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Introduction

In this report we look at the scientific research questions that could be addressed by a constellation of altimeters and what further research is needed to fully utilise such a system. The contents are based on the previous GAMBLE reports on sea state, sea level, orbit determination and the operators workshop. We have defined scientific research to include research into pre-operational oceanography, but not the real time supply of data to operational entities. The document is divided into three sections looking at sea surface topography, sea state and non-ocean applications. The non-ocean applications section includes both land and ice applications. Scientific research in general is driven by one of two motivations; requirements from some user or the scientist's curiosity. Satellite remote sensing, with its large capital requirements. is generally driven by the former and user requirements will be our driver in this report. In some cases however we will introduce some ideas motivated purely by curiosity.

User Requirements

The reports from the other Work Packages have been invaluable in helping set out the requirements for future research. In summary the themes that have arisen are:
From the climate/ocean research community

  Can we measure mesoscale ocean variability?
  Can we measure barotropic ocean variability?
  Tidal issues, in particular tides at high latitudes and baroclinic tides.
  Can altimeters measure changes in ocean parameters (sea level, wave height, …) as the climate warms?
  Can altimetry contribute to the study of CO_2 (and other gas) transfer in and out of the ocean?
  How can altimetry contribute to studies of coastal currents?
  How are we to do long term calibration of altimeter missions?

From the wave/offshore community

  Accurate predictions of swell
  Better predictions of quickly evolving severe events.
  Better understanding of how rogue waves occur,
  Improved statistics of extreme events.
  Are altimeter measurements of high winds and waves reliable?
  Better reliability in nowcasts and forecasts of surface and subsurface currents.
  Where are the major sources of error in wind/wave models?
  Can we measure wave steepness or breaking with altimeters? Are these related to structural damage?
  It should be noted that even with a constellation of a dozen or satellites, radar altimetry is not a good method of monitoring wave conditions in a coastal area compared to coastal radar, say.

On the more technical level:

How would a constellation of altimeters relate to sea surface height from GNSS reflectometry or wide-swath altimeters

What are the prospects for cheap dual frequency or synthetic aperture Cryosat type altimeters.

What impact will the measurement of the geoid by GRACE/GOCE have on the use of altimeter constellations?

Clearly the area where constellations of altimeters are going to have the most impact is in mapping the oceans. In general we are looking for research areas where progress can be made from improved spatial/temporal sampling. However there are other areas that will support the use of constellations. For example the identification of rogue waves in altimeter products or the development of cheap dual frequency altimeters. In addition, many climatologies (e.g., of monthly mean wind speed and wave height) will be improved simply by virtue of higher sampling, since sparse sampling can often be identified as the principal source of uncertainty in the sample mean (e.g., Woolf and Challenor, 2002). In some cases (notably wind speed) present-day sampling is inadequate for a complete monthly climatology at a scale appropriate to the autocorrelation length scale of the measured variable.

Sea Surface Topography

A lot of the research topics involving mapping the ocean are presented in the High-Resolution Ocean Topography report by Chelton (2001). However that report only considers wide swath altimeters and small constellations of a few satellites. In Gamble we have been considering constellations from a few satellites to the 12 or so in the GANDER concept. One of the major issues for any large constellation of altimeters, where cost and mass considerations may not allow sophisticated tracking systems, is orbit determination. The WP4 report has shown that is not a major issue. Cross-overs with well tracked altimeters and relatively cheap tracking systems such as laser retroflectors mean that the problem can be solved.

The main requirements for improved coverage in space and time are the need to look at coastal processes, mesoscale and barotropic fields.

