Progress in ERS Orbit and Tracking Data Analysis

R. Zandbergen(1), J.M. Dow, Near-Earth Navigation and Geodesy Section ESA/ESOC

F. Martínez Fadrique(2), M. Romay Merino(2) and R. Píriz(2) Robert-Bosch-Strasse 5, D-64293 Darmstadt, Germany

(1) Logica, London, UK

(2) GMV SA, Madrid, Spain

Abstract

This paper presents the activities over the last few years of the orbit determination and prediction systems for ERS-1 and ERS-2 at the European Space Operations Centre, concentrating on the operational support of the ERS missions, the evaluation of the precise tracking data of the two satellites and the calibration and exploitation of the altimeter instruments.

The operational highlights of the ERS-2 mission are presented briefly and the relative calibration of the ERS-2 radar instrument is discussed, taking a close look at the improved geophysical models used for processing the altimeter measurements. The precision of the altimeter measurements used as satellite tracking data is discussed, together with that of the S-band ranging and doppler and laser ranging data for both satellites, and the PRARE ranging and doppler data for ERS-2, demonstrating the success of this new tracking system.

The current state of the accuracy of the determined orbits is evaluated both for the routine operational and high-precision orbit solutions, using statistics of the precise tracking measurement residuals and internal and external comparisons of the orbit solutions.

Introduction

The ERS series of satellites has been designed for observing the Earth's oceans, coastal zones and ice-covered areas using a variety of radar instruments from an altitude of just under 800 km. One of these instruments, the radar altimeter, has played a key role in defining the required orbit determination accuracy for these missions. The use of the altimeter height measurements for determining the ocean circulation would only be possible if the radial orbit component could be determined with an accuracy of 10 cm for such a low orbit, with a similar requirement on the accuracy of the geoid model.

The European Space Operations Centre, responsible for controlling the satellites, has the task of providing the predicted orbit for operational purposes and the determined orbit with a minimum delay for the use in Fast-Delivery products of the scientific instruments. This task has been fulfilled by the Near-Earth Navigation and Geodesy section (NNG) of the Orbit Attitude Division of ESOC. In parallel, with a delay of a few more days, NNG has been computing high-precision restituted orbit data for both satellites based on additional precise tracking data, including altimeter height measurements reprocessed by NNG. Whereas the requirements on the operational orbit determination are significantly less stringent than the above-mentioned 10 cm, the precise orbit determination has always striven for the highest accuracy possible, by constantly improving the models and processing techniques involved.

The ERS-1 satellite was launched successfully on 17 July 1991. ERS-1 was successively placed in various orbits with different ground track repeat cycles. The success of this mission is evident from the fact that after the nominal mission duration of two years, ERS-1 has been operated for three more years until its hibernation in June 1996. The ERS-2 satellite was launched on the early morning of the 21st of April 1995. This satellite is a close copy of ERS-1, with among others a new PRARE instrument. Prior to the launch of ERS-2, ERS-1 was placed in a 35-day repeat orbit, the same as the intended operational orbit for ERS-2, in order to exploit the possibility of flying a tandem mission. After a successful lift-off on Ariane flight 72, the satellite was accurately injected into an orbit phased with that of ERS-1. Both satellites now overfly the same ground track, with ERS-2 trailing ERS-1 by exactly one day. Figure 1 shows the history of the ground track differences since the launch of ERS-2.

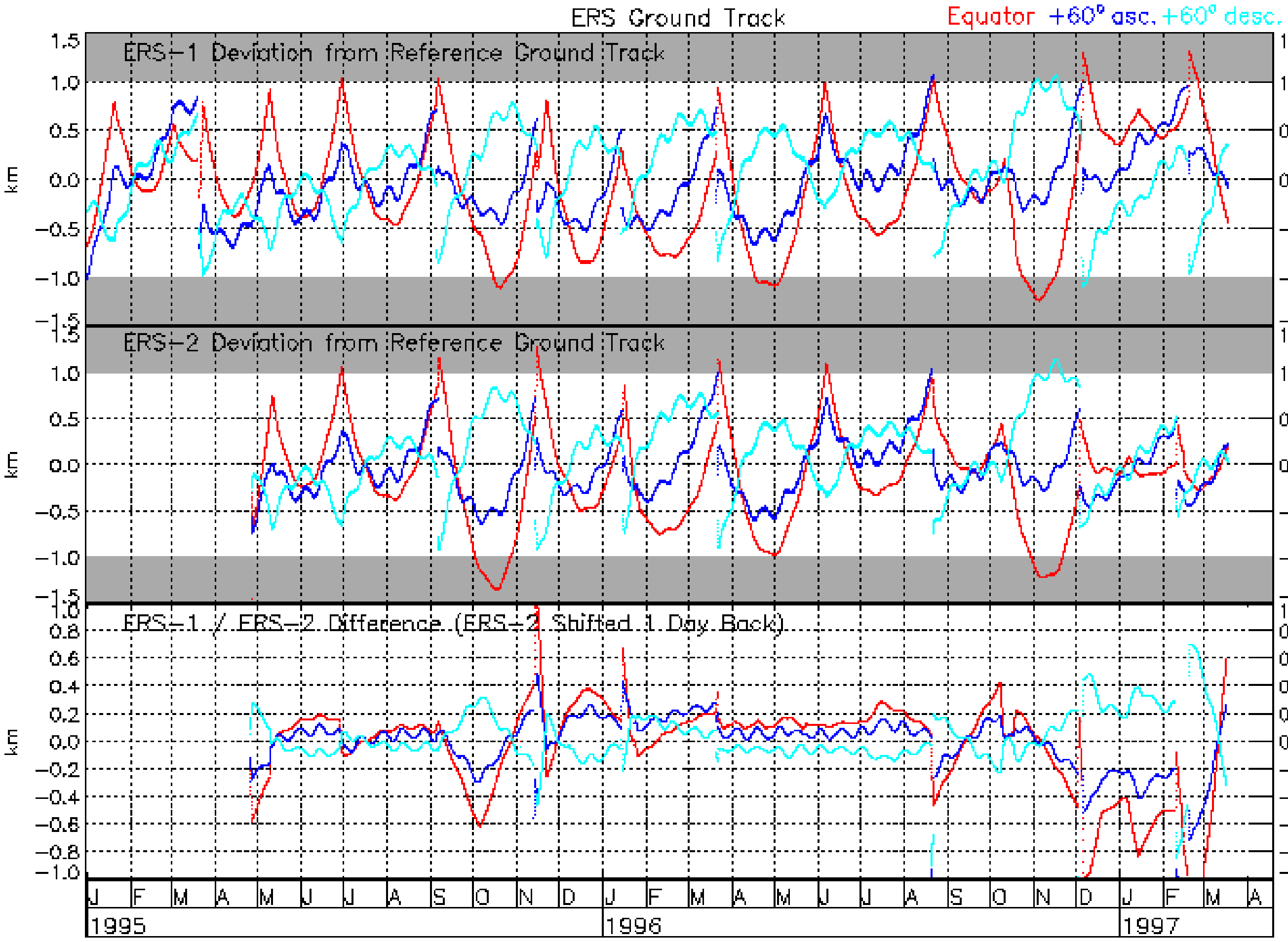

Figure 1: ERS-1 and ERS-2 absolute and relative ground tracks compared with the reference orbit.

