GAMBLE: A Thematic Network under the EC Fifth Framework Programme
Deliverable 6b

Final Report for GAMBLE WP 4: Orbit Determination and Satellite Tracking Workshop

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1 April 2003

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This document was typeset with $\LaTeX 2_\varepsilon$.
The layout was designed by Remko Scharroo © 1993–2002

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Chapter *1*

Introduction

Satellite tracking and orbit determination are essential elements of most satellite missions. Knowledge of the spacecraft position at any time is a requirement for communication and planning. For altimetry satellites however, the orbit determination results are also an essential part of the scientific data. It provides the link between the range observation made by the altimeter instrument and the terrestrial reference frame. The accuracy requirements for the Precise Orbit Determination (POD) of altimeter satellites, such as Jason-1 and Envisat, are therefore several orders of magnitude higher than for most other satellites [*Montenbruck and Gill*, 2000]. Any errors in the orbit determination also directly affect the accuracy of their scientific products. All altimeter-carrying satellites have therefore been equipped with high-precision tracking capabilities, such as SLR, DORIS and GPS. And over the past decades, there has been an ongoing development in POD techniques and the modelling of the measurements and the forces acting on the satellites.

The objective of GAMBLE Work Package 4 (WP4) is to present an overview of current and future developments in the field of orbit determination and satellite tracking, and to provide recommendations for the next generation of altimeter missions. This report provides the answers to the following issues involved in the orbit determination for the next generation of altimeter missions:

- What are the future developments and limitations of the tracking systems and POD strategies?
- What are the recommended tracking systems for the future altimeter missions?
- How can possible future low-cost altimetry missions benefit from the simultaneous measurements made by the very precise altimeter satellites that will replace Jason-1 and Envisat?

The current and future status of the three high-precision tracking systems is discussed first in Chapter 2. In Chapter 3, the developments in POD strategies and modelling will be further discussed. Finally, in Chapter 4, the initial recommendations that can be made regarding the future missions will be summarised.

Chapter 2

Tracking Systems

Past altimetry missions have used a variety of precise tracking systems (see Table 2.1), each with its own characteristics, strengths and weaknesses. The SLR, DORIS and GPS systems can be considered as prime candidates for future missions. These tracking systems, and the augmentation by altimeter data, will be discussed in this Chapter.

Tracking system	TRANET/ OPNET	SLR	DORIS	PRARE	GPS	Orbit Error
Measurement Precision	range-rate 2-10 mm/s	range 0.5-5 cm	range-rate 0.35-0.5 mm/s	range + range-rate 2.5 cm, 0.25 mm/s	phase 0.2-0.5 cm	(cm)
Seasat	yes	yes	no	no	no	30
Geosat	yes	no	no	no	no	10
ERS-1	no	yes	no	failed	no	5
TOPEX/Poseidon	no	yes	yes	no	yes	2
ERS-2	no	yes	no	yes	no	4
GFO	no	yes	no	no	failed	5
Jason-1	no	yes	yes	no	yes	2
Envisat	no	yes	yes	no	no	3
Cryosat	no	yes	yes	no	no	3
Jason-2	no	yes	yes	no	yes	2

Table 2.1 Types of tracking systems on past current and future altimeter missions and their state-of-the-art or expected radial orbit precision.

2.1 SLR

The technique of Satellite Laser Ranging (SLR) [*Noomen*, 2001] provides a direct and unambiguous observation of the distance between a laser station on the surface of the Earth and a spacecraft equipped with a passive and inexpensive laser retroreflector. The range measurement is computed by measuring the observed round-trip time of the laser pulse, divided by two and multiplied by the speed of light in vacuum. The application of the laser technique originated in the 1960s. The measurement precision has increased from about 2 m at that time, to a few millimetres at present. Apart from being a tool for precise orbit determination of satellite, the global network of laser ranging systems was set up to monitor plate tectonics, establish the position and motion of the Earth's centre of mass, and track the orbit and attitude variations of the Moon.

