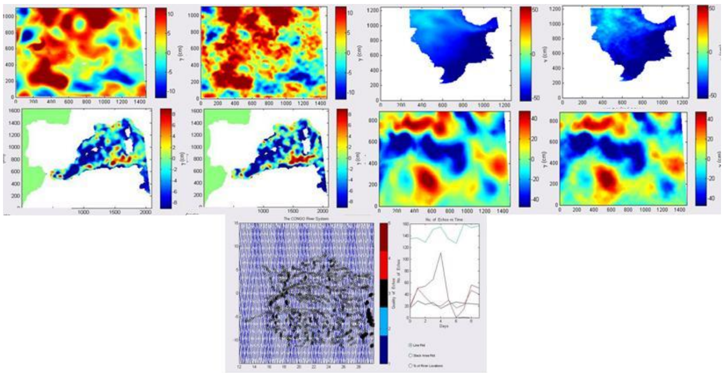
Fine Scale Altimetry - Executive Summary



PROJECT
Scientific Assessment of Fine Scale Altimetry Using a Constellation of Small Satellites
WORK PACKAGE NUMBER
SS C Z
DOCUMENT NUMBER
0153819
6305/09/NL/AF
REVISION
1
REVISION OR RELEASE DATE
14/6/13
STATUS
Release

PREPARED BY

Kathryn Graham

REVIEWED BY

Rachel Bird / Mike Cutter

APPROVED BY

Surrey Satellite Technology Limited
Tycho House
20 Stephenson Road
Surrey Research Park
Guildford, Surrey
GU2 7YE, UK
Tel: +44 1483 803803
Fax: +44 1483 803804
Email: sstl@sstl.co.uk

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DOCUMENT REVISION STATUS

Last Edited Date	Revision / Release Number	Status	Edited By	Pages / Paragraphs Affected
3/2/2011	1.01	Draft	K Graham	New Document
21/1/2013	1.02	Draft	K Graham	Addition of new sections
24/1/2013	1.03	Draft	K. Graham	Some review comments
22/4/2013	1.04	Draft	K Graham	Incorporated final comments
14/6/13	1	Release	K Graham	

1 INTRODUCTION

1.1 Scope

The study team are pleased to submit this executive summary to the work conducted under ESA contract 6305/09/NL/AF titled 'Scientific Assessment of Fine Scale Altimetry Using a Constellation of Small Satellites'. The study aimed to parametrically establish the link between numbers of satellites, their orbits and configuration to user requirements. In order to do this the team conducted a user needs analysis and literature review. This was then followed by the development of a Matlab model in order to model constellation performance for a selection of target regions.

Once the tool was developed, the model was used to assess different altimeter constellations of varying number, configuration, orbit repeat cycle and instrument error, with the aim to assess their performance.

This report describes the user analysis, the model that was developed and the subsequent modelling that was performed using the model.

1.2 Applicable Documents

Applicable Documents identified in the following text are identified by **AD-n**, where "n" indicates the actual document, from the following list:

AD#	Title	Customer Ref. #	Doc #	Revision	Date
[AD 1]	Scientific Assessment of Fine Scale Altimetry Using a Constellation of Small Satellites. Statement of Work	Appendix 1 to AO/1-6305-09-NL/AF	EOP-SFT-2009-09-1415	1.1	6/11/2009
[AD 2]	Scientific Assessment of Fine Scale Altimetry – Technical Proposal	AO/1-6305/09/NL/AF	0138329	1.0	1/3/2010
[AD 3]	Scientific Assessment of Fine Scale Altimetry – Financial and Management Proposal	AO/1-6305/09/NL/AF	0138326	1.0	1/3/2010
[AD 4]	Scientific Assessment of Fine Scale Altimetry Using a Constellation of Small Satellite – Literature Review and User Needs Analysis	AO/1-6305/09/NL/AF		1.0	16/11/2010

1.3 Reference Documents

Documents referenced in the following text, are identified by **RD-n**, where "n" indicates the actual document, from the following list:

RD#	Title	Date
[RD01]	Phalippou, l., E. Caubet, L. Rey, P. Clavary, D. Murat, J. Richard, G. Angino, E. Thouvenot, G. Carayon, N. Steunou, C. Mavrocordatos, P. Escudier, 25 years of altimeter development and Alcatel Alenia Space, ESA SP-614, Proceedings of the Symposium on "15 years of progress in radar altimetry", Venice Lido (Italy), 13-16 March 2006	2006
[RD02]	Phalippou, L., and V. Enjolras, Re-Tracking of SAR Altimeter Ocean Power-Waveforms and Related Accuracies of the Retrieved Sea Surface Height, Significant Wave Height and Wind Speed, Proc. IEEE IGARSS 2007	2007
[RD 03]	Y. Le Roy, M. Deschaux-Beaume, C. Mavrocordatos, F. Borde, SRAL, A Radar Altimeter Designed to Measure Several Surface Types, SPIE Remote Sensing Conference, 20-23 September 2010, Toulouse	2010
[RD 04]	Richard, J., Y le Roy, E. Thouvenot, P. Escudier, Altimetry Payload Specification for Iridium NEXT. White paper for Iridium NEXT initiative.(http://www.iridium.com/DownloadAttachment.aspx?attachmentID=689)	2008
[RD 05]	Cutter, M.A., K.L. Graham, S.C. Giwa, S. Mackin, M Vanotti, A Constellation Of Small Satellites Providing Operational Oceanographic Data, Small Satellites Symposium, International Astronautical Congress, Daejeon, Korea, October, 2009.	2009

2 EXECUTIVE SUMMARY

2.1 Study Aims

The aim of this study is to look at the capabilities of state of the art small satellite radar altimeters and establish parametrically the link between the altimeter constellation size, configuration and performance levels required to satisfy a range of user requirements including ocean circulation patterns, coastal phenomena and in-land water monitoring.

In order to assess this link the study developed a tool to model constellation configuration versus user needs in order to assess the capabilities required in the constellation and its configuration. The first stage in the study was to survey previous work in the area and to examine the user needs in the three applications areas, namely ocean, coastal and in-land water regions.

The study was divided into 4 key work areas, namely

- Literature and User needs Analysis
- Assessment Model Design and Analysis
- Assessment Model development
- Constellation Option Definition and End to End Performance analysis.

This executive summary provided an overview of the main areas of work and provides an overview of the developed model. .

