Tidal corrections of the ERS-1 satellite altimeter data in the Mediterranean Sea

D. Arabelos, S.D. Spatala, I.N. Tziavos

Department of Geodesy and Surveying, University of Thessaloniki
540 06 Thessaloniki, Greece.

M. Sevilla, C. de Toro, R. Vieira

Instituto de Astronomia y Geodesia (G.S.I.C. -U.C.M.), Facultad de Cienzias Mathematicas
Ciudad Universitaria, 28040 Madrid, Spain.

Abstract. *Two tidal models for the Mediterranean Sea are recently available. From these models tidal heights have been computed and used to correct the altimeter data of the first 10 ERM's of ERS-1. Comparisons of the statistics of the differences between ERS-1 and OSU91 before and after the tidal correction do not present a significant improvement. In terms of the standard deviation (sd) of the aforementioned differences a small decrease is observed for most of the ERM's, but there are also cases in which the sd increases. Significant information was obtained by analyzing the power spectrum at main tidal frequencies during the stacking procedure of the altimeter data. Another test carried out in our study was the comparison of the results of the crossover analysis of the ERS-1 data in the Mediterranean before and after the tidal correction. The very small decrease (at the order of several mm) of the rms of the crossover differences after the tidal correction could be inperpreted either as ineffectiveness of the model or as an indication that the tidal signal in the Mediterranean is weak enough and for this reason could be ignored in several applications.*

Introduction

Tidal corrections is necessary to be applied to satellite altimeter data especially in open oceans. In such cases there are global tidal models available for more than ten years ago (e.g. Schwiderski, 1980 a,b, 1983). The tidal information is needed in two phases of the processing of the data, i.e., during the orbit estimation procedure as well as for the correction of the individual altimeter heights. In closed sea areas like Mediterranean Sea the amplitude of the tidal effect is small in comparison to that in extended open ocean areas. Consequently, the tidal effect it is not expected to affect the orbit estimation. Moreover, for data of the Exact Repeat Mission (ERM) type, the tidal effect is minimized or vanished through the stacking procedure of the data. This is useful for some applications such as the estimation of the sea surface heights (SSHs) in areas where tidal models are not available. On the other hand tidal corrections of the altimeter data are necessary in oceanographic and other applications.

It is well known that the global tidal models are not valid for closed seas. Recently, two tidal models have been computed for the Mediterranean: The first one for the Western and Central part of the Mediterranean (Toro et al., 1993), further on called CSIC model, and the second one for the entire area (Canceill, et al., 1992), further on called CNES model. Both models are based on surface data and have been computed using different methods. A direct comparison of tidal models is not possible, since they are composed from amplitude and phase parameters. On the other hand it is interesting to have a comparison of the tidal models with an independent source like satellite altimeter data, since the tidal information is inhered in the altimetric signal. In the frame of this comparison it is also very interesting to check the importance of the tidal corrections on altimeter data in the Mediterranean basin, especially for applications in physical geodesy .

In this case our expectation is that, after the tidal correction, the altimeter data should be more smooth, e.g., in terms of the sd of the differences between SSH and OSU91A geopotential model. This expectation is based on the instantaneous character of the tidal effect.

The goal of this study was to investigate these models by analyzing the effect of the tidal correction on the individual altimeter heights and to give an assessment of their quality. More explicitly, our study was based on the comparison of the statistics of the ERS-1 altimeter data, as well as on the comparison of the results of the crossover analysis before and after the tidal corrections. Moreover, the comparison of the power spectrum at main tidal frequencies before and after the tidal corrections was a useful tool in order to assess the quality of the models.

The tidal Models

1. *CSIC model.*

The CSIC tidal model for the Western and Central Mediterranean consists of only three semidiurnal constituents (M2, S2 and N2) and is valid for the sea area $[35^o \leq \phi \leq 45^o, -5.5^o \leq \lambda \leq 8.25^o]$. The modeling for the amplitudes and the phase differences was carried out through the smooth surface fitting with irregular distributed data points of a considerable number of non singular stations. The interpolation function was estimated for the nodes of a set chosen in a way to adapt itself in a best possible way to the coastal boundaries.

2. *CNES model*

The CNES tidal solution for the entire Mediterranean consists of nine tidal groups, 4 main semidiurnal (M2, S2, K2, and N2), 4 main diurnal (K1, P1, O1 and Q1) and one quarter diurnal (M4). This solution was computed by means of a finite element in-time spectral hydrodynamical model, taking into account the propagation driven by the Atlantic input tidal wave and the astronomical tide generating potential and ignoring meteorological effects. According to Canceill et al. (1993) the accuracy is about 1 cm for the amplitudes of M2 and S2, 0.5 cm for the other wave groups and 15 degrees for the phase differences. This accuracy estimation was based on comparisons with a set of 84 tide gauges. In our experiments the quarter diurnal wave M4 was not used.

Data analysis

The editing procedure of the ERS-1 altimeter data has been made by the same way with that described in a previous paper (see, Arabelos et al., 1993). Tidal heights have been computed at a number of 54089 subsatellite points distributed in the entire Mediterranean using the CNES model and 11608 subsatellite points distributed in the Western and Central part using the CSIC model. These tidal heights have been used for the correction of the above mentioned subsatellite points. Four different files were created including tidal corrected and uncorrected data. Two of the files are referred to the Western and Central Mediterranean and two to the entire Mediterranean. In Tables 1-3, the statistics of the tidal heights, and of the differences (ERS-1 – OSU91A) before and after the tidal correction is presented for the following cases: (a) CNES model, entire Mediterranean, (b) CNES model, Western and Central part and (c) CSIC model, Western and Central part.

The range of the tidal heights according to CNES model within the period of 34 days for the entire Mediterranean is not negligible (0.4 m for the ERM 1 to 1.05 m for the ERM 10) as it is shown in Table 1. The corresponding sd varies from 5.8 to 7.2 cm. The effect of the tidal corrections on the ERS-1 altimeter data according to CNES model is observed by comparing the statistics of the differences (ERS-1 – OSU91A) for each of the 10 ERMs before and after the tidal correction. It was expected a decrease of the sd of these differences after the tidal correction. On the contrary, there are only 7 ERMs (marked by a star) presenting a small decrease of the sd at the order of several mm, while in 3 ERMs the sd increased.

