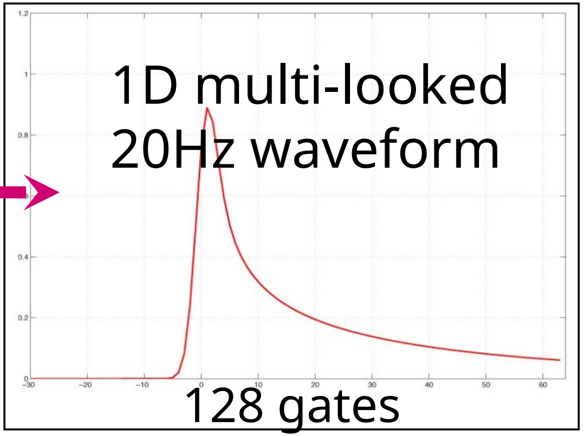
Synthetic aperture

- Doppler shift of chirps depend on along-track location (steady surface)

- PRF: 17800 Hz
- Bursts: 85.7hz (Np=64 pulses)

$$\Delta X_{groundcell} = \frac{PRF \lambda h}{2 V_{sc} N_p}$$

$V_{s/c}$



Ground Resolution Cell (~300m, indepent of SWH)

Original animation by Keith Raney

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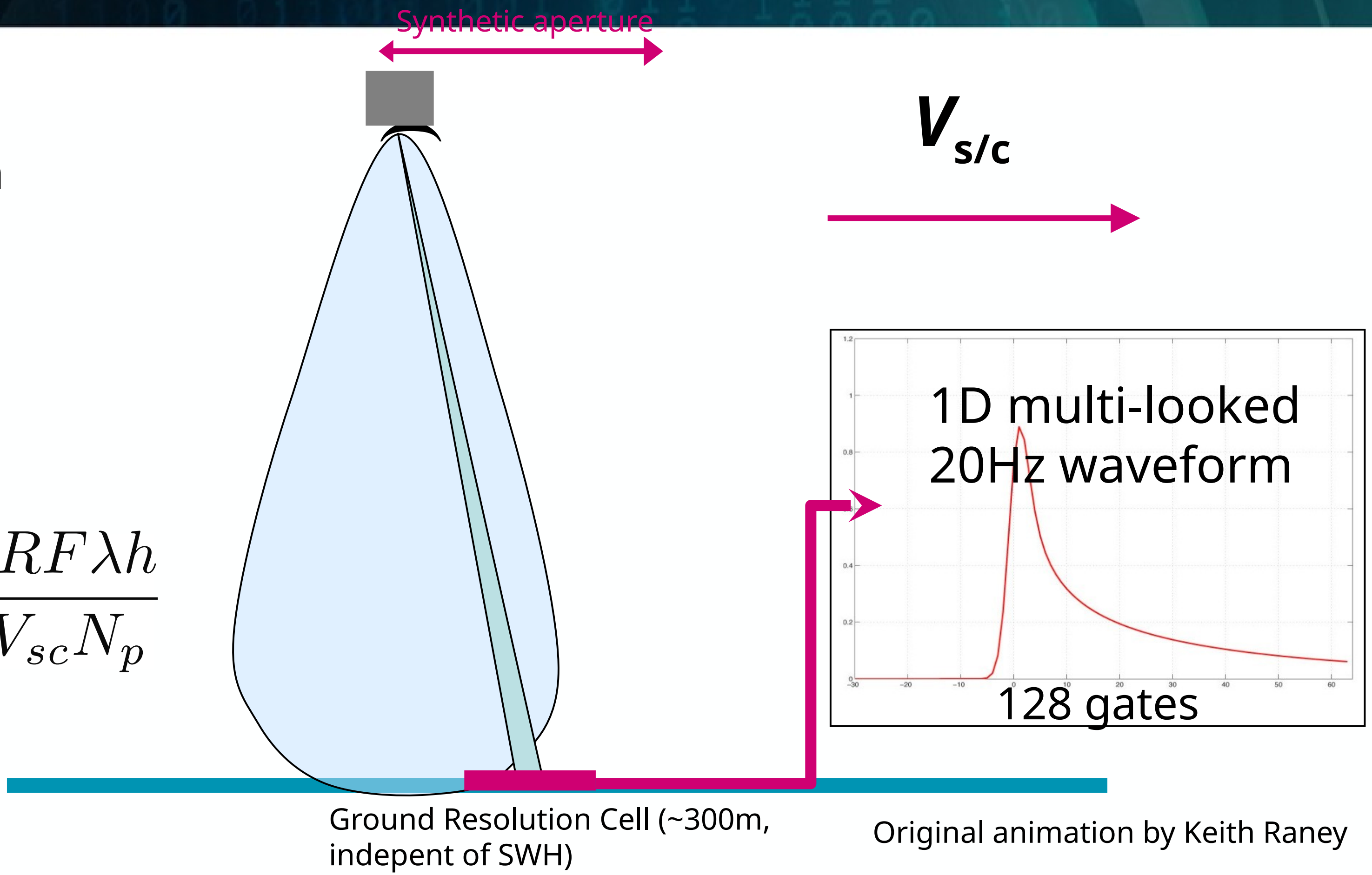

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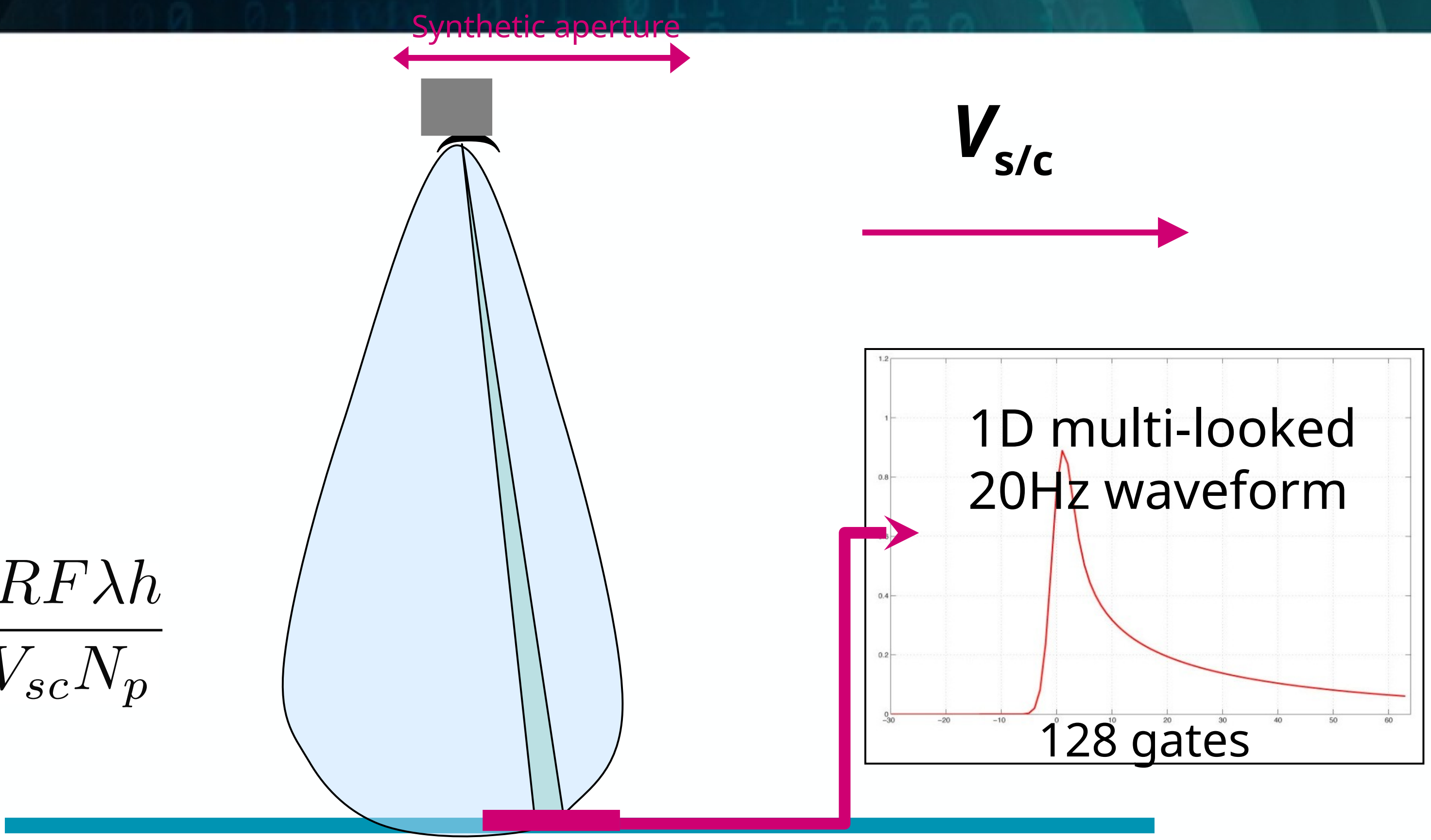

