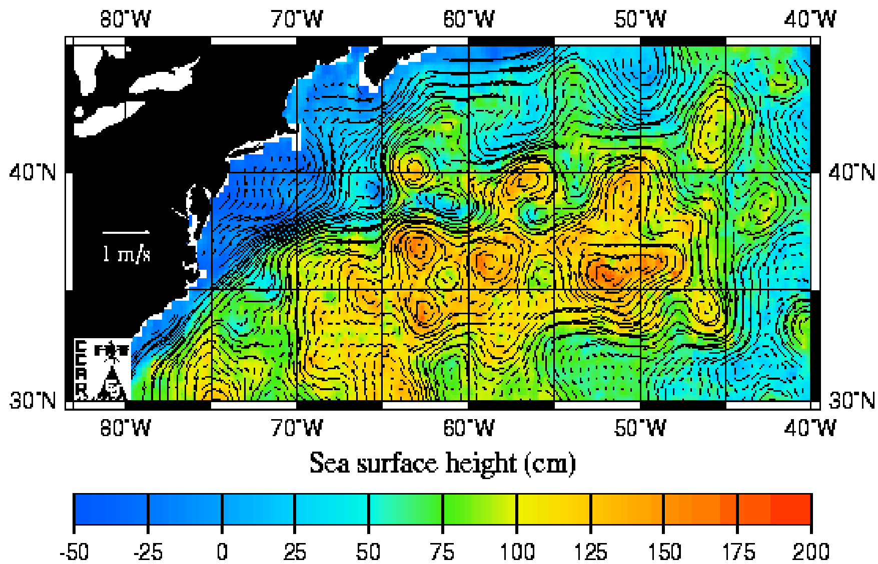
BNSC Service Mission Support (SMS) Programme

Ocean Currents from space



Orbital Studies – report for WP31

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1 Introduction to Precise Orbit Determination

Orbit determination is the methodology by which precise positioning of Earth Satellites is determined by numerical integration of the equations of motion with orbital parameters recovered in a differential procedure by minimising differences between the computed orbit and the available tracking data. Accuracy of the orbits is dependent on the precision of the force models and the quality and quantity of tracking data. The satellite force model incorporates both gravitational and non-gravitational forces with the integration undertaken in an inertial frame. The Earth's gravity field, represented as a truncated expansion of spherical harmonics, is the dominant force. Other gravitational forces such as third body attraction from the moon and planets are significant but not a major source of error. Surface forces, including air-drag and direct and indirect solar pressure, are more problematic. A macro model for the surface structure is usually employed to good effect for direct solar radiation and earth reflected and infrared radiation with uncertainty in photon-surface interaction accommodated by estimating a scaling factor. Air-drag is proportional to neutral air density as obtained from a thermospheric model. Input parameters include the solar and geomagnetic fluxes while other parameters such as altitude, latitude, longitude, solar hour angle etc are computed within the software. However, a static thermospheric model is incapable of resolving the complex dynamic behaviour of the upper atmosphere with a corresponding deficiency in estimation of neutral air-density. For this reason, orbital analysts estimate multiple scale factors for drag with additional empirical once-per-revolution along-track and across-track accelerations to 'soak up' mismodelling in the forces.

Recent improvement in accuracy of orbital positioning of altimeter satellites is directly related to the improvement in modelling the Earth's gravity field. Table 1 summarises the increased accuracy of TOPEX/Poseidon associated with refinement in geopotential over the past decade. Radial orbit errors for TOPEX/Poseidon of about 1cm are expected from covariance analyses of EGM-96. Each refinement corresponds to a further addition of tracking data with satellites with different orbital inclinations required to separate individual harmonics in the lumped values.

Crucial to orbital accuracy is the altitude of the near-circular orbit. Altimeter satellites have been inserted into three distinct orbits characterised by their orbital inclinations, altitude and repeat period as summarised in Table 2. In terms of accuracy, the lower orbits of GEOSAT/GFO and ERS/ENVISAT are separable from the more precise orbits of TOPEX/Poseidon and Jason-1. There are two reasons for this, namely the attenuation of the gravity field with height and the exponential decrease of neutral air-density with altitude. Both imply a reduction in mismodelling as the altitude increases. The attenuation property means that the less well known higher degree and order gravity field terms are not as significant while a decrease in air density reduces the impact of aerodynamic effects for the higher orbit.

Table 1: Gravity field enhancement 1988-2000

Gravity Model	Date	Degree and order	Data	T/P radial error (cm)
GEM-T1	1988	36	Satellite	25.0
GEM-T2	1990	36	Satellite	10.2
GEM-T3	1994	36	Combination	6.8
JGM-1	1994	70	Combination	3.4
JGM-2	1994	70	Combination	2.2
JGM-3	1996	70	Combination	1.1
EGM-96	1996	360	Combination	0.9

Data: Satellite: satellite tracking only
Combination: satellite tracking, altimetry and gravimetry

The essential connection between the Earth Centred Fixed reference frame to which the tracking data relate and the inertial frame in which the Newtonian mechanics are formulated and integrated is achieved through rotation matrices including precession, nutation, polar motion and earth rotation. Earth rotation, polar motion and a correction to the theories for nutation are determined from several geodetic techniques (e.g. GPS, VLBI, SLR) with combination solutions published by the International Earth Rotation Service. Such values are available for post-processing but use of predicted values does not lead to significant degradation in orbital accuracy.

The radial height, or more correctly, the normal height is an essential component of Geophysical Data Records of satellite altimetry and associated geophysical corrections and parameters. In that context, the precise orbital ephemeris (POE) is computed well after the event allowing sufficient time for collection of ancillary and all tracking data. In addition, medium orbital ephemeris (MOE) are often delivered after a shorter time lapse of say three days to allow the altimetry etc to be applied to near real-time applications such as sea-ice location. MOE orbits are slightly less accurate than POE given use of intermediate geophysical data, reduced tracking data and the time lapse constraint. Real time ephemeris (RTE) can also be computed onboard some satellites utilising data available onboard, predicted ancillary data and possibly a simplified computational model. Such computations rely on onboard tracking systems and processors with any required data and parameters either pre-determined or uploaded by telemetry.

Table 2: Altimeter satellites, tracking, altitude etc and SXO accuracy

altitude 1340km	inclination 66°	repeat period 10day	
satellite	Operational period	Tracking	SXO residual (cm)
TOPEX/Poseidon	1992-	SLR, DORIS, GPS	6-7
JASON-1	2001-	SLR, DORIS, GPS	

altitude 800km	inclination 108°	repeat period 17day	
satellite	Operational period	Tracking	SXO residual (cm)
GEOSAT	1985-1990	OPNET/TRANET	12-15
GFO	1998-	SLR, GPS (failed)	9-10*

altitude 800km	inclination 96°	repeat period 35day	
satellite	Operational period	Tracking	SXO residual (cm)
ERS-1	1991-1996	SLR, PRARE (failed)	9-10*
ERS-2	1995-	SLR, PRARE	9-10*
ENVISAT	2002-	SLR, DORIS	

* without use of supplementary single-satellite crossover data or dual satellite crossover to enhance less accurate orbit to accuracy of higher satellite (say T/P).

2 Tracking Data Types

We subdivide this section into subsections based on the various tracking data types appropriate for an Ocean Currents mission. Particular emphasis is placed on the accuracy and delivery time of each orbital product. A subsequent section assesses the impact and viability of each data type for the candidate missions for ocean current monitoring.

