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The SARAL/AltiKa Altimetry Satellite Mission

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Abstract

The India-France SARAL/AltiKa mission is the first Ka-band altimetric mission dedicated to oceanography. The mission objectives are primarily the observation of the oceanic mesoscales but also include coastal oceanography, global and regional sea level monitoring, data assimilation and operational oceanography. Secondary objectives include ice sheet and inland waters monitoring. One year after launch, the results widely confirm the nominal expectations in terms of accuracy, data quality and data availability in general. Today's performances are compliant with specifications with an overall observed performance for the Sea Surface Height RMS of 3.4 cm to be compared to a 4 cm requirement. Some scientific examples are provided that illustrate some salient features of today's SARAL/AltiKa data with regard to standard altimetry: data availability, data accuracy at the mesoscales, data usefulness in costal area, over ice sheet and for inland waters.

1. The SARAL/AltiKa program

The SARAL (Satellite for ARgos and ALtika) program is a joint mission conducted by the Indian Space Agency (ISRO) and the French Space Agency (CNES) dedicated primarily to ocean observations.

The SARAL and ARGOS-3/SARAL Memorandum of Understanding was signed on February 2007. As its name indicates, two missions are onboard the SARAL satellite (Figure 1), which is based on the ISRO "Small Satellite Bus" platform:

- AltiKa: a nadir altimeter in Ka-band
- ARGOS-3: the new generation of ARGOS instrument (ARGOS is a worldwide location and data collection system, see e.g. www.argos-system.org).

Exploratory technical developments have been conducted since 1998 and phase B on the instrument was conducted by CNES as early as 2003. By the end of 2009, a formal agreement has been reached with EUMETSAT to take part in the SARAL/AltiKa mission.

SARAL was launched on February 25, 2013 at 12:31 UTC. It reached its final orbit on March 13. The AltiKa altimeter has been switched on February 26 at 01:42 UTC. Cycle #1 began on March 14 at 05:39 UTC.

In order to continue the time series and to benefit from the existing mean sea surface, SARAL flies on the same orbit as ENVISAT. The orbit is almost polar (the final inclination reached is 98.55° as ENVISAT), sunsynchronous and with a 35-day repeat cycle (see Table 1 for all the orbit elements)

The overall SARAL designed lifetime is 5 years, but the mission will continue as long as the satellite and the ground segment continue to operate. The lifetime requirement of the AltiKa payload is just 3 years but with an objective of 5 years. Regarding ARGOS-3, the lifetime requirement is 5 years with an objective of 7 years.

The main responsibilities of the two main partners are as follows. The SARAL Satellite is composed of a spacecraft bus IMS-2 (Small Satellite Bus) developed by ISRO and a payload developed by CNES. The IMS-2 platform is designed for satellites in the range of about 500 kg at launch. The payload is composed of the AltiKa altimeter-radiometer (see also Steunou *et al.*, 2014a, b), a Doris system for precise orbit determination (POD) (see also Jayles *et al.*, 2014), and a Laser Retro-reflector Array instrument used for precise calibration of other POD instruments. EUMETSAT ensures the distribution of SARAL/AltiKa payload and auxiliary data to CNES and to ISRO, the Near-Real Time processing of SARAL/AltiKa Operational Geophysical Data Record (OGDR) data and the Near-Real Time dissemination of the SARAL/AltiKa products to users outside of India.

2. Scientific Objectives

The SARAL/AltiKa mission is an answer to the needs expressed by the oceanographic community (IGOS, GODAE, OSTST) since 2000: "Continuity of high accuracy, high resolution Near-Real Time observations of the ocean surface topography is required. At least, 2 simultaneous altimetry missions are required (including one of the Jason reference class)." As a consequence, the SARAL/AltiKa mission is considered as a "gap filler" between ENVISAT (lost in April 2012) and Sentinel-3 (expected by mid-2015) (see also Vincent *et al.*, 2006).

SARAL/AltiKa's main scientific objective is to provide data products to the oceanographic research user community for studies to improve our knowledge of the ocean mesoscale variability, thanks to the improvement in spatial and vertical resolution brought by SARAL/AltiKa. Ocean mesoscale variability is defined as a class of high energy processes, with wave-lengths in the 50 km to 500 km range (the internal Rossby radius), and with periods of a few days to a few months. The kinetic energy of mesoscale variability is often an order of magnitude more than that of the mean circulation. A description of the mesoscale is thus essential for understanding ocean dynamics, including mean circulation and its climatic effects, through the major contribution of the mesoscale turbulence to the shaping of the mean circulation.

This main scientific objective is divided into sub-themes of mesoscale ocean dynamics: observations, theoretical analyses, modelling, data assimilation, etc. This will lead to an improvement of our understanding of the climate system through its key ocean component and especially the role and impact of mesoscale features on the climate variability at large spatial and temporal scales. It will also bring a contribution to the study of coastal dynamics which is important for many downstream applications including operational oceanography which is seeking large amounts of *in-situ* and space-based data.

SARAL/AltiKa's secondary objectives include the monitoring of the main continental water levels (lakes, rivers, enclosed seas), the monitoring of large-scale sea level variations, the observation of polar oceans (thanks to the high inclination of its orbit), the analysis and forecast of wave and wind fields, the study of continental ice (thanks to the lower penetration in Ka-band) and sea ice, the access to low rains climatology (enabled in counterpart to the sensitivity of Ka-band to clouds and low rains) and the marine biogeochemistry (notably through the role of the meso- and submeso-scale physics).

75 Pis (32 proposals from Indian institutions, 16 proposals from 7 French institutions, 27 proposals from non-Indian and non-French institutions) have been selected by CNES and ISRO to form the SARAL/AltiKa science team (Table 2). All the proposals provide a good coverage of the topics mentioned above. Among them, many proposals contribute to the calibration and validation plan, concerning on-site verification, global and regional in-situ verification, global statistical and cross-calibration analysis, specific studies (rain effect, sea ice), wet tropospheric correction, sea surface bias, wind and waves. Those studies will permit to assess the SARAL/AltiKa capability to respond to the scientific objectives.

3. AltiKa system description and specifications

The AltiKa altimeter follows on from existing nadir altimeter (Poseidon-3 on Jason-2) but operates in a single frequency band: the Ka-band. It is the reduced ionosphere effects in Ka-band that makes it possible to use a mono-frequency altimeter. The higher frequency (35.75 GHz compared to 13.5 GHz on Jason-2) leads to a smaller footprint (8 km diameter compared to 20 km on Jason-2 and to 15 km for ENVISAT) and so a better spatial resolution. The higher Pulse

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Repetition Frequency (4 kHz compared to 2 kHz on Jason-2) permits also a better along-track sampling of the surface. Moreover, the enhanced bandwidth (480 MHz compared to 320 MHz on Jason-2) enables a better resolution of the range (see also Steunou *et al.*, 2014a).

The altimeter shares the antenna with a K-Ka bi-frequency (23.8 GHz and 37 GHz) radiometer. The radiometer is required to correct the altimeter range for the wet troposphere path delay. The retrieval algorithm consists of a neural network whose inputs are the two Brightness Temperatures (BTs) measured by the radiometer and the altimeter radar backscatter. The novelty of AltiKa is that the altimeter and the radiometer operate at the same frequency. One aspect to underline is that the radiometer in Ka-band and the altimeter have the same footprint and the same antenna; that is to say the measurements of the 2 instruments are exactly collocated.

The radiometer has an on-board calibration. The "hot calibration" consists in the measure of the thermal emission of an internal load. The "cold calibration" is performed using a sky horn to get the cold reference point. The present frequency of calibration is one calibration cycle for 2 antenna cycles (see also Steunou *et al.*, 2014b; Picard *et al.*, 2014).

