Metrology for Earth
Observation and Climate

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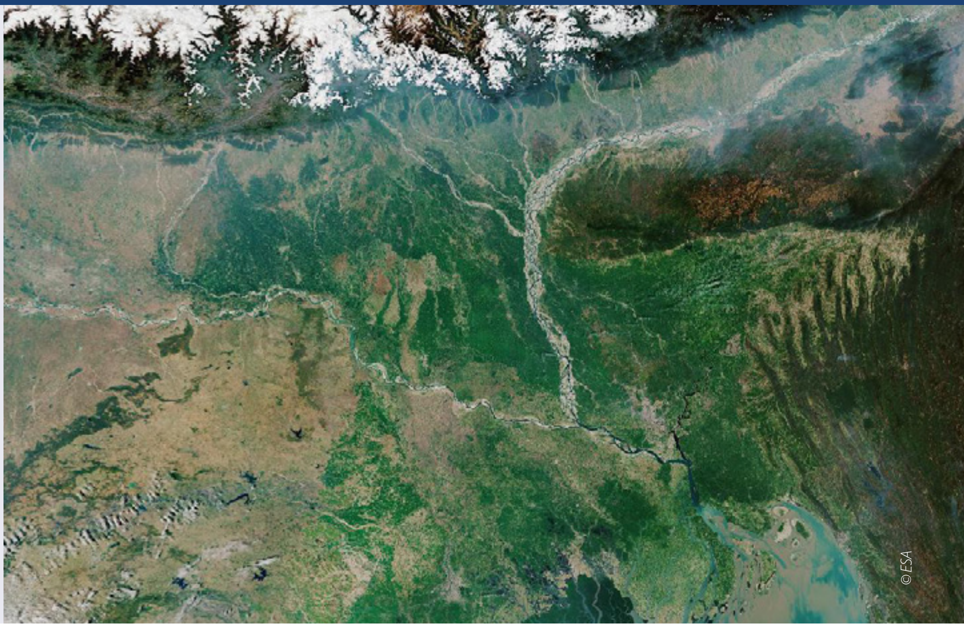
research and innovation programme and the EMPIR Participating States

Uncertainty characterisation of sea level measurement by satellite radar altimetry

Pioneering the application of metrologically-rigorous approaches to satellite altimetry



Copernicus Sentinel-3 image, captured on 31 March 2020 over the Ganges Delta – the world's largest river delta that lies in both Bangladesh and the State of West Bengal in India. With a population of over 100 million people, it is one of the most densely populated deltas in the world and is extremely vulnerable to effects of climate change.

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Introduction

Satellite altimetry data records from 1993 to 2021 indicate that Global Mean Sea Level (GMSL) is rising by 3.3 ±0.3 mm per year and accelerating at a rate of 0.12 ±0.05 mm/yr^2 [1]. Regional and local sea level rises can be even more significant: coastal sea level rise is a major driver of societal impacts from climate change [2]. To make the necessary predictions to support coastal climate adaptation measures, sea level rise will need to be monitored with higher reliability than currently delivered [3]. Sea level measurements with much lower uncertainties could also support important research topics in the climate sciences relating to the water cycle and heat transfer between the atmosphere and ocean [1], [4]. As uncertainty requirements become more challenging, it is increasingly important to establish rigorous end-to-end uncertainty analysis, moving beyond the statistical and comparison methods currently in use. Such approaches could also inform satellite instrument design for the next-generation satellites.

Challenge

The Global Climate Observing System committee (GCOS) defines what are called Essential Climate Variables (ECVs) to encourage systematic observations of changes to the Earth's climate. GCOS identifies 'sea level' as an ECV. Sea level provides information about ocean volume changes caused by thermal expansion and water transfer from land in the form of melted ice or liquid water [3].

Benefiting from global coverage and continuity in data collection over three decades, satellite radar altimetry has been the primary means to measure sea level. Although the uncertainty of sea level estimates from recent missions is far lower than those of early radar altimetry missions, more reliable measurements are required to tackle some specific scientific questions. These are: closing the sea level budget (that is, to show agreement between sea level rise as observed and the sum of all contributions to such rises as quantified independently); characterising sea level rises due to the emission of greenhouse gases; and estimating the Earth's energy imbalance [4]. Adequate answers to these questions would open the possibility of improved climate system modelling, and consequently, formulating more adequate responses. However, GMSL data records have, to date, not met the latest GCOS requirements for uncertainty stability [5].

The European Space Agency (ESA) is interested in understanding where scientific research efforts and instrument engineering improvements are needed to develop a next-generation altimeter system (including data processing) to meet GCOS (and climate science) requirements. For this, ESA gathered a consortium of experts to (a) determine what uncertainties were needed for satellite altimetry to contribute to climate science questions, (b) produce a fully documented and traceable end-to-end uncertainty budget for sea level according to metrological principles, and (c) determine methods to validate obtained uncertainties.

