

**SPACE-BASED OBSERVATIONS  
IN  
THE GLOBAL OCEAN OBSERVING SYSTEM:  
THE OPERATIONAL TRANSITION ISSUE**

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**ABSTRACT** – *The heritage of past and current oceanographic space missions has paved the way for the incremental implementation of the space component of the Global Ocean Observing System. Because they have already demonstrated their “pre-operational” maturity, in terms of end-to-end performances, value to users and affordability, altimeter and scatterometer missions are the first immediate candidates for operational transition. Short-term decisions are therefore required to secure continuity and enhancement of the current altimeter and scatterometer systems in the GODAE timeframe and beyond. Additional efforts are still needed to assess and demonstrate at global scale the potential operational value of ocean colour missions and SAR-based observations of ocean wave spectra. Any transition towards sustainable and permanent operational systems cannot take place without timely, convergent and co-ordinated initiatives from space agencies and operational user entities. Significant investments will be necessary on all sides, as one must not only acquire and operate operational systems, but also prepare for their future evolution. Aggressive R&D programmes and demonstration missions will remain necessary to assess new observing techniques, with a view to ultimately improving the scope, performances and affordability of the operational systems and services. The long gap between SEASAT and ERS, and between CZCS and SEASTAR, demonstrate the danger of oceanography falling between two stools, if development and operational agencies do not balance their respective investments, or if they compete for the same shrinking resources or fail to agree on appropriate transition scenarios.*

## **1 INTRODUCTION**

Some 10 years after the SEASAT proof of concept mission, ERS and TOPEX-POSEIDON have become cornerstones of the integrated observing strategy of the World Ocean Circulation Experiment, along with the necessary *in situ* observations. Their altimeter and scatterometer payloads are providing a consistent series of global measurements of the surface forcing and the ocean topography. These data series complement the sea surface temperature maps already available from operational meteorological and other satellites. Their long lifetime has allowed a wider spectrum of ocean variability to be documented, including several ENSO episodes, and also

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<sup>1</sup> The views in this paper are not necessarily the official EUMETSAT position.

stimulated the development of global ocean models with data assimilation capabilities. The successful scientific integration of these missions, along with the short-lived ADEOS and the potential of the SEASTAR ocean colour mission marks a transition from ocean remote sensing or space oceanography to operational oceanography. This change is much more than mere semantics because it has created the awareness and know-how necessary for developing operational oceanography worldwide. This will be continued through experiments like GODAE, which will remain critically dependent on the continuation of space-based measurements.

Beyond this *satisfecit*, oceanography requires new impetus and incremental investments to transition towards the permanent operational systems required by the climate agenda, long term research programmes like CLIVAR, and marine meteorology.

The following sections analyse the heritage of past and current ocean space programmes and the short term perspectives, and identify the critical incremental steps necessary to secure continuity of key measurements within and beyond the decisive "GODAE time window". In light of past history, conditions for the steady development of operational space-based ocean services are briefly discussed.

## **2 SEA SURFACE TEMPERATURE MEASUREMENTS FROM SPACE**

SST measurements have been available since the late seventies from the AVHRR imagers flown on the NOAA operational meteorological satellites of the TIROS series. Continuity and enhancement of such measurements is secured in the short and medium term, in particular by NASA (MODIS on EOS-TERRA and EOS-PM), ESA (ATSR on ERS and ENVISAT), NASDA (GLI on ADEOS-2), EUMETSAT (EPS) and NOAA (POES) missions. Highly accurate pre-operational instruments like ATSR and MODIS are expected to pave the way for the next generation of polar orbiting meteorological imagers, which should be wide-swath sensors with enhanced self-calibration capabilities in the infrared.

In parallel, split window observations are becoming available from operational meteorological geostationary satellites like GOES and Meteosat Second Generation (MSG), to be launched in 2000. More frequent observations will give access to diurnal variations and to more representative measurements in the tropical regions frequently obscured by clouds.

