Metrology for Earth
Observation and Climate

EMPIR EURAMET
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Metrological approach to hydrological measurements – establishing collaborations in satellite radar altimetry

Introduction

Hydrology is the science of studying the occurrence and distribution of water bodies above and below the Earth's land surfaces, and how each varies across both space and time [1]. Hydrology plays a fundamental role in the assessment and management of water resources; mitigation of hydro-hazards such as floods and droughts; and in resolving hydro-political tensions like transboundary water disputes [2]. Understanding the location and fluxes of water is also essential for improving the scientific understanding of the water cycle, a key component of understanding the Earth's climate [3]. Over the last few decades, satellite remote sensing has provided hydrologists with an unprecedented wealth of data. The continuous deployment of operational satellites and the introduction of cutting-edge missions, like the recently launched SWOT, promise to enhance an already-valuable archive of observations, augmenting both the quantity and quality of hydrological data available to researchers.

Within the MetEOC-4 project, NPL performed a scientific study using the example of satellite radar altimetry, which provides hydrological studies with water height information. The study aimed to identify knowledge gaps in satellite hydrological observations that relate to the concept of uncertainty. The question is whether a metrological approach towards uncertainty characterisation can provide both hydrology and Earth Observation (EO) satellite communities with appropriate solutions.

Challenge

Lakes, reservoirs, rivers, estuaries, and flood plains constitute hydrological water bodies [4]. Satellite radar altimetry is arguably one of the strongest means available to the hydrology community for monitoring inland water bodies because of its benefits of continuity, global coverage, open access, and insensitivity to light and cloud conditions [3]. Expanding opportunities from new satellite sensors with improved spatial resolution and coverage, particularly the SWOT mission launched in December 2022, offer unprecedented opportunities to this community.

The water level of these inland bodies can be inferred from satellite radar altimetry which measures the two-way travel time of a radar pulse to estimate the distance between the satellite and surface water: known as the 'range'. After applying atmospheric and geophysical corrections to the range, the water level can be derived by subtracting the range from the satellite orbital altitude (Equation 1 in Figure 1) [3]. Despite this straightforward relationship between the satellite measurement and the water surface height, deriving water level from satellite altimetry is challenging. Satellite altimetry was developed and optimised for monitoring open oceans, giving it a coarser spatial resolution than would be desirable for inland applications [4]. While more recent mission concepts and processing techniques offer far better spatial resolutions, the size of altimetry footprint continues to be a major source of contamination in deriving inland water levels.

Copernicus Sentinel-2 image of Lake Titicaca. Covering an area of around 8300 km^2, Lake Titicaca lies on the high Andes plateau and straddles the border between Peru (to the west) and Bolivia (to the east). The waters of Titicaca are essential to the wellbeing of millions of people who rely on the lake for agriculture, fishing, and tourism, as well as water birds and animals that live along and on its shores.

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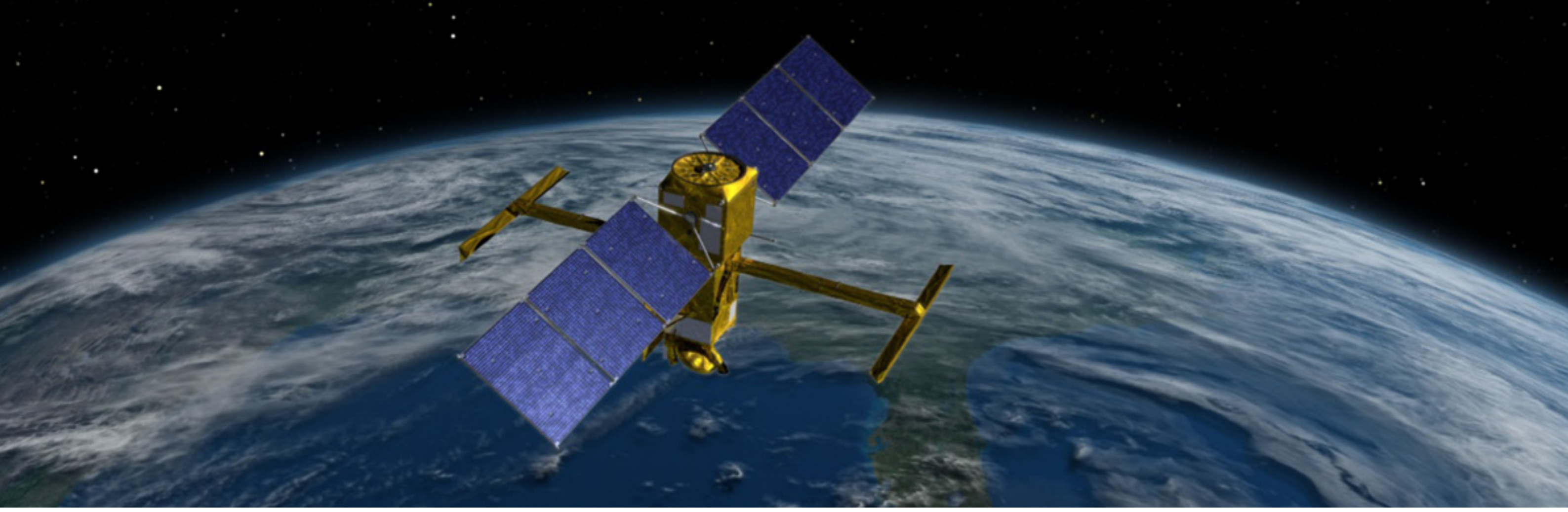
High uncertainty of the applied corrections is a further challenge. For instance, the correction for the radar signal being slowed by water vapour in the atmosphere, the 'wet tropospheric correction', makes assumptions that are invalid over land surfaces. Other sources of complexity include insufficient sampling (in location and time) of water level time series; difficulties in identifying outliers; and inter-mission biases which limit the ability to reliably merge water level time series from different missions. These and other factors affect the uncertainty associated with altimetric water level estimations.