The tracking data

For routine operations, both satellites possess an S-band antenna with transponder which is used (apart from telecommanding and telemetry) for ranging and doppler tracking. It is located on the Earth-facing side of the satellite body, not far from the satellite's centre of mass. On the same side are located the altimeter dish, a laser retro-reflector (LRR) and the PRARE antenna. Both satellites have been tracked by SLR stations from the very start of their missions. The responsibility for supporting the laser stations with accurate predictions lies with the German Processing and Archiving Facility (D-PAF). This facility also produces preliminary and final high-precision orbits.

The altimeter instrument plays a key role in the ERS support and data analysis activities at NNG. The measured heights are intended for oceanographical studies, but it has been long recognised that the global coverage of the data from this instrument would make it a powerful tracking device, and this feature has been exploited by ESOC from the start, both in operational and precise orbit determination. This means that models have to be supplied for the geophysical effects the instrument is intended to measure, in addition to those required already for the geophysical application of the data. A key value in the use of the altimeter data is that of the instrument's range bias. These values for the two satellites have been obtained using dedicated calibration campaigns. The calibration for ERS-2 will be discussed in one section of this paper.

Orbit determination and control of the ERS satellites

The orbit control task of ESOC consists of the routine tasks of determining the satellite orbits once per day, maintaining a 6-day prediction interval and correcting the orbit using manoeuvres to keep the orbit parameters inside the prescribed deadbands. In addition there are activities during more critical operations such as launch and early orbit acquisition and, for ERS-1, changing the repeat orbit characteristics.

The operational orbit determination uses S-band tracking and fast delivery altimeter height data. The S-band data comprises range and range-rate measurements from the Multi-Purpose Tracking System (MPTS) of the Kiruna station, which are available a few minutes after each pass. An automatic software sequence checks the arrival of the data after each pass, and sends warning messages to the Spacecraft Controller's console if anomalies are detected. Fast-delivery altimeter data are available at ESOC within 3 hours after they have been received on the ground. All tracking data are preprocessed immediately once they have been received. The details of the tracking data processing are given in Table 1.

Once per day, the orbit determination sequence is executed automatically, using the tracking data from the last three days in a batch least squares estimation process, updating the orbit file, including a prediction for the next days. The central day of the three-day moving window provides the final operational orbit solution. As a result, this orbit is available to users with a delay of only one day. The models used in the routine orbit determination are also included in Table 1.

The precise orbit determination (POD) system of ESOC has been developed from the routine orbit determination software, but whereas the routine system was `frozen' at the start of each mission, the POD system has been constantly improved. An automatic batch least squares orbit determination sequence runs for a four-day arc, to update the orbit file and all reports available on the NNG WWW site. The results are typically available with a delay of one week, the time needed to collect most of the laser tracking data.

The most important aspect of the POD system of ERS is to minimise the radial orbit error, which is needed for the application of the altimeter data to oceanographic research. POD re-uses the preprocessed S-band tracking data from the routine system, applying some further corrections. Laser tracking data are retrieved automatically, once per day and are preprocessed immediately once they have been received. The laser station coordinates have been computed at ESOC using a TOPEX/Poseidon and Lageos multi-arc solution. For ERS-2 also the PRARE data are being evaluated for precise orbit determination. This subject is treated separately below. The details of the tracking data processing are also given in Table 1.

S-band data tropospheric correction:	Oper: Hopfield POD: Empirical model with pass-dependent height scale parameter
S-band data ionospheric correction:	Oper: Bent POD: Covered by tropospheric correction
S-band range bias:	All: Fixed satellite transponder delay Oper: Estimated arc-dependant bias POD: Estimated pass-dependant bias, additional centre-of-mass correction
S-band doppler bias:	Oper: Estimated arc-dependant bias POD: Estimated pass-dependant bias
S-band station coordinates:	Oper: GPS solution and local survey [Becker et al, 1992]
S-band data normal points:	All: 20-second interval for ranging and range-differences
S-band data cut-off elevation:	All: 10 degrees
Altimeter data corrections:	Oper: Fast Delivery product values, OSU-91A geoid POD: See article text
Altimeter data normal points:	Oper: 80-second normal points fitting 20-second data
Altimeter bias:	All: Arc-dependant value estimated
Laser (SLR) tropospheric correction:	Marini-Murray
SLR range corrections:	LRR centre-of-mass offset correction
SLR normal points:	Following Herstmonceux recommendations
SLR cut-off elevation:	5 degrees
SLR station coordinates:	computed from a TOPEX/Poseidon, and Lageos multi-arc solution [Rutkowska et al, 1995], no net rotation Nuvel plate motion
Prare Tropospheric correction:	Provided with the data
Prare Ionospheric correction:	Using DRVID difference, provided with the data
Other Prare corrections:	Centre-of-mass offset, station mechanical centre corrections, antenna phase, external calibration provided with the data
Prare normal points:	15-second for ranging, 30-second integration for doppler
Prare cut-off elevation:	15 degrees
Prare station coordinates:	Estimated in multi-arc solution, initial values provided by GFZ.
Reference frame:	All: Mean equator and equinox of J2000.0
Gravity model:	Oper: JGM-3, truncated at degree and order 36 POD: JGM-3 (70,70), one cycle-per-revolution along-track and cross-track accelerations estimated per arc. (previously: GS-4591, JGM-1, and -2). All: Luni-solar gravity
Tides:	All: Frequency-dependent solid-earth tides, Wahr model POD: Ocean tides: 30 constituents to degree and order 6, some coefficients adjusted in a multi-arc solution
Air density model:	All: MSIS (1983)
Satellite air drag model:	Oper: Daily Cd estimation, constant effective frontal area POD: Detailed Cd modelling based on spacecraft geometry and aerodynamic flow; scale factor estimated every three hours
Radiation pressure model:	Oper: Fixed direct solar radiation pressure coefficient, constant effective frontal area POD: Direct solar radiation pressure model, taking into account spacecraft geometry, albedo and IR radiation perturbations

Orbit manoeuvres:	All: Impulsive delta-V or constant accelerations (depending on duration), estimation of corrective factors
EOP	All: IERS Earth orientation parameters

Table 1: Models used in the orbit determination and prediction of ERS satellites

Altimeter data processing

A major effort was put into the altimeter data processing for the high-precision orbit determination, where the data are reprocessed using more accurate correction models. When used as high-precision tracking data, the measurement correction models used are as follows.