The same effect is observed in Tables 2 and 3, where a direct comparison of the effect of the tidal corrections according to each of the two models on the same altimeter data is possible.

There is a small disagreement (up to 6.8% in the case of ERM 2) in the number of data of each ERM. This disagreement is due to the different way followed by each model to adapt the coastal boundaries and could not distort the results of the statistics. In the case of CNES (Table 2) there are only 4 ERMs presenting a decrease of the sd after the correction, while in the remaining 6 ERMs a increase of the sd up to 2.5 cm is found. The situation is slightly better with CSIC model (Table 3): 6 ERMs show decrease of the sd after the correction, 3 ERMs show increase, while in two ERMs there is no change of the sd after the tidal correction. Concerning the range of the tidal heights within a 34 days period, the tidal correction is considerably higher in the case of CNES model than that of CSIC model. The same is valid for the sd of the tidal heights.

Commenting the results mentioned above it is not easy to decide about the effectiveness of the tidal corrections of the altimeter data using the models under consideration. Trying to explain this behavior of the tidal corrections the tidal heights along a number of selected tracks were plotted (see Figure 1). Tracks 325 and 10 belong to the Western part of the Mediterranean covered by both models, while tracks 840 and 88 belong to Central and Eastern Mediterranean, respectively. The tidal heights along these tracks are shown in Figures 2 to 9.

From Figures 2 and 3 it is evident that not only the amplitude but also the phase difference are quite different in the two models: For CSIC model (Fig. 2) an increase of the tidal height is observed when the time increases. The absolutely different situation is valid for the CNES model (Fig. 3). Moreover, there are some other problems affecting the models in a different way. So the CNES tidal heights present discontinuities (expressed by the characteristic step form of his plot) probably due to numerical problems during the finite element solution or to low resolution. The CSIC model presents also some large local distortions like those shown on the left side of Figure 2, or on the right side of Figure 4 or the smaller observed in the centre of Figures 4 and 6, but in general is smoother than the CNES model.

In the case of track 325 (see Figures 4 and 5) the pattern of the tidal heights from the two models is almost similar, but there is a serious amplitude and phase shift between them. After 34 days (one repeating period) in the place of the track 325 we have the track 826. Now the agreement of the two models is much better than before both in amplitudes and in phases as it is evident in Figures 6 and 7.

Table 1. Statistics of the tidal heights and of the differences of (SSH - OSU91) before and after the tidal correction for the first 10 ERM's of ERS-1 according to CNES tidal model. Test area is the entire Mediterranean Sea. Unit is (m).

		Tidal heights				ERS-1 – OSU91 (before the tidal correction)				ERS-1 – OSU91 (after the tidal correction)			
ERM	Number of data	Min. value	Max. value	Mean value	Standard deviation	Min. value	Max. value	Mean value	Standard deviation	Min. value	Max. value	Mean value	Standard deviation
1	4601	–0.189	0.376	–0.002	0.070	–3.348	4.265	0.058	1.363	–3.350	4.141	0.060	1.361*
2	5523	–0.657	0.307	0.004	0.068	–4.587	3.804	0.037	1.253	–4.574	3.792	0.032	1.249*
3	4357	–0.287	0.188	–0.001	0.071	–3.583	5.228	0.167	1.327	–3.616	5.116	0.168	1.329
4	4479	–0.241	0.287	0.005	0.072	–4.038	4.583	–0.363	1.260	–4.084	4.596	–0.368	1.271
5	3999	–0.771	0.165	0.017	0.072	–3.270	5.999	0.332	1.310	–3.182	6.106	0.349	1.307*
6	4891	–0.216	0.188	–0.001	0.058	–4.122	4.323	0.257	1.290	–4.148	4.278	0.259	1.284*
7	7323	–0.418	0.302	0.004	0.070	–3.918	4.824	0.067	1.482	–3.847	4.854	0.063	1.471*
8	6969	–0.379	0.210	0.000	0.069	–4.350	5.981	0.447	1.826	–4.502	5.942	0.448	1.836
9	5896	–0.340	0.181	–0.005	0.069	–4.332	3.862	-0.228	1.332	–4.288	3.834	–0.223	1.320*
10	6751	–0.773	0.276	0.004	0.072	–3.407	5.084	0.150	1.421	–3.453	5.055	0.146	1.420*

* decrease of the standard deviation of the differences (SSH– OSU91) after the tidal correction.

Table 2. Statistics of the tidal heights and of the differences of (SSH - OSU91) before and after the tidal correction for the first 10 ERM's of ERS-1 according to CNES tidal model. Test area is the Western Mediterranean Sea. Unit is (m).

		Tidal heights				ERS-1 – OSU91 (before the tidal correction)				ERS-1 – OSU91 (after the tidal correction)			
ERM	Number of data	Min. value	Max. value	Mean value	Standard deviation	Min. value	Max. value	Mean value	Standard deviation	Min. value	Max. value	Mean value	Standard deviation
1	1187	–0.163	0.147	–0.010	0.068	–2.909	2.405	–0.760	1.127	–3.039	2.378	–0.750	1.151
2	1171	–0.112	0.161	0.013	0.072	–3.957	2.254	–0.806	1.111	–3.941	2.295	–0.819	1.136
3	813	–0.144	0.162	0.001	0.069	–3.583	2.756	–0.430	1.294	–3.616	2.770	–0.431	1.323
4	1073	–0.135	0.170	–0.035	0.085	–3.230	2.507	–0.990	1.098	–3.161	2.540	–1.025	1.121
5	910	–0.110	0.112	0.020	0.053	–3.178	2.605	–0.053	1.501	–3.270	2.624	–0.073	1.517
6	1033	–0.175	0.128	–0.008	0.054	–3.994	2.940	–0.437	1.303	–3.949	2.830	–0.429	1.271*
7	1510	–0.163	0.200	0.016	0.074	–3.918	3.339	–0.697	1.641	–3.847	3.224	–0.713	1.529*
8	1450	–0.104	0.152	0.002	0.081	–4.350	4.292	–0.704	1.582	–4.502	4.297	–0.706	1.576*
9	1202	–0.167	0.150	0.005	0.071	–4.332	2.117	–0.891	1.377	–4.254	2.076	–0.896	1.339*
10	1259	–0.078	0.104	0.022	0.042	–2.963	3.268	–0.506	1.357	–3.003	3.239	–0.528	1.361

* decrease of the standard deviation of the differences (SSH– OSU91) after the tidal correction.