In a paper that summarised contributions and recommendations coming out of the '25 Years of Progress in Radar Altimetry' symposium in 2018 [5], it was recommended that the uncertainty in observational data and assimilation processes be characterised through a systematic



An artist's concept of the SWOT spacecraft (February 2015). SWOT is the first mission to use the concept of radar interferometry to provide a global survey of both ocean topography and terrestrial surface waters. The mission was jointly developed by NASA and Centre National D'Etudes Spatiales (CNES) with contributions from the Canadian Space Agency (CSA) and the United Kingdom Space Agency. Courtesy NASA/JPL-Caltech

and rigorous approach and as part of a dedicated plan. The paper also recognised the challenges of applying altimetry data to the practice of hydrology. Not surprisingly, similar concerns are shared by other communities. In the report published by the World Meteorological Organization (WMO) in 2023 on vision and strategy for hydrology and hydrological research [2], methodological attribution of uncertainty to data, proper archiving of processes and procedures, and effective communication of uncertainty information to end-users were recurring themes.

The MetEOC-4 scientific study focused on radar altimetry measurements of lakes and rivers, while also considering how these findings could apply to other hydrological objects and other satellite observations. Lakes and rivers were chosen as they are closely tied with two of the Essential Climate Variables (ECVs) identified by the Global Climate Observing System (GCOS) committee – 'lakes' and 'river discharge'.

Solution

As described by Equation 1 (in Figure 1), the water level at point x can be inferred by estimating the distance between the satellite and the water surface R; applying relevant atmospheric $\sum c_{\text{atm}}$, and geophysical, $\sum c_{\text{geo}}$ corrections; and finally subtracting the corrected range from the satellite orbital altitude. These calculations are performed independently by several data providers [6]–[8] using similar satellite data, and their own processing chains. They provide hydrological information through data repositories, most commonly in the form of water level time series either for a lake, or at several locations along a river. Processing almost always involves some form of weighted averaging of different height estimates obtained during a single overpass. For instance, in the simplified example shown in Figure 1, the dots represent individual observations by the satellite sensor that are averaged together.

In the MetEOC-4 project, a detailed analysis of the scientific literature and reports from data providers was undertaken to define areas for future collaborative work, where metrology could be valuable. Four specific challenges in the application of altimetry data for hydrology purposes are described as follows.

Reliability of uncertainty estimates

Different data providers have different processes and different approaches to providing uncertainty information. However, it is common to define the uncertainty of the final height estimate during one overpass to be the standard deviation of all height estimates during that overpass [4]. While using a standard deviation as a metric to represent uncertainty is common, when calculated over the different observations in a single satellite overpass (the dots in Figure 1) this does not account for uncertainties in the atmospheric and geophysical corrections and in orbital heights, as these components do not vary over the timescale of that single overpass (often a fraction of a second). The data currently provided often does not explain the origin of uncertainty estimates so end-users may misunderstand the data provided.

Work is required to improve the reliability of uncertainty estimates and the transparency of the description of what is needed. Some significant sources of uncertainty such as the wet tropospheric correction (described above), need careful analysis as the uncertainties associated with these will include effects that are random and systematic over a time series, as well as those with more complex correlations. These needs were identified in the reviews described in the Challenge section (above) [2], [5].