## **3 ALTIMETRY AND OCEAN TOPOGRAPHY**

The development of altimetry has been steady and the benefits outstanding. There has been a quasi-continuous series of missions, starting with GEOSAT (1985), and then ERS-1/2 (1991 and 1995), and TOPEX-POSEIDON (1992). These will continue into the next century with JASON-1 and ENVISAT, both of which are scheduled for launch in 2000.

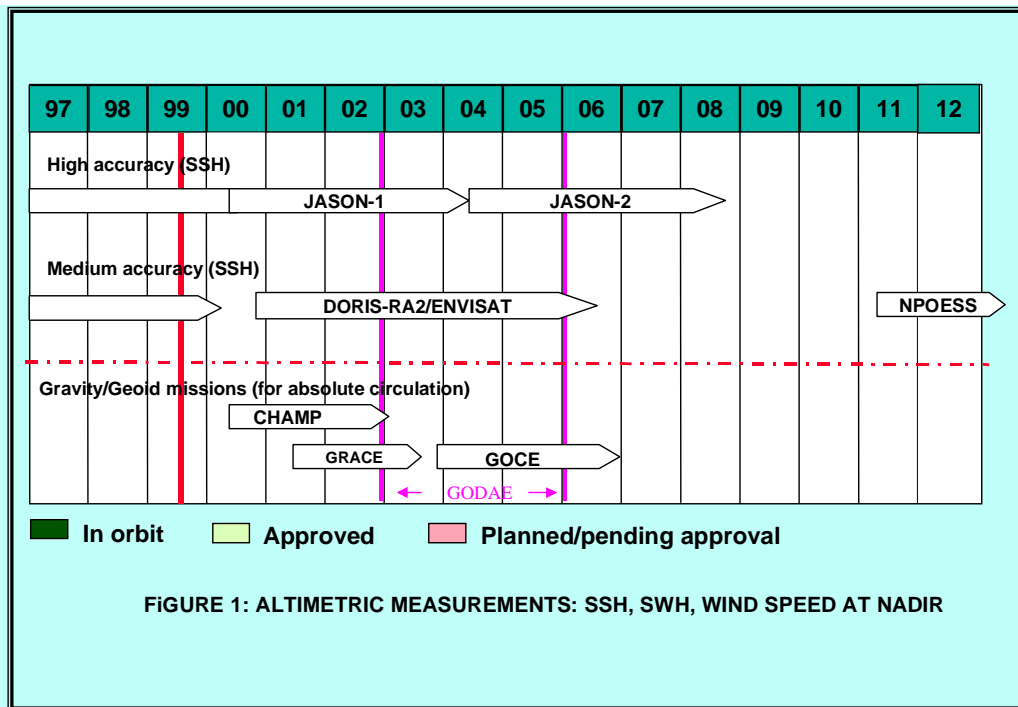
The most relevant parameter to climate is sea level, which, at this point in time can only be measured on global scale by altimeter systems. The increasing performances of the above systems have cut the error budget on sea surface height by several orders

of magnitude, down to the centimetre level. The consequent reduction in the correlated part of the error now means that large-scale ocean circulation patterns can be extracted. Similarly, based on accurate sensor calibration and improved understanding of measurement physics, the global mean sea level anomalies can be monitored and compare well with measurements from sea gauges. On the user side, an integrated approach, using in situ data and modelling, has resulted in cross-benefits, along the same lines that have been achieved by meteorological NWP systems. For example, the assimilation of highly accurate TOPEX/POSEIDON data has highlighted shortcomings of ocean models in their ability to handle salinity, and analysis of the data has also led to scientists revisiting the theory of Rossby wave propagation. Moreover, since the parallel operations of TOPEX-POSEIDON and ERS, the user community has had access to a two-satellite system, with unprecedented space-time sampling and coverage of the global ocean, including the Polar Regions, and pre-operational near real time data services.

