Design of the future altimetry missions: development and use of an « end-to-end » mission simulator

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Abstract

In the current frame of debates on future altimetry constellation design, the need for a decision-making tool has been highlighted by CNES and realised through the development of an *end-to-end* altimeter mission simulator. This simple, flexible and evolutive tool aims at examining the merits of various observing configurations and discriminate among them. The present study describes the first prototype of this *end-to-end* mission simulator for altimetry. Based on a simplified version of the recently published Ensemble Twin Experiments methodology (Mourre *et al.*, 2006), the simulator aims at quantifying the potential of an altimetry observing system by estimating its ability to reduce the statistical error of a storm surge model of the Bay of Biscay. Relative performance score helps discriminate the various observing scenarios (number of satellites, orbits, instrument type, …). Some validation and application case results are presented. Especially, the phasing between the orbits of Jason-1 and Jason-2 after switching into a science/application phase of the tandem mission is analysed with the *end-to-end* mission simulator.

1. Methodology

Framework

The methodology comes within the specific framework of Observing-Systems Simulation Experiments (OSSEs, Arnold and Dey, 1986). More particularly, the so-called "Twin Experiments" method is a practical and efficient way to assess the observing capability of a given altimetry system: in this method, observations are generated from a "control" simulation (from an oceanic numerical model), and then assimilated in a "free" simulation. The **performances of the system** are thus estimated **in terms of a model error reduction** (*i.e.* through the way the assimilated simulation gets closer to the control run) performed via a **data assimilation system**.

Model configuration : MOG2D model (Lynch and Gray (1979), adapted by Greenberg and Lyard)

- Barotropic, non linear, Finite Element method for spatial resolution
- zone = Bay of Biscay + English Channel + Celtic Sea, nested in European shelf area (**Fig. 1**)
- Sea Level Anomaly, barotropic velocities
- Atmospheric forcing : surface pressure and 10 meters-wind velocity (from ARPEGE products).
- Tidal forcing
- European shelf solution used as open boundary conditions
- Time period : 16/11/1999, 00h➔01/12/1999, 00h

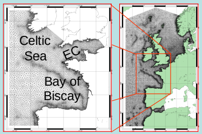


Fig. 1: FE mesh used in the study: Bay of Biscay + English Channel + Celtic Sea nested in European shelf

Experiment configuration

In addition, as a prior requirement (and a research subject) for data assimilation, the specification of model errors has shown to be much more complicated in Shelf and Coastal Seas (hereafter SCS) than in the open ocean: SCS model errors appear to be inhomogeneous, non-stationary, anisotropic and multi-scale (Echevin *et al.*, 2000; Auclair *et al.*, 2003; Mourre *et al.*, 2004, Lamouroux *et al.*, 2006), due to strong non-linearity of SCS dynamic processes, intense control of coastlines and bathymetry, and fast response to atmospheric forcing.

In our study, the forecast errors are approximated from a **100 Ensemble (Monte Carlo) simulations** of the model in **response to 10 meters wind and surface atmospheric pressure forcing errors** (Lamouroux, 2006). The errors statistics can thus be estimated by the **ensemble variance of the model** (Evensen, 2003).

➔ In this context, the so-called "Ensemble Twin Experiments" allow to assess the performance of an observing system by its capability to reduce the ensemble variance of the model.

Data assimilation methodology

For analysis step, NOVELTIS implemented the sequential **Reduced-Order** data assimilation code **SEQUOIA**, used with the **Optimal Interpolation MANTA** kernel (De Mey, 2005), that NOVELTIS set up in an Ensemble Reduced Order data assimilation configuration: error statistics are computed in the form of **ensemble EOFs** and used to perform analysis steps over the 100 ensemble simulations. The **pseudo-observations** are extracted from the model reference simulation corresponding to a non-perturbed run, given a user-build altimetry configuration. For a given analysis step, innovations (differences observations-model proxy) are computed in a **4 day-window** centred around the analysis time (smoother mode). Analysis steps are **performed daily**.

In this first step study, NOVELTIS has performed **Simplified Ensemble Twin-Experiments**, i.e. the methodology involves no sequential control of the model, as illustrated on **Fig. 2**. The ensemble error reduction is only estimated at analysis time, but is not propagated in time via the model.

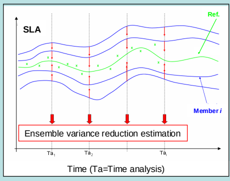
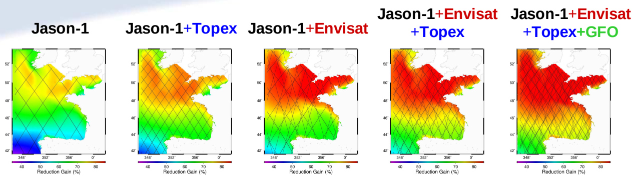


Fig. 2: schematic view of the analysis system implemented in the simulator

5. Satellite systems performances

First scientific validation results



Jason-1	Jason-1+Topex	Jason-1+Envisat	Jason-1+Envisat +Topex	Jason-1+Envisat +Topex+GFO
64.0 ± 18.3 **%**	**69.8** ± 16.9 **%**	**74.7** ± 11.5 **%**	**76.1** ± 11.8 **%**	**79.0** ± 9.1 **%**

(**Synthetic gain ± temporal standard deviation** in terms of ensemble variance reduction over the period)

Same hierarchy than the one exposed by **Pujol et al., 2008** [(1)]

[(1)] Pujol, M.-I., S. Dobricic, N. Pinardi and M. Adani, Impact of multi-altimeter sea level assimilation in the Mediterranean Forecasting model, to be submitted to J. Atmos. Oceanic. Technol., 2008.