The ionospheric correction provided with the URA FD products is removed, and a correction based on the Bent model is applied.

The dry tropospheric correction is taken from the URA FD products. This correction is based on the Saastamoinen 1972 model, and it makes use of the latest ECMWF pressure field.

For the wet tropospheric correction, the constant 10 centimetres zenith correction applied at the station in the generation of the URA FD altimeter products, is removed and a better correction applied. A model for the wet tropospheric correction has been developed at ESOC. This model has been computed fitting, in a least squares sense, time dependent spherical harmonic functions up to degree and order 20, to 14 months (August 1992 to October 1993) of meteorological data from the ECMWF. The rms of the differences between the solution obtained and the ECMWF data is about 4 cm. This model has been tested by comparing its values with those provided with the ERS-1 Radar Altimeter Fast Delivery Products (FD), Quick-Look Ocean Product Records (QLOPR) and Ocean Product Records (OPR), and in the TOPEX/Poseidon Merged Geophysical Data Records (GDR-M). The comparison showed that the wet tropospheric correction model developed at ESOC is in good agreement with any of the corrections applied to the altimeter products. The best agreement was with the TOPEX/Poseidon microwave radiometer correction values. Also, the level of agreement between the ESOC model with any of the other models is not worse than the level of agreement observed between two different meteorological models.

The electromagnetic bias is mainly a function of the significant wave height and the wind speed. The coefficients of the available models have to be calibrated in flight. The very strong correlation between the electromagnetic bias and the altimeter bias make it very difficult to calibrate these parameters simultaneously. Three algorithms have been compared at ESOC: the one used for Topex data, the one used for Poseidon data and a standard model consisting of a scale factor times the SWH. The latter was selected and the level of agreement between this algorithm and the other two models is quite good, especially after the estimating this scale factor. The mean value of the differences is about 0-2 mm, while the rms of the differences is about 10-15 mm.

The centre of mass correction is different for ERS-1 and ERS-2 by about 15 mm. It should be noted that the values are variable due to fuel consumption, but the variation in the Z-component has been less than 1 mm during the lifetime of ERS-1.

The determination of the altimeter bias to an accuracy of a few centimetres is not possible prior to the launch. Therefore it is necessary to calibrate the height bias after launch. During the routine and precise orbit determinations, the bias is always estimated for each arc.

The deformation of the solid earth due to external gravitational forces is modelled following a simplified model by Schwiderski [Schwiderski, 1981].

The ocean tide correction applied is based on the Schwiderski NSWC tidal models.

The ocean loading effect on the ocean bottom has been considered. The correction applied to the altimeter data is based on the same models as for the ocean tides.

Sea surface model

The sea surface is not the geoid because of ocean currents, tides, winds and other factors. The dynamic sea surface topography (SST) is expressed as a series of coefficients to Legendre functions, which are estimated by evaluating the difference between the mean sea surface (MSS) observed during one month and the geoid, after corrections for tidal effects have been applied.

From the ERS-1 launch till January 1995 the OSU-91A geoid model was used to correct the altimeter measurements. Using this geoid model and the estimated dynamic SST, the altimeter residuals were about 19-22 cm. The analysis of repetitive tracks of ERS-1 and TOPEX/Poseidon showed that the OSU-91A model (which has a grid size of 0.25 degrees in longitude and latitude) has errors in excess of 3.5 meters at some locations.

Using ERS-1 altimeter data from March 29 to December 31, 1994 a very high resolution Mediterranean MSS model was developed (about 17 km in north-south direction, and 13 km east-west). The use of the new MSS model reduces significantly the altimeter residuals. Using the OSU-91A model the altimeter residuals were greater than 60 cm in the Mediterranean sea. The ESOC Mediterranean MSS model was tested using two 10 day cycles of independent TOPEX/Poseidon data. The altimeter residuals went down from 60 cm to 12-13 cm over this region.

Figures 2 and 3 show the differences between the ESOC MSS model and the OSU-91A model in the Mediterranean sea, and the accuracy of the model. The plot showing the accuracy of the model represents an upper limit of the model error, because also errors due to tides, sea level variability, ionosphere, troposphere, ocean circulation, etc. are represented in it. Thanks to the delay in the ERS-2 launch the geodetic phase of ERS-1 could be extended, and the ESOC model could be extended to cover the full globe using this data. The resolution was reduced to 0.3 degrees (about 33 km at the equator). For the North and Central Atlantic, as well as for the Mediterranean sea, altimeter data from the 1st of April 1994 to the 3rd of January 1995 were used, while for the rest of the world data from the 1st of April till the 31st of July 1994 were used [Romay et al, to be issued]. To eliminate the long-term sea surface variability, the dynamic SST was removed during the estimation of the MSS model. The monthly long wavelength dynamic SST models computed at ESOC, based on the OSU91A geoid model were used for that purpose [Romay et al, 1992-1995]. The use of the new ESOC MSS model reduces the altimeter residuals from 19-22 cm to 12-14 cm. Again this model was tested using independent TOPEX/Poseidon data and the altimeter residuals were down to 12-13 cm when using the new model. The global accuracy of this model is estimated at about 8 cm.

