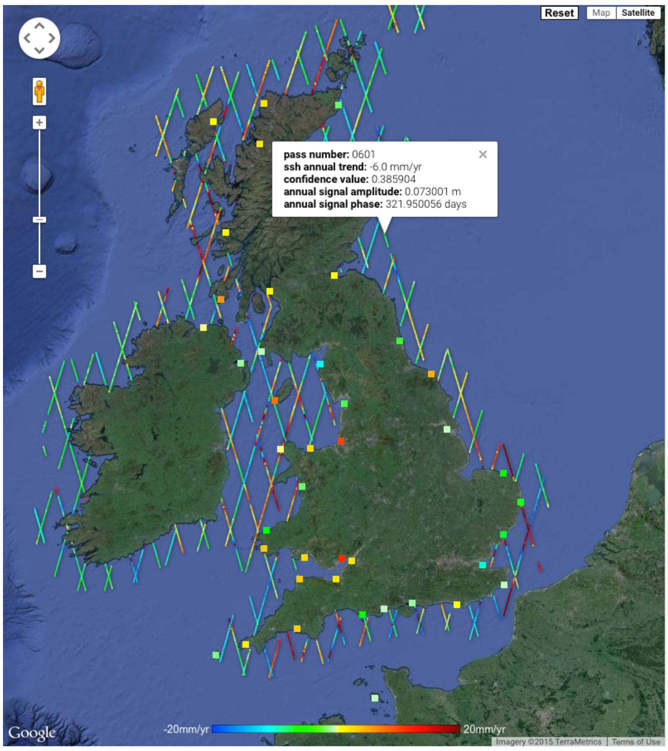
Sea Level SpaceWatch

Space for Smarter Government Programme

Final Report and Executive Summary
Version 1.0
20th May 2015



REPORT for the Space for Smarter Government Programme
The work described in this report was done under a grant from the UK Space Agency
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CHANGE RECORD

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Sea Level SpaceWatch is a short-term project, funded by the UK Space Agency under the Space for Smarter Government Programme (SSGP), and carried out over January to March 2015. The project developed a prototype service to support national flood defence planning, which when operational would provide systematically updated sea level advice around the UK using data from space-borne altimeters in combination with tide gauge data.

The aim of the UK Sea Level SpaceWatch service is to complement and supplement the UK Climate Projections (UKCP09) observed climate data for sea level and the MCCIP (Marine Climate Change Impacts Partnership) reports, providing the latest figures on observed sea level around the UK in a rolling archive. The availability of shorter-term (one year) estimates of the sea level rise rate next to the longer-term rates will give planners the opportunity to verify the regional variability of sea level around the UK at multiple time scales and observe the presence of any significant inter-annual changes.

The initial phase of Sea Level SpaceWatch, as supported under SSGP, comprised the development and review of a demonstration web based service with coastal sea level data products generated from Radar Altimeter data from the European Space Agency Envisat mission. These data, covering the period 2002-2010, were generated using new processing schemes developed at NOC which allowed the retrieval of valid data from the Envisat altimeter closer to the coast, and at higher resolution, than was previously available. The costs of managing and maintaining UK coastal defence infrastructure are very high (~£10billions), so enhanced information on sea level variability which supports improvements in the efficiency of investment decisions could lead to significant long term savings.

This project was guided and reviewed by three core users: the Climate Change Committee, the Environment Agency and Natural Resources Wales. The service was presented and reviewed at a workshop at the National Oceanography Centre in Southampton, attended by users and sea level scientists. The conclusions of the workshop were that the service did meet core user needs, filling a key gap in the information needed by those responsible for assessing the future risk of coastal flooding and for planning our coastal defences, but that some further developments were needed. In particular an integrated sea level information service is needed, which brings together key statistics and analyses from both satellites and tide gauges, and presents them in a way that is easily interpreted and applied by the key agencies.

Therefore it is planned to apply for support to complete these further developments, leading to a business plan for implementation of an operational sea level service for coastal defence planning within 12 months.

Acronyms and Abbreviations

Abbreviation	Meaning
ALES	Adaptive Leading Edge Subwaveform Retracker - the coastal altimeter processor developed at NOC
CCC	Climate Change Committee
CCI	Climate Change Initiative
CCRA	Climate Change Risk Assessment
CNES	Centre National d'Etudes Spatiales - The French Space Agency
COASTALT	An ESA-funded project to develop and promote Coastal Altimetry
CP4O	Cryosat Plus for Oceans. ESA and CNES funded project to promote ocean application of Cryosat SAR altimeter data.
Cryosat	ESA satellite altimeter mission to measure the cryosphere (2010-)
Csv	Comma separated values
DARD - NI	Department of Agriculture and Rural Development – Northern Ireland
EA	Environment Agency
ECV	Essential Climate Variable
Envisat	ESA Earth Observation Mission, operational from 2002-2012
EO	Earth Observation
ERS-1	ESA Earth Observation Mission, operational from 1991-2000
ERS-2	ESA Earth Observation Mission, operational from 1995-2011
ESA	European Space Agency
IPCC	International Panel on Climate Change
Jason-1, Jason-2	US French Satellite Altimeter missions (2001-2013, 2008-)
JASON-CS, Sentinel-6	Joint US, European Satellite altimeter mission, it will carry a SAR mode altimeter and fly on the Jason series reference orbit.
MCCIP	Marine Climate Change Impacts Progamme
MSL	Mean Sea Level
Netcdf	Self describing data format, commonly used in scientific research
NOC	National Oceanography Centre
NRW	Natural Resources Wales
NTSLF	National Tide and Sea Level Facility
QA	Quality Assurance
SAR	Synthetic Aperture Radar
SatOC	Satellite Oceanographic Consultants
SEPA	Scottish Environment Protection Agency
Sentinel-3	Series of EO satellites in the EC/ESA Copernicus programme that will operate SAR mode radar altimeters
SLA	Sea Level Anomaly
SLSW	Sea Level SpaceWatch
SSGP	Space for Smarter Government Programme
SSH	Sea Surface Height
SSHA	Sea Surface Height Anomaly
SWH	Significant Wave Height
S-3	Sentinel-3: ESA EO mission due for launch in 2015
Topex-Poseidon	US French satellite altimeter mission (1992-2006)
TWLE	Total Water Level Envelope
UKCP09	UK Climate Projections (2009)
WCMC	Wales Coastal Monitoring Centre

1 INTRODUCTION

1.1 Project Objectives

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1.2 Report contents

In the following sections of this report we review the user requirements for the Sea Level SpaceWatch Service, provide an introduction to the science and innovation behind the data products on which the service is based, present the prototype service and an analysis of the initial products, review this service in terms of how well it meets the key user needs, and finally provide conclusions and recommendations, which include key steps on a roadmap to implementation.

