Tidal Analysis of SWOT During the 1-Day-Repeat Mission Phase

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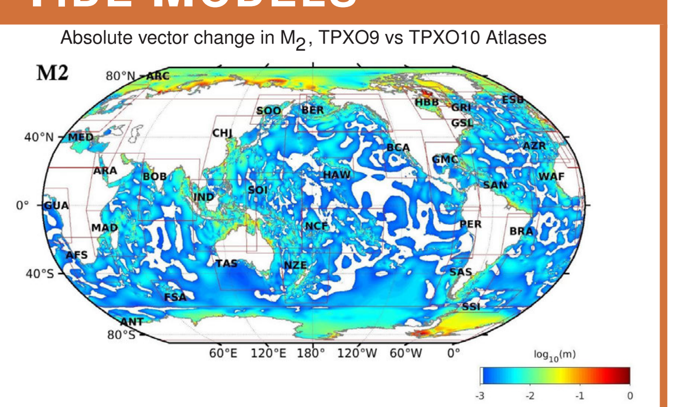
Overview

The main goal of our work has been to construct models of both barotropic and baroclinic tides which the SWOT project can use to remove tidal variability from the sea-surface height (SSH) measurements. The problem of baroclinic tides is an exceedingly difficult one. We have concentrated on (1) constructing models of a few primary tidal constituents that remain phase-locked with the tidal potential, and (2) assessing the non-phase-locked components, mapping how these vary geographically, and identifying what (alias) frequencies are most affected.

Our analyses of SWOT data have focussed on the 1-day-repeat mission phase, during which it is straightforward to identify the dominant M_2 semidiurnal variability. Tests of models via variance reduction statistics are complicated by contamination by O_1 which aliases to a frequency which cannot be distinguished from M_2. Main tasks:

- Verify that tidal corrections are applied correctly within products.
- Intercompare the L2 and L3 products and familiarize ourselves with the extensive flagging metadata on the products.
- Perform tidal analyses in coastal areas where large-amplitude small-horizontal-scale barotropic tides have not been mapped previously with nadir altimetry.
- Evaluate the performance of baroclinic tidal corrections in the open ocean.
- Investigate potential sources of systematic errors affecting tides (e.g., the long-wavelength crossover correction).

Barotropic Tide Models



We are developing new tide models, GOT5 and TPXO10, which resolve more of the tidal spectrum and incorporate more satellite data than our previous models.

TPXO10-Atlas consists of a $\frac{1}{6}^\circ$ global model combined with a suite of thirty-two 3-km-resolution regional coastal models. The models assimilate:

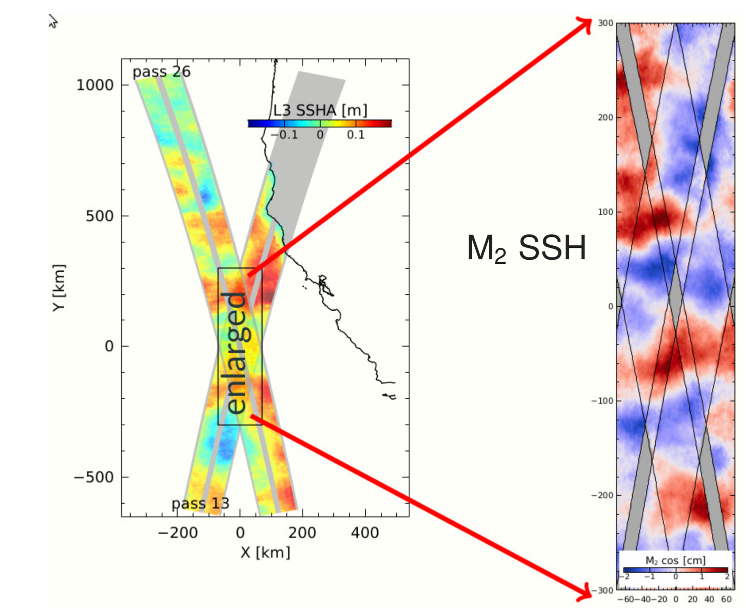
- Topex/Jason, 1132 cycles compared to 685 cycles for TPXO9 products;
- Topex/Jason on interleaving tracks – same as for TPXO9-atlas;
- Cryosat-2 data for Antarctic (ANT) and Arctic (ARC) patches for 4 major constituents: M_2, S_2, K_1, O_1;
- Coastal tide gauges from multiple sources, including Stammer's and Ant P & K; however, *no shallow or deep tide gauge data sets were used for assimilation.*