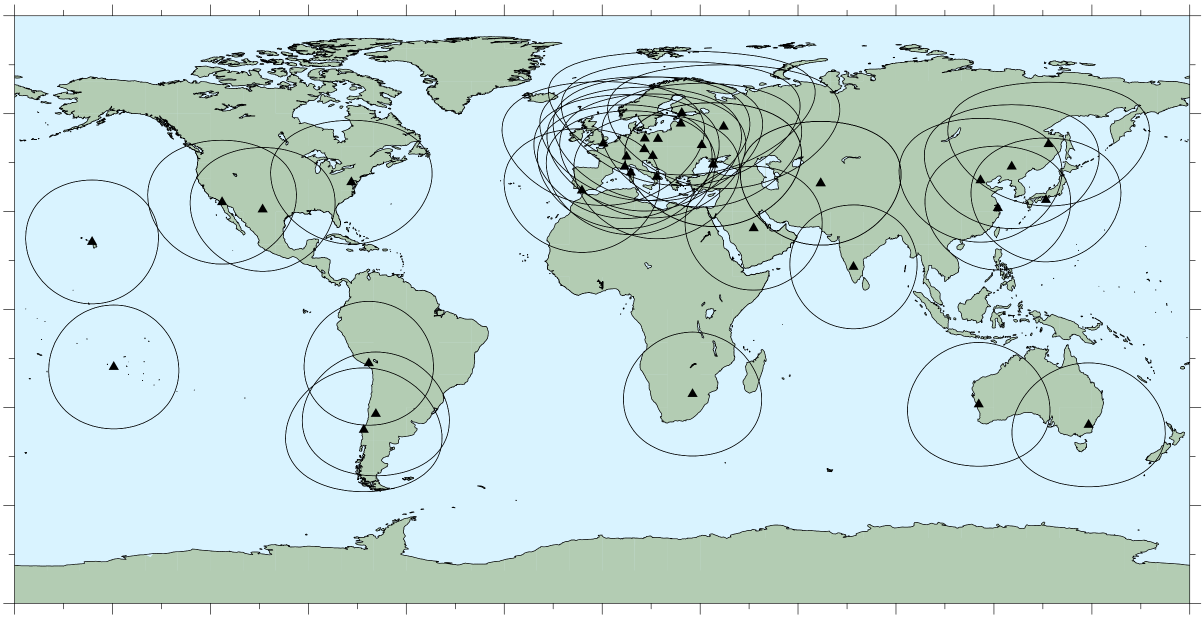

Figure 2.1 Global distribution of present SLR stations. Planned stations in India and Argentina are shown as well. Visibility circles are displayed for a satellite at an altitude of 800 km, with a minimum elevation of 10°.

The International Laser Ranging Service (ILRS), established in 1998 by the global SLR community, is the official organisation which coordinates all aspects of laser ranging, from instrument development and data acquisition, to the computation of science products [*Pearlman et al.*, 2002].

However, the costs of building, maintaining and operating the network of SLR stations are not covered by the specific satellite missions or by a single agency. The stations are under the responsibility of mostly government-funded research institutes in several countries. On the one hand this makes SLR a very low-cost tracking option for future satellite missions. On the other hand, some of the stations, even ones which are among the best in terms of performance, are under a near-constant threat of being closed due to budget cuts. And some initiatives for new stations which would strengthen the technique have an even harder time.

Despite these difficulties, both the number of stations and the number of satellites have increased steadily over the past decades. In addition, performance enhancements have also come from developments like real-time data processing, satellite pass interleaving and system upgrades. Although the majority of the stations is still located in the Northern hemisphere (see Figure 2.1), and particularly in Europe, new stations in locations such as South-Africa, South-America and India are planned, or have been installed in the recent past. The aim is to distribute the stations more evenly across the globe, which will significantly strengthen the SLR capabilities for satellite tracking as well as precise positioning.

