

Absolute Calibration of the ERS-2 Altimeter using UK Tide Gauges

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Abstract. This paper describes the use of UK tide gauges, the sea level data from which have been located in the same geocentric reference frame as altimeter data from ERS2 using Global Positioning System (GPS) receivers, to provide an ongoing absolute calibration of the altimeter bias. The method is an extension of earlier work for TOPEX/Poseidon. However, the present analysis extends to the ERS-2 altimeter, which flies on a sun-synchronous orbit. The S_2 tide error of ERS-2 will be aliased to a permanent local bias, so it cannot be detided by the harmonic method which was used in TOPEX/Poseidon calibration. The calibration sites were chose at the TOPEX/Poseidon and ERS-2 dual-satellite crossover points, in order to use TOPEX altimeter data to extract the tidal parameters. These tidal parameters were applied to ERS-2 altimeter data to reduce the affect of tide differences between data from the ERS-2 calibration sites and tidal gauges. The time-averaged ERS-2 biases are derived over 24 crossover points in 6 tidal gauges, and the mean is 44.0cm with a 6.6cm RMS. When using first 1000 days TOPEX/Poseidon data which is not overlay with ERS-2 data, the time-averaged biases is only a few millimetres different at each site. It suggest that other sun-synchronous satellites (with or without an overlap with TOPEX/Poseidon) can be similarly evaluated.

Keywords. Satellite altimetry, ERS-2, calibration

1 Introduction

Several altimetric satellites were launched in the past decade for oceanographic purposes. Among them, ERS-2 (the second European Remote-Sensing Satellite), the successor of ERS-1, was launched on 21 April 1995 into near-circular orbit with a 35 days exact repeat period. Compared with TOPEX/Poseidon calibration (see Christensen et al. (1994), White et al., (1994), Ménard et al. (1994), Murphy et al. (1996) Mitchum (1998, 2000) and Exertier et al. (2000) for examples of different approaches to T/P calibration), relatively little calibration has been performed for the ERS-2 altimeter. Moore (2001) used dual satellites crossovers to analyse ERS-2 altimetric bias relative to TOPEX/Poseidon, and Moore et al. (1999b) also investigated the stability of ERS-2 altimetry during the ERS tandem mission. This paper describes a study of the utility of UK tide gauges equipped with Global Positioning System (GPS) receivers to provide an ‘absolute’ calibration of the range measurements by the ERS-2 radar altimeter (i.e. a determination of altimeter range bias).

This study is an extension of the determination of the biases of the TOPEX and Poseidon altimeters by Dong et al. (2002). In that study, a number of gauges around the UK were used to calculate time-averaged TOPEX and POSEIDON biases with a precision of approximately 2 and 3 cm respectively.

The values of rms of the time series of gauge minus POSEIDON altimeter residuals after applying TOPEX derived tide-difference correction are in most cases comparable to those from TOPEX data, suggesting the possibility of extending that method to ERS-2 and/or Jason-1 altimetry. Compared with the TOPEX/Poseidon calibration exercise, the ERS-2 study is more difficult because ERS-2 flies on a sun-synchronous orbit. In this case, the S₂ tide will produce an unknown local mean relative bias which will influence the absolute calibration. The ERS-2 calibration also expect a poorer precision due to its smaller data set (up to this study, only 55 ERS-2 cycles were available) and poorer measure precision.

2 Method of Analysis

The altimeter bias can be expressed as

$$\text{Bias} = [\text{Sea level}_{\text{tg}} - \text{Sea level}_{\text{alt}}] - [\text{Geoid}_{\text{tg}} - \text{Geoid}_{\text{alt}}] \quad (1)$$

where the sea level information for both data types must be measured within the same geocentric reference frame. The method for ERS-2 is based on the previous study for TOPEX/Poseidon, but the significant difference is the dual satellite crossovers are selected as calibration sites. At crossover site, the TOPEX derived tidal parameters can be applied to ERS-2 altimeter data. It is based on two features of the ERS-2 mission: longer repeat period and sun-synchronous orbit. The exact repeat period of ERS-2 is 35 days, which means only 55 cycles are available by May 2001. For a sun-synchronous orbit, the ocean tidal height of S₂ component is frozen when the satellite flies over one calibration site, which means a local bias will be introduced to the calibration result.

