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eo-tides: Tide modelling tools for large-scale satellite Earth observation analysis

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Summary

The `eo-tides` package provides powerful parallelized tools for integrating satellite Earth observation (EO) data with ocean tide modelling. The package provides a flexible Python-based toolkit for modelling and attributing tide heights to a time-series of satellite images based on the spatial extent and acquisition time of each satellite observation (Figure 1).

`eo-tides` leverages advanced tide modelling functionality from the `pyTMD` tide prediction software (Sutterley et al., 2017), combining this fundamental tide modelling capability with EO spatial analysis tools from `odc-geo` (odc-geo contributors, 2024). This allows tides to be modelled in parallel automatically using over 50 supported tide models, and returned in standardised `pandas` (McKinney, 2010; pandas development team, 2020) and `xarray` (Hoyer & Joseph, 2017) data formats for further analysis.

Tools from `eo-tides` are designed to be applied directly to petabytes of freely available satellite data loaded from the cloud using Open Data Cube's `odc-stac` or `datacube` packages (e.g. using Digital Earth Australia or Microsoft Planetary Computer's SpatioTemporal Asset Catalogues). Additional functionality enables evaluating potential satellite-tide biases, and validating modelled tides using external tide gauge data — both important considerations for assessing the reliability and accuracy of coastal EO workflows. In combination, these open source tools support the efficient, scalable and robust analysis of coastal EO data for any time period or location globally.

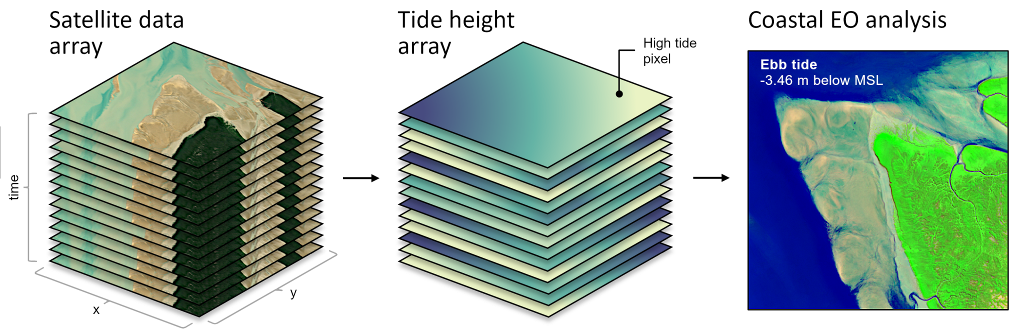

Figure 1: An example of a typical `eo-tides` coastal EO workflow, with tide heights being modelled into every pixel in a spatio-temporal stack of satellite data (for example, from ESA's Sentinel-2 or NASA/USGS Landsat), then combined to derive insights into dynamic coastal environments.

Statement of need

Satellite remote sensing offers an unparalleled method to view and examine dynamic coastal environments over large temporal and spatial scales (Turner et al., 2021; Vitousek et al., 2023). However, the variable and sometimes extreme influence of ocean tides in these regions can complicate analyses, making it difficult to separate the influence of changing tides from patterns of true coastal change over time (Vos et al., 2019). This is a particularly significant challenge for continental- to global-scale coastal EO analyses, where failing to account for complex tide dynamics can lead to inaccurate or misleading insights into coastal processes observed by satellites.

Conversely, information about ocean tides can also provide unique environmental insights that can greatly enhance the utility of coastal EO data. Conventionally, satellite data dimensions consider the geographical "where" and the temporal "when" of data acquisition. The addition of tide height as a new analysis dimension allows data to be filtered, sorted and analysed with respect to tidal processes, delivering a powerful re-imagining of traditional multi-temporal EO data analysis (Sagar et al., 2017). For example, satellite data can be analysed to focus on specific ecologically-significant tidal stages (e.g. high, low tide, spring or neap tides) or on particular tidal processes (e.g. ebb or flow tides; Sent et al. (2025)).