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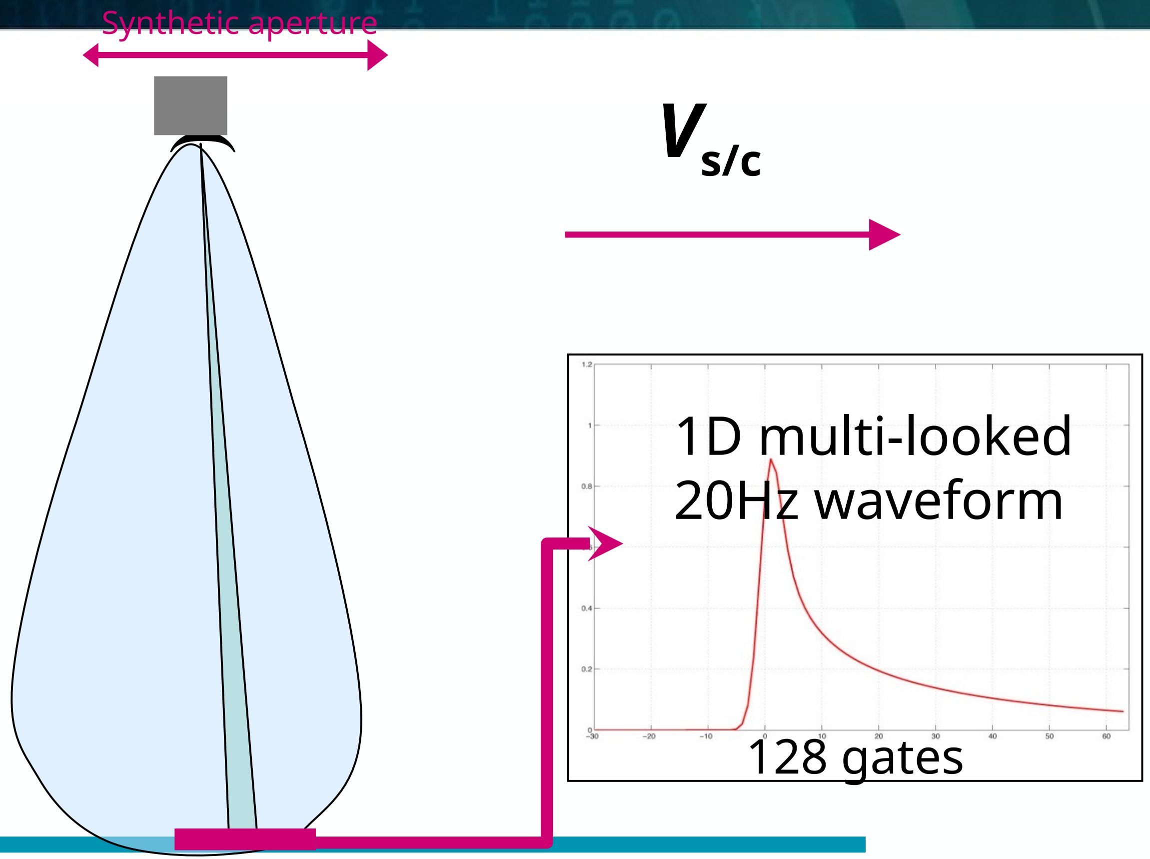

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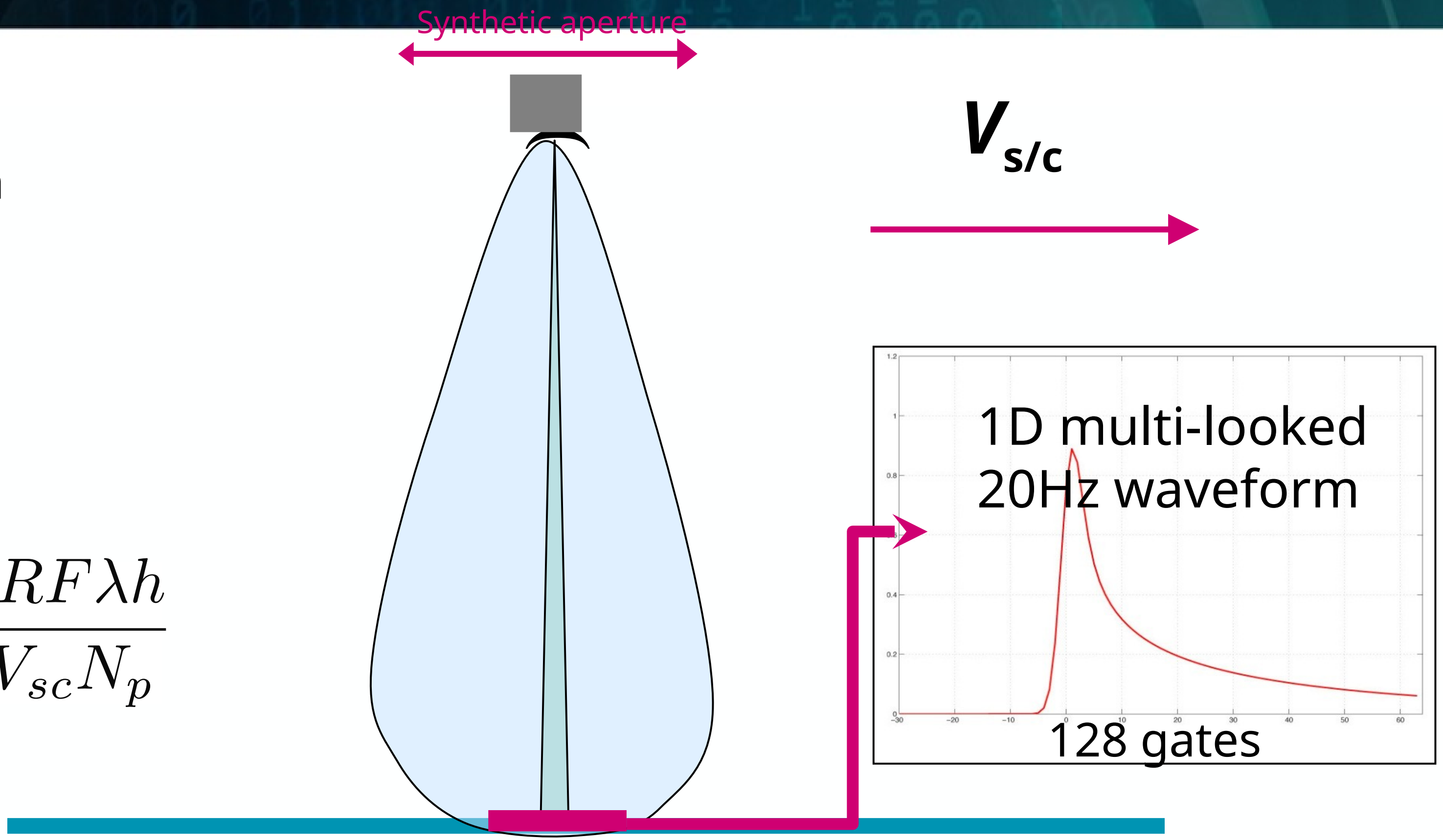