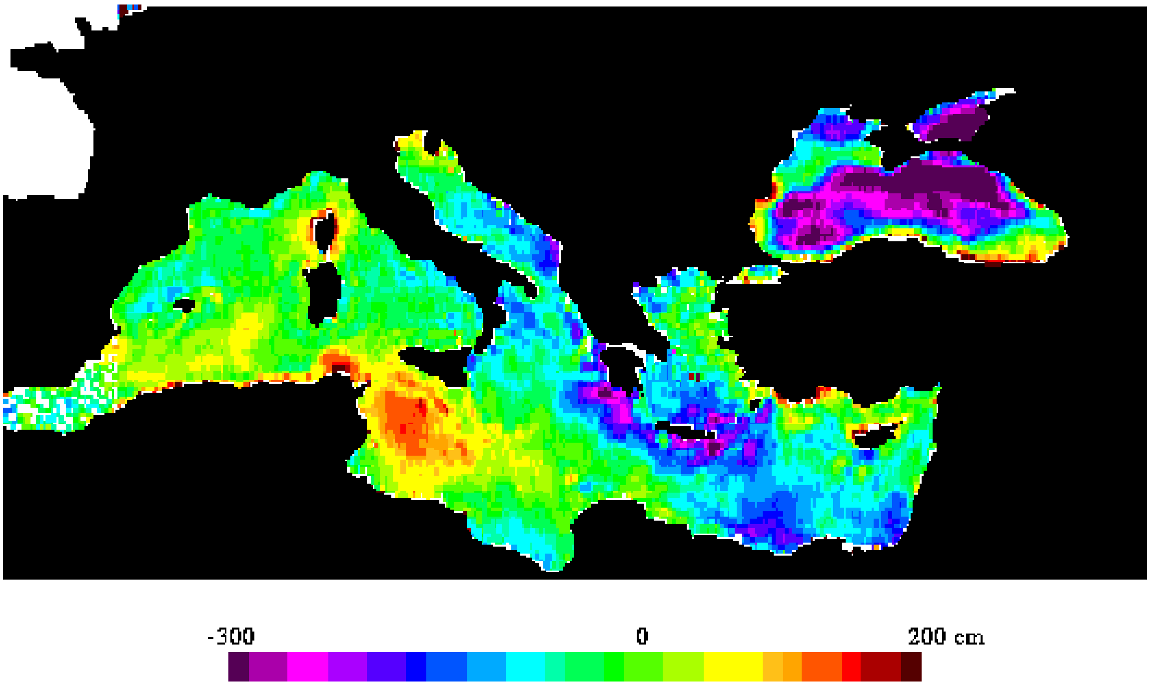

Figure 2: ESOC Mean Sea Surface model for the Mediterranean and Black Seas, derived from ERS-1 altimeter data.

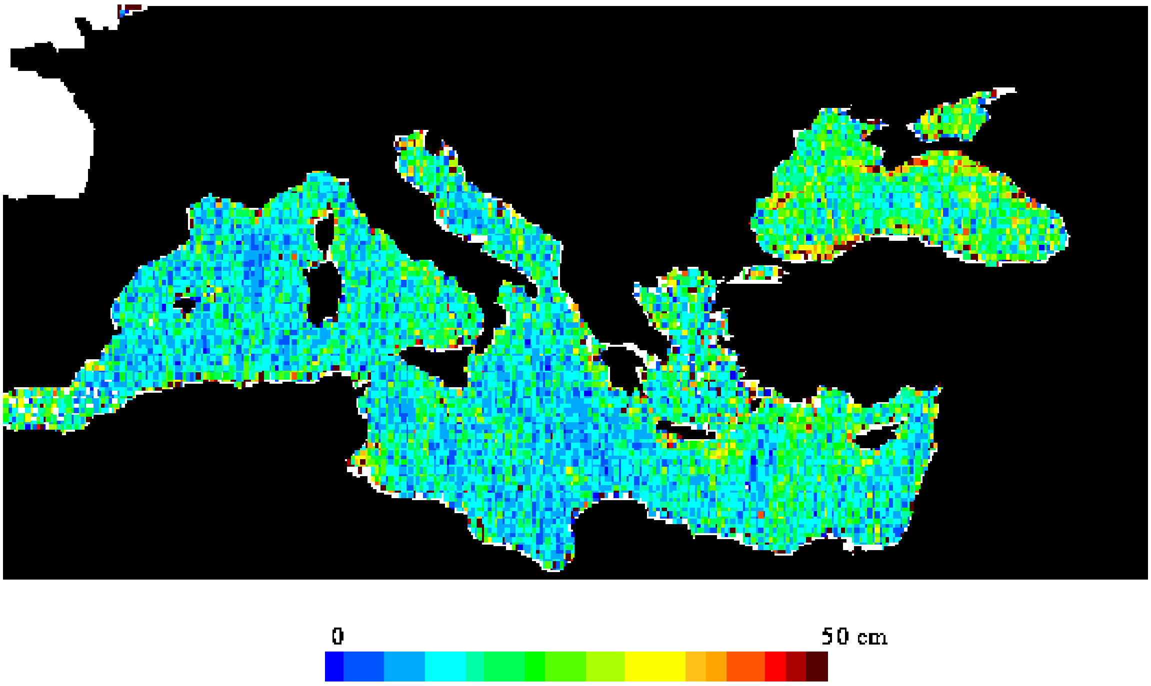

Figure 3: Error estimate of the ESOC Mean Sea Surface model for the Mediterranean and Black Seas

The MSS model computed at ESOC has henceforth been used as the reference for the dynamic SST models. The MSS model computed at ESOC is not the geoid, but to degree and order 25 the differences between this surface and the geoid (adjusted for the permanent tide) are very small. Mean dynamic SST models have been computed monthly at ESOC since May 1992. The accuracy and the resolution of these models have been improved since then. The accuracy is now estimated to be better than 4 cm.

Orbit prediction and determination accuracy

A set of mission requirements has been imposed on the accuracy of the predicted and determined operational orbits. The verification of the orbit prediction accuracy is possible by confronting the predictions with the determined orbits a few days later. Verifying the orbit determination accuracy is possible by comparing the routine orbit with the high-precision orbit available a few days later, or by looking at the tracking data residuals. The results of these have in the past been published monthly [Romay et al, 1992-1995], and are currently available in near real time on the NNG WWW site. This paper can only give a summary of some of the recent results.

The along-track orbit prediction accuracy of the routine orbit determination for the beginning of the ERS-1 mission (where predictability was difficult due mainly to the high solar activity, but also to less accurate force modelling) may be confronted with that of the current ERS-2 predictions: then 500/2800 m after 1/3 days and currently 20/80 m. The current results are well inside the requirements, due to the low solar activity.

Table 2 shows the tracking data residuals from the routine orbit determination, for the same two periods. Range residuals are one-way values. Here the differences are due to the improved modelling since 1991.

Measurement type	ERS-1 commissioning	Current
S-band ranging	511	80
S-band doppler	3.3	0.6
Altimeter height	269	75

Table 2: Routine operational S-band orbit determination residuals (rms in cm, cm/s)

The current values for the routine system are believed to represent the limit for the geophysical models used (in particular the gravity model).

The accuracy of the high-precision orbits may be evaluated by inspecting the tracking data residuals and by comparing the orbits internally (routine vs. high-precision, overlap tests) and with external solutions (D-PAF preliminary solutions). Table 3 shows the tracking data residual statistics of the POD system for the early phase of the ERS-1 mission (spring 1992) and for the current ERS-2 solutions (November 1996). Again, range residuals are one-way values.