As was pointed out in the WP2 report, altimeter sea surface topography gains greatly in utility if it is assimilated into a numerical model of the ocean. Moreover, recently the combination of altimetry sea surface topography and the vertical density structure derived from the Argo profiling floats has provided a unique opportunity for relating the surface topography to varying water masses and stratification. Colour and SST imagery can help as well. This method is expected to improve until the full implementation of 3000 Argo floats is achieved in 2004. There are a number of research questions related to assimilation. So far, studies have, understandably, concentrated on the effect an additional one or two satellites has on assimilation. There remain fundamental questions about the number of satellites and assimilation. What is the optimal number of altimeters (clearly at some point adding extra instruments does not add significant amounts of information)? In an eddy resolving (permitting) model to get the large scale flow correct do we need to constrain every eddy with observations or is it possible to describe the eddy field statistically only constraining the occasional eddy, as at present? Coastal processes, in general, require a much higher space-time sampling than even 12 altimeters could provide, but even here similar considerations apply to open water. However the constraints from assimilating such data will be much stronger than for a small number of satellites. The research currently being carried out by Baptiste Mourre (LEGOS) and Francis Debost (LEGI) presented at the Gamble workshop on orbit configuration is starting to address these problems.

The problems of identifying features and these assimilation problems are related. If we can identify a feature in the altimeter data then, crudely, the assimilation process will be able to constrain the model to ‘fit’ that feature. Assimilation schemes have been proposed that explicitly identify features and ‘move’ them to the correct place in the model, this principle could be applied to all assimilation systems. With the altimeter coverage from two satellites it is possible to identify features such as baroclinic Rossby waves, and the major current systems. When we come to the mesoscale however, it is possible to identify eddies on a single pass (but not in an unambiguous way - size and position are confounded) but they then disappear from view before reappearing on the next set of tracks. This makes it almost impossible to track the eddies in time as it cannot be proved which eddy from track A is which eddy on track B. The combination of single track altimetry and ocean models can improve this as has been shown by UK Met Office. Constellations will solve this problem and allow new research areas such as the tracking of Agulhas eddies across the South Atlantic and, in conjunction with sea surface temperature data, estimation of the heat transport from the Indian to the Atlantic Oceans.

Mesoscale features are generally hard to detect in altimeter data because of the poor spatial resolution of current configurations. This is perhaps most severe in coastal regions where both the spatial as well as the temporal variability are big. Barotropic signals can have large spatial signals but travel very rapidly so are difficult to detect. They are clearly seen in altimeter data. In the past they were removed by an inverse barometer correction, recently the trend has been to use the output from barotropic models to make these corrections. These barotropic models are not only used as a correction for altimetry but also for time dependent gravity data from satellites such as GRACE. The input to these barotropic models is usually surface pressure and there is no assimilation of data. Because of the difficulty of observing barotropic signals in the ocean they have proved hard to verify. Frequent data from a constellation of altimeters would enable us first to verify how good these models are, and secondly to assimilate the data into the models themselves.

There are other phenomena, for example tsunamis and storm surges, where the sampling of one or two altimeters makes it impossible to detect the signal at the sea surface. Large constellations offer the promise of detecting such signals. Operationally this could be very important as both tsunamis and storm surges cause considerable amounts of damage, and loss of life particularly in the developing countries.

Sea State and Other Ocean Parameters

A constellation of altimeter satellites gives us much better spatial and temporal sampling to examine the wave climate. The research possibilities follow from this. We can divide the research opportunities into three areas: wave climate, extremes and new parameters.

Wave climate encompasses both the definition of the present and past wave conditions and the assimilation of data in wave models.