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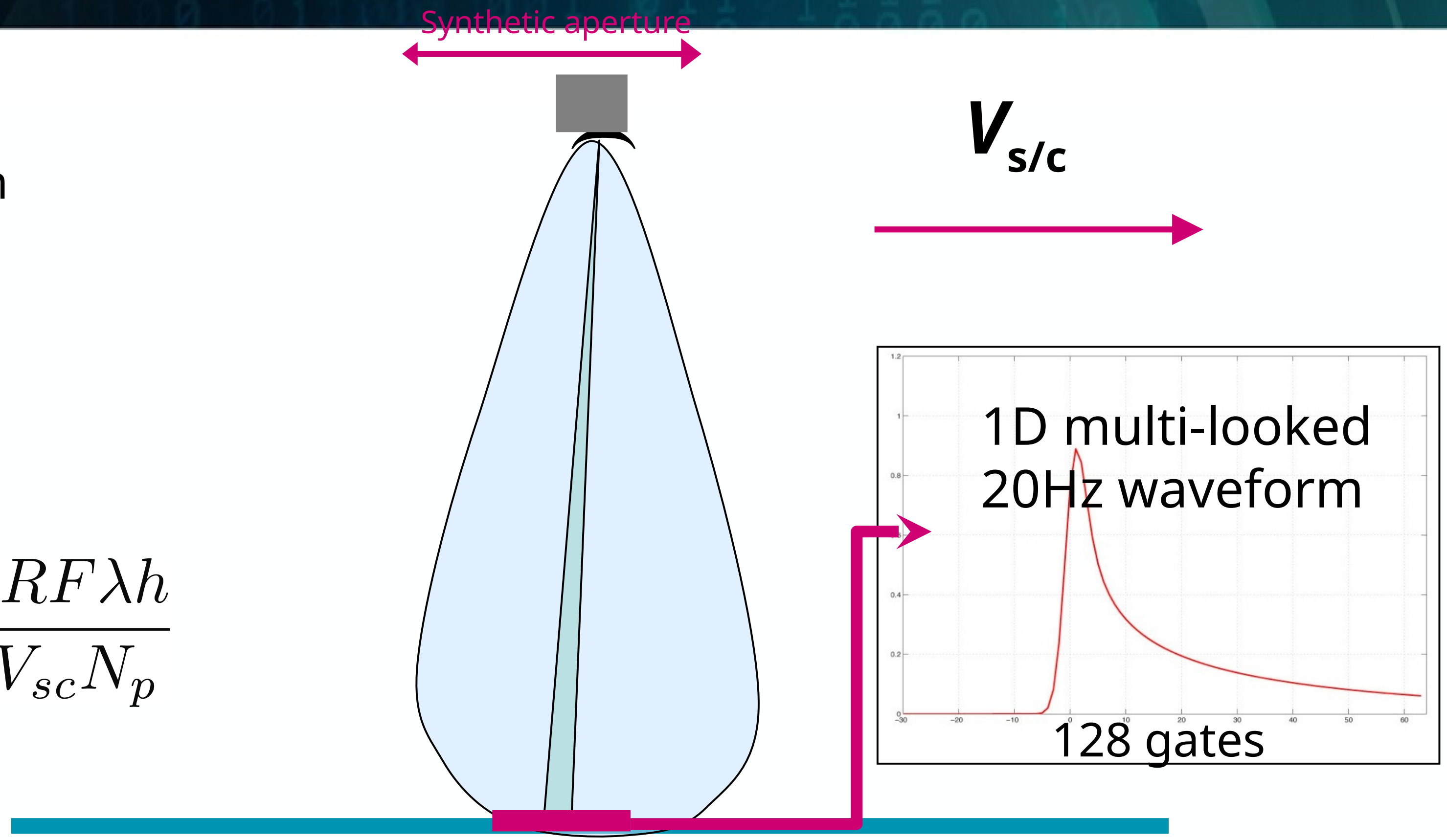

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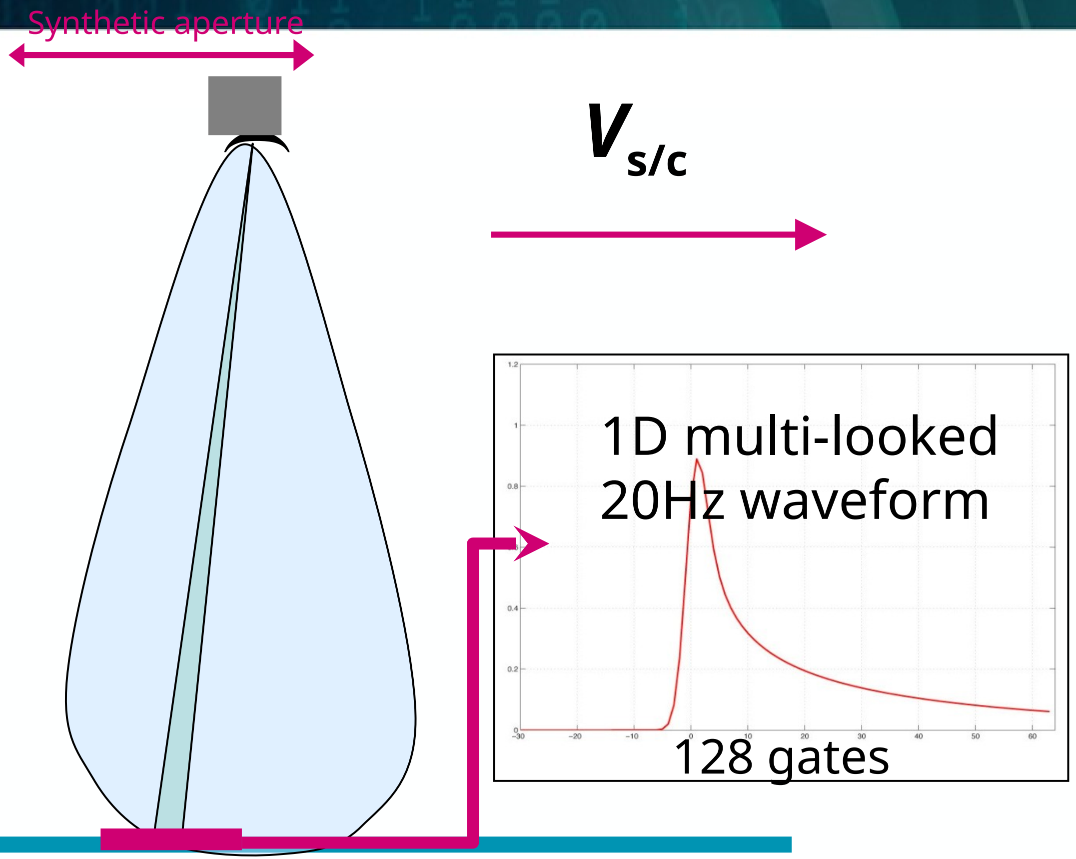

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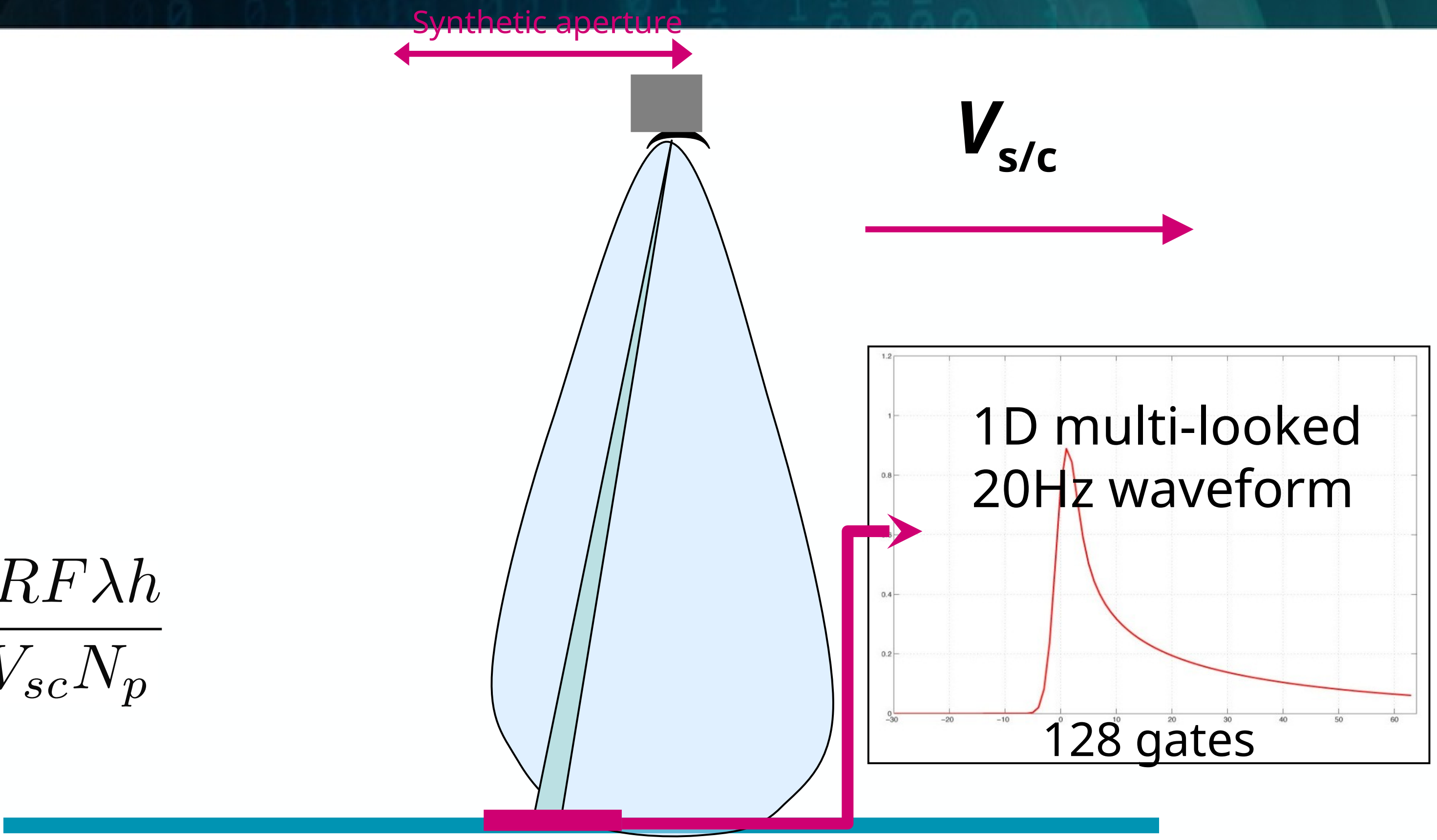

