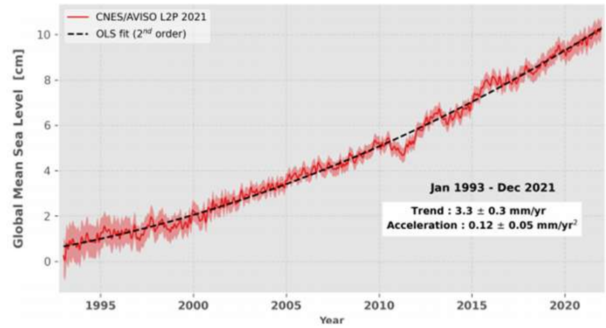
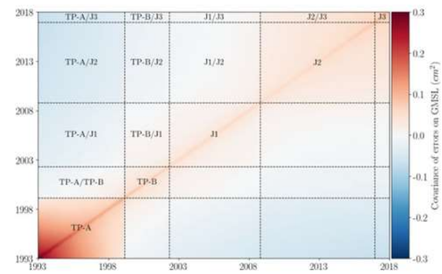
This presentation presents the work of the ASELSU project, a project conceived by Craig Donlon of ESA and funded by ESA. The project consortium is led by Michael Ablain of Magellium, with other partners listed. I am a metrologist – that is, measurement scientist (see later) and will be presenting our work.

Sea level rise uncertainties

Over 1993-2021, the **global mean sea level** (GMSL) rose by +3.3 mm/yr (*u* = 0.33 mm/yr) (90 % confidence level) and accelerated by 1.2 mm/yr (*u* = 0.6 mm/yr) per decade

(updated from Ablain et al., 2019 and Guérou et al., 2022).





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First, to motivate the project. At this conference, we’ve been discussing all the progress over the last 30 years in establishing high quality altimetry and we now have this long, valuable record of global mean sea level and the regional sea level changes. The recent papers by Michael Ablain and Adrien Guerou and colleagues have considered the different sources of instrumental and correction uncertainties and their error correlation scales, with an observation covariance matrix, that has informed an uncertainty on the sea level trend …

But, now things are changing. The requirements for S6-MF were produced a decade ago, and now we look forward a decade to consider what we need for Sentinel 6 next generation. What will be the science that we get from that new mission? If we think about the focus of the GCOS requirements, they have moved from being about individual ECVs to being about the Earth cycles, and therefore we can ask the question of what quality of data do we need to get from S6-NG in order to constrain the water cycle, or to constrain the Earth energy balance – and what improvements in S6-NG, and its processing, are needed to meet those requirements?

Requirements identified in Meyssignac et al. (submitted 2022)

	GCOS (2011) requirements	Current uncertainty over 20 years	New stability requirements*
GMSL trend	< 0.3 mm/yr	0.3-0.5 mm/yr	< 0.1 mm/yr
GMSL acceleration	Not defined	0.07-0.12 mm/yr²	< 0.05 mm/yr²
MSL trend (~100 km)	< 1 mm/yr	0.78-1.22 mm/yr	< 0.5 mm/yr
MSL acceleration	Not defined	0.06-0.12 mm/yr²	Not defined

Uncertainties are indicated at the 5-95 % confidence level.
*Endorsed by C3S. Presented in OSTST-2019. Publication recently submitted

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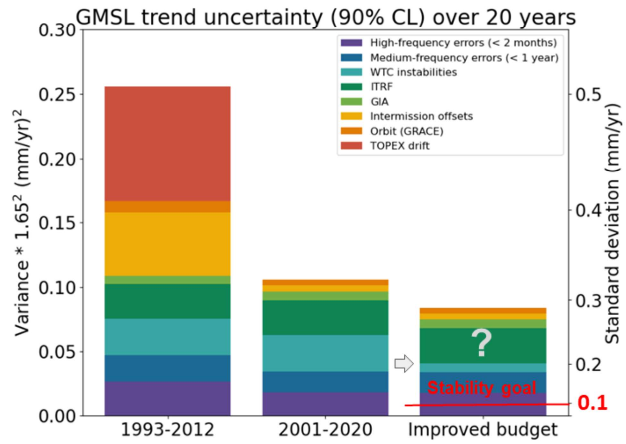
Sentinel 6 MF was built to meet the GCOS requirements identified in 2011 – but we are now asking for more. Benoit Meyssignac has led some studies to identify the requirements for both global and regional mean sea level trends to be able to close the water cycle and energy balance. These expanded uncertainties have been endorsed by the Copernicus Climate Change Service, and were presented at an earlier OSTST. Very recently, and as part of the ASELSU project, Benoit has submitted a paper summarising the explanations of these requirements. What you see here are very small uncertainties, so we need to put these into context.