Table 3. Statistics of the tidal heights and of the differences of (SSH - OSU91) before and after the tidal correction for the first 10 ERM's of ERS-1 according to CSIC tidal model. Test area is the Western Mediterranean Sea. Unit is (m).

		Tidal heights				ERS-1 – OSU91 (before the tidal correction)				ERS-1 – OSU91 (after the tidal correction)			
ERM	Number of data	Min. value	Max. value	Mean value	Standard deviation	Min. value	Max. value	Mean value	Standard deviation	Min. value	Max. value	Mean value	Standard deviation
1	1198	–0.184	0.007	0.009	0.047	–2.909	2.395	–0.787	1.117	–2.962	2.316	–0.796	1.111*
2	1091	–0.014	0.068	0.004	0.034	–3.879	1.560	–0.822	1.068	–3.909	1.574	–0.826	1.065*
3	840	–0.035	0.016	0.011	0.052	–2.968	2.756	–0.528	1.314	–2.910	2.726	–0.539	1.294*
4	1043	–0.053	0.046	0.012	0.052	–2.645	2.391	–0.924	1.069	–2.628	2.402	–0.935	1.078
5	918	–0.021	0.003	0.021	0.036	–3.167	2.605	–0.049	1.499	–3.257	2.578	–0.070	1.499
6	1040	–0.027	0.000	0.001	0.046	–3.994	2.940	–0.436	1.299	–4.012	2.885	–0.437	1.285*
7	1556	–0.037	0.042	0.009	0.046	–3.918	3.339	–0.706	1.625	–3.890	3.363	–0.714	1.626
8	1472	–0.025	0.000	0.011	0.035	–4.350	4.292	–0.699	1.580	–4.441	4.327	–0.710	1.580
9	1219	–0.038	0.018	–0.002	0.049	–4.332	2.117	–0.899	1.374	–4.312	2.145	–0.897	1.368*
10	1270	–0.012	0.034	0.013	0.038	–2.900	3.247	–0.506	1.353	–3.006	3.316	–0.518	1.358

* decrease of the standard deviation of the differences (SSH– OSU91) after the tidal correction.

In the last two Figures (8 and 9) tidal heights from CNES model are plotted in the Central and Eastern part of the Mediterranean. The gap at the centre of Figure 8 corresponds to the interruption of the track 840 by the West Sicily. The curve on the left of this Figure probably reflects the propagation of tidal wave through the opening between Sicily and Tunis (840 is an ascending track) while the drop on the right is probably due to the presence of the two big islands Corsica and Sardinia.

Finally, Figure 9 is a plot of tidal heights corresponding to the descending track 88 in the Eastern part of the Mediterranean. In this case the amplitude is considerably high but there is not possible to compare this pattern with another. The step forms appearing in the previous figures are also characteristic in this last figure.

The tidal height depends on three parameters: Latitude, longitude and time. In the case of altimeter data in a closed sea area like Mediterranean, the time needed for one pass of the satellite amounts several tens of seconds, so time could be considered as constant for the same track, i.e. the instantaneous character of the tidal height do not affect the altimeter data in this case.

It is interesting to note that in the case of the entire area with CNES model and into the period of one ERM (35 days) the range of the tidal heights varies between 0.404 m to 1.049 m for the 10 ERMs. In spite of this considerable range, the effect of the tidal correction is too small according to the results of the previous analysis.

Significant information concerning the effect of the tidal correction could also be obtained during the stacking procedure of collinear tracks applied to performe mean tracks. In Fig. 10 the mean track (ERS1 - OSU91) after stacking of the descending tracks 88, 589, 1090, 1591, 2092, 3094, 3595 and 4096, before tidal correction (squares) and after tidal correction using the CNES model (crosses) is presented. The differences (after - before the correction) are shown in Figure 11. It is clear from this figure that the correction in this case corresponds to a displacement of the mean track to about 4 cm downward, while the positive and negative 1 cm peaks probably represent numerical errors. In Figure 12 the differences of the sd of the residuals with respect to the mean track before and after the correction are shown. There are only two peaks at the level of 1 cm due to numerical errors. In Figure 13, the differences of the power at the frequency of M2 waves before and after the correction are plotted. It was expected, a decrease of the power after the tidal correction, since the tidal signal at this frequency should be removed through the correction. On the contrary, we have also cases of increasing power, as well as cases with no change of this magnitude.

Another way to estimate the effect of the tidal correction on the altimeter data was the comparison of the results of the crossover analysis before and after the tidal correction. These results are presented in Table 4. There is again a small disagreement in the number of the data for the reason mentioned before. The study of the results of Table 4 shows also very small changes before and after the correction. The more significant from these changes is the 5 cm decrease of the mean value of the unadjusted crossover differences. It is mentioned that similar results were obtained in the case of a tidal model for the Aigean sea (Arabelos and Spatalas, 1992).

Conclusion

An attempt is made to assess the quality of the tidal models recently available in the Mediterranean and estimate the effectiveness of the tidal corrections on the altimeter data. Several experiments were performed based on the analysis of data corrected by each model separately in the area covered by both models as well as based on the analysis of the data in the entire Mediterranean, before and after the tidal correction according to CNES model.

These experiments show that there are significant differences between the two models.

The sd of the data corrected according to CSIC model is lower, for the most ERMs, than that applied to the data corrected according to CNES. It is interesting to note that the CSIC model describes better the tidal signal in the Western Mediterranean than the CNES model.

The range of the tidal heights according to CNES model varies for the period of one ERM from 0.404 m to 1.049 m. In spite of this considerable range, the effect of the tidal correction is too small. This is clear during the procedure applied to performe mean tracks as well as through the analysis of the crossover differences before and after the tidal correction.

The very small decrease (at the order of several mm) of the rms of the crossover differences after the tidal correction could be inperpreted either as ineffectiveness of the tidal model or as an information that the tidal signal in the Mediterranean is weak enough and for this reason could be ignored in several applications.

