2025 TU Delft Sea Level Summer School – Computer Exercise
Using SWOT L3 Data
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A notebook with the tutorial is accessible here:
Goal: get familiar with SWOT L3 data, that is, learn what is provided with it, the corrections applied, how to plot the data.
During the morning lectures you learned about the principles of SWOT and saw some applications. In this tutorial, you will get hands-on on some SWOT data, learning some basics of how to open the data, how to manipulate it, some basic plots, and some applications.
This tutorial uses Python to deal with SWOT. Why?
Python is open source.

- Python several tools that makes it easy to deal with the data (e.g., xarray).
- You can easily run a Jupyter notebook on Google Colab, making it easy for teaching tutorials.
- The SWOT community is working mainly on python making it easier to follow the examples.
- AVISO, CMEMS and JPL PODAAC have jupyter notebooks and python scripts to directly download data.

That being said, you can you use your favorite programming language, and simply use this tutorial as a basis.
We will work with one swath (pass number 236), which crosses the North Sea. Data can be downloaded here:
https://drive.google.com/file/d/1js5cvDL8_tqZePIg4hs73Sd2vZxBkJOu/view?usp=drive_link

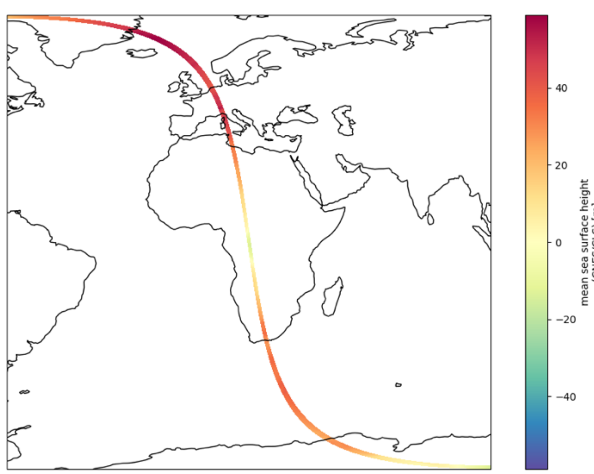

Figure 1. Mean sea surface of Pass 236.

You are welcome to download any other pass and cycles on your own. An example of how to download data from AVISO via ftp can be found on the SWOT GitHub community page.

4. Load Tide Gauge data

1. **Data exploration.**
   Open one cycle (tip: use xr.open_dataset() function) and explore the dataset.
   a. Which variables are there?
   b. What are the dimensions of the variables?
   c. What is the difference between the different sea-surface height anomalies provided?
   d. Plot the entire swath (reproduce figure 1).
   e. How long does the cycle take to complete (i.e., what is the first and the last time step recorded)?
   f. When will be this swath repeated again (i.e., when is the next cycle)?
2. **Region selection and Quality Flags**
   a. Plot the SSHA (unedited) over the North Sea (lon -12 to 12, lat from 48 to 62 degrees north). An auxiliary function is given on the notebook.
   b. Look at the quality_flag variable. Which values do we have flagged? Can we trust the data in the Wadden Sea?
3. **Altimetry principles and corrections**
   The surface topography is determined by radar altimeters by measuring the travel time of an emitted radar pulse from the satellite to the surface of the ocean (very simplistic explanation).
   The echo of the radar is known as a waveform. From the waveform, we can deduce several parameters, such as the radar range (used to estimate the surface topography), the backscatter coefficient (which informs us about the roughness of the surface), the significant wave height (estimated from the slope of the waveform) and wind speed (derived from the backscatter coefficient and the SWH).
   By knowing the altitude of the satellite and having the travel time, it is possible then to determine the surface topography:
   Surface topography = satellite altitude – (altimeter range + geophysical corrections)
   A set of corrections need to be applied to altimeter range. We won't go into all of them, because several are applied at lower processing levels. For example, instrument corrections are applied at the raw data. Some of the main corrections are:
   - Corrections for perturbations of the radar wave as it crosses the atmosphere;
   - Correction for how the sea state directly affects the radar wave (sea state bias, or electromagnetic bias)
   - Tidal corrections (ocean tides (barotropic and internal ones), solid earth, pole tides and loading effects)
   - Corrections for how the ocean responds to the atmosphere.

Some of the corrections are applied at raw data or Level 1. The level 3 data, provides 3 corrections so that the user can add them back and use their "favorite one". These are DAC, internal tide and ocean tide.

a. Look at each of these corrections, what do they mean? Plot each of them.
b. Compute the SSHA uncorrected and plot it. How different is it?
c. Look at sigma0. What does it mean?
d. Which features can you see from the sigma0?