Level 3 GMSL uncertainty budget

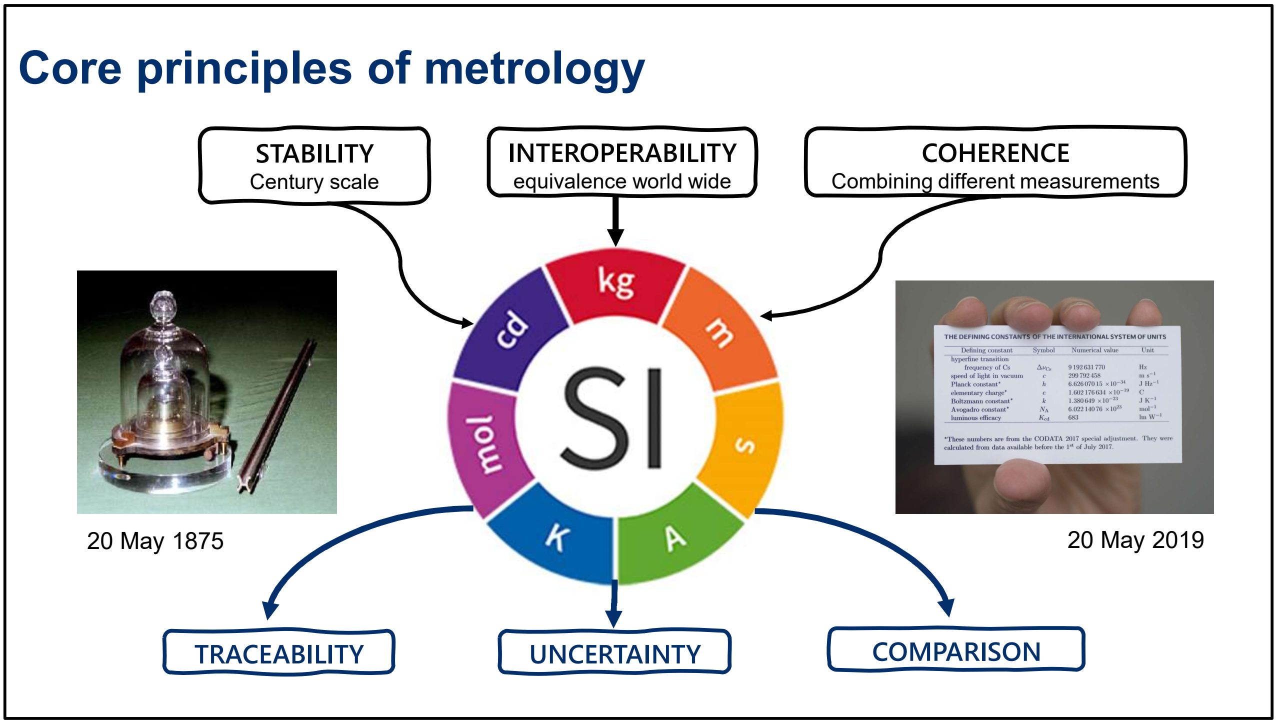
→ Main limitations of the current approach :

- All uncertainty with high frequency error correlations < 1 year (including instrumental errors) are merged together
- Potential instrumental uncertainties with error correlations > 1 year not described because unknown (e.g. SSB)
- Error and uncertainty budgets are provided by ad hoc studies (e.g., based on Cal/Val methods) that are themselves limited by their uncertainties.