The first step was to identify suitable ERS-2/TOPEX dual-satellites crossover points which should be not too far from tide gauges. The average ERS-2 tracks were reconstructed over particular ERS-2 cycles (cycle 21 to cycle 40 selected here, nearly 1997-1999), and TOPEX average tracks come from orbit information over cycle 140 to cycle 180 (nearly October 1996-November 1997). Then a segment-by-segment method was used to search crossover location. The British tide gauges are located at high latitude, where the longitude-latitude plot of TOPEX tracks is considerably curved and the coastline is irregular. In this situation, the crossover points near the coast are easy to be missed for some rapid search methods

such as eastimating from the coordinates of the extremes top and bottom latitudes of each pass. On segment-by-segment method, all segments (here one segment is a line combined by two continue 1-second sampled altimeter footprints) of one satellite were compared with each segment of the other satellite to decide whether a crossover point exists. After editing the observations outside the studying region before doing a search, it needs only several minutes to complete this procedure using a normal workstation.

In the vicinity of crossover points near the UK (with latitudes between 50°N-60°N), the change of latitude and longitude for ERS-2 is nearly linearly, so we can linearly interpolate in calculating the crossover coordinates for each overlap of ERS-2 and TOPEX tracks. The nearest crossover points for 4 situations (ERS-2 ascendant pass vs. TOPEX ascendant pass, ERS-2 ascendant pass vs. TOPEX descendant pass, ERS-2 descendant pass vs. TOPEX ascendant pass, ERS-2 descendant pass vs. TOPEX descendant pass respectively) were selected as calibration sites for each tide gauge (Figure 1).

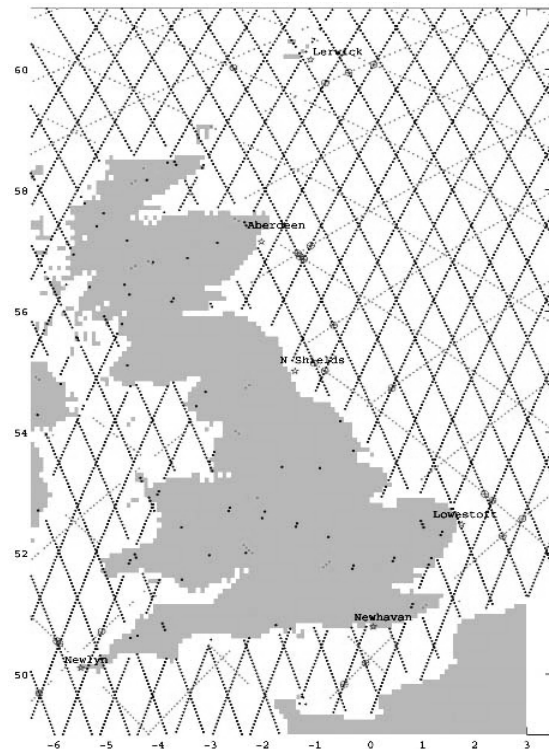


Fig. 1 shows the locations of 24 calibration sites (circles) around 6 UK tide gauges. Dark lines are ERS-2 tracks, and light lines are TOPEX tracks.

The data processing employed for the tide gauge is essentially the same as that used in Dong et al (2002). To summarise, six tide gauges (Figure 1) provide an approximately even distribution around the UK. The tidal gauge measurements were transferred to a geodetic coordinate system by measuring the height of the tide gauge benchmark above the ellipsoid via GPS and levelling techniques. The tide gauge ellipsoidal heights were computed based on the campaign measurements, from a total of 11 campaigns carried out between 1991 and 1999. Centimetric repeatability of vertical positioning has been achieved at these locations. More detail about GPS measurement in these gauges can be found in Dong et al (2002). The Tide gauge sea level at the time of the satellite overpass was obtained by linear interpolation of values integrated over 15 minutes (centred on the hour, 15 minutes past etc.).