Tracking systems considered include

- optical, e.g. camera, SLR
- doppler ground to satellite, e.g. DORIS
- doppler satellite to ground, e.g TRANET, S-band
- microwave satellite to ground to satellite, e.g. PRARE
- microwave satellite-to-satellite, e.g. GPS, GRACE inter-satellite range, TDRSS
- altimetry e.g. single and dual satellite crossovers

Several are historical e.g. cameras and TRANET and have been superseded or of insufficient accuracy e.g. Doppler measurements based on satellite transmitted S-band to ground stations or to the Tracking and Data Relay Satellite System (TDRSS). All the other systems have been used on one or more of the current altimeter satellites (ERS-1, TOPEX/Poseidon, ENVISAT, GFO, Jason-1). Each tracking system has its inherent advantages and disadvantages and it is customary to incorporate two or more tracking types per mission to mitigate against possible systematic errors and as insurance if, as happened with GFO, one system fails. Particular emphasis is given to SLR, DORIS and GPS as these will be seen to offer the greater potential for “Ocean Currents”

2.1 Satellite Laser Ranging (SLR)

Development.
SLR began in the early 1960's, at which time ranging precision was at the metre level. During the 1970s the accuracy of the best systems was at the decimetre level, limited mainly by the relatively long laser pulse-lengths that were in routine use at the time. For a typical pulse-length of some 30cm, a large uncertainty exists in the measurement because it is impossible to relate the detected photons to their position within the pulse. However, advances in both laser and electronic technology continued such that within ten years the best systems were obtaining single-shot precisions of a few centimetres. During the mid 1990's it became clear that a coherent organisation was required to address the many

demands for mission support that were being placed on the rather loosely-organised international SLR network. The International Laser Ranging Service was formed in 1998, based on the successful model adopted by the International GPS Service (IGS) several years earlier. The ILRS comprises a Central Bureau, the Tracking Stations, two Data Centres, Analysis and Associate Analysis Centres and an elected Governing Board (GB). The GB in particular has responsibility for recommending to the ILRS tracking network that it track a given set of satellites. With such a recommendation, the Data Centres are committed to archiving the observations and (a subset of) the Analysis Centres to producing orbital predictions for distribution to the network. Tracking support for new missions is solicited by making an application to the ILRS based upon the scientific needs of the proposed mission and the technical feasibility of the required support. The GB makes a decision, following recommendations provided to it from the ILRS Missions and Analysis Working Groups. An application form for the process is available through the ILRS website (http://ilrs.gsfc.nasa.gov)

Technique.

The technique of SLR is, in principle, very simple. Short pulses of laser light are emitted from a telescope that is driven to follow the predicted position of an orbiting satellite, the time of emission is accurately recorded and an interval counter is started. Each pulse of light reaches the corner-cube retro-reflectors on the satellite, and is directed back towards the telescope. Upon receipt of the reflected laser light, a high-speed detector generates an electronic signal that stops the interval counter, thus recording the round-trip time of flight. Half this time of flight multiplied by the speed of light gives the range to the satellite at the emission time of the laser pulse, also known as the epoch of the observation.

Given the objective of making range measurements to a precision of a few millimetres, it is straightforward to estimate the precision with which the epoch of an observation must be recorded. The speed of a typical geodetic satellite in its path around the Earth is about 5 km s^{-1}, or 5×10^6 mm s^{-1}. Thus the epoch should be recorded to a precision of better than a microsecond. To achieve this precision, most stations record observational epochs with respect to the timescale broadcast by the Global Positioning System (GPS), which is precisely related to and closely aligned with Universal Time (UTC). The range measurement itself must, of course, be made to the required precision of a few millimetres, which, in terms of two-way measured time of flight, is equivalent to a precision of better than about 20 picoseconds (20 ps = 20.0×10^{-12} s). In order to convert this measurement precision into measurement accuracy, range calibration measurements are frequently carried out to a nearby reflective target-board, whose accurate distance from the invariant point of the ranging telescope has been independently surveyed. The calibration measurements are used to determine the sum of the internal electronic and optical-path delays in the ranging system, which is then removed from each raw range observation during a pre-processing stage of data reduction.

Tracking Stations.

There are currently more than 35 active SLR systems in the worldwide network, regularly contributing observations to the data centres, from where they are rapidly available to the analysis community. Many of these instruments routinely achieve a normal point range precision of better than 1 cm rms. Many of the systems are associated with geodetic and astronomical stations, which also operate other geodetic systems such as permanent GPS receivers, DORIS beacons, VLBI antennae and gravimeters.

The geographic distribution of the current (2002) ILRS tracking network is shown in Figure 1, taken from the ILRS website. As is apparent, the distribution of tracking stations is not ideal, but has improved significantly during the last few years, with new stations being established in Australia (Mount Stromlo), South Africa (Hartebeestoek) and Chile (Concepcion). The clustering of stations in Europe, forming the ILRS sub-network named EUROLAS, is in fact an advantage, with sometimes conflicting tracking support being shared amongst the component stations. A further advantage which has been exploited and which will be discussed later in this report is the use of SLR measurements obtained quasi-simultaneously by several of the EUROLAS stations.

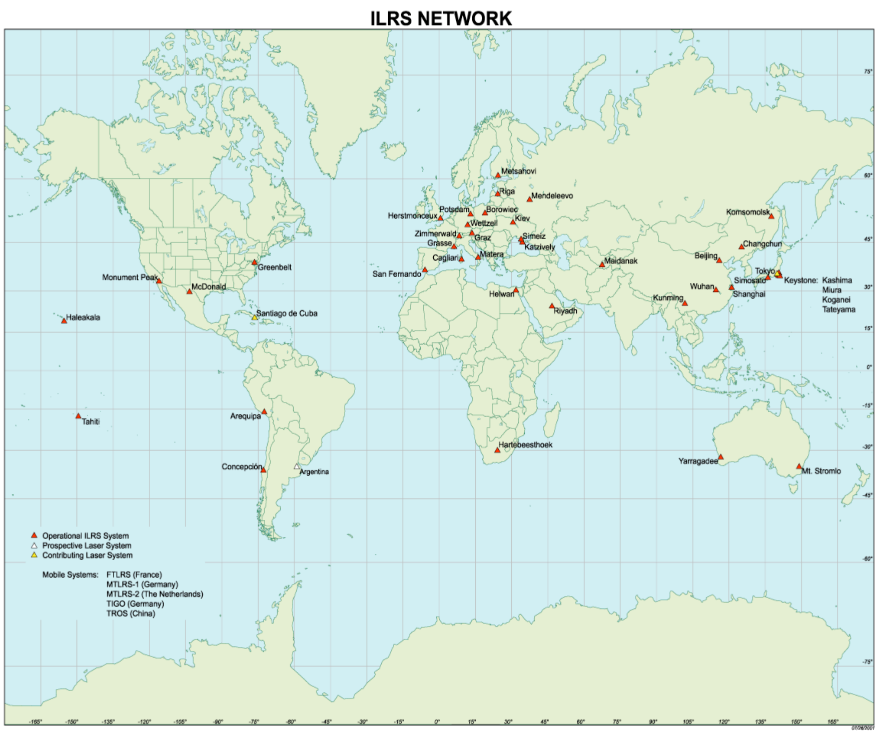
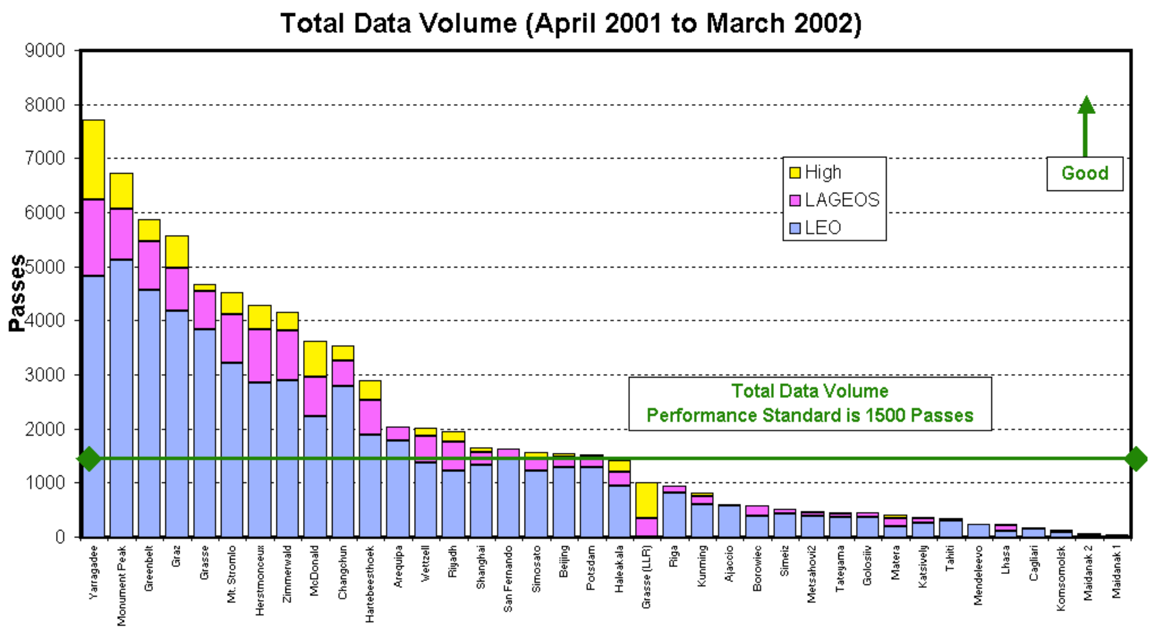
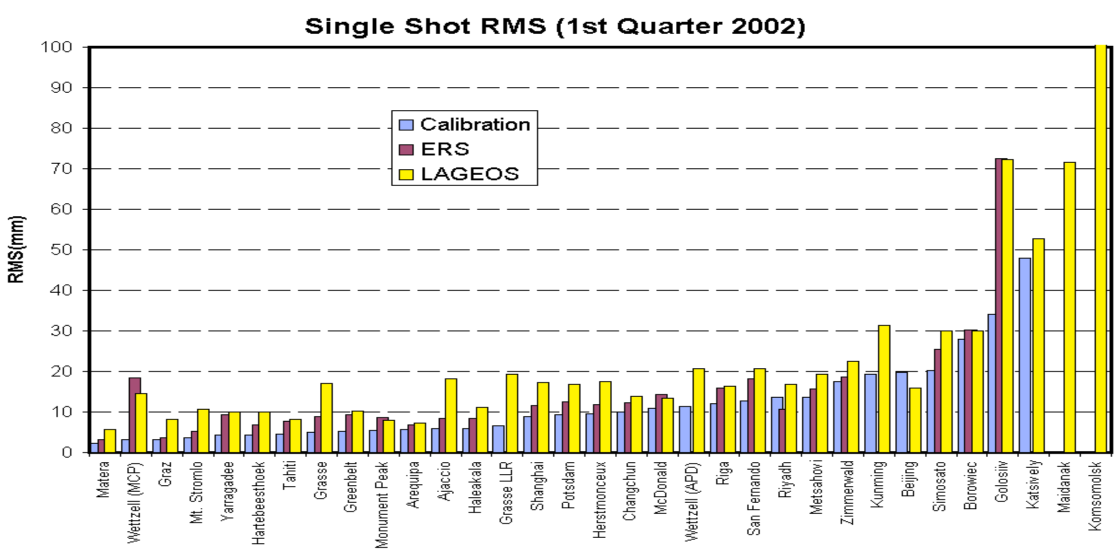