Environmental and geophysical corrections of course contribute also to the Sea Surface Height (SSH) error budget. The ionospheric effect is dramatically reduced in Ka-band with respect to the Ku-band. Indeed, the attenuation due to the ionosphere is proportional to the inverse of the frequency squared, so the attenuation in Ka-band is about 7 times lower than in Ku-band. In

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the AltiKa products (like in Jason-2 products), the ionospheric correction will be inferred from a total electron content model, e. g. from the global ionospheric mapping (GIM) model.

The wet tropospheric correction, corresponding to the range delay due to atmospheric water vapour, is estimated thanks to the BTs measured by the radiometer, and the ECMWF model (like Jason-2).

The Sea State Bias (SSB) consists of an empirical correction derived from altimeter data analysis, to adjust the sea surface height "seen" by the altimeter. Indeed, wave troughs reflect radar signals better than crests do. Since altimeters measure the height of reflecting surfaces, the measurements are slightly biased toward troughs. At least one year of AltiKa data will be needed to tune the correction. In the meanwhile, the formula SSB = 3.5% of Significant Wave Height (SWH) has been used as a first approximaiton of the SSB table.

4. Mission operations

The SARAL/AltiKa satellite was put into orbit by a PSLV vehicle supplied by ISRO, and launched from the Satish Dhawan Space Centre in Sriharikota, India, the main ISRO launch base, on February 25, 2013 at 12:31 UTC. All payload instruments were put in operation within 12 hours of launch. The first waveform was acquired 16' after AltiKa was switched on at 1:42 UTC on February 26th, 2013 only 13 hours after lift-off.

The planning after launch can be summarized by the following usual major steps. We started with an assessment phase of 2 months, concluded by the fully satisfactory in-flight assessment review held on CNES Toulouse side. Then we completed the verification phase of the mission, which begun with cycle 1, that is to say since the well-functioning satellite reached its final orbit and crossed the equator at the predefined longitude of the first ascending node.

After a quick validation performed by the mission project, the Near-Real Time products (Operational Geophysical Data Record -OGDR- and Interim Geophysical Data Record -IGDR-) were delivered in "T" version (for test) to the SARAL/AltiKa PIs from respectively March 21st and 28th, 2013. Taking into account the good quality of the data assessed by the project and the PIs, it was decided to deliver the O/IGDR data to all users starting in June 2013, although the first verification workshop did not take place until later.

Regarding the offline products (Geophysical Data Record -GDR-), the first cycle in "T" version was delivered to the SARAL/AltiKa PIs on August 6. A dedicated verification workshop has been organized in August 2013 to officially validate these products.

It has also to be noticed that the SARAL data have been included in the Near-Real Time Ssalto/Duacs process since July 2, 2013 (see also Faugere *et al.*, 2014). These multi-mission products integrating the SARAL/AltiKa mission are delivered to all users.

5. In flight calibration assessment

The validation and analysis of the quality of user products is a key contributor to the success of any altimetric mission. Conventional validation tools are widely used since the launch of Topex/Poseidon. This includes editing procedures (described in the SARAL/AltiKa Products Handbook *http://www.aviso.altimetry.fr/fileadmin/documents/data/tools/SARAL_Altika_products_handbook.pdf),* a large number of statistical monitoring and visualization tools, mono-mission crossover analysis, sea level anomalies analysis as well as multi-mission analysis. They provide essential metrics regarding mission performance to the scientific and operational users. A precise calibration between mission, as well as the careful monitoring of the mission performance over time, are also crucial to ensure the continuity of the historical satellite altimeter record and to allow for the completion of climatic studies. This analysis is done on the long-term basis but a specific activity is ensured during the first months of the mission.

The first point to look at is the **data coverage**, in particular over the ocean. To do so, missing measurements are monitored toward the reference ground track (i.e. assuming a full coverage of the satellite data whatever the conditions are). The comparison to another mission is also essential. This is usually done with respect to the Jason-2 reference mission. The SARAL/AltiKa data return is remarkably high with a very few missing data over ocean. Over all surfaces, SARAL/AltiKa has less missing measurements than Jason-2 (not shown here – see Philipps *et al.*, 2014) and slightly less data over the ocean. Over the ocean, the data coverage is greater than 99.5%, which significantly exceeds the mission requirements (Vincent *et al.*, 2006). Before launch, concerns were raised about the sensitivity of the Ka-band to rain events, leading to missing and invalid measurements. Several studies were performed in order to analyse the potential impacts of the rain on the data return (Tournadre *et al.*, 2014). The result of those studies (based on conservative hypothesis and system margin) was that about 5% of data could be lost due to rain events. This is actually not observed and this is explained by the excellent behavior of the AltiKa altimeter which provides a better signal to noise ratio that what was anticipated.

The second point is the **result of the editing** procedure. Data selection is required in order to screen the data for spurious records. Obviously this screening depends on the user application and users are advised to tune the editing criteria provided in SARAL/AltiKa Product Handbook to their own needs. Over the open ocean about 2.5% of SARAL/AltiKa data are edited which is less than we get on the Jason-2 mission (3.5%). This might be explained by the editing thresholds currently used on SARAL/AltiKa mission that could be too high. But this is also explained by the altitude of the satellite and the frequency used by the altimeter. Indeed the SARAL/AltiKa Ka-band altimeter has a much lower footprint size than that of Jason-2 Ku-band altimeter. The radius of the footprint is half, thus including much fewer rain cells, sigma_0 bloom events and other heterogeneities of the surface that might impact the Ka-band waveform. This is clearly illustrated by the map in Figure 2 which displays the number of edited measurements over one year of the SARAL/AltiKa mission compared to Jason-2 (left) and to ENVISAT (right). One can observed that fewer SARAL/AltiKa data are edited compared with the Jason-2 mission in the area of rain cells (e.g. around Indonesia) and in the area of sigma_0 blooms (e.g. in the Mediterranean sea). Compared to ENVISAT (same altitude, Ku-band) 3 years before, we can notice that there is slightly more data edited on SARAL/AltiKa mission. This is explained by the Ka-band frequency which is more sensitive to the rain cells than the Ku one's.

Sea Surface Height differences at **crossovers** is the main metric to assess the overall performance of satellite altimetry missions. When applied to a single mission, crossovers provide information about the SSH consistency between ascending and descending tracks. When crossovers are estimated from two different missions, they provide a relative SSH bias estimation and allow detection of potential regional biases and/or drifts between missions. Crossover SSH differences are computed selecting time differences shorter than 10 days (in order to minimize the impact of the ocean variability), and performing a geographical selection to remove high latitudes, shallow waters (depth lower than 1000 m) and areas of high oceanic variability. The figures obtained for the SARAL/AltiKa mission are of the same order as those obtained for Jason-2 mission (see e.g. Prandi *et al.,* 2014). This is remarkable only one year after launch for this new technology mission. Also future evolutions, mainly on the wet tropospheric correction and sea state bias, will further improve the SARAL/AltiKa data quality in the next product version (currently planned early 2015). The same result is obtained on the Sea Level Anomalies: SARAL/AltiKa data quality is as good (or even slightly better) as for Jason-2. Looking at the SARAL/AltiKa and Jason-2 maps (Figure 3), we can observe the same oceanic signals. The mean bias between SARAL/AltiKa and Jason-2 mission is -4.8 cm and remains to be explained (see also Philipps *et al.*, 2014).