As required in the Grant award letter, a financial report is included as Annex A.

We provide an outline programme for the final pre-operational developments to the Sea Level SpaceWatch service in Annex B

2 USER REQUIREMENTS

2.1 Overview – Requirements for regional variability in mean sea level

The Sea Level SpaceWatch (SLSW) service is directed at the government agencies responsible for flood defence planning with the aim of complementing and supplementing the UK Climate Projections (UKCP09) observed climate data for sea level and the MCCIP (Marine Climate Change Impacts Partnership) reports. This is achieved by providing the latest figures on observed sea level around the UK in a rolling archive. The availability of shorter-term (one year) estimates of the sea level rise rate next to the longer-term rates will give planners the opportunity to verify the regional variability of sea level around the UK at multiple time scales, and to observe the presence of any significant inter-annual changes.

To this end the SLSW team engaged with key users from the UK Climate Change Committee, and the Flood and Coastal Erosion Management team within the Environment Agency, to ensure the service met their requirements, summarised below

2.2 The Climate Change Committee

The UK Climate Change Committee (CCC) was established by the UK Climate Change Act (2008) and is responsible for providing 5-yearly updates to the Climate Change Risk Assessment (CCRA), which has the following objectives:

- Assess current vulnerability to climate, adaptation
- Assess future risks and adaptation
- Summarise priorities for 2018-22 (including evidence gaps)

The next draft CCRA evidence report will be prepared for peer review in October-November 2015

The types of sea level information the CCC needs, ideally in the form of a synthesized expert analysis of evidence with links to the supporting data, are:

- Regional trends in mean sea level around the UK.
- Regional trends in peak tides (e.g. highest tide level per annum).
- Number of times tide level thresholds are exceeded.
- Number of times coastal defences are breached per annum, and location.
- Comparison of current trends in sea level with future projections; which pathway are we currently following?

2.3 The Environment Agency

The Environment Agency has responsibility to provide the strategic overview for flood and coastal erosion risk, and operational responsibility for preventing and managing flooding from rivers and sea. Coastal flooding is the 2nd highest priority on the National Risk Assessment and the costs of managing and mitigating this risk are very high. The estimated replacement value of EA maintained Flood Risk Managements assets is £24bn, and the present value of the cost of managing flood and erosion risks over the next 100 years is £25bn (for projects where benefits outweigh costs).

The EA works with local bodies to establish Shoreline Management Plans. These plans consider three time scales (20, 50 and 100 years) and are based on range of inputs including estimates of flood probabilities, models of shore erosion, etc.

The overall aim of these plans is to manage risk by applying management at appropriate times, and key issues that inform this strategy are:

- Mean Sea Level (MSL) change will strongly govern future flood probabilities.
- Coastline position is strongly dependent on Mean Sea Level and timing of acceleration.

- To identify adaptable pathways they need a good understanding of possible future trajectories of sea level trends.
- Large investment decisions need long lead times. It is essential that we monitor trend particularly to pick up accelerations.

2.4 Devolved Agencies

Devolved agencies in Scotland (Scottish Environment Protection Agency - SEPA), Wales (Natural Resources Wales - NRW and the Wales Coastal Monitoring Centre - WCMC) and Northern Ireland (Department of Agriculture and Rural Development – DARD) have similar responsibilities and interests, but due to the short time scale and limited resources of the project the team was only able to get additional direct input from Natural Resources Wales.

NRW noted that, in addition to the management of coastal defences, there is also a responsibility to preserve sensitive habitats (Natura 2000) from sea level rise and associated flood impacts[1]. In the event that it is not possible to preserve existing habitat, he cost of compensatory habitat creation are estimated to be of the order of ~£100k per hectare and an NRW briefing note estimates that 784 hectares are at risk in the next 10 years (with more than double that by 2055)

NRW strategic planning is based on UKCP09[2] median (95 percentile) profile sea level rise scenario. The NRW flood and operational risk management department would require ongoing monitoring of real sea level rise against the UKCP09 trajectory. This information will help manage both their flood risk management of Wales and their provision of adequate compensation habitat.

NRW are looking for the following information from the satellite sea level service

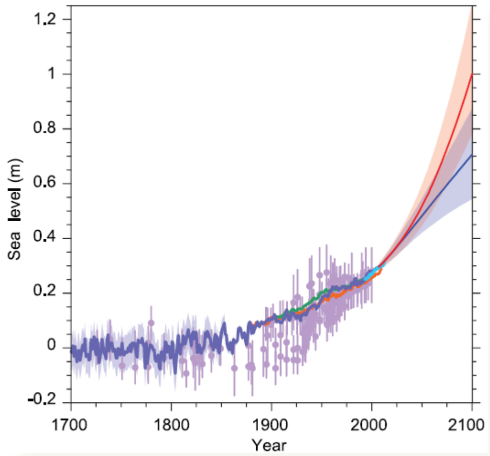
- Do the altimeter data confirm whether the observed trend is consistent with UKCP09 sea level projections?
- Can the altimeter data be used to provide confidence levels and an indication of whether the observed change is statistically significant?

