Summary
S6NG Orbit Workshop

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Workshop Outcomes

- Cal/Val: Results of past tandem missions – Michaël Ablain and Eric Leuliette
- Precise Orbit Determination POD - Alexandre Couhert and Frank Lemoine
- Continuity of global and regional sea level record – Noemie Lalau
- Tidal studies – Richard Ray
- Continuity in the estimate of the ocean heat content (including deep ocean), ocean heat uptake and earth energy imbalance - Maria Hakuba and Benoit Meyssignac

Summary Cal/Val: Results of past tandem missions

- ➔ Having tandem phases between successive reference mission very important to maintain accuracy.
- ➔ Tandem phases allow precise calibration of two altimeters with the detection of **systematic instrumental and POD differences** of a few millimeters to a few centimeters at different spatial scales from a few hundred kilometers to the global scale.
  - ◆ At global mean, tandem phases allowed to accurately link GMSL time series together with an uncertainty between **0.2 and 0.6 mm** (1-sigma)
  - ◆ At regional scale (a few hundred km) tandem phases allowed to detect systematic regional MSL differences **until 2 mm** (at 1-sigma)
- ➔ Tandem phases are also necessary as a **reference period** to quantify improvements in altimeter instrumental processing and POD solutions to reduce systematic differences in MSL.
- ➔ **Need to investigate the far-reaching consequences of no tandem phase in case of change of orbit.**
- ➔ **Another question: what about a step approach to change the orbit? Over several missions**

Summary Precise Orbit Determination POD -

- Platform:
  - Make flips at zero-beta values to facilitate in-flight calibration of the position of the phase centers of the DORIS/GNSS/SLR instruments to improve the validation of the orbits:
  - Improvement of the knowledge of surface force induced errors are necessary (drag, thermal effects, SRP) using an accelerometer (very low frequency measurements ~10^{-4} Hz?)

- Orbit:
  - Inclination: avoid draconic periods close to the geophysical annual and semi-annual periods
  - Altitude: **above 1000 km looks preferable** to limit drag and time-variable gravity modeling errors, and also to reduce ionosphere effects affecting GNSS receivers
  - What would be the consequence of absence of DORIS in S6C and then S6NG? How would we validate the POD performance? (new study?)

Continuity of global and regional mean sea level data record

- ➔ **We have built a uniquely stable global sea level record for over 30 years. We really need to maintain this.**
- ➔ With the existing tandem phases, we can ensure precise continuity with reduced impact on MSL trend uncertainties:
  - Global offset uncertainty: **0.2 – 0.6 mm** (1-σ)
  - Regional (a few hundred km) MSL offsets uncertainties : **2 mm** (1-σ), $CI_{95\%}$=[0.7 - 4.3]
  - Impact on GMSL trend uncertainty: < 0.04 mm/yr over 20 years (90 % CL)
  - Impact on RMSL trend uncertainty: < 0.5 mm/yr over 20 years (90 % CL)
- ➔ **The potential Sentinel-6 Next Generation orbit change challenges the way we ensure this continuity. How long would it take to get back to such a performance if the orbit was changed**

Summary Tidal studies

• M2 trends in the open ocean exist, of order 0.2 mm/y or less, evidently caused by the ocean's increasing stratification.

• M2 trends in Yellow Sea are important, of order 2 mm/y, caused mostly by land reclamation, secondarily by stratification & SLR.

• Open-ocean tide trends are difficult to map, even with T/P-J-S6.

• **Mapping results based on non-T/P-J-S6 data are not encouraging. However, if S6NG is in a different orbit, it will be challenging to extract new trend information that can build on the current T/P-J-S6 time series.**

• Work needed: experiment with different ways to combine Envisat/SARAL and Sentinel-3 with current T/P-J data. Can it be done?

Summary Continuity in the estimate of the ocean heat content and EEI

Time alone will improve uncertainties, provided the sources of uncertainty are kept at current declining levels.

- Altimetry Orbit uncertainty currently contributes at ~0.17 mm yr−1.