Acknowledgements

Thanks are due to O. B. Andersen for supporting the CNES tidal model and the software for the computation of the tidal heights. The paper has been carried out in the framework of the GEOMED project supported by the European Community contract no. SC1*-CT92-0808 and a project in the frame of the bilateral scientific and technological cooperation between Greece and Spain supported by the Research Committee of both countries.

References

Arabelos, D. and S.D. Spatalas (1992): Tidal effect s on satellite altimeter data in a closed sea area. Proceedings of The First Continental Workshop on the Geoid in Europe, Towards a Precise Pan-European Reference Geoid for the Nineties, Prague, May 11-14, 1992.

Arabelos, D, S.D. Spatalas and I.N. Tziavos (1993): Crossover analysis of ERS-1 altimetry in the Mediterranean Sea and inversion of the adjusted data to recover gravity anomalies. Mare Nostrum, GEOMED Report - 3.

Arabelos, D and I.N. Tziavos: Geoid mapping in the Mediterranean Sea using heterogeneous data. In "Mare nostrum" Report of GEOMED project, Milan 1992.

Bracewell, R.: The Fourier transform and its applications. 2nd ed. McGraw-Hill, New York, 1986.

Canceill, P., R. Agelou and P. Vincent, (1992): Barotropic tides in the Mediterranean Sea from a finite element numerical model. Submitted for publication in JGR.

Schwiderski, E.W. (1980): Ocean tides, Part. I: Global ocean tidal equations. Marine Geodesy 3, 161.

Schwiderski, E.W. (1980): Ocean tides, Part. II: A Hydrodynamical Interpolation Model Marine Geodesy 3, 219.

Schwiderski, E.W. (1983): Atlas of the ocean tidal charts and maps, I, The semidiurnal lunar tide M2. marine Geodesy, 6, 219-265.

Tscherning, C.C., R. Forsberg, and P. Knudsen: The GRAVSOFT package for geoid computation. Presented at the 1. Continental Workshop on the Geoid in Europe, Prague, May 11-14, 1992.

de Toro, C., R. Vieira,M.J. Sevilla .(1993): Ocean tidal Models of M2 and S2 constituents for the Western and Central Mediterranean.Mare Nostrum-GEOMED REPORT 3. Milano.

Figure Captions

Fig. 1. ERS-1 test tracks in the Mediterranean Sea. From West to East: 325, 10, 840 and 88.

Fig. 2. Tidal heights along the track 10 according to (CSIC) model. Unit is (cm).

Fig. 3. Tidal heights along the track 10 according to (CNES) model. Unit is (cm).

Fig. 4. Tidal heights along the track 325 according to (CSIC) model. Unit is (cm).

Fig. 5. Tidal heights along the track 325 according to (CNES) model. Unit is (cm).

Fig. 6. The same as in Figure 4, after 34 days. The number of the track is 826. Unit is (cm).

Fig. 7. The same as in Figure 5, after 34 days. The number of the track is 826. Unit is (cm).

Fig. 8. Tidal heights along the track 840 according to (CNES) model. Unit is (cm).

Fig. 9. Tidal heights along the track 88 according to (CNES) model. Unit is (cm).

Fig. 10. Mean track (ERS1 - OSU91) after stacking of the descending tracks 88, 589, 1090, 1591, 2092, 3094, 3595 and 4096, before tidal correction (squares) and after tidal correction using the CNES model (crosses). Unit is (m).

Fig. 11. Differences between the mean tracks of Figure 10. Unit is (m).

Fig. 12. Differences between the sd of the residuals with respect to the mean tracks of Figure 10. Unit is (m).

Fig. 13. Differences between the power at the frequency of M2 waves in the case of mean tracks of Figure 10. Unit is (cm^2).

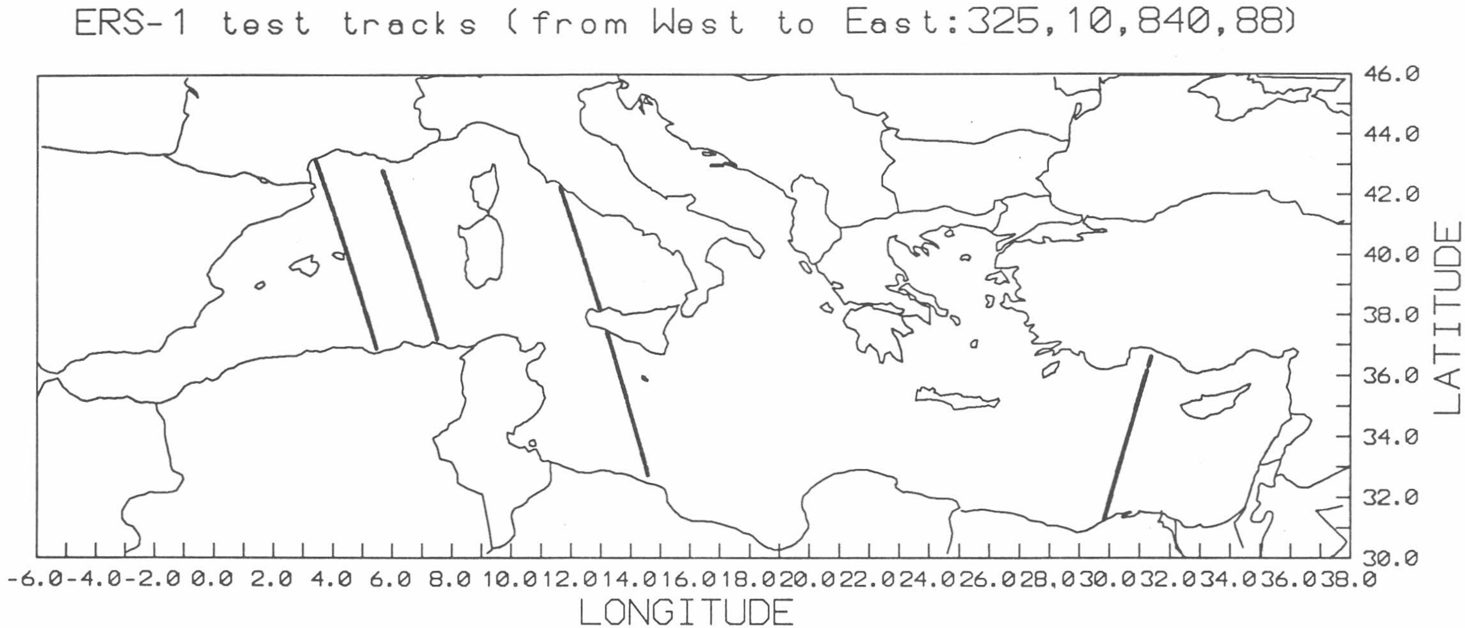

Fig. 1. ERS-1 test tracks in the Mediterranean Sea. From West to East: 325, 10, 840 and 88.