Altimeter systems also provide co-located measurements of significant wave height and wind speed, at nadir. Such observations are now available in real time from ERS and assimilated by global numerical wave prediction models like the WAM model operated at ECMWF. The increasingly long observational series collected from GEOSAT, ERS-1, ERS-2, TOPEX/POSEIDON and JASON-1 offers potential for the computation of ocean wave statistics, including probability of occurrence of extreme events, in any part of the global ocean.

In the short term the future looks secure (figure 1), with a two-satellite altimeter system being maintained for the next five years with JASON-1 and ENVISAT. A third mission could even be available, if the problems encountered by GEOSAT-FO (not represented in figure 1) since its 1998 launch could be fixed. It is foreseen that the combined use of their data with measurements from independent gravity missions such as CHAMP (1999), GRACE (2000) and possibly GOCE (2003?) will be another breakthrough. It should enable absolute estimates of ocean currents, to be obtained by subtracting an independent estimate of the geoid from individual altimeter height measurements.

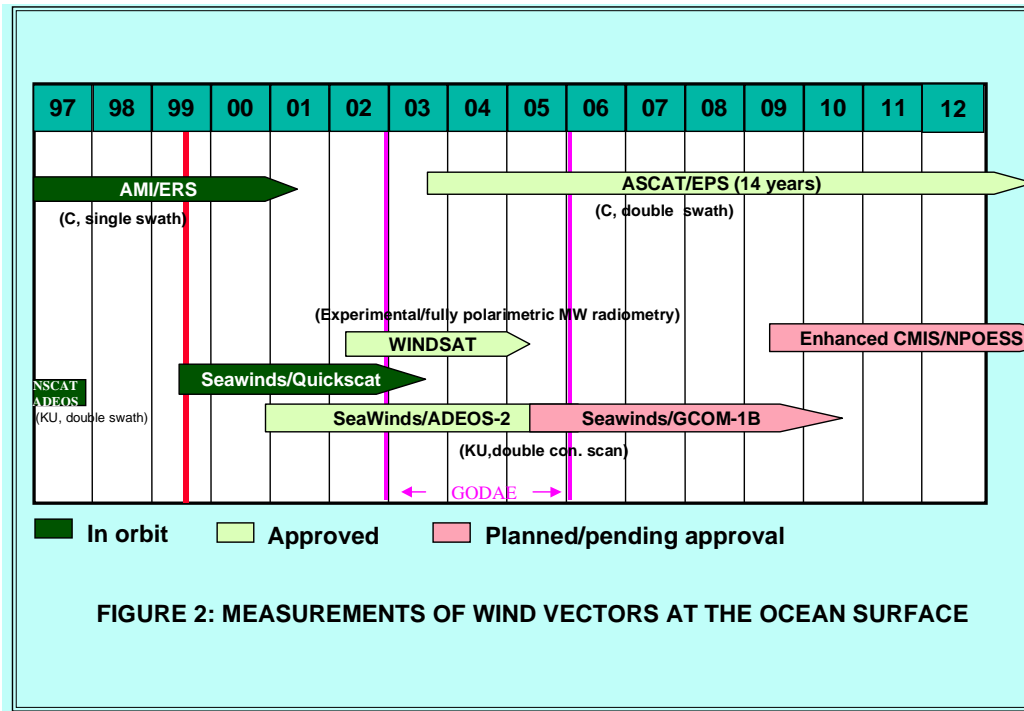
A first firm decision is however needed in the very short term to secure continuity through JASON-2 measurements in the GODAE window (figure 1). Further decisions will be needed to maintain a multi-satellite system providing the required accuracy, coverage and sampling beyond the GODAE window, after the end of life of Envisat. Such a system should provide an affordable service equivalent to one JASON-class mission and one or two medium accuracy missions of the ENVISAT class. Its configuration will need to be decided in the 2003 timeframe. In the meantime, several options need to be evaluated, taking into account results of R & D and demonstration missions aimed at validating new candidate observing techniques. Wide Swath Ocean Altimetry, Ka-band altimeter micro-satellite missions of medium accuracy and GPS reflection systems deserve consideration in this respect.



