# Coastal Ocean Tide Modeling


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## ABSTRACT

Ocean tides play a significant role in climate due to its complex interactions between ocean, atmosphere, and sea. Tidal currents create turbulent mixing, tidal dissipation affects oceanic transport and thus climate and internal tidal mixing affects general circulation. Due primarily to the availability of TOPEX/POSEIDON (T/P) satellite altimetry and advances in numerical modeling methodologies, semidiurnal and diurnal barotropic ocean tides are known in the deep ocean (depth > 1000 m) to within 2 cm rms and with a spatial resolution of 50 km. Tides are significantly less known in the coastal regions, over continental shelves, and in polar oceans due primarily to limited observations with adequate spatial resolutions, as well as complicated spectra due to non-linear hydrodynamics. Baroclinic or internal tides have been observed from T/P and modeled but not well known globally. Our investigation aims to improve tides employing empirical and assimilation methods and using multiple satellite altimetry data (T/P, ERS, GFO, JASON, ENVISAT, JASON-2) in the coastal regions, including Yellow Sea, East China Sea, Sea of Japan, Patagonia, Indonesian Sea, Atlantic Canadian Shelf, and Hudson Bay. Multiple altimeter data are to be used to enhance spatial resolution and to mitigate tidal aliasing. 3-D modeling and data assimilation will be conducted to improve $M_2$ and $K_1$ internal tides modeling over the Atlantic, Indian and Pacific basins. The Jason-2 Wide-Swath Ocean Altimeter (WSOA) will be assessed for its potential to improve coastal tides by using the off-nadar data in the form of slope measurements. In this paper, we address issues of potential mitigation of tidal aliasing using dual-satellite crossover data and polar ocean tide modeling.


## Improved Temporal Samplings at Crossover Locations

To study the feasibility of improving ocean tide modeling by use of multiple satellite altimeter data, we performed a frequency analysis for simulated T/P and ERS altimeter data at single- and dual-satellite crossover points using periodograms defined for arbitrary sampling intervals [Mautz, 2002]. A global optimization method of least squares employed in this study makes it possible to analyze spectra of time series data sampled at uneven sampling rates. We use this technique to estimate Lomb-Scargle periodogram of satellite altimeter data sampled at a crossover location having either mixed sampling periods (dual satellite crossovers) or a single sampling period with sampling at different phases (single satellite crossovers).

Simulated data of ~8 year data span were generated for both satellites. The results shown below demonstrate that appropriate harmonic analyses for single- and dual satellite crossover data can identify "true", non-aliased values of harmonic parameters (frequency, phase, and amplitude) accurately for the dominant tides depending on their amplitudes and data noise level. Periodic time sampling results in an exactly repeating spectrum of time series data

### Periodogram of simulated T/P Single satellite crossover data. Gaussian noise of 3 cm added without bias or drift

| Harmonics | True/Aliased Frequency cycle/day | Estimated Frequency cycle/day | True Amplitude cm | Vector Difference cm |
|---|---|---|---|---|
| $M_2$ | 1.932274 | 1.932273 | 16.6 | 0.18 |
| $S_2$ | 2.00/ 0.0170 | 0.017012 | 5.0 | 4.05 |
| $K_1$ | 1.002738 | 1.002734 | 11.1 | 0.34 |
| $O_1$ | 0.929536 | 0.929538 | 10.9 | 0.28 |
| $N_2$ | 1.90/ 0.0202 | 1.432113 | 4.0 | 1.19 |
| $P_1$ | 0.997262 | 0.997243 | 3.8 | 0.81 |
| $K_2$ | 2.01/ 0.0115 | 0.616649 | 1.4 | 0.87 |
| $Q_1$ | 0.89/ 0.0144 | 0.417809 | 2.6 | 5.09 |
| Annual | 0.002738 | 0.002739 | 8.5 | 0.20 |
| Root Sum of Squares | | | | 6.74 |

along with the inherent frequency folding of original spectrum. Thus, an even sampling results in aliasing for spectral contents whose frequencies are higher than the Nyquist rate. However, periodograms for unevenly sampled data are not periodic in frequency, so that they can reduce aliasing. Mautz's global optimization algorithm for a sum of squared fit residuals (negative Lomb-Scargle periodogram) successfully searches for many of true tidal frequencies verifying this possibility of reduced aliasing. Thus, the numerical test results of frequency analysis herein indicate a clear advantage of using altimeter data at single- and dual-satellite crossover locations in tidal analyses to mitigate tidal aliasing problems.