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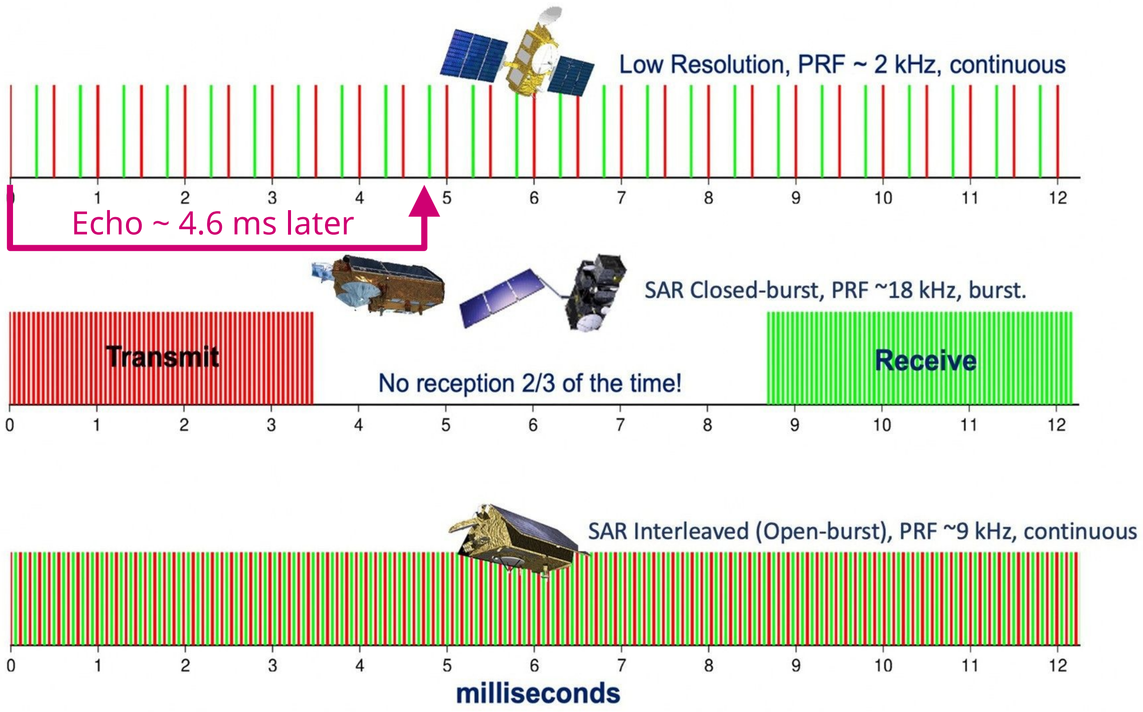
Design of pulses & bursts

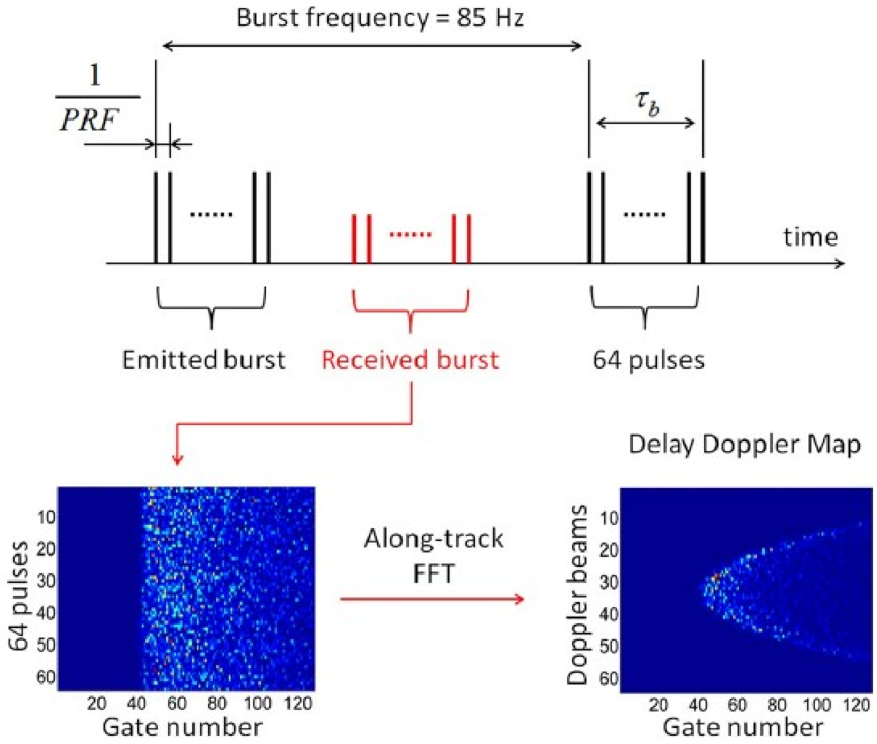
- Different satellites have different transmission schemes
- Modern satellites: interleaved pulses
- Modern satellites also offer an pseudo “low resolution mode” product
- Exercise: compute satellite distance travelled (speed is ~7km/s) for a round trip versus pulse duration



Donlon et al. 2021

Building SAR waveforms

- More involved due to moving satellite platform and burst processing
- Fast fourier transform maps received echos on along track doppler bins (64)