Measurement type	ERS-1, spring 1992	ERS-2, 1996
S-band ranging	120	65
S-band doppler	0.55	0.16
Altimeter height	56	14.7
Laser ranging	16	5.7

Table 3: High-precision orbit determination residuals (rms in cm, cm/s)

The fit of the laser residuals is a good indication of the orbit accuracy, as long as not too many measurement correction parameters are solved for. Figure 4 shows some recent laser statistics per arc (rms residuals, nr of passes per arc). The best stations produce residuals in the 4-5 cm range. This number includes the contribution of the along-track and cross-track orbit errors as well as tracking modelling errors. As may be observed in Figure 4, the number of passes varies considerably from summer to winter, but it is typically between 8 and 15 per day. Since the duration of a pass is about 10 minutes, large gaps between consecutive passes exist, and while SLR residuals provide an upper limit of the radial orbit error during passes, they do not provide significant information during gaps. The S-band residuals for the precise orbits are close to the limit of the performance of these systems, and provide no information about the accuracy of the orbits.

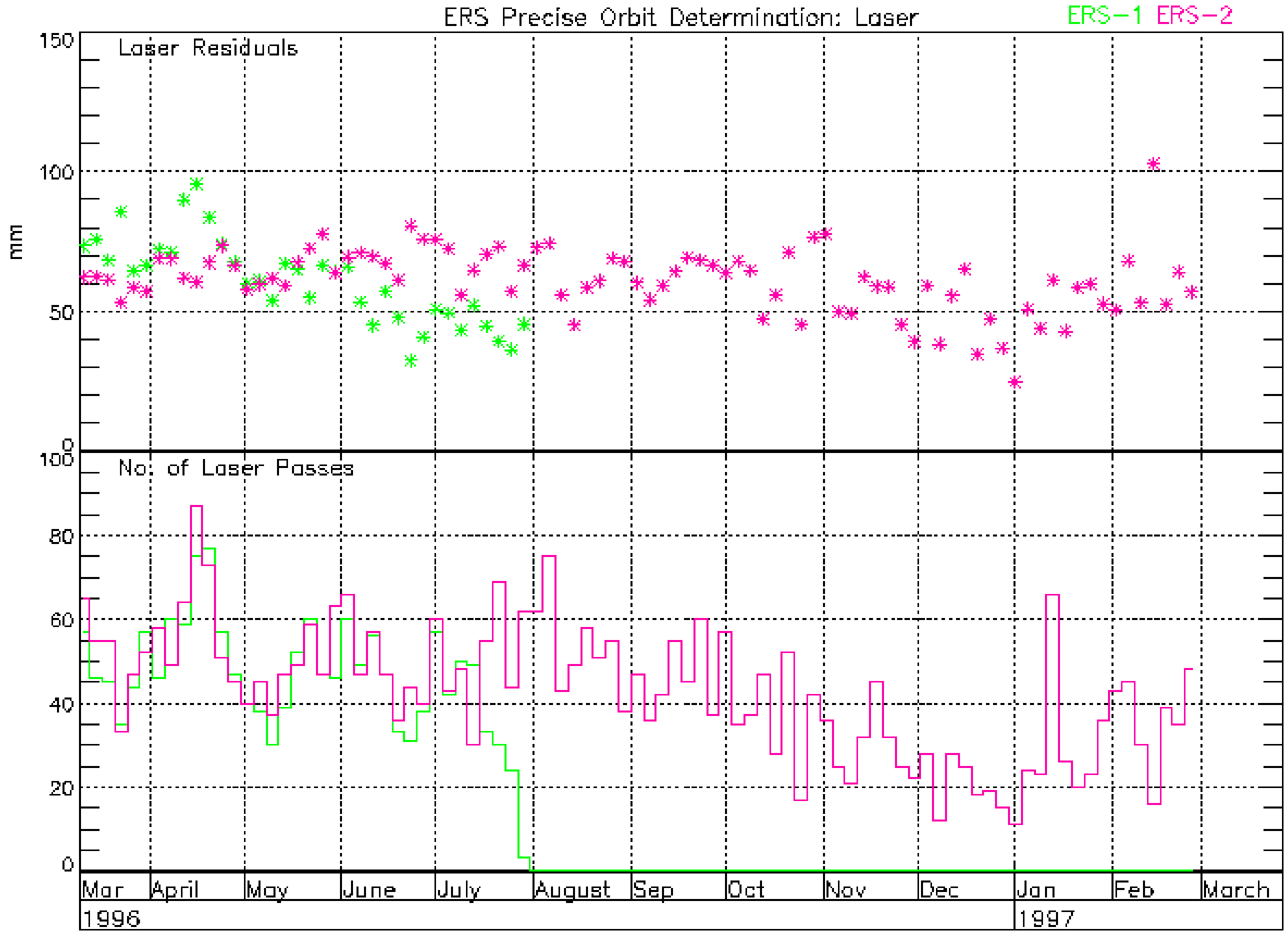

Figure 4: SLR arc statistics for the last year.

The altimeter residuals of the precise orbit solutions are now significantly smaller than pre-launch expectations. Altimetry provides a pure radial measurement, therefore radial orbit errors go directly into the altimeter residuals. Altimeter residuals however are not a real indication of the radial orbit error, since they are also affected by uncertainties in the geoid, sea surface topography, solid and ocean tides, propagation errors, electromagnetic bias, etc. Thus they represent an upper limit for the radial orbit error. Once the contribution of each of the error sources has been evaluated, the contribution of the radial orbit errors to the altimeter residuals can be inferred. This yields that the radial accuracy of the orbits computed at ESOC is estimated between 5 and 8 centimetres.

Orbit comparisons (both internal and external) may be used to verify this conclusion (see Table 4). This gives a clear estimate of the accuracy of the current routine operational orbit solutions: about two meters for the absolute position errors and about half a meter in the radial direction. For the precise orbits none of the indications presented above can be considered definitive, although the altimeter residuals give probably the most reliable indication. The indications seem to agree to a value of the order of 8 cm.

Comparison	Radial	Along-track	Cross-track
ESOC operational vs. ESOC precise	50	200	100
D-PAF preliminary vs. ESOC precise	10	40	40

Table 4: Orbit comparison for ERS-2 (rms in cm)

ERS-2 altimeter calibration

To ensure compatibility between the altimeter data from ERS-1 and ERS-2, a relative calibration between the two satellites was selected for ERS-2. The work done at ESOC was part of a cooperative effort between many European centres with expertise in altimeter data processing, the results of which will soon be published [Romay et al, to be published].

To estimate this relative altimeter bias between ERS-2 and ERS-1 four different techniques have been used at ESOC (see also [Dow et al., 1996]).