Due to the reliability and strength of SLR, and since a laser reflector is a relatively simple and low-cost addition to a satellite's payload, most altimeter satellites have benefited from it. In fact, if not for the support of the SLR community, the ERS-1 and GFO altimetry missions would not have succeeded in their scientific objectives after their radiometric tracking instruments (PRARE and GPS, respectively) had failed.

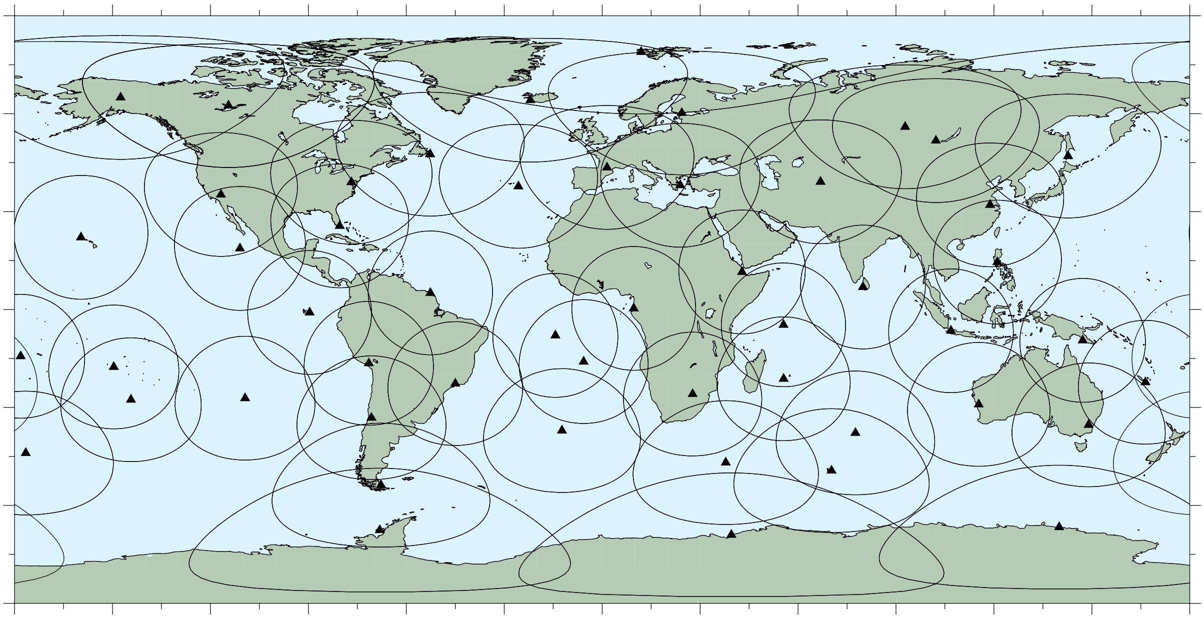

Figure 2.2 Global distribution of DORIS beacons. Visibility circles are shown for a satellite at an altitude of 800 km, with a minimum elevation of 10°.

The SLR measurements have also proved essential for the verification and calibration of other tracking instruments and of course the altimeter instruments [*Exertier et al.*, 2001]. In addition, altimetry missions benefit from the important contribution of SLR in the definition of gravity field, geocentre, scale and Earth rotation models.

Drawbacks of SLR tracking are the limited global network coverage, its tracking restrictions due to visibility conditions, and restrictions on scheduling, manpower and financing.

2.2 DORIS

The DORIS system [*Tavernier et al.*, 2002] was designed by the French Space Agency CNES, in partnership with France's mapping and survey agency IGN and the space geodesy research institute GRGS. The system consists of a ground network of around 60 beacons, more or less evenly distributed over the globe (see Figure 2.2), which transmit radio signals at dual frequencies. On-board the satellite, the Doppler shift of the signals is translated into range-rate observations. The various tropospheric path delays are corrected by using meteorological information gathered at the beacon, while ionospheric delays are corrected using the secondary frequency.

The first DORIS receiver was launched on board the SPOT2 satellite in 1990, followed by TOPEX/Poseidon, SPOT3, SPOT4, Jason-1, Envisat and SPOT5. In the future, Cryosat and Jason-2 will also be equipped with a DORIS receiver.

