Radar Altimetry Theory in the Polar Ocean

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Overview

• Why: the importance for the Arctic
• What is satellite altimetry
• How to derive SSH, SWH and wind speed
• Satellite at worlds end
• Conventional (LRM) vs SAR
• Polar Ocean
Satellite Altimeters

JASON 1/2/3

Envisat

Cryosat

Sentinel 3A+3B

GFO

TOPEX/POSEIDON

SARAL
• Nadir looking
• Only one point
• PRF=2-4000 kHz
• 1 hz = 6 km
• 20Hz =300 m
• <100 m
The coverage of the sea surface depends on the orbit parameters (inclination of the orbit plane and repeat period).

<table>
<thead>
<tr>
<th>Repeating (ERM)</th>
<th>Satellite</th>
<th>Repeat Period</th>
<th>Track spacing</th>
<th>Inclination Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeating (ERM)</td>
<td>ERS1/ERS2/ENVISAT</td>
<td>35 days</td>
<td>95 km</td>
<td>98°(+/-82)</td>
</tr>
<tr>
<td></td>
<td>Sentinel 3A+B</td>
<td>27 days</td>
<td>70/35 km</td>
<td>98°(+/-82)</td>
</tr>
<tr>
<td></td>
<td>JASON 1-2-3</td>
<td>9.915 days</td>
<td>315 km</td>
<td>66.5°</td>
</tr>
<tr>
<td>Geodetic</td>
<td>Cryosat-2</td>
<td>369 days</td>
<td>7 km</td>
<td>88°</td>
</tr>
</tbody>
</table>
What can satellite altimetry provide

• Mapping sea level (and its changes and its rise)
• Sea level extremes & predictions
• Mapping freshwater storage and
• Mapping ocean currents and freshwater-fluxes
• Mapping gravity field and bathymetry
• Mapping sea ice thickness and decline (mass)
• Mapping of ice-sheet and ice-caps
• Mapping of River and lakes.

• SATELLITE ALTIMERY PROVIDE LONG TERM MONITORING AND UNIQUE SPATIAL SAMPLING.
Principle of satellite altimetry

(1) Radars transmit pulses of electromagnetic radiation at radio frequencies.

(2) The radar pulse is scattered or reflected by solid surfaces.

(3) The backscattered pulse (echo) is detected by the radar receiver.

(4) The pulse travel time is recorded.

(5) The travel time is converted into the distance (range) separating the radar and the surface.
**How: Conventional LRM (low resolution)**

**WF = FSSR * PTR * PDF**

WF : Waveform  
FSSR : Flat Sea Surface Response  
PTR : Point Target Response  
PDF : Probability Density Function of wave heights within footprint

**IMPORTANT………..**

Typical foot-print is 100-300 km²  
ALL REFLECTORS (ocean, sea ice, land) within footprint contribute to waveform. Water is better reflector than i.e. land – so will dominate…
From Power(t) to Epoch or sea surface height (waveform fitting)

- Amplitude of the signal → wind speed
- Slope of leading edge → significant wave height
- Epoch at mid-height → sea-surface height
- Waveform
Altimetric Observations

Trick:
You turn accurate time (epoch) into Range(Distance x2) and hence SSH

Based on Equation: \[ \text{Range} = \text{time} \times \frac{c}{2} \]
c is speed of light (nearly constant)

\[ \text{SSH} = \text{Height}_{\text{sat}} - \text{Range} \]

\( \text{Height}_{\text{sat}} \) is determined using GPS or DORIS/Laser ranging
Relative to the reference ellipsoid
Ellipsoid is “best” mathematical model of the Earth Shape (WGS84)
Correcting the Range.

$$SSH = H - R_{\text{ange}} - \Delta h_{\text{dry}} - \Delta h_{\text{wet}} - \Delta h_{\text{iono}} - \Delta h_{\text{ssb}} - h_{\text{tides}} - h_{ib} - h_{\text{geoid/MSS}}$$

Range correction  Surface+ Geophysical Corrections

Range is derived from the time  \( R_{\text{ange}} = \text{time} \times c/2 \)
Altimetry at worlds end

- TOPEX/Poseidon, Jason-1,-2,-3
- Geosat, GFO
- S3A S3B
- ERS-1, -2, N1, HY2,SARAL
- IceSat
- CryoSat-2 , IceSat-2

Global sea level estimates leave out the Arctic Ocean (Jason based)
The Arctic Ocean

Conventional altimetry is frequently contaminated in the presence of sea ice due to the large footprint.
Conventional:
Jasons, SA, ERS+ENV + HY
SAR altmeters
Cryosat-2, S3A+3B
Next generation
S6 (2020) Both
SWOT (Ka SAR-in)
S9 (multifrequency)
Cryosat-2 not SAR everywhere
Modemask controlled by 80% Arctic
Sentinel 3A+3B only SAR
Surface of the waveform footprint

Radius of the waveform footprint (km)

ERS-1  ERS-2  Topex  P-1  J-1  RA-2  J-2  CS-2 LRM  CS-2 SAR  HY-2  AltiKa  S3 LRM  S3 SAR

Surface of the waveform footprint (km²)
Far smaller change that SAR altimetry is contaminated due to smaller footprint

Notice: All reflectors within footprint contribute to waveform
Maximum precision (minimum SSH std) =>
maximum number of uncorrelated looks

Smaller $X_{Dop}$ implies larger number of looks per second $N_{sec}$

...but of course there are other considerations and trades
Delay/Doppler ~ x2 better than conventional
Unfortunately