Halimi et al. 2014

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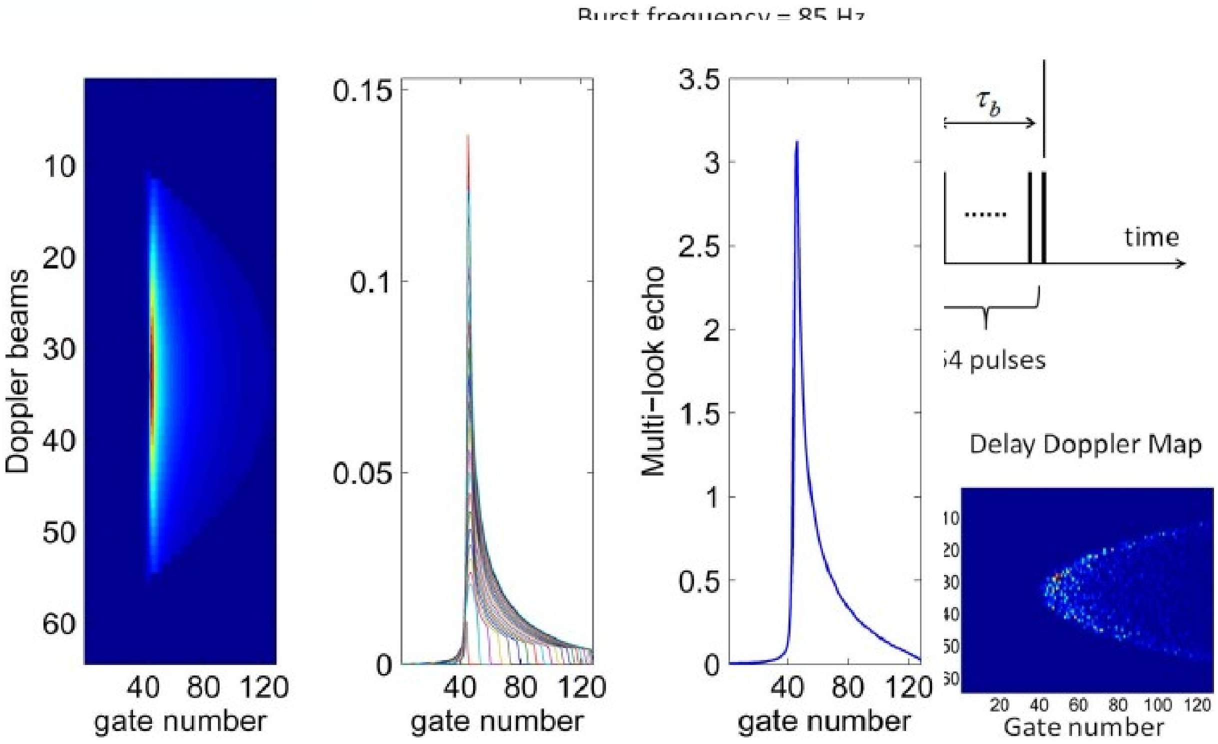
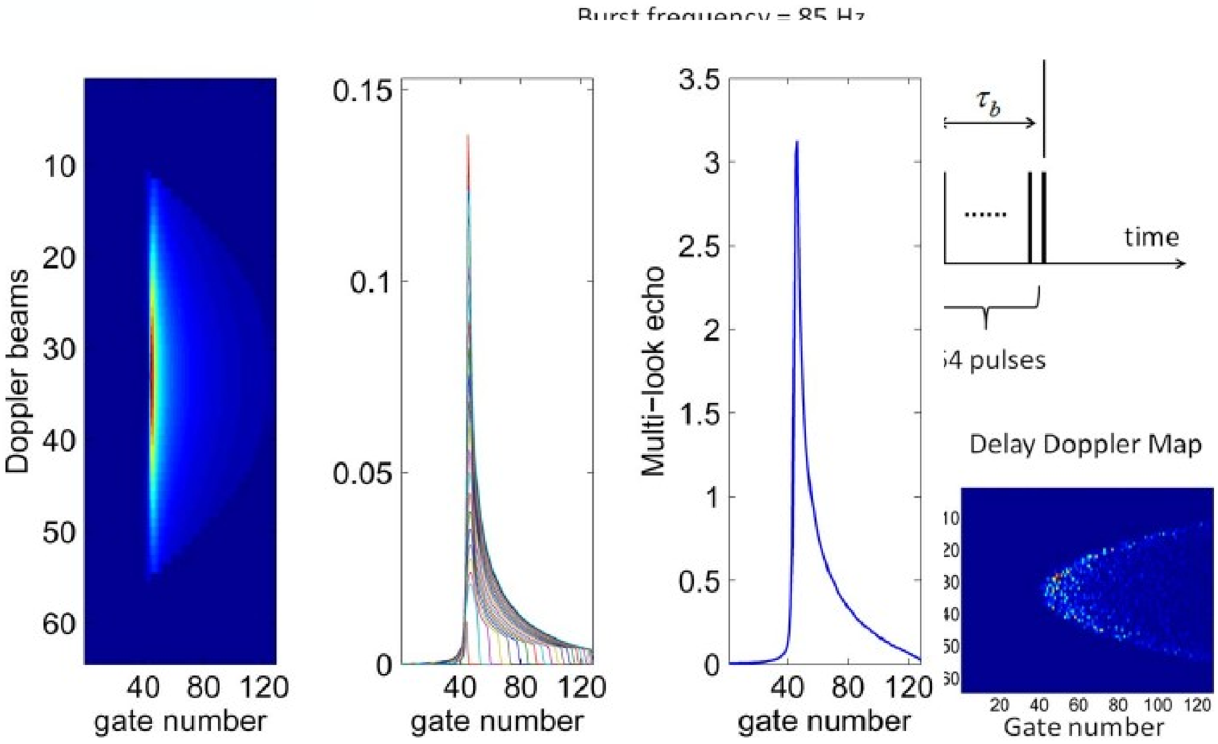


Halimi et al. 2014

Building SAR waveforms

- More involved due to moving satellite platform and burst processing
- Fast fourier transform maps received echos on along track doppler bins (64)
- Corrections for (known) target movement aligns the front
- “Multi-looking” sums sub-waveforms to increase accuracy
- SAR waveforms are generally ‘pointier’ than those from conventional pulse-limited altimetry
- Retracking methods can than be applied to estimate range