There have been significant technological developments in both the space and ground segment for DORIS. Jason-1 and SPOT5 are equipped with miniaturised versions of the receiver, which require considerably less power and mass. In addition, the receivers on board Jason-1, Envisat and SPOT5 are all capable of receiving signals from two beacons simultaneously, with a reduced noise level, increasing the number and quality of the data points. One of the most impressive enhancements on the space segment is the DORIS DIODE Navigator, which is capable of delivering both time tagging and an orbit accurate to up to 30 cm radially, in real-time, on board the spacecraft [*Jayles et al.*, 2002].

The DORIS ground segment is continually updated. Improvements in the latest generation of beacons include the possibility to shift the emitted frequencies, in order to allow the closer placement of several beacons without interference. This is especially important in order to obtain dense tracking for satellites in lower orbits. New beacons have been installed, and the monumentation of old beacons has been improved in the ongoing effort to push the accuracy of DORIS orbits and positioning to the limit.

2.3 GPS

NAVSTAR GPS is a satellite-based radio navigation, positioning and time-transfer system. The GPS space segment consists of 24 satellites deployed in six evenly spaced orbital planes at an altitude of 20200 km. The satellites transmit binary codes on one or both of two carrier frequencies. Since the early 1990's, these signals have been used for the positioning of low Earth orbit satellites. GPS space receivers have now been miniaturised, and can be manufactured at relatively little cost. They require very little power and mass, and are used frequently on microsatellite and even nanosatellite platforms. These receivers are capable of tracking up to 12 GPS satellites at the same time, providing an excellent tracking geometry and coverage.

The accuracy of orbits determined using data from such receivers is at the order of metres, which is excellent for most applications, but clearly not sufficient for todays centimetre-level altimeter missions. A more precise type of GPS receiver was therefore developed at JPL, and first flown on TOPEX/Poseidon. The current generation of JPL GPS space receivers, named BlackJack, can track up to 12 dual-frequency signals simultaneously for POD purposes. The receiver provides integrated carrier phase measurements, in addition to pseudoranges, which allows orbits to be computed at the level of 2–3 cm. The excellent tracking geometry and coverage allows for reduced-dynamic and kinematic orbit determination, so that force model errors become largely irrelevant. Orbits for the gravity mission CHAMP, the first to fly a BlackJack GPS receiver, have now also reached the few-cm level, despite the very large drag and gravitational perturbations at its altitude of 450 km. These results are very promising for future altimetry missions.

Europe has recently started its own global navigation satellite system project, named Galileo. The fully deployed Galileo constellation will consist of 27 operational satellites in three orbit planes at an altitude of 23616 km. Galileo is supposed to reach its full operational status in 2008.

2.4 The use of altimetry in orbit determination

For missions which have to rely only on SLR measurements for orbit determination, such as ERS-1 and GFO, the altimeter data can be used to augment the SLR tracking data [*Scharroo and Visser*, 1998]. Especially the sea-surface height differences at crossover points are a powerful addition in times of sparse SLR tracking. Of course, there is a fear that ocean signals that are to be retrieved from the altimetry will be absorbed in the orbit. This effect will be restricted by using the measurements in a dynamic orbit determination, with a conservative force model parameterisation scheme. In such a case, the altimetry can help in more accurately scaling the atmospheric drag model, for example, which leads to a considerably more accurate orbit, compared to using SLR data alone. The main signature of drag perturbations on the orbit (a decrease in the altitude of a few centimetres up to metres per day) is quite different from any known ocean signal. In addition, such drag scaling parameters are generally estimated over intervals spanning multiple orbit revolutions. Therefore, their capability to capture ocean signals is thought to be virtually non-existent.