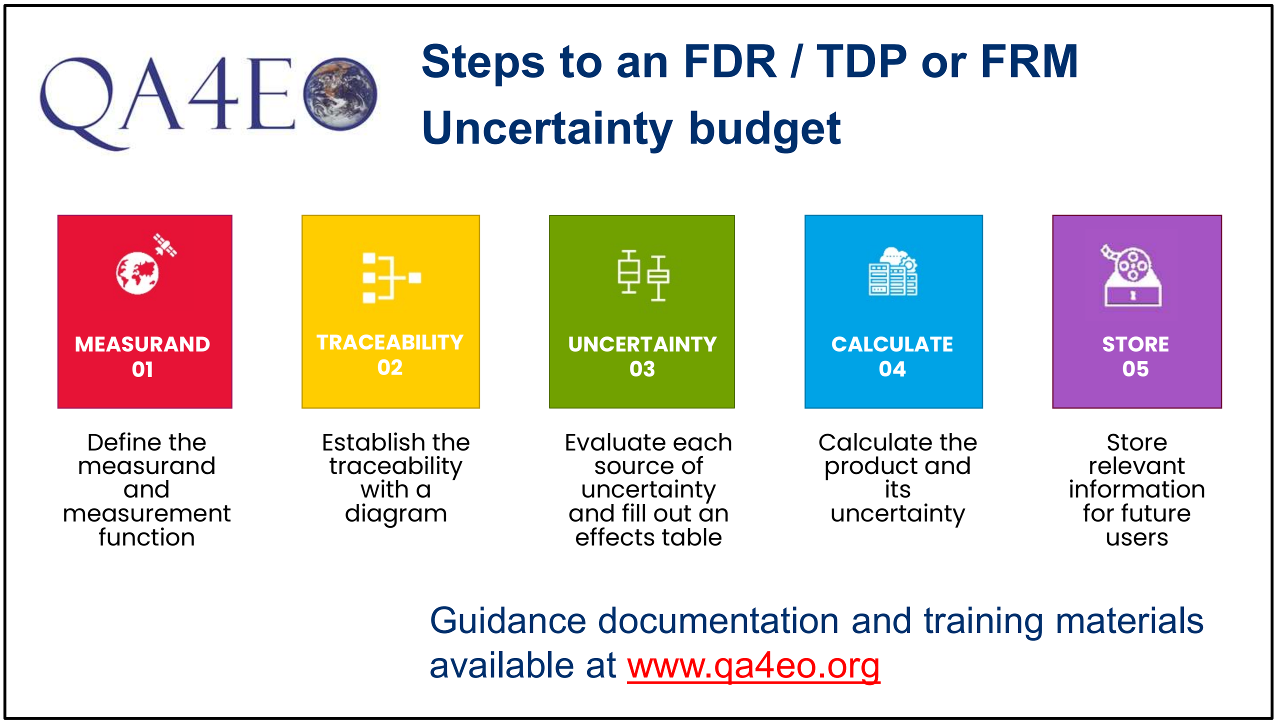


The altimeter record has been improving – partly from instrument improvements, and partly from improved methods of processing and correcting effects. So we can see here the improvements already achieved in the uncertainties. But it's clear that further work is needed on all sources of uncertainty to bring the combined uncertainty below the stability goal.
bias correction.
In order to improve uncertainties we have to understand their origins. In earlier work, we made a number of simplifications. For example, all uncertainties with high frequency error correlation scales (i.e. where we consider they vary with timescales less than one year) were combined, and considered as one 'noise' term that was estimated from the data and from comparisons with other instruments and methods, which have uncertainties themselves. Some other sources of uncertainty were not fully known, such as the sea state.