Another important metric is the **spectrum analysis.** Compared to Jason-2 and CryoSat-2 (SAR mode) data, the SARAL/AltiKa spectral content (Figure 4) is the same for all wavelengths below 70 km. We can also notice a much lower white noise, which is due to the excellent Ka-band retracking performances and also to the 40 Hz rate (compared to 20 Hz on Jason-2 and CryoSat-2 missions). We can also observe a different signature of the spectral hump. This signature is

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linked to the altimeter response to events such as $sigma_0$ blooms or rain cells which tends to modify the altimeter waveforms and thus the retracking estimates made by the current algorithms (based on the Brown model) (Dibarboure *et al.,* 2014). This is not the case on Cryosat-2 SAR data due to thin stripe-shaped footprint.

Finally, Table 3 provides metrics regarding the system budget, the actual figures computed with flight data are fully inline with the mission requirements, except for the Wet Troposphere correction. The present correction derived for Ku-band is not accurate enough for Ka-band. Algorithmic improvements are underway.

6. Some scientific results

It is not in the scope of this paper to summarize the scientific applications that have already been made or will be made with the SARAL/AltiKa data. Papers in the same issue of the journal will address many of these aspects in various scientific domains. It is however very comforting to notice even at this stage that the scientific objectives of the mission are very well covered. The following are just a few illustrative examples of the use of the use of SARAL/AltiKa data.

6.1. Ease of use: Impact of AltiKa data on operational models

Altimetry is one of the most important data sources for assimilation into operational models. Operational models require the data in Near-Real Time, when the environmental corrections and precision orbit are not available in their most accurate form on the geophysical data records. SARAL/AltiKa represents the beginning of a new class of altimeters operating at Ka-band frequency with a small footprint and high pulse rate. Prior to assimilation, the altimeter

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data passes through quality control (QC) developed in various places. Early results from the QC performed at Naval Research Laboratory (see Richman *et al.*, 2014) showed SARAL/AltiKa to perform at or better than previous Ku-band altimeters, with lower sensor noise and fewer data dropouts. To check the impact of SARAL/AltiKa on the operational models, a six month series of data denial experiments were performed using the operational Gulf of Mexico forecast model in a nowcast mode. Compared to the operational model, the SARAL/AltiKa-only nowcast has ½ the RMS error in steric SSH and mixed layer depth compared with the Jason-2-only nowcast (Figure 5). From these experiments, it is not possible to determine if the performance gain with SARAL/AltiKa comes from the better performance of the altimeter or from the different track spacing of SARAL/AltiKa. To test the performance versus sampling difference, the data denial experiments were performed using ENVISAT and Jason-2 in 2009. ENVISAT and SARAL/AltiKa follow the same track, but have very different sensor performance. In these experiments, neither altimeter has a significantly smaller RMS error compared to the operational model assimilating all data. Thus, closer track spacing of the ENVISAT - SARAL/AltiKa altimeters is not sufficient to explain the improved model nowcasts with SARAL/AltiKa and the better performance of SARAL/AltiKa leads to a better nowcast.

6.2. Mesoscale data: SARAL's contribution to the search for missing flight MH370

The search off Western Australia for buoyant debris from Malaysia Airlines flight MH370 lasted from March 18 to April 28, 2014. Altimetric sea level observations from SARAL/AltiKa, Jason-2 and Cryosat-2 were used to estimate the trajectories of debris items from the 8 March time of the crash until each day of the search. The error of this process was estimated by hindcasting the trajectories of drifters that were either deployed during the search, or were already in the region. Here, we focus on the extraordinary results for just one drifter. Global Lagrangian Drifter 56566 became caught in a cyclonic eddy in December 2013 and on March 8 was close to where the plane was thought to possibly have crashed. Figure 6 shows the looping trajectory of the drifter from January 1 to May 31, as well as trajectories of some "model drifters" which are initialized along the trajectory of the real drifter at 4-day intervals, and travel at the velocity estimated in Near-Real Time by the system running at CSIRO (http://oceancurrent.imos.org.au/). The model drifters continue to loop around the eddy in similar fashion to the real drifter for a remarkably long time - up to 130 days. The distance separating the model drifters from the real one is consequently restricted to being less than the ~100 km diameter of the eddy until late May, when many model drifters depart from the eddy. Retention of model drifters in the eddy depends on the eddy being sampled frequently and accurately enough for it to appear consistently in the analysed sea level fields. Neither Jason-2 nor Cryosat-2, alone or in combination, can provide adequate density of sampling at this latitude to achieve this result. Scott *et al*. (2012) found that the median error of hindcasting drifter trajectories for 7 days was about 100 km, and one might reasonably conclude that the error grows rapidly after that. The present case study, however, shows that there are exceptions to that rule: drifting items trapped inside long-lived eddies such as the one documented here, can sometimes be followed for surprisingly long times using the present constellation of 3 altimeters.

6.3. Coastal altimetry: The emerging potential of SARAL/AltiKa

Satellite altimetry represents a mature technology in the open ocean. However, coastal altimetry records have remained largely unexploited, due to several factors such as inaccurate geophysical corrections as well as environmental issues and land contamination in the footprint. In the last years, dedicated efforts have been made in the coastal altimetry community aiming at extending the capabilities of current altimeters closer to the coastal band. The launch of the SARAL/AltiKa altimetry mission signifies a major step forward in this context. Here we show an illustration of the performance of SARAL/AltiKa in the coastal band. We focus on the Ibiza Channel where the North-South water exchanges play a key role in controlling the circulation variability in the Western Mediterranean at a wide range of scales (mesoscale, seasonal and inter-annual). In this area, the track no 16 from SARAL/AltiKa intercepts the domain covered by the coastal high-frequency radar system operated by SOCIB (Balearic Islands Coastal Observing System), which provides hourly surface currents, with a 3 km spatial resolution and a range up to 60 km. Five cycles (June 2013- November 2013) of SARAL/AltiKa along-track data are analyzed and compared with HF radar. Additionally, we evaluate the records from Jason-2 track no. 187, which crosses SARAL/AltiKa track no. 16 over Ibiza Island. The first insights using the standard AVISO Near-Real Time products (filtered with 42 km Lanczos filter and subsampled at a resolution of 14 km) put in evidence the emerging capabilities of SARAL/AltiKa in the coastal zone. Indeed, while SARAL/AltiKa data are retrieved at a distance of only 7 km from the coast, all the available measurements from Jason-2 are located farther than 24 km off Southwest Ibiza (Figure 7a,b). This prevents an exhaustive intercomparison between Jason-2 and HF radar as there are only 3 valid Jason-2 points in the

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area covered by HF radar. On the contrary, SARAL/AltiKa, with 5 valid points, reveals coherent mesoscale features (Figure 7c, d) with a high level of temporal variability (see Pascual *et al.,* 2014, for more details) among the different cycles and with general good agreement with HF radar fields (correlations higher than 0.65). This illustration highlights that SARAL/AltiKa is providing reliable data in the coastal band, representing a challenge for the new era of satellite altimetry observations and the use of synergetic approaches through the combined use of multi-platform systems supports the investigation of unresolved scientific questions in the coastal area. Upcoming SARAL/AltiKa assessment studies should address the application of ad-hoc coastal-oriented altimeter corrections, including the exploitation of high-frequency measurements and the review of the data recovery strategies near the coast (e.g. Troupin *et al.*, 2014).

6.4. SARAL/AltiKa for Ice

Altimetry is a powerful tool for ice sheet mass balance and for sea ice thickness estimation. An altimeter operating in Ka- instead of Ku-band is far from being insignificant for these studies.