- Our requirements will be affected by GMSL stability changes

- Forthcoming studies of orbit change implications for GMSL stability should include implications on OHC & EEI estimation.

Summary Questionnaire

Which orbit choices would you prefer, and what would be your main reasons?

What risks or challenges should be considered if the altimeter reference mission was moved to a new orbit?

Which scientific studies might be disrupted or no longer feasible?

What advantages for scientific studies would you anticipate from an orbit change?

Do you have any additional thoughts or recommendations to share?

Responses obtained from 17 people.

Which orbit choices would you prefer, and what would be your main reasons?

- **From 17 responses, 12 in favor of keeping the existing orbit.**
- **We need an orbit that keeps the MSL historical record** as accurate as possible, including the monitoring of tidal frequencies (so not sun-synchronous)
- **We should not destroy our existing long terms Climate Data Record** required for assessing long-term change. The long-duration time series is making it possible to resolve ever-smaller tides over time.
- **No change from the reference orbit!** It has the highest merit. It is the only choice if one is serious about controlling the MSL/OHC/EEI uncertainties and reducing the uncertainty below the needed 0.1 mm/yr objective.
- **Ensure the continuity of long time series**, which are very useful for monitoring climate signals (G/RMSL) and for analyzing cyclical signals (barotropic and baroclinic tides), which remain a significant source of error in coastal altimetry.
- **Keep the same orbit altitude with a 10-day repeat cycle for S6NG providing** new measurements along consistent reference tracks. This is crucial for our operational services offering hydrological products, such as altimetry derived water level measurements over growing number of monitored inland water bodies. Having a unique multi-decadal same orbit derived altimetry data record is invaluable for all applications.
- **Keep the repeat cycle as close as possible to 10 days**; otherwise, there is nothing that will make "continuity" between S6 and S6NG.
- Maintain the existing reference track to **ensure the integrity of the sea-level climate data record**. Deserves appropriate scrutiny given the likely cost implication.

Which orbit choices would you prefer, and what would be your main reasons?

- **5 out of 17 in favor of moving into a different orbit:**

- **High inclination orbit if it is not disruptive with climate record.** To better cover the Arctic and southern Ocean as it will see strong climate change signals. Is required to close the sea level change budget.
- **Need for fast revisit times**, is nowadays better mitigated with parallel missions.

- The original SeaSat orbit with a repeat period of 17.05 days is **optimized for ocean mesoscale sampling**, which falls in line with the altimetry project mission at the Naval Oceanographic Office, which is to provide sea surface height anomaly, significant wave height, and marine wind speed to the Navy's ocean circulation model.

What risks or challenges should be considered if the altimeter reference mission was moved to a new orbit?

- 17 responses
- The existing sea-level climate data record is a seminal record of fundamental societal importance. Decisions of profound importance are, and will continue to be, made based on this record. The record needs to be maintained.
- **The public can appropriately demand confidence in the sea level record. Any change to the construct of the record will undoubtedly attract unhealthy skepticism and undermine confidence,** especially in an increasingly populist and partisan world – that is inevitable and not necessarily a reason to maintain the current orbit at all cost.
- **Moving to a new orbit weakens assessment of long-term change**, which is particularly important in communicating with skeptics
- **Greatest risk are to increase the uncertainty on the MSL record and the possibility of introducing b**iases to long-term trends (despite the best mitigation efforts).
- **Great risk to not being able to compute inter-mission bias with enough accuracy.** Only tandem phases have proven efficiency for doing that.
- After changing the orbit decadal-scale changes of HF error aliasing (tides, atmosphere, DAC, ionosphere : none of them is stationary) **could not be investigated, let alone disentangled** from technical/engineering problems.
- **Huge risk that S6NG becomes just "another altimeter"** which is not needed anymore. Hence it will not be funded. If we move the orbit by too much, we will lose the identity of the mission. Interruption of the long time-series over virtual hydro or coastal stations. With swath, no more measurements at nadir. **Loss of continuity!!!**

What risks or challenges should be considered if the altimeter reference mission was moved to a new orbit?