The ERS-2 altimeter data employed were those provided by the University of Newcastle. Data were corrected for the Earth body tide and ocean loading in order to reference the altimeter tidal signals to the solid Earth as far as possible for consistency with the gauge. No pole tide correction was applied because the tide gauges will measure the pole tide. The ocean tide difference between tidal gauge and crossover will be corrected by TOPEX derived parameters later. A local geoid model was used to relate the geoid undulation from the altimeter points to tide gauge sea level after a simple transformation of the altimeter data to the GRS-80 reference system. In the present analysis, geoid-differences were obtained from the EGG97 model provided on CD-ROM by H.Denker and colleagues from the Institut für Erdmessung, University of Hannover. EGG97 differs from the earlier EGG96 (Denker et al., 1996) only in the underlying global geoid model and the spectral weights employed. The model error of the geoid difference between tidal gauge and crossover is 1-2 cm.

The ocean tide differences cannot be extracted from ERS-2 data just as we state before. A regional ocean tide model can be used, but in this research ocean tide information were extracted from TOPEX data. No Poseidon data was employed because Poseidon data comprised only 10 percent of TOPEX data and there is a possible relative bias between the TOPEX and Poseidon altimeters.

The altimeter and tidal gauge data was processed in several steps. At first, along track altimeter data was linear interpolated to produce a time series at each crossover point for both TOPEX and ERS-2 sea surface height. In this step, no filter was used

for either TOPEX or ERS-2 altimeter data because of edge effect problem. Among 6 tidal gauges, 5 are coastal gauges, so that most calibration sites are too close to the end of continuous observations. In another side, the along track noise should have not little affect to TOPEX derived tidal parameters. Then 15 minute interval tidal gauge data was interpolated according to TOPEX and ERS-2 time series respectively. The TOPEX altimeter data and corresponding tidal gauge data was used to extract the tide differences between tidal gauge and crossover point. After these tidal parameters are applied to ERS-2 time series, one ERS-2 bias could be calculated by average the sea level difference between tidal gauge and ERS-2 using equation 1.

3 Tide Difference Error of the S₂ Constituent

Because the ERS-2 repeat period is exactly 35x2 = 70 times the S₂ period, the ocean tide height of S₂ is frozen at one location. In this case, the error of S₂ constituent cannot be averaged over time as other constituents, so it should be considered as a systematic error.

In the process of ERS-2 calibration, the systematic error due to S₂ constituent is not caused by S₂ at either the tide gauge or the calibration site, but by the S₂ tide-difference. Based on this concept, the differences of main ocean tide constituents between tide gauge and calibration site can be estimated. The sea level difference Δh can be fitted with a harmonic representation

$$\Delta h = \Delta a + \Delta b \cdot t + \sum_j [\Delta c_j \cos(\omega_j t) + \Delta d_j \sin(\omega_j t)] \quad (2)$$

where, Δa and Δb are mean sea level at epoch and the rate of change of mean sea level. ω_j is the angular frequency of constituent j. Δc_j and Δd_j are the parameters of constituent j. The coefficients Δc_j and Δd_j can be estimated from the sea level differences series by least squares method.

For the method of least squares, the observation equations are written

$$Y = H \cdot X + \varepsilon$$

$$A = (H^T H)^{-1}$$

where

Y = observations
A = given parameters
X = estimated parameters
 $\mathcal{E}$ = errors

Let A_{cc} and A_{dd} be the elements of the principal diagonal of matrix A corresponding to coefficient Δc_j and Δd_j (S_2 constituent). Their formal error can be calculated as

$$\sigma_{\Delta c} = \sqrt{A_{cc}} \sigma_{\Delta h}$$

$$\sigma_{\Delta d} = \sqrt{A_{dd}} \sigma_{\Delta h}$$

Here, $\sigma_{\Delta h}$ is standard derivation of the residuals.