For ice sheet mass balance, the decrease of penetration depth within the snow, from 2 to 12 m for the Ku-band to less than 1 m for the Ka-band and the sharper waveform, which is less sensitive to volume echo in terms of height retrieval, ensures a temporal stability that allows to obtain elevation trends with good confidence. Moreover, SARAL/AltiKa being on the same historical 35 day orbit than ERS-1-2 and ENVISAT allows to extend the survey for more than 20 years (Rémy *et al*., 2014). Figure 8 shows the dramatic loss of volume of the Pine Island Glacier is the

West Antarctica which increases since 1995. In the central part of the glacier, the loss is now around 1.8 m/yr even at few hundred km from the coast.

For sea ice, this phenomenon also seems to play a role but the major AltiKa contribution yields from the narrower antenna aperture and in higher spatial resolution than previous altimeter. Indeed, the first echo is more likely to be at nadir decreasing influence of the off-nadir signal that often affects the retrieval measurement. Some studies in this issue confirm the ability of AltiKa to detect leads and coastal polynyas as well as to represent spatial and temporal dynamics of water openings.

Moreover, an unexpected contribution seems to be the very high sensitivity of the Ka-band backscatter to the snow and ice state, probably due to the altimeter wavelength. A few dB change may occur in a few weeks for any kind of snow or ice surface, even in the central part of the Antarctica ice sheet. Kouraev *et al.* (2014) observe a significant decrease of up to 15 dB at the end of ice season over Lake Baïkal. The field measurements acquired along the SARAL/AltiKa tracks in Spring 2013 and Spring 2014 allow to suggest an important role of ice metamorphism and re-crystallisation.

6.5. Inland waters: First applications of SARAL/AltiKa data

Satellite altimetry for inland water applications has evolved from investigation of water height retrieval to monitoring and discharge estimations since last two decades. Recent research focuses on integrating altimetry with other remote sensing techniques and hydraulic models to deal with key inland water resources problems such as flood (discharge, water spread and volume), water level monitoring in the highly braided/fragmented river systems, rating curve generation for remote locations, reservoir operations, calibration of river/lake models etc.

Worldwide, the number of meteorological stations as well as the operational discharge monitoring stations has been decreasing continuously since the 1970s. SARAL/Altika aims to investigate the Ka-band altimetry efforts along with Ku-band altimetry missions for meeting the growing demand of altimetry data for hydrological studies.

Three examples of SARAL/Altika applications viz. (a) river flow modeling (b) braided river system and (c) sea feed lake are evoked in this article. First one is coupling the SARAL/Altika data with Hydraulic model (HEC-RAS) for modeling the flood wave and associated water spread for the Tapi River India (Figure 9). It has been observed that retrieved water levels plays a vital role to plug in as the flow boundary conditions for steady state river flow simulations as well as for the model calibration (R^2 = 0.98, RMS = 0.67m) and generation of rating curves at various remote locations. Further, water spreads corresponding to various flood wave conditions in the upstream were simulated which is very crucial for developing the efficient flood risk alarm systems (Gupta *et al.*, 2014). Second example is water level retrieval in a highly braided Brahmaputra river system. Validation results found to be superior than using the previous altimetry mission Jason-2 (RMS = 0.41 m for SARAL/Altika, RMS = 0.87 m for Jason-2). This improvement may be attributed to Ka-band altimetry from SARAL/Altika which provide fine resolution data to identify the waveforms with less contamination due to presence of sand bars/islands and vegetation within the altimeter footprint. Third application was water level retrieval over Sea feed Lake, Chilika in the eastern region of India through development of an algorithm based on the clustering technique and properties of the waveform which gave encouraging results (RMS = 1.2 m) in the absence of satisfactory results from existing

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algorithms and will be useful for tidal modeling.

Future prospects which SARAL/Altika offers would be application towards (a) improved parameterization of hydraulic/hydrological models (b) water volume estimations (flood plains/lakes) (c) river characteristics (cross section, longitudinal profiles etc.) (d) Integration of remote sensing based techniques such as radar altimetry, microwave SAR, gravity anomaly and optical for hydrology solutions from satellite platform (e) other ancillary applications such as surface soil moisture, land use/cover, heavy rainfall estimation due to more attenuation in the Ka-band etc.

7. Conclusion

SARAL/AltiKa was launched on February 25, 2013. More than 18 months later, we have observed many tangible signs of success. As of today, all components of the SARAL/ALTIKA system are working properly. First calibration and validation investigations have shown that the quality of the data meets the expectations and initial mission requirements. Data have been delivered to users in a very rapid manner. The quality of all products is in line with mission requirements. Some preliminary scientific investigations have been undertaken and a large part of the scientific community has quickly seized the opportunity offered by these data.

The India-France SARAL/AltiKa mission is the first Ka-band altimetric mission dedicated to oceanography. With regard to the Ku-band, the use of the Ka-band actually leads to an improved vertical and along-track resolutions and better discrimination in transition zones thus leading to the expected improvements in looking at the oceanic mesoscales and the coastal ocean. Actually, performances appear to be quite similar, and sometimes better, than the Ku-band reference altimetric satellites such as Jason-2. The known effect of rain on the Ka-band was such to put some uncertainty on the full availability of data in some regions. In fact, the larger sensitivity to small rates of rain was found to be less constraining than expected. On the other hand, improved ability in coastal area is confirmed and improved resolution in general is validated so far.

The SARAL/AltiKa mission was seen as motivated by a **necessity** by the research and operational oceanographic community because of the need to fill the gap after the 5 year's ENVISAT mission and before Jason-3 and Sentinel 3. It was seen also in the **continuity** of previous altimetric satellite missions for the oceans, benefitting from the technological maturity that has been achieved within the space agencies and their associates. Due to this maturity, no experimentations in orbit were required and confidence was seen from most of the components. Even though, there are significant **innovations** and technological improvements in the SARAL/AltiKa project due to the Ka-band used. Thus we meet the requirements on instrument performances, especially for the coastal ocean. At this stage, necessity, continuity and innovations, that motivate the SARAL/AltiKa mission seem to be relatively well fulfilled.

Clearly, there is still much work to be done, e.g. through ongoing actions led within the CNES PEACHI project. PEACHI's aims are to further improve the processing algorithms, including computation of the SSB table and an ice retracking algorithm. In particular some algorithms (the neural network used for radiometer data ground processing, the Sea State Bias computation, the altimeter wind speed and ICE2 retracking, and others) still need to be tuned.

Therefore, the SARAL/AltiKa Ka-band altimetric mission takes a full position in the altimetric satellite constellation that has been built over years providing a major push to oceanographic sciences. It is likely that innovations brought by the Ka-band may bring some opportunities to understand Ku better. Extended capabilities that are offered by the Ka-band allow to open even more widely some new frontiers of altimetry such as coastal oceanography, cryosphere, hydrology, beyond the traditional scope of the open ocean investigations. If a successor were to be considered for SARAL/AltiKa, this is on these new scientific directions that most of the openings might be seen.

Ka-band altimetry, with SARAL/AltiKa as the today's most emblematic declination, can be seen also as a step towards improved resolution altimetry and a preparation for the Surface Water and Ocean Topography (SWOT) NASA-CNES mission project (http://swot.jpl.nasa.gov/). Indeed, SWOT will provide a 2D altimetric view with a high resolution thus extending the capabilities of nadir only altimetry, but will also use the Ka-band thanks to the KaRIN instrument (Ka-band Radar INterferometer).