An initial study was performed by the ESA-supported Assessment Sea Level Rise Stability Uncertainty (ASeLSU) project, delivered through a consortium of Magellium, Centre National de la Recherche Scientifique (CNRS)/Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), and Collecte Localisation Satellite (CLS) based in France, and NPL, UK. A bottom-up uncertainty analysis for the Copernicus Sentinel 6-Michael Freilich satellite observations focused on the altimeter. Propagation of uncertainties involved a thorough understanding of the altimeter waveform (the raw returned radar pulse), tracking, and retracking processes that determine the measured distance between a satellite and ocean surface — and estimates of corrections due to the 'sea state' (that is the interaction of the radar pulse with the waves of a sea surface), as well as corrections due

to time delays in the ionosphere (upper atmosphere). Subsequent work will consider the effects of satellite orbit determination and the corrections for tides and orbital variations. While these processes are linked through several parameters, they are typically developed, implemented, and assessed by different teams of experts.

In the ASeLSU project, previous activities from the whole altimetry community were collated and some approximations and assumptions established for earlier generations of altimeter missions were identified as no longer satisfactory. Flowcharts and uncertainty diagrams were produced that highlighted the origins of uncertainty and approximations. The framework for this analysis and presentation built on work in the EMRP and EMPIR project series MetEOC-1, 2, and 3, as well as the Horizon 2020 project FIDUCEO. The framework was originally developed for radiometric satellite missions, however, the ESA mission scientist requested translation of these approaches to active sensors such as a radar altimeter.

A gap identified in the ASeLSU analysis was in understanding of the propagation of uncertainties through sea state corrections. The surface of the ocean is a mixture of waves – from the long-period swell waves down to the tiniest wind-blown ripples. The interaction of the radar pulse, which has a footprint of around 300 m by 2 km, with this surface needs to be appropriately modelled through a 'sea state' correction, which depends on wind and the overall height of waves. In turn, however, the best estimates of both wind speed and the height of the waves are derived from the shape of the returned radar pulse. Because of this interdependence, understanding how uncertainties propagate through this complex analysis is far from straightforward [6].

Solution

In the EMPIR project MetEOC-4, a continuation of the project series that first developed methods for applying metrological principles to radiometric satellite sensors, a detailed scientific analysis was carried out to identify how uncertainties could be propagated through these corrections.

Figure 1 shows one of the outputs of the ASeLSU study: an overview diagram showing propagation of uncertainties from altimetry instruments, through corrections, to the global mean sea level (GMSL) and its trends. In the MetEOC-4 analysis sea state bias (SSB) correction, wind speed calculation and ionospheric corrections were investigated (highlighted in blue). NPL developed simulation tools in Python for the various processing steps, that simulated a Low-Resolution Mode (LRM) altimetry waveform with different levels of simulated noise added, based on quantities determined in the uncertainty analysis. The simulated waveform was processed in the same way that a real waveform is processed, through the so-called 'retracker' – a processor that fits the waveform to an expected model and derives basic physical parameters such as significant wave height. These parameters were then fed into other algorithms to estimate wind speed and sea state bias using reference look-up tables provided by the ASeLSU project partners at CLS, who also provided support on implementing the retracker. The simulation output estimations of range (the distance between the satellite and surface water), sea state bias, and ionospheric corrections – components associated directly with the altimeter – and identification of correlation patterns.

The JCGM Guide to the Expression of Uncertainty Measurement [7] provides two approaches to metrological uncertainty analysis: the law of propagation of uncertainties (LPU) and Monte Carlo Analysis (MCA). Due to the complex correlation effects and the highly non-linear nature of this study, MCA was chosen, which involved creating 1000 examples of altimetry waveforms, differing due to fully random thermal (additive) and speckle (multiplicative) noise. Each waveform was then propagated through the full processing chain to obtain retracking parameters, output sea state bias, and ionosphere corrections. The analysis provided the first insights into the shape and significance of correlations between these parameters throughout the official altimetry processing chain, specifically for the Copernicus Sentinel-6 Michael Freilich satellite. The results showed mild to strong correlations between parameters in many instances, highlighting a need for further studies of such patterns.

Outcome

These outputs were presented at the 2022 Ocean Surface Topography Science Team Meeting (OSTST), an annual event for altimetry experts globally to share research and evaluations of mission activities [8]. OSTST 2022 was organised by CNES, NASA, NOAA, EUMETSAT, and ESA in Lido (Venice, Italy) from 31 October to 4 November. The concept of uncertainty tree diagrams was especially well received by several altimetry scientists in the poster presentation session. Similarly positive responses applied to the initial findings of the study – that took the form of characterised error correlation structures between several intermediary parameters in the altimetry processing chain – emphasising the necessity of implementing end-to-end uncertainty analysis for complex EO thematic data products (see [8]).

This study provides tools for further insights into the trend and acceleration of GMSL and the effects of sources of uncertainty. For example, rather than only completing the processing chain for the altimeter instrument, the same approach to studying uncertainties could be applied to the onboard microwave radiometer (used to establish the amount of water in the atmosphere and how this slows down the radar pulse) and satellite orbital positioning. Such comprehensive and exhaustive research will likely identify potential improvements that may advance next-generation altimetry missions. To put it into context, improved uncertainty characterization, as required by GCOS, will open the possibility of answering some fundamental climate change questions, likely to result in better-informed climate action plans.