Wave climate

There are a number of areas where constellations of altimeters will help in the definition of the wave climate. At present using two altimeters in the TOPEX/POSEIDON and ERS orbits we can define monthly mean wave climate fairly accurately on a 2°x2° square grid over the globe. North and South of 66° where we no longer have TOPEX/POSEIDON data the convergence of the ERS tracks means that we can to some extent maintain accuracy. Comparisons have been made with NDBC buoys to show that in deep water the satellite average is representative of the average at a point within the grid cell (Cotton and Carter, 1994). Because of the lack of buoy data in the Southern Hemisphere we do not have the same confidence in the climatologies in these areas compared to the North Atlantic and Tropical Pacific. We do know that 2° squares are not suitable for semi-enclosed seas such as the North Sea and the Mediterranean. During the UK JERICHO project (Cotton et al., 1999) an attempt was made to reduce the size of the averaging grid to look at wave conditions in the Southern North Sea. The minimum grid cell to contain the required number of passes per month (5) was found to be 1° x 2° (Cotton and Carter, 1994; JERICHO, 1999; Woolf and Challenor, 2002). If we are to conduct research into wave climatology and its changes over time and space in these important semi-enclosed areas we need a finer grid than is delivered by two satellites. Similarly in the open ocean 2° squares have been forced on us and a finer grid would be useful for a number of research topics, for example wave height in storms (particularly associated with highly concentrated meteorological features such as Polar Lows) or looking at the interaction of waves with currents, in particular the Agulhas Retroflection. Having more passes per month per square will also make for superior climatologies as the variability of the estimates will be reduced. As the number of satellites is increased it will become possible not only to define the monthly mean but also the within month variance, a parameter it is impossible to measure with satisfactory accuracy at present. We will return to this subject when we discuss extremes below.

There are other areas of research concerning wave climate that will be opened up by a constellation of altimeters. One of these is the detection and tracking of swell. One of the current deficiencies in wave models is the way they deal with swell. Altimeters can detect the swell that is generated by a storm and in principle can track it across the ocean. At present this is difficult because of the poor sampling. Given a constellation however it would be possible to track the progress of a swell system simultaneously in both the wave model and in the satellite data. Such studies would increase our knowledge of the way swell propagates across the ocean and how swell is represented in models. The prospect of measuring both wind speed and significant wave height (SWH) for these tracked swell systems also opens new avenues of research into atmosphere-ocean interactions, e.g. the role of sea state for the propagation of atmospheric systems and for air-sea momentum transfer, which would benefit weather forecasting models. Such research is already under way for hurricanes using SAR images, from which both wind and sea state information can be extracted, although the present sampling by a single satellite (even if using SAR in widescan mode) allows only for occasional and brief monitoring of the features of interest.

The calibration of wave measurements from satellites and the verification of wave models are closely connected. The number of coincidences between models and altimeters is so much higher than the coincidence of either with wave buoys that it makes sense to calibrate one against the other with the buoys being used as an additional constraint (the use of triple collocations –buoy, satellite and model - is an important area of research in satellite calibration, e.g. Stoffelen, 1998; Tokmakian and Challenor, 1999; Caires and Sterl, 2003). We know that both wave models and altimeters work reasonably well for the majority of waves. In the extreme ranges there is more doubt. At very low wave heights (SWH ~ < 0.5 m) we know that altimeters will fail to work, similarly somewhere above 20m SWH they will fail to produce good estimates. Little is known of the behaviour of wave models in these high sea state regimes. Having a constellation of altimeters, all calibrated to each other and the global buoy network should provide enough coincidences to collect data in this important (but sparsely populated) region of large significant wave height.

Extremes

One important potential application of altimeter data is the calculation of extreme wave heights for design conditions. The advantage of a satellite-based approach is that it should be possible to estimate the extreme conditions in a consistent way across the globe. There have been a number of attempts to do this (see for example Henrique et al, 2001). However the application of altimeter data to these problems suffers from one major drawback; the sampling is so infrequent that it is not possible to guarantee that we have observed the extreme conditions in a month. In fact it is highly unlikely that we have done so. This contradicts some of the assumptions made in the methods used to estimate the return values. A number of techniques have been suggested to get around this problem. The one followed by Tournadre and Ezraty (1990) is to assume that the altimeter data are equivalent to 3 hourly buoy data. Henrique et al (2001) assume that the problem does not exist and that they have measured the true monthly extremes. Robinson and Tawn (2000) look at this problem from the theoretical point of view and show that because of the reduced sampling the estimated return value will be biased low. Increasing the number of observations by increasing the number of satellites will reduce this problem. Research is needed into this problem and into ways of solving it. Another aspect of extreme value theory that needs research is the problem of estimating extremes of a field of data rather than at a single point. Although this could be looked at with existing data the improved identification of extremes from a constellation will make this a much more tractable problem.