[1] NRW Briefing Note: National Habitat Creation Programme
[2] UK Climate Projections (2009): http://ukclimateprojections.metoffice.gov.uk

3 COASTAL SEA LEVEL FROM SATELLITE ALTIMETERS - THE SCIENCE AND THE CHALLENGE

3.1 Introduction: Regional Sea Level Variability

It is now well established that global sea level is increasing, currently at a rate of over 2.5 mm / year and that this rate of increase is expected to increase further, with the latest IPCC reports projecting a rise of ~53cm by 2100 (median value relative to 1986-2005 for the RCP4.5 scenario). However, this rise is geographically non-uniform, with significant regional variability (Figure 1) such that some regions show a higher rate of increase and other regions even showing a slight decrease. Also this rise is not steady in time, with short-term variability on a range of time scales (daily, seasonal, inter-annual, decadal) due to different influencing factors. A wider discussion of these factors is beyond the scope of this report (see e.g. Calafat et al, 2012), but it is clearly important to measure and understand these regional and short-term variations in sea level, so that appropriate planning can be made for the sea level change expected for the local coastline. The objective of the Sea Level SpaceWatch service is to provide this locally relevant sea level information to the key user agencies.



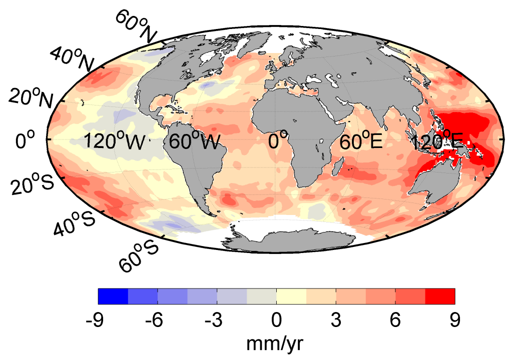


Figure 1: (Left) Global Sea Level rise, measured and projected, according to IPCC AR5. (Right) Distribution of sea level trends from satellite altimetry, showing significant regional variability.

3.2 Sea Level Measurements from Tide Gauges and Satellites

Tide gauges have been providing sea level measurements at some sites for over a hundred years. They make continuous measurements and are the current basis for monitoring tides, surges, flooding events and long term sea level at key locations across the world's oceans. In the UK, 43 tide gauges form the UK Tide Gauge Network and are operated by the National Oceanography Centre (NOC) on behalf of the EA. These data, and related analyses and expertise, are made available through the National Tide and Sea Level Facility (NTSLF). However, whilst tide gauges provide continuous measurements, data are only available at limited number of specific tide gauge locations. Tide gauge sea level measurements are site specific and can be significantly influenced by local factors, such as the oceanographic dynamics of the local area (e.g. bay or estuary) and by local land movement.

Satellite radar altimeters have been providing continuous, accurate, global measurements of sea level for over 20 years, since the launch of ERS-1 in 1991. The satellite radar altimeter sea level data record, particularly that of the Topex-Poseidon and Jason series of satellites, is now well established as an accurate climate quality record, and has been the basis for providing the global trend over recent years. Recently The European Space Agency (ESA) has initiated a number of projects to support the production of Essential Climate Variables (ECVs) under its Climate Change Initiative (CCI) programme, one of which is directed towards producing a Sea Level ECV product. However, although the coverage of satellite altimeters is global, measurements at any given location are intermittent, with the revisit time determined by the satellite orbit (10 days for the Topex/Jason series of satellites, 35 days for ERS-1, ERS-2, Envisat and AltiKa).

So, whilst tide gauge data provide continuous coverage at a limited number of sites, the satellite data provide much wider spatial coverage, but with intermittent sampling (Figure 2). Only by bringing together data from both sources can we identify regional patterns of variability and provide a link between sea level measurements in the open-ocean, shelf seas and coastal zones. However, making the direct connection between the sea level measured by a tide gauge and that measured by a satellite altimeter is not a trivial exercise, as the two measurements will be separated in time and space and one must understand how all the components contributing to the total sea level vary in the locale of the tide gauge (Figure 3). One must also of course take care to ensure consistent corrections are applied to both sets of data.

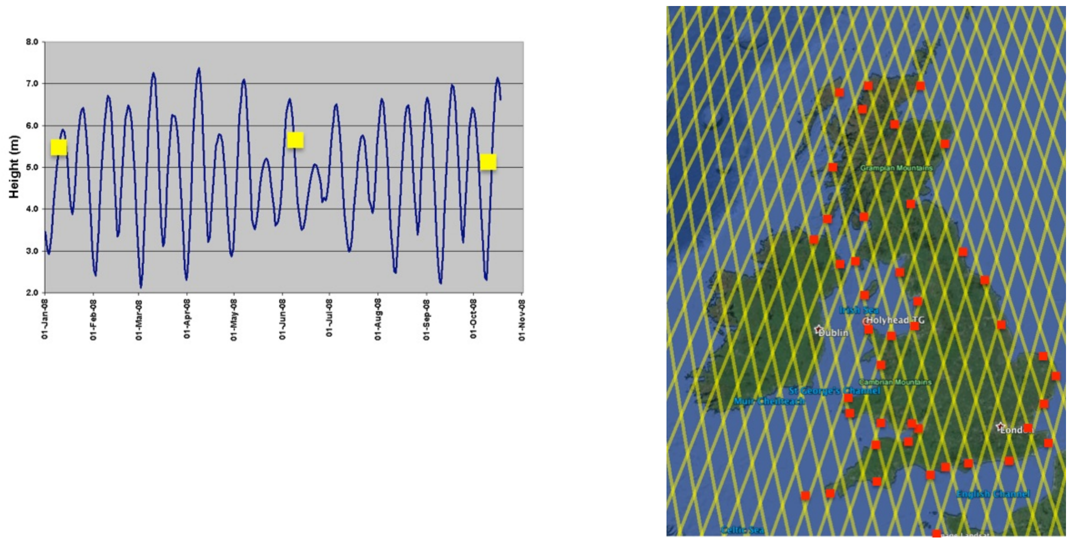


Figure 2: (Left) Example tide gauge record. Yellow squares indicate representative sampling interval from satellite altimeter. (Right) UK Coastline with Envisat 35 day repeat tracks in yellow, and the locations ot the 34 gauges of the UK tide gauge network indicated in red.

