Tracking and Retracking

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Outline

• On-board tracking is built into the instrument
  – Why is it needed?
  – What are the consequences?
• Examples of coastal waveforms
• Why and how of retracking
• Various approaches to retracking
• Caveats and conclusions
Why on-board tracking? -1

Instrument bandwidth limits the precision in a single range measurement to about 50 cm.

The single-measurement signal-to-noise ratio is 1:1.

Conventional altimeters use "incoherent averaging" to achieve better SNR and finer precision.

This requires two things:

1. Signal must remain aligned during averaging (the instrument must be "tracking" correctly).

2. Measurements must be uncorrelated; pulse repetition frequency limited to ~2.5 kHz or less. This is NOT true of an instrument using SAR processing, e.g. CryoSat-2, Sentinel-3, NEWEX, Water/HM.
1 Averaging Waveforms: What are individual/burst echoes

- Traditionally altimeters have averaged a certain number of IEs together to both reduce the noise and reduce the bandwidth needed.
- For Envisat 100 IEs are averaged and waveforms processed onboard at 18Hz.
- But every 180 seconds Envisat can send to ground 1.141 seconds of individual echoes (20 AE waveforms).
- The first 16 IEs cannot be retrieved resulting in 1984 IE per burst.
Burst Echo distribution for cycle 33

Distribution changes month by month, but remains locations are almost constant
Typical ocean waveform

- Top shows averaged waveform
- Bottom shows IEs for this waveform cycling through. Some averaging is required for a Brown model fit.
Why on-board tracking? -2

Both the orbit and the Earth are elliptical. This causes the range between instrument and target to move by \( \sim 25 \) m/s. An on-board "tracker" forecasts the expected range and range-rate to align successive pulses for averaging.

If the statistical properties of the reflecting surface (wave height, sigma-0) and range and range-rate have been smoothly varying for 2 to 3 seconds, then the forecast of the track point will be fairly accurate, and the received waveforms may be averaged properly. (Jason-2 may forecast via real-time orbit and elevation model look-up; instruments to date use the "tracker" to follow the past history of recently measured range values.)
On-board tracker effects

A resonance around 0.4 Hz amplifies noise (& signal) at a period of ~2.5 seconds, or 14 to 18 km wavelength.

The group delay is ~0.25 sec for signals of interest; this shifts features down-track 1.5 to 1.7 km.

The noise appears smoothed but is correlated along-track in the on-board-tracked range data. Retracking whitens the noise. (63 mm vs. 70 mm @ 10 Hz.)
The available waveform

The on-board tracker's forecast of \( r, \frac{dr}{dt} \) are used to average pulses received over \( \sim 0.05 \) s.

The average waveform (shown here) is used on-board to update the tracker's forecast.

Usually only this average waveform, available at 20 Hz sampling rate, is available to us for further processing.

Noise is always proportional to power. The waveform has this simple shape only if the reflecting surface is statistically homogeneous (all ocean, not mixed w/land).
"Simple" (Brown model) waveform

If the reflecting surface is homogeneous (open ocean, not coastal, no rain or $\sigma_0$ bloom), the antenna is simple, and the antenna mispointing is small, then a 5 parameter ("Brown") model adequately fits the waveform.

Arrival time yields range. Rise width yields SWH. Amplitude and AGC yield $\sigma_0$. Plateau decay yields off-nadir pointing.
Land contamination in the waveform adds returned power with different $\sigma_0$ and range, altering waveform shape, perturbing tracker

Proximity of effect depends on land height and $\sigma_0$ and is different at Ku, C, L and Ka bands. Thus dual-$f$ iono and SWH estimates also affected.
Where in the waveform the land contamination appears depends on the height and areal extent of the land, as well as its proximity to the nadir point.

How the waveform is affected depends on Area_{Land} times \sigma_{0,\text{Land}} relative to Area_{Ocean} times \sigma_{0,\text{Ocean}}. If \sigma_{0,\text{Land}} < \sigma_{0,\text{Ocean}} (often true), the effect can be small. In some environments, however (coral atolls) \sigma_{0,\text{Land}} > \sigma_{0,\text{Ocean}} & the effect is large.
Coastal zone waveform

- Top: averaged waveform just off coast.
- Bottom: IEs cycling through.
- Both coastal and inland water waveforms show more coherent features than their ocean counterparts.
When the land returns less power than the water, the waveform plateau drops (as here). This island is small so the ocean can be tracked very close to the coast (< 1 km). But this is not always true.
Examples of coastal and hydrologic waveforms
(Ku and C bands)

Next slides illustrate the great diversity of waveforms near the coasts and over the hydrologic basins.