2.2 Literature Review and User Needs

A general literature review of satellite altimetry was conducted summarising the end- to end performance capabilities of current and planned satellite radar altimeters, Figure 2-1 illustrates past, present and future satellite radar altimetry missions.

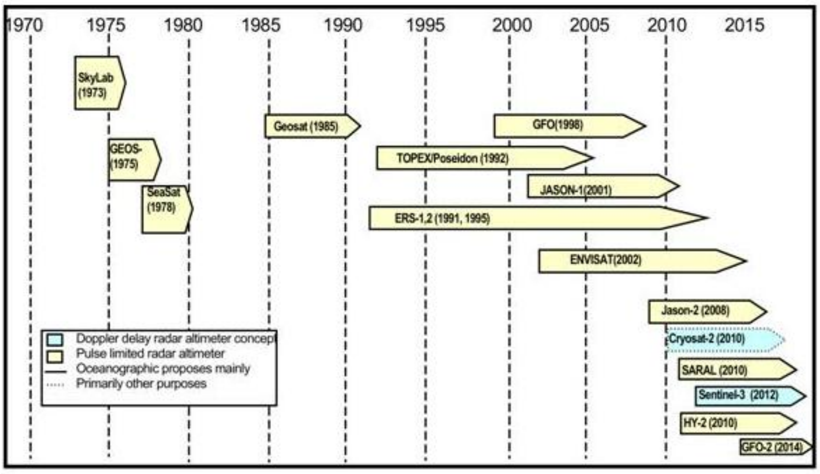


Figure 2-1: Past, present and future satellite radar altimetry missions.

The study focussed on, but not limited to, altimeters that could be mounted on small satellite platforms with the potential capability to monitor fine scale variability in open and coastal oceans and inland waters. The model allows the user to model operational systems, e.g. Jason, either independently or together with other operational systems or constellations. The study indentified the key performance characteristics of 4 complete small satellite altimeter systems that were used as inputs to the following stage of this study, the model to assess the performance capabilities of different configurations of altimeters.

	Poseidon 3	**Alti-Ka**	***SRAL LRM / SAR***	***Thales low mass, low power concept***	***SSTL small altimeter study***
Mission	Jason2	SARAL	*Sentinel-3*	*Jason heritage*	
Characteristics					
Main target application	Ocean	Ocean	*Oceans*	*Oceans (meso and sub meso scale), sea state*	*Ocean and Coastal*
Secondary application	Inland waters + coastal zone (Poseidon 3)	Inland waters + coastal zone	*RLH, Ice*	*Geodesy, inland waters, land and ice surfaces*	*Investigating inland waters*
Altitude	1347 ± 15 km	800 km	*814km*	*Not stated (for Iridium – but performances for JASON orbit given*	*800km*
Frequency (GHz)	13.575(Ku) / 5.3 (C)	35.5	*13.575 /5.41*	13.575	*13.75*
Tx Bandwidth (MHz)	320 / 100-320	480	*350/320*	320 / 100-320	*320*
Pulse width	105.6 µs	105.6 µs	*49 µs*	105.6 µs	*95 µs*
PRF (kHz)	1.8/0.3-0.45	4	*1.92/ 18.2 C-band:0.28*	1.8/0.3-0.45	*2 /18*
Range Resolution (cm)	46	30	*45 (single shot)*	46	*47*
Tx power	(W) 7 / 30 (SSPA)	2 (SSPA)	*25W*		*5.2W / 0.47W*
Range noise over ocean @ SWH=2m &1Hz	1.7 cm	0.8 cm	*LRM: 1.3 (Est) SAR < 1.0 (Est)*	1.7 cm	*1.7 cm (Est)*
Power consumption (W)	80 (without antenna feed thermal control)	< 80 (including radiometer)	*LRM:87 SAR:95*	*56*	*54.6 (LRM mode), 64.4 (DDA mode)*
Total (altimeter) Mass (kg)	58 with redundancy	33 (including radiometer) (without redundancy	*62 Kg*	*27 Kg*	*26.3 (inc GNSS)*
Data rate	22kb/s (J1) / 22 or 37 kb/s (J2)s	38 kb/s	*LRM:92 kbs SAR: 11 Mbps*	*25 kbps*	*47 kbps (LRM) / 12.9 Mbps (DDA)*
Performance					***GDR product***
Range – Range Noise	1.7 cm	0.8 cm	*LRM: 1.4 (Est) SAR 0.8 (Est)*	1.7 cm	*1.7 (Est) /*
Sea State Bias	2.0 cm	2.0 cm	2.0 cm*(Est)*	2.0 cm	*2.0 (Est)*
Ionospheric Error	0.7 cm	0.3 cm	0.5 cm	2.0 cm	*2.0*
Dry Trop Error	0.7 cm	0.7 cm	0.7 cm	0.7 cm	*0.7*
Wet Trop Error	1.2 cm	1.4 cm	1.4 cm	3.7 cm	*3.7*
Total RMS	3.1 cm	2.7 cm	3,.4 cm*(Est)*	5.0 cm	*4.8 (Est)*
POD GPS	2.5 cm	2.5 cm	2 cm*	2.5 cm	*2.5*
Total RMS with POD	4.0 cm	3.7 cm	4.5 cm	5.6 cm	*5.4 (Est)*
Sea state Parameters					
Significant Wave Height	0.4m / 10%	To be determined	To be determined	0.4m / 10%	To be determined
Backscatter	0.7 dB	To be determined	To be determined	0.7 dB	To be determined
Wind Speed	1.5 ms-1	To be determined	To be determined	1.5 ms-1	To be determined

Table 2-1: Known or estimated characteristics of selected options for small satellite radar altimeters. From [RD 01], [RD 02], [RD 03], [RD 04] and [RD 05]. ESA POD requirements for Sentinel-3 are 8cm for < 3h, 3 cm < 2 days, 2cm ~ 30days, LeRoy Pers. Comm.

Table 2-1 lists the key characteristics for the selected options for small satellite radar altimeters.