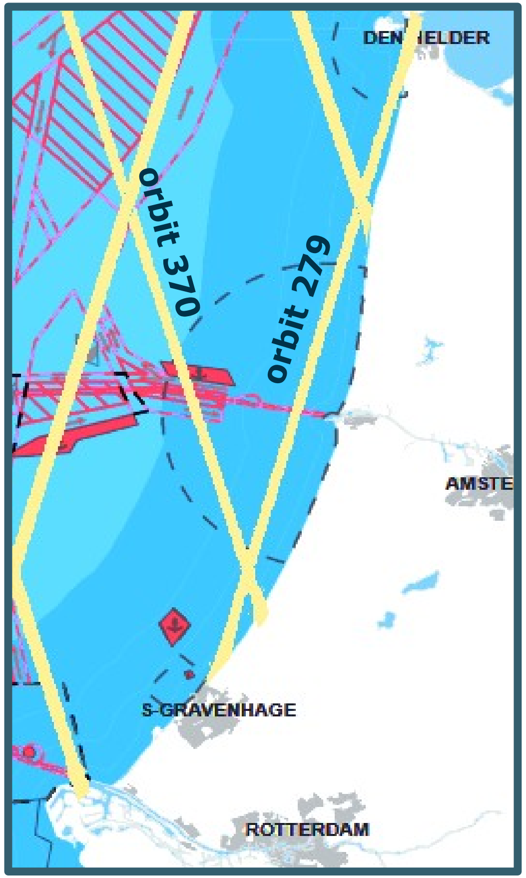


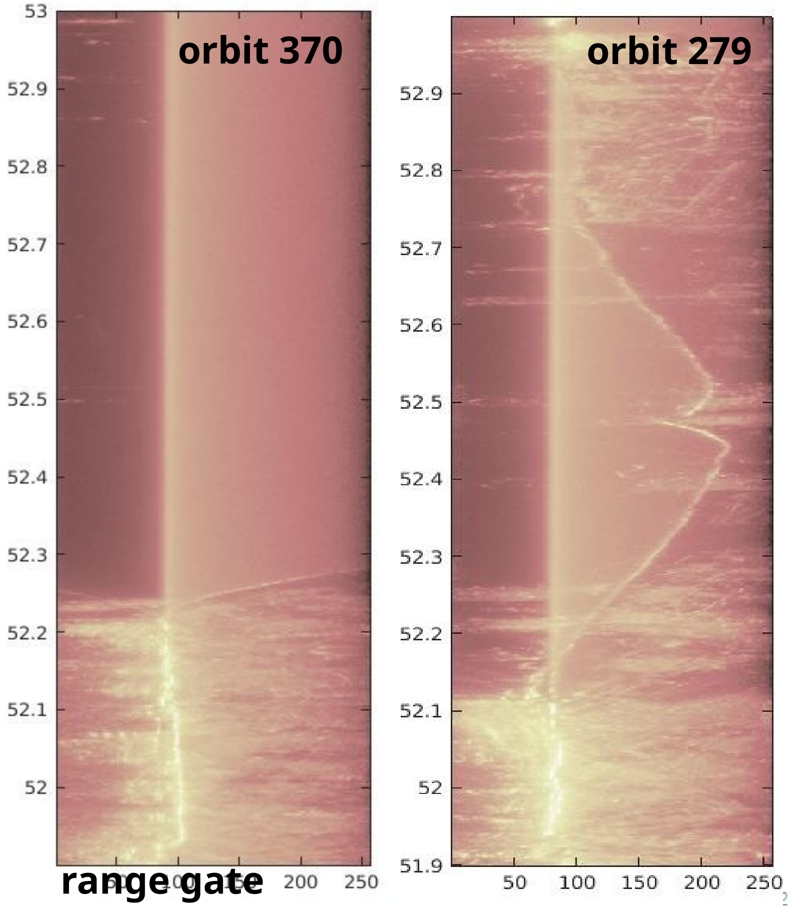
Halimi et al. 2014

Example coastal SAR waveforms

Images: Frithjof Ehlers TU Delft

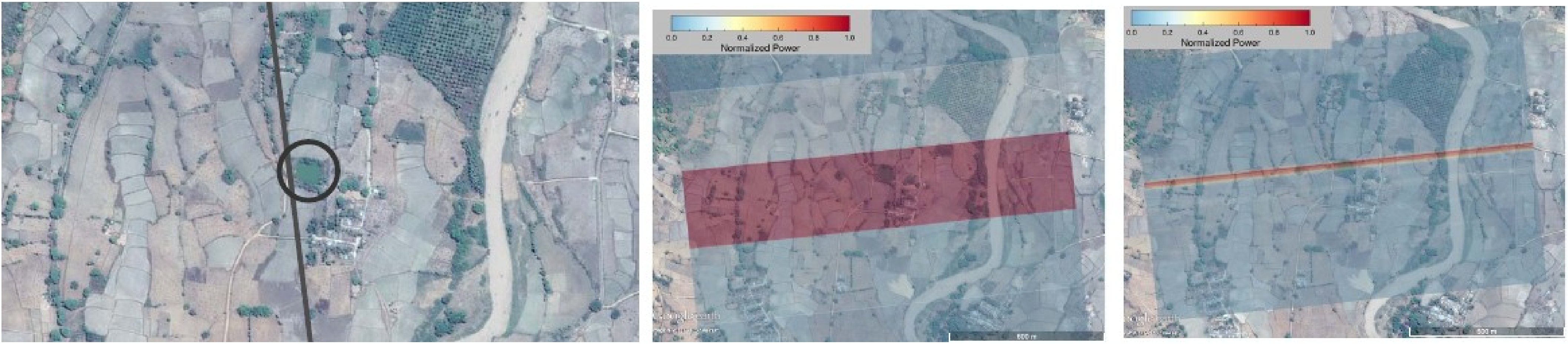
- SAR altimetry allows higher along-track resolution
- Echos come from sea but also beaches, dunes, buildings etc.
- Challenge is to retrack the hi-res waveform for correct signal of interest





Recent developments: fully-focused SAR

- Coherent targets are illuminated over ~2s (~1.4km track)
- Idea is to process echos ('focus') over a larger exposure time at once
- Larger synthetic aperture → higher along-track resolution (in theory 0.5 meter!)



From Egido and Smith 2017

Applying (Geophysical) corrections

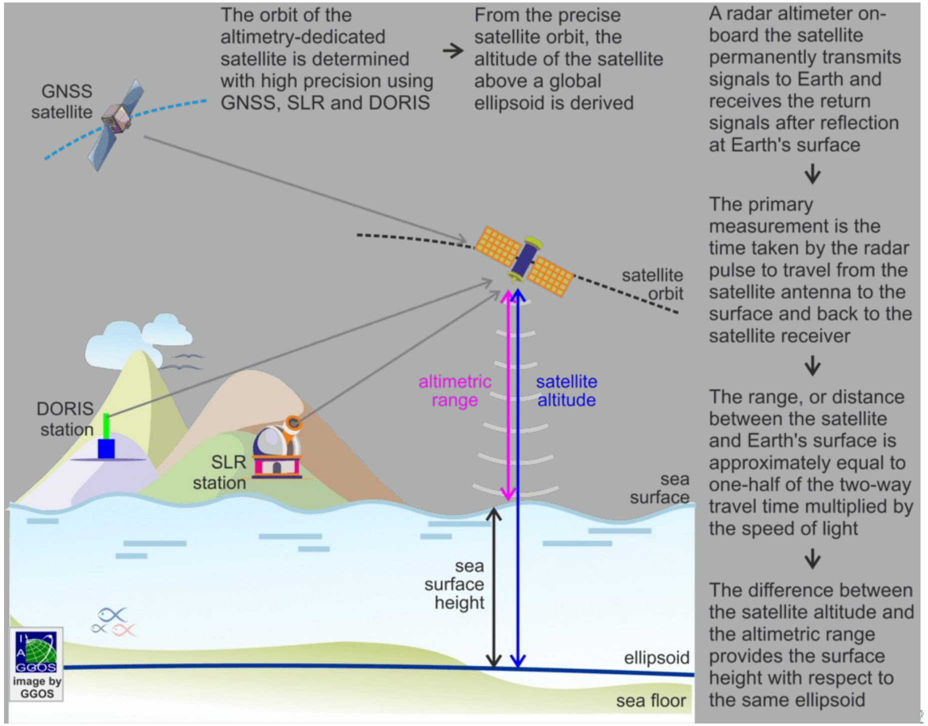
So you have range estimates, what now?

Sea (water) surface height

$$h_{water} = h_{sat} - r_{alt} \left(+ \sum h_{corr} \right)$$

$$\sum h_{corr} = -\delta h_{dry} - \delta h_{wet} - \delta h_{iono} - \delta h_{ssb} - \delta h_{tides} - \delta h_{dac}$$

- Altimetry provides heights relative to an ellipsoid
- Various corrections need to be applied

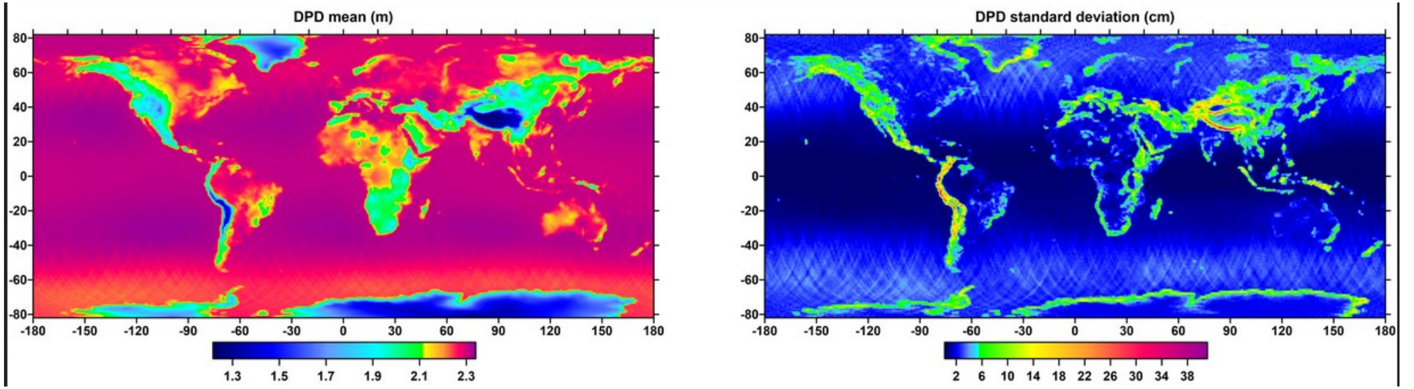


Path delay due to dry troposphere

- dry troposphere correction (DTC)
  - Absolute value ~2.3m varies by 0.2m
  - Latitude dependency
- Usually based on atmosphere model output (ECMWF, NCEP..)

$$\Delta R_{dry} \approx -\frac{0.0022768 p_s}{1 - 0.00266 \cos 2\psi - 0.28 \cdot 10^{-}}$$

Saastamoinen model depends on surface pressure, surface height and latitude



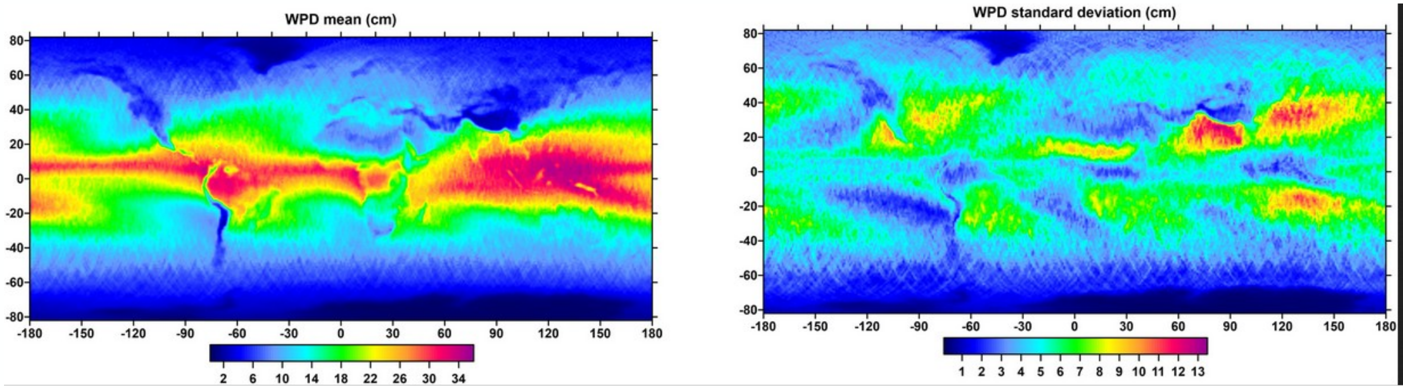
Dry-path delay from Fernandez et al. 2021