Figure 1. The ILRS Tracking Network.

Not all of the ILRS stations are of equal productivity or produce data of comparable quality. The ILRS sets criteria that all stations should aspire to and to reinforce this requirement the CB regularly produces 'league tables' showing the current ranking of all the stations in terms of their productivity and data quality.

Shown in Figures 2 and 3 are recent ILRS productivity and ranging precision charts. The productivity results are based on numbers of passes of high satellites (GLONASS & GPS), LAGEOS (I & II) and LEO (all gravimetric, altimetry & SAR satellites) that were obtained by each station. The results on precision give the single-shot RMS (mm) on average obtained by each station during calibration, ERS-2 and LAGEOS ranging. As expected, the precision decreases for most stations as the laser retro-array size increases from the usual single-cube or flat board calibration target, through the small cluster on ERS-2, up to the 60cm-diameter LAGEOS sphere.





Figures 2 & 3. Tracking Station League Tables.

<u>Satellites.</u>

Some twenty-five satellites are routinely tracked by the worldwide network of tracking stations, for a variety of scientific applications. The satellites fall into three main classes: geodetic, applications and navigational. In addition, currently two stations routinely make laser range measurements to the Moon.

The geodetic satellites are small, spherical and inert, containing a high-density core and a surface uniformly covered with corner-cube retro-reflectors. They are designed to have a small area to mass ratio to minimise accelerations due to non-gravitational forces such as from solar radiation pressure. The principal geodetic satellites are the two LAGEOS' at heights of 6000Km. They are extensively used for geocentric terrestrial reference frame determination, Earth rotation and for determination of and monitoring changes in low frequency terms in gravity field models.

The applications satellites are large, irregularly shaped and carry a large number of remote-sensing devices as well as solar arrays for generating power. The principal active satellites in this class are ERS-2 and ENVISAT, the US Navy GEOSAT Follow-On (GFO-1), and TOPEX/POSEIDON and its follow-on mission, JASON-1, joint French-USA altimetry satellites. A further class of applications satellites that require SLR support are the gravity field missions of CHAMP (450 Km) and the two GRACE satellites (500 Km). These satellites require precise tracking to calibrate their altimetry observations and to assist in precise orbit determination.

The role of SLR in navigation satellite support is mainly confined to an independent check on the quality of the orbital information derived by the radio-metric tracking systems. To enable this work two of the constellation of GPS satellites and all the satellites of the Russian GLONASS system, which orbit at altitudes of 20,000Km, carry retro-reflector arrays.

Because of the different heights of all these satellites, their times of visibility during which range observations from a given tracking station can be attempted varies from two minutes or so for the low CHAMP, to 40 minutes for LAGEOS, to five hours for the high-altitude ETALON, GPS and GLONASS satellites. Tracking station schedules are usually based upon the times of passes of the `primary' satellites such as LAGEOS, ERS-2 and ENVISAT, but modern systems can rapidly switch from tracking one satellite to tracking another to maximize their operational efficiency. Shown in Table 3 for illustration is the daily number of passes of ERS-2 tracked by the ILRS network during the week of 2002 June 24-30. Tabulated for each station is the number of passes obtained each day and the weekly total number of passes (Pass) and number of observational normal points (Obs). Normal points are formed at the stations by compressing raw data into (for ERS-2) 15-second bins.

Station	Name	24	25	26	27	28	29	30	Pass	Obs
1824	Kiev	.	1	.	1	1	.	1	4	59
1863	Maidanak1	.	1	.	.	1	1	1	4	19
1864	Maidanak2	.	1	.	.	.	.	.	1	5
1870	Mendeleevo	.	.	.	1	.	.	1	2	17
1873	Simeiz	1	2	.	2	2	.	2	9	94

1893	Katzively	.	.	.	.	.	.	1	1	8
7080	McDonald	.	.	.	.	.	3	2	5	34
7090	Yarragadee	1	2	.	1	1	2	.	7	177
7105	Greenbelt	3	1	2	2	.	1	2	11	177
7110	Mon Peak	2	.	1	1	1	2	1	8	118
7124	Tahiti	.	.	.	1	1	.	.	2	29
7210	Haleakala	.	.	.	.	1	1	1	3	31
7237	Changchun	2	1	2	2	1	1	2	11	152
7403	ArequipaT3	1	.	1	1	3	.		6	60
7501	Hartebeest	2	3	2	2	1	.	.	10	134
7810	Zimmerwald	.	1	3	1	.	3	1	9	99
7811	Borowiec	1	1	1	.	.	.	.	3	33
7824	S.Fernando	1	2	.	1	.	.	.	4	34
7832	Riyad	2	2	1	.	.	1	2	8	114
7835	Grasse	2	2	.	2	.	1	.	7	172
7836	Potsdam	1	.	1	1	.	.	.	3	49
7839	Graz	1	.	2	2	.	2	3	10	220
7840	Herstmon	3	3	1	3	1	1	.	12	140
7849	Mt.Stromlo	3	2	.	.	1	1	.	7	69
8834	Wettzell	.	2	1	1	.	.	.	4	44
Daily	Totals	26	27	18	25	15	20	20	151	2088

Table 3. ILRS Network Pass Statistics for ERS-2 for the Week 2002 June 24-30.

Environmental Corrections.