	Poseidon 3	Alti-Ka	*SRAL LRM / SAR*	*Thales low mass, low power concept*	*SSTL small altimeter study*
Mission	Jason2	SARAL	*Sentinel-3*	*Jason heritage*	
Characteristics					
Main target application	Ocean	Ocean	*Oceans*	*Oceans (meso and sub meso scale), sea state*	*Ocean and Coastal*
Secondary application	Inland waters + coastal zone (Poseidon 3)	Inland waters + coastal zone	*RLH, Ice*	*Geodesy, inland waters, land and ice surfaces*	*Investigating inland waters*
Altitude	1347 ± 15 km	800 km	*814km*	*Not stated (for Iridium – but performances for JASON orbit given*	*800km*
Frequency (GHz)	13.575(Ku) / 5.3 (C)	35.5	*13.575 /5.41*	13.575	*13.75*
Tx Bandwidth (MHz)	320 / 100-320	480	*350/320*	320 / 100-320	*320*
Pulse width	105.6 µs	105.6 µs	*49 µs*	105.6 µs	*95 µs*
PRF (kHz)	1.8/0.3-0.45	4	*1.92/ 18.2 C-band:0.28*	1.8/0.3-0.45	*2 /18*
Range Resolution (cm)	46	30	*45 (single shot)*	46	*47*
Tx power	(W) 7 / 30 (SSPA)	2 (SSPA)	*25W*		*5.2W / 0.47W*
Range noise over ocean @ SWH=2m &1Hz	1.7 cm	0.8 cm	*LRM: 1.3 (Est) SAR < 1.0 (Est)*	1.7 cm	*1.7 cm (Est)*
Power consumption (W)	80 (without antenna feed thermal control)	< 80 (including radiometer)	*LRM:87 SAR:95*	*56*	*54.6 (LRM mode), 64.4 (DDA mode)*
Total (altimeter) Mass (kg)	58 with redundancy	33 (including radiometer) (without redundancy	*62 Kg*	*27 Kg*	*26.3 (inc GNSS)*
Data rate	22kb/s (J1) / 22 or 37 kb/s (J2)s	38 kb/s	*LRM:92 kbs SAR: 11 Mbps*	*25 kbps*	*47 kbps (LRM) / 12.9 Mbps (DDA)*
Performance					***GDR product***
Range – Range Noise	1.7 cm	0.8 cm	*LRM: 1.4 (Est) SAR 0.8 (Est)*	1.7 cm	*1.7 (Est) /*
Sea State Bias	2.0 cm	2.0 cm	2.0 cm*(Est)*	2.0 cm	*2.0 (Est)*
Ionospheric Error	0.7 cm	0.3 cm	0.5 cm	2.0 cm	*2.0*
Dry Trop Error	0.7 cm	0.7 cm	0.7 cm	0.7 cm	*0.7*
Wet Trop Error	1.2 cm	1.4 cm	1.4 cm	3.7 cm	*3.7*
Total RMS	3.1 cm	2.7 cm	3,.4 cm*(Est)*	5.0 cm	*4.8 (Est)*
POD GPS	2.5 cm	2.5 cm	2 cm*	2.5 cm	*2.5*
Total RMS with POD	4.0 cm	3.7 cm	4.5 cm	5.6 cm	*5.4 (Est)*
Sea state Parameters					
Significant Wave Height	0.4m / 10%	To be determined	To be determined	0.4m / 10%	To be determined
Backscatter	0.7 dB	To be determined	To be determined	0.7 dB	To be determined
Wind Speed	1.5 ms^{-1}	To be determined	To be determined	1.5 ms^{-1}	To be determined

Table 2-1: Known or estimated characteristics of selected options for small satellite radar altimeters. From [RD 01], [RD 02], [RD 03], [RD 04] and [RD 05]. ESA POD requirements for Sentinel-3 are 8cm for < 3h, 3 cm < 2 days, 2cm ~ 30days, LeRoy Pers. Comm.

In addition the study reviewed the limited available literature on assessment models that have been developed to analyse the performance of satellite altimeter constellations.

For the User Needs Analysis we have drawn on the requirements for altimeter-derived products of different user communities. We have also considered the results of a survey of the user community carried out by the PISTACH and COASTALT projects. These do not take into account regional differences in requirements (e.g. between North East Atlantic and South Atlantic) beyond the general categorisation of open and coastal ocean.

For the purposes of this analysis we have grouped the user requirements in terms of the applications and associated user groups as listed in the table below.

Application	Primary User Groups	Secondary User Groups
Improved parameterisation of ocean systems (meso-scale and smaller scale).	Primarily Oceanographic Research, Ocean Modellers (assimilation), climate and seasonal prediction	Users of Operational Ocean Modelling, Offshore and Coastal Operations, Carbon production are listed under those topics
Coastal features	Primarily Oceanographic Research at current stage of maturity	Potentially wide range of operational uses (ship routing, fishing, operational planning and design, coastal defences). But user requirements are sourced from a COASTALT / PISTACH questionnaire where 87% of respondents were from oceanographers in the public sector
Operational ocean modelling	Primarily oceanographic scientists and national meterological / eanographic agencies	Shipping and marine operations, ship routing, operational planning (derived climatologies), search and rescue, fisheries
Numerical Weather Prediction	National and international meteorological agencies	Shipping and marine operations, ship routing, marine design (derived climatologies),operational planning, search and rescue
Monitoring of dynamic weather systems.	Shipping and marine operations, ship routing, marine design, operational planning, search and rescue, Numerical Weather Prediction (assimilation)	Met-Ocean research, hurricane research and modelling,
Offshore and coastal operations (including ship routing, search and rescue, design criteria)	Shipping and marine operations, ship routing, marine design, operational planning, search and rescue	
Tide Modelling	Oceanographic research, ocean modelling, geodetic research	Operational Ocean Modelling, Offshore and Coastal Operations,
Sea Floor Topography	Geodetic research, oceanographic research, ocean modelling	Operational Ocean Modelling, Offshore and Coastal Operations,
Inland waters	Water supply monitoring, climate research	
Carbon production, CO_2 transfer (physical and biological pumps).	Climate research	

Table 2-2: Application Themes and Associated User Groups

For each of these applications performance requirements for three products groups were addressed (Near real time, interim geophysical data record and Geophysical data record.).

This analysis helped to define final performance requirements against which the performance of different altimeter configurations can be assessed. The results of the analysis are summarised in Table 2-3.