- Risk of degradation in measurement quality. **Therefore, there is a non-negligible risk of failing to detect, understand, and correct anomalies in future Sentinel-6C measurements if a different orbit from the historical one is chosen.**
- **Interrupt and/or stop providing supporting some operational services,** some data applications, that specifically rely on the continuity and reliability resulting from the same consistent validated altimeter reference mission orbit, to numerous customers and users in need of continuation of the long-term climate data record.
- **New Cal/Val activities and resulting issues for new orbit mission measurements** would require additional work for new mission algorithm and product development, release, and interpretation for most groups and customers. Some calval initiatives using ground truth measurements may become more difficult to plan, with a more diverse set of orbits.
- In theory, can the new orbit be occupied for 25+ years? **Long-duration observations are uniquely valuable, so we should try to achiev**e what might now seem like an impossibly-long time horizon for a series of missions.
- Continuation of climate record consistency, for example, no trends should be introduced by orbit difference. A multiple-year overlap between old and new orbits should be a requirement.

What risks or challenges should be considered if the altimeter reference mission was moved to a new orbit?

- Increasing the ocean measurement over the polar regions can be done by interleaving another S3 into the S3 pair of missions. Within the orbit options, none of them is at 27 days but what is more important, none of them is sun-synchronous. What makes me think that we don't want sun-synchronous orbit for the ocean, but why are we keeping it in S3NGT??
- Why don't we unify the orbits between S6NG and S3NGT making them complementary (from the topography point of view)
- **Bespoke processing for RA data collected in ice-covered waters will be required. Tidal** corrections in the Arctic are not as reliable (due to a lack of coverage by historical altimeters) and will need special attention.
- **There are many studies showing the TOPEX / Poseidon - JasonX - Sentintle6A orbit is not good for mesoscale eddy sampling.** The inclination makes the TOPEX orbit rather high in latitude. If you are interested in ocean mesoscale, you're spending a lot of time over ice. What is the payoff? People have had decades to develop applications.
- Who is really using the data for ice? For ice, there is much more much better information from microwave, visible, and SAR. Spend the time observing features that matter. Otherwise, you are wasting data, and the cost per useful observation is higher than necessary.

Which scientific studies might be disrupted or no longer feasible?

- 15 responses
- **Any related study concerning long-term trends is vulnerable.**
- **Anything that is based on long time series** (coastal MSL series, tides, hydrology stations…) and any signal that is small enough to be hidden by geographical/ sampling variability.
- Mean sea-level rise is probably the most important, but estimates of long-term changes in mesoscale eddies, boundary current strength and location, and internal tides could all be biased by a change.
- **Increasing the uncertainty on the MSL record would increase the uncertainty in the sea level decomposition and derived quantities such as the Earth Energy Increase, and other metrics monitoring the anthropogenic impact on climate change**
- The characterization of the error on sea level record and our ability to determine sea level acceleration might be compromised or even un-feasible.
- **Studies which rely on existing crossover points**. Possibly time investment is needed to re-tune multi-mission altimetry calibration. (operational) Ocean data assimilation schemes which rely on the existing repeat orbits may be affected

Which scientific studies might be disrupted or no longer feasible?

- **Assessments of non-phase-locked tides require an excellent reference orbit; this could become challenging.** Studies of smaller linear and higher-order tides (see Richard Ray's works over the last few years) depend on having the longest possible records on exact repeat tracks. Studies of trends and interannual variability of the barotropic tides would be significantly complicated by a switch to new ground track.
- **Change in continental hydrology in the frame of CC: It will be quite tricky to keep inland water coverage if the orbit is change.** We will lose some targets that have been monitored every 10 days during the las 30 years. For the ocean, some cross overs with buoys might be also disrupted and new alignments might need to be done. On the same way, passes over transponders or corner reflectors might be discontinued between S6 and S6NG.
- **Numerous users and customers are in need of consistent validated long-term water level information** derived from altimetry data for various scientific research topics, or operational applications and services, especially forecast systems, climate, extreme events, sea level rise, inland water and ice changes, etc. If the longest stable climate data record is to be disrupted, we lose the advantage of same reference measurements, and the accuracy and validity of scientific conclusions, important for any future changes.

