Design of the future altimetry missions: a first prototype of an « end-to-end » mission simulator

J. Lamouroux(1) , L. Roblou(1), J. Lambin(2), P. De Mey(3), F. Lyard(3), E. Jeansou(1)

(1) **NOVELTIS**, 2 av. de l'Europe, Parc Technologique du Canal, 31526 Ramonville St-Agne, France : **http://www.noveltis.fr**
(2) **CNES Toulouse**, 18 av. Edouard Belin 31 401 TOULOUSE CEDEX 9 : **http://www.cnes.fr**
(3) **Pôle d'Océanographie Côtière (POC-LEGOS)**, OMP, 14 Av. Edouard Belin, 31 400 Toulouse, France : **http://poc.omp.obs-mip.fr**

Corresponding author: Julien Lamouroux, **julien.lamouroux@noveltis.fr**

Abstract

Operational oceanography reached a new level with the publication of the first global forecast bulletin by the French group MERCATOR in October 2005. Since then, global ocean fields are available in real time not only for scientific studies but also for commercial or military applications. At a regional scale, the knowledge of the coastal dynamics takes part in key challenges for our society among others the response of the coastal ocean to the global climate changes (extreme events, shore erosion, eutrophication...), marine pollution management or marine security monitoring. However, as for the deep ocean, coastal hydrodynamics models still remain limited in precision due to uncertainties in the atmospheric forcing fields, in the bathymetry solutions or in the boundary conditions prescription for instance. In this framework, data assimilation appears to be a solid and efficient technique to improve the quality of model solutions and the range of forecasts.

Satellites observing systems provide a dense and repetitive network of observations needed for ocean modelling. However, such remote-sensed systems are costly and it is then essential to examine the merits of the available observing configurations in order to find the best compromises between the needs of the scientific community and of socio-economic partners. This poster presents a first prototype of an "End-to-End" Mission Simulator for altimetry. Based on a simplified version of the recently published Ensemble Twin Experiments methodology (Mourre et al., 2004), 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. In these conditions, it is expected that this "End-to-End" Mission Simulator will constitute a powerful decision-making tool to help CNES in the definition of the future altimetry observing systems.

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

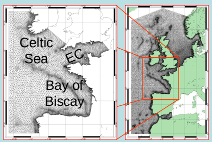


Fig. 1: FE mesh used in the study: Bay of Biscay + English Channel + Celtic Sea nested in European shelf

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.

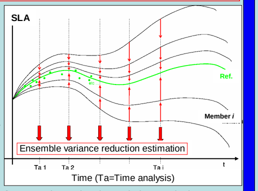
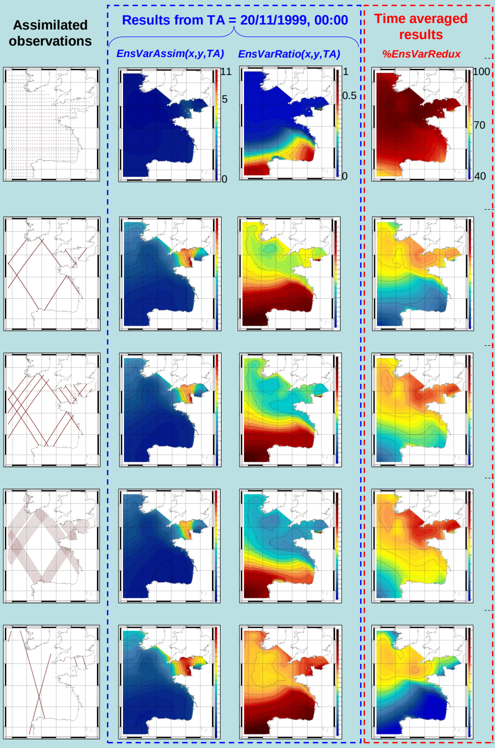


Fig. 2: schematic view of the analysis system implemented in the simulator

5. Validation / Satellite systems performances

- **Validation methodology:** assimilation of pseudo-observations from a regularly spaced 654 points grid (shown on **Fig. 4**). Analysis are performed every 24h, with data extracted at time analysis only.
- Estimation of performances of 4 altimetry configurations based on **JASON-1, JASON-1+TOPEX/POSEIDON tandem, WSOA** (on a JASON orbit) and **ENVISAT** specifications
- For a given diagnostic (cf §3 for definitions), scales and colorbars are identical for each satellite
- **The ensemble variance before correction at Tª is displayed on Fig. 5** (§2)