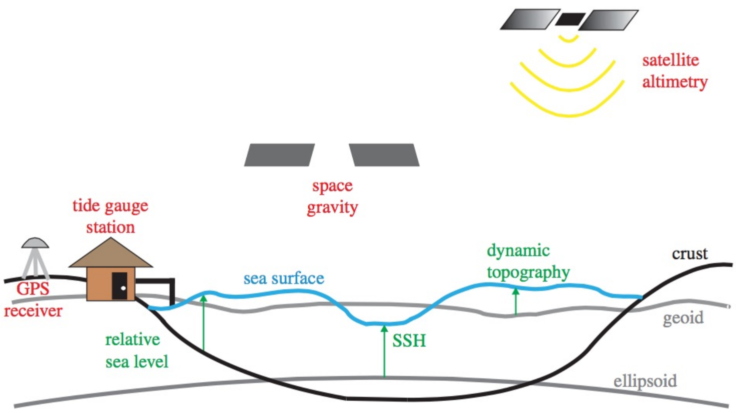


Figure 3: The additive components to sea level from the reference level (the ellipsoid) to the sea surface. To link the altimetry measurement to the tide gauge measurement we must now how all these factors vary between the two measurement points, in time and in space. SSH – Sea Surface Height. From Tamisea et al. (2015), Reproduced from Phil. Trans. Roy Soc.

3.3 Coastal Measurements from Satellite Altimeters – The Innovation in Sea Level SpaceWatch

Until recently, it was not possible to retrieve useful sea level measurements close to the coast. There are two main reasons for this:

- The proximity of the coast in the “footprint” of the altimeter produces artefacts in the returned signal, which routine processing is unable to deal with.
- Corrections must be applied to the derived range, and these can become inaccurate close to the coast.

Recent improvements in processing schemes (pioneered at NOC), together with the availability of better local corrections now mean that accurate sea level measurements can be derived right up to the coast, and at a higher along track resolution (Figure 4).

NOC is providing a lead to the international community in these developments through the ESA supported COASTALT network (see e.g. Cipollini et al, 2014a), and has developed and implemented a coastal post-processor called ALES (Adaptive Leading Edge Subwaveform retracker) that can be applied retrospectively to available satellite data products to produce a historical coastal altimeter data set.

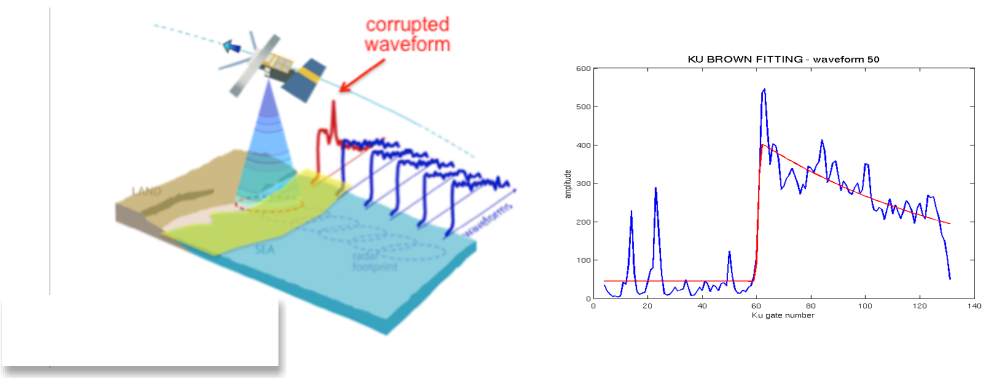


Figure 4: Coastal Altimetry. (Left) Depiction of satellite altimeter orbit crossing coastline, and the impact on the returned signal. (right) Example of corrupted Envisat waveform with Brown model fitting (figure by J. Gomez-Enri)

The ALES processor has been tested and validated through application in the Northern Adriatic and the German Bight as described in Passaro et al (2014) and Passaro et al (2015)

Other recent developments have lead to further improvements in the coastal altimeter record. A new design of radar altimeter, the “Synthetic Aperture Radar” (SAR) altimeter, has been developed and is currently operating on the ESA Cryosat mission (launched in 2010). Although the main purpose of the mission is to measure the earth’s ice coverage, this innovation also offers significant improvements to ocean measurements through an increased along track resolution (to 250m) and increased precision in sea level and wave height measurements. The ESA- and CNES-funded Cryosat Plus for Oceans (CP4O) project, led by SatOC (see http://www.satoc.eu/projects/CP4O/) investigated the benefits and promoted ocean applications of Cryosat SAR altimeter data. It is clear from work carried out in this project by NOC that SAR altimetry will also provide much better measurements right up to the coast, though again careful and specific coastal processing will be needed (see e.g. Cipollini et al, 2014b). This new type of altimeter will be flown on the Sentinel-3 series of satellites (the first of which is due to be launched late 2015), and on the JASON-CS/ Sentinel 6 satellite (due to be launched in 2020). The funding for these missions is secure, and through these missions, the future availability of high quality coastal measurements from satellite altimeter data is assured until at least 2030.

4 THE SEA LEVEL SPACEWATCH PROTOTYPE SERVICE

4.1 Data and Processing

The aim of the prototype Sea Level SpaceWatch service was to provide information on observed sea level around the UK by processing space-borne altimeter data, and to provide that information alongside equivalently processed tide gauge data. This would then allow planners to verify the regional variability of sea level at multiple time scales and observe the presence of any significant inter-annual changes.

Satellite Altimeter Data Processing

To produce the new satellite derived coastal sea level measurements needed for the service, Envisat altimeter data products (as made available by ESA) for October 2002 to October 2010 were processed by NOC, to produce two quantities:

- TWLE - Total Water Level Envelope: The total level including tides and atmospheric forcing – useful as a reference and because it displays extreme events (surges)
- SSHA - Sea Surface Height Anomaly: The anomaly with respect to the mean sea surface, with tides/atmospheric effects removed. Sea level rates of change are calculated from this value.