Path delay due to atmospheric moisture

- wet troposphere correction (WTC)
  - Absolute value < 50cm
  - Spatially and temporally variable
- Preferably based on onboard-radiometer data or (locally) GNSS derived watervapour
- But not all satellites carry a radiometer so for those corrections using model data need to be used

$$\Delta R_{wet} \approx -\left(0.101995 + \frac{1725.55}{T_m}\right)\frac{TCWV}{1000}$$

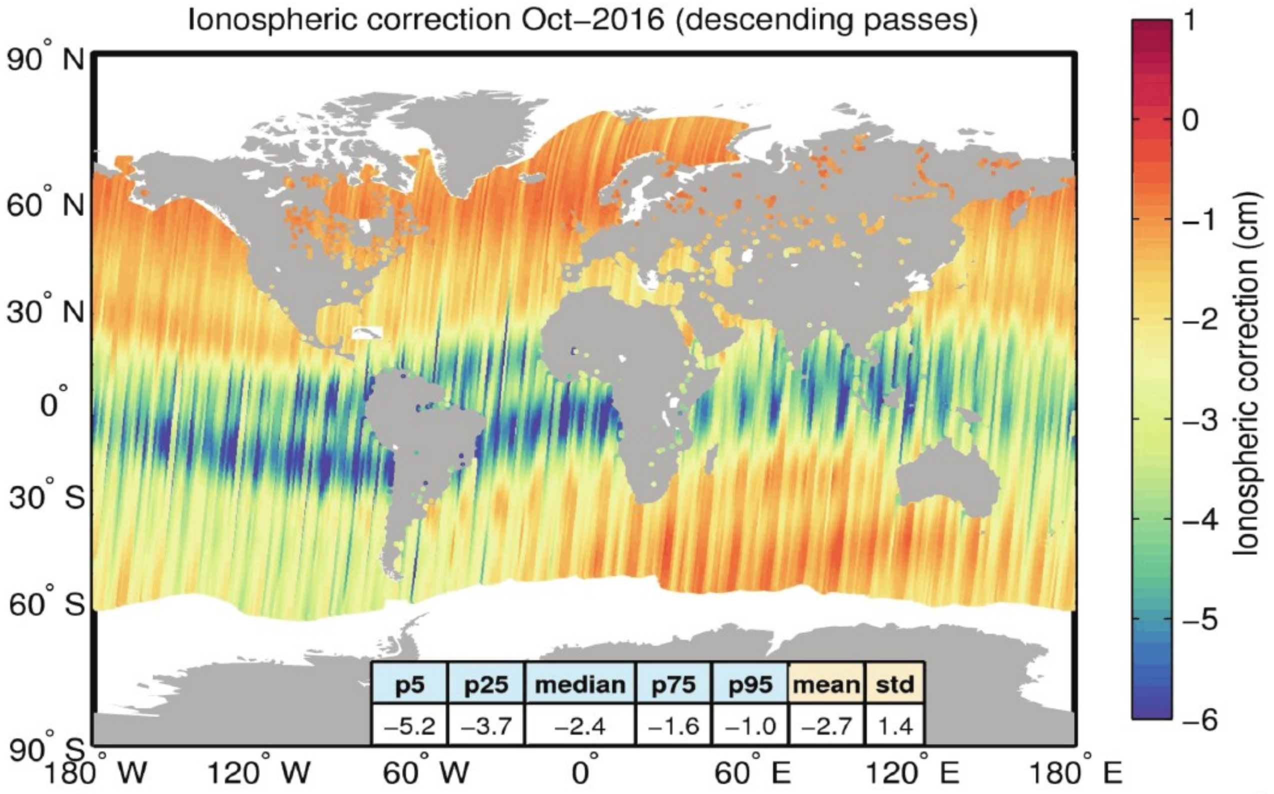
TCWV: total tropospheric water vapour,Tm: tropospheric temperature



wet-path delay from Fernandez et al. 2021

Ionospheric corrections (IC)

- Charged particles (electrons) in the ionosphere cause delays for electromagnetic waves
  - Absolute value 2 -20cm +/-2cm
  - Varies spatially (correlates with magnetic field)
  - 11 year cycle
- Strong frequency dependence allows them to be computed to first order on dual-frequency platforms (e.g. C + K band)
- Single freq satellites need corrections using ionospheric models (e.g. GIM)