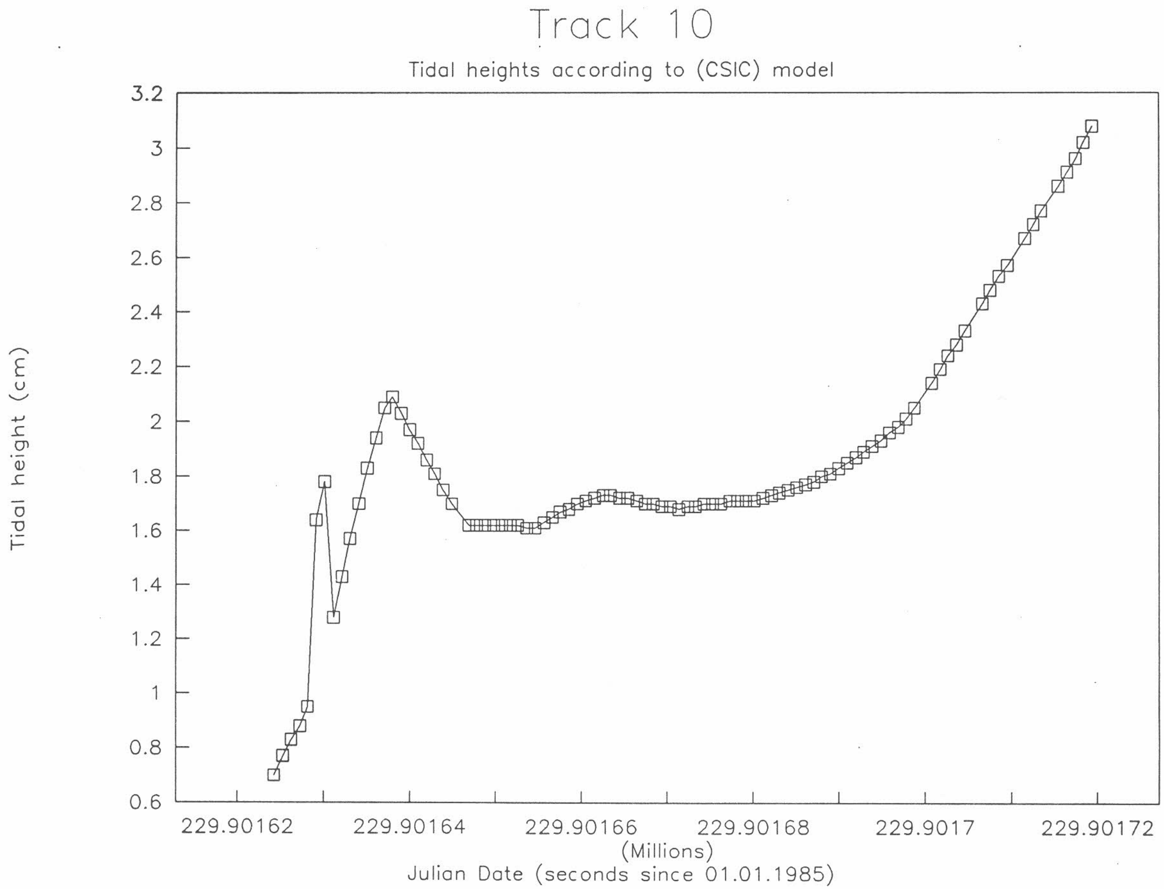

Fig. 2. Tidal heights along the track 10 according to (CSIC) model. Unit is (cm).