VALIDATION:

- Strong and uniform reduction of ensemble variance (*gain(Tª)* **~ 94%**), especially in the EC (*%EnsVarRedux*~90%)
- *EnsVarRatio(x,y,TA)* close to 0.1 in a wide part of the domain, and is at least lower than 0.6 (lower correction in the south of domain, but where errors are weak)
- At least, up to 70% of ensemble variance reduction over the domain and period (*%EnsVarRedux*>70) ➔ **Synthetic gain ~ 78%**

JASON-1:

- Efficient ens. var. reduction in the north of domain, in Celtic Sea. Residual error cell in the EC. Same remark as above concerning the lower correction in the south of Bay of Biscay (hereafter "BoB").
- ~70% of correction in the EC, ~50% in the Bob (*%EnsVarRedux*)
- *gain(Tª)* **~ 65%**
- **Synthetic gain ~ 54%**

JASON-1 + TOPEX/POSEIDON:

- Better correction in EC than JASON: ~80% of correction (but residual error cell still remains).
- Space correction zone is increased with respect to the one obtained with JASON-1: ~65% of correction in the Bob
- *gain(Tª)* **~ 70%**
- **Synthetic gain ~ 60.5%**

WSOA (on a JASON orbit)**:**

- EC error regime is better controlled. The residual cell also better constrained
- More than 70% of ens. var. reduction (*%EnsVarRedux*) for a wide part of the domain.
- *gain(Tª)* **~ 75%**
- **Synthetic gain ~ 62.5%**

ENVISAT:

- Mean correction over the domain: EC errors regime is less controlled (~50% of correction at Tª, ~60% over period); the efficient correction zone is mainly localized in Celtic Sea. Less than 40% of correction in BoB
- *gain(Tª)* **~ 56%**
- **Synthetic gain ~ 50%**

- **In the study framework**, ENVISAT appears to be less efficient than other configurations; but less observations are available and then assimilated, so that a poorer sampling of errors pattern is achieved.
- **In the specific modelling framework** (oceanic response to uncertainties in atmospheric forcing + Simplified Ensemble Reduced order Data Assimilation methodology), the **`WSOA technology + JASON orbit`** system appears to be the **most efficient configuration to control the errors of the model,** especially in the EC and Celtic Sea where stands most of the error of the model (Lamouroux *et al.*, 2006).

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.

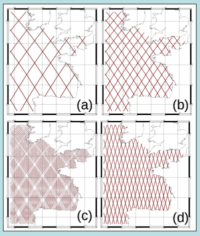


Fig. 3: (a)JASON-1, (b)JASON-1+TOPEX/POSEIDON tandem, (c) JASON+WSOA on an JASON orbit and (d) ENVISAT altimetry configurations computed by the simulator.

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:

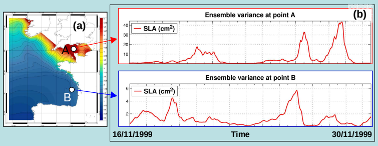


Fig. 4: (a) time averaged and **(b)** time evolution of SLA ensemble variance in 2 points of the domain (extracted from Lamouroux, 2006)

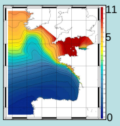


Fig. 5: SLA ensemble variance at 20/11/1999 (cm²)

➔ 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 *Tª*

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

- NOVELTIS has implemented and validated a Simplified Ensemble Reduced-Order Data Assimilation methodology, in collaboration with POC and CNES teams.

In the specific modelling framework presented here:

- Firsts tests of various altimetry configuration performances have provided **encouraging results**. Further experiments should be carried on and refined.
- The simulator appears to be an **efficient tool to estimate the performances** of various altimetry configuration and **to discriminate** among them.
- Simple, highly flexible and evolutive, this prototype constitutes a first version of a powerful tool for **designing orbit for multi-satellite altimetry systems** (JASON-3, SWOT, SENTINEL-3…)

In a close future, NOVELTIS recommends further developments, in close collaboration with CNES and POC:

- Implement a **more complex data assimilation scheme** such as Reduced-Order Ensemble Kalman Filter or Ensemble Kalman Filter (with sequential control of the model errors)
- Improve the discrimination process by considering **other oceanic processes and error sources**, such as tides and bathymetric perturbations (basing on Mourre *et al.,* 2004, for instance).

- **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.