From these further derived parameters were calculated and are provided:

- rolling annual mean in SSHA
- rolling one-year trend in SSHA
- overall trend (in SSH) over whole time series
- amplitude of the annual SSH signal over whole time series
- Time of maximum of the annual SSH signal (in days) over whole time series

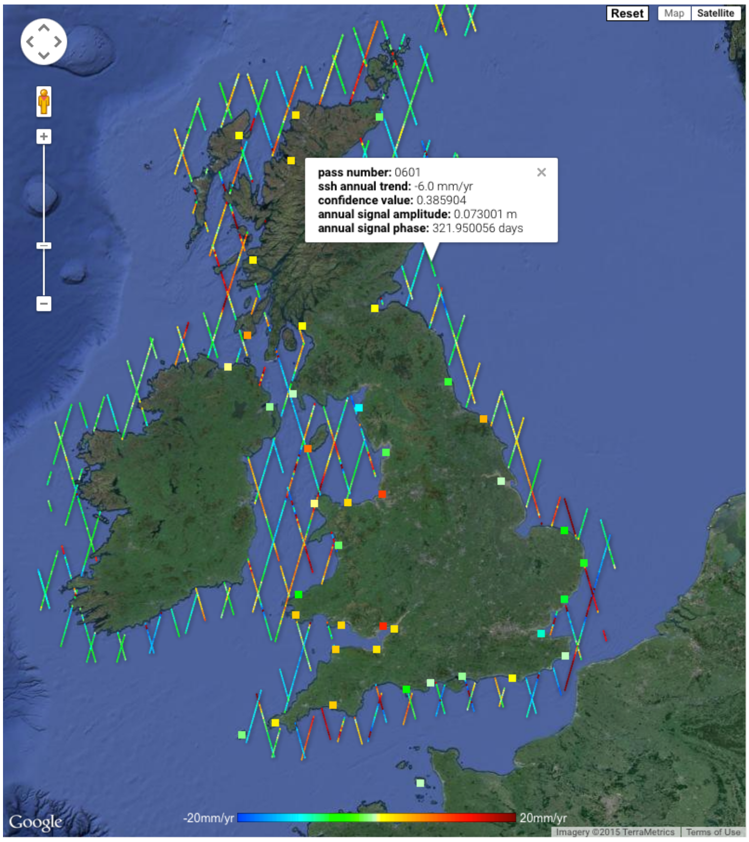


Figure 5: A Snapshot from the Sea Level SpaceWatch Web Page

Tide Gauge Data Processing

Equivalent processing was applied to tide gauge data for the 43 tide gauges in the UK network. TWLE and sea level residual data were downloaded from the NTSLF, and processed to provide equivalent estimates of trends and the amplitude and phase of the annual cycle in sea level.

4.2 Web Presentation

The altimeter and tide gauge data have been uploaded and made available on the Sea Level SpaceWatch web page (http://www.satoc.eu/projects/sealevelsw/). The altimeter sea level trend data (mm/yr) are colour coded and provided at 3.5 km intervals along track. Each point is clickable to bring up a pop up window with the trend, annual cycle amplitude and phase, and also provides download access to the trend data (csv format). A confidence value for the sea level trend estimate is also provided: this is the *p*-value that allows the computation of the level of statistical significance (in percent) as 100 × (1 - *p*). The colour key for sea level trend is given at the bottom of the page. The tide gauge sea level trend data are colour coded on the same scale, and the pop up windows for the tide gauge data provide the maximum recorded tide, the trend, and provide download access to the full statistics for the tide gauge location (netCDF format). Figure 5 provides an example snapshot from the web page.

The Sea Level SpaceWatch users were invited to view the web page and provide feedback. Their comments will be discussed in the next section of the report.

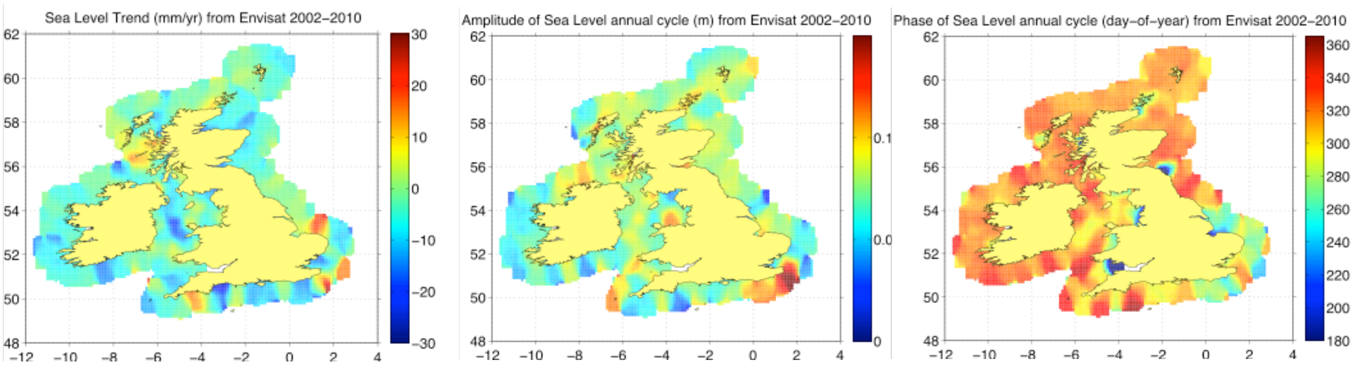


Figure 6: Maps of gridded Envisat altimeter sea level data (2002-2010): (Left) Long term trend in mm/yr; (Centre) amplitude of the annual cycle (mm), (right) time of maximum of annual cycle (day number)

4.3 Interpretation

To support an initial interpretation of the data, maps of sea level trend, the amplitude of the annual cycle, and the timing of the maximum of the annual cycle were generated (Figure 6).

For this figure, to ease interpretation, the data have been gridded, but the reader should be aware that these measurements are only made on the tracks and at the locations indicated on Figure 5, and so should be careful not to infer conclusions in areas where there are no altimeter measurements.

Some patterns are seen to emerge, though the period of data (2002-2010) is not sufficiently long to support any firm conclusions.

- The amplitude of the annual cycle appears largest at the SE corner of the English coast.
- The time of the maximum of this cycle is early October along most of the coast, and approximately 30-40 days earlier in the SE.
- From this limited time series (2002-2010) there is no clear geographic pattern in sea level trend.