Low Resolution Mode

SAR Mode

SARin Mode

PRF 1970 Hz

PRF = 17.8 KHz

PRF Burst 85.7 Hz => 11.7 ms

Tracking low bandwidth mode FFT 128 points

PRF Burst 85.2/4 = 21.4 Hz => 46.7 ms

Tracking Time = 30 ms

TRACKING CYCLE
Polar Ocean – Arctic Waveforms
Waveforms in the Arctic

Arctic waveform

Ocean waveform

Data provided by CLS/CNES
Classification

Pulse Peakiness (PP)

\[ PP = \frac{65535}{\sum_{i=0}^{127} p_i} \]

Francis (1991), Laxon (1994), and Stenseng (2014a)
C2+S3 Additional Classification using multi-look “stack” (SAR)

Sea ice

Lead in sea ice
Waveforms in the Arctic

Arctic waveform

Ocean waveform

Data provided by CLS/CNES

Computing the Std of the looks (Stack Std Dev)
Classification

Ocean

Sea ice

Leads
Retracking

- SAMOSA3 Physical retracking.
- SAMOSA3L adapted for Leads
- Yields 3 parameters (h, swh, s0)
- If only height is required
- Simple EMPERICAL retrackers
- Results in more data and is
- Preferred due to processing time
Example: Empirical Threshold Retracking

\[ P_b = \frac{1}{5} \sum_{i=m-2}^{m+2} p_i \]

\[ E = \frac{F_T \cdot P_b - p_{j-1}}{p_j - p_{j-1}} + j - 1 \]

Davis (1997) and Stenseng (2011/2014a)
Application: Precision and Accuracy

Precision by radar design (basically the std of ssh).

Accuracy is dependent on range corrections (ability to re-measure ssh).

<table>
<thead>
<tr>
<th>Oceanography + Climate</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice-sheet topography + dynamics</td>
<td>Accuracy and Precision</td>
</tr>
<tr>
<td>Gravity &amp; Bathymetry</td>
<td>Precision</td>
</tr>
<tr>
<td>Mean Sea Surface</td>
<td>Precision and Accuracy</td>
</tr>
<tr>
<td>Seaice-Freeboard</td>
<td>Precision and Accuracy + Geoid</td>
</tr>
<tr>
<td>Mean Dynamic Topography</td>
<td>Precision and Accuracy + Geoid</td>
</tr>
</tbody>
</table>

Need highest precision for many purposes
Precision is determined by radar design.
Higher precision than today requires higher PRF and or Open burst or alternative processing (Smith) ?

K. Raney
Range accuracy

Arctic Sea Level trend (68°N – 82°N)

Average linear trend 2.2 mm/year. Large inter-annual variations (AO driven).
The accuracy of the geoid height/slope determines gravity accuracy and hence the bathymetry prediction accuracy. Hence range PRECISION is the important quantity.
DTU15 MSS and Free Air Gravity

Stenseng et al. (2013/2014)
Open issues – Future research

- Sampling (lack of data - Seasonality)
- Snagging + Swath processing
- Snow on Sea ice (next presentation).
- Ocean tides
**Seasonality**

**Western Arctic:** Through retracking (ALES+ or more tolerant editing) the number of available data increases a lot.
Snagging and (SARin)

- Bright off nadir like Leeds dominates
- Range to target longer $\rightarrow$ surface lower
- Cross-track angle from SARin
- Caviat: Lover precision.
  - Only 1 burst per radar cycle (vs. 4 in SAR)
Swath processing (SARin and SWOT)
Freeboard and snow on sea-ice

Diagram illustrating the detection of snow and ice freeboard using radar and laser measurement techniques.
We need better Arctic Ocean Tides
**Sampling and Accuracy**

**Tide Gauge:**
High temporal sampling

**Satellite altimetry:**
low temporal sampling
=> Aliasing

"Critical Sampling" (cryosat-2 vs annual signalers/envisat/saral/hy-2 vs S2)"
Sampling:
The FUNDAMENTAL Arctic Problem is Alias Periods

<table>
<thead>
<tr>
<th>Tides</th>
<th>Tidal Period, hours</th>
<th>ERS/ENVISAT SARAL (35 day)</th>
<th>TOPEX/POSEIDON 10-Day Repeat Orbit</th>
<th>Cryosat-2 (369 day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₂</td>
<td>12.42</td>
<td>-95</td>
<td></td>
<td>20.1 years</td>
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<tr>
<td>S₂</td>
<td>12.00</td>
<td>∞</td>
<td>-59</td>
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<td>N₂</td>
<td>12.67</td>
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<tr>
<td>K₂</td>
<td>11.97</td>
<td>183</td>
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<tr>
<td>O₁</td>
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<td>P₁</td>
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<td>Mₘ</td>
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<tr>
<td>M₇</td>
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<tr>
<td>Sₘₕ</td>
<td>4383.00</td>
<td>183</td>
<td>183</td>
<td></td>
</tr>
</tbody>
</table>

Actually
All > likely lifetime
Of Cryosat-2.
Questions?
If you are still awake!
Bibliography

Validation: IceBridge

Stenseng, 2014b and Dominguez, 2014
Validation: IceBridge
Leads in aerial photos and CryoSat-2 data

- Detected ~80% of leads >500 m²
- LiDAR observations ~4 cm std. dev.
- Mean difference 0 cm Only 34 collocated observations

Stenseng
(2014b)