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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 parallelised tools for integrating satellite Earth observation (EO) data with ocean tide modelling. The package provides a flexible Python-based toolkit for attributing modelled 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 capability with EO spatial analysis tools from odc-geo (odc-geo contributors, 2024). This allows tides to be modelled in parallel 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 EO analysis.

eo-tides tools can be applied to petabytes of freely available satellite data loaded from the cloud using Open Data Cube (ODC)'s odc-stac or datacube packages (e.g. using Digital Earth Australia or Microsoft Planetary Computer's STAC SpatioTemporal Asset Catalogues). Additional functionality allows users to assess potential satellite-tide biases and validate modelled tides with external tide gauge data — critical considerations for ensuring the reliability and accuracy of coastal EO workflows. These open-source tools support the efficient, scalable and robust analysis of coastal EO data for any time period or location globally.

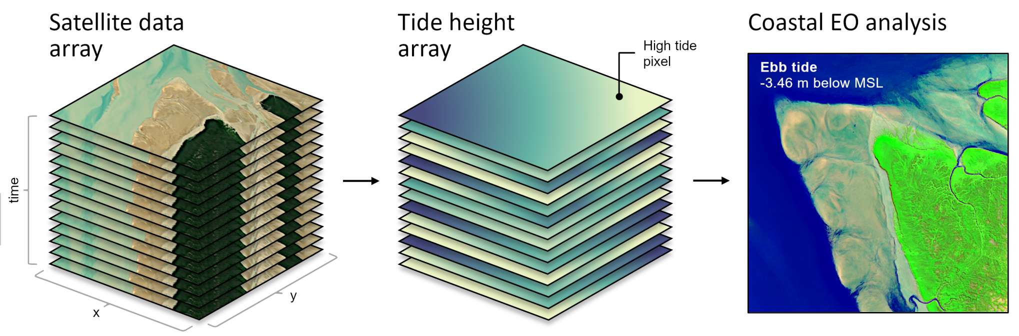

Figure 1: A typical eo-tides coastal EO workflow, with tide heights modelled into every pixel in a spatio-temporal stack of satellite data (for example, from Sentinel-2 or Landsat), then combined to derive insights into dynamic coastal environments.

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Statement of need

Satellite remote sensing offers an unparalleled resource for examining dynamic coastal environments through time or across large regions (Turner et al., 2021; Vitousek et al., 2023). However, the highly variable influence of ocean tides can complicate analyses, making it difficult to separate the influence of changing tides from patterns of true coastal change (Vos et al., 2019). This is a particularly challenging for large-scale coastal EO analyses, where failing to account for tide dynamics can lead to inaccurate or misleading insights into satellite-observed coastal processes.

Conversely, information about ocean tides can provide unique environmental insights that can significantly enhance the value of EO data. Traditionally, satellite data dimensions include the geographic "where" and temporal "when" of acquisition. Introducing tide height as an additional analysis dimension allows data to be filtered, sorted, and analysed based on tidal dynamics, offering a transformative re-imagining of traditional multi-temporal EO analysis (Sagar et al., 2017). For instance, satellite data can be analysed to focus on ecologically significant tidal stages (e.g., high tide, low tide, spring or neap tides) or specific tidal processes (e.g., ebb or flow tides; Sent et al. (2025)).

This concept has been used to map coastal change at continental-scale (Bishop-Taylor et al., 2021), map intertidal zone extent and elevation (Bishop-Taylor et al., 2019; Murray et al., 2012; Sagar et al., 2017), and creating tidally-constrained coastal image composites (Sagar et al., 2018). However, these methods have traditionally relied on bespoke, closed-source, or difficult-to-install tide modeling tools, limiting their reproducibility and portability. To support the next generation of coastal EO workflows, there is a pressing need for efficient open-source tools for combining satellite data with tide modeling. `eo-tides` addresses this need through functionality offered in five main analysis modules (`utils`, `model`, `eo`, `stats`, `validation`).

Features

Setting up tide models

The `eo_tides.utils` module simplifies the setup of ocean tide models, addressing a common barrier to coastal EO workflows. Tools like `list_models` provide feedback on available and supported models (Figure 2), while `clip_models` can significantly improve performance by clipping large high-resolution model files (e.g. FES2022) to smaller study area extents.

```
──────────────────────────────────────────────────────────────
 🌊      | 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 that clearly identifies available and supported tide models.

Modelling tides

The `eo_tides.model` module is powered by tide modelling functionality from the `pyTMD` Python package (Sutterley et al., 2017). `pyTMD` is an open-source tidal prediction software that simplifies 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. `pyTMD.io` contains routines for reading and spatially interpolating major constituent values from commonly available ocean tide models.

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 parallelised processing for improved performance (Table 1). Additional functions like `model_phases` classify tides into high/low/flow/ebb phases, critical for interpreting satellite-observed coastal processes like turbidity (Sent et al., 2025).

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

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

Combining tides with satellite data

The `eo_tides.eo` module integrates modelled tides with `xarray`-format satellite data. These functions (Table 2, Figure 3) can be applied to attribute tides to satellite data for any coastal location on the planet, for example using open data loaded from the cloud using ODC and STAC (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 satellite image time-step - Single tide height per image can produce artefacts and discontinuities - Fast, low memory use - Ideal for local, site-scale analysis	- Assigns a tide height to every individual pixel through time - Produce spatially seamless results across large regions - Slower, higher memory use - Ideal for large-scale coastal product generation

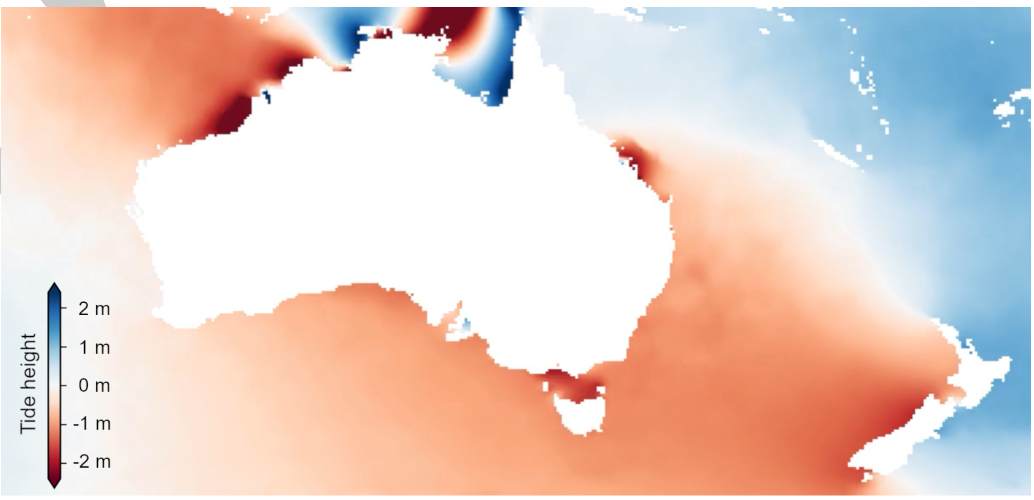

Figure 3: An example spatial tide height output produced by the `pixel_tides` function.

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Calculating tide statistics and satellite biases

The eo_tides.stats module identifies biases caused by complex tide alaising interations that can prevent satellites from observing the entire tide cycle (Bishop-Taylor et al., 2019; Eleveld et al., 2014; Sent et al., 2025). The tide_stats and pixel_stats functions produce useful statistics that summarise how well satellite data captures real-world tides (Figure 4).

```
🌊 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.
```

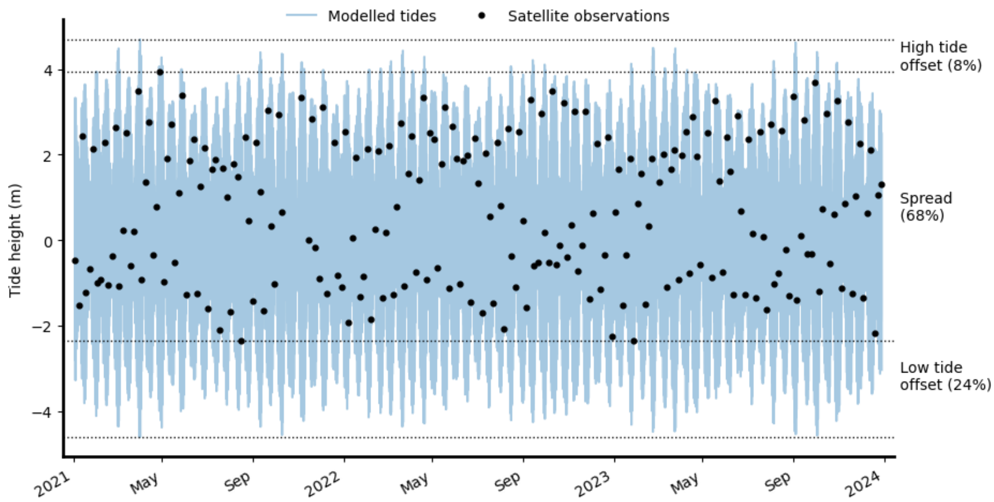

Figure 4: An example of tidally-biased satellite coverage, where only ~68% of the astronomical tide range is observed.

Validating modelled tides

The eo_tides.validation module validates modelled tides against observed sea-level measurements, assisting users to evaluate and select optimal models for their application (Figure 5).

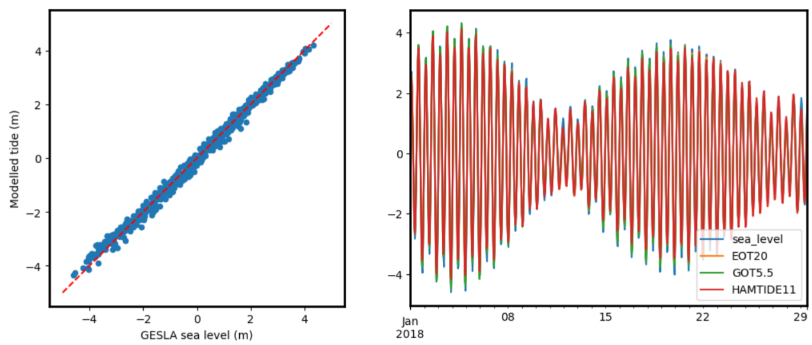

Figure 5: A comparison of multiple tide models (EOT20, GOT5.5, HAMTIDE11) against observed sea level data from the Broome 62650 GESLA tide gauge.

Research projects

Early versions of eo-tides functions have been used for continental-scale intertidal mapping (Bishop-Taylor et al., 2024), multi-decadal shoreline mapping across Australia (Bishop-Taylor et al., 2021) and Africa, and for correcting satellite-derived shoreline in the CoastSeg Python package (Fitzpatrick et al., 2024).

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