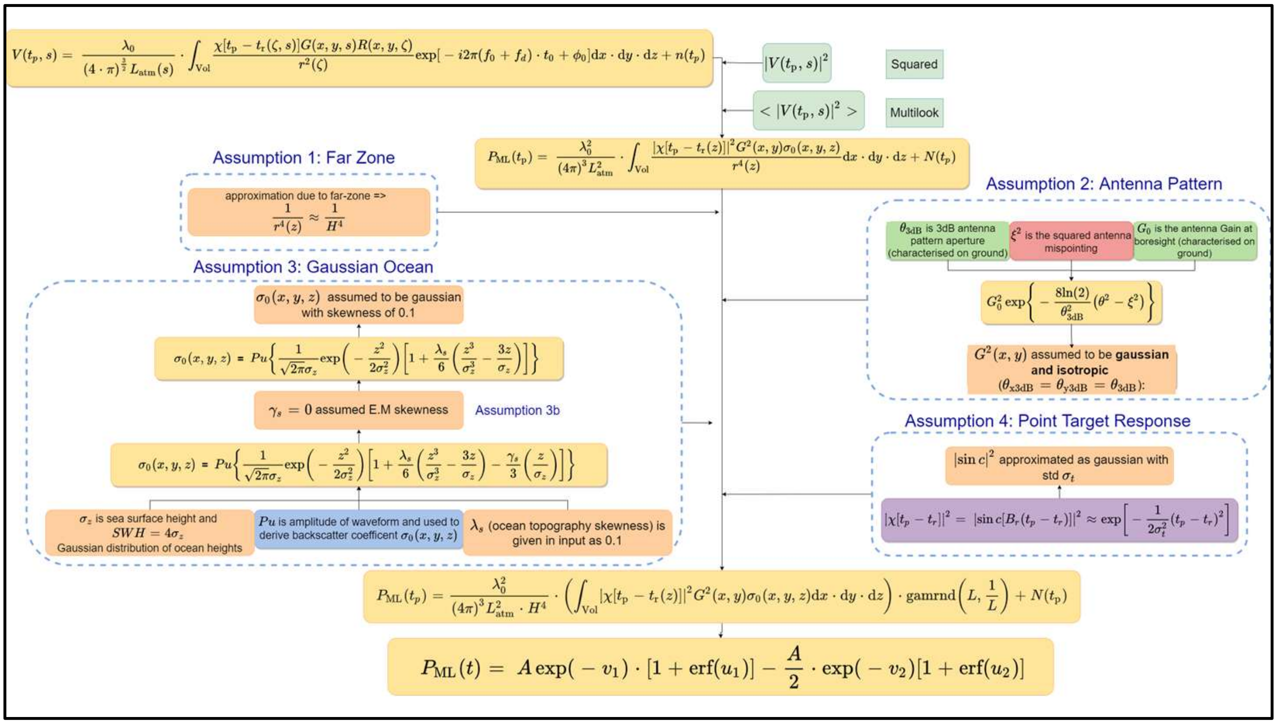
So we need to consider a new framework for thinking about and analysing uncertainties, so that we can get a more robust estimate, and understand how the uncertainties can be improved. In the ASELSU project we've focused on the uncertainties linked to the altimeter itself (the blue and purple sections of this graph) – so not the WTC or orbit. But the principles that we're using here can later be applied to the other sources of uncertainty. [yes, it's a lot of work for just a small part of the combined uncertainty…]



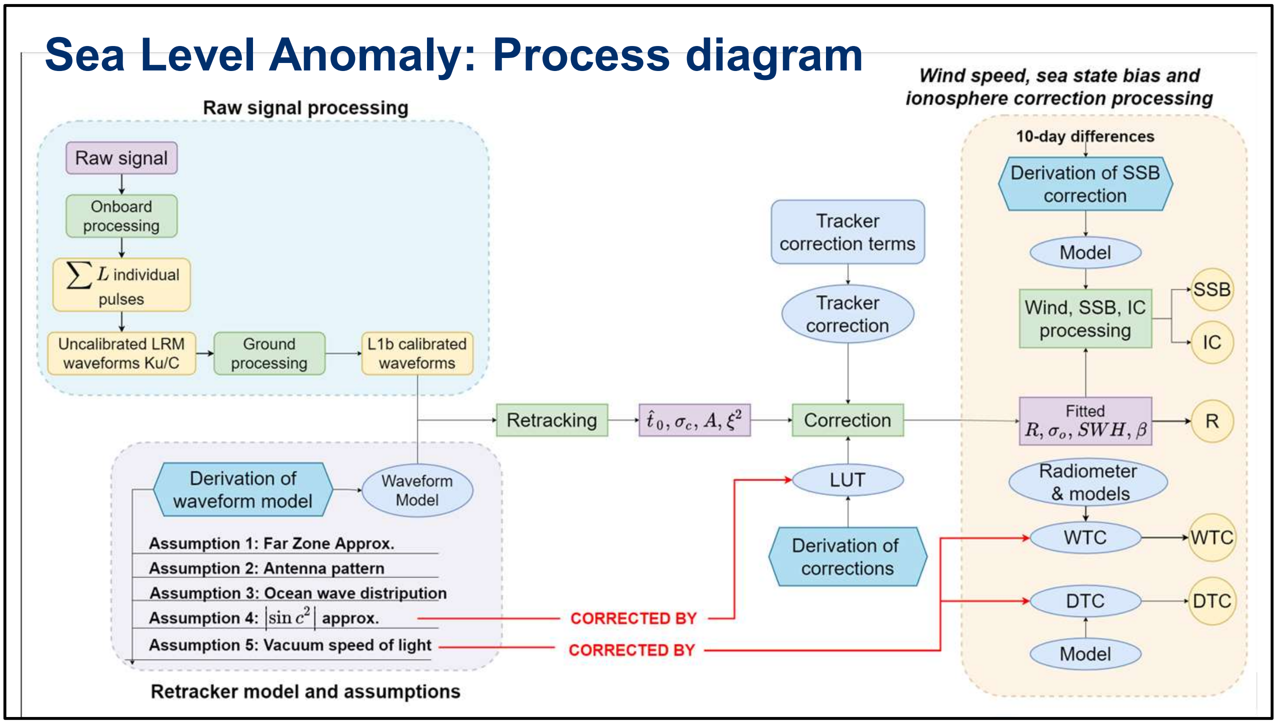
So the framework that we are using comes from metrology – that is the science of measurement, the discipline, and community responsible for ensuring the stability, interoperability and coherence of the SI units. Metrology has ensured that the metre, kelvin, kg and other units have remained constant since 1875, even as we've moved from physical artefacts to physical constants as the reference. It ensures measurements worldwide are equivalent and we can combine different types of measurement in a coherent way. Metrology has achieved this through three methods – traceability, uncertainty and comparison. And my personal work has focused on how to apply these principles systematically to satellite Earth observation – always in collaboration with expert teams who already think about these things.