Which scientific studies might be disrupted or no longer feasible?

- **Bass Strait validation facility** that has provided a sustained contribution to altimeter validation since the launch of TOPEX/Poseidon. The site has sustained in situ instrumentation at offshore comparison points that service the reference track, Sentinel-3A and Sentinel-3B. The site also played an important role over the SWOT validation phase. At worst, a shift to a new orbit would require reconfiguration of the site and selection of a new comparison point.
- **While not impossible, this would break a sustained record where we have detailed understanding of local site conditions (tides, waves, troposphere etc).** A significant shift in location may prove logistically prohibitive. The location of the existing in situ facilities warrants some consideration. The relative validation approach using the global tide gauge network will also be impacted to some extent. The approach by Watson et al. (2015) was reliant on the long record along the reference track to estimate residual tidal energy between the tide gauge and offshore points. Reliance on tidal models is likely to be acceptable, but that change to the "ALT-TG" noise characteristics will be complex depending on the orbit characteristics. This will likely have some impact on the quality of the tide gauge validation that can be achieved (noting this could potentially improve depending on the proximity of a new orbit to tide gauge locations).

- I cannot think of any if we have a tandem S3NGT satellites.

What advantages for scientific studies would you anticipate from an orbit change?

- 13 positive responses
- **High-latitude coverage and longer duration (lower cost). Better Arctic ocean change, possible land-applications in fragile high latitude zones (e.g. permafrost, inland waters in remote areas).** Covering higher latitude, e.g., Arctic and Antarctic coast, will recover a missing puzzle of the global sea level. will enable a wide range of advantageous and timely studies, including, studies of sea level variability, significant wave height, wind speed, mean sea surface, geostrophic circulation, Arctic marine geoid, sea ice.
- **A higher inclination orbit offering increased higher latitude coverage would offer several benefits (e.g. sea-level fingerprint studies being** closer to the source of mass loss, further improvements to high latitude tidal models which are important for e.g. GRACE de-aliasing, and truly 'global' sampling of the Earth's Oceans, rather than the current ±66° limit). Maintaining a mix of inclinations across the constellation is a further important consideration.
- **A change in orbit could lead to different or less problematic tidal aliasing. The** orbit change could provide interesting examples of tidal phenomena (in either SSH or sigma0) at locations which were not measured by the reference mission. Although SWOT and CryoSat-2 are providing similar information, a long-duration mission in a new (tide-resolving) orbit would eventually provide new information. A key criterion for me is to at least maintain a non-sun synchronous orbit with a repeat period favorable for tidal studies. Particularly in the coastal domain, data from a new track would be beneficial to constrain tidal models – albeit with obvious challenges.

What advantages for scientific studies would you anticipate from an orbit change?

- There are many arguments against the need to maintain the 'reference' orbit. Ocean prediction has been degraded for decades because of the requirement to maintain the reference, **so performing studies to show that it may not be needed would be beneficial.**
- Saving money to spend on a different sensor that would provide different science (not topography). If we break continuity on a unique a 35-year Climate record, it is ONLY because of budget concerns. So, we might as well bite the bullet and cancel the S6 series altogether and spend the money elsewhere.

Do you have any additional thoughts or recommendations to share?

- 12 responses
- It is essential that we have the most accurate MSL record possible. We need, now more than ever to monitor the anthropogenic impact to monitor if we are doing the right things
- The ultimate impact on science depends on what other altimeters are operating. If the same orbit can only be continued with lower quality data, at some point the benefit of continuity is eliminated. Ending a continuous timeseries is a one-way trip.
- **Have a good discussion and make the right decision!** We should conduct OSSEs as a community effort. Need also to consider other orbit changes, such as for S3-NG.
- The polar altimetry community strongly support consideration of a lower orbit/higher inclination of the Sentinel-6 Next Generation (S6NG) mission to obtain long-term coverage of the rapidly changing Arctic Ocean. Without such measurements, global sea level cannot be fully quantified and understood.