- Global calibration
- Local calibration in the Mediterranean sea
- Global calibration using the biases from the precise orbit solution
- Sea surface differences

The altimeter data used in all methods are the Fast Delivery altimeter products, processed at ESOC as described above. One additional altimeter data correction was taken into account during this exercise: the effect of the altimeter clock asymmetry, which has been retrieved from the satellite telemetry, and is expressed as a series of constant values over periods of several days. It is generally referred to as the SPTR (Single Point Target Response) correction.

The use of four different techniques will help in quantifying the error involved in the bias estimation. Errors in the corrections applied to the altimeter data will affect almost in the same way all global methods. It can be expected that these errors will influence in a different way the local calibration, therefore the difference between the value computed from the global analysis and the one computed from the local analysis will provide an indication about systematic errors introduced by the corrections.

In the global calibration technique, all altimeter measurements are corrected for propagation effects, and referred to the reference ellipsoid by applying all known oceanographic corrections as listed above. These values are then compared with the height of the satellite above the reference ellipsoid determined from the precise orbits. The difference represents the altimeter bias and the various correction model errors. The average for each 24-hour time interval is assumed to be the bias, since it can be expected that over longer time intervals most of the other errors will be averaged out. Furthermore, model errors that do not average to zero will be similar for ERS-1 and ERS-2 and will mostly be removed in the estimation of the relative bias.

Altimeter bias values have been computed at ESOC since 3 May 1995. Since that time, ground processing Look-Up Tables were updated several times, and the Electromagnetic (EM) bias calibration value was updated several times at ESOC as more accurate estimations were available. Since the 25 June 1995 the correction models have been stable and the values presented below are based on data taken from that time till the end of 1995. The standard deviation associated with the altimeter bias will indicate the internal consistency of the solution.

The reason for a local calibration using only data of the Mediterranean sea is to try to quantify the effect of errors in some of the correction models not averaging out globally. Otherwise this method is identical to the one presented above. The main reasons for selecting the Mediterranean sea are its small ocean tide amplitudes, low wave height (small EM bias correction), high accuracy of the orbits since a lot of SLR stations are located in Europe and the low influence of ocean circulation and ocean variability. There are only about three Mediterranean passes per day, therefore time intervals longer than a day had to be used. Since 25 May altimeter bias values have been computed every five days. The values obtained using this technique are noisier than those from the global calibration.

The altimeter bias value is one of the parameters solved for when computing the precise orbits for ERS-1 and ERS-2. To compute these orbits altimeter normal points are used as tracking data. Every four days a value of the altimeter bias for each satellite is computed, based on the same dynamical and altimeter corrections for both satellites. The difference between the two altimeter bias values represents the relative bias. This method was originally not considered for calibration purposes, but the stability of the solution was quite remarkable.

Finally, every month a dynamic SST model is computed. Since the launch of the ERS-2 satellite this model is computed using data from both satellites. For the months of June to September 1995 two SST models were computed, one for each satellite. The mean value of the differences between the two models also represents the relative altimeter bias.

The relative altimeter bias found using each of the techniques, as well as a value indicating the consistency of the solution is represented in Table 5.

Method	Relative bias (cm)	Sigma (cm)
Global solution	0.7	1.3
Mediterranean solution	0.1	2.6
Orbit solution	0.7	1.4
Sea Surfaces differences	0.8	0.6

Table 5: ERS-2 relative altimeter bias values

A weighted fit between all the methods results in a relative altimeter bias of 0.7 cm. Unfortunately, there is no definite technique to evaluate the error associated with the estimated altimeter bias value. For each of the methods used it is possible to give an indication about the consistency, but there are errors associated with the method used which cannot be easily quantified. Most errors will be averaged out using global calibration methods, but there is always a remaining part of the error which is not eliminated just by averaging out. Orbital errors can be geographically correlated, and as the altimeter data is not completely global, mainly because of land regions and also because only data preprocessed at Kiruna is used in the analysis, this could lead to a systematic error in the altimeter bias calibration.

To evaluate the remaining part of the error which can not be eliminated by averaging out, a set of local calibrations using data over the month of August has been carried out. The relative altimeter bias has been solved for in 30x30 degree regions. In every region the contribution of the systematic error will be different, therefore the standard deviation will give an upper limit for the total remaining or systematic error. This value has been combined with the above uncertainty, yielding the final uncertainty of 2.0 cm. This uncertainty value may be considered as too pessimistic because there is a quite large uncertainty associated with each 30x30 degrees altimeter bias determination which is not really due to the systematic error contribution.

PRARE data processing

The Precise Range and Range-rate Equipment (PRARE) was installed on board of ERS-2 as one of the precise orbit determination tracking systems. PRARE is an autonomous spaceborne two-way, dual frequency microwave-tracking system with its own telemetry, telecommand, data storage, timing and data transmission capability. It allows precise range, range rate and ionospheric measurements at sub-decimetre level of accuracy. The PRARE tracking data consist of two-way range measurements and one-way doppler measurements (range differences). These data (currently revision 5) are preprocessed at GFZ-Potsdam. The data available to ESOC belong to the MEX network, of which initial coordinates were provided by GFZ with an accuracy of 0.5 m.

For the purpose of precise orbit determination a better estimate of the station coordinates was required. A dataset containing PRARE (revision 4), SLR and altimetry was prepared in order to obtain a PRARE solution consistent with the SLR station coordinate solution from the ITRF93 and with the geophysical models used in the SLR/altimetry precise orbit determination described above. In single-arc orbit determination (normal equation generation) the same models were applied as in the POD system described above. For the PRARE data preprocessing the models applied are also given in Table 1 (except for the ionospheric correction, which was still based on the dual-frequency correction). Four-day arcs in the time span from 01/05/1996 to 31/10/1996 were processed to obtain the observation equations. Selected arcs were used in the multi-arc solution, in which the following parameters were estimated:

Coordinates of all PRARE stations (unconstrained)
Coordinates of all SLR stations constrained to 1 cm w.r.t. the initial value
Daily polar motion parameters constrained to 0.1 mas w.r.t the initial value
Daily Earth rotation timing (UT1) constrained to 0.1 ms w.r.t. the ITRF93 value

Two iterations were required, and with this solution no more than 5% of the measurements were rejected in most arcs. This yielded a useful criterion for arc selection in a third iteration, giving the final PRARE station network solution. It is to be noted that the doppler measurements did not play a role in this arc selection since, after the second iteration, changes of the order of 5 cm in the station position did not affect in a noticeable manner either the residuals or the number of rejections.

This solution is consistent between iterations 2 and 3 within 5 cm. Taking into account that the ERS-2 orbit is not ideal for station position determination, this is possibly the best achievable accuracy with the described method. The solution is also consistent with the ITRF93 reference frame within 0.3 mas in terms of pole orientation and within 0.1 ms in terms of Earth rotation synchronisation.