In the case of ERS-2, the observation time passing the calibration site for cycle N is

$$t = (N-1)T + t_0$$

So

$$\omega \cdot t = \omega(N-1)T + \omega \cdot t_0 = 2(N-1)\pi + \omega \cdot t_0$$

where

t_0 = time of ERS-2 passing the calibration site at cycle 1

T = exact repeat period for one cycle (35 days for ERS-2)

So, the tidal height difference of S_2 tide when ERS-2 passes the calibration site is

$$\Delta h_{S_2} = \Delta c_{S_2} \cos(\omega_{S_2} t) + \Delta d_{S_2} \sin(\omega_{S_2} t)$$

$$= \Delta c_{S_2} \cos(\omega_{S_2} t_0) + \Delta d_{S_2} \sin(\omega_{S_2} t_0)$$

where

Δh_{S_2} = tidal height difference of S_2 between tide gauge and calibration site

Δc_{S_2} , Δd_{S_2} = parameters of constituent S_2

Because the coefficients a and b are independent, then,

$$\sigma^2_{\Delta h_{S_2}} = \sigma^2_{\Delta c_{S_2}} \cos^2(\omega_{S_2} t_0) + \sigma^2_{\Delta d_{S_2}} \sin^2(\omega_{S_2} t_0)$$

$$= A_{cc} \sigma^2_{\Delta h} \cos^2(\omega_{S_2} t_0) + A_{dd} \sigma^2_{\Delta h} \sin^2(\omega_{S_2} t_0)$$

In practice, A_{cc} is nearly equal to A_{dd} because that there are enough TOPEX cycles (about 300 in this paper) used and the exact repeat period of TOPEX is significantly different to the period of the S_2 constituent. So we have

$$\sigma^2_{\Delta h_{S_2}} \approx A_{cc} \sigma^2_{\Delta h}$$

The above equation shows the system error due to the S_2 constituent is not sensitive to the time when ERS-2 passes over the calibration site. So that S_2 causes a local bias for any sun-synch satellite and therefore the local S_2 errors can be calculated at each dual-crossover location (as shown in Table 1).

Table 1. Absolute bias of ERS-2 altimeter

T Pass	E Pass	Dis (km)	N	EB (cm)	RMS (cm)	ES ₂ (cm)	TB (cm)	Nam
189	887	46.7	46	47.1	5.7	0.6	-1.6	LW
094	515	83.7	47	51.1	8.2	1.1	10.5	LW
189	704	45.7	48	44.3	5.7	0.6	0.9	LW
170	160	67.5	46	42.2	7.2	0.7	-3.4	LW
087	057	47.4	50	38.1	5.3	1.0	-1.3	AB
196	057	52.0	49	37.5	4.3	1.1	-0.1	AB
087	618	57.4	49	46.4	6.0	1.0	-1.2	AB
196	618	58.6	49	47.0	5.3	1.1	-1.2	AB
163	057	96.5	52	32.2	7.4	1.5	-1.2	NS
239	446	122.9	51	60.3	7.1	2.0	7.8	NS
120	532	36.4	46	60.3	3.1	0.8	3.7	NS
120	601	27.4	50	41.6	5.5	0.8	1.2	NS
137	973	57.1	51	49.0	15.6	2.6	7.7	LO
120	973	63.5	48	38.7	11.3	2.0	-0.4	LO
137	732	79.7	49	40.6	13.8	3.1	4.6	LO
120	274	59.7	48	38.3	8.6	1.9	1.0	LO
137	687	67.4	41	46.2	14.1	3.8	1.9	NH
137	360	112.9	44	39.4	20.9	5.6	-1.5	NH
222	687	42.1	42	45.3	9.1	2.6	0.4	NH
222	360	41.3	44	43.1	9.3	2.6	0.8	NH
239	573	74.0	52	41.1	9.4	1.6	-0.8	NL
070	029	59.5	48	42.5	11.3	2.1	0.1	NL
239	160	73.0	54	45.7	13.3	3.1	0.5	NL
070	704	53.2	49	39.2	8.2	2.1	-0.2	NL