Comments J. Church

1. **Perhaps we should think about what changes in the Earth system we would expect in the future.** Richard Ray raised the issue of increased stratification. But I suspect a bigger change is the change in the geoid from changes in land water storage and changes in the mass of the Greenland and Antarctic ice sheets (both critical issues). Perhaps these will be measured by time variable gravity missions but perhaps we should think about how these will be expressed in sea level changes – for North America/Europe these will likely result in less/greater sea level rise from Greenland/Antarctic than the global average and different patterns elsewhere. Again this is a critically important issue. Should we be aiming at measuring this sea level signal and not just rely on gravity missions? Perhaps this issue needs t be factored into future studies?

2.If there is a change in the orbit, then there needs to be AT LEAST a one year overlap between the two missions. And we have learnt a lot such that with at least a year overlap then many of the issues are likely to be addressed.

3.I had not thought about the movement of the absolute measurement sites. Chris Watson might have a better idea but **I suspect that it would be very difficult to set up a new absolute calibration site in Australia –** the funding situation has changed significantly but there are new players who might be interested.

4.I did not understand the difference between a future reference orbit and a non reference orbit.

5.This is more a funding rather than a science question – what ensures continuity in the longer term. Would less expensive satellites help secure the indefinite funding of future missions.

Sugested Studies:

- ESA-supported **ORBITAS study** aims to assess the impact of the S6-NG orbit change, including on the continuity of global and regional sea level measurements
- Objectives:
  - Quantify the potential continuity loss under several S6NG orbit scenarios
  - Evaluate alternative calibration strategies, including multi-mission crossovers

Sugested Studies:

- **Overall sampling:**
- Investigations using Sentinel-3A, 3B, SARAL and SWOT data, at least on initial inspection, seem to yield ~comparable GMSL records noting reliance on existing tidal models and differences in instrument performance as well as sampling. While I would like to see a detailed study before concluding, my sense is that an orbit change *and* maintaining the integrity of the GMSL record are not mutually exclusive. Should there be an orbit change, I do however have a clear preference on the type of orbit which I outline below.

We should conduct OSSEs as a community effort to look at all aspects, including eddy sampling and high-latitudes and CAL/VAL aspects.

Need also to consider other orbit changes, such as for S3-NG.

- **Required Tide studies**
- Work needed: experiment with different ways to combine Envisat/SARAL and Sentinel-3 with current T/P-J data. Can it be done?

Summary Cal/Val: Results of past tandem missions

➔ Work is required to what extent existing CAL/VAL sites have to be rebuild/shifted etc and what this implies.

- **We need to comprehensively understand any possible systematic effect of any change and plan ongoing validation carefully. Can we ensure that alias periods of periodic and quasi-periodic signals are well understood?** Can we reasonably predict likely envelopes of systematic differences driven by sampling alone? One of the many successes of altimetry has been the way in which validation is integral to mission design.

- **A hallmark of altimetry missions is a diverse array of validation approaches which are ongoing and intrinsic to mission operation – the cyclic release / understand / improve / update approach has served the community brilliantly.**

- Some aspects of validation such as the long term in situ validation sites have the potential to be impacted depending on the placement of a new orbit. Purely from a public confidence perspective, maintaining connection with these long-term series provides both a scientific connection, but a qualitative one as well. Apart from the quantitative benefit, the qualitative nature of such a connection back to independent physical measurement evidence is important not to underestimate. I elaborate further on the potential disruption to in situ validation below.

Required POD studies

- The accuracy of current GNSS orbits still needs to be thoroughly validated using SLR and DORIS
- Determine the required performance for an accelerometer adapted for altimeter missions (along-track only?)
- Identify which background models have inadequate quality, which error models we have, and how to use them?