Application	Parameter	Spatial Resolution	Time Resolution	Latency	Accuracy	Comments
Lower Mesoscale variability	Sea surface topography	25-50 km	5 days	3 days	2-4 cm	
Sub- mesoscale variability and coastal features	Sea surface topography	10 km	1-2 days	1 day	1-2 cm	
Coastal features[1]	Sea surface topography, wave and wind fields	10 km	1-2 days	1-2 days	SSH 1.5-4 cm SWH 10% WS 1.5 ms^{-1}	Accurate corrections required
Ocean Modelling[2]	Sea surface topography, wave and wind fields	20-40 km	1 day	< 5 hours	SSH 6 cm SWH 10% WS 1.5 ms^{-1}	primarily real time use
Numerical Weather Prediction	Wave height, wave period, wind speed and sea ice cover	2-25 km 25-250km	1h-12h 6h-1d	1-4 hours (global) 0.5 – 2 hours (regional) 6h – 1d	SWH 20-50cm Ta 1s WS 3ms^{-1} 25-50% Max	Real Time use
Dynamic Ocean Weather Systems	Sea surface topography, wave and wind fields	25-50 km 10-250 km	< 5 days 6-24h	1 day	SSH 2.5 cm SWH 10cm Ta 1s WS 3 ms^{-1}	Real time and climatological use Ka band limited use
Offshore operations – real time	Currents waves winds	10-30 km	1h	20mins-1hr	0.1 ms^{-1} / 5° SWH 0.5m Ta 0.5s WS 2 ms^{-1}	
Offshore operations - climatological	Currents waves winds	1° x 1°	1 mon	1 mon	0.05 ms^{-1} / 1° SWH 0.1m Ta 0.1s WS 0.5 ms^{-1}	
Tides near coasts and topography	Tidal constants-sea surface height	10 km	> 100 visits	N/A	1-2 cm	Number of visits refers to the number of samples to the same point in order to assess tidal component, need to avoid tidal aliasing
BarotropicTides	Tidal constants-sea surface height	5 km	> 100 visits	N/A	2 cm	
Non-linearTides	Tidal constants-sea surface height	5 km	> 100 visits	N/A	1 cm	
Sea Floor Topography	Sea surface topography	1-2 km	N/A	N/A	1-2 cm	Non repeat mission orbit preferred
Carbon Production / PCO_2	SSH (Carbon) Air sea gas transfer velocities (PCO_2)	18 km 25 – 100 km	2 days 24h	1 mon 1 mon	3 cm 1 cm hr^{-1}	Users also require co-located wave information, sea surface and windspeed information
Inland Waters	Range, sigma0 (for soil moisture)	~km	Days - weeks	N/A	< 5 cm	Waveforms must be re-tracked with land re-tracker

Table 2-3 Summary of key user requirements for fine scale altimetry

[1] Also mean sea level, sea level anomaly and coastal mean dynamic topography are required.
[2] Also mean dynamic topography is required

2.3 Assessment Model Description

This software is an assessment tool written in MATLAB that allows the user to generate any number of orbits / satellite constellations for altimetry satellites in order to predict, either the sea surface height error or a combination of corrections errors. This MATLAB software is designed to help the user to design the best satellite configuration, where by maximising the minimum error of the sea surface height error or a combination of corrections errors. Thus, there is a trade off between spatial and temporal sampling from different satellite orbits.

Within the last ten years there have been a number of publications on the effectiveness of using multiple altimetry satellites to improve the sea surface height fields. The most influential altimetry missions are Topex/Poseidon, Jason 1 & 2, ERS and ENVISAT. Topex/Poseidon and Jason 1 & 2 follow a repeat cycle of ten days with an orbit altitude of 1336.66 km and a maximum ground track separation of 315 km at the equator. The method that is software uses is similar to Le Traon et al.'s work where they merge data from multi-satellites to produce sea surface height fields (see http://www.aviso.oceanobs.com/en/altimetry/index.html). Le Traon et al. has shown repeatedly this methodology is sound and robust.

The user can model:

- Different satellite constellations, either from pre-loaded files or generated in the tool
  - Therefore can model any orbits you wish, e.g.
    - Constellation configuration
    - Orbits, altitude etc
    - Repeat cycles
    - Inclinations
- Can include operational satellites, e.g. Jason, Sentinel-3 etc
- Different regions
- For oceanographic models:
  - Different instrument error
  - Different temporal sampling (3 hourly to every 2 days)
- For in-land regions
  - Different temporal and spatial steps.

The model is run through a Graphical User Interface through Matlab. As options are selected new menus appear in the user interface. The model will visualise the tracks for the region selected, see Figure 2-2.

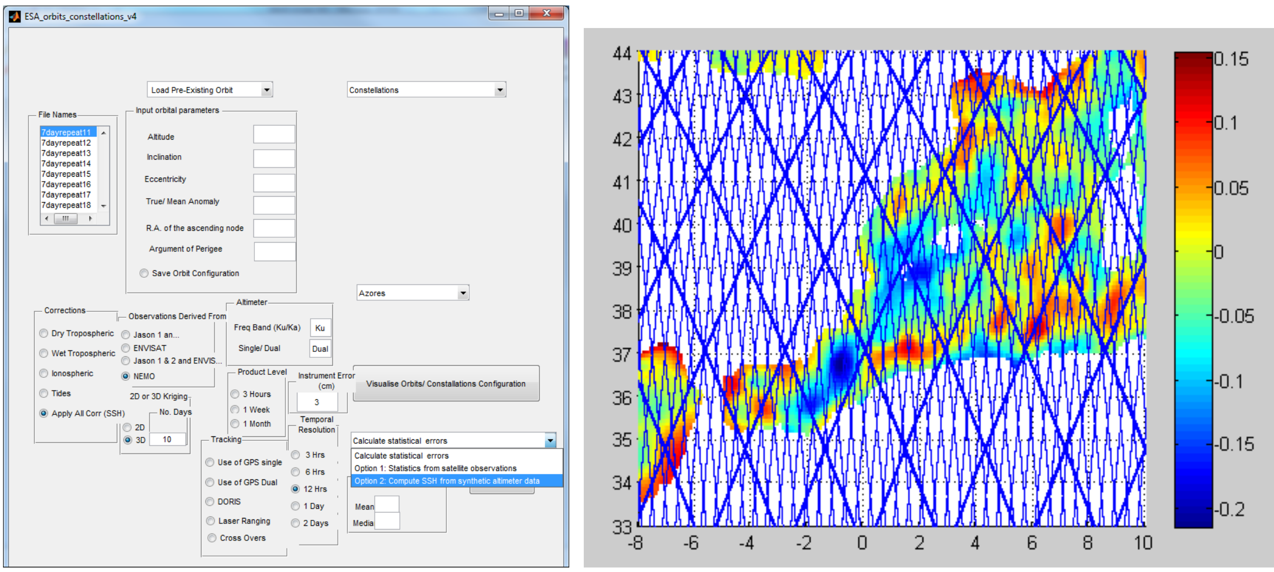


Figure 2-2: The assessment model graphical user interface and plot of tracks over region.