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List of tables

Table 1: SARAL/AltiKa orbit elements

Orbit element	Value
Repeat period	35 days
Number of revolution within a cycle	501
Apogee altitude	814 km
Perigee altitude	786 km
Inclination	98.55 deg
Argument of perigee	90.0 deg
Local time at ascending node	06:00
Earth Longitude of equator ascending crossing of pass1	0.1335 deg
Ground track control band	+/- 1 km

Table 2: List of SARAL/AltiKa Principal Investigators

PI Name	Institution	Investigation
Achuta Rao K.	IIT, Delhi	Sea level at seasonal and interannual timescales
Arnault S.	LOCEAN, Paris	Tropical Atlantic
Balchand A. N.	CUSAT, Kochi	Ocean circulation features
Basu S. K.	SAC, ISRO, Ahmedabad	Data Assimilation into OGCM
Birkett C.	University of Maryland, College Park	Inland Surface Waters
Birol F.	LEGOS, Toulouse	Coastal oceanography
Bosch W.	DGFI, Munich	Calibration and Tides
Bowers T.	NMOC, Stennis Space Center	Inclusion into Navocean altimetry data processing
Calmant S.	LEGOS, Toulouse	Inland waters
Chander Sarad	SAC, ISRO, Ahmedabad	Retrieval and range corrections
Chao Y.	JPL, Pasadena	Regional Oceanography
Chapron B.	IFREMER, Brest	Sea ice, rain, spectral analysis
Chaudahary H. S.	IITM, Pune	Ocean modelling

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Chauhan Prakash	SAC, ISRO, Ahmedabad	Retrieval and range corrections
Cheng K.	National Chung Cheng University, Taiwan	Taiwan Seas and the Great Lakes
Cretaux J. F.	LEGOS, Toulouse	Inland waters
Deng X.	University of Newcastle	Mesoscale variability in the Leuwin Current
Dibarboure G.	CLS, Toulouse	Validation, Cross-calibration and Multi-mission Merging
Durand F.	LEGOS, Toulouse	AltiKa, gliders and XBTs in the South-West Pacific
Dutta S.	IIT, Gauhati	River level modelling
Dwivedi Suneet	Allahabad University	Ocean modelling
Esselborn S.	GFZ, Potsdam	Coastal Altimetry and tide gauges in the Indian Ocean
Eymard L.	LOCEAN, Paris	MicroWave Radiometer
Fenoglio-Marc L.	Darmstadt University of Technology	Coastal Altimetry
Filizola N.	Amazonas State University, Manaus	Altimetry in the Amazon rivers
Gairola R. M.	SAC, ISRO, Ahmedabad	Moonsoon wind and precipitation

Gnanaseelan C.	IITM, Pune	Understanding the vertical structure of the tropical Indian Ocean
Griffin D.	CSIRO, Hobart	Assimilation into the Australian Bluelink system
Gupta P. K.	SAC, ISRO, Ahmedabad	Land hydrology
Hareesh Kumar	NPOL, Cochin	North Indian Ocean
Ichikawa K.	Kyushu University, Fukuoka	Tsushima Strait
Janssen P.	ECMWF	Global Validation and Assimilation of Wind and Wave Products
Kishtawal C. M.	SAC, ISRO, Ahmedabad	Tropical cyclone prediction
Kumar R.	SAC, ISRO, Ahmedabad	Assimilation in Indian coastal regions
Lazaro C.	Universidade do Porto	Subtropical Atlantic
Lee H.	Ohio State University	Surface water in the Congo Basin and over Arctic lakes
Lefèvre J. M.	Météo-France, Toulouse	Sea-state analysis and prediction in coastal regions
Lillibridge J.	NOAA, College Park,	Demonstration Project for Operational Applications
Majundar	SAC, ISRO, Ahmedabad	Geoid/gravity anomaly

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Tapan		
Mehra P.	NIO, Goa	Validation at Karwar and Kavarati
Menemenlis D.	JPL, Pasadena	Global ocean data assimilation
Mercier F.	CLS, Toulouse	Waveforms Analysis
Mertikas S.	Technical University of Crete, Chania	Calibration and Validation in the island of Gavdos and Crete
Mihir Kumar Dash	IIT-CORAL, Kharagpur	Feature based Study of the Indian Ocean circulation
Naik R. K.	NRSC, ISRO, Hyderabad	Ocean modelling
Nerem S.	University of Colorado, Boulder	Global mean sea level
Nino F.	LEGOS, Toulouse	Waveform inversion for continental waters
Oza S. R.	SAC, ISRO, Ahmedabad	Inter-annual polar ice surface characteristics
Pascual A.	IMEDEA, Islas Baleares	Coastal and Mesoscale studies in the Balearic Sea
Prasad K. V. S. R.	Andhra University, Visakhapatnam	Vishakhapatnam coast
Quartly G.	NOC, Plymouth	Waveforms Analysis
Rajesh S.	WIHG, Dehradun	Geodynamic applications
Ramesh Kumar	NIO, Goa	Ocean Atmosphere interactions

Remy F.	LEGOS, Toulouse	Survey of Snow and Ice Surface
Richman J.	NRL, Stennis Space Center	Global mesoscale ocean prediction
Rosmorduc V.	CLS, Toulouse	Helping AltiKa Data Users
Santosh Kolte	Nirma University	Land hydrology
Sasmal S. K.	NRSC, Hyderabad	Analysis of waveform in different types of Indian coastal waters
Scharroo R.	EUMETSAT, Frankfurt	Cross-calibration and validation of the decadal sea level record
Seyler F.	ESPACE, Montpellier	Water resources management
Sharma R.	SAC, ISRO, Ahmedabad	Mesoscale variability in the Tropical Indian ocean
Sharma Sanjay	Kohima Science College	Rainfall characteristics
Shukla A. K.	SAC, ISRO, Ahmedabad	Calibration and Validation
Shum C. K.	Ohio State University	Coastal Ocean, Solid Earth and Ice-Sheets
Singh D.	IIT, Roorkee	Land hydrology
Smith W.	NOAA, Washington	Inter-comparison of SSH random noise levels
Somayajulu Y. K.	NIO, Goa	Coastal Regions of India
Sreejith K.	SAC, ISRO, Ahmedabad	Andaman Subduction Zone

M.		
Thakur Praveen	IIRS, ISRO, Dehradun	Land hydrology applications
Turiel A.	CSIC, Barcelona	Ocean studies for climate purposes
Varma A. K.	SAC, ISRO, Ahmedabad	Estimation of Precipitations
Verron J.	LGGE, Grenoble	Assimilation for physical ocean prediction and ecosystem monitoring
Vialard J.	LOCEAN, Paris	Sea level variability in the Northern Indian Ocean Coastal Waveguide
Vigo I.	Universidad de Alicante	Geostrophic currents for the global ocean and the Mediterranean sea
Watson C.	University of Tasmania, Hobart	Calibration and validation over ocean and ice

Table 3: AltiKa error budget. All numbers are in cm.

(for 1s average, 2m SWH, 1dB ů0)	**GDR requirement**	**Observed**
Altimeter noise	1	0.8
Ionosphere	0.3	0.3
Sea state bias	2	2
Dry troposphere	0.7	0.7
Wet Troposphere	1.2	1.5
Altimeter range after corrections (RSS)	2.6	2.7
Orbit (Radial component) (RMS)	Req : 3 Goal : 2	2
Total RSS Sea Surface Height	4	3.4
SWH	6.5	5