#### 4 WIND VECTOR MEASUREMENTS AT THE OCEAN SURFACE

While altimeter and SSMI-class microwave imaging radiometers (SSMIS, AMSR on ADEOS-2, AMSR on EOS-PM, CMIS on NPOES...) deliver observations of the wind speed at the ocean surface and important information on sea ice, scatterometry is currently the only proven technique for mapping ocean surface wind vectors.

It took 13 years to replace the SEASAT scatterometer, but ERS-1, despite its limited coverage, had the considerable merit of providing a real time data service. This has been used to evaluate the C-band backscatter and wind measurements, improve the retrieval algorithms, and enable real time data assimilation in meteorological NWP models. The ECMWF and the UK Meteorological Office have measured a positive impact on weather forecasting when scatterometer data has been assimilated, and ECMWF has shown that this impact is increasing with the use of advanced, more dynamically consistent 4-DVAR techniques. As a result, the value of the data has been recognised by the operational user community, and EUMETSAT was able to commit to operate a series of three improved, double-swath instruments, over 14 years starting in 2003, as part of its EPS Programme. In the meantime, ESA has agreed to continue to operate its ERS missions until the end of ENVISAT commissioning, and is considering to bridge the gap to METOP-1, assuming that ERS satellite resources remain available. In parallel, the QUICKSCAT mission follows the 8 months of NSCAT/ADEOS data and delivers high-resolution KU-band measurements. QUICKSCAT and the subsequent Seawinds on ADEOS-2 mission (2000) are expected to provide measurements until 2004. Indeed postponement of the ADEOS-2 launch into 2001 would reduce the overlap period with QUICKSCAT but would secure continuity beyond 2005.



Overall a two-satellite system is expected to be maintained and enhanced until 2004-2005 (see figure 2), assuming no premature in-orbit failure. Despite the single swath of ERS this will provide the sampling and coverage required to capture critical weather patterns and to document the atmospheric forcing of the diurnal and inertial ocean response. This is essential for the meteorological and oceanographic communities. After the end of the expected end of life of ADEOS-2, in 2004, only one line of operational measurements is committed through ASCAT on EPS. Therefore, we are now close to the time when a firm decision is needed to secure the continuity of the second line of missions, with a Seawinds follow-up instrument on GCOM-1B. There is no alternative to cover the gap between 2004 and 2009, as there are no plans to fly a follow-up to the WINDSAT mission in this timeframe. WINDSAT, to be launched in 2002, is a proof of concept mission for a fully polarimetric microwave radiometry technique to be proven in orbit. If the mission is successful, the CMIS instrument to be flown on NPOES could be enhanced to measure wind vectors, but starting only in 2009. In this context, the risk of a 5-year gap is very significant.

## 5 OCEAN COLOUR AND OCEAN BIOLOGY

It took about 15 years to launch a successor to CZCS, but, paradoxically, a large number of missions have now been launched or are planned world-wide that will focus on ocean colour observations to serve climate research and coastal monitoring. SEAWIFS, MOS and IRS-P4 are already in orbit and will overlap with the forthcoming MERIS on ENVISAT (2000), MODIS on TERRA (2000), GLI on ADEOS-2 (2000), MODIS on EOS-PM-1 (2001). Follow-on missions are planned at least by India (IRS-P series), Japan (GCOM series) and the US (VIIRS on NPOES Preparatory Programme and NPOES).

In this context, the real challenge in this area following this fantastic burst of data will be to shape the ocean colour component for the necessary operational observing

system. These will of necessity need to be affordable and be based on the analysis of results from the on-going research and requirements reviews. No further decision can be justified prior to a co-ordinated assessment of the potential operational value of global ocean colour measurements. This is the challenge of the forthcoming years. From a climate perspective, one key scientific challenge is the estimation of the global ocean primary production and its variability. CEOS has stimulated initiatives aimed at co-ordinating efforts across the missions involved. The SIMBIOS project is planning multi-sensor calibration and validation activities, while the International Ocean Colour Co-ordinating Committee (IOCCG) is co-ordinating the Ocean Biology Project, aimed at understanding ocean biogeochemical and ecosystem processes by combining ocean colour and other remote sensing satellite data with in-situ measurements.