### Periodogram of simulated T/P and ERS-2 Dual satellite crossover data. Gaussian noises of 3 cm added to T/P data and 8 cm added to ERS-2 data without bias or drift

| Harmonics | True Frequency cycle/day | Estimated Frequency cycle/day | True Amplitude cm | Vector Difference cm |
|---|---|---|---|---|
| $M_2$ | 1.932274 | 1.932279 | 16.6 | 0.59 |
| $S_2$ | 2.000000 | 2.000012 | 5.0 | 0.48 |
| $K_1$ | 1.002738 | 1.002738 | 11.1 | 0.11 |
| $O_1$ | 0.929536 | 0.929541 | 10.9 | 0.36 |
| $N_2$ | 1.895982 | 1.895984 | 4.0 | 0.23 |
| $P_1$ | 0.997262 | 0.291297 | 3.8 | 0.30 |
| $K_2$ | 2.005476 | 1.020117 | 1.4 | 0.22 |
| $Q_1$ | 0.893244 | 0.316972 | 2.6 | 5.73 |
| Annual | 0.002738 | 0.002731 | 8.5 | 1.10 |
| Root Sum of Squares | | | | 5.91 |

## An Approach to Quantify Improvement of Tidal Data Analysis

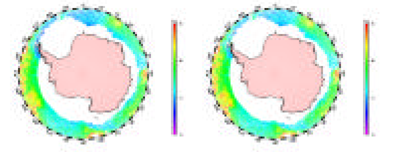
For single satellite crossovers, Smith (1999) discusses in detail through the concept of the aliased phase advance of a tide within one repeating cycle between measurements along two crossing tracks. The aliased phase advance of a tidal harmonic depends on the repeating period and latitude of a crossing point. Also, he explains further advantages of using single satellite crossover data over along-track data in terms of separating aliased frequencies that are very close to each other. In our study of improving ocean tide models, we will extend Smith's work on the use of single crossover data in ocean tide modeling to the case of dual satellite crossover data.

## Tidal Solutions at Crossover Locations

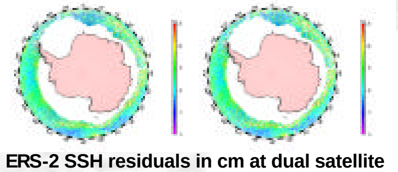
In this study, a point-wise tidal analysis was performed using the TOPEX and ERS-2 altimeter data in the Southern Ocean below 58°S at each of crossover locations. Ole Andersen's (1994) orthotide tidal analysis software was used to solve for 8 dominant short period tidal constituents along with 4 long period tides. SSH data of TOPEX cycles 4–364 and ERS-2 cycles 1–79 were processed.

### Performance comparison of ocean tide models in the Southern Ocean below 58°S in terms of standard deviation of crossover SSH residuals after correcting for ocean tide of each model in cm (SS stands for Single Satellite and DS Dual Satellite)

| Crossover Data | # cross-overs | This Study | NAO99 | TPXO. 6.2 | CATS02. 01 |
|---|---|---|---|---|---|
| TOPEX DS | 13,518 | 8.3 | 8.5 | 8.7 | 9.1 |
| TOPEX SS | 2,023 | 8.3 | 8.5 | 8.6 | 9.1 |
| ERS-2 DS | 13,518 | 13.6 | 13.7 | 13.8 | 14.2 |
| ERS-2 SS | 5,129 | 13.2 | 14.0 | 14.1 | 14.6 |



TOPEX SSH residuals in cm at dual satellite crossover locations after removing the ocean tide solution of this study (left) and NAO99 tide model (right)

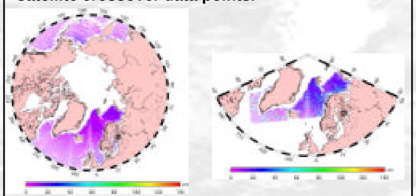


ERS-2 SSH residuals in cm at dual satellite crossover locations after removing the ocean tide solution of this study (left) and NAO99 tide model (right)

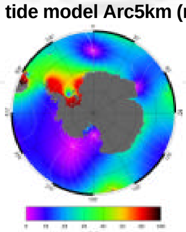
RMS discrepancy of point-wise tidal solution obtained in this study at TOPEX single satellite crossover points compared with other tide models in cm. Root Sum of Squares (RSS) differences of 8 short period tides are about 2 cm.

| Model | $M_2$ | $S_2$ | $N_2$ | $K_2$ | $K_1$ | $P_1$ | $Q_1$ | $O_1$ | RSS |
|---|---|---|---|---|---|---|---|---|---|
| NAO99 | .58 | 0.95 | .46 | .19 | 0.89 | .30 | .46 | .62 | 1.72 |
| CATS02.01 | .65 | 1.03 | .53 | .45 | 1.06 | .31 | .50 | .70 | 1.98 |

The point-wise tidal solution of this study performs well in the Arctic Ocean region also. For 6,658 ERS-2 single satellite crossover points above 50°N, residual ERS-2 SSH data has an average standard deviation of 10.5 cm after removing 8 short-period constituents of the tidal solution of this study. The Oregon State regional tide model Arc5km differs from ERS-2 SSH data by ±15.5 cm (standard deviation) for 4,196 single satellite crossover data points.



ERS-2 SSH residuals in cm at single satellite crossover locations near the Arctic Ocean after removing the ocean tide of this study (left) and the Oregon State regional tide model Arc5km (right)



M2 tide of preliminary regional assimilation model (Matsumoto, 2004) on a ¼ x 1/12-degree grid based on altimeter data of TOPEX and ERS-2

## Conclusions and Future Work

- Preliminary orthotides tide solution using ERS-2 and T/P crossover data in the Southern Ocean and the Arctic Ocean indicates improvement over contemporary tide models.
- Future tide solution improvement is anticipated using data assimilation technique with hydrodynamic modeling and using additional data (ENVISAT, GFO, JASON, etc.).