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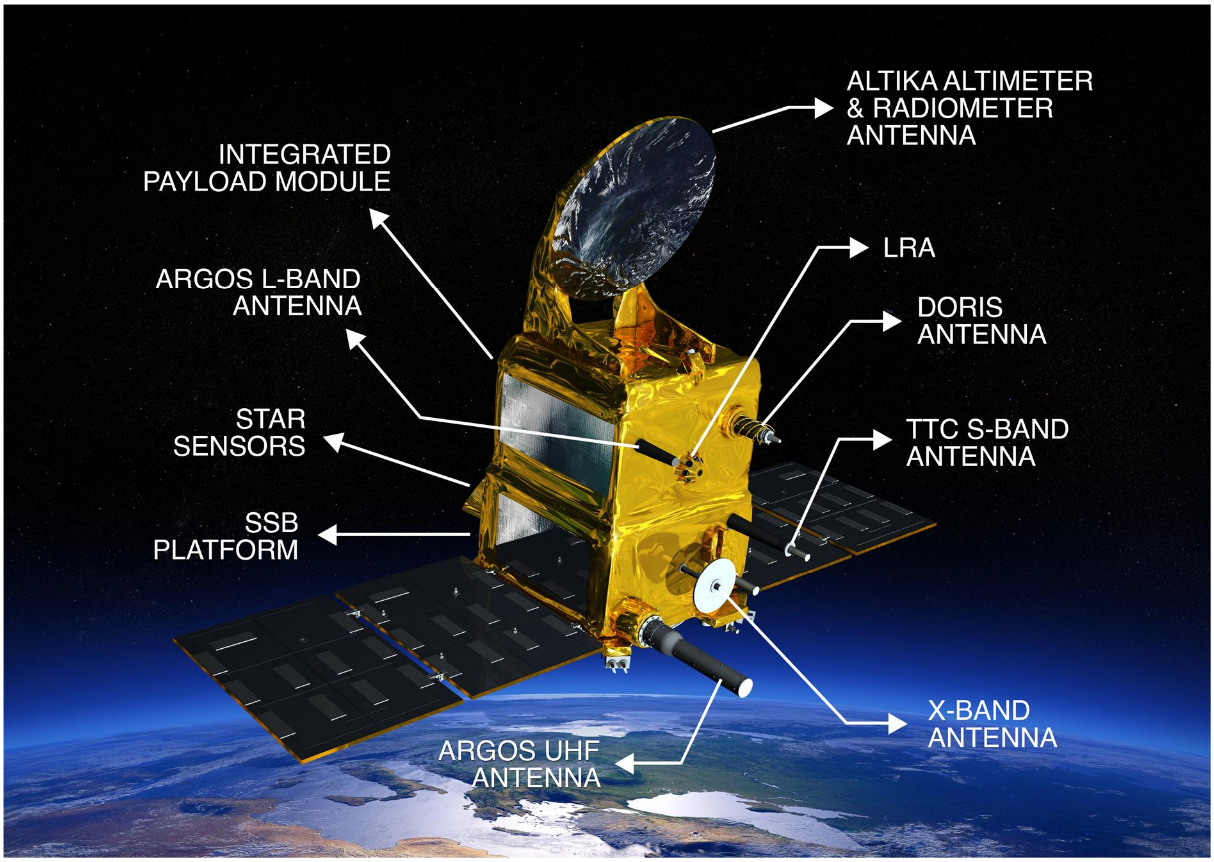
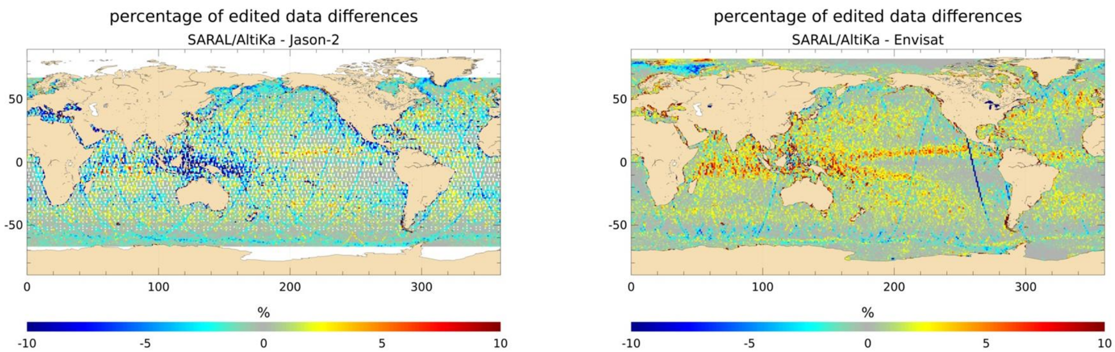
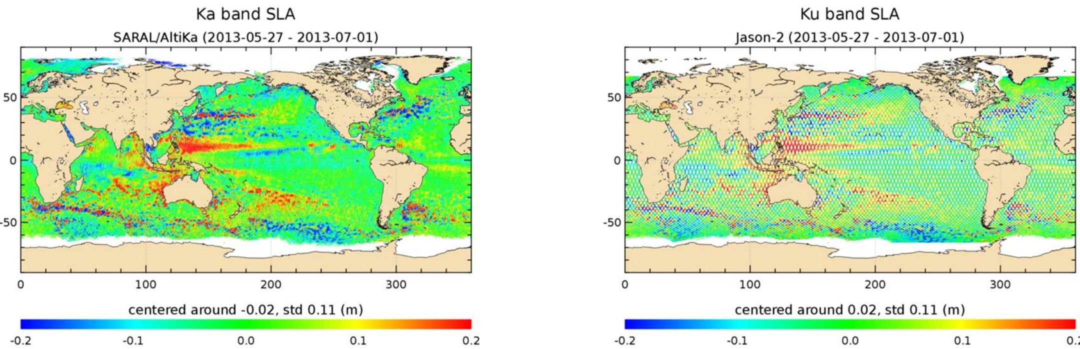


Figure 1: View of the various components of the SARAL/AltiKa satellite



a) b)

Figure 2: Number of SARAL/AltiKa edited 1Hz measurements averaged per box and compared to the one obtained on Jason-2 and ENVISAT missions: SARAL/AltiKa – Jason-2 (a), SARAL/AltiKa – ENVISAT (b).



a) b)

Figure 3: Comparison of SARAL/AltiKa (a) and Jason-2 (b) SLA data over the same period

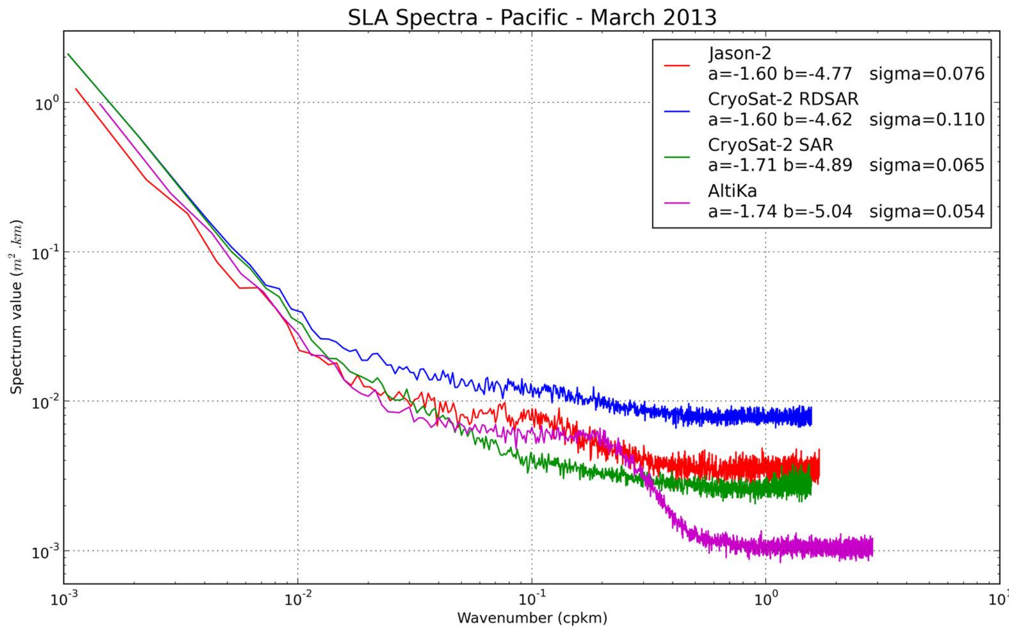
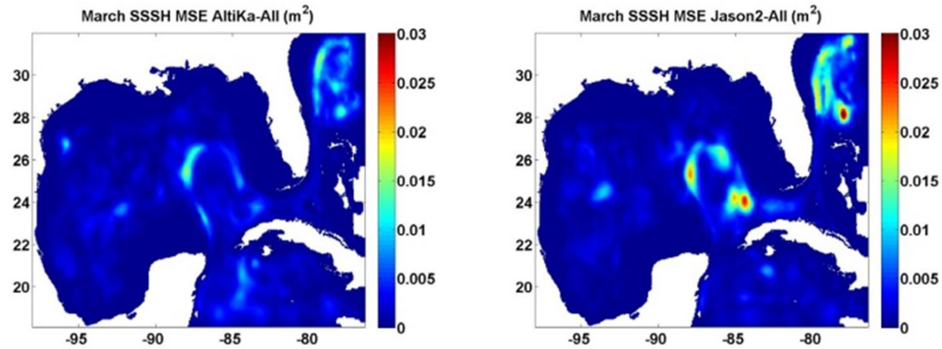


