Performance evaluation of the Amplitude Compensation and Dilation Compensation retracking algorithm

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Alba Granados[1], Mònica Roca[1], Chris Ray[1]

[1] isardSAT S.L., Barcelona, Catalonia

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NOTES: This work is the analysis of the Amplitude Compensation and Dilation Compansation (ACDC) retracking algorithm with S3A Delay-Doppler altimetric data, previously tested with CryoSat-2 data showing good performances compared to the in-house conventional open ocean retracker DeDop-Waver (Makhoul *et. al*, 2018). This work was developed within the Sea State Climate Change Initiative (CCI) project.

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Introduction

- Aim to improve the precision of geophysical parameter estimates (SSH and H_s) retrieved from open ocean Delay-Doppler altimetric echoes.
- The Amplitude Compensation and Delay Compensation (ACDC) strategy is proposed as a solution as it leads to an improved signal-to-noise ratio and speckle reduction by performing an effective equalisation of the stacked waveforms.
- An in-house Delay-Doppler Processor for Sentinel-3 altimetric data has been ajusted to include the ACDC algorithm at stack level.
- Specific processing blocks have been reviewed, namely:
  - new strategy of selection of the initial estimates epoch/H_s,
  - thermal noise estimation
- The performance of the retracker is evaluated in terms of the geophysical parameters SSH and H_s with S3A altimetric data and compared against operational L2 products and isardSAT's in-house conventional SAR altimetry retracker for open ocean (DeDop waver).

NOTES:

This retracking approach compensates the waveforms at each Doppler look of the orginal stack for both variations in amplitude (AC operation) and dilation (DC operation) in range. Hence, an effective equalisation of the different waveforms (one per Doppler beam) to the central zero-Doppler beam is performed. This leads to an improved signal-to-noise ratio and speckle reduction and a simplified multilook power waveform model.
The ACDC algorithm is implemented at stack level, which implies the processing of intermediate L1B-S product within the Delay-Doppler processing chain.
Specific processing blocks have been reviewed to improve precision which I'll go through.
We have evaluated the algorithm against operational L2 products and retrieved geophysical parameters with our in-house conventional SAR altimetry retracker (DeDop waver).

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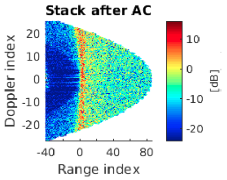
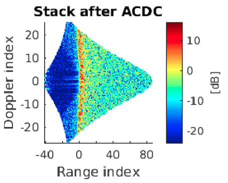
The ACDC algorithm

SAR altimetry waveform model $P_{k,l} = P_u \cdot B_{k,l} \cdot \sqrt{g_l} \cdot f_0\left(g_l \cdot (k - epoch)\right)$

(Ray et al., 2015)





$\boxed{1}$ Amplitude Compensation (AC)

$$P^{AC}_{k,l} = \frac{P_{k,l}}{B_{k,l}\sqrt{g_l}} = P_u f_0\left(g_l \cdot (k - epoch)\right)$$

$\boxed{2}$ Dilation Compensation (DC)

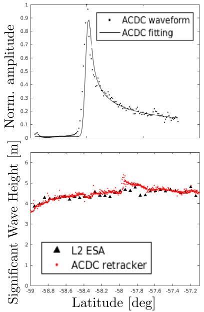
$$P^{ACDC}_{k,l} = P_u f_0\left(g_0 \frac{g_l}{g_0} \cdot (k - epoch)\right) = P_u f_0\left(g_0 \kappa_{k,l}\right),$$

$$\text{with} \quad g_l \equiv g_l(H_s) \text{ and } B_{k,l} \equiv B_{k,l}(epoch)$$

NOTES:

The ACDC algorithm takes as starting point a lower order approximation of the theoretical model for SAR altimeter open ocean backscattered echo developed by (Ray *et al.*, 2015).
The fundamental observation on which the ACDC algorithm is built is that the waveforms in the different Doppler beams l are dilated versions of the same waveform and that the scale of the dilation is set by the parameter g_l.
∗ In the AC step: we can compensate the variation in the maximum power of each beam by the amplitude factor B_k and the dilation term g_l, obtaining the amplitude compensated (AC) stack. Notice that the AC power has the same peak amplitude, for all values of the Doppler index.
∗ In the DC step: noting that the power in each Doppler beam is a range-dilated version of the Doppler zero beam via a known dilation term g/g_0, it is possible to compensate for this variation. We can write the AC power in terms of the DC range κ, independent of the Doppler index. In the figure, it can be seen that, after dilation compensation, the mean AC power depends only on range and not on Doppler.
Note how the AC and DC steps depend implicitly on H_s and epoch.

The ACDC algorithm



(epoch, H_s, σ_0)

$\boxed{3}$ Multilooking

$$\Psi_n = \frac{\sum_{k,l} w(\kappa_{k,l} - n\delta) P_{k,l}^{ACDC}}{\sum_{k,l} w(\kappa_{k,l} - n\delta)}$$

$\boxed{4}$ Retracking

$$\underset{\beta=(P_u, g_0, \epsilon)}{\text{minimise}} \frac{1}{2} \sum_n (\Psi_n - \Psi_n^{model}(P_u, g_0, \epsilon))^2,$$

$$\text{with} \quad \Psi_n^{model}(P_u, g_0, \epsilon) = P_u \cdot f_0(g_0 \cdot (\kappa_n - \epsilon))$$

NOTES: Because the ACDC stack is independent of the along-track/Doppler direction we can construct a ACDC multilook waveform by performing a weighted (w) average of all power waveform samples in the map that have nearly (δ) the same DC range with some weighting functions.
The resulting ACDC multilook measured waveform can be fitted by a model function of that form via the solution of a least-square-problem. The g_0 is dependent on the significant wave height, and ϵ is the ''error'' in estimating our initial k_0.
ACDC processing allows to implement a simpler and faster retracker, which is intrinsically included in the processing itself as specific initial estimates of epoch and H_s are required for its operation.

Evolution of specific processing blocks

- **Decrease sensitivity to initial parameters and algorithm convergence**:
  To overcome divergence issues and spurious energy distribution of H_s related to the initial geophysical parameter choice, the following strategy has been adopted:
  1. process the whole track I: perform the AC and DC steps at each surface with initial epoch and H_s estimated in the previous surface, and iterate over each surface. Smooth the resulting time series.
  2. process the whole track II: perform the AC and DC steps at each surface with initial epoch and H_s from step 1.

- **Dynamic thermal noise estimation**:
  For each surface, find N_s such that $\frac{\partial \Psi_n}{\partial n}|_{n=n_{N_s}} \leq \beta$, for a given constant threshold β, and estimate the noise for range gates $n \in [1, N_s]$.

NOTES: The key steps of AC and DC performed on the stack require initial estimates of the geophysical parameters. The selection of these estimates has been shown to have an effect in the final retracked time series. Examples of these effects are divergence issues and spurious energy distribution of H_s. A specific strategy has been followed to better allow the convergence and decrease the sensitivity to initial estimates of the ACDC method.
The noise floor estimates included in the fitting model is estimated within a dynamic window based on first derivatives.

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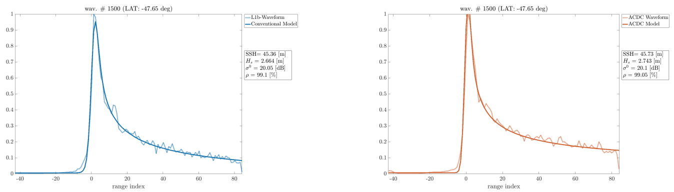
Evaluation of the ACDC retracker

The accuracy and precision of the ACDC retracked H_s estimates are to be compared. Three metrics are evaluated:

- Level of noise: 20 Hz standard deviations.
- Comparison against L2 EUM products (bias): 2D histograms
- Wave spectral variability (power spectral density function)



Example of fitted SAR altimeter open ocean backscatter echoe with the in-house conventional DeDop-waver retracker (left), and ACDC (right).