It is clear that there are anomalies where crossing tracks appear to show contradictory trends. Also so far no interpretation has been attempted to relate the satellite trends to those calculated for the tide gauges. These issues require further investigation so that the potential users can be assured the features seen represent real signals in sea level. After further processing to lengthen the period covered by the data, the next steps in interpretation would investigate these issues, and consider if further screening of the data and review of some of the corrections is necessary.

Nonetheless it can be concluded from this initial data set that:

- Altimetry has the potential to provide sea level information (trends, variability, seasonal signals) in the coastal region.
- Altimeter data provide a fine spatial sampling along satellite tracks that nicely complements the virtually continuous temporal sampling by tide gauges.
- Altimeter data link the open ocean, shelf seas and coastal zone in a way that cannot be achieved with other observational techniques at present.

5 USER EVALUATION

Users from the Committee for Climate Change and the Environment Agency (Flood and Coastal Erosion Risk Management) were asked to comment on the prototype service as it was developed and were provided early access to the demonstration web page.

Towards the end of the project, an open Sea Level SpaceWatch workshop was held at NOC (Southampton), which attracted over 20 registered attendees including user representatives from the CC, EA and Natural Resources Wales, representatives from the UK and European Space Agencies, and sea level scientists, confirming widespread interest in the service. All were invited to comment on the service and offer recommendations. The comments are summarised below:

5.1 Requirements / Usefulness of Data

What are the key gaps in information for coastal flooding planning?

- Information on uncertainty is as important as trends.
- It is important to clearly state the period of data used to derive the trends.
- It is important to provide regional information. High spatial resolution not needed by CCC, EA NRW, but it would be more helpful to provide data on a regional / catchment basis, e.g. to match the shoreline management plan regions
- However, the Channel Coast Observatory would like high spatial resolution data, especially wave data up to coast, noting that wave buoys are expensive to maintain.
- 10 years is not a long enough period to derive reliable trends, need to use the whole 25-year satellite altimeter data set at least (40 years suggested as a minimum for trends from tide gauge data).
- Suggest these data should also be fed into future climate change reports.

Are the parameters proposed useful to you? If not, what parameters are your priorities?

- Sea level is the key parameter for coastal flood planning
- Significant wave height would be useful for the Channel Coast Observatory, and could be fed into the Wavenet website
- Could the service offer a tool kit to provide a range of processing options to apply to the extracted data?

What is the preferred update frequency?

- The most accurate altimeter data product, which is the default input to Sea Level SpaceWatch, is provided offline with a delay of ~ 1 month. The initial service basis is that processing is carried out on a monthly basis and that the statistics and trends are calculated and updated on the website. This approach was acceptable to the users.

5.2 Subsidiary Data

Are there other data sources / types that would be useful as subsidiary information?

- The issue of tying down reference levels across tide gauges and altimetry should be further investigated, including the impact of sub-selecting the tide gauge data time series to match the altimeter sampling.
- Need to include atmospheric effects on tide gauge sea-levels.
- It was noted that extreme return periods for tide gauge locations are available as a GIS layer. Could this be added to the web presentation?

5.3 Presentation

Is the web presentation easy to interpret? How could it be improved?

- Suggested to have sectors or regions, clickable to provide summary plots (e.g. to match the shoreline management plan regions)
- Smoothed map is easier to interpret, (but need to be careful – as users may believe there is real data in grid squares only populated by interpolation.)
- Need to have information on appropriate length scales for gridding.
- The track data are useful in some cases (e.g. for the Channel Coast Observatory).

Does the data download capability include the right parameters? Are the data provided in a format easy for you to use?

- Yes want downloadable data, with explanatory text file.
- In general netcdf is not used, would normally use simple text, csv, format
- Most users would probably want single point data sets (and not track data).

5.4 Potential Value of the Service

It is difficult to put a precise monitory value on the service as it would not replace or result in directly reduced costs of an ongoing service or responsibility. However, noting that term running costs for the service are estimated (roughly) to be ~£15-20k per annum, it can be seen that this cost would be recouped by the agencies if the service resulted in just a 0.01% efficiency improvement in the management of flood and erosion risks (derived from the PCv estimate for this cost of £25bn over 100 years). Further savings could result from potential reduction in costs of compensatory coastal marine habitat creation.

A business plan could aim for co-funding from DEFRA, EA, NRW, in partnership with others (e.g. the Welsh Government funded Wales Coastal Monitoring Centre, the Scottish Environment Protection Agency, and Department of Agriculture and Rural Development - Northern Ireland).

5.5 Summary

Users confirmed that the satellite-derived regional sea level variability information provided by Sea Level SpaceWatch filled a key information gap and was of significant interest and value to them. They would like to see an operational service and believed there was scope for a credible business case to support the cost of this service. The users offered the following statements of support:

Climate Change Committee:

“The Adaptation Sub-Committee of the Committee on Climate Change has two statutory roles under the UK Climate Change Act; to provide advice to Government on the risks and opportunities posed by climate change, and to evaluate progress with adaptation in England. To undertake both roles, the Adaptation Sub-Committee requires indicators of trends in vulnerability, exposure, action and impacts related to climate change adaptation. The Sea Level SpaceWatch programme’s work to improve and summarise satellite data on sea level rise around the UK would be an extremely useful contribution to our work. In particular, regional average data on observed sea level trends to date is a key gap in our current suite of indicators on changes in climate-related hazards over time. We are also interested in trends in peak sea level, the relationship between past trends and future projections, and observed incidences of overtopping of coastal defences.”