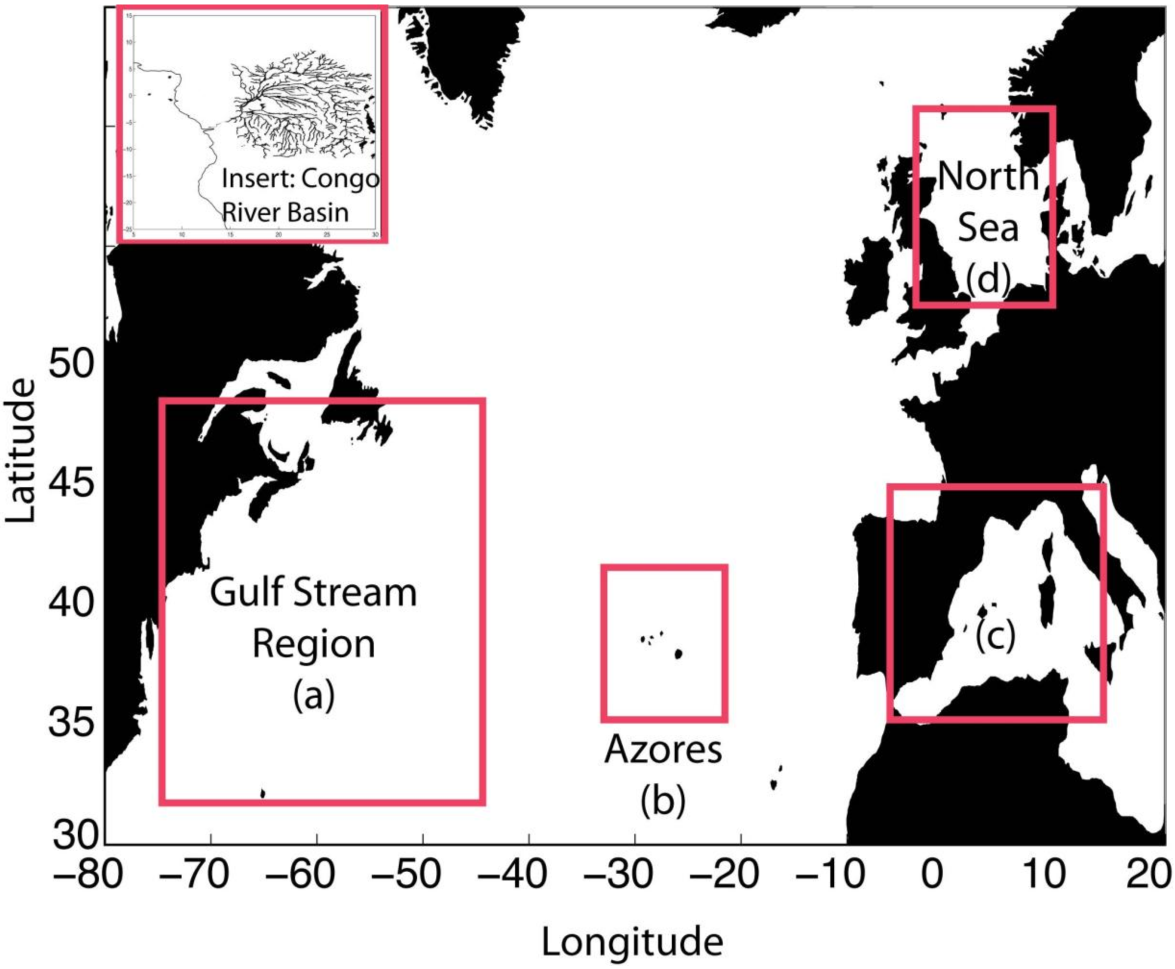


Figure 2-3: Regions that are currently implemented within the model.

The user can implement an instrument error to examine the error level required to detect features in the region of interest, this error value can be used to represent the absolute instrument error, or the performance for different altimetric products, e.g. a near real time product error of the order of 10cm or a non-time critical report 2cm.

The model at this stage has 2 forms of output depending on whether the region is inland water or oceanographic.

The included regions are characterised in Table 2-4.

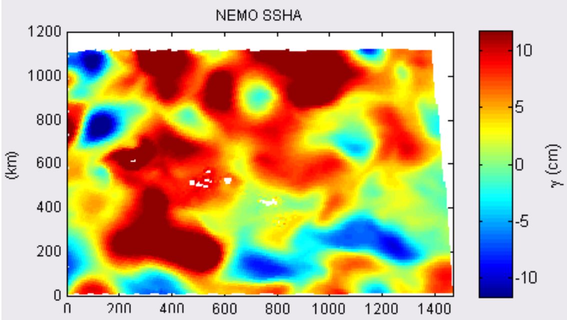
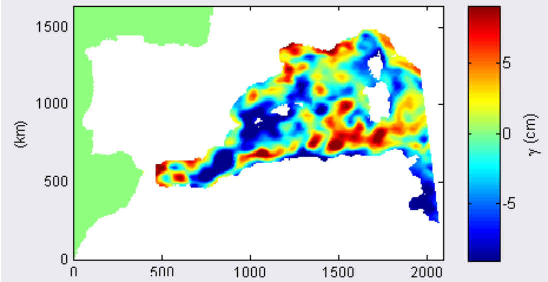
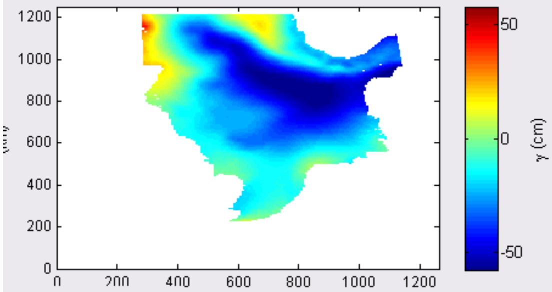
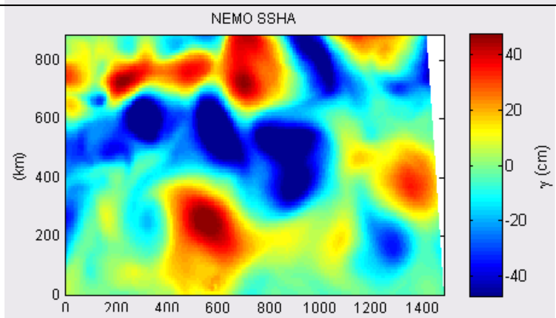
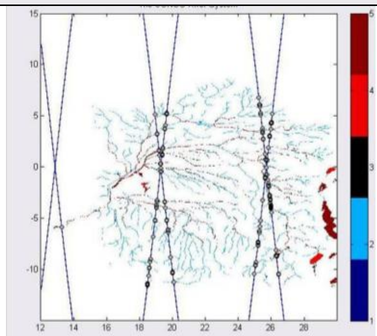
Region	Level of Variability	Stability	
Azores	~ +/- 10cm	Features remaining over several days	
Western Mediterranean	~ +/- 10cm – but slightly smaller than the Azores	Features remain roughly in the same place but do vary in height over the period of a few days	
North Sea	~ +/- 50cm	The North Sea is highly dynamic and the whole region can move by as much as 50 cm over the course of a day, and large scale changes can occur in just 2-3 days.	
Gulf Stream	~+/- 40cm	Features remain fairly stable of the period of several days.	
In-land Water: Example, Congo River system	Wide range of possible quality conditions for the river system	N/A	