## **6 SAR OBSERVATIONS OF SEA ICE AND OCEAN WAVES**

Pre-operational and operational SAR missions have been developed or are planned by ESA (ERS-1, ERS-2 and ENVISAT), NASDA (J-ERS-1 and ALOS) and the Canadian Space Agency (RADARSAT-1 and RADARSAT-2), securing continuity of observations well into the next decade.

Like optical high-resolution imagery missions, SAR missions have targeted a multi-segment user community. This is because SAR systems have a broad range of capabilities and serves a great number of applications in various disciplines. They provide in particular operational sea ice monitoring services relevant to polar oceanography and navigation. A commercial approach has generally been adopted in order to develop the market, optimise the use of the limited coverage of these demanding payloads and generate revenues as a measure of success.

Concerning ocean waves, ESA took the pioneering initiative to develop and operate a pre-operational "wave mode" global service, providing 6 x 7 km "imagettes" every 200 to 300 km along the ERS and ENVISAT track. The objective was to deliver in real time a low bit rate product which could be used on a global basis, in combination with altimeter and scatterometer observations, to document some spectral features of the ocean wave spectrum. The current products are used to evaluate the outputs of global wave models, but, despite significant efforts, their quality has so far failed to meet the expectations of those who had planned for real time assimilation, on a global basis. Fortunately, further efforts are underway to improve the product, based on the processing of complex "imagettes". Promising results have been already obtained and need to be evaluated with ENVISAT.

Overall, considering the firm plans of ESA (ENVISAT, 2000), CSA (RADARSAT-2, as a follow-up to RADARSAT-1) and NASDA (ALOS, 2001), comfortable SAR capabilities will continue to be available, well into the next decade, for sea ice and ocean wave monitoring. From a Global Ocean Observing System perspective, a first challenge is to demonstrate the operational value of a global "wave mode" service. If this challenge is met, a good case could be presented to all SAR operators for such a low bit rate service. A second objective is to secure adequate resources for sea ice monitoring at high latitudes, in combination with passive microwave observations from SSM/I and follow-up sensors. In Europe, the overall issue could be considered beyond ENVISAT, as part of the on-going ESA Earth Watch studies.

## **7 DATA COLLECTION SYSTEM**

Space-based data collection systems (like ARGOS, ORBCOM...) play indeed a key, integrating role in any global ocean observing system, providing a unique capability to collect and merge in-situ sub-surface and surface observations in real time. In 2000, second generation systems will be able to downlink commands to subsurface floats popping up at the surface, e.g. to determine their next immersion depth. This could be a key element of the ARGO long term observing strategy.

## **8 AFFORDABILITY AND REPLACEMENT REQUIREMENTS**

One cannot address the transition towards operational systems without considering costs, acquisition and replacement approaches, keeping in mind that the objective is to be seen as a relatively small increment to the current meteorological global observing system.

As a result of continuous R & D efforts and investments by space agencies, the development cost of a small satellite altimeter (JASON) or scatterometer mission, including satellite, payload, launch service and typically 4 years of operation, has been reduced very significantly. JASON-1, a newly developed system, will have more capabilities than TOPEX/POSEIDON but will be a factor of 3 lower in cost. This is due to technology infusion, and to payload miniaturisation, which has proved to be much easier for low power microwave payloads than for ambitious optical instruments.