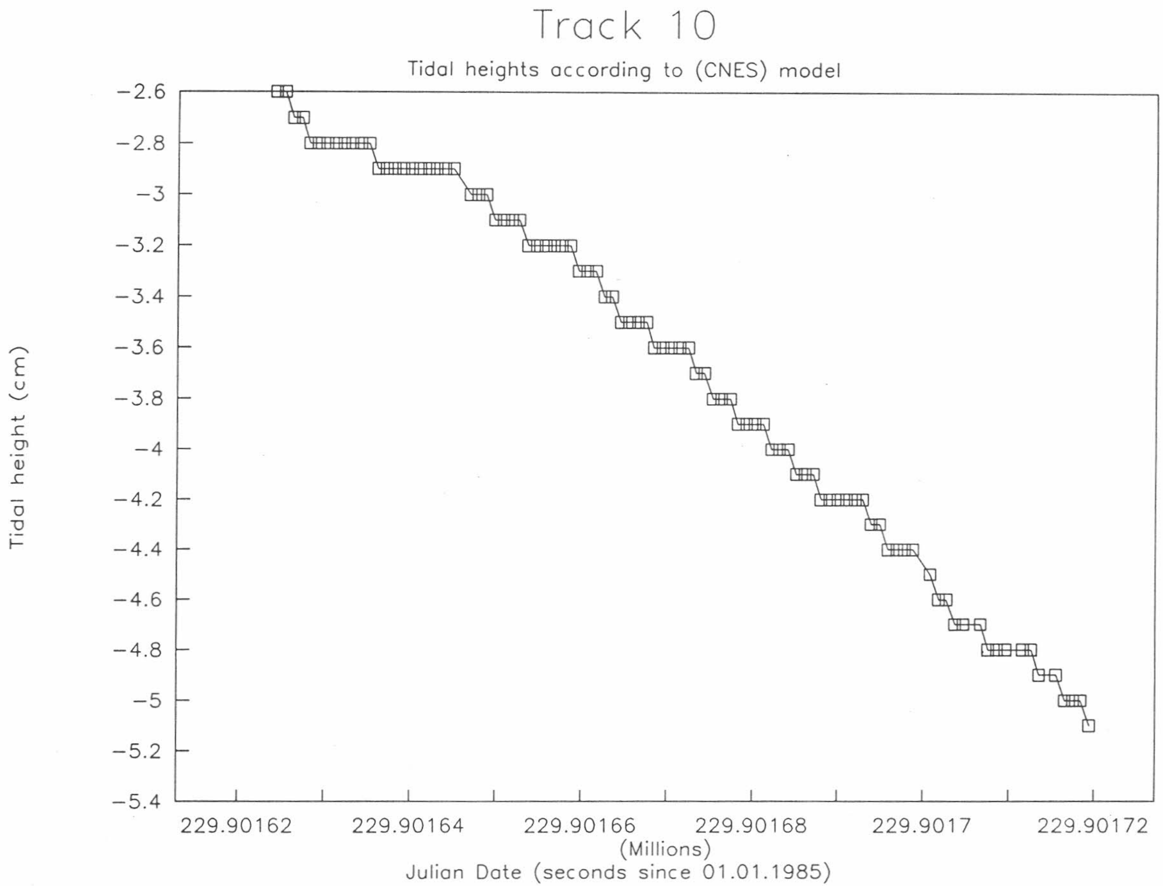

Fig. 3. Tidal heights along the track 10 according to (CNES) model. Unit is (cm).

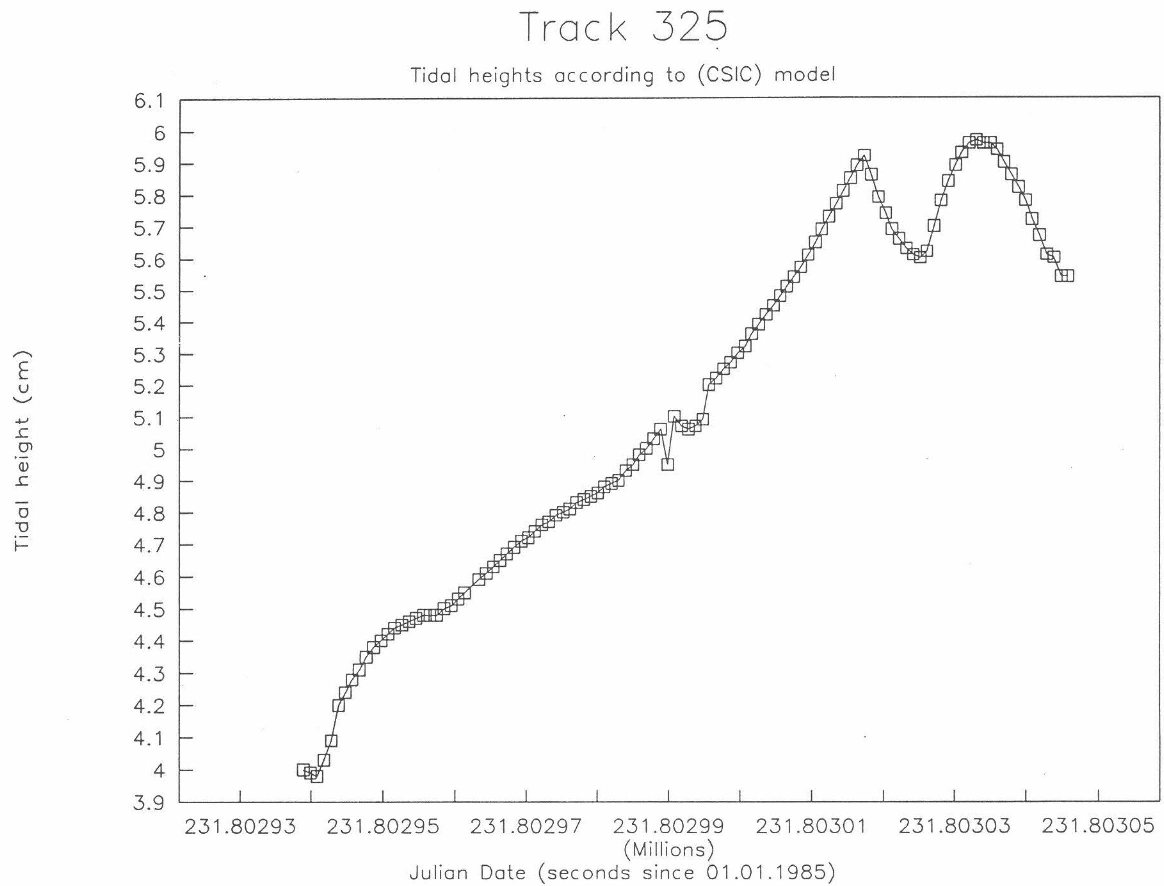

Fig. 4. Tidal heights along the track 325 according to (CSIC) model. Unit is (cm).