It is frequently quoted that SLR is a very 'clean' technique, meaning that, provided care is taken to estimate system internal electronic delays through frequent calibrations, range precision is not compromised by having to estimate environmental effects during processing. The atmospheric delay on the transmitted and returning laser pulse as it passes through the atmosphere equates to a zenith range correction of about 2m, increasing to some 10m at an elevation of 20˚. An expression for the delay is usually derived in the form of an integral of the group refractive index of the atmosphere, the refractivity itself being a function of the laser wavelength, the total atmospheric pressure, the temperature and the partial water vapour pressure. Meteorological measurements can be made at the observing station, from which their values are estimated at each point along the light path using a simple model of atmospheric temperature lapse rate, etc. It is then possible to integrate the refraction equations and derive an expression from which the refraction delay may be computed as a function only of station meteorological values and laser wavelength. The standard model in use for analysis of laser ranging observations is that of Marini and Murray. Provided that atmospheric pressure is measured at the site to an accuracy of better than 0.2mb, it has been shown that the model is accurate to better than 10mm for zenith angles of from zero to 70°.

Predictions and Data Availability Cycle.

In the long term the range data secured by the global network of laser ranging stations are archived in ILRS Global Data Centres. Identical data sets are maintained at the Crustal Dynamics Data Information System (CDDIS) in Washington and the EUROLAS Data

Centre (EDC) in Munich. They are then freely available via FTP transfer to anyone who wishes to use them. For the particular purpose of maximising the data yield from the network, in terms both of quantity and quality, observing stations, data centres and analysis centres collaborate closely in a daily cycle of data transfer and data processing, with the end result that predictions are supplied daily or sub-daily to the stations and compressed, fully-corrected data reaches the analysis community within hours of the observations being made.

Rapid MEO SLR Orbits.

Given this rapid availability of range data from the ILRS network, it is possible to compute SLR-only orbits for most of the satellites on a daily basis to a 3D accuracy of perhaps 30cm. In the absence of up-to-date geophysical information, non-gravitational forces are modelled empirically and corrections estimated to Earth orientation parameters, the whole process being fully automated. In addition, for those passes that are tracked quasi-simultaneously by two or more good SLR systems say from the EUROLAS cluster, a short-arc correction can be computed and applied to the MEO orbit determination. In this way, orbits precise to better than 10mm radially during the time-period of tracking can be estimated and used for calibration/validation of altimeter measurements, as a check on ranging precision and as an independent, rapid check on MEO orbits determined say from DORIS or SXO. An example of post-fit residuals from a short-arc solution for ENVISAT is shown in Figure 4.

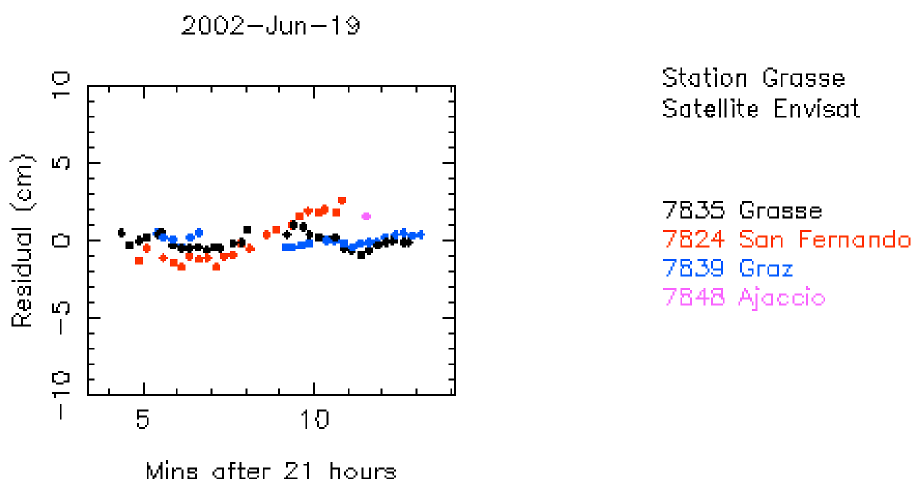


Figure 4. Residuals from a short-arc ENVISAT orbital solution for four stations.

Future Development

From the international organisational point of view, the ILRS looks set to become one of the Services, along with IGS, IVS (for VLBI), IERS, PSMSL (mean sea level), IDS (probably, for DORIS), of the International Association of Geodesy. Funding of individual ILRS components, of course, remains the responsibility of agencies and governments within individual countries. From a business point of view, there appears to be no reduction in the number of new missions that will require SLR tracking support, with ICESAT, ADEOS-2, CRYoSAT and GOCE all scheduled for launch within the next two years or so. Technologically, the greatest improvements are likely to be in the tracking stations themselves, with the anticipated field trials during 2002/2003 of the NASA 'SLR2000' prototype system. This autonomous, eye safe, high repetition rate system is expected to replace the NASA tracking systems and to be generally available for purchase from about 2004 onwards. The advantages of a network of such systems are their homogeneity and the potential elimination of system-dependent range bias problems that continue to affect some systems in the current network. Although the single shot precision of the SLR2000 system will be no better than the best systems in the current network, the high repetition rate and absence of bias will ensure mm-level normal point precision.

2.2 DORIS

DORIS is an acronym for Doppler Orbitography and Radiopositioning Integrated by Satellite. The system was developed by the French groups CNES (Centre National d'Etudes Spatiales), IGN (Institut Geographique National) and GRGS (Groupe de Recherche en Geodesie) for scientific and operational requirements in precise orbit determination. The DORIS on-board equipment first flew on the SPOT 2 Earth observation satellite launched in February 1990. Subsequent launches carrying DORIS include all SPOT satellites, TOPEX/Poseidon, launched in August 1992 and still operational, the TOPEX/Poseidon follow-on, Jason-1 and ENVISAT (Guijarro et al, 2002). The ground segment is shared by all DORIS missions. DORIS now has over a decade of success behind it.

The system is based on a permanent network of beacons that provide a ground-to-satellite relative velocity based on the Doppler principle of a satellite equipped with the necessary onboard hardware. Current onboard receivers acquire a measurement every 10sec. At the moment the DORIS network comprises of about 60 beacons hosted by institutes in more than 30 countries. A plot of the beacon locations for the JASON-1 satellite altitude is given as Figure 5. Note that visibility circles effectively cover the Earth's surface with the satellite in range of a beacon for about 85% of the time. Visibilities could be increased down to the horizon but, as for GPS, it is customary to disregard the low elevation data due to contamination by thermospheric effects.

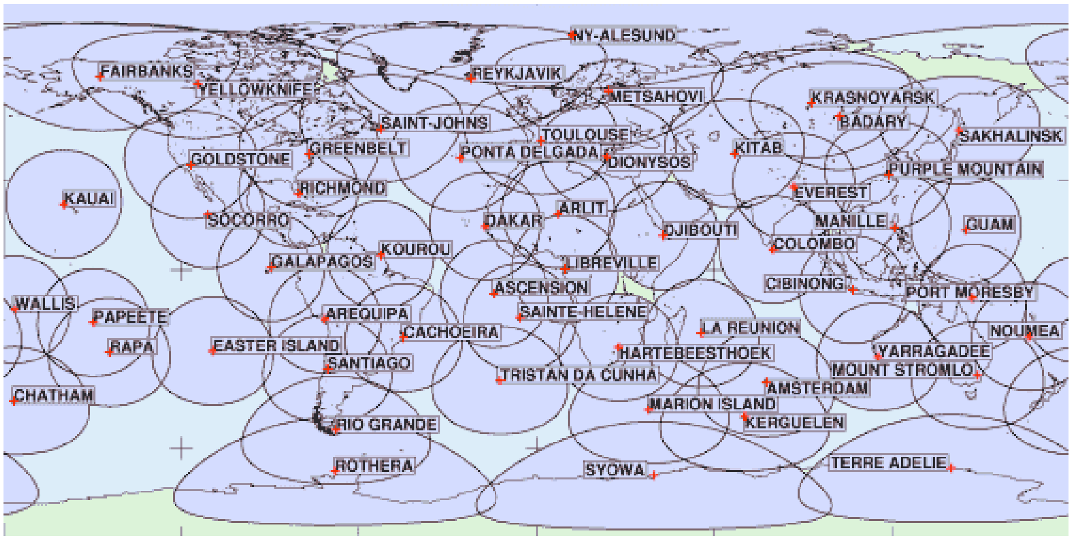


Figure 5. Doris Network of Orbitography Beacons and their Spatial Coverage (CNES).