They also illustrate:

- the Ku / C relationship
- how sometimes, waveforms are modified from 20 km of the coastline
- how sometimes, nominal waveforms are observed even very close to the coastline (over Rennes Lake for example)
- the dynamic of the signal (how they are progressively corrupted)

A retracker designed to recover range, SWH and $\sigma_0$ from coastal or inland water environments will need to be able to adapt to all of the diverse waveform shapes shown in the next slides.
Jason-1, C188, P85, Ku band

Senetosa calibration site

Measure 1

Measure 50

5 km
Jason-1, C188, P85, C band

Measure 1

Senetosa calibration site

Measure 50

5 km
Jason-1, Cycle 188, Pass 37 (over Chile), Ku band
Jason-1, Cycle 188, Pass 37 (over Chile), C band
Jason-1, Cycle 188, Pass 76 (over Canada), Ku band
Jason-1, Cycle 188, Pass 37 (over Amazonia), Ku band
Jason-1, Cycle 188, Pass 76 (over Rennes Lake, Canada), Ku band
Jason-1, Cycle 188, Pass 76 (over Rennes Lake, Canada), C band
Quasi Specular components

- Coast on the left (starting 50km away on right)
- Waveforms appear free of distortion at first.
- The distinct parabola shape component is caused by an off-nadir bright/still target such as a river or harbour
Multiple Quasi-Specular components

- A large amount of contamination with multiple quasi-specular targets
Bursts over the Congo Basin I

33/Dec 2004

34/Jan 2005

36/Apr 2005

37/May 2005
Congo

Ortho_h of burst echo and 18Hz equivalent over Congo Basin

E.A.P.R.S.
**Motivation**

**Data**

**Method**

**Results**

**Conclusions**

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**GOAL:** Coastal altimetry in MED

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Figure 1. Envisat tracks and tide gauge stations with monthly data from PSMSL (square) and with hourly data from local organisations (circle). Bathymetry and elevation from GEBCO.
RECOSETO PROJECT AREA / WEST MED

**GOAL:** Coastal altimetry

Figure 3. Location of Topex/Poseidon and ERS-2/Envisat tracks in a sub-region
Topex JPL-re-tracked data wrt GDR (1Hz)

Figure 4. Genova, left: selection criteria and flags (Table 1, 2), right: selection criteria from table and no flags applied.
Error in bathymetry? (distance to coast?)

2 bathymetries ... →

Ligurian Coast (Genova)
Error in bathymetry? (distance to coast?)

... and their difference
What is retracking?

Retracking is modeling the returned waveforms to estimate parameters (range, SWH, $\sigma_0$, attitude). It is done on the ground, after the data are acquired. ((Full waveform data may be available only after real time -- 1 to 3 days?)
Potential benefits of retracking

Reduced noise level, decorrelation of noises, and recovery of data closer to land.
ERS-1 Geodetic Mission
Flat-patch echoes around Indonesia

Ruffled water in coastal regions or with the presence of islets.

Material for Coastal Zone workshop 2008
Simple Multi-target response

Multiple brightly reflecting surfaces within the altimeter footprint.
Complex Multi-target response around Indonesia from ERS1 GM

- Combination of ocean component and rough terrain.
Quasi-specular echoes around Indonesia from ERS1 GM

- Caused by harbours, estuaries and other still water bodies.

Material for Coastal Zone workshop 2008
Comparison with OPR

Intensity of blue indicates quantity of additional data in EAPRS system.

In addition to coastal zones, areas with a high concentration of very low sea state are also flagged in RADS.
Counts of waveforms shape in coastal regions (excluding cryosphere) binned by distance from coast.

Show a high concentration of non-ocean like waveforms ramping up from 12km to the coast.
Quality of Envisat waveforms significantly increases the percentage of waveforms classed as ocean-like.

Additional complication of dynamic mode switching means a direct comparison cannot easily be performed.
Types of retrackers

"Simple" retrackers:

• Fit a Brown model to each waveform independently.
• Maximum likelihood weighting increases noise in SSH!
• (Is this the standard ocean data product?)

Constrained (smoothing) retrackers:

• "Simple" retracking with constraints added to reduce SSH noise.
• Reduce freedom in other parameters, introducing along-track correlation in other variables.

Adaptive retrackers:

• Fit different models to different waveforms.
• May recover data from heterogeneous surfaces (coast).
• Track point bias (height calibration) and SSB can change.
Errors retracking range & SWH, 1

Noise is proportional to power in altimeter waveforms, and so is *asymmetrically* distributed around the track point. This inevitably causes *correlation* in the random errors in range and SWH estimated by retracking. Some of the SSH random error is "leakage" of SWH random error.
Maximum likelihood parameter fitting, by down-weighting the plateau region, actually makes this correlation worse, and results in typical uncertainties in range of 3.9 cm, for a 1-Hz average at 2 m SWH. (This is a zero-mean error, not a sea state bias error.)
Constrained (smoothing) retrackers

Smith and Sandwell use a two-pass process with explicit along-track smoothing of SWH, $\sigma_0$, $\xi^2$.

Rodriguez and Callahan implicitly smooth: degrees of freedom @ 20 Hz in range, but 1 Hz in SWH, $\sigma_0$, $\xi^2$.

Maus and Fairhead use an along-track smoothing spline to constrain SWH, $\sigma_0$, $\xi^2$.

Others?