So far in this section we have discussed what may be described as the conventional approach to extremes. Taking a time series and using it to estimate the significant wave height that will be exceeded on average every hundred years, say. Recently there has been a lot of interest in so-called ‘rogue waves’. A rogue wave occurs when an individual wave is much higher than Gaussian statistics would predict for that sea state (significant wave height). At present altimeters estimate the significant wave height within the footprint. An interesting research topic would be to see if any information on the non-linearity of the sea (Challenor and Srokosz, 1989 for skewness from altimeter) or on the highest waves could be extracted. If it could, it would become much easier to map out where and when in the world we could expect to see rogue waves. Assuming linear wave mapping under range propagating conditions (still controversial) investigation of individual waves in SAR imagery has shown that rogue waves may be much more prevalent that previously believed (Rosentahl et al., 2003).

Other Ocean Parameters

In recent years the estimation of new parameters from altimetry has been the subject of considerable interest. Of particular interest are wave period (Davies et al., 1998; Sarkar et al., 1999; Gommenginger et al, 2003), precipitation (Quartly 1998; Tournadre and Morland 1997), wind stress (Elfouhaily et al., 1998; Gommenginger et al. 2002,) and gas transfer velocity (Glover et al, 2002). All these parameters are in their infancy and further research is needed into their properties. Wave period can be estimated from a single frequency radar while precipitation and a proposed method of deriving gas transfer velocities need dual frequency altimeters. Wind stress requires one or two frequencies depending on the method used (Gommenginger et al., 2002).

The global mapping of wave period has been attempted with visual observations from ships (Hogben and Oliver, 1986; Gulev et al., 2003). However the quality of these data is very poor. Altimetry offers the best chance to produce global climatologies. (SAR can only measure the long waves and thus produces a biased estimate of wave period). As for wave height, with the current coverage data can only be produced on a 2°x2° square. The same circumstances hold for period as for height. The current grid over which we are averaging is much too coarse to allow serious scientific research into the climatology of wave period in semi-enclosed seas and is on the margin for the deep ocean. Combining the wave period data with wave height information will allow us to look at wave slope, another important parameter whose geographical distribution has been little studied.

Precipitation and gas transfer involve the use of dual frequency altimeters. This additional capability would have to be factored into the cost of any constellation but would add significantly to the capability (as well as allowing the ionospheric correction to be easily calculated). Precipitation changes on very small scales and the very narrow swath of the altimeter has meant that it is difficult to produce reliable climatologies from a single altimeter (TOPEX). A large enough constellation would be able to produce climatologies with small enough uncertainty to allow the study of precipitation changes over the ocean from year to year and month to month.

Air-sea gas transfer is a very important topic but gas transfer velocities are very difficult to measure. In a ground-breaking paper Glover et al (2002) produce an algorithm to estimate the gas transfer coefficient from dual frequency altimeter data. Knowledge of the geographical distribution of gas transfer (and its integrals over various ocean basins) is vital if we are to understand the flux of carbon in and out of the ocean. Mapping such a parameter is very difficult, if not impossible, with only one or two satellites. A constellation would help us to produce credible maps and hence obtain integrated estimates of the fluxes of gases such as CO_2 over the oceans.

It may also be possible to make good estimates of wave breaking from satellites. Srokosz (1986) proposed a relationship between the fourth moment of the wave spectrum and the frequency of wave breaking. Since this moment is theoretically closely related to altimeter backscatter, altimetry provides a method of retrieving wave breaking frequency. Also, Zhao and Toba (2001) report a relationship between whitecap coverage, wind speed and wave height. Whitecap coverage could be retrieved from altimetry using that relationship. Since some models of gas transfer relate transfer velocity to whitecap coverage and wind speed (e.g., Woolf, 1997) or whitecap coverage alone (Zhao et al. 2003), this provides the possibility of retrieving gas transfer velocities from single-frequency altimetry. However, an enhancement of existing sampling density is highly desirable if not essential.