RMSE "Ground Truth" Comparisons :: RMS (cm) :: Shelf stations (195)

	Q_1	O_1	P_1	S_1	K_1	$2N_2$	N_2	M_2	S_2	K_2	M_4	MS_4
FES14	0.79	0.92	0.66	0.88	1.39	0.54	1.48	3.47	2.18	0.91	0.65	1.71
EOT20	0.80	0.90	0.71	0.87	1.39	0.51	1.43	3.18	2.11	0.84	0.70	
GOT4.8	0.82	1.00	0.84	0.90	1.54		1.98	4.88	2.78	1.48	2.23	
GOT5.1	0.80	0.92	0.70	0.76	1.37	0.56	1.45	3.28	2.12	0.86	0.63	1.23
GOT5.5	0.77	0.87	0.64	0.71	1.35	0.49	1.39	2.83	1.91	0.77	0.65	1.16
TPXO10	0.76	0.79	0.64	0.89	1.16	0.55	1.21	2.06	1.47	0.75	0.66	0.71

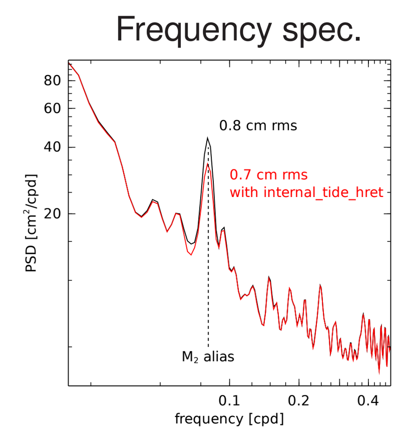
Main results from analysis of SWOT data during the Cal/Val (1-day-repeat) phase

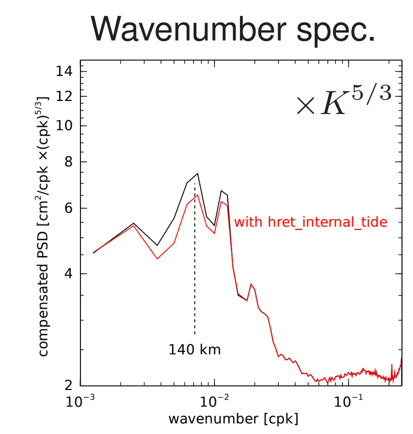
Harmonic analysis in the California Current



3 cm M_2 waves propagating southward are easily resolved. Tidal predictions computed from SWOT explain more variance in nadir missions than tidal predictions based on HRET81.

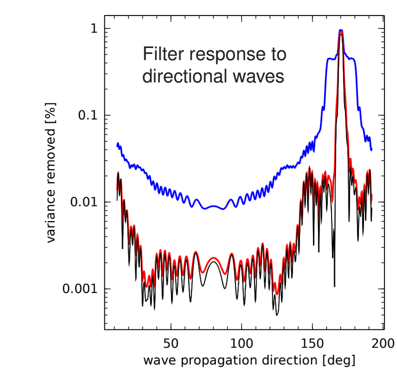
HRET81 typically removes < 50% of the tides





Along-track SSH spectrum is shown for the original SSH (black) and for the "internal_tide_hret"-corrected SSH (red) along a segment of pass 15 through the middle of the tropical Pacific. The tidal correction removes only about 25% of the tidal peak here.