Each continuously transmitting beacon emits a dual frequency signal at 401.25 and 2036.25 MHz to permit recovery of the ionospheric propagation effects in the standard manner. The beacon hardware consists of an ultra-stable oscillator, an omni-directional antenna, a battery pack for autonomous power and a meteorological package for measuring temperature, pressure and humidity as required for tropospheric corrections to the derived range-rate. Each beacon transits the dual frequency signal, beacon identifier, meteorological data and time-tag. Two master beacons at Toulouse, France and Kourou (French Guiana) are connected to the control centre to permit both uploads to the onboard system and synchronisation of the DORIS system with International Atomic Time (TAI). The DORIS control and processing centre at Toulouse also monitors the beacon network and onboard system and coordinates telemetry downloads, pre-processing and archiving.

The onboard payload consists of a dual frequency receiver that measures the frequency of each channel signal and the time of the reception. Beginning with Jason-1 and SPOT5 the onboard payload will be able to perform self-synchronisation and self-initialisation. New 3.0 beacons will contain the TAI time in their signal, which will be used to synchronise the onboard clock.

DORIS provides a global tracking data set for MOE and POE computations (Vincent et al, 2001). However, DORIS can also supply RTE when onboard management of DORIS is combined with a real-time orbit determination process, DIODE (DORIS Immediate On-board orbit Determination). DIODE is a software package that processes the up-link Doppler measurements received by the onboard DORIS segment. DIODE was first used on SPOT4 in 1998 with a 99.5% availability and reliability over a 3-year period. A second generation DIODE is integrated on SPOT5, Jason-1 and ENVISAT. In the second generation phase measurements replace the Doppler measurements. Real time orbits can be combined on the ground to produce Operational Science Data Records available within 3hrs. To reduce onboard computation time a simplified force model and state vector of adjusted parameters is coded. For example, the gravity field is restricted to degree and order 40. DIODE computes positions and velocities with TAI datation at 10sec intervals.

DIODE comprises a numerical integrator with associated force mode including an appropriate simple macro model of the surface structure (e.g. box-wing model for satellite and solar-panel) to compute position/velocity every 10sec. A measurement model processes the received beacon signals and eliminates the ionospheric effect using the dual frequencies. A Kalman filter procedure then utilises the DORIS data to refine the state vector, which includes position, velocity and the frequency bias and correction to tropospheric delay for each pass over a beacon.

The First Generation DIODE of SPOT4 has proved very robust and achieved near 6m accuracy well within the 100m rms and 200m maximum error requested for each component. The Second Generation represents a considerable improvement (Jayles and Rozo, 2002). The size of the program is some 7500 lines of code requiring 75Kb of memory. This enhancement has been implemented at CNES with measurements from TOPEX/Poseidon. Comparisons against the POE (2-3 cm rms accuracy) show that DIODE is near 30cm rms in accuracy. The radial component has near 5cm error rms with a maximum value of 20cm. Such results were obtained on a 64-bit workstation. With the current onboard processor a numerical degradation is expected to result in a radial rms error of about 13cm. Of course improvements in numerical precision or more likely the use of a higher specification processor onboard would achieve the higher accuracy results.

Table 4. Comparison of DIODE RTE against POE for TOPEX/Poseidon cycle 232. Results from Jayles et al (2000). Results obtained on 64-bit workstation. Actual on-board processor for Jason-1 equates to about 13cm rms error in radial direction.

	Minimum (cm)	*Maximum (cm)*	*Average (cm)*	*RMS (cm)*
Radial	-21.4	20.6	0.1	5.1
Along-track	-65.0	88.1	7.8	17.2
Across-track	-86.9	92.2	0.1	25.3

2.3 PRARE

The GFZ/Dornier system PRARE is a space-borne, two-way, two-frequency microwave satellite tracking system that has been in routine operation onboard the second European Remote Sensing satellite ERS-2 since May 1st, 1995. PRARE onboard ERS-2 has produced up to 50 000 once-per-second range measurements per day, which show a mean measurement accuracy between 2.5 and 6.5 cm (two-way range data) and 0.1 mm/s (two-way range-rate data) respectively. PRARE downlinks a X-band carrier of 8489 MHz and a S-band carrier of2248 MHz. Ground transponders follow the satellite across the sky, process the ionospheric propagation from the dual frequencies, with that and other parameters uplinked via a X-band carrier of 7225.296 MHz. Apart from the ionospheric delay from the quasi-simultaneously transmitted X- and S-band signals, the hardware signal delay and meteorological measurements for computation of the tropospheric refraction index are uplinked from each transponder.

The space-borne segment on ERS-2 has four independent channels allowing uplink from four ground stations. Each channel tracks the selected station automatically as long as visibility is maintained and carries out the range and range-rate measurement. The latter are determined by integrating over 30sec intervals. In total about 30 ground-stations were deployed of which 12 were in Germany mainly for operational and experimental reasons. In practice, a maximum of about 18 were available in 1997 for orbital computations supplying about 90 passes of range and range-rate data. Operational difficulties related to the robustness of the ground stations particularly with the moving antennae and attached cables reduced this number to 8 or lower for 1999 onwards. Furthermore, there are no clear plans to place PRARE onboard any future launches. PRARE, as a system, inherently has, the edge over DORIS for orbital work, particularly as it yields a range measurement, but that is offset by the comparative records of the two tracking systems particularly in terms of robustness, economy and autonomy. Further, DORIS is a truly global network. The French offer, and ESA’s acceptance, of DORIS for ENVISAT probably means that PRARE is consigned to history.

2.4 GPS

GPS receivers have been flown on several satellites including TOPEX/Poseidon. As for standard receivers, space GPS can be single frequency code receivers or geodetic quality receivers utilising phase and code and the two frequencies. The former are applicable for geolocation to say 30m but an ocean current mission will require the centimetre or at worst sub-decimetre accuracy of the latter. Under that proviso we restrict our discussion to the “BlackJack” receiver developed by the Jet Propulsion Laboratory (JPL). JPL's BlackJack GPS receiver is a high-precision space-rated GPS receiver with dual-frequency tracking capability. BlackJack is an unclassified receiver, and uses a patented codeless processing technique that allows it to utilize the P-code signal without knowledge of the encryption Code and is controlled through flexible and versatile software implementations of BlackJack. GPS flight receivers are, or will be, used on the following space missions: SRTM (2000), SAC-C (2000), CHAMP (2000), JASON-1 (2001), VCL (2003), FEDSat (2001), ICESat (2002), and GRACE (2002). The BlackJack receiver on CHAMP (Kuang et al, 2001) weighs 3.5kg and uses less than 10W.

A low orbiting satellite and each spacecraft of the high orbiting GPS satellite configuration establish a so-called high-low satellite-to-satellite (SST) link. Each of the GPS spacecrafts is transmitting a PRN modulated L1 and L2 signal which the BlackJack receiver onboard the low satellite acquires for a maximum of 12 satellites at the same time. From these signals the orbiting receiver generates at a frequency of 0.1 Hz pseudo-ranges and carrier phases for all satellites that were in lock at this time instant. By using pseudo-ranges from at least 4 different GPS space crafts with known ephemeris at the same time, both the three-dimensional coordinates of the low satellite receiver and their respective change with time can be solved for, thus a navigation solution is obtained. In addition, BlackJack solves for the offset between the GPS receiver time and the GPS time in order to provide an extremely accurate synchronisation pulse for the onboard subsystem. The accuracy of the navigation solution depends on the availability of the classified P-code inside the receiver and the satellite constellation used for coordinate determination and can range down to a few meters after post-processing. With the less precise but unclassified C/A-code an accuracy of several tens of meters is still obtainable after post-processing. By making use of the much more precise carrier phase tracking data and a simultaneous full dynamic solution for the orbits of the GPS satellites, corrections for reference frame and dynamic and measurement model parameters, high accuracy results for the low satellite will be achievable.