Table 2-4: Characteristics of the featured regions.

2.3.1 Oceanographic regions

There are 2 modelling options for assessing constellation performance included within the model.

2.3.1.1 *Statistics from Satellite Observations*

To compute the mapping error from the statistics of the sea surface for all the corrections. From a mixture of altimeter and model data we will compute the covariance function for both space and time. Using standard geo-statistical optimal interpolation (OI) methods we can then compute the variance for a prediction at any point in the area of interest (Cressie 1993). Summary of the error field, e.g. maximum and mean error can be easily displayed. As the covariances (/semi-variograms) are computed and stored prior to running the program the processing of this method is relatively fast.

2.3.1.2 *Compute Sea Surface Height (SSH) from synthetics Altimeter*

In addition to the statistical method (which is dependent on the assumptions about the shape of the covariance, etc.) a facility has been provided where data will be taken from a sea surface height field supplied by the UK Met Office. This data is accessed from the NEMO model, which assimilates in situ and satellite based data every day and forecasts up to 5 days ahead. The model uses an historical data comprised of a mixture of in-situ and modelled data. This data is known as the model ‘truth’. Using the same geo-statistical methods as in the statistical error determination the model computes predictions of the sea surface height from the synthetic altimeter data (including realistic user specified errors) and compare these with the model ‘truth’. Thus, the error statistics will be the actual error in reconstruction rather than the statistical formal error. Again summary statistics of the errors can be computed and displayed.

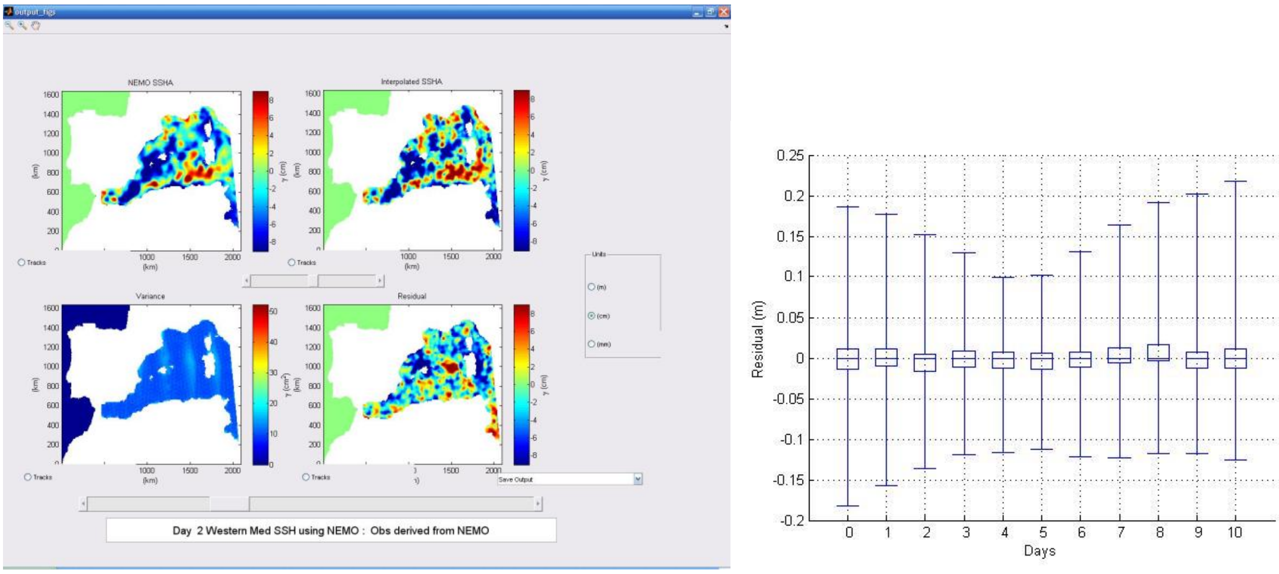


Figure 2-4: Model output for the oceanographic cases. Left: The NEMO model SSH (top left) compared to the Interpolated SSH using the satellite constellation (top right). Also included are variance (bottom left) and residual (bottom right) plots. Right is the residual error summary by time sampling period.

2.3.2 Inland Water

The model has separate functionality for modelling inland water systems. The data sets provided for this modelling consists of a map of the Congo river system and for each point along the river, in 0.5’ steps (equating to 0.9km steps for latitude) is a ‘quality’ flag indicating the altimeter response that can be retrieved for that point. The model then determines the number of accesses to the river system, where the nadir point under the satellite crosses the river and outputs these accesses as a function of the radar echo quality level defined for those points. This allows the user to compare the number of accesses to the river system for the different constellations for different echo retrieval quality levels.

The model also allows the user to plot where these accesses are occurring thus enabling the user to see how well the river system is sampled and where the satellite track would cross over or follow the track of the river. This geometry is potentially interesting, for if the satellite ground track follows the course of a river, it improves the probability of a good quality river echo and thus achieving a good water height measurement.

The user has the flexibility in the model to change the spatial sampling used to retrieve accesses, in order to optimise computational time, the access plotting feature allows the user to determine if the sampling used is sufficient to capture all the potential accesses.

The quality levels included in the assessment model are:

1. Bodies of water not currently obtained by altimetry
2. Small water bodies not currently obtained by altimetry (not in current river and lake mask)
3. Poor altimeter echo retrieval
4. Medium altimeter echo retrieval (usually one or more outliers (occasions where the result is clearly erroneous due to poor echo retrieval)
5. Good altimeter echo retrieval (no outliers, clear annual signature).