The long-wavelength correction is crucial



We have developed a "linear proxy" of the nonlinear long-wavelength (crossover) correction used on the L3 product in order to quantify how much the correction could absorb internal tide signals. While the effect is generally negligible (10% or less) it could have an impact on some tidal studies, and the "linear proxy" can be applied directly to L2 data if the L3 data are, for some reason, unsuitable.

Testing Baroclinic Tide Models with SWOT

Different tide models are available for the M_2 baroclinic tide:

- **HRET81** – Based on least-squares optimization of a kinematic wave model to exact-repeat altimetry from the 1993-2018 era (Zaron 2019). This model provides the "internal_tide_hret" correction on existing SWOT products.
- **HRET14** – Based on mixed-norm optimization of a kinematic wave model utilizing exact-repeat, long-repeat/geodetic mission, and surface drifter trajectories data (Zaron & Elipot 2023). Altimetry data are from 1993-2022 and drifter data are primarily from 2008-2022.
- **M9509** – Based on a combination of plane-wave fitting and spatial Fourier filtering using all available altimetry from the 1995-2009 era (Zhao 2023).
- **M1019** – Same as M9505 but using altimetry from the 2010-2019 era (Zhao 2023).

The table below shows statistics for averages over all SWOT passes during the 1-day-repeat orbit phase: explained variance, E_i [mm^2]; predicted variance, P_i [mm^2]; ratio of explained to predicted variance, $R_i = E_i/P_i$; and explained variance of the bias-corrected model, E_i^* [mm^2].

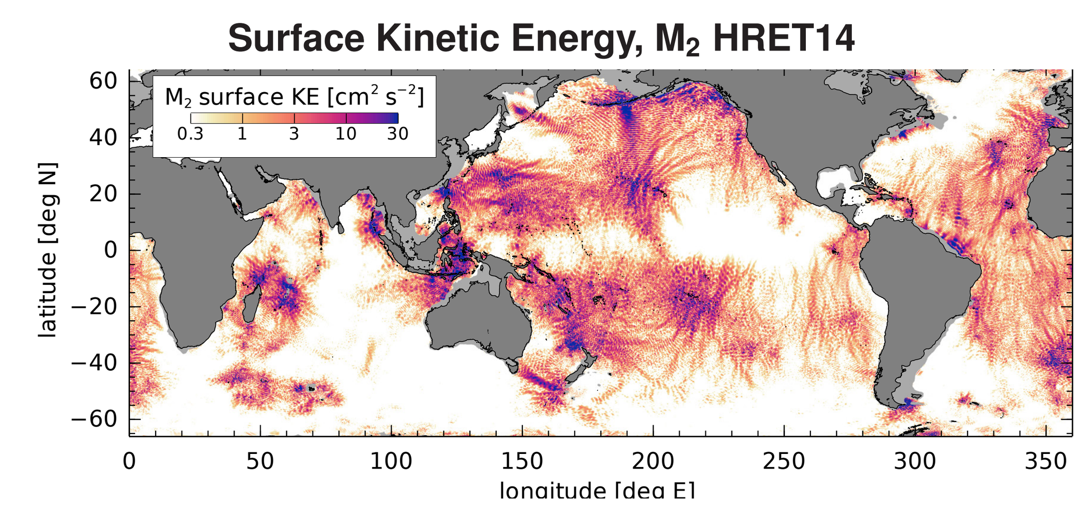
Explained and Predicted Variance (mm^2), M_2

i	Model	Explained E_i	Predicted P_i	Ratio $R_i = \frac{E_i}{P_i}$	Bias-Corrected E_i^*
1	M9509	13.3	11.5	1.16	13.4
2	M1019	16.6	12.6	1.32	17.0
3	HRET81 (M_2 mode-1)	16.7	17.7	0.94	16.7
4	HRET81 (M_2)	17.7	17.8	0.99	17.7
5	HRET14 (M_2)	20.8	15.8	1.32	21.2

This comparison found support for the trends in baroclinic M_2 identified by Zhao (2023), but the models developed there are not accurate enough to be used for tidal prediction compared to models which do not account for the changing tides.