NOTES:

The performance of the retracker is evaluated in terms of the geophysical parameters estimates sea surface height (SSH) and significant wave height (H_s), and compared against SAMOSA-based conventional retrackers (operational L2 and in-house DeDop-waver retracker).
To this end, three metrics are evaluated: level of noise as a function of sea state, power spectral distribution, and comparison against operational wave model.
The levels of noise are computed in the following way. First, outliers are removed (Tukey's fences definition). Second, the variance of the 20 Hz parameters vector is computed for every 20 consecutive samples after detrending. Finally the square root of the mean of this variance is computed for different sea states with 0.2 m step size.
A bias analysis of retrieved H_s is performed by comparison against operational L2 products with a two-dimensional histogram. Similarly to the noise level calculation, the median of the 20 Hz parameter vector is computed for every 20 consecutive samples after detrending. A two-dimensional histogram is plotted for the resulting 1 Hz series. Pearson correlation coefficients, slope of linear fit, and standard deviations and median of the difference between series are also computed.
The power spectrum density (PSD) function of the retrieved H_s series is plotted against the PSD of EUMETSAT products according to the Welch periodogram algorithm.

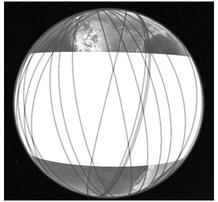
Dataset

The evaluation is performed over a S3A L1b Delay-Doppler input dataset used in the Round Robin exercise of the Sea State CCI project (Schlembach et al., 2020).

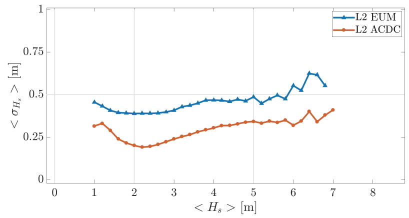
Standard L1b and L2 products of the EUMETSAT CODA are used for the processing and the analysis.

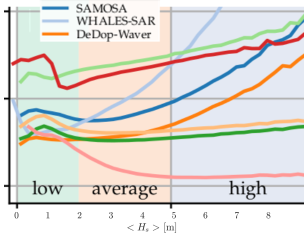
30 passes, ~ 16 cycles (02-2017 to 06-2018)

For computational convenience, the processing is divided into batches of data covering 15 degree latitude regions from -30° to 30°.

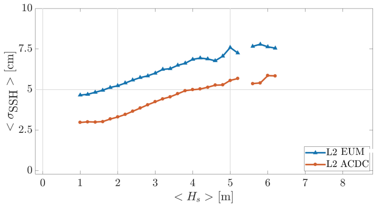


■ Noise levels of retracked H_s and SSH





(Schlembach et al., 2020)

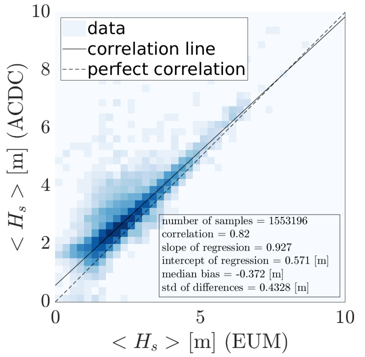


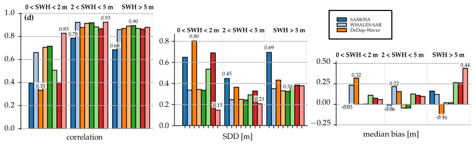
- Clear improvements across all sea states, as compared with the standard product.
- 10 to 15 cm improvement in H_s precision (peak of 20 cm for 2 m wave height).
- Improvement of about 2 cm in SSH precision.