Non-Ocean Applications

Although Gamble is specifically concerned with the oceans there are a number of research and operational aspects over both ice and land surfaces that should be considered. Altimetry over land has been carried out experimentally for a long time (e.g. Berry 1995 and 1999). Initial investigation was limited by two factors: the complex echo shapes returned from the continually varying topography, and the inability of altimeters to track these rapidly changing surfaces.

In the past few years, research on interpreting individual land echoes has advanced to the point where most echo shapes can be interpreted. The development by ESA of an additional operating mode which increases the ability of the instruments to track over land and ice surfaces has permitted data to be gathered over the majority of the earth's land surfaces. These advances have opened up a range of novel applications for satellite altimeter data, including mapping, surface hydrology and surface texture studies.

One of the key applications addressed by these data is the global land hydrology budget. It has recently (Berry, 2002) been shown that huge decadal time series of river and lake heights were gathered by the Topex and ERS altimeters, with data from over three quarters of the world's major lake systems and most of the major river systems. As water resources in many parts of the world become increasingly scarce, the ability to provide independent global measurement and monitoring of water usage and distribution across national boundaries and from source to estuary of the strategic 'river corridors' becomes ever more important. Lake systems integrate precipitation: lake time series contain unique climate indicators and with a decadal time series already gathered and several further years from current missions, the continuation of this data stream is required to allow identification of climate shifts.

The current datasets are, however, critically constrained in terms of sampling frequency, and can only identify seasonal and inter-annual variation. For most human-oriented applications, measurements are really required every 2-4 days. With such a system, returning data in near-real-time, drought prediction and mitigation, famine forecasting, flood prediction, hydropower applications and global monitoring of the earth's land water resources all become achievable. Mapping of snow extent and derivation of snow depth are also possible.

The additional ability of such a constellation to return near-real-time data over the cryosphere should also not be neglected. Many applications are very effectively addressed by the availability of a spatially and temporally dense dataset. One clear operational application is the monitoring and mapping of Arctic sea-ice extent for ship routing. Additionally, the investigation of Antarctic land ice would benefit greatly from the provision of a dense and uniform dataset: even Cryosat will operate only in pulse-limited mode over the interior of Antarctica. A constellation solution could therefore provide far more data over the cryosphere than any current or planned mission. Combination of the land surface hydrology, snow cover, and land ice mapping would allow the earth's freshwater resources to be effectively monitored globally.

Research into Constellations

So far we have considered research topics that can be tackled with a constellation of altimeters. Research is also required to provide an objective and scientific basis for recommendations on the specifications of any proposed altimeter constellation (number of satellites, orbits, instrumentation.). First there is the question of the optimal number for a constellation. *A priori* we would expect the added utility of each satellite to fall as the number of satellites increases (see figure 1). However we need to accurately calculate these curves, in particular we need to know the slope – what additional utility do we gain from increasing the number in the constellation from n to n+1? This clearly depends upon the spatial and temporal scales of the parameter being studied. We would not expect to get the same answer for significant wave height as for sea surface height, for example. Some work has been carried out on this problem, for example the analysis of TOPEX/Poseidon and JASON data in the WP-2 supplementary report. However there is still more work needed in particular for non-sea surface height data products. A twist on this problem is the inclusion of new technology in the constellation: a wide-swath altimeter (WSOA) is due to fly on JASON-2; and SWIMSAT, which measures the wave spectrum has been proposed to ESA. How would the inclusion of such systems in a constellation improve our understanding of the oceans? At the moment, little or no work has been done on this problem. The proponents of such systems naturally concentrate on the use of a single system. However it is likely that these new technologies would be much more effective when used in combination with the improved sampling provided by a constellation. Once a constellation was established the risk involved in flying a new altimeter design would be reduced since the failure of a single component would have less effect than the loss of a stand alone mission. We will return to this issue later.