For BlackJack, the time calibration accuracy is better than 1μs from GPS time with resolution 0.1 ns. The dual-frequency range and integrated carrier at 1s intervals for precise orbit determination has precision

- Phase (ionosphere-free) < 0.2 cm
- Range (ionosphere-free) < 30 cm

JPL are developing a space borne real-time orbit determination capability, both in terms of the hardware and software. In terms of software, RTG (Real Time GIPSY) is being developed as a real time version of their GIPSY-OASIS software (Bar-Sever, 2002; and http://gipsy.jpl.nasa.gov/igdg/system/). RTG will be used on the ground to compute real-time estimates of the GPS space craft orbits, 1s GPS clock corrections and tropospheric delay parameters for a ground based network of dual-frequency receivers relaying data to JPL in real-time. The differential corrections are subsequently packaged for relay to other users either through the Internet or via three Inmarsat geosynchronous communication satellites. The former uses both broadband connections and telephony including wireless telephones as in the Iridium system. Alternatively, Inmarsat will relay the correction packages for global availability on L-band for reception anywhere on land, in air or space. Special Navcom hardware is needed to receive the Inmarsat L band. The three geosynchronous satellites provide coverage between latitudes 75°N and 75°S. Beyond these latitudes the Iridium system must be used. The Iridium system has be shown to be fairly reliable in terms of internet connectivity and is being tested in operation by flights over Greenland.

Table 5. RTG accuracies for BlackJack GPS receivers with L-band correction

Satellite	Altitude (km)	Radial rms (cm)	Cross-track rms (cm)	Along-track Rms (cm)
Jason-1	1340	7	5	17
CHAMP*	450	11	8	26

* Deduced from CHAMP 30cm 3D rms and Jason-1 coordinate accuracies

JPL is developing the necessary hardware for dual GPS and L-band Inmarsat capability and will test RTG on the orbiting Argentine satellite SAC-C. SAC-C carries BlackJack but does not have the L-band reception capability. An assessment of the RTG system has been performed by JPL on the ground using GPS data from the BlackJack receiver on Jason-1. Utilising the real-time orbits and clocks as available from RTG, the 'real-time' orbital errors for Jason-1 on utilising the L-band correction stream is summarised in Table 5 relative to POE orbits that are sub decimetre accurate in 3D rms. These results are pertinent to a low Earth orbiter at 1300km altitude and are lower bounds for missions at lower altitudes. Similar simulations with CHAMP at an altitude of 450km gave 30cm 3D rms accuracy are also included in the table.

For POE/MOE experience with CHAMP presents the best evidence of appropriate methodology and accuracy. CHAMP is the first geodetic-quality space-rated (BlackJack) receiver in a low Earth orbit of 450km. As part of the IGS LEO Pilot Project analysis centres were invited to submit precise orbit solutions for a 10day trial period. 13 analysis centres accordingly responded. The CHAMP Orbit Comparison Campaign was coordinated at ESOC with the aim of analysing precise orbit solutions from the different centres. Objectives of the Orbit Comparison Campaign included

- To offer external reference orbits for all centres involved in CHAMP POD and the IGS LEO Pilot project in general, so that any remaining systematic errors can be easily identified
- To obtain insight in the status of CHAMP POD and assess precision levels

Extensive analysis, re-analysis and comparisons lead to the following conclusions

- The only point-positioning solution had to be excluded for lack of precision. After one year of CHAMP POD: (reduced-) dynamic solutions have become clearly superior to point-positioning solutions, while most people expected the opposite.
- The most accurate 3D positioning is 7-8cm rms.

Given that CHAMP is at a lower altitude than an "Ocean Currents" mission, POE/MOE for a candidate satellite carrying a BlackJack or equivalent GPS receiver should yield 3D rms positioning at about 5cm. It is interesting to note that for Jason-1 POD first validation results at CNES [2002-04-24] give the agreements summarised in Figure 6. Note the excellent coherence of the different orbit determinations, though obtained with various types of observations. ELFE is the reduced-dynamic solution that is utilised on the GDR. One can conclude that DORIS and GPS yield orbits of comparable accuracy and that the MOE orbits for a satellite at 1340km are of 2-3cm radial accuracy rms.

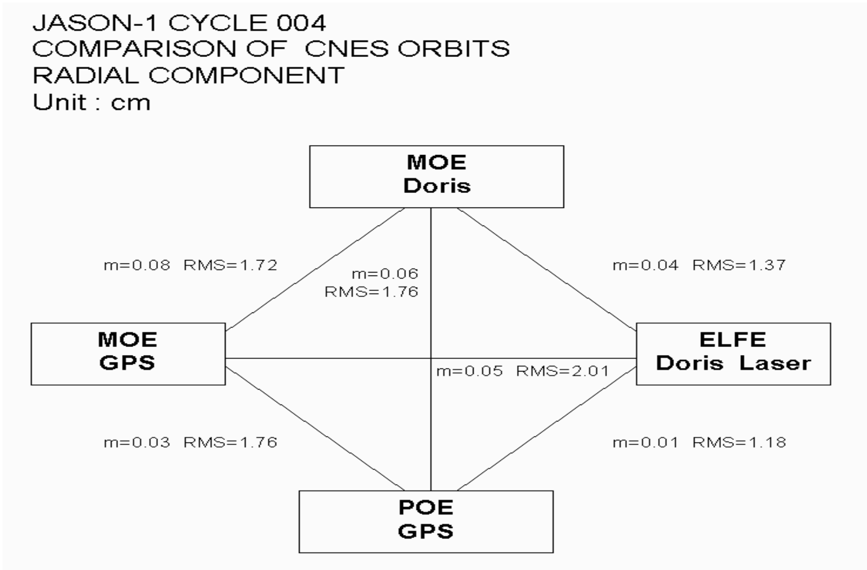


Figure 6. Jason-1 POD first validation results (CNES).

2.5 Single and Dual Satellite Crossovers

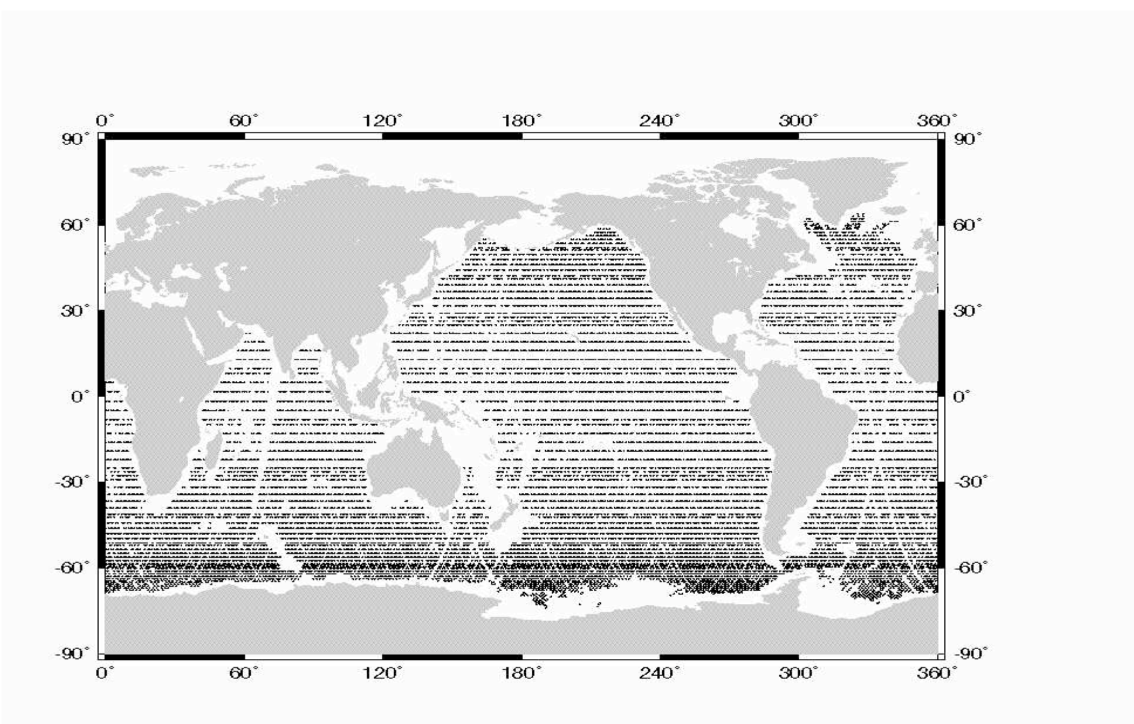
Altimetric crossovers occur at the intersection points of altimeter satellite ground tracks. In the case of single satellite crossovers (SXO) both tracks pertain to a particular satellite and the crossovers are located at the intersection of an ascending and descending arc. A dual satellite crossover (DXO) involves two satellites with a ground track from one crossing that of another. A crossover difference is, as the name suggests, the difference of the altimetric heights of the two measurements. The respective heights will have different time datation, which for SXO data ranges from just over a single orbital period to half the repeat cycle. The strength of crossover differences lies in the fact that geographically correlated terms in both measurements will cancel. In particular, the geoid height (or equivalently mean sea-level height), which is the greatest source of uncertainty, is eliminated in a crossover difference. The remaining difference is a measure of the variability in the components of the altimetric range between the two epochs. If the epochs are restricted to be close (i.e. within 5-10 days) the ocean variability will be small and the crossover residual effectively quantifies the error in the respective normal heights as determined by precise orbit determination. However, alongside the geoid height any other geographically correlated signal will be unobservable. Thus, for SXOs, the geographically correlated orbit error is unobservable with the SXO residual dominated by twice the anti-correlated error, namely the component of the orbital error that changes sign from ascending to descending arcs. For DXOs, it is usual to combine a higher accuracy orbit (e.g. TOPEX/Poseidon) with one of lower accuracy. In that case the less accurate orbit dominates the residual. The crossover difference can then be interpreted as a tracking data type that provides a measure of the normal height difference between the (lower) less accurate orbit and the (higher) reference orbit. Figure 7 plots the SXO and DXO (with TOPEX/Poseidon) locations for cycle 49 of the ERS-2 35day repeat orbit. A maximum time difference of 10 days has been utilised. An almost complete global coverage is evident.