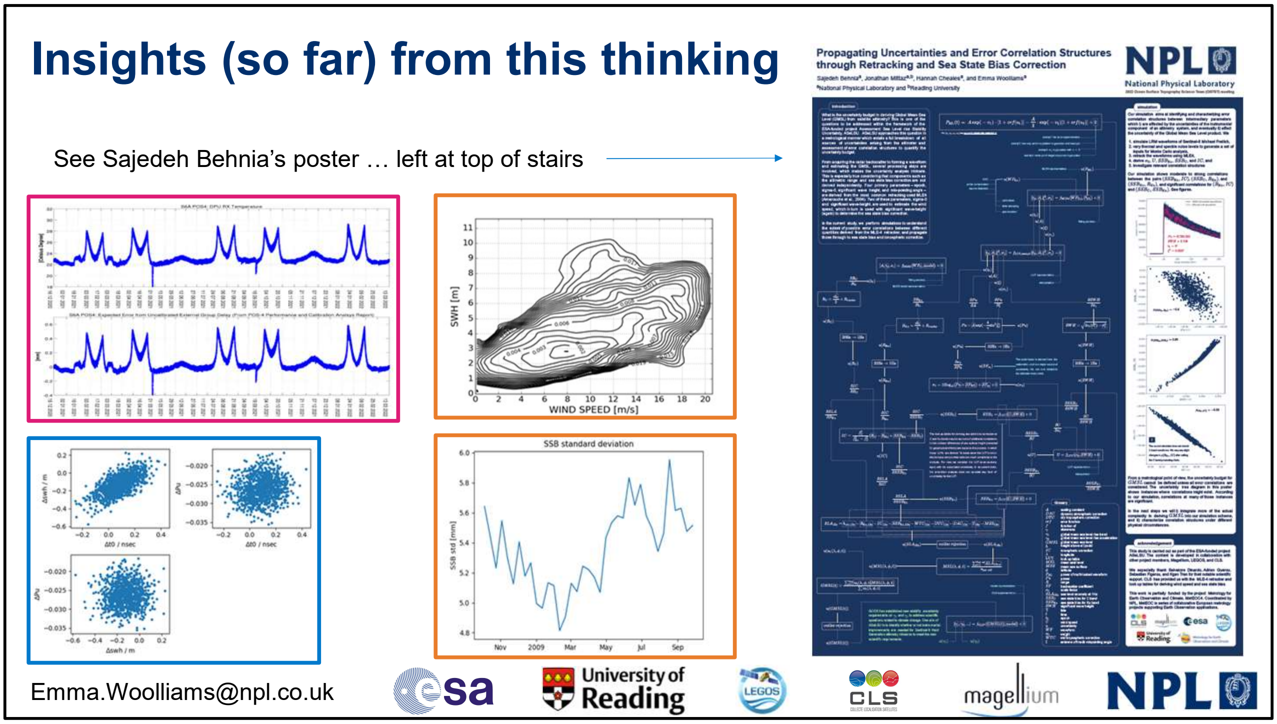
Over multiple projects – of satellite and in situ data, for passive and active sensors, we at NPL have defined a structure for thinking about uncertainties. These principles have been documented on the QA4EO website, where you can find detailed training material and short summaries of this approach along with links to open source Python tools to store and propagate uncertainty information. Within ASELSU we have looked at these steps for the altimeter sensor on Sentinel 6. This has encouraged us to think about exactly what is being measured, and how we create the traceability from the very rawest data through to a global mean sea level trend.