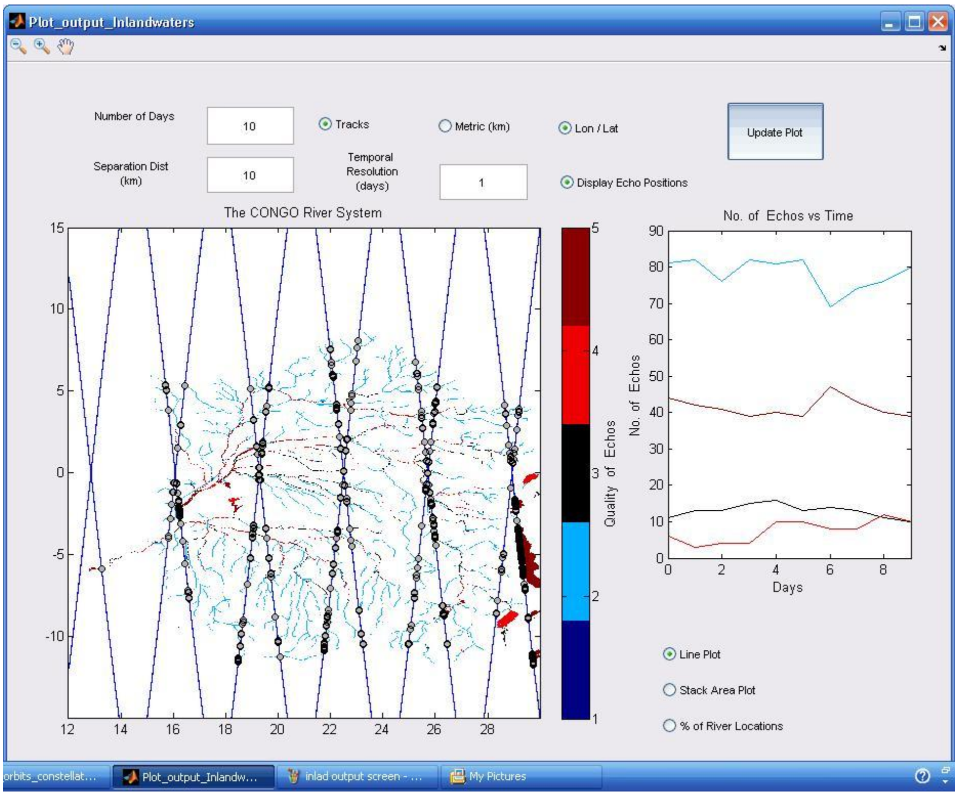


Table 2-5: Example inland water results output.

2.4 Constellation Option Definition and End to End Performance Analysis

2.4.1 Constellation options

The study aimed to explore the impacts of spatial and temporal sampling, influenced both by the number of satellites and the repeat cycle. It also addresses the error performances required for the different regions. In addition some more ‘special’ cases are explored, looking at loss of operational satellites, the inclusion of operational systems and 3 hourly timeliness (with poor spatial coverage).

In addition to exploring constellation options for modelling the various regions, a range of different instrument errors were assessed for a baseline of 16 satellites. This is in order to explore the impact of the instrument error on the results both as a result of the instrument design and also post processing/ product level. For example a near real time product would be expected to have a high instrument error of the order of 10cm. As models are used for modelling the ionosphere and troposphere this error could be reduced, further longer term orbit analysis would allow the final product to have a much reduced instrument error to of the order of 2-3cm.

A summary is provided in Table 2-6.

#	# of satellites	Configuration	Repeat cycle	Instrument Error
1	4	equally spaced in 1 plane (4/1/0)	1 day	3cm
2			7 day	3cm
3	8	equally spaced in 1 plane (8/1/0)	1 day	3cm
4			7 day	3cm
5	16	equally spaced in 2 planes (16/2/1)	1 day	3cm
6			3 day	3cm
7			7 day	3cm
8				5cm
9				7cm
10				10 cm
Special cases				
11	8	8/8/2 to provide 3 hourly revisit	3 hourly	3cm
12				7cm
13	16	2 constellations of 8/8/2 to increase spatial sampling of 3 hourly case	3 hourly	3 cm
14				7cm
15	14	operational - loss of one satellite per plane	7 day	3cm
16				7 cm
17	8 plus Jason	equally spaced in 1 plane plus Jason	7day	3cm
18				10cm
19	16 plus Jason	equally spaced in 2 planes (16/2/1) plus Jason	7 day	3cm
20				10cm
21	32	4 planes of 8 satellites	7 day	3cm

Table 2-6: Constellation options used for the study

2.5 Modelling Conclusions

A wide range of constellation options have been modelled for the study, exploring the effects of numbers of satellites, repeat cycles and required error performance.

The Table 2-6 summarises the results for the 5 regions (Figure 2-3 specified) in the model. The regions have very different characteristics and as such there are slightly different conclusions for each case. 4 satellites are found to be insufficient in most cases to model the variations in sea surface height for the different regions. Certainly a constellation of 8 satellites would be of great benefit, providing the repeat cycle is either 3 or 7 days. For regions where features are relatively small, higher measurement accuracy is required. For regions with large high variability regions, lower accuracy products (errors in SSH of ~ 10cm) do provide good indicators of the variability in the region, with higher accuracy products improving the knowledge of the variability. For regions with high temporal variability as well, a larger constellation of 16 satellites is required. For the North Sea region, a much larger constellation of 32 satellites was explored, and although there was some improvement in the performance, without further work its difficult to determine if this significant increase in satellite number would provide meaningful improvements.

Some analysis explored increasing the temporal sampling for the 8 and 16 satellite cases, this was performed at the expense of spatial sampling. Preliminary results indicate that the improved temporal sampling did not improve the constellation performance and in fact due to the reduction of spatial sampling the constellation performance was poorer, however, this was on a small set of constellations configurations and as such further analysis trading between temporal and spatial sampling is recommended.