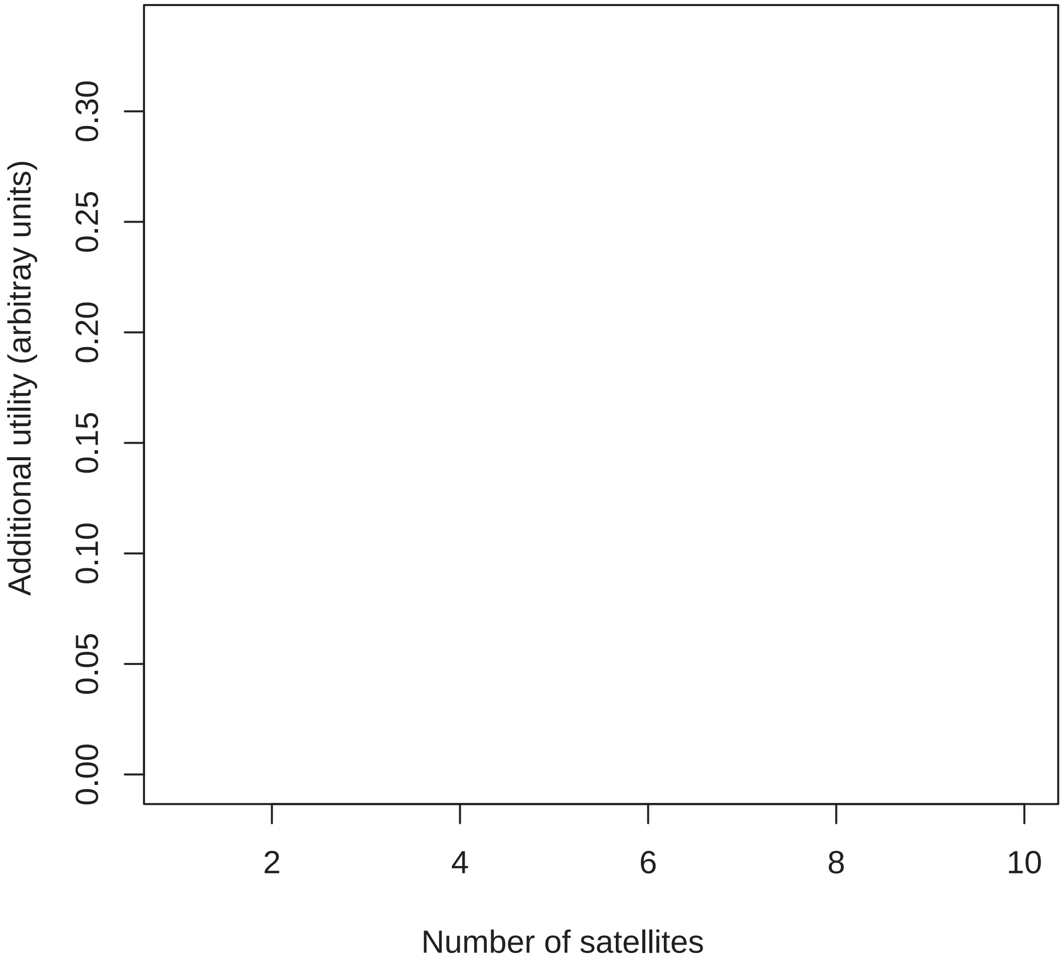

Figure 1. A schematic of the additional utility from added satellites to the constellation

Contingency/Degradation

Any instrument has only a limited lifetime and at some point its measurement accuracy will degrade and eventually it will cease to operate all together. Any proposal for an operational altimeter constellation would need to take this into account in any plans. We need research into how well a degraded constellation will work as well as how to design an optimal one. Such work would need to address issues such as is it more cost effective to have excess capacity (spare altimeter systems in space) or take the risk of a failure. If all systems degrade at the same rate are spare systems worthwhile, and what should the replacement rate be? We have a very small sample of altimeter satellites to gather reliability statistics from so this is a challenging exercise.

Conclusions

The last decade has seen radar altimetry moving from a research topic towards an operational system. The next step is to go from a few satellites launched for research purposes to planned constellations optimised for applications. In this report we have considered what research can be carried out with such a constellation and what research is needed to optimise a system of altimeters for operational purposes. If altimetry is going to complete the transition from a research tool to an operational system to be used in support of EU policy the issues addressed in this report will have to be tackled.

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