SXO and DXO data provides an important mechanism for refining the less accurate orbit to a level not far short of the reference orbit. The crossover data can either be used as an additional tracking data type in a precise orbit determination or a correction to the less accurate orbit can be derived by a cubic-spline fit through the residuals. Both are powerful techniques. The latter has the advantage of simplicity with the enhanced orbit rendered consistent with the reference orbit. The former permits the extension of the state vector to incorporate short-term drag scale factors (e.g. every quarter revolution) to absorb uncertainty in the force model. In both cases the crossover residuals in the POEs are reduced to a level not far short of that of TOPEX/Poseidon. Computations at Newcastle, by Lemoine and Zelensky (2001) and from the AVISO expert system reports for TOPEX/Poseidon yield

- Reduced dynamic Topex/Poseidon orbits: SXO residuals 6-7cm
- GFO (ERS) orbits: SXO residuals ≈ 7.5 (7.8) cm
  DXO residuals ≈ 7.0 (7.6) cm

Which compare favourably with the SXO residuals of Table 2.

The current radial positioning accuracy of 2-3 cm rms for TOPEX/Poseidon plus other errors in the geophysical corrections yields crossovers of 6-7cm rms. Use of SXO and DXO data for GFO and ERS yields corresponding SXO residuals of near 7.5cm, which equates to an orbital error of just 5cm radially. Given that SXO residuals are typically 9-10cm (see Table 2) if such data is not used within the orbital computation, the use of SXO and/or DXO data reduces the radial orbit error from 7-8cm to about 5cm.



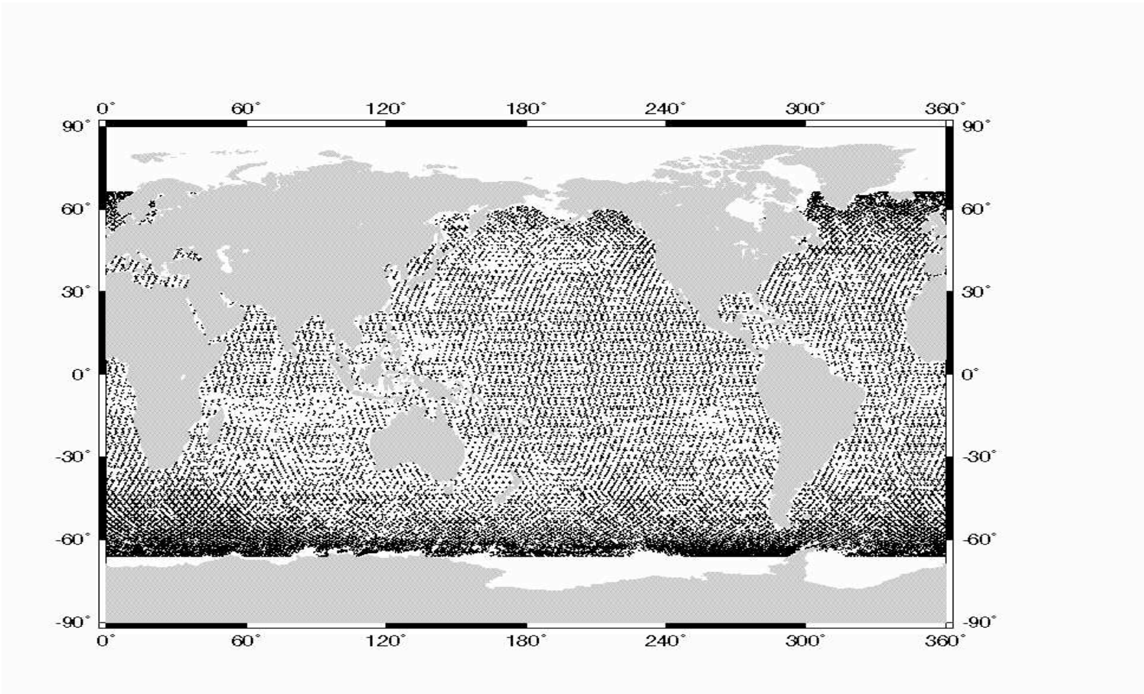


Figure 7. ERS-2 single satellite crossover locations (upper) and dual ENVISAT-TOPEX/Poseidon (lower) crossover locations with epochs separated by 10 days or less

2.6 Inter-satellite Ranging Systems

An inter-satellite range/range-rate measurement system is a key instrument if the baseline between a tandem pair of satellites is crucial to the scientific or operational output. Several systems including inter-satellite laser ranging and microwave devices have been proposed. The former is potentially more accurate but the technology is unproven. The latter is the key science instrument of the Gravity and Circulation Experiment (GRACE), which was launched March 2002. GRACE is a tandem pair of satellites with a K-band ranging (KBR) system to measure the one-way range change between both satellites with a precision of about 1μm per second. The hardware consists of a single horn antenna for transmission and reception of the dual-band (24 and 32 GHz) k-and ka-band microwave signals; an ultra-stable oscillator (USO) serving as a frequency reference; a microwave assembly for up-converting the reference frequency, down-converting the received phase from the other satellite to approximately 2 MHz and for amplifying and mixing the received and the reference carrier phase; and an instrument processing unit (IPU) used for sampling and digital signal processing of the k-band carrier phase signals and the data of the GPS space receiver and the star camera assembly (SCA). The SCA gives the required orientation of the space-craft in space.

Both KBR systems on the GRACE-A and GRACE-B satellites are completely identical, except in frequencies, which are shifted by 500 KHz to avoid cross-talk between transmitted and received signals and to offset the down-converted signal from zero frequency. Each satellite transmits carrier phase signals on two frequencies allowing for ionospheric corrections. The 10 Hz samples of the phase change at the two frequencies for each satellite are down-linked to ground. The appropriately decimated linear combination of the sum of these phase measurements at each frequency gives the ionosphere-corrected measurement of the range change between the satellites. To reduce measurement errors, the KBR temperature has to be controlled to 0.2 K. Additionally multipath effects are reduced by stringent spacecraft pointing requirements (< 1 mrad) and representative antenna and spacecraft front panels.