With the obtained coordinates for the PRARE station network and using the same models described above, PRARE orbits are now computed routinely at ESOC. To keep consistency with the standard ESOC precise orbit determination, the data are processed in 4-day arcs starting at noon. Measurement residuals are shown in Figure 5. The data before March 1996 is sparse and its quality lower. From this time onwards the number of passes increases and from the residuals can be seen that the data quality is stable after April, yielding 1-way residuals of 5-6 cm range and 0.5-0.6 mm/s doppler. These results are comparable with the accuracy of the SLR based orbit determination. This conclusion is confirmed by Figure 6, showing the rms comparison between these two orbits. The cross-track orbit difference is still relatively large, but this is partly due to the presence of the less precise S-band data used in the POD solution, which is not used in the PRARE solutions.

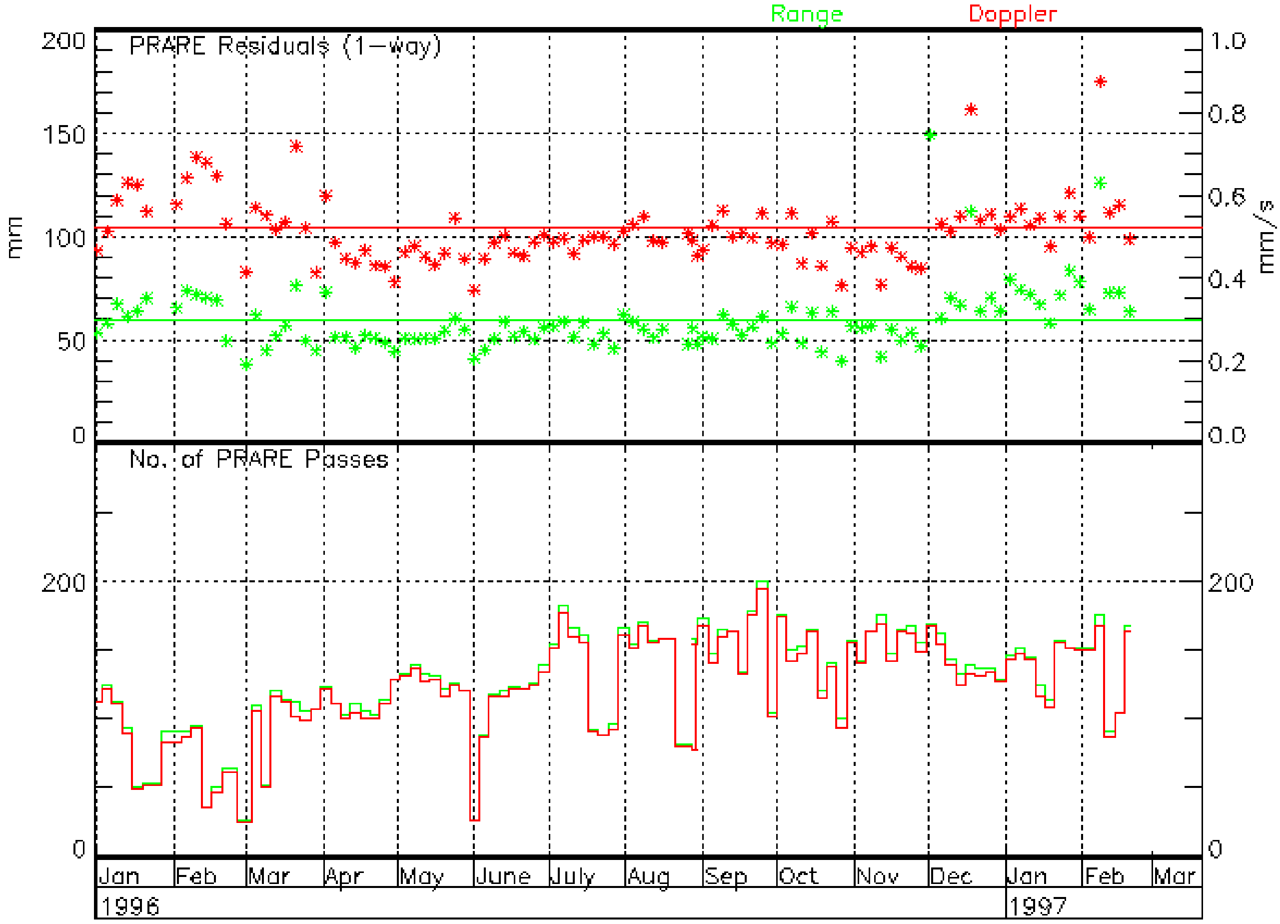

Figure 5: PRARE arc statistics for the last year.

