# Satellite Observations to Retrieve Tidal Sea Level and Tidal Currents

Prediction of tides is important for many things, including safe navigation, coastal engineering and surveying. To determine tidal constituents, a sea level time series from a tide gauge can be used. Satellite altimeters are able to measure sea level differences. These measurements have been used to describe the large-scale tides in the open ocean. This article describes a technique for obtaining tidal information in coastal areas by combining satellite data with in situ measurements.<P>

Tides are responsible for a large part of the movement of water in oceans and seas. The ability to predict tides is important not only for shipping, but also for many human activities at sea such as surveying and engineering projects in coastal areas. Fortunately, tides are very regular and can be described well with only a limited set of tidal constants. These constants, amplitudes and phases, can be obtained from a tidal analysis of measured sea level time series. Sea levels are measured in many major ports around the world. However, outside these ports, only limited data are available and, if available, little is know about the quality of these data.

Satellite altimeters can measure sea level from space. Scientists have demonstrated how useful these data are to determine large-scale tides in the open ocean. In coastal areas, tides become more pronounced than on deep water and vary on shorter length scales. At ARGOSS, we have developed techniques to combine satellite data and in situ measurements to obtain reliable tidal information, aiming especially at coastal areas, where human activities are more intense and economic interests higher.

## Measuring Sea Level from Space

Satellite altimeters can measure the sea level with a root-mean-square error of about 5cm. This is an incredible technological feat if one considers that the instruments fly at an altitude of 800–1,300km with a velocity of 6–7km/s. Still, these measurements have been collected on a routine basis for over 15 years now and continue to fill huge databases. There are several different satellite altimeters that measure, or have measured, sea level, with different characteristics. One important characteristic is the satellite’s orbit, which determines the length of time before a satellite passes over the same spot. For the analysed satellites, this recurrence time varies between about 10 and 35 days. There is a trade-off between the spatial and temporal density of the data collection: the shorter the recurrence time, the wider the distance between two neighbouring ground tracks. For tidal analysis, measurements from the Topex/Poseidon/ Jason satellite family are1 favourite because of their accuracy and 10-day recurrence time, meaning there are relatively many measurements per location, but the distance between ground tracks is about 3°. The gaps in this network of ground tracks can be filled up with data from the ERS1/ERS2/Envisat family, with an interval of about 1° between ground tracks, but per location there are fewer measurements to analyse. The Geosat Follow-On mission has characteristics in between these.

## Data Processing

Tidal stations sample the sea level at intervals of 1 hour or even a few minutes. A traditional harmonic analysis of a time series of a few months already gives a good assessment of the main tidal constants. The sampling interval of satellite measurements is larger than the main tidal periods of once or twice per day so that harmonic analysis is not useful. As the frequencies of the main tidal constants are exactly known, it is possible to determine these constants with the help of a least-squares fitting technique.

A more serious problem is the low number of measurements per location. In 2008, some 600 measurements could be collected for a location on a Topex ground track; on an ERS track, we would get only about 200 measurements. This means that outliers in the data can have a large effect on the tidal analysis, especially on the smaller constants. Deviations from the tidal predictions are not necessarily measuring errors. Other effects, such as wind set-up and atmospheric pressure, also influence sea level. In the analysis of long time series, these additional effects average out. With a short time series, careful quality control and outlier detection are needed.

The inverse barometer (IB) correction is a standard approximation to compensate for atmospheric pressure. It assumes an adiabatic equilibrium between the air pressure and the weight of the displaced water column. In practice, the equilibrium is dynamic and the local pressure can be associated with a wind field that adds a set-up. In our analysis, we assumed that the IB correction has a local strength, a factor that is determined in the tidal analysis. A factor of 1 means that the IB correction is a good (statistical) approximation. Closer to the coast we see higher values, meaning that the effect is stronger than the static equilibrium assumption predicts. An advantage of this analysis is that the influence of atmospheric variations on the tidal analysis averages out quicker. However, it will also be useful in the forecast mode, as it better models the local effect of air pressure (forecasts) in a statistical sense.

Other ways to estimate and improve the quality of the measurements involve smoothness assumptions. The sea level measurements along a ground track made in one overpass are essentially a snapshot of the sea surface and should be a smooth curve. This makes it possible to separate the difference between the analysed tide and the measured sea level into short-scale ‘noise’ and long-scale sea level anomaly. These two have different statistical properties, which can be used in the correction. In addition, the analysed tidal constants are assumed to be spatially smooth, so deviant results can be re-analysed to determine what caused the deviations and impose smoothness in a guided least-squares analysis.

Another type of smoothness follows from the observation that large-scale patterns of the phases of tidal constants with nearby frequencies (the group of diurnal and semi-diurnal tides) look very similar. At each location, the phases are approximately a smooth function of the frequency of the tidal constants and the form of this smooth function varies slowly with the location at sea. The same holds true for the tidal amplitudes, if they are scaled with the equilibrium tide amplitudes. The equilibrium tide can be computed analytically everywhere, and would be the true tide if the water would react instantaneously to the gravitational tidal forces and no land masses would be in the way.

An advantage of imposing this frequency smoothness (also called response analysis) is that theassessment of small tidal constants can be guided by the larger ones that have a better accuracy. It also makes it possible to use measurements from satellites in a sun-synchronous orbit, such as the ERS family. Normally, it is not possible to analyse sun-related tidal constants from time series that are sampled at intervals of 24 hours or multiples of this. However, imposing frequency smoothness – with smoothness parameters borrowed from Topex measurements – solves this problem and makes it possible to determine the tides along the spatially much denser ERS tracks.

## Results

The combination of all satellite tracks provides a good spatial overview of the tidal pattern in which finer details and the position of several amphidromes are clearly visible. Assimilation of these results in a tidal model provides the final product: tidal constants on a dense, regular grid.

## Validation

To determine how accurate the tidal constants derived from satellite measurements are, validation studies were carried out around the UK, where many in situ measurements are available. In this study, the amplitudes and phases of satellite M2 constants were compared with the results of over 200 stations. Figure 4 shows the results. The two upper plots give a spatial overview of the amplitude and phase residues (satellite minus in situ), while the two lower plots show the statistics in the form of histograms. The overall standard deviation of the amplitude residues is about 6cm, and for the phase residues about 4°.

## Conclusion

For accuracy, satellite measurements of sea level cannot beat the decades-long hourly records collected at main ports. However, now they can favourably compete with 1-month dedicated measurement campaigns to retrieve tidal constants. As satellites measure worldwide, and just as easily in remote areas that are difficult to access with traditional sensors, they provide a cost-effective alternative.