This concept has been used to map tidally-corrected annual coastlines from Landsat satellite data at continental scale (Bishop-Taylor et al., 2021), generate maps of the extent and elevation of the intertidal zone (Bishop-Taylor et al., 2019; Murray et al., 2012; Sagar et al., 2017), and create tidally-constrained imagery composites of the coastline at low and high tide (Sagar et al., 2018). However, these approaches have been historically based on bespoke, closed-source or difficult to install tide modelling tools, limiting the reproducibility and portability of these techniques to new coastal EO applications. To support the next generation of coastal EO workflows, there is a pressing need for new open-source approaches for combining satellite data with tide modelling.

The `eo-tides` package aims to address these challenges by providing a set of performant open-source Python tools for attributing satellite EO data with modelled ocean tides. This functionality is provided in five main analysis modules (`utils`, `model`, `eo`, `stats`, `validation`) which are described briefly below.

Key functionality

Setting up tide models

The `eo_tides.utils` module simplifies the setup of global ocean tide models, addressing a common barrier in coastal EO workflows. Tools like `list_models` provide feedback on available and supported models (Figure 2), while `clip_models` can be used to improve performance by clipping large model files to smaller regions of interest, significantly reducing processing times for high-resolution models like FES2022.

Comprehensive documentation is available to guide users in setting up commonly used tide models, including downloading, uncompressing, and organizing data files.

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```
──────────────────────────────────────────────────────────────
🌊       | Model             | Expected path
──────────────────────────────────────────────────────────────
✅       | EOT20             | tide_models/EOT20/ocean_tides
❌       | FES2014           | tide_models/fes2014/ocean_tide
✅       | HAMTIDE11         | tide_models/hamtide
...        ...                 ...
──────────────────────────────────────────────────────────────

Summary:
Available models: 2/50
```

Figure 2: An example output from `list_tides`, providing a useful summary table which clearly identifies available and supported tide models.

Modelling tides

The `eo_tides.model` module is powered by advanced tide modelling functionality from the pyTMD Python package (Sutterley et al., 2017).

`pyTMD` is an open-source tidal prediction software that aims to simplify the calculation of ocean and earth tides. Tides are frequently decomposed into harmonic constants (or constituents) associated with the relative positions of the sun, moon and Earth. For ocean tides, `pyTMD.io` contains routines for reading major constituent values from commonly available tide models, and interpolating those values to spatial locations. Information for each of the supported tide models is stored within a JSON database that is supplied with `pyTMD`. `pyTMD.astro` contains routines for computing the positions of celestial bodies for a given time. Namely for ocean tides, `pyTMD` computes the longitudes of the sun (S), moon (H), lunar perigree (P), ascending lunar node (N) and solar perigree (PP). `pyTMD.arguments` contains routines for combining the astronomical coefficients with the "Doodson number" of each constituent, along with routines for adjusting the amplitude and phase of each constituent based on their modulations over the 18.6 year nodal period. Finally, `pyTMD.predict` uses results from those underlying functions to predict tidal values at a given location and time.

The `model_tides` function from `eo_tides.model` wraps `pyTMD` functionality to return tide predictions in a standardised `pandas.DataFrame` format, enabling integration with satellite EO data and parallelized processing for improved performance. Parallelisation in `eo-tides` is automatically optimised based on available workers and requested tide models and tide modelling locations. This parallelisation can significantly improve tide modelling performance, especially for large-scale analyses run on a multi-core machine (Table 1). Additional functions like `model_phases` classify tides or determine flow/ebb tides, critical for interpreting satellite-observed coastal processes like changing turbidity and ocean colour (Sent et al., 2025).

Table 1: A benchmark comparison of tide modelling performance with parallelisation on vs. off, for a typical large-scale analysis involving a month of hourly tides modelled at 10,000 modelling locations using three tide models (FES2022, TPXO10, GOT5.6).

Cores	Parallelisation	No parallelisation	Speedup
8	2min 46s ± 663 ms	9min 28s ± 536 ms	3.4x
32	55.9 s ± 560 ms	9min 24s ± 749 ms	10.1x

Combining tides with satellite data

The `eo_tides.eo` module integrates modelled tides with `xarray`-format satellite data. For tide attribution, `eo-tides` offers two approaches that differ in complexity and performance:

tag_tides assigns a single tide height per timestep for small-scale studies, while pixel_tides models tides spatially and temporally for larger-scale analyses, producing a unique tide height for each pixel in a dataset {tab:tide_stats}.

These functions can be applied to free and open satellite data for any coastal or ocean location on the planet, for example using data loaded from the cloud using the Open Data Cube and SpatioTemporal Asset Catalogue (STAC contributors, 2024).

Table 2: Comparison of the `tag_tides` and `pixel_tides` functions.

`tag_tides`	`pixel_tides`
- Assigns a single tide height to each timestep/satellite image	- Assigns a tide height to every individual pixel through time to capture spatial tide dynamics
- Ideal for local or site-scale analysis	- Ideal for regional to global-scale coastal product generation
- Fast, low memory use	- Slower, higher memory use
- Single tide height per image can produce artefacts in complex tidal regions	- Produce spatially seamless results across large extents by applying analyses at the pixel level

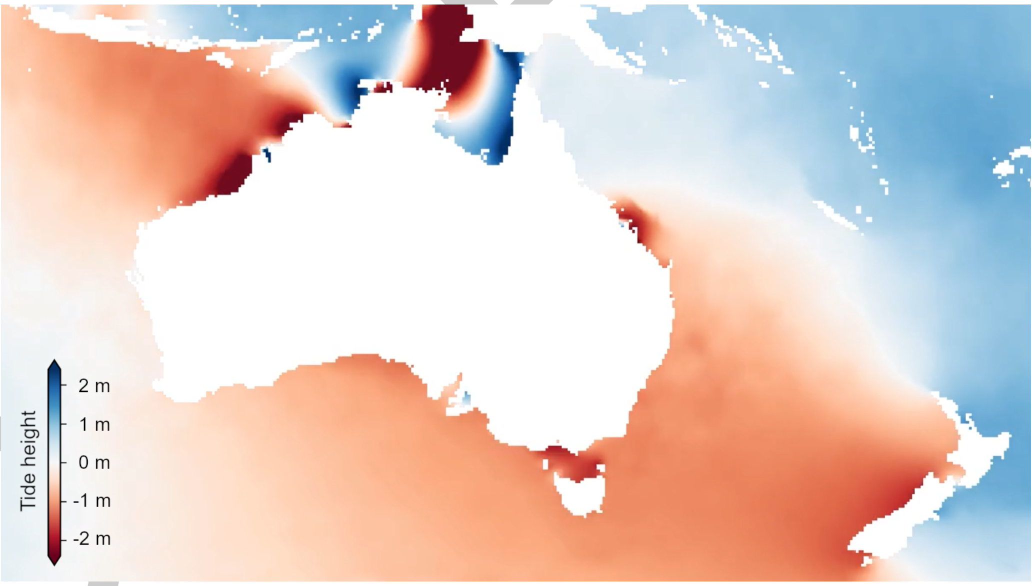

Figure 3: An example tide height output produced by the `pixel_tides` function, showing spatial variability in tides across Australasia for a single timestep.

Calculating tide statistics and satellite biases

The `eo_tides.stats` module identifies biases caused by complex tide alaising interactions interactions between tidal dynamics and satellite observations. These interactions can prevent satellites from observing the entire tide cycle (Eleveld et al., 2014; Sent et al., 2025), and cause coastal EO studies to produce biased or misleading results (Bishop-Taylor et al., 2019). The module produces a range of useful statistics that summarise how well a satellite time series captures real-world tidal conditions, include spread (coverage of tide range) and high/low-tide offsets (missed tidal extremes). Automated reports and plots provide insights further insights into potential biases affecting the analysis.

```
🌊 Modelled astronomical tide range: 9.30 metres.
🛰️ Observed tide range: 6.29 metres.

🔴 68% of the modelled astronomical tide range was observed at this location.
🟢 The highest 8% (0.77 metres) of the tide range was never observed.
🔴 The lowest 24% (2.25 metres) of the tide range was never observed.

🌊 Mean modelled astronomical tide height: -0.00 metres.
🛰️ Mean observed tide height: 0.69 metres.

⬆️ Mean observed tide height was 0.69 metres higher than mean modelled astronomical tide
```

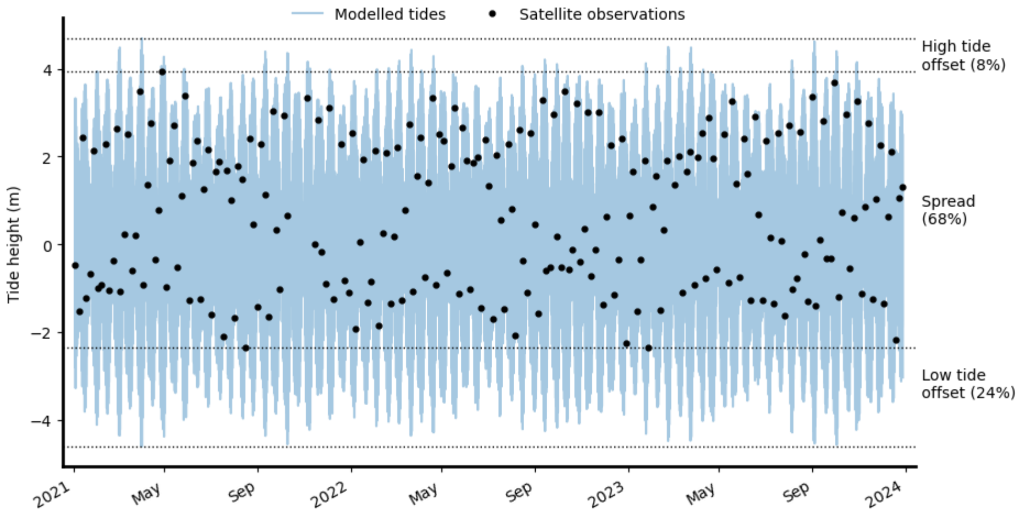

Figure 4: An example of tidally-biased satellite coverage, where the sensor only observes ~68% of the modelled astronomical tide range and never observes the lowest 24% of tides. Satellite bias plots show satellite observed tides as black dots, overlaid over the full range of modelled tides (blue lines).

Validating modelled tides

The `eo_tides.validation` module validates modelled tide heights using high-quality sea-level measurements from the GESLA Global Extreme Sea Level Analysis (Haigh et al., 2023) archive, providing error metrics like RMSE and MAE (Figure 5). It enables comparison of multiple tide models against observed data, allowing users to choose optimal tide models for their specific study area or application (Figure 5).

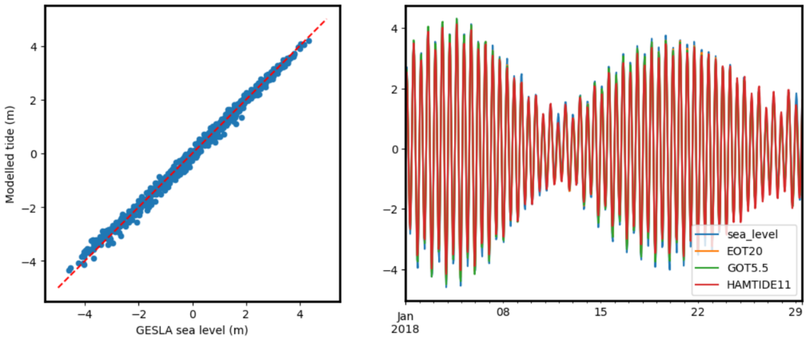

Figure 5: An example comparison of modelled tides from multiple global ocean tide models (EOT20, GOT5.5, HAMTIDE11) against observed sea level data from the Broome 62650 GESLA tide gauge, Western Australia.

Research projects

Early versions of `eo-tides` functions have been used for continental-scale intertidal zone elevation and exposure mapping (Bishop-Taylor et al., 2024), multi-decadal shoreline mapping across Australia (Bishop-Taylor et al., 2021) and Africa, and to support tide correction for satellite-derived shorelines as part of the `CoastSeg` Python package (Fitzpatrick et al., 2024).

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