KBR can be used in MOE and POE to position absolutely and relatively a tandem pair of satellites. Although designed primarily for gravity field refinement the system is capable of determining inter-satellite baselines and angles to a higher accuracy than achievable with conventional tracking.

2.7 Summary of POE, MOE and RTE Accuracies

Accuracy, is currently a function of latency, tracking availability and altitude of the satellite. In Table 6 we attempt to summarise the expected radial accuracy for satellites at the altitudes of TOPEX/Poseidon and ERS for different data types and latency. These results are based on experience and published results but some caution must be exercised, as several configurations are currently untried while others are based on simulations that may not be as accurate in reality. DORIS or GPS provide the global tracking data stream with SLR as insurance, calibration tool and for rapid independent orbit validation. For an Ocean Current Mission involving an altimeter, SXO and DXO data with a high accuracy orbit such as Jason-1 will provide additional data, which, used in combination with SLR, can produce orbits of accuracy not far short of those of the reference satellite.

Table 6. Best estimate of rms radial accuracy for Precise Orbital Ephemeris (POE) of latency a few weeks; Medium Orbital Ephemeris (MOE) of latency 2-3 days and Real Time Ephemeris (RTE).

Altitude (km)	Tracking	POE (cm)	MOE (cm)	RTE (cm)
1340	SLR, DORIS	2	3	
	SLR, GPS	2	3	
	DORIS (DIODE)			7*
	GPS (RTG)			8
800	SLR, DORIS	4-5	5	
	SLR, GPS	4-5	5	
	SLR, Altimetry	5-6	7	
	DORIS (DIODE)			11*
	GPS (RTG)			11

* 64-bit processor

3 Application to Proposed Methodologies

The section considers each of the proposed "Ocean Current" methodologies in terms of orbital positioning. To facilitate cross-reference with each proposal, details are given in full even if, as for the altimeter-based missions, the details are identical.

1. ***Altimeter Microsats at say 600-800km altitude***.

Requirement: Radial positioning sub-decimetre, 1-10cm
Geolocation 10-100m

Comment: Altimeter microsats are analogous in requirements to existing altimeter missions.

POE: 4-5cm radial accuracy achievable with DORIS or GPS (+ SLR).
Alternatively, SLR + altimetry can give near comparable results

MOE: 5-6cm accuracy achievable with DORIS or GPS (+ SLR).
SLR + altimetry can give near comparable accuracies but requires 'quick-look' altimetry, orbits etc for reference satellite(s)

RTE ~ 11cm accuracy achievable with DORIS (DIODE) or GPS (RTG)

Geolocation criterion satisfied for all latencies.

2. Broad beam or scanning altimeters (600-800km altitude)

Requirement: Radial positioning sub-decimetre, 1-10cm
Geolocation 10-100m

Comment: Broad-beam or scanning altimeters are analogous in requirements to existing altimeter missions.

POE: 4- 5cm radial accuracy achievable with DORIS or GPS (+ SLR).
Alternatively, SLR + altimetry can give near comparable results

MOE: 5-6cm accuracy achievable with DORIS or GPS (+ SLR).
SLR + altimetry can give near comparable accuracies but requires 'quick-look' altimetry, orbits etc for reference satellite(s)

RTE: ~ 11cm accuracy achievable with DORIS (DIODE) or GPS (RTG)

Geolocation criterion satisfied for all latencies.
Alternative low cost single frequency code GPS

3. ***Bistatic altimeters (600-800km altitude)***

Requirement: Radial positioning sub-decimetre, 1-10cm
Geolocation 10-100m

Comment: Bistatic altimeters are analogous in requirements to existing altimeter missions.

POE: 4- 5cm radial accuracy achievable with DORIS or GPS (+ SLR).
Alternatively, SLR + altimetry can give near comparable results

MOE: 5-6cm accuracy achievable with DORIS or GPS (+ SLR).
SLR + altimetry can give near comparable accuracies but requires 'quick-look' altimetry, orbits etc for reference satellite(s)

RTE: ~ 11cm accuracy achievable with DORIS (DIODE) or GPS (RTG)

Geolocation criterion satisfied for all latencies.
Alternative low cost single frequency code GPS

4a ***Across-track interferometers.***

Requirements: Relative inter-satellite baseline length to ~ 1m
Relative inter-satellite baseline angle to ~ 1°
Geolocation 10-100m

Comment: Baseline angle determined from star cameras or precise orbits

POE: ~ 10 cm absolute accuracy achievable with DORIS or GPS (+ SLR).
Positioning accuracy within baseline requirement

MOE: ~ 15 cm absolute accuracy achievable with DORIS or GPS (+ SLR).
Positioning accuracy within baseline requirement

RTE: ~ 30 cm absolute accuracy achievable with DORIS or GPS (+ SLR).
Positioning accuracy within baseline requirement

Geolocation criterion satisfied for all latencies.
Alternative low cost single frequency code GPS

4b Al***ong-track interferometers***

Requirements: Relative along-track separation to ~ 10 cm

Relative across-track/vertical separation to ~ 0.1 – 1.0cm
Geolocation 10-100m

Comment: Severe inter-satellite separation beyond conventional tracking techniques. Along-track separation is marginal for DORIS/GPS but cross-track requirement is unobtainable. Inter-satellite tracking allied with precise star cameras is required, e.g. K-band ranging (KBR)

POE: ~ 10 cm absolute accuracy achievable with DORIS or GPS (+ SLR).
Combined with KBR may give required along-track and across-track/vertical separations (more study required)

MOE: ~ 15 cm absolute accuracy achievable with DORIS or GPS (+ SLR).
Combined with KBR may give required along-track and across-track/vertical separations (more study required)

RTE: ~ Real time computations of positioning and inter-satellite separation would appear to be unlikely in real-time

Geolocation criterion satisfied for all latencies.
Alternative low cost single frequency code GPS

4 Conclusions

Work Package WP31: Orbital Studies has investigated past, present, and, for the case of inter-satellite tracking, near future techniques for tracking low Earth orbiters. Improvements in precise orbit determination for altimeter satellites over the past decade have been associated with

- Gravity field enhancement
- Orbit determination techniques introducing empirical/stochastic parameters for surface force and other modelling errors
- Improved accuracy and global distribution of tracking data e.g. DORIS, GPS
- Use of altimetry in the form of single (SXO) or dual satellite crossovers (DXO) as additional tracking data in both dynamic/reduced dynamic procedures and in empirical enhancement of less accurate orbit via cubic splines.

Orbital ephemerides for an Ocean Currents mission can be classified as precise (POE) computed with a latency of weeks; medium (MOE) with a latency of 2-3 days and real-time (RTE). Accuracy, at the date of writing, is a function of latency, tracking availability and altitude of the satellite. DORIS or GPS provide the global tracking data stream with SLR as insurance, calibration tool and for rapid independent orbit validation. For an Ocean Current Mission involving an altimeter, SXO and DXO data with a high accuracy orbit such as Jason-1 will provide additional data, which, used in combination with SLR, can produce orbits of accuracy not far short of those of the reference satellite. Table 6 summarises the expected radial accuracy for satellites at the altitudes of TOPEX/Poseidon and ERS for different data types and latency. Some caution must be exercised with these results, as several configurations are currently untried while others are based on simulations that may not be as accurate in reality.

The orbital accuracies constituent our understanding at the time of writing. Further developments in DORIS and GPS, particularly in RTE, are likely over the near future and gravity field solutions from the dedicated gravity field models will also help to reduce the quoted values.

Table 3 shows that SLR has the capability to deliver a large number of passes/observations for an Ocean Currents mission. However, such a mission, if financed by private means with products sold commercially, is a different proposition to the geodetic and science application satellites tracked to date. National agencies from the various countries sponsoring SLR may need persuasion to contribute to a commercial mission and their participation, under current agreements, cannot be guaranteed. DORIS would require cooperation from the control and processing centre at Toulouse with GPS similar support probably from JPL. Negotiations for hardware, software support and control and processing may well be the determining factor in deciding between DORIS and GPS as the orbital accuracies are comparable.

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