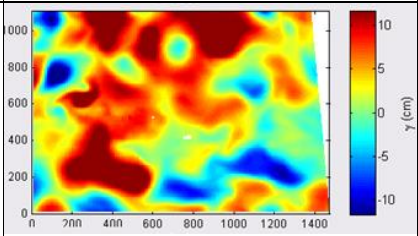
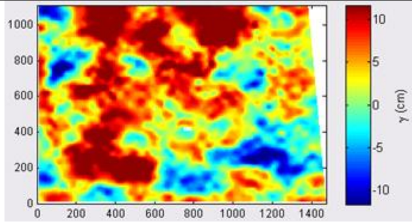
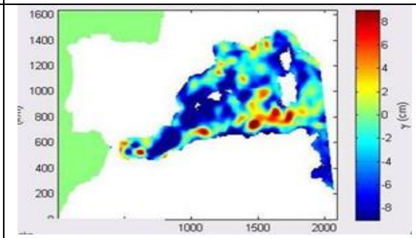
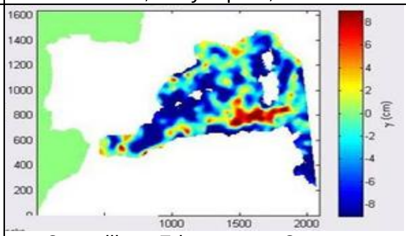
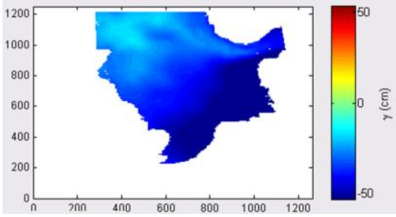
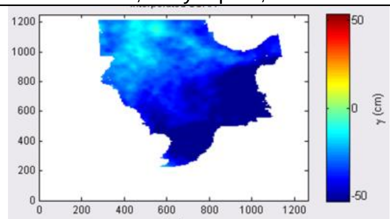
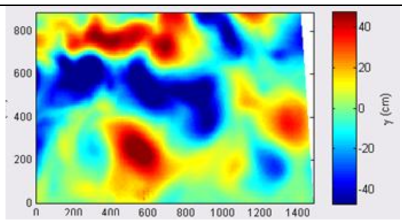
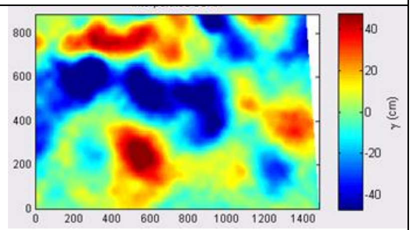
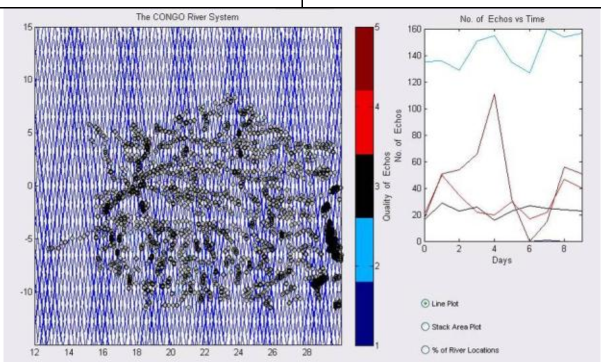
Region	Constellation conclusions	Model	Constellation prediction
Azores	Higher accuracy products required. At least 8 satellites with repeat cycles of 3 or 7 days are required. The 4 satellites with a 7 day repeat do model many of the features.		 8 satellites, 7day repeat, 3cm error
Western Mediterranean	Higher accuracy products needed. At least 8 satellites with repeat cycles of 3 or 7 days.		 8 satellites, 7day repeat, 3cm error
North Sea	For the North Sea temporal and spatial sampling is critical. A minimum of 16 satellites is required to start modelling the features. For this case NRT products with errors of 10cm, though less accurate are able to detect the key features.		 16 satellites, 7 day repeat, 3cm error
Gulf Stream	Similarly to the North Sea, features in the Gulf Stream are large. As such the NRT products do provide knowledge of the key features of the region. 4 satellites (with 7 day repeat) are able to detect key features, however, increasing to 8 or 16 satellites improve the detail and accuracy of the prediction.		 8 satellites, 7 day repeat, 3cm error
Congo River system	For river level monitoring the more spatial access available the greater the chance of achieving an echo. Once spatial sampling is achieved, improving temporal sampling would be of benefit. Basically the more satellites the better, provided their ground tracks are well distributed.	 16 satellites, 7 day repeat orbit	

Table 2-7: Constellation conclusions by region

2.6 Summary of Model capabilities

The model that has been developed provides the user with a wide range of options for trade-off analysis. The model can:

- Model operational altimeter systems and constellations of satellites
- Model any user inputted instrument error thus allowing for trades in
  - Instrument design performance
  - Product levels and thus how well the system would meet end user requirements
- 4 different oceanic regions, which model a range of features
  - Both strong and weak oceanic features
  - Storm surges
  - Coastal areas
- 1 inland water river system,
- The model has a range of outputs, which the user can use to assess the utility of the constellation, both statistical performance levels and example output.
- The tool has the capability to allow the user to select any time period from within the model data, e.g. The North Sea dataset spans 45 days, but the user can select a time period within that to assess.
- The user can look at the statistical performance versus different error corrections schemes such as GIM model.

Modelling has been conducted for 21 different constellation/ error cases for the majority of the included regions. This has demonstrated the models utility and provided some interesting insight into constellation configurations for modelling the included regions.

2.7 Recommendations for further work

Work exploring the data within the model. This analysis has used the first 10 days for the 4 oceanographic regions. Each dataset should be analysed to determine what features are present through the dataset.

Also a limited set of numbers of satellites, repeat cycles and error values have been assessed and the work can be further extended. In addition the data that has been generated could be analysed to a greater extent, e.g. following the performance for particular features in order to assess performance.

One difficulty from this work is that some of the interpretation of results is still rather subjective. Therefore it would be beneficial for users to look at the data and compare the predicted with the actual to determine how valuable they would find the result.

The model that has been developed is powerful for assessing the utility of constellations for the different regions. However, it is clear that the results are dependant on the features the regions contain, and in addition these regions do not represent all the potential user needs. The addition of further regions would be of benefit for expanding the range of user needs that are modelled and further determining how the regions characteristics influences the results.

The model has the facility to quantify the performance when either or both tropospheric humidity and ionospheric models are used instead of, respectively, a microwave radiometer and/or dual band altimeter. The models are the European Centre for Medium-Range Weather Forecasts (ECMWF) & National Centers for Environmental Prediction (NCEP)) tropospheric models and the Global Ionospheric Model (GIM). Currently the software assessment model includes only the ionospheric model. The inclusion of these extra models would enable an assessment to be made of the potential of just using models rather than carrying either or both the dual band altimeter and microwave radiometer.

Currently there is only one inland water region in the model; there would be benefit in adding in further regions, particularly at different latitudes.