Standard retracking, with freedom in all parameters @ 20 Hz, has higher noise levels, and even worse when SMLE (maximum likelihood) weighting is used.
Repeat profiles

The overall rms error in range can be cut by 40% if other parameters have their degrees of freedom restricted, by smoothing them along-track.

For $\sigma_0$ and maybe SWH this is not a good assumption at the coast.
On-board tracker effects

A resonance around 0.4 Hz amplifies noise (& signal) at a period of ~2.5 seconds, or 14 to 18 km wavelength.

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Adaptive retrackers

Brown echos

Peaky echos

Noisy echos

Large peak echos

Linear echos

Attempt to model all waveform shapes, not only the Brown model shape expected of a homogeneous ocean surface.
Waveforms processing in PISTACH, CNES project

PISTACH is an example of "adaptive tracking"
Waveforms classification

Class 1
Brown echos

Class 2
Peak echos

Class 3
Very noisy echos

Class 4
Linear echos

Class 5
Peak at the end echos

Class 6
Very large peak echos

Class 12
Brown + Peak echos

Class 23
Peak + Noise

Class 13
Brown + leading edge perturbation

Class 24
Brown + Peak + linear variation

Class 15
Brown + increasing leading edge

Class 21
Brown + Peak echos

Class 35
Leading at the end + noise

Class 16
Brown + strong decreasing plateau

Class 99
??

Class 0

Doubt

CS 32
Noise reduction on the waveforms (from A.Ollivier’s PhD Thesis)

Main benefits:

- **Reduction of the standard deviation of the estimates**: The SVD filtering allows (for SSH) a reduction ratio from 1.2 (for small SWH) to 2 (for higher SWH). For SWH=8m, the SSH Std goes from 14 cm without SVD filtering to 7 cm with SVD filtering.
- **Resolution gain**: The SVD filtering allows to go from a 7 km resolution (actual 1Hz sampling) to a 1.2 km resolution (6Hz) with the same precision on the SSH.

⇒ **Work under progress**
Retracking algorithms

PISTACH will process waveforms with several retracking algorithms (in //)

- Retracking with analytical formulation
- Empirical model retrackers (beta-retrackers,
- Retracking without models (EDP, Offset Centre of Gravity, Median, …)
- …

- Need of intercalibration between output
- Analysis of the dependancies between parameters
- …
Tracker sea state bias (SSB)

Ideally, the track point of a tracker or retracker detects the median of the vertical distribution of radar scatterers (in a Brown model waveform).

If the distribution of scatterers is not equal to the sea surface height (SSH) distribution, we can have an "electro-magnetic (EM) bias".

If the SSH distribution is skewed, the median does not equal the mean and we have a "skewness" bias.

However, empirical estimates of SSB show dramatic changes when the tracking algorithm changes. We must keep this in mind when considering adaptive trackers. (Both PISTACH and P. Berry's group are trying to do account for these changes in track point.)
Sea state bias examples

Empirical SSB of on-board-tracked SSH (left), and retracked SSH (right). Changing the tracking method changes the SSB. Implied: the absolute height calibration also changes?
Conclusions, on-board tracker

Conventional altimeters require some form of on-board tracking to permit the alignment of successive returned pulses for averaging.

Under ideal conditions (homogeneous reflecting surface changing only slowly) the on-board tracker introduces correlated errors, noise resonances, and delays. These can be mitigated by retracking.

Over heterogeneous or rapidly changing surfaces (e.g., mixed land and water) the on-board tracker will be biased, waveform averaging will be non-ideal, and data may be lost. Where not lost, retracking will be needed.
Coastal waveform conclusions

Land may alter the shape of ocean waveforms when the nadir point is within 20 km (10 km typically) of the coast. If the coastal land is not mountainous and $\sigma_0$ is low, the waveform distortion may be mild until quite close to the coast, and simple (Brown model) retracking may work*. Adaptive retracker can recover data under a variety of conditions on land and ice as well as ocean, and these can be used where the simple Brown model fails.

*For discussion: are other problems (wet delay, tides, ?) more serious than retracking under these conditions?
Conclusions, retracking - 1

The following applies to retracking everywhere, whether in the open ocean or the coastal zone:

1. Waveform noise introduces random errors in estimated parameters (range, SWH, $\sigma_0$, attitude).

2. These estimation errors are inevitably correlated (among one another, not necessarily along-track).

3. Noise in one parameter (e.g., range) may be reduced by restricting the degrees of freedom, at the expense of enforcing along-track smoothness in another parameter (e.g., SWH).

   Along-track smoothness of parameters (other than attitude) is certainly wrong at the coast.
Conclusions, retracking - 2

Retrackers that adapt to changing waveform shapes will enhance data recovery close to the coast, however:

1. Loss of information in the plateau region will degrade estimates of $\sigma_0$ and attitude, and is likely to change the bias in estimates of range and SWH.

2. As a consequence of 1, the SSH bias and the Sea State Bias may be unknown and may have jump discontinuities whenever the adaptive tracker branches to a new waveform shape or type.