The new HRET14 baroclinic tide model provides predictions for the M_2, S_2, N_2, K_1, and O_1 tides.

Surface Kinetic Energy, M_2 HRET14

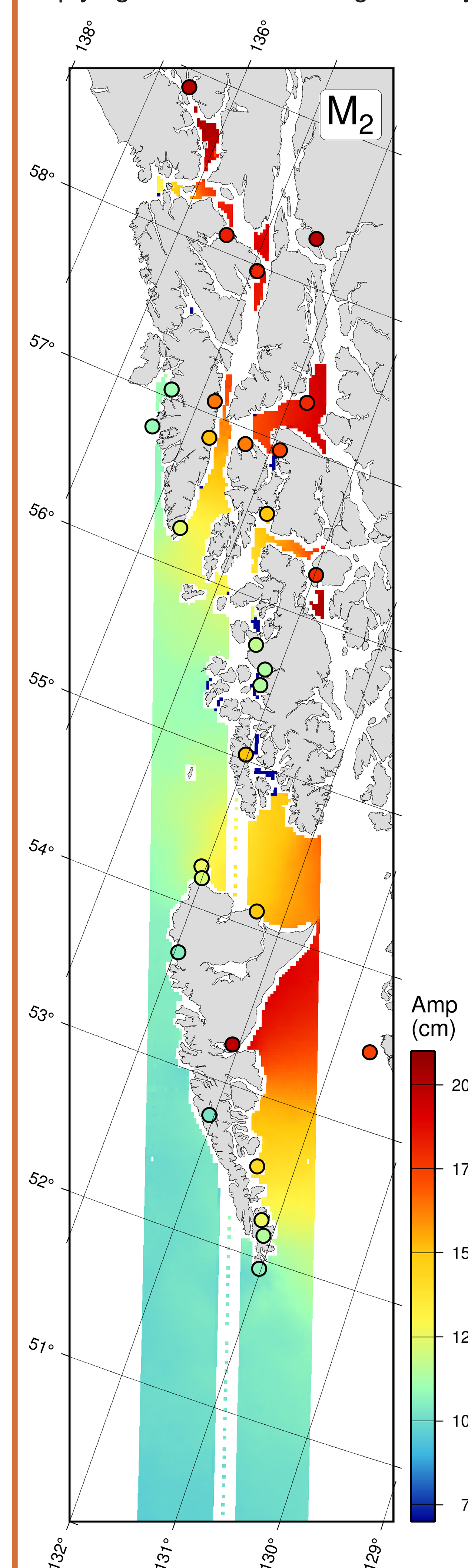


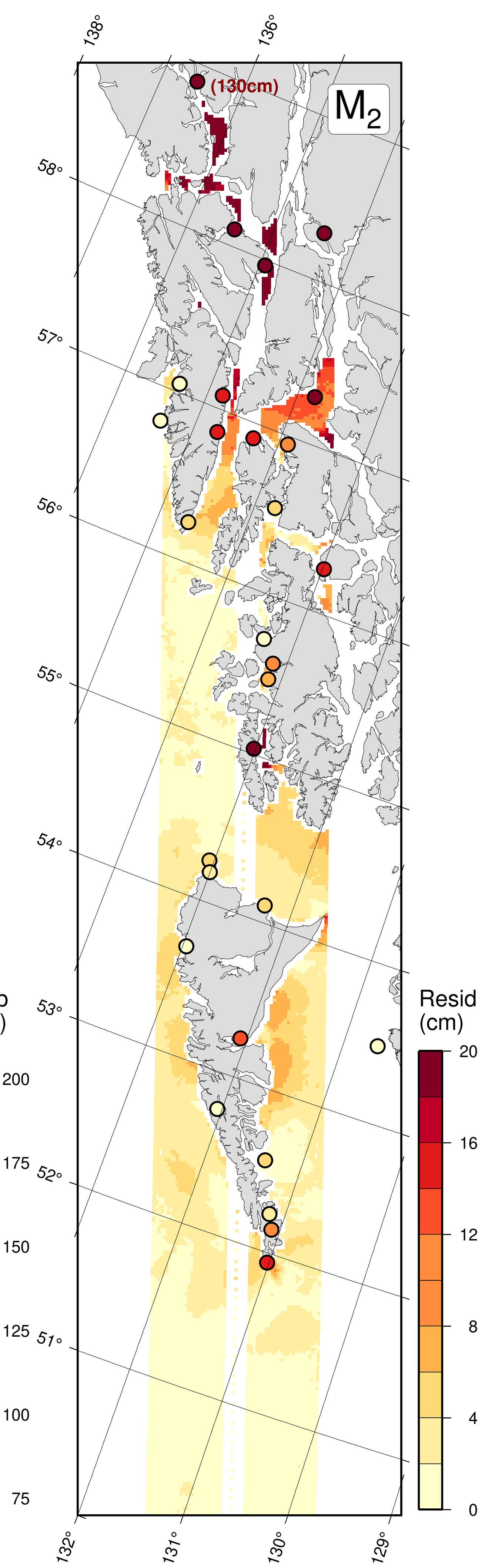
The comparisons also revealed that the HRET14 M_2 solution is biased too small by about 15%. The HRET14 tide model is now available at the NASA PO.DAAC (search on *BAROCLINIC_HRET14*).

- Zaron (2019) Baroclinic tidal sea level from exact-repeat mission altimetry. *J. Phys. Oceanogr.*, 49(1):193–210.