The Environment Agency (Flood and Coastal Erosion Risk Management)

“This work is important to the Environment Agency and other risk management authorities and in particular to the long-term and strategic planning of flood and erosion risk management infrastructure at the coast for the following reasons.

i. Infrastructure investment decisions on the coast made in response to sea level rise will be very sensitive to the timing of investment. This is due (in part) to the economic discounting of the investment costs. It is essential, therefore that we have quality data and information on trends in regional sea level change. Such information will help decision makers either a) move investment decisions further in to the future thus saving the tax payer £m's or b) provide compelling evidence that the decision to invest now is a robust one.
ii. Delivery of infrastructure necessarily requires a long lead time, as options to deliver desired policies at the coast are explored and schemes move with increasing certainty through the strategy phase to design and delivery. The story of Thames Barrier is an obvious illustration of this point; conceived in response to the 1953 east coast floods, first operational in 1983 – a lead time of 30 years. Early detection of the any acceleration in sea level rise is essential for the risk management authorities to plan for an appropriate response.
iii. The spatial resolution of the data derived from altimetry provides valuable insight in to the processes which may be driving regional variations in sea level which are difficult to resolve from the single point tide gauge information. This might potentially allow the development of a lot more locally specific advice on future trends, which could lead to large efficiencies in the delivery of infrastructure at the coast.
iv. Delivery of habitat to compensate for coastal squeeze.

Moving this work forward, I really see this work as being very complimentary to the Class A gauge network - not a replacement of the A gauge network! I would like to see a proposed strategy on how best these data could be brought together to develop trends in MSLR and provide future projections with quantified uncertainties. I feel the ambition to develop an operational service to deliver such information on perhaps an annual basis is the right one, but there are intermediate measured steps that need to be taken first.

The potential of this work is clear and we would like to continue to support your work to develop the science toward this goal."

6 CONCLUSIONS AND RECOMMENDATIONS – ROADMAP TO IMPLEMENTATION

6.1 Summary

A prototype Sea Level SpaceWatch Service has been developed over a three-month period and provided to users for review. The service was also presented to a wider group of users and scientists at a workshop held at NOC in March 2015.

It was confirmed that the Sea Level SpaceWatch service meets key information needs of the Climate Change Committee, the Environment Agency and the Welsh Government and the Wales Coastal Monitoring Centre and potentially SEPA and DARD-NI, who require information on regional trends in sea level, and a comparison of these against climate projections.

6.2 Requirements and Plans for Further Developments

Some further development / refinement of the service is recommended:

- A longer period of altimeter data is required to support reliable trend estimates.
- Analysis of the outputs is needed to understand apparent anomalies that may require further screening of the data and some of the corrections.
- Separation of the output into different regions would be helpful – e.g. into Shoreline Management plan regions. Assessment of the outputs could also be provided at this regional level.
- Consideration of how best to integrate the satellite data with other sea level information (e.g. relevant statistics derived from from tide gauges and models)
- The Channel Coast Observatory would like the service to include significant wave height data.

A fuller description of the work needed to complete the development of the Sea Level Service ready for operational implementation is provided in Annex B. It is anticipated that this work could be completed within 6-12 months, at an estimated cost of £70-1£00k

6.3 Towards a Business Case for Operational Implementation

Following the additional development outlined above, it is estimated that the long term running costs would be ~£15-20k per annum, based on a monthly effort to process and validate the data and an annual update to the trend information. This cost would be recouped by the agencies if the service resulted in just a 0.01% efficiency improvement in the management of flood and erosion risks (derived from the PCv estimate for this cost of £25bn over 100 years). Further savings could result from potential reduction in costs of compensatory coastal marine habitat creation.

A business plan could aim for co-funding from DEFRA, EA, NRW, in partnership with others (e.g. the Welsh Government funded Wales Coastal Monitoring Centre, the Scottish Environment Protection Agency, and Department of Agriculture and Rural Development - Northern Ireland).

If funding for the further necessary development could be found quickly, an operational service could be available within 12 months.

6.4 Possible International Implementation

There is evident potential and value for implementing an equivalent overseas service, particularly in areas where there is little local infrastructure in terms of tide gauge networks. Support for European implementation may be possible through ESA or EC funding (e.g. the ESA Integrated Applications programme, or Horizon 2020).

ACKNOWLEDGEMENTS

The Sea Level SpaceWatch team would like to acknowledge:

- The funding support from the UK Space Agency through the Space for Smarter Government Programme
- The enthusiastic and unfunded engagement of the user agencies: The UK Climate Change Committee, The Environment Agency, and Natural Resources Wales
- The attendees at the Sea Level SpaceWatch Workshop at NOC on 30th March 2015

REFERENCES

Calafat, F.M.; Chambers, D.P.; Tsimplis, M.N.. 2012, Mechanisms of decadal sea level variability in the eastern North Atlantic and the Mediterranean Sea. Journal of Geophysical Research, 117 (C9). C09022. 10.1029/2012JC008285

Cipollini, Paolo; Vignudelli, Stefano; Benveniste, Jérôme. 2014a, The Coastal Zone: A Mission Target for Satellite Altimeters. Eos, Transactions American Geophysical Union, 95 (8). p72. 10.1002/2014EO080006

Cipollini, P.; Gommenginger, C.; Snaith, H.M.; Cotton, P.D.; Dinardo, S; and Benveniste, J; 2014b, An Evaluation of CryoSat-2 SAR Mode Performance Around the UK Coasts, AGU Fall meeting, San Francisco, USA 15-19 December 2014

Passaro, Marcello, Cipollini, Paolo, Vignudelli, Stefano, Quartly, Graham D. and Snaith, Helen M. 2014, ALES: A multi-mission adaptive subwaveform retracker for coastal and open ocean altimetry. Remote Sensing of Environment, 145, 173-189. (doi:10.1016/j.rse.2014.02.008)

Passaro, Marcello; Fenoglio-Marc, Luciana; Cipollini, Paolo. 2015 Validation of significant wave height from improved satellite altimetry in the German Bight. IEEE Transactions on Geoscience and Remote Sensing, 53 (4). 2146-2156. (doi: 10.1109/TGRS.2014.2356331)

Tamisea, M.E; Hughes, C. W.; Williams, S. D. P.; and Bingley, R. M., 2015, Sea Level: Measuring the Bounding Surfaces of the Ocean. Phil. Trans. R. Soc. A. 372, 20130336, http://dx.doi.org/10.1098/rsta.2013.0336

RELEVANT WEB LINKS

Sea level SpaceWatch: http://www.satoc.eu/projects/sealevelsw/
Climate Change Committee: http://www.theccc.org.uk
Channel Coast Observatory: http://www.channelcoast.org
Cryosat Plus for Oceans (CP4O): http://www.satoc.eu/projects/CP4O
European Space Agency Earth Observation: http://earth.esa.int
European Space Agency Climate Change Initiative - Sea Level: http://www.esa-sealevel-cci.org
Marine Climate Change Impacts Programme: http://www.mccip.org.uk
Satellite Applications Catapult: https://sa.catapult.org.uk
Space for Smarter Government Programme: http://www.spaceforsmartergovernment.uk
Wavenet:
http://www.cefas.defra.gov.uk/our-science/observing-and-modelling/monitoring-programmes/wavenet.aspx
UKCP09: http://ukclimateprojections.metoffice.gov.uk
UK Space Agency: https://www.gov.uk/government/organisations/uk-space-agency

ANNEX 1 FINANCIAL REPORT

In the tables below we provide details of expenditure by fund heading, including a summary of staff effort expended.