A related technique is the use of dual-satellite crossovers. For example, radial orbit errors of a satellite such as ERS-1 or ERS-2 can be corrected by minimising the sea-surface height differences between that satellite and TOPEX/Poseidon, under the assumption that the TOPEX/Poseidon orbit is much more accurate [*Traon and Ogor*, 1998; *Moore et al.*, 1999]. Again, when such a technique is used in a dynamic orbit determination, rather than in an empirical way [*Rummel*, 1993], the likelihood of aliasing actual sea surface features into the orbit is significantly reduced, if not eliminated [*Scharroo*, 2002].

In the case that a GANDER-type constellation is able to provide accurate height measurements, this technique can be used to save costs on DORIS receivers or BlackJack type GPS receivers. A constellation of sixteen satellites will provide ample crossovers points with a reference mission such as Jason-2.

The use of altimetry in orbit determination is, however, limited to the determination of the orbital altitude. Some knowledge of the horizontal position of the satellite (*i.e.*, latitude and longitude) is still required. Doppler tracking of the transmitted signal as received by the ground stations may be sufficient for this purpose and may be enhanced by limited SLR tracking. Orbit errors of several metres in horizontal direction are still acceptable as a first approximation.

When such limited Doppler tracking is enhanced with single and dual-satellite altimeter crossover measurements, a radial orbit precision of around 10 cm can be obtained. This number depends largely on the accuracy at which satellite surface forces (drag and solar radiation) can be modelled. During periods of low solar activity, such orbit precision can be met more easily than during periods of high solar activity.

Chapter 3

Orbit Determination Strategies

3.1 Dynamic orbit determination

Dynamic orbit determination is the most traditional and general method used in the computation of satellite orbits. The orbit is integrated from an initial state (position and velocity vector), making use of dynamic force models. The differences between the computed orbit and the tracking observations are then minimised in an iterative least-squares adjustment of the initial position and velocity, together with several force and measurement model parameters [*Montenbruck and Gill*, 2000]. Since the quality of the orbits is strongly dependent on the quality of the force models, a lot of effort has been put in the improvement of these force models in the past. In the next two sections, these developments and the current state of the art will be briefly summarised.

3.1.1 Gravitational force models

Uncertainties in the Earth's gravity field have long been the major error source in orbit determination of altimetry satellites. A huge improvement in gravity field modelling was made possible by past altimeter missions, with their high accuracy satellite tracking and altimeter measurements. This has reduced the radial orbit error from meters in the 1980's to centimetres nowadays. The effect of the Earth's gravity perturbations decreases rapidly with the orbit altitude. The effects on TOPEX/Poseidon and Jason-1 at 1336 km, are therefore much smaller than on Geosat, GFO, ERS and Envisat, at roughly 800 km.

Gravity field models are generally generated using tracking data from a variety of satellites at different inclinations and altitudes, combined with surface gravity and altimeter measurements. For this reason, the gravity-induced orbit error of a certain satellite for a certain model, depends heavily on how much tracking data of this satellite (or other satellites in the same or similar orbit), have been used in the generation of this model. Therefore, so-called tailored models have been generated to push the orbit accuracy to its limits. Examples of these are JGM-3 for TOPEX/Poseidon and Jason-1 [*Tapley et al.*, 1996], DGM-E04 for ERS-1/2 [*Scharroo and Visser*, 1998] and PGS7727 and PGS7751e for Geosat and GFO (F. Lemoine, priv. comm.).

Using these tailored models, gravity-induced radial orbit errors are brought down to the few cm level. However, in reality there is only one gravity field, so the concept of several optimum gravity models, depending on the orbit, is physically not very realistic, but remains to date general working practise.

The GRIM5-C1 model [*Gruber et al.*, 2000] represents the current state of the art in long wavelength gravity field modelling for POD, providing improvements over earlier models for both the TOPEX/Poseidon and ERS orbits. The successor of GRIM5, with CHAMP data included, is EIGEN-1S [*Reigber et al.*, 2002]. However, this model does not provide an improvement over GRIM5 in POD of the current altimetry satellites.