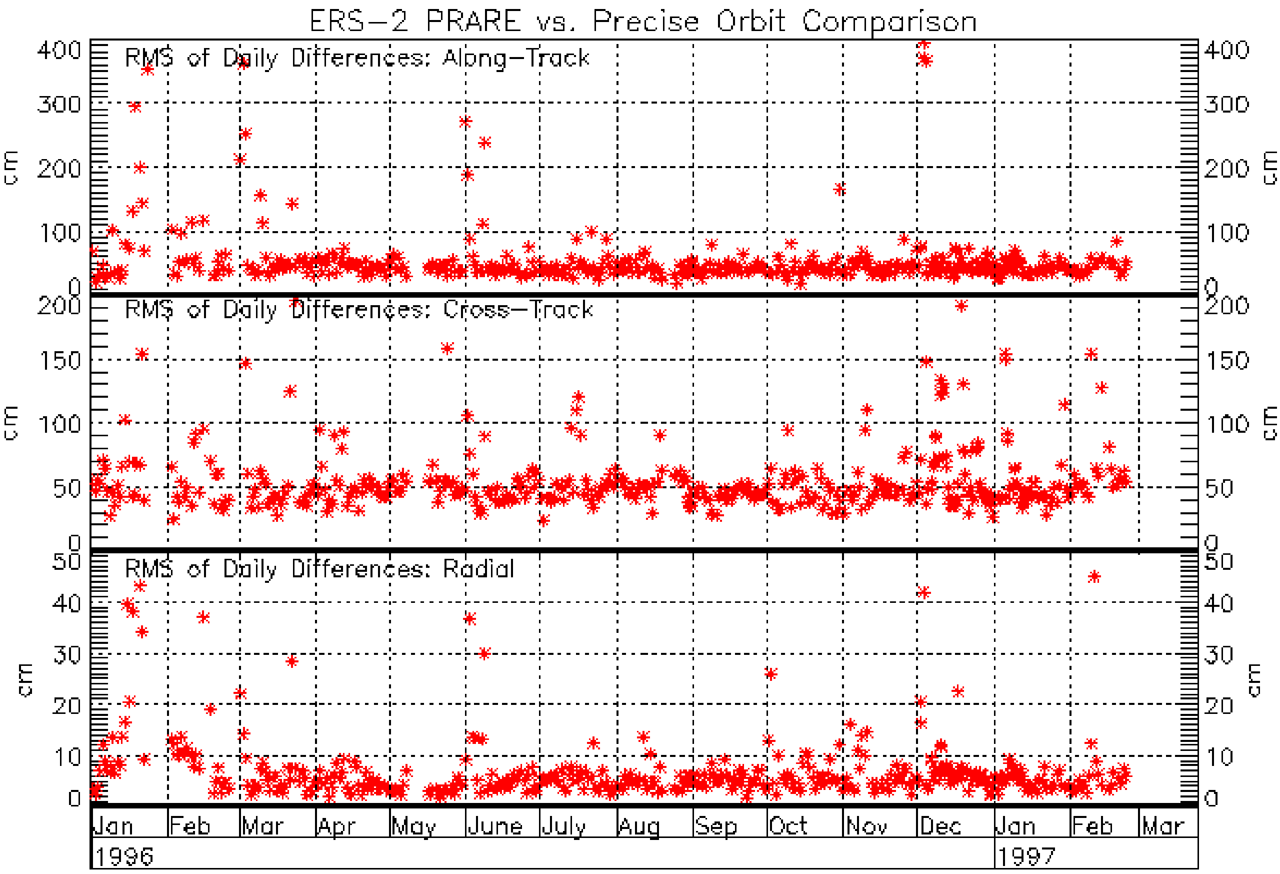

Figure 6: Comparison between standard ESOC precise and ESOC PRARE orbit solutions

Conclusions

The operational orbit determination system for ERS has been shown to be able to produce determined and predicted orbits with accuracies much better than required. This is in part due to the low solar activity during this stage of the mission, and in part to the progress in the precise orbit determination that was done in parallel. As for the accuracy of the precise orbit determination, the radial orbit error is judged to be less than 10 cm, a value previously only considered possible for the much higher TOPEX/Poseidon satellite.

The ERS-2 altimeter provides a continued stream of height measurement data compatible with that from the successful ERS-1 altimetry mission. An altimeter data preprocessing system has been implemented and used extensively. This has allowed the computation of very accurate Mean Sea Surface and Dynamic Sea Surface Topography models, and to calibrate the ERS-2 altimeter instrument. The accuracy estimated for the MSS models is about 8 cm, and of the calibrated relative altimeter bias about 2 cm, the bias itself being essentially zero.

The PRARE instrument of ERS-2 is producing all-weather tracking data with range accuracies similar to that of laser data (6 cm) and doppler accuracies not much higher than those of the DORIS system (0.5-0.6 mm/s). The PRARE station coordinates provided by GFZ cannot be directly used in the ERS-2 precise orbit determination because of their relatively low precision. The PRARE station coordinates solution from ERS-2 orbit determination can only generate results to an accuracy about 5-6 cm.

The quality of the orbit determination with PRARE is not very sensitive to station outages since the global coverage and number of usable measurements is very high. Also the distribution of stations is better than that of the SLR network (for ERS-2), which is very concentrated in Europe. The productivity of the network is finally reasonable. Still not all stations are fully operational, but those that are, are producing precise data.

The experience gained at ESOC with the routine and precise orbit determination for ERS-1 and ERS-2 will be exploited to its maximum for the future Envisat-1 mission. This mission is very similar to those of ERS-1 and ERS-2, but it will take place during the next solar maximum, causing air drag levels (and unpredictability) similar to that of the start of the ERS-1 mission, confronting the precise orbit determination community in general and ESOC in particular with a new challenge.

The latest information about the ERS routine, precise and PRARE-based orbit determination at ESOC is available on-line at the NNG WWW site

References

M. Becker, E. Groten, K. Sauermann.
Location of ESA tracking sites by GPS, *ESOC Contract 9166/90/D/IM(SC), July 27, 1992.*

J.M. Dow, M. Romay Merino, R. Píriz, H. Boomkamp and R. Zandbergen.
High precision orbits for ERS-1: 3-day and 35-day repeat cycles. *Proceedings Second ERS-1 Symposium - Space at the Service of our Environment, Hamburg, Germany, 11-14 October 1993. 1349-1354.*

J.M. Dow, M. Rosengren, X. Marc, R. Zandbergen, R. Píriz and M. Romay Merino.
Achieving, Assessing and Exploiting the ERS-1/2 Tandem Orbit Configuration, *ESA Bulletin 85, February 1996.*

C.R. Francis.
The calibration of the ERS-1 Radar Altimeter. *ER-RP-ESA-RA-0257. ESA/ESTEC, Noordwijk, The Netherlands. March 1993.*

D. D. McCarthy (ed.).
IERS Technical Note 21: "IERS Conventions (1996)", *Paris, July 1996.*

M. Romay Merino, J.M. Dow, R. Píriz and R. Zandbergen.

ERS-1 Flight Dynamics Reports: ERS-1 Orbit Reports 1 to 39. *ESA/ESOC Darmstadt, 1992-1995.*

M. Romay Merino, R. Píriz, R. Zandbergen and J.M. Dow.
ERS-2 Altimeter Calibration at ESOC, *Final report of the ERS-2 MWR and RA Commissioning Working Group, to be published, ESRIN.*

M. Rutkowska, M. Romay Merino, S. Schillak, and J.M. Dow.
Improvement of the SLR Borowiec Station Position in the Global Network ITRF91. *Adv. Space Res. Vol. 16, No. 12, pp.(12)97-(12)100, 1995.*

E.W. Schwiderski.
The NSWC global ocean tide data tape (GOTD), its features and application, random-point tide program. *NSWC TR 81-254, 1981.*

R. Zandbergen, J.M. Dow and S. Martin.
ERS-1 operational orbit determination and prediction. *Proceedings of the ESA Symposium on Spacecraft Flight Dynamics, held in Darmstadt, Germany, 30 September - 4 October 1991 (ESA SP-326, December 1991), pp. 105-108.*

R. Zandbergen, J.M. Dow, M. Romay Merino and R. Píriz.
ERS-1 and ERS-2 operational and precise orbit determination. *Advances in Space Research, vol. 16, No. 12, pp. 105-108, 1995.*

R. Zandbergen, J.M. Dow, M. Romay Merino, R. Píriz and F. Martínez Fadrique.
ERS-1 and ERS-2 tandem mission: orbit determination, prediction and maintenance, *Paper presented at the 31st COSPAR Scientific Assembly, Birmingham, UK, 17-18 July 1996.*