The study was also presented at the BIPM workshop Metrology for Climate Action 2022, as Sea level rise due to climate change: What do we know? The resulting workshop report published by BIPM endorsed the pioneering role of the ASeLSU project for adapting end-to-end uncertainty analysis for satellite missions [9]:

> *'Errors in satellite-derived climate data records are particularly complex, but progress has been made in applying FIDUCEO principles for E2E budget analysis in some cases. Use of E2E understanding to drive satellite mission requirements/ analysis has even fewer exemplars (ASELSU seems to be pioneering here). Overall effectiveness of satellite observations will be enhanced by adopting these principles.'*

All 1200 islands that make up the Republic of Maldives are featured in this image captured by the Copernicus Sentinel-3 mission. One of the world's lowest-lying countries, more than 80% of the Maldives' land is less than one metre above mean sea level, making its population of over 500 000 people extremely vulnerable to sea swells, storm surges and severe weather. Copernicus Sentinel-6 will take on the role of radar altimetry reference mission, to allow for further climate research and help scientists monitor the effects of climate change.

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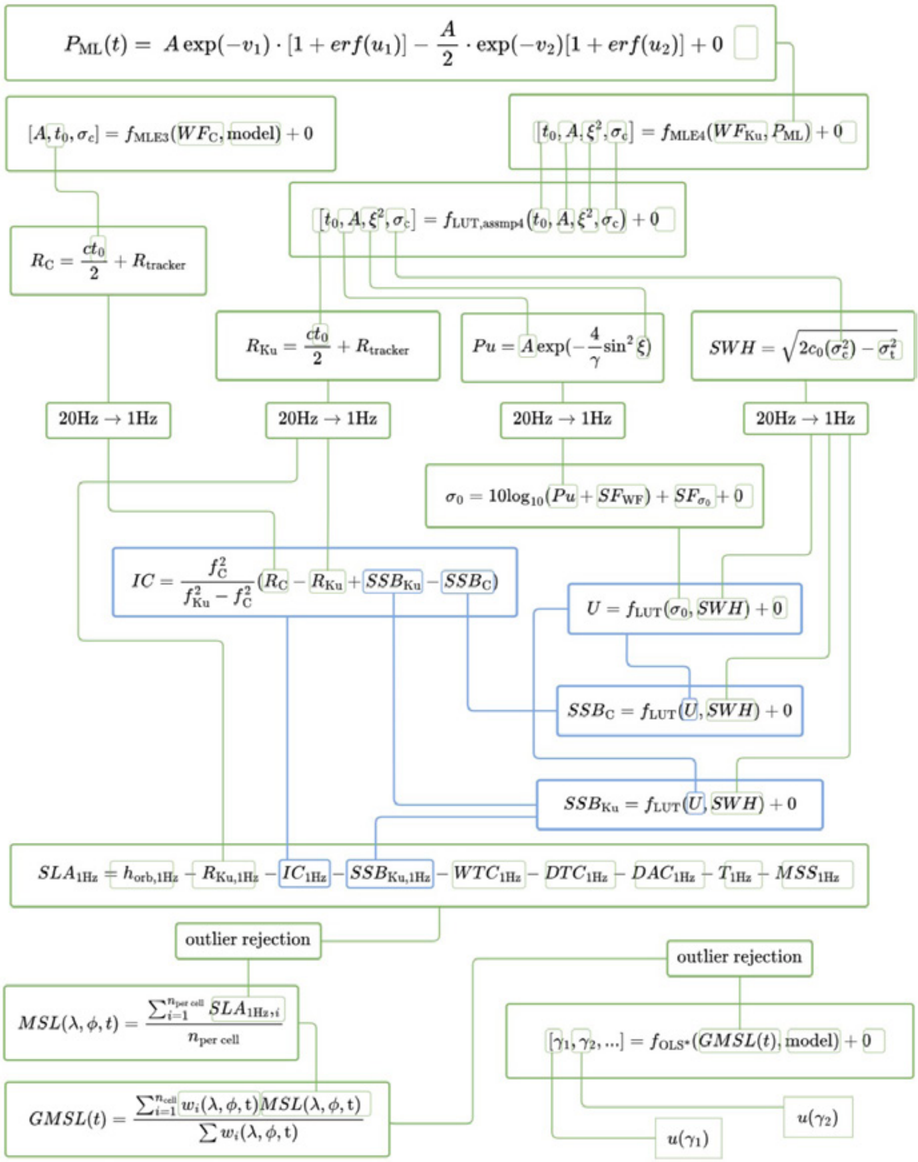

Figure 1. A simplified uncertainty tree diagram for altimetry processing over Sentinel-6 Michael Freilich data. Sections highlighted in blue were covered by the MetEOC-4 study. A fuller diagram is available in Behnia et al (2022).

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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.