The GRACE mission promises the delivery of a mean Earth gravity field and its seasonal variations at an accuracy that will eliminate most of the gravity-induced orbit error. The twin GRACE satellites were successfully launched in early 2002, and the first publicly available gravity models are expected to be released in 2003.

3.1.2 Non-gravitational force models

Non-gravitational forces, or surface forces can be defined as forces which are caused by the momentum exchange of particles (photons, molecules, and atoms) with the outer surface of the spacecraft. The most important surface forces for altimetry satellites are:

- Direct solar radiation pressure;
- Earth albedo radiation pressure;
- Earth IR radiation pressure;
- Thermal re-radiation of the spacecraft;
- Atmospheric drag.

With the increase of gravity model accuracy, non-gravitational force models have become one of the most important limiting factors in precise orbit determination. Contrary to gravitational forces, the non-gravitational perturbations depend on satellite characteristics, such as shape, size, mass and surface materials. The sensitivity to these perturbations is proportional to the area to mass ratio. Since area grows as the square and mass as the cube of the linear dimension, larger satellites, such as Envisat, are generally less sensitive to non-gravitational perturbations than their smaller counterparts, ERS. Similarly, Jason-1 is much more sensitive to non-gravitational accelerations than TOPEX/Poseidon.

Atmospheric drag is the most difficult perturbation to model at the moment, mainly due to the uncertainties in atmospheric density. The thermospheric density model MSIS-86 [*Hedin*, 1987], is still the most accurate for POD applications. Unfortunately, newer models have not been able to offer an improvement yet [*Doornbos et al.*, 2002].

In terms of mission planning, there are two density variations which are of prime importance. First of all, the density of the upper atmosphere decreases close to exponentially with altitude. This makes it easier to determine accurate orbits for TOPEX/Poseidon and Jason-1, at an altitude of 1336 km, than it is for other altimetry satellites, which are typically at an altitude of 800 km. Secondly, the atmospheric density at a certain altitude can change with one to two orders of magnitude over the 11-year solar activity cycle. Not only is the average density much higher during high solar activity, there are also much larger variations which are quite difficult to model. The next generation of altimeter satellites will be launched around 2006, during solar minimum, which will enable orbit determination at the few-cm level even at lower altitudes. However, given the longevity of the current altimeter satellites, the next generation will ultimately reach the next solar maximum. In order to reach the goal of consistently highly accurate dynamic POD under all conditions, much work still needs to be done on improving models of the thermospheric density.

3.2 Reduced-dynamic and kinematic orbit determination

In reality, force model errors in dynamic POD are absorbed to some degree by the estimation of force model parameters, such as density and radiation pressure scale factors and empirical accelerations. The number of these parameters that can be estimated successfully depends on the density of the tracking data. With high density tracking data from GPS or DORIS, it is possible to estimate more and more of these parameters. In doing so, the resulting orbit will get closer to the tracking data and will be less vulnerable to dynamic force model errors. This strategy, especially when applied in combination with a Kalman filter approach in the estimation step, is known as reduced-dynamic POD.

In the extreme case, the orbit is directly determined from the tracking measurements in a geometric approach, in which force models become irrelevant. This kinematic POD approach is possible using the dense three-dimensional tracking data provided by GPS. The kinematic approach places high demands on the tracking data, as the solution during any lapse in tracking can become unbounded, and any systematic errors in the data will be present in the orbit, which is not the case when dynamic models are applied. The so-called short-arc orbit determination, where the orbit is adjusted using simultaneous tracking of three or more SLR stations over a short time span, is also a form of kinematic POD. This technique is frequently applied for altimeter range calibration campaigns.

3.3 State-of-the-art orbit determination

During the last decade orbit errors of altimeter satellites have come down by more than an order of magnitude, and more advances are expected when new gravity models based on CHAMP, GRACE and GOCE data have been produced. Although the improvement of gravity field models has been an important contributor to the reduction in orbit errors, the possibility of near-continuous tracking by DORIS and/or GPS introduced a new era in orbit determination in which uncertainties and errors in dynamic models can be counterbalanced by a multitude of tracking data. Using the radar altimeter as an additional tracking system is a poor-man's approach that provides similar capabilities.