p5	p25	median	p75	p95	mean	std
−5.2	−3.7	−2.4	−1.6	−1.0	−2.7	1.4

Image: Jérôme Benveniste

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Dettmering et al 2021

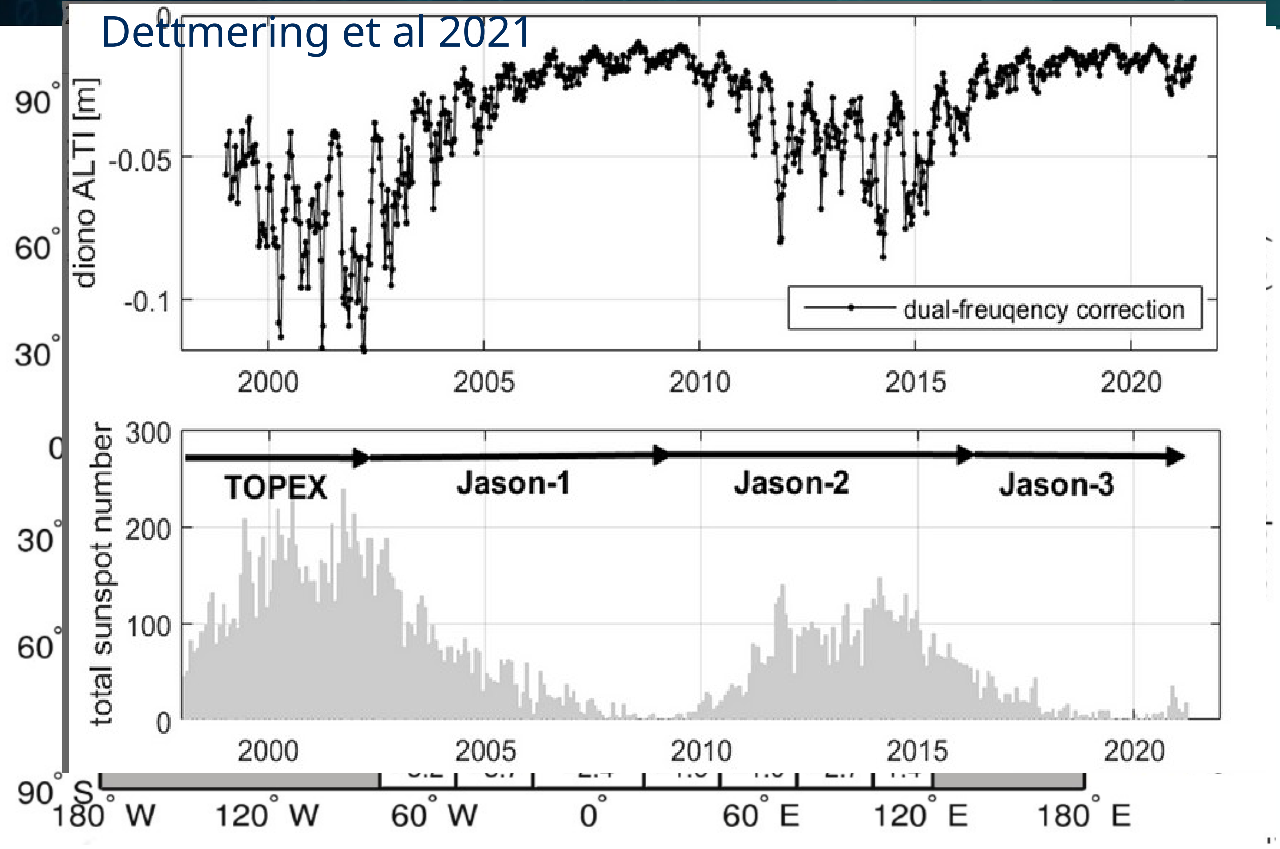


Image: Jérôme Benveniste

Sea state bias

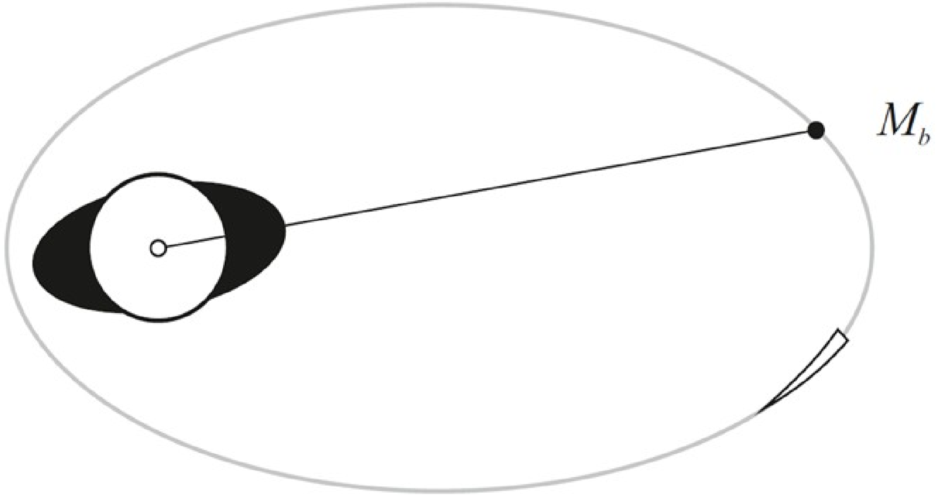
- Sea surface creates a bias towards the troughs
- Sea surface state also influences waveform retracking → tracker bias
- Skewness of waves (non-symmetry)
- Order of magnitude ~10-20 cm
- Usually corrected for with emprical models. E.g. computed SWH (from retracking), but other methods exists too (using e.g. wave model data)
- Large uncertainty for ocean applications but less relevant for inland water

Troughs are better reflectors than peaks

$$ssb \approx \beta * SWH$$

Tidal corrections

- Tidal effects
  - Ocean tides
  - Solid earth tide
  - Pole tide (~14 month fluctuations in Earth rotation)
    - Solid earth
    - Ocean
  - Tidal loading (ocean tides deforming the Earth's crust)
- Corrections, based on (empirical) models are often provided in altimetry files, not all of them may be applicable to inland altimetry
- Radar altimetry is also used to compute ocean tide models (e.g. eot20 https://essd.copernicus.org/articles/13/3869/2021/)



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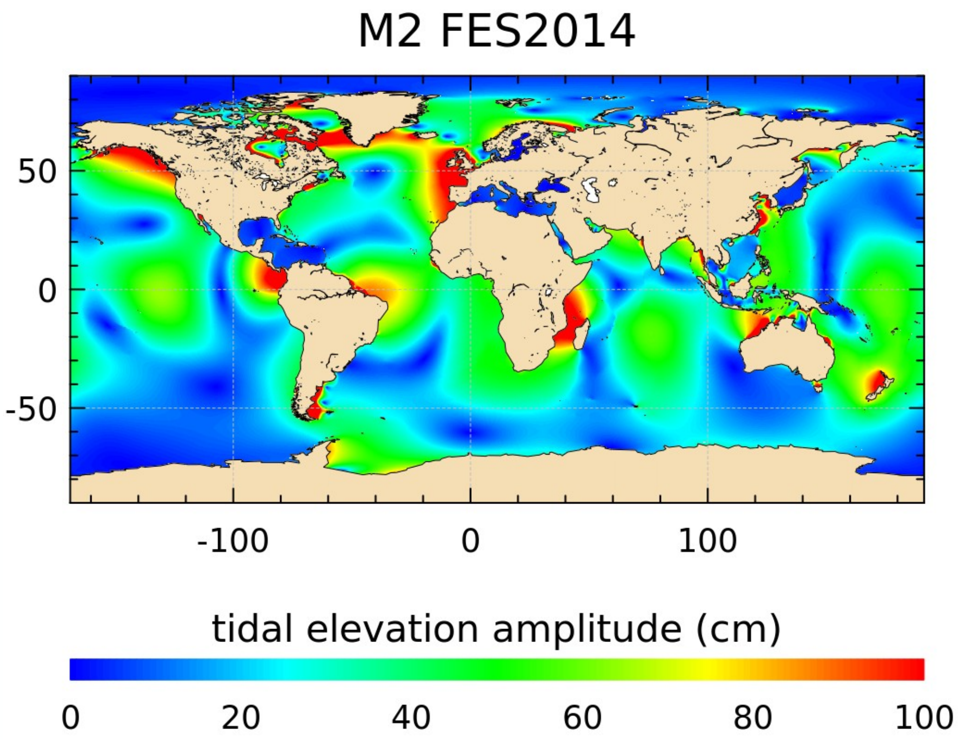


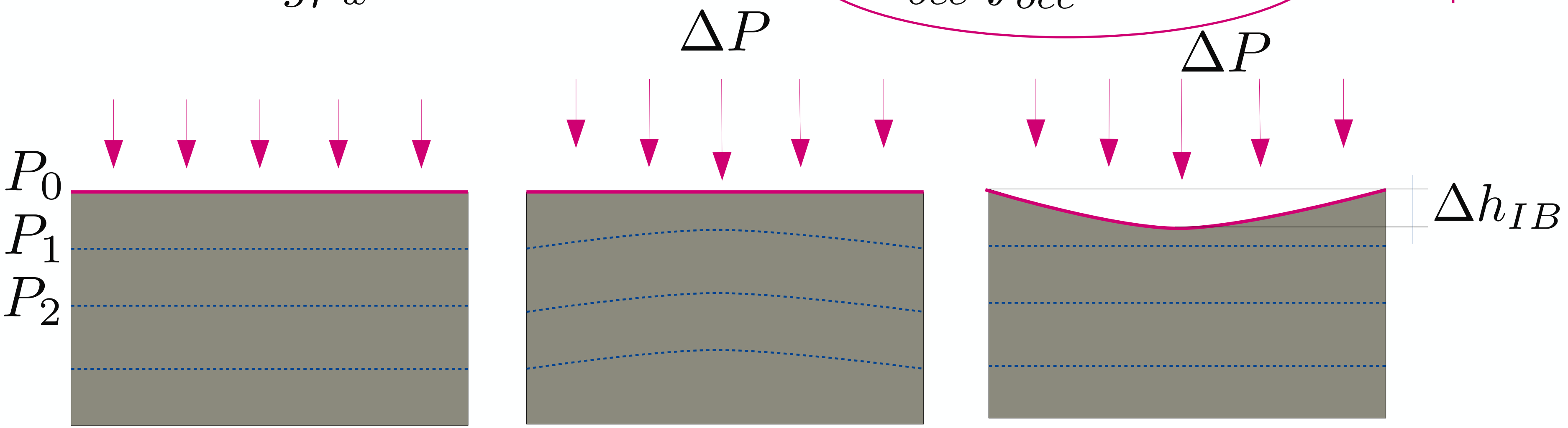
Dynamic atmosphere correction

- Short term (< 20 days) ocean response to wind and pressure (order of centimeters)

- Corrections usually provided derived from barotropic ocean models

$$\Delta h_{IB} = \frac{\Delta P}{g\rho_w}, \qquad \Delta P = P_{surf} - \frac{1}{A_{oce}} \int_{oce} P_{surf}\, d\omega$$

Averaged ocean surface pressure



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- SAR altimetry is pulse limited cross-track and beam limited along-track
- The principle of SAR altimetry is that the velocity of the satellite creates a doppler effect relative to the surface
- Standard delay doppler can achieve an along-track resolution of 300m
- Fully focused SAR can theoretically even go to 0.5 m
- In order to get meaningful surface water heigths: several corrections need to be applied
  - Wet and dry troposphere corrections
  - Ionospheric correction
  - Sea state bias
  - Tides
  - Dynamic atmosphere corrections

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Which of these corrections can be derived from onboard observations?