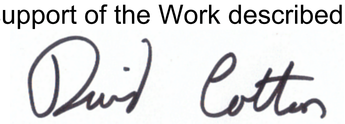
Budget Summary

Fund Heading	Total
Staff Costs	£63,091
Research Costs	-
Travel and Subsistence	£1,040
Workshops / Meetings	£2,000
Other Costs	-
Total	**£66,131**

Summary of Staff Costs

Staff Member	Role	Organisation	No. of Days	Total Cost
Cotton, David	Lead Applicant	Satellite Oceanographic Consultants	12	£10,560
Ash, Ellis	Web page development	Satellite Oceanographic Consultants	20	£17,600
Cipollini, Paolo	Altimeter/ tide gauge data processing and analysis	National Oceanography Centre	32	£19,482
Kevin Horsburgh	Sea Level Scientist	National Oceanography Centre	5	£4,490
Snaith, Helen	Altimeter/ tide gauge data processing and management	National Oceanography Centre	18	£10,959
Total			**87**	**£63,091**

I certify that this statement of costs is true and accurate and confirm that such expenditure has been used entirely in support of the Work described in this report

Signed: 

Date: 20/05/2015

Name: Dr David Cotton, SatOC Director and Project Manager

ANNEX 2 OUTLINE OF FURTHER PRE-OPERATIONAL DEVELOPMENT WORK

The review of the prototype Sea Level SpaceWatch service identified that further development / refinement of the service was required before it would be ready for operational implementation. We have identified 5 necessary tasks, which are described below:

Task 1: Extend the Sea Level SpaceWatch Time Series

1.1 Satellite Data Processing

Processing of a longer period of altimeter data (1992-2015), to support reliable trend estimates. To be carried out at SatOC under licence to NOC (who retain IPR), with NOC support for installing the processing scheme at SatOC. Source data acquired from ESA, and CNES (Aviso)

1.1.1 Install Coastal Processor at SatOC

1.1.2 Modify processing as necessary following report from Task 2.

1.1.3 Process additional altimeter data sets:

Additional satellite altimeter data sets would include:

- Topex, Jason-1 and Jason-2
- ERS-1 and ERS-2 (from the REAPER reprocessed data set)
- AltiKa data
- Preparation for processing Sentinel-3 data.

1.2 Tide Gauge Data Processing

Processing of a longer period of Tide Gauge data to match that of the altimeter data (1992-2015). To be carried out at NOC, on data provided by NTSLF. To consider possible inclusion of additional parameters as identified by users.

1.2.1 Establish TG processing at NOC, including generation of additional parameters as required.

1.2.2 Modify processing as necessary following report from Task 2.

1.2.3 Process longer time series of TG data to match that of altimeter data

Inputs: Satellite data from ESA and CNES (Aviso), Tide Gauge data from NTSLF, processing software from NOC.

Outputs: Satellite data: extended time series data sets on existing and new satellite tracks. Tide Gauge data: extended time series (and possibly new parameters?).

Task 2: Analysis and Validation

To be done at NOC.

2.1 Analyse the initial and updated Sea Level SpaceWatch data set, identify anomalies / issues and investigate how they can be dealt with (e.g. through more rigorous QA?).

2.2 Carry out Tide Gauge / Altimeter data comparison and consider sources of potential differences (corrections, tide models, sampling,..)

Input: Initial and updated SLSW data set

Output: Report with recommendations for processing, to be fed back into Task 1 to test and check outputs.

Task 3: Modify and Update Service Presentation

To be done at SatOC, links with Task 4 to gain user feedback

3.1 Review presentation requirements with users, options include

- Separation of output into different regions (shoreline management plan areas?).
- Separate page for track data and shoreline data (and SWH)?
- Include other requested information / statistics from Tide Gauge analysis (CCC requested trends in peak tides (highest tide level per annum); exceedance of tide level thresholds, breaches of coastal defences.
- Plot against projections of Mean Sea Level that are currently used in planning.

3.2 Update web page presentation

3.3 Load in updated data sets

Inputs: Initial SLSW web page, user comments; SLSW satellite and tide gauge data products

Output: Revised web page populated with new SLSW satellite and tide gauge data products

Task 4 User Assessment

Users to include CCC, EA, SEPA, NRW, Welsh Government – Wales Coastal Monitoring Centre, DARD-NI, CCO, plus others for possible overseas implementation.

Closely connected to Task 3

4.1 Initial Stage - Describe proposed modifications to the presentation of the output and get feedback

4.2 Mid stage – to present modified pages with new data

4.3 Present final version to showcase output and build support for a business case

Inputs: Initial and updated SLSW web pages

Output: Recommendations for web page improvements

Task 5 Business Plan Development

- UK Implementation – Proposal for an initial 5 years service to UK users, supported through co-funding from relevant agencies.
- Europe Implementation – Need to identify and engage potential locations, users and regional sea level expertise. Could be supported by EC (H2020), ESA (IAP)
- Outside Europe – Identify priority areas where sea level is a pressing issue and where local infrastructure is inadequate to support sea level information needs. Work with DFID and relevant international agencies to get detail on requirements and to identify potential sources of funding support.

Inputs: Costs of service implementation and provision, service description, user requirements, estimates of benefits

Output: Business Plan(s) for UK, European and International Sea Level SpaceWatch service.