(study shown at the OSTC Workshop CEOS-Eumetsat in jan. 2008 – based on real altimetry data assimilation in a 3D baroclinic model, region = Mediterranean Sea, period = 6 months, assimilation method = 3DVAR)

Case study : choice of the 'new' Jason-1 orbit

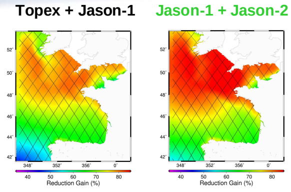
One major issue to be discussed during the 2008 OSTST meeting is the phasing between the orbits of Jason-1 and Jason-2 after switching into a science/ application phase of the tandem mission.

The **TP/Jason-1** tandem mission had a very small (7') difference between the overflight times of the two satellites crossing a given latitude in interleaved orbits. This near simultaneous overflight of two satellites allows the computation of the along-track component of geostrophic velocity.

However, the spatial/temporal sampling resulting from this orbit phasing is not optimal for mapping the variability of the ocean.

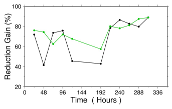
A proposal for a new orbit phasing for the science/application phase of the tandem mission of **Jason-1/Jason-2** consists in a **5 day time lag** between the overflight times of the two satellites in interleaved orbits whose ground tracks remain the same as the TP/Jason-1 Tandem Mission.

Here we assess the benefit of this new orbit phasing by comparing the two configurations with the simulator.



Topex + Jason-1	Jason-1 + Jason-2
69.8 ± 16.9 **%**	**75.1** ± 9.3 **%**

Model error (ensemble variance) reduction gain



Better performance of the new tandem mission orbit '**Jason-1+Jason-2** ' for data assimilation in storm surge model (probably due to a better temporal sampling)

2. Observation scenarios

Satellite tracks generation

The altimetry configuration is set up by the user, given a set of simple **orbit parameters** to specify:

➔ Inclination, altitude, number of revolutions per cycle, number of Earth rotations with respect to its orbit plane, initial longitude/latitude, instrumental noise level

As a prior requirement from CNES, NOVELTIS has implemented a **multi-satellite configuration**. In this prototype tool, the user can thus test either **nadir** and/or **wide swath** altimeters. In a wide swath altimeter configuration, one can also tune the **cross/along track resolution** and the **crosstrack number of "cells"**.

Fig. 3 presents 4 altimetry configurations, based on (a) JASON-1, (b) JASON-1+TOPEX/POSEIDON tandem, (c) WSOA on an JASON orbit and (d) ENVISAT specifications. One cycle is represented.

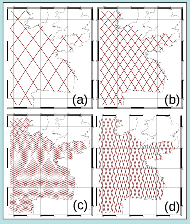


Fig. 3: (a)JASON-1, (b)JASON-1+TOPEX/POSEIDON tandem, (c) JASON+WSOA on an JASON orbit and (d) ENVISAT altimetry configurations computed by the simulator.

Pseudo-observation generation

The simulator computes the space-time positions of the user-built altimetry configuration over the whole study period and domain. Pseudo-observations are then generated by extracting the model proxies (from the reference simulation, *cf* §1) at the space-time altimetry positions. These pseudo-observations are then noise-added following a gaussian noise of zero-mean and standard-deviation specified by the instrument noise level (user given).

3. Characterization of model errors

In the specific configuration of oceanic response to uncertainties in atmospheric forcing:

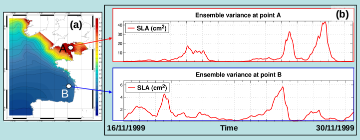


Fig. 4: **(a)** time averaged and **(b)** time evolution of SLA ensemble variance in 2 points of the domain (extracted from Lamouroux, 2006)

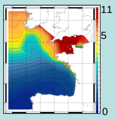


Fig. 5: SLA ensemble variance at 20/11/1999 (cm²)

➔ Inhomogeneous distribution of SLA errors (Fig.4):

- **max. error structures in EC**, weaker in Bay of Biscay (Fig. 4-(a))
- errors are variable in time (Fig. 4-(b)) and space (see for instance **Fig. 5**)

4. Analysis diagnostics

NOVELTIS designed 4 analysis diagnostics estimating the **ensemble variance reduction**:

At analysis time:

- $EnsVarAssim(x,y,T^a) = \mathrm{var}^{ensemble}\left(SLA_i^{assim}(x,y,T^a)\right)$ (*i* =member index) : map of the ensemble variance after assimilation (to be compared with $\mathrm{var}^{ensemble}\left(SLA_i^{no-assim}(x,y,T^a)\right)$, *i.e.* ensemble variance before correction
- $EnsVarRatio(x,y,T^a) = \dfrac{\mathrm{var}^{ensemble}\left(SLA_i^{assim}(x,y,T^a)\right)}{\mathrm{var}^{ensemble}\left(SLA_i^{free}(x,y,T^a)\right)}$: map of the ratio between ensemble variance after and before assimilation. The closer to zero, the better correction.
- $Gain(T^a) = 100\left(1 - \dfrac{\overline{\mathrm{var}^{ensemble}\left(SLA_i^{assim}(x,y,T^a)\right)}^{x,y}}{\overline{\mathrm{var}^{ensemble}\left(SLA_i^{free}(x,y,T^a)\right)}^{x,y}}\right)$: space averaged value for ensemble variance reduction at T^a

Over the period:

- $\%EnsVarRedux = 100\left(1 - \dfrac{\overline{\mathrm{var}^{ensemble}\left(SLA_i^{assim}(x,y,T^a)\right)}^{time}}{\overline{\mathrm{var}^{ensemble}\left(SLA_i^{free}(x,y,T^a)\right)}^{time}}\right)$: map of the percentage of ensemble variance reduction over the whole period.

Synthetic:

- $\text{synthetic gain} = 100\,\overline{\left(1 - \dfrac{\overline{\mathrm{var}^{ensemble}\left(SLA_i^{assim}(x,y,T^a)\right)}^{x,y}}{\overline{\mathrm{var}^{ensemble}\left(SLA_i^{free}(x,y,T^a)\right)}^{x,y}}\right)}^{time}$: synthetic space-time averaged value for the ensemble variance reduction.

Conclusions / Perspectives

In the specific modelling framework presented here:

- The simulator is confirmed as an **efficient tool to estimate the performances** of various altimetry configurations. Its ability to **discriminate among** such configurations has been validated against the efficiency of an advanced methodology, implementing a 3D-model and a complex analysis system assimilating real observations (Pujol *et al.*, 2008).
- Basing on the simulator's results, orbit re-configurations (phase, interleave orbits) can be proposed for current in-flight missions. First studies have been performed, with a comparison between historical TP/Jason-1 configuration and a new phasing of Jason-1/Jason-2 orbits. Results show better performances for the new orbit configuration.

In a close future, further developments of the simulator should be achieved in close collaboration with NOVELTIS and POC, for instance:

- **extending the period of simulation** of the "storm-surge" simulator, in order to refine the statistical coherency and reliability of the results
- enhancing the simulator versatility by considering **other oceanic processes**, such as **tides** (involving important questions such as the impact of **tides aliasing** in observation)
- improving the **observation error budget** of the pseudo-data (impact of satellite roll, specific error budget for coastal measurements, etc …)
- implementing more **advanced – but still "cheap" - analysis methods**

- **Arnold, C. P. and Dey, H. C**. Observing-systems simulation experiments: past, present and future. *Bull. Amer. Meteor. Soc*, 67:687-695, 1986
- **Lynch, D.R. and Gray, W.G**. A wave equation model for finite element tidal computations. *Computers and Fluids*, 7:207-228, 1979
- **Echevin, V., De Mey, P., Evensen, G**. Horizontal and vertical structures of the representer functions for sea surface measurements in a coastal circulation model. *J. Phys. Oceanog.*, 30:2627-2635, 2000
- **Auclair, F., Marsaleix, P., De Mey, P**. Space-time structure and dynamics of the forecast error in a coastal circulation model of the Gulf of Lions. *Dyn. Atm. Oceans*, 36:309-346, 2003
- **Mourre, B., De Mey, P., Lyard, F., and Le Provost, C**. Assimilation of sea level data over continental shelves : an ensemble method for the exploration of model errors due to uncertainties in bathymetry. *Dyn. Atm. Oceans*, 38:93-121, 2004
- **De Mey, P**., The MANTA analysis kernel, *Pers. Comm.*, 2005
- **Lamouroux, J**., De Mey, P., Lyard, F., Jeansou, E. Control of a barotropic model of the Bay of Biscay in presence of atmospheric forcing errors. Submitted to *J. Geophys. Research-Oceans*, 2006
- **Lamouroux, J**. Erreurs de prévision d'un modèle océanique barotrope du Golfe de Gascogne en réponse aux incertitudes dans les forçages atmosphériques : caractérisation et utilisation dans un schéma d'assimilation de données à ordre réduit. PhD. 2006. Université Paul Sabatier, Toulouse.
- **Pujol, M.-I.**, S. Dobricic, N. Pinardi and M. Adani, Impact of multi-altimeter sea level assimilation in the Mediterranean Forecasting model, to be submitted to J. Atmos. Oceanic. Technol., 2008.