Although ERS-2 mainly relies on SLR tracking enhanced with altimeter data, its orbits are accurate to about 4 cm in radial direction. Envisat orbits, with DORIS data included, probably approach the 3 cm level. The radial orbit errors of TOPEX/Poseidon and Jason-1 are currently estimated at the 2–3 cm level. For Jason-2, despite its larger appendages compared with Jason-1, radial orbit errors will likely not exceed this level. Because of its high altitude, Jason-2 is not very sensitive to atmospheric drag. The most uncertain part of the non-conservative force modelling will be the effect of solar radiation pressure. This effect can be minimised by using DORIS and/or GPS tracking in reduced-dynamic orbit determination.

Chapter 4

Conclusions and Recommendations for Future Missions

Several recommendations for the planning of future altimeter missions can be made using the details on tracking systems and precise orbit determination presented in the previous Chapters. Some of these recommendations might conflict with each other, or with restrictions on costs, mass, etc. In these cases, further discussion could be required, both inside or outside the framework of GAMBLE.

4.1 Orbit choice

The final recommendations concerning orbit choice shall be made under GAMBLE Work Package 8: *Constellation Optimisation*. Still at this point, the following suggestions can be made:

- In order to obtain multi-decadal time-series of altimetry data over the same ground tracks, the orbit choices of both TOPEX/Poseidon/Jason-1 and ERS-1/ERS-2/Envisat must be adopted for their follow-on missions.
- Solar activity will be at a minimum in its 11-year period around 2006. Still, if GRACE models have eliminated the gravity-induced radial orbit error, drag perturbations will likely remain a large error source at lower altitudes. The choice of a high altitude orbit is recommended.

4.2 Tracking systems

- Future high-accuracy altimeter satellites should carry either a GPS/Galileo or DORIS receiver for high-accuracy, near-continuous tracking. The near-continuous tracking allows reduced-dynamic orbit determination, a technique that provides highly accurate orbits by minimising the effect of dynamic model errors.
- In addition, a laser retroreflector is required for several purposes: for additional high-accuracy tracking, for validation of the radiometric tracking, for calibration of the altimetric range, and as a fail-safe backup tracking device.
- The TOPEX/Poseidon and Jason-1 missions have proven that each of the three available tracking devices (SLR, DORIS and GPS) adds unique and valuable

information to the computed orbits and to the improvement of force and measurement models. It is therefore recommended to take this combination into consideration for the follow-on missions of Jason-1 and Envisat as well.

4.3 Other general issues

- When real-time orbits are required, the DORIS/DIODE navigator system is a flight-proven technology. Onboard orbit determination at the same precision using GPS is more difficult, because of the need for auxiliary information. However, this might also become possible in the near future.
- In the design of new satellites, a large solar array may be required to generate sufficient power. Also, mass generally has to be minimised in order to reduce launch costs. Despite this, it is still advisable to take the area to mass ratio into account during the design of altimetry satellites. A low area to mass ratio can greatly improve dynamic orbit determination, because of the lower sensitivity to surface forces.
- Radial orbit errors are currently reduced to the level of 2–3 cm, mainly because of the effective use of DORIS tracking data. Even with its larger appendages, orbits of Jason-2 are expected to have a 2 cm radial orbit precision.

4.4 GANDER specific issues

- A high-precision tracking system for GANDER only needs to be considered if its altimeter instrument is upgraded for making sea-height measurements. Otherwise, the use of NORAD elements may be sufficient.
- If sea-height measurements will be part of the GANDER products, it might be possible to use crossovers with a reference-class mission such as Jason-1, in order to generate GANDER orbits. These orbits will likely be accurate enough to study mesoscale ocean signals. However, because crossovers only contain information in the radial direction, another means of tracking will be required to fix the orbit in the along-track and cross-track directions.

  Sparse tracking makes it impossible to use reduced-dynamic orbit determination. This will also limit the achievable orbit precision.

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