Transparency of information about intersatellite bias correction

Users want time-series data that are as long and as detailed as possible, with high temporal resolutions. Data providers build such time-series by combining data from different satellite altimetry missions. Individual satellites have limited lifetimes and space agencies operate successor missions in the same orbit. In these cases, data series from the two missions are combined sequentially. Additionally, satellites from different space agencies, or satellites with different primary applications, can fly simultaneously, in different orbits. For larger water bodies, data from these different satellites can be combined to provide a more complete time series, although care is needed to account for the fact that those different satellites are likely to pass over different points on the water body. Therefore, for hydrology applications, data from different satellites is often merged to generate long time-series [9].

The problem, however, is that time-series derived from different missions show height biases with respect to one another. These biases, referred to as inter-satellite or inter-mission biases, change from one geographic location to the other, and from one water body to the next. Some data providers [6], [7] give a brief description of their approach to estimating biases, some report only numerical biases for each station, and others don't report this at all. There is a need for more transparency from data providers, although this gap is partially caused by a lack of well-established and community-agreed approaches for estimating such biases. Metrological guidelines on uncertainty estimation and comparison analysis could help bring transparency to the specific example of estimating inter-satellite biases.

Validating satellite observations with in-situ measurements

In-situ measurements are used by the hydrology community and data providers to assess the quality of the satellite-derived measurements through comparison. These comparisons can include radar, lidar or ultrasonic gauges mounted under bridges or on piers, pressure sensors on river- or lake-beds, or campaigns using rafts or drones with GNSS (e.g. GPS) receivers. There is often no metrologically robust assessment of the uncertainties of in-situ measurements, nor of the process used to compare those in-situ observations with the satellite. Such comparisons need to consider the fact that the satellite overpass is not at the same location and/or time as the in-situ observations and that the satellite footprint covers a much larger area. A good example of such uncertainty analysis was performed by the St3TART project consortium, including NPL, in 2022-23 [10]. Such work needs to be extended to other sites.

Common language

The BIPM-WMO Metrology for Climate Action workshop recommendations highlight the importance and challenge in many scientific disciplines of bringing metrological terminology to observation communities [11]. In the hydrological community too, words such as 'error', 'uncertainty', 'bias' and 'noise' are used in conflicting ways by different scientists. Some projects, such as FDR4ALT [12] and St3TART initiated the integration of metrological approaches and frameworks to assessments of uncertainties in satellite-derived hydrological products for some satellite and in-situ products; however, there is further development needed and such methods must be adopted more extensively by the wider community to fully realise potential impacts. There is a strong need for metrologists to engage with this community.

Outcome

The MetEOC-4 scientific study investigated ways in which satellite altimetry was used to measure the heights of lakes and rivers for hydrological applications. In this study, four areas for future collaborative work were identified. By enabling NPL to engage with data providers developing hydrological time-series from satellite products, this study established collaborations responding to these four areas. As a result of such collaborations, particularly through the St3TART and FDR4ALT projects, some pioneering data providers now offer satellite and in-situ observations with uncertainty assessments calculated through a metrological approach. Considerable further efforts are required in this area, and the MetEOC-4 study has positioned the metrology community to lead such efforts.

Equation 1

$$h_x = h_{sat} - (R + \sum C_{atm} + \sum c_{geo})$$

h_x	height of point x wrt ellipsoid
h_{sat}	altitude of satellite (orbital height)
R	range (measured distance)
C_{atm}	atmospheric correction
C_{geo}	geophysical correction

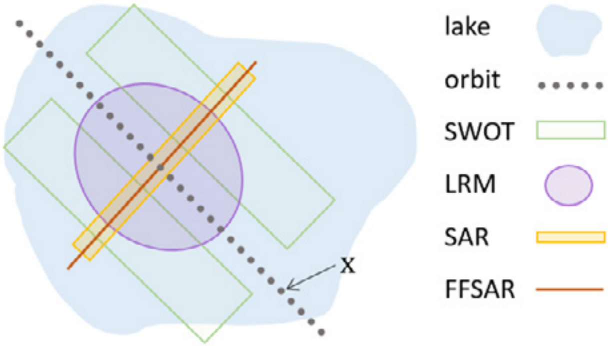


Figure 1: Schematic view of an altimetry satellite overflying a lake. There is a height estimate for each sample . Different types of altimetry footprints are shown.

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For more information visit www.meteoc.org

From 2011 to 2023, the NPL-coordinated MetEOC series of projects — supported by EURAMET's European Metrology Research Programme (EMPR) and European Metrology Programme for Innovation and Research (EMPIR) — encouraged collaboration between European National Metrology Institutes (NMIs) and partners in industry or academia. MetEOC combined ground, atmosphere, and space-based measurements to develop metrology tools and frameworks to support climate observation systems capable of increasing understanding of the drivers of climate change.

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