The method involves developing lots of diagrams, and here I'll only show a couple. This first diagram is showing the current derivation of the Brown model that the waveforms are fit to in retracking from, at the top, the complete radar equation, for LRM mode. What we bring out and emphasise in this diagram are the approximations that go into this derivation. In order to integrate the power equation analytically, we need to approximate all the terms with Gaussians. Some of these, especially assumption 4, are partially corrected later in the processing, but others aren't. As we move towards trend uncertainties of 0.1 mm, we must rethink each of these approximations, how the uncertainty associated with the approximation may lead to biases or trends. I'm aware now that new methods are being developed to replace the fourth assumption.



Once we’ve derived a waveform model, we can look at the overall process from raw signal to the range, SSB and IC. This diagram shows some of the main steps in that, and we can investigate each of these and think about the propagation of uncertainties through this process.



As an example, here are some of the detailed studies that we have done. On the right you can see Sajedeh Behnia's poster – which you can find on the left at the top of the stairs – she has a detailed diagram for the processing of the range and the SSB and IC corrections and a study of the correlations between these terms introduced even with random noise on the waveform.

The focus on SSB is very important, because at the moment it's based on an empirical correction with a lot of assumptions, and it's not clear what covariance scales there are from the uncertainties in the SSB. At the moment those uncertainties are packaged in the high frequency uncertainties, and the spatial / temporal correlations are not well understodd. Therefore we have opened up the correction to understand those processes. The contour plot graph is from the analysis of the SSB correction, as also discussed in the earlier presentation. Those studies have also shown annual and interannual variations in the SSB correction error, which are not currently considered in the look up table.

Bat ears = temperature sensitivity of the external group calibration (delay path on board satellite)

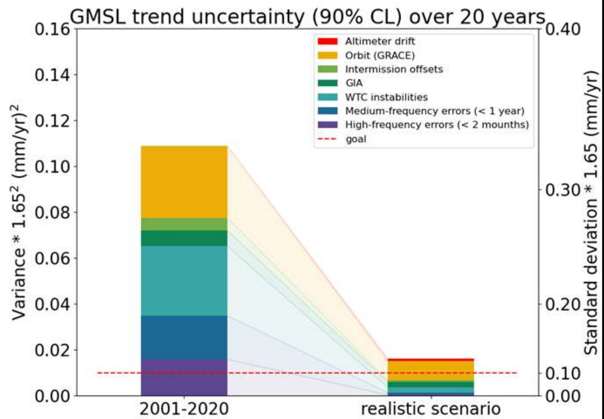
- External path is calibrated at one Temperature on-ground
    - Such approximation is not compensated for in the ground-processing
    - TAS document (*Sentinel-6 Poseidon-4 Performance and Calibration Analysis*) gives us the relation “external group path” = f(Temperature)=> function linear with slope **0.09 mm/°C for Ku band**

Suspected impact: correlated errors in time (M-shape pattern spans ~ 60 days) and occurs approximately every 6 months (follow the sun beta-prime angle).

Next steps …

- Original ASELSU project finishes at the end of the year:
  - Produced systematic review of current processing assumptions and sources of uncertainty to give comprehensive end-to-end uncertainty analysis for altimeter
- Extension / development
  - Many altimeter terms need more work!
  - Atmospheric corrections, especially WTC
  - Precise Orbit Determination (POD) analysis
  - Glacial isostatic adjustment
  - Inter-mission effects

Very preliminary considerations of possible progress



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The ASELSU project has been a one year project that ends at the end of this year, and what it has begun is a comprehensive end-to-end uncertainty analysis for the altimeter. Most importantly, it has established a framework for asking the right questions about the uncertainties. But this is very much the beginning of a longer process. The graph on the right shows the type of work needed to get close to the required uncertainties for the Sentinel 6 next generation. The most important areas for further work, beyond continuing the analysis of the altimeter, are the WTC, which is the most important at global scales and the POD, which is most important at regional scales.

Thank you for your attention, and thanks to my co-authors for their many discussions on this work, and to the ASELSU project. More material on the metrological approach, including guidelines and python tools, are given on the QA4EO website.