In an operational perspective, it is however appropriate to make a distinction between development costs and recurrent costs. After a successful transition, it is reasonable to assume that the recurrent cost is borne by the operational agencies representing the user entities. Additional investments are needed from the development agencies to support R&D efforts plus demonstration missions, and for the development of the first satellite in a new operational series. In this perspective, it is worth noting that the typical recurrent cost of a full small satellite mission like JASON-2 or a recurrent QUICKSCAT lies in the 100 M\$ range, including satellite, payload, launch services, commissioning and 4 years of operations. Annualised, the costs represent about 25 M\$ per year of operation, and significantly less if the lifetime exceeds the four years. Although the addition of two or three mission lines represents a significant investment, it is more than one order of magnitude less than the cost of a large multi-purpose or SAR mission and compares favourably to the development cost of one complex optical instrument like MERIS or MODIS. It is also a small fraction of the cost per year of the current global operational meteorological satellite systems of the World Weather Watch. It should be further noted that such costs are expected to be shared by contributing agencies, based on international co-operation.

Low recurrent costs can be fully maintained or reduced only in the case of bulk acquisition. This is the current practice in the procurement of operational meteorological satellites. Beyond cost efficiency, this approach is the only one compatible with the early availability of replacement satellites needed to overcome in-orbit or launch failure. In the case of the transition from pre-operational or research

missions, special arrangements and pooling of resources between development and operational agencies are needed to preserve common interest.

## **9 OVERALL PERSPECTIVE AND CONDITIONS FOR SUCCESS**

Overall, continuity of space-based measurements of ocean topography, sea surface wind vectors and other ocean parameters cannot be taken for granted beyond the scientific and pre-operational success of the current satellite missions, without timely, convergent and co-ordinated initiatives from the development and operational agencies. Based on small satellites and advanced sensor technology the operational implementation of follow-on missions to JASON-1, QUICKSCAT and SEASTAR is now clearly affordable.

Nevertheless, such an operational oceanographic system still represents a significant additional investment. It will only be justified by the integration of requirements and the combined benefits to the various user communities and application areas. In this respect, oceanography is fortunate in that most measurements of ocean surface parameters, if available in real time, are now at the crossroads of oceanography, marine meteorology and climate monitoring. On the one hand, the real time assimilation of wind and wave data in NWP and sea state models has a demonstrated impact on operational forecasts. On the other hand, the increasing interest of operational entities in coupled modelling systems aimed at improving ENSO and seasonal prediction is closing the gap which has so far prevailed between numerical weather prediction, oceanography and climate research.

This convergence of needs presents the opportunity to enable a timely transfer of proven missions to operational entities, aggressive development of innovative sensor technology and observing techniques by space agencies and, last but not least, more productive, short loop interactions and cross-support between the operational and research user communities. It is clear that satellites will remain a critical component of any global ocean information system, and the necessary sustainable integrated systems will require quick, convergent and explicit articulation of research and operational programmes. As an example in the short term, operational agencies are expected to continue and enhance observations of sea surface temperature and to be increasingly involved in the implementation of scatterometer and altimeter missions. This should leave the resources available within development agencies to demonstrate promising new observing techniques, such as very low frequency microwave radiometry, fully polarimetric microwave imagery, interferometric wide-swath altimetry and detection of ocean-reflected GPS signals. In turn these new capabilities will improve our ability to map sea surface salinity, surface wind vectors, and surface topography, respectively. In order to speed up the transition, it is necessary to assess the incremental value of the new capabilities in the actual operational context. It is therefore essential that early open and real-time access to data from demonstration mission be given to the worldwide user community, whenever justified.

Timely investments and decisions, with an appropriate balance between operational and innovative demonstration programmes, are vital to the steady development of operational oceanography. Indeed, as demonstrated by the long gap between SEASAT and ERS, between CZCS and SEASTAR, operational oceanography may well fall between two stools, if development and operational agencies do not balance their respective investments, or if they compete for the same resources or fail to agree on



appropriate transition scenarios. Planning will also continue to require international co-operation and co-ordination, e.g. in the framework of the Integrated Global Observing Strategy promoted by CEOS, in order to avoid major duplication of efforts, whilst preserving the minimum redundancy required by operational services.