TP, TOPEX pass index; EP, ERS-2 pass index; D, Distance between tidal gauge and crossover location; N, number of ERS-2 altimeter data; EB, time-average ERS-2 bias; RMS, the standard derivation of EB; ES₂, error of S_2 tide difference; TB, time averaged TOPEX bias; Nam, tidal gauge name; LW, Lerwick; AB, Aberdeen; NS, N.Shields; LO, Lowestoft; NH, Newhaven; NL, Newlyn

4 ERS-2 Absolute Bias Results

Table 1 presents estimates of bias for each of the tide gauges employed in this research (4 crossovers were used for each tide gauge). At each site, at least

41 valid ERS-2 observations were obtained from total 55 cycles available.

Although the ERS-2 bias values obtained were found varying over 32.2cm to 60.3cm, we found the worst values are occurred on N. Shields. The numbers from remaining 5 gauges fell in a reasonable range of 38.1cm-51.1cm, while the differences between TOPEX biases (column 8 in table 1) are a few centimeters at the same crossover points. However, while the bias value obtained using different gauges are essentially the same (to within 13cm), the result from North Shields is very bad. At North Shields, the bias values of two ERS-2 descending passes (pass 446 and 532) are more than 20cm larger than those of the corresponding two ascending passes.

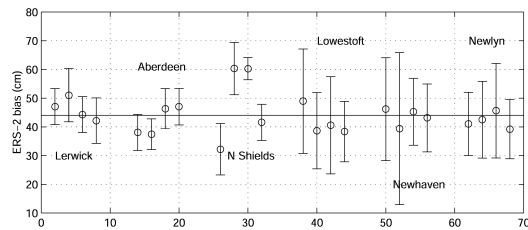


Fig. 2 ERS-2 bias in cm. The average over 24 numbers is 44.0cm with a standard deviation of 6.6cm.

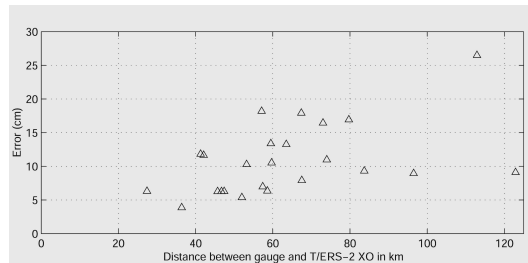


Fig. 3 shows the relation of error (including formal error and the systematic error of S_2 constituent) as a function of the distance from the tide gauge to the crossover point.

The formal error of S_2 tidal height, which manifests itself as local bias in the case of ERS-2 data, is only 1 cm at North Shields, so it cannot be responsible for above bias difference. Meanwhile, the mean TOPEX bias at these two ERS-2 descending passes is 5.7cm greater than that at two ascending passes, which suggest sea surface topography difference and Geoid model error cannot explain most of the difference. One possible explanation concerns radial orbit error. The zeroth-order radial orbit errors due to the static geopotential is time independent at each location along ascending or descending track, but they are

different for ascending pass and descending pass even at the same location (Rosborough, 1986). This may causes a big local bias somewhere. A short-arc precise orbit determination with the Herstmonceux laser ranging system or other precise ephemeris may help to answer this question. These biases with the error (formal error plus S_2 error) also plot in figure 2. The average bias over 24 crossover points were 44.0cm with a root mean square error of 6.6cm.

Figure 3 shows the relation between ERS-2 bias error (including formal error and the systematic error of S_2 constituent) and distance from the tide gauge to the crossover point. It seems the error is below 12 cm when the distance is less than 55km. When the distance increases to 55-80km, the errors may reach to about 18 cm. An error of 26.5cm occurs in Newhaven, where the sea level change is relative complex. We also can found from table 1 that there is smaller rms for 3 northern gauges where the sea is more open where the 3 southern gauges located. So, for coastal tidal gauges, the altimetric sea level signal is still difficult to be cancelled by nearby tidal gauge even the distance is only about 100 km.