4. **Oceanography from SWOT** (problem designed by Bjarke Nilsson and Ole Anderson)
The ocean topography can tell us a lot about the ocean surface. Here we will see how SWOT observe some of these features.
The feature oceanographers are most often interested in is the sea surface height anomaly (SSHA), as it reveals many dynamic features of the ocean surface. The SSHA is defined as the difference between the sea surface height (SSH) measurement and the mean sea surface (MSS):

$$SSHA = SSH - MSS \qquad (1)$$

However, some features, such as seamounts, do not show itself in the SSHA, but are clearly observed in the full sea surface heights (SSH). In order to save space, the only height measurement provided in the datafile is SSHA. But since the MSS is also provided, one can easily compute the SSH.
Another feature of interest for oceanographer are geostrophic currents. Geostrophic currents are an oceanographic feature directly linked to the ocean topography, as described by the equations for geostrophic currents eastward (u) and northward (v):

$$u = -gf\frac{\partial ADT}{\partial y} \quad \text{and} \quad v = gf\frac{\partial ADT}{\partial x} \qquad (2)$$

where g is gravity (can be set as 9.82 m/s), f is the Coriolis parameter and ADT is the Absolute Dynamic Topography. One of the unique things with SWOT is the ability to get two-dimensional observations, and we can therefore compute the gradient in both directions from a single pass. With conventional altimetry you would need several individual passes, and compute those gradients at crossover points! This allow us to compute features such as geostrophic currents.
Other features of interest for geodesists, such as gravity disturbances caused by seamounts, are often better visualized by the sea-surface-slopes (SSS) instead of the sea surface heights (SSH):

$$\xi = \frac{\partial SSH}{\partial y},\ \eta = \frac{\partial SSH}{\partial x}, \qquad (3)$$

as there is a direct relationship between those features.
The Coriolis parameter is given as

$$f = 2\Omega \sin(\phi), \qquad (4)$$

where Ω is the rotation rate of the earth (7.292 · 10−5/s) and ϕ is the latitude in radians

The geostrophic currents are caused due to the ocean not being at rest at an equipotential surface (geoid), which is why it depends on the Absolute Dynamic Topography (ADT), which is the measure of the sea surface height (SSH) above the geoid (N);

$$ADT = SSH - N. \tag{5}$$

The difference between the MSS and the geoid is the mean dynamic topography:

$$MDT = MSS - N. \tag{6}$$

For more information about altimetry principles:

- https://www.aviso.altimetry.fr/en/techniques/altimetry/principle/pulses-and-waveforms.html#:~:text=Analyses%20from%20waveforms%20over%20heterogeneous,on%20flat%20surfaces%20or%20wetlands.
- https://sentiwiki.copernicus.eu/web/altimetry-processing
- https://sentiwiki.copernicus.eu/web/s3-altimetry-instruments#S3-Altimetry-Instrument-Backgrounds

For more information on corrections:

- https://altimetry.esa.int/caw10/old.esaconferencebureau.com/docs/default-source/17c07-img/5-overview-of-altimetry-corrections5eee.pdf?sfvrsn=2
- https://www.aviso.altimetry.fr/index.php?id=5159

a. Compute the SSH and ADT from the variables in the file. Plot them.
b. Compute the Coriolis parameter (f = 2*omega*sin(lat)). Plot it.
c. Based on the SSH, compute the slopes at each grid point. (tip: use the numpy function gradient).
d. Our data is aligned on the along- and cross-track directions, and not on cartesian coordinates. Based on the orbital inclination of SWOT, which is 78 degrees, we can estimate a rough orbital angle theta (theta = 180 – (90-swotinclination)). Using a rotation matrix (https://en.wikipedia.org/wiki/Rotation_matrix), we can then rotate the slopes from the along and cross-track directions to north-east directions.
   Compute the orbital angle θ, and convert the Along-Track and Cross-Track slopes into North-South and East-West slopes and plot. What changed?
e. Compute the slopes now based on the ADT (remember to convert it to N-E direction).
f. Compute the Coriolis parameter.
g. Now you have all the ingredients to compute the geostrophic currents. Compute the Geostrophic Currents u, v and the magnitude, and plot it.
h. In the datafile the variables ugos and vgos are already provided and contains the geostrophic currents. Compare your own geostrophic velocity with the provided ones. They can be used to check if your computation is correct, but might not be exactly identical due to a different noise filter that has been applied.

5. **Added value of SWOT**
   a. Up to now we have been working with only a single cycle. Open one year of SWOT data, which has been provided (tip: use xr.open_mfdataset()).
   b. From CMEMS, load 1 year of L4 grridded all-sat altimetry product. Note, for this you need to have a Marine Copernicus User. You can register, for free, here: https://data.marine.copernicus.eu/register
   c. Compare SWOT data with gridded L4 altimetry data (based on conventional nadir altimeter). Which features can be seen with SWOT that couldn't be detected in the L4 altimetry?
   d. Load time series from 3 tide gauges in the Dutch Wadden see, available here: https://drive.google.com/file/d/1cdoe_j6XB4CIM3KoN0txvrRL0XZfkeMR/view?usp=sharin . This data was downloaded from CMEMS (https://data.marine.copernicus.eu/product/INSITU_GLO_PHY_SSH_DISCRETE_MY_013_053/services), and then combined into a single netcdf for simplicity.
   e. Now, compare SWOT data both with the tide gauge data and with L4 altimetry product. For this, you will need to match the time series both in space (i.e., find the altimetry point closest to the tide gauge), and in time (i.e., find tide gauge measurement at the time of the swot pass).
   f. Overlay SWOT SSHA on sea-surface temperature (SST). For this, zoom-in in the Mediterranean Sea (latitude range from 32 to 45 degrees North, longitude range from 0 to 15 degrees east). Do you see any patterns?