Figure 4: SLA spectrum comparison for SARAL/AltiKa (pink), Jason-2 (red), Cryosat-2 (blue, green) in March 2013.



a) b)

Figure 5: RMS error in March 2014 between model assimilating SARAL/AltiKa only (a) and Jason 2 only (b).

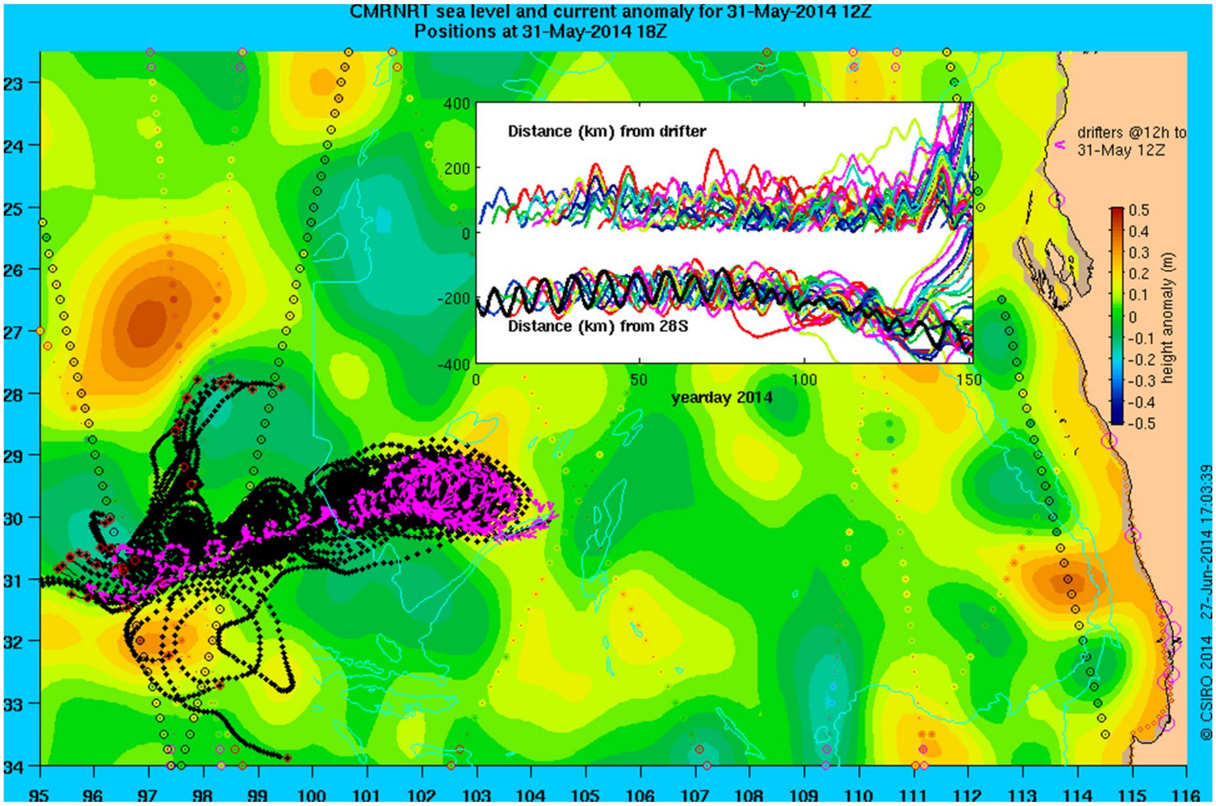


Figure 6: Trajectory of Global Lagrangian Drifter 56566 from January 1, 2014 to May 31 2014, shown as magenta arrow heads looping to the west. Trajectories of model drifters released along its path are shown as black dots. These travel at the velocity determined by geostrophy from the sea-level anomaly field shown in colour (plus an estimate of the temporal mean from an ocean model). Altimetric sea level estimates are overlain on the fitted surface, with SARAL estimates identified by black circles. The inset shows the time history from January 1, 2014 of i) the distance between modeled drifters and the real one, and ii) the meridional position of both.