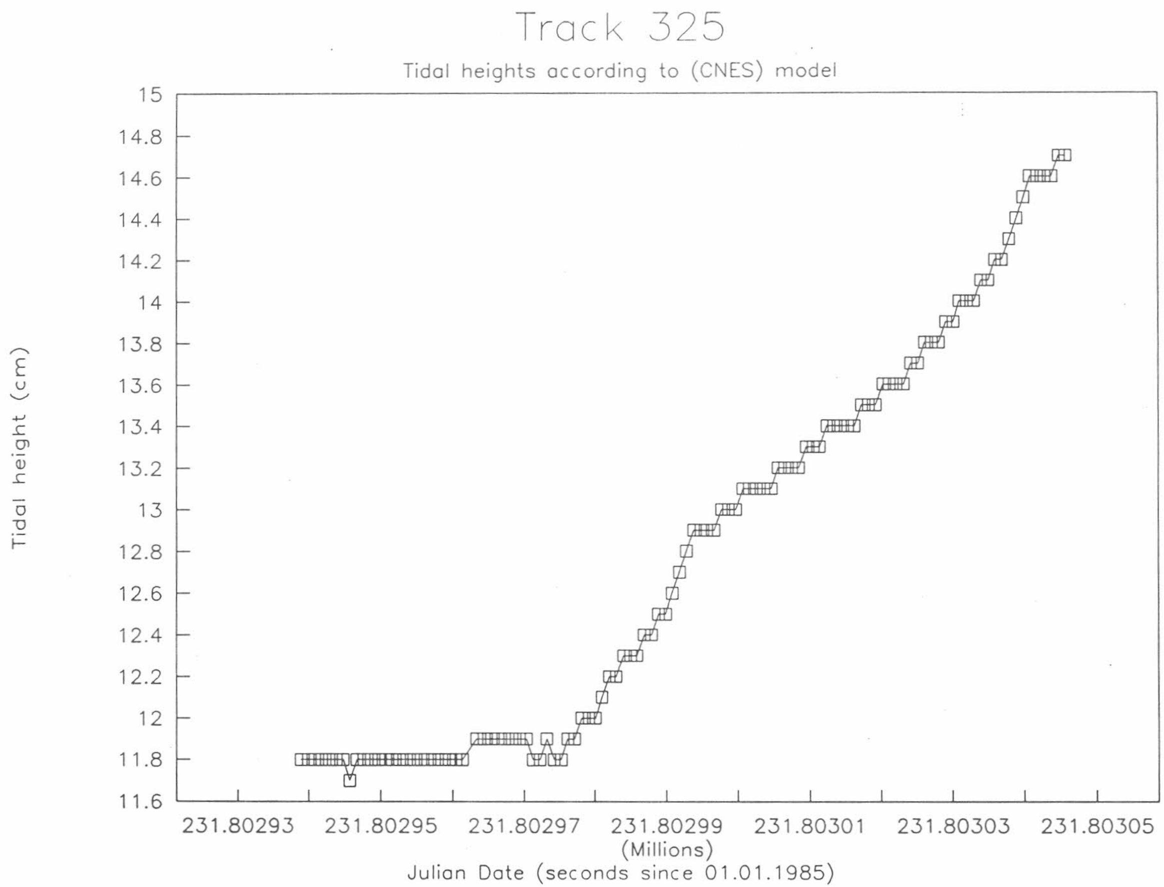

Fig. 5. Tidal heights along the track 325 according to (CNES) model. Unit is (cm).

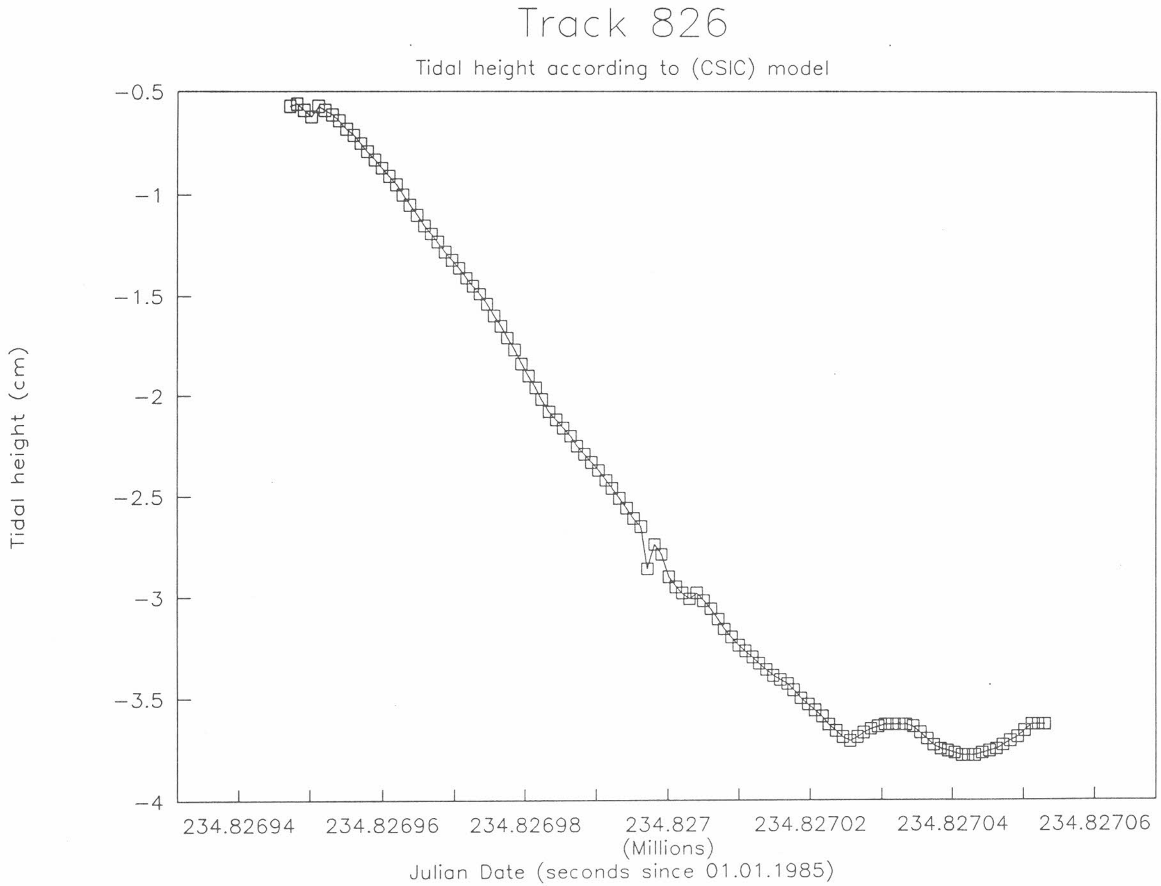

Fig. 6. The same as in Figure 4, after 34 days. The number of the track is 826. Unit is (cm).

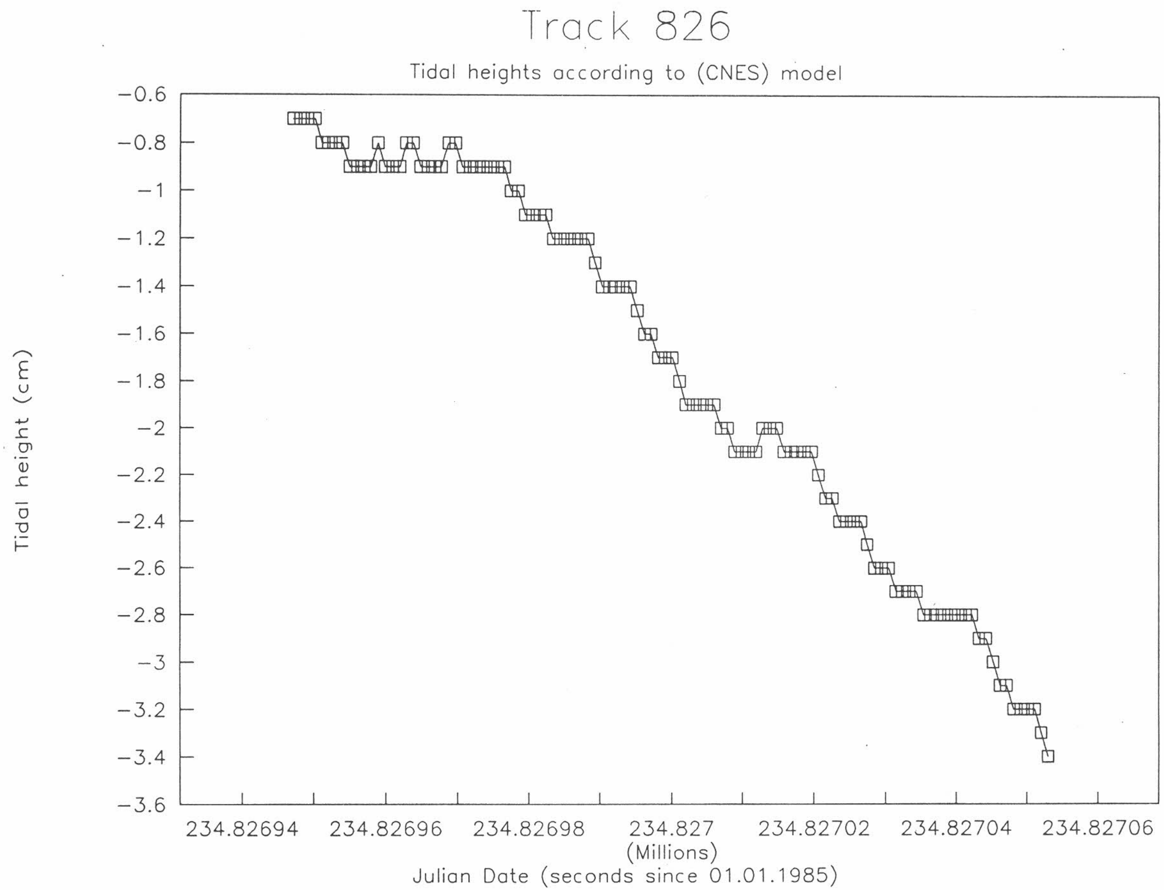

Fig. 7. The same as in Figure 5, after 34 days. The number of the track is 826. Unit is (cm).

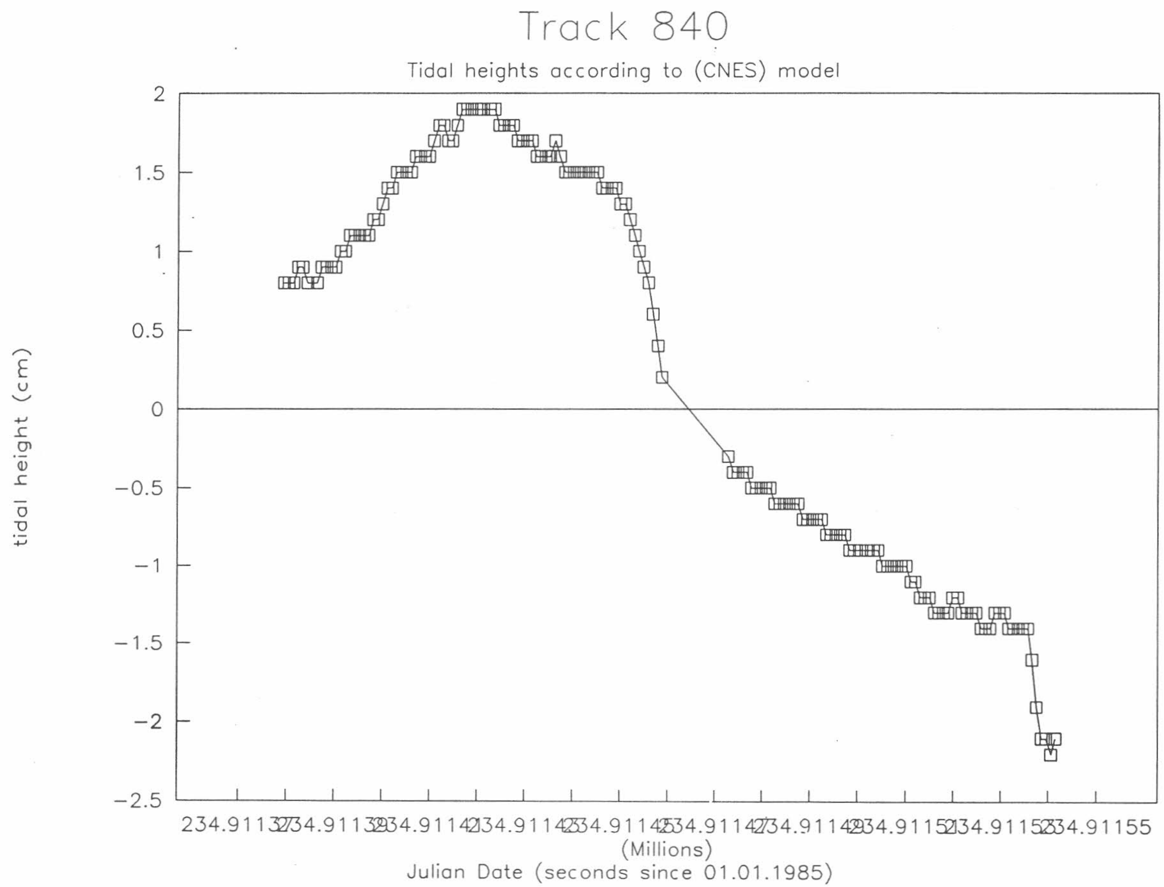

Fig. 8. Tidal heights along the track 840 according to (CNES) model. Unit is (cm).