There is not always another high-precision altimeter flying simultaneously when a sun-synchronous altimeter needs to be calibrated. In that situation, historical altimeter data provide a possibility to be used to calculate the tide parameters at a calibration site, as the main characteristics of the tide hardly change in a few years. To test this possibility, the first 2 years (1993-1994) of TOPEX data was used to extract the tide parameters instead of using all TOPEX data set as before. In this case, the resulting ERS-2 average bias was found to be 43.4cm, little different to the result obtained using the complete TOPEX data set. At most sites, the differences are no more than 5 cm, but 2 sites with TOPEX descending pass show a significant difference (Figure 4, plotted as crosses). Further information shows there are only 32 and 33 TOPEX observations existing during the first two years at these two sites, which seem not enough to provide a stable solution for 26 tidal parameters estimated in equations 2. When the data sample was extending to 1000 days, biases at these two sites are close to that from whole TOPEX data set (Figure 4, plotted as circles). Although the difference reached a few centimeters at single calibration site, the average bias difference over all 24 calibration sites is less than 1 cm for both cases. It suggests that available TOPEX data set has the

ability to provide useful tidal information for the calibration of future sun-synchronous altimetry.

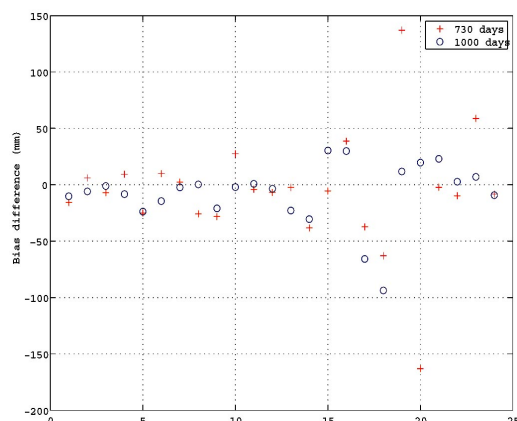


Fig. 4 difference of the bias by using full TOPEX data and first 700(cross)/1000(circle) days data.

5 Summary

As an extension of TOPEX/Poseidon absolute calibration, UK tide gauge data, TOPEX-derived tidal parameters, GPS measurements and a local geoid model are used to provide an absolute calibration for ERS-2 altimeter. The calibration sites were chosen at TOPEX/ERS-2 dual-crossover so the TOPEX data was used to correct ocean tide in ERS-2 altimeter data. A segment-by-segment method was introduced to search these crossovers nearby tidal gauges.

In the case of ERS-2, the ocean tide height of S_2 is frozen at one location as a local bias, so it will produce a systematic error. This error is not sensitive to when ERS-2 passes over the calibration site, and the paper also gives a formula to estimate this error. Over 24 crossovers used here, this error changes from no more than 1 cm to 5.6 cm in different sites. So using more tide gauges seems helpful to reduce the effect of S_2 tidal error.

The time-averaged ERS-2 biases derived over 24 crossovers fit each other without no more than 13 cm except for N Shields. There, the bias values of two ERS-2 descending passes (pass 446 and 532) are more than 20 cm larger than those of the corresponding two ascending passes. Neither S_2 tidal error, sea surface topography nor Geoid model error can explain this difference. A possible source is geography-related orbit error due to potential model error, which may be examined by short arc precise orbit determination or using other precise

ephemeris. After all, the average value over 24 biases was 44.0 cm with a root mean square error of 6.6 cm.

The relation of calibration error and the distance seems not very clear, although the error is less than 12 cm when the distance is close than 55 km in compare with about 18 cm when the distance increases to 55–80 km. An obvious fact is smaller rms for 3 northern gauges where the sea level signal is less complex. It seems the altimetric sea level signal is still difficult to be cancelled by nearby coastal tidal gauge even the distance is only about 100 km.

The possibility of using historical altimeter data provides tide parameters for the calibration of future altimeter missions. When the first 1000 days TOPEX data (which not overlap ERS-2 mission) was used to calculate ERS-2 bias, the mean of 24 differences is less than 1 cm although the difference reached quite a few centimeters at single calibration site. It suggests that available TOPEX data set has the ability to provide useful tidal information for the calibration of future sun-synchronous altimetry.

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