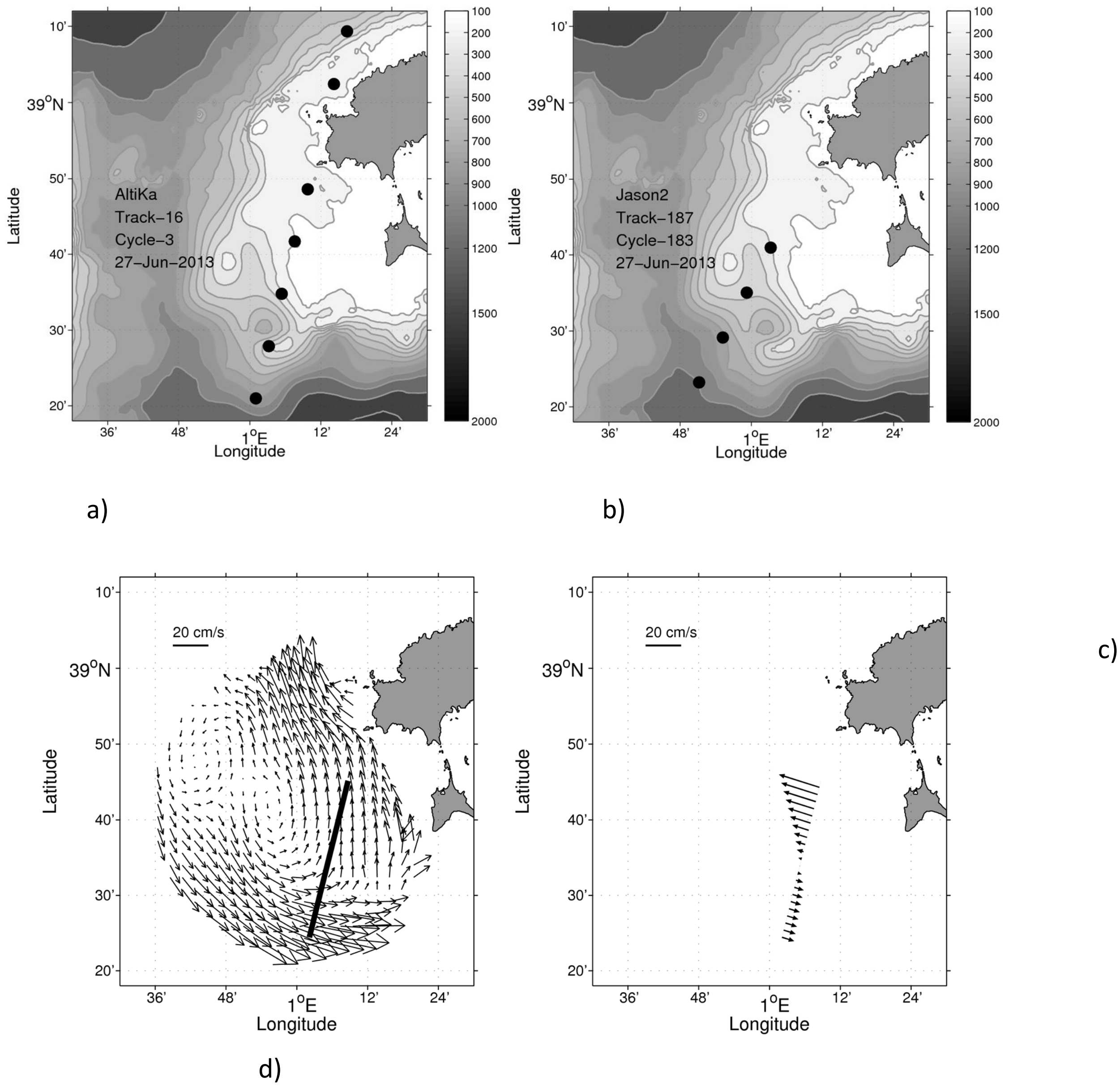


Figure 7: Spatial distribution of SARAL/AltiKa (a) and Jason-2 (b) SLA along track near-real time data available for 27-June-2013. Note that the points are separated 14 km as the 1 Hz products delivered in near-real time by AVISO are sub-sampled one out of two (for the specific products of the Mediterranean Sea) and SARAL/AltiKa track no. 16 is a descendant pass while Jason-2

track no. 187 is an ascendant pass. Qualitative comparisons between HF radar surface velocities (c) and SARAL/AltiKa absolute geostrophic currents perpendicular to track no. 16 for 27-June-2013 (d). The black line in (c) denotes the coverage of SARAL/AltiKa vectors. Both platforms reveal the presence of a cyclonic circulation with an associated North-East coastal current close to Ibiza Island of the order of 20-30 cm/s. Differences of the order of a few cm/s and up to 10 cm/s might be due to several factors such as instrumental radar errors, inaccurate altimeter corrections, suspicious coastal editing and low signal to noise ratio (SSH gradients of the order of only 2-4 cm). See Troupin *et al.,* 2014 and Pascual *et al.,* 2014 for more details.

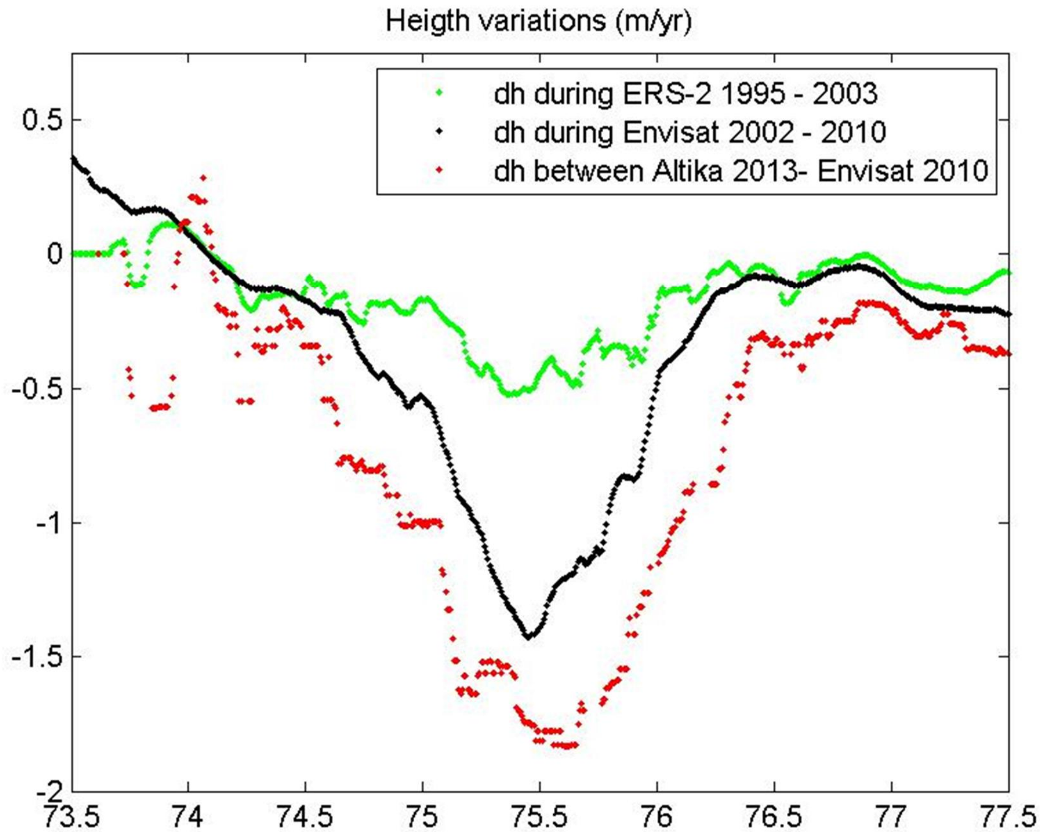


Figure 8: Loss of altitude for the Pine Island Glacier at few hundred km from the coast in m/yr. The loss was around 0.1 m/yr during the ERS-2 period, increased to 1.20 m/yr during the ENVISAT period and now reaches quite 1.8 m/yr.

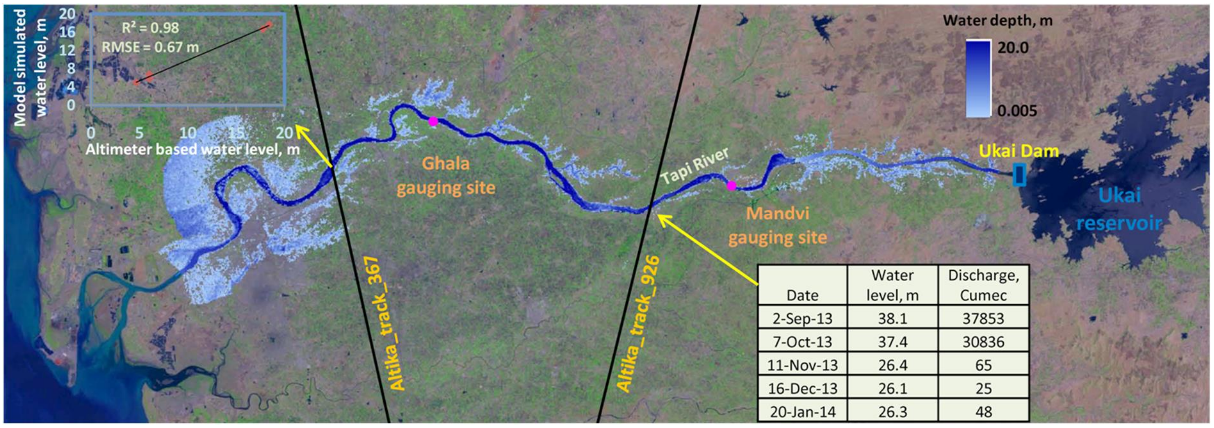


Figure 9: Example of coupled satellite altimetry with hydraulic model for the parameterization, calibration and simulation of water spread in the flood plain for Tapi River, India.