- Zaron and Elipot (2023) New Estimates of Baroclinic Tidal Sea Level from Lagrangian Drifters and Satellite Altimetry, *J. Atmos. Oceanic Technol.*, in review.
- Zhao (2023). Satellite evidence for strengthened M_2 internal tides in the past 30 years. *Geophys. Res. Lett.*, 50: e2023GL105764.

Coastal tides from SWOT

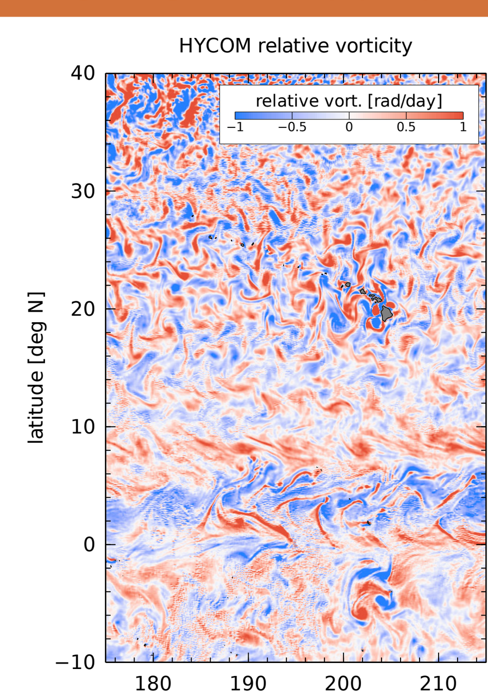
M_2 tide derived from SWOT Pass 26 (coastal Alaska/British Columbia) reveals large and complex amplitudes (below left). Tide gauges and SWOT show large and consistent differences with model FES2014 (below right), implying that SWOT can significantly improve the model.

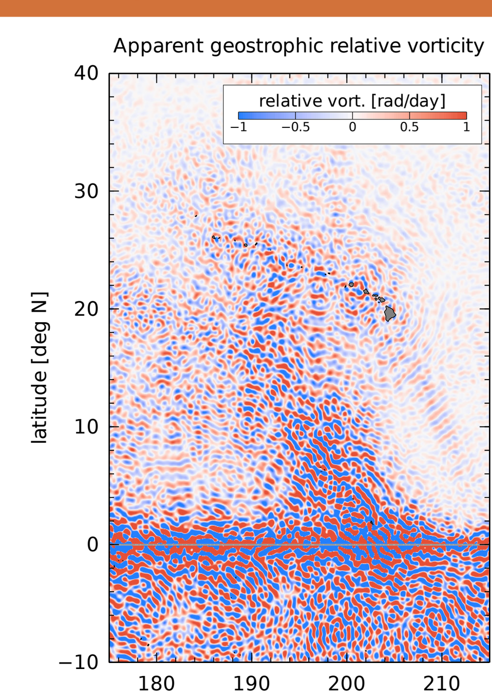




2024-2028 SWOT-ST Project: Rationale

The SSH associated with balanced dynamics is likely to be obscured by residual tidal SSH with cannot presently be predicted throughout the tropics and subtropics. Snapshots show the (left) surface relative vorticity in Global HYCOM and (right) the apparent relative vorticity which would be inferred from uncorrected baroclinic tides. The latter have been estimated based on a snapshot of the predicted M_2 tide, scaled by 1/2 (i.e., assuming roughly 50% of the tidal variability is predictable).





2024-2028 SWOT-ST Project: Objectives

- We will develop a 4D-Var data assimilation system based on the Coupled-mode Shallow Water model (CSW; Kelly et al 2016) to assimilate SWOT data globally over 28-day windows to map the instantaneous tide, i.e., the phase-locked and modulated components.
- We will use SWOT data to refine our models of barotropic tides around complex coastlines, and use these models to study tidal transport and energy dissipation.
- We will develop a suite of corrections for tidal and other high-frequency variability in the Great Lakes, enabling the mapping of geostrophic currents from SWOT data.
- We will investigate the potential for large-amplitude nonlinear internal tides to complicate or contaminate maps of the barotropic tides derived from SWOT and previous nadir missions.
- We will continue our studies of tidal dynamics using the SWOT data in tandem with nadir altimetry, other remote-sensing data, and in-situ data.

Kelly, S. M., Lermusiaux, P. F. J., Duda, T. F., and Jr., P. J. H. (2016). A coupled-mode shallow water model for tidal analysis: Internal-tide reflection and refraction by the Gulf Stream. J. Phys. Oceanogr., 46:3661–3679

Publications & Manuscripts

Submitted manuscripts utilizing SWOT data:

- Hart-Davis M., Andersen O.B., Ray R., Zaron E.D., Schwatke C., Arildsen R., Dettmering D. Tides from SWOT: Insights into complex coastal regions. *Geophysical Research Letters.*
- Zaron E.D. The Significance of the Long-Wavelength Correction for Studies of Baroclinic Tides with SWOT. *Earth and Space Science.*
- Tchilibou M., Carrere L., Lyard F., Ubelmann C., Dibarboure G., Zaron E.D., Arbic B.K. What can we learn from internal tides with the 1-day phase of SWOT? focus on the Amazon area. *Journal of Geophysical Research-Oceans*

Manuscripts utilizing HRET14:

- B. Yadidya, B. K. Arbic, J. F. Shriver, A. D. Nelson, E. D. Zaron, M. C. Buijsman, and R. Thakur, Phase-accurate internal tides in a global ocean forecast model: Potential applications for nadir and wide-swath altimetry, *Geophys. Res. Lett.*, **51**:e2023GL107232, 2024.
- Z. Caspar-Cohen, A. Ponte, N. Lahaye, E. D. Zaron, B. K. Arbic, X. Yu, S. LeGentil, and D. Menemenlis, Combining surface drifters and high resolution global simulations enables the mapping of internal tide surface energy, *Science Advances*, in review, 2024.