NOTES: On the top left figure, the noise levels of the retracked H_s are shown. Results of the parameter series from L2 EUMETSAT standard products are also shown for comparison, as well as the levels of noise obtained in the Round Robin exercise (top right figure). The ACDC retracking outperforms conventional S3A processing across all sea states analysed here, with 10 to 15 cm improvement in precision, and a peak of 20 cm for 2 m wave heights. As for the precision in SSH retrieval, the figure below shows that ACDC retracking has the best performance, with an improvement of about 2 cm in SSH.

Comparison against wave model (bias)

Two-dimensional histogram of ACDC retracked H_s against EUMETSAT products



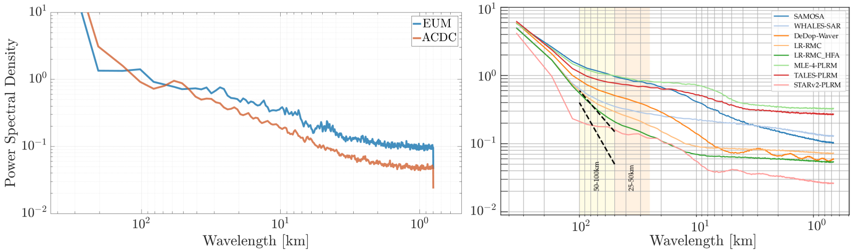


Correlation, standard deviation of differences (SDD) and median bias computed in (Schlembach et al., 2020)

- The correlation is 0.82, similar to the one obtained with the in-house DeDop-Waver open ocean retracker.
- Large bias affecting mainly low sea states. In line with in-house DeDop-Waver.
- Reduction of bias may be achieved by use of LUTs to adjust the PTR width to H_s.
- Std of differences is 0.43, similar to DeDop-Waver results.

NOTES: H_s estimates are evaluated against reference L2 EUMETSAT products via the two-dimensional histogram in the figure. High-intensity colours indicate a large number of points within the 0.25 m^2 cell (logarithmic scale). From the point distribution at low sea states, the ACDC algorithm appears to overestimate H_s. This is also apparent in the in-house conventional retracker DeDop-Waver, as shows the Round Robin results in the top right figure. It is worth pointing out that none of the retrackers developed by isardSAT make use of external loop-up table to correct the Gaussian approximation of the true PTR, which leads to an error bias increase. The correlation is 0.82, which is a similar value to the one obtained with the in-house DeDop-Waver open ocean retracker by averaging over all sea states (see top right figure). The standard deviation of the differences between the two products is 0.43, also similar to the ones obtained with DeDop-Waver.

■ Wave spectral variability



Power spectral density function (PSD) of H_s estimates with ACDC retracker and standard EUMETSAT products (left), and for different DD retrackers in (Schlembach et al., 2020) (right)

- Reduced noise levels over all scales below $\sim$ 40 km.
- Spurious ripples visible in the in-house open ocean DeDop-waver retracker are absent in the ACDC retracker.

NOTES: The power spectral density computed with the Welch algorithm shows lower power levels over all scales below about 40 km. The noise plateau is similar to the one obtained with the DeDop-Waver (right figure).

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Summary and conclusions

- Test products used in the Sea State CCI project for Delay-Doppler S3A altimetric data over a large extension have been used to evaluate the ACDC retracking algorithm.
- The noise levels of both H_s and SSH estimates are noticeably reduced with the AC and DC strategy performed on the DD stack: 30% to 50% reduction for H_s, and 15% to 35% for SSH.
- The bias of H_s compared to the EUMETSAT official products and the noise plateau in the PSD is in line with the conventional in-house DeDop-Waver retracker.
- The simplicity of the analytical model has great potential in terms of computational time.

Possible directions of future work:

- Further improvements of the ACDC algorithm would include the use of a look-up table to adjust the PTR width to sea state, thereby reducing the bias.
- Reduce further the senstitivity to initial estimates and computational time: reformulate minimization problem (ML/Bayes)
- Extend the analysis to S6A high resolution altimetric data.

Thank you for reading!

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