Retracking CryoSat-2 Ocean Waveforms for Optimal Gravity Field Recovery

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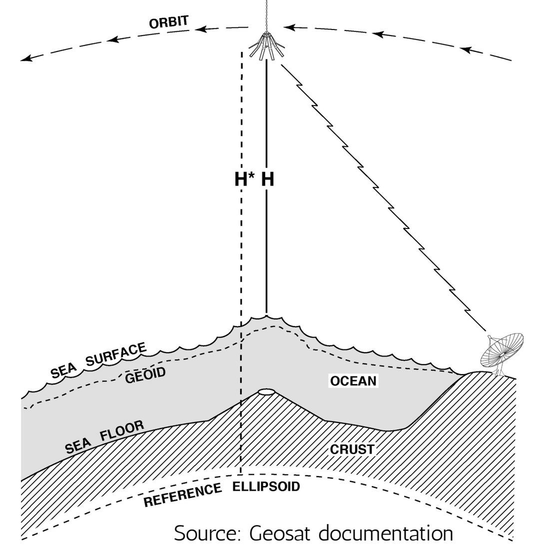
Main Ideas:

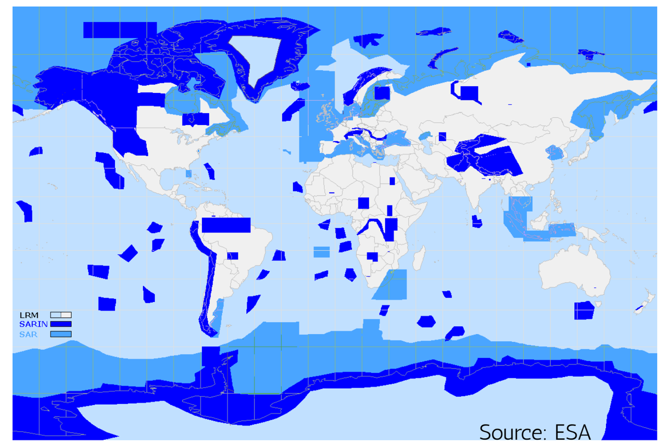
- Our objective is to improve the accuracy of the marine gravity field by a factor of 2-4 to better resolve ocean floor tectonics.
- CryoSat-2 (CS) is the first satellite altimeter in 15 years to provide complete ocean coverage at 2-4 km track intervals, allowing for dense spatial sampling.
- The CS altimeter has a new Synthetic Aperture Radar (SAR) mode that could offer an improvement in gravity accuracy over prior missions.
- Sea surface measurements are extracted from altimeter waveforms through retracking. We are developing new retracking methods to process CS data for gravity field recovery.
- Preliminary analysis shows that the range precision of CS altimetry is at least 1.5 times better than previous altimetry missions (Geosat and ERS-1).

1. Background on Satellite Altimetry

CryoSat-2 orbits at an altitude H* (~ 720 km) and the altimeter emits radar pulses. The arrival time of the return signal from the sea surface gives H, and sea surface height is H*-H.



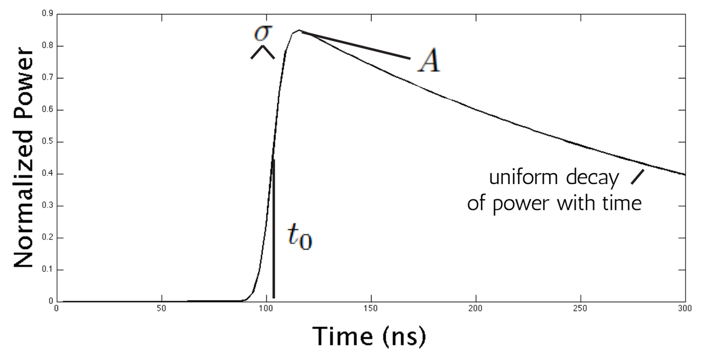
Source: Geosat documentation

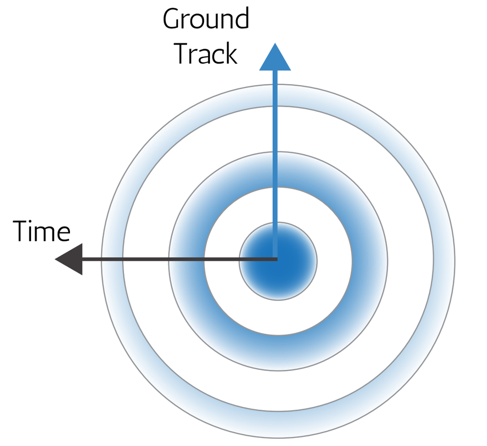


The CS altimeter operates in 3 exclusive modes over different geographical regions:

LRM - "classic" mode used by all previous altimeters, used over most oceans
SAR - forms a narrow beam by focusing like synthetic aperture radar
SARIN- uses 2 receiving antennas to get across-track slope over ice

LRM Waveform and Footprint





The CryoSat-2 LRM mode operates as a pulse-limited altimeter but with a pulse repetition frequency about twice that of the ERS-1 instrument. The radar waveforms can be fit to the following mathematical model (Smith and Sandwell, 2005, modified from Brown, 1977):

$$M(t;t_0,\sigma,A)=\frac{A}{2}\left[1+\operatorname{erf}\left(\frac{t-t_0}{\sqrt{2}\sigma}\right)\right]\begin{cases}0 & t<t_0\\ \exp\left[-\alpha(t-t_0)\right] & t_0\le t\end{cases}$$

t - time since pulse transmission

σ - arrival rise-time parameter, related to ocean wave height

t_0 - arrival time of waveform

A - waveform amplitude

2. Approximate SAR Waveform Model

The CryoSat-2 SAR mode data undergoes processing to reduce the radar footprint along the satellite ground track. In addition, waveforms from nadir and off-nadir angles are combined to create multiple looks at a ground location. Together, these result in an impulse-like waveform shape for the SAR mode.

We seek a simplified model for the SAR mode waveform based on a boxcar beam (Raney, 1998). The assumptions of our approximate SAR model are:

- along-track SAR footprint (~ 270 m) is much smaller than the cross-track beam-limited footprint (~ 1.5 km)
- the roughness of the sea surface is described by a Gaussian distribution of wave heights
- antenna mispointing is accounted for in an ad-hoc manner
- only nadir-pointing beams are considered, and not the full multi-looked waveform

We start by specifying the flat surface response:

$$F(t)=A\left(\frac{1}{t_p}\right)^{1/2}\exp(-\alpha(t-t_0))\begin{cases}0 & \tau<0\\ (t-t_0)^{1/2} & 0\le t-t_0<t_p\\ (t-t_0)^{1/2}-(t-t_0-t_p)^{1/2} & t_p\le t-t_0\end{cases}$$

t_p - pulse duration

α - power decay rate

If we convolve this with a Gaussian distribution representing sea surface roughness,

$$G(t)=\frac{1}{(2\pi)^{1/2}\sigma}\exp\left(-\frac{(t-t_0)^2}{2\sigma}\right)$$

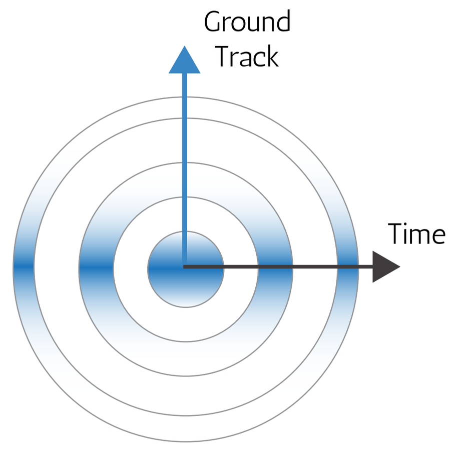
then we arrive at the following expressions for the model waveform and its derivatives:

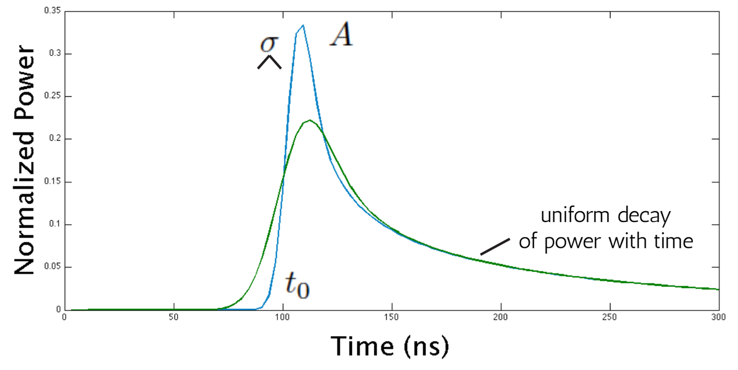
$$M(t;t_0,\sigma,A)=F(t)*G(t)$$
$$=\frac{A}{4}\left(\frac{2\sigma}{t_p}\right)^{1/2}\left[\exp\left(-\frac{1}{4}\eta^2\right)D_{-3/2}(-\eta)-\exp\left(-\frac{1}{4}\zeta^2\right)D_{-3/2}(-\zeta)\right]\begin{cases}0 & t<t_0\\ \exp\left[-\alpha(t-t_0)\right] & t_0\le t\end{cases}$$

$$\eta=\frac{t-t_0}{\sigma}\qquad \zeta=\frac{t-t_0-t_p}{\sigma}$$

$$\frac{\partial M}{\partial\sigma}=\frac{A}{4}\left(\frac{2}{\sigma t_p}\right)^{1/2}\left\{\frac{1}{2}\left[\exp\left(-\frac{1}{4}\eta^2\right)D_{-3/2}(-\eta)-\exp\left(-\frac{1}{4}\zeta^2\right)D_{-3/2}(-\zeta)\right]\right.$$

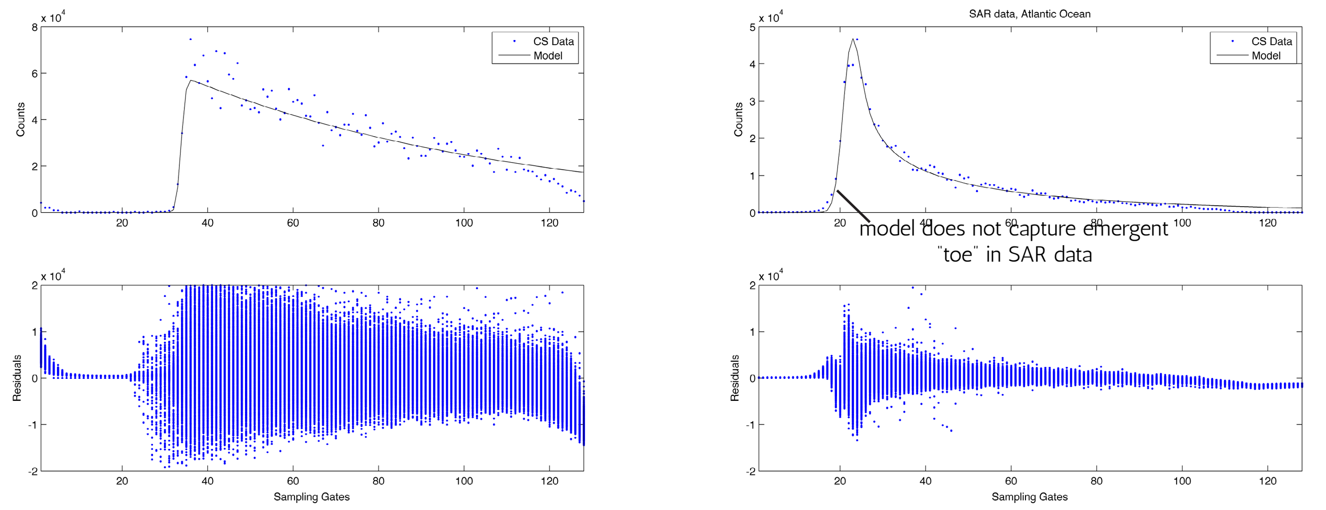
$$\frac{\partial M}{\partial t_0}=-\frac{A}{4}\left(\frac{2}{\sigma t_p}\right)^{1/2}\left[\exp\left(-\frac{1}{4}\eta^2\right)D_{-1/2}(-\eta)-\exp\left(-\frac{1}{4}\zeta^2\right)D_{-1/2}(-\zeta)\right]$$



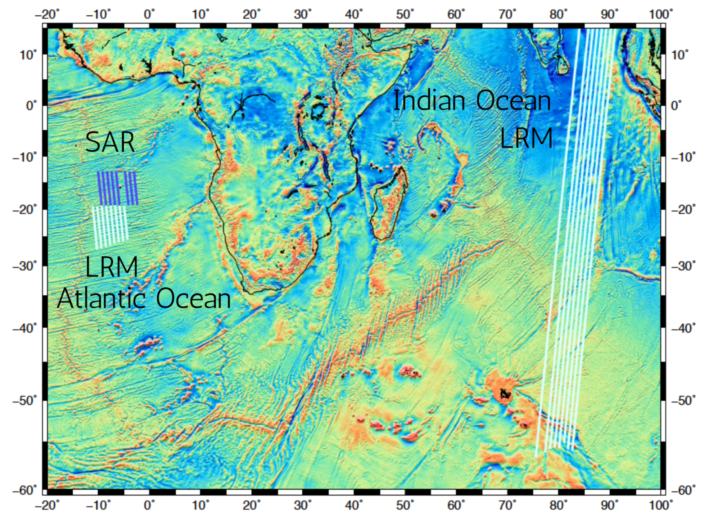


SAR Waveform and Footprint

3. Waveform Retracking of CryoSat-2 Data



We build our retracking routines by using the mathematical expressions for the LRM and SAR model waveforms then performing a nonlinear least-squares fit to the available waveform data. We also apply a two step retracking scheme (Smith & Sandwell, 2005) and so perform a 2-parameter fit after smoothing the rise-time parameter results of the 3-parameter fit. To estimate the precision of the CryoSat-2 data, we compute the standard deviation of the difference between the retracked heights and a mean sea surface model (EGM 2008), as well as the median average deviation of the slopes. For comparison, typical MAD values for ERS-1 and Geosat are 3.31 and 3.43.



Source: Marine Gravity Anomaly, v18.1, Smith & Sandwell, 2009

LRM Data, Indian Ocean

	3-Parameter Retracking		2-Parameter Retracking	
Track	Std. Dev., Heights (cm)	MAD, Slopes (μrad)	Std. Dev., Heights (cm)	MAD, Slopes (μrad)
1	7.21	2.69	4.53	2.16
2	7.24	2.82	4.54	2.13
3	6.95	2.61	4.31	1.99
4	6.61	2.51	4.11	2.02
5	6.83	2.76	4.24	2.13
6	7.11	2.85	4.45	2.19
7	7.16	2.85	4.51	2.18
8	6.23	2.32	3.94	1.71
Average	6.92	2.67	4.33	2.06

LRM Data, Atlantic Ocean

	3-Parameter Retracking		2-Parameter Retracking	
Track	Std. Dev., Heights (cm)	MAD, Slopes (μrad)	Std. Dev., Heights (cm)	MAD, Slopes (μrad)
1	5.93	1.98	3.81	1.34
2	4.98	2.01	3.20	1.40
3	5.44	2.26	3.55	1.57
4	6.00	2.27	3.84	1.75
5	6.00	2.24	3.85	1.72
6	5.55	2.18	3.59	1.51
7	5.22	2.08	3.40	1.64
8	6.33	2.35	4.04	1.66
Average	5.68	2.17	3.66	1.57

SAR Data, Atlantic Ocean

	3-Parameter Retracking		2-Parameter Retracking	
Track	Std. Dev., Heights (cm)	MAD, Slopes (μrad)	Std. Dev., Heights (cm)	MAD, Slopes (μrad)
1	4.69	1.78	4.59	1.72
2	4.82	1.68	4.77	1.68
3	4.89	1.61	4.82	1.55
4	5.05	1.52	4.87	1.46
5	4.73	1.81	4.54	1.74
6	5.90	1.83	5.66	1.86
7	5.62	2.51	5.36	2.31
8	5.61	2.17	5.36	1.97
Average	5.16	1.86	5.00	1.79

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This poster is organized as follows:

Main Ideas in Study	C41A-0376		Results Summary
Altimetry Concepts	Our New Work: Math Model	Model Fitting for CS Data	Updating Gravity using CS Data

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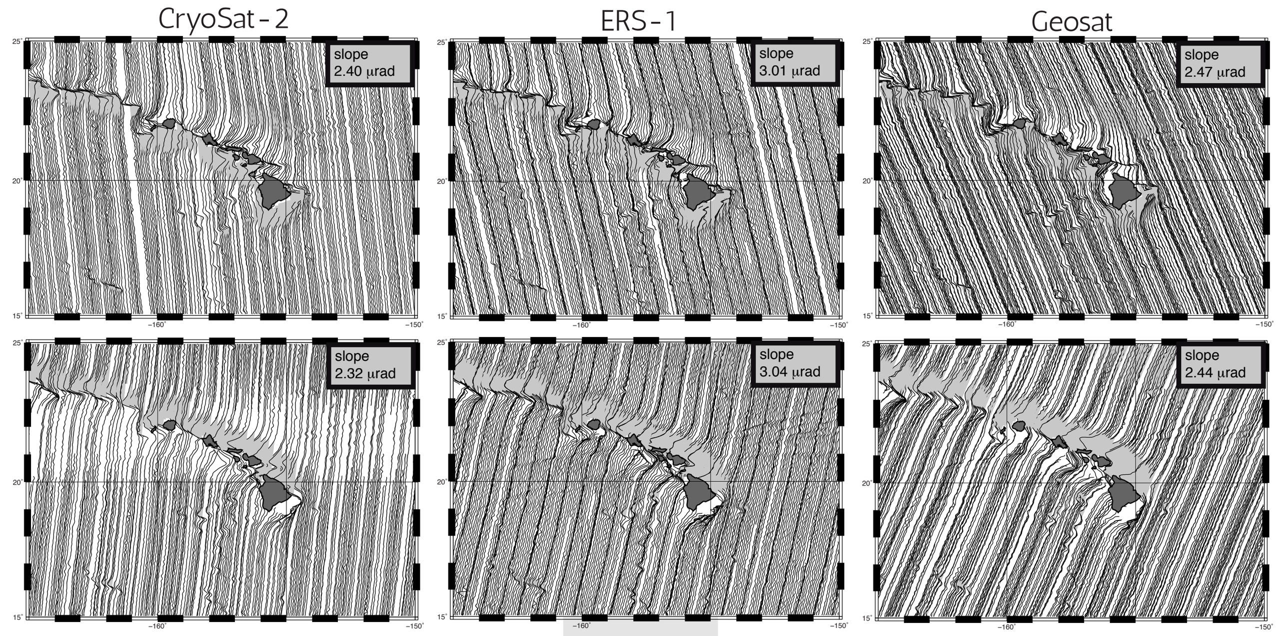
Summary of Results:

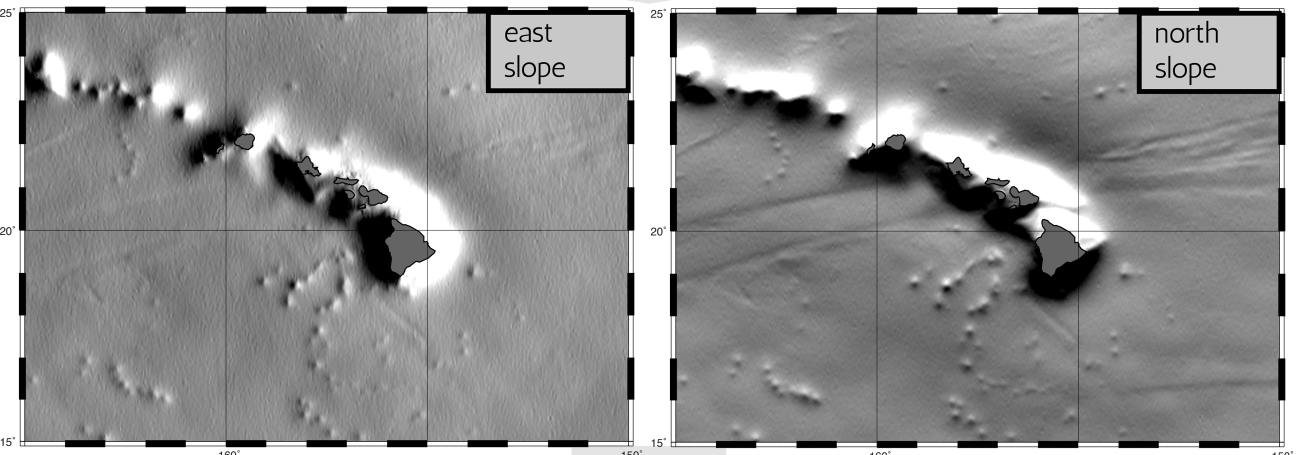
- We have developed an analytic expression for the shape of the CryoSat-2 SAR return signal from a rough ocean surface.
- This analytic expression may be suboptimal because it does not capture the full complexity of the SAR signal. In particular it does not capture the emergent "toe" of the waveform. However, the simplicity and robustness of the approach enables us to quickly retrack the entire data set.
- Our results demonstrate that the range precision of data from both the SAR and LRM modes (in terms of the deviation of the retracked slopes from the EGM 2008 mean sea surface) is at least 1.5 times better than data from previous altimeter missions (Geosat and ERS-1)
- For LRM data, applying a two-step retracking approach leads to 2 times better precision.
- These findings suggest a factor of 2 improvement in global gravity accuracy after 3 years of CryoSat-2 data collection.

4. Gravity Field Recovery using CryoSat-2 Data

The sea surface slopes from retracked CS waveforms are combined with ERS-1 and Geosat data to compute a marine gravity model as follows:



biharmonic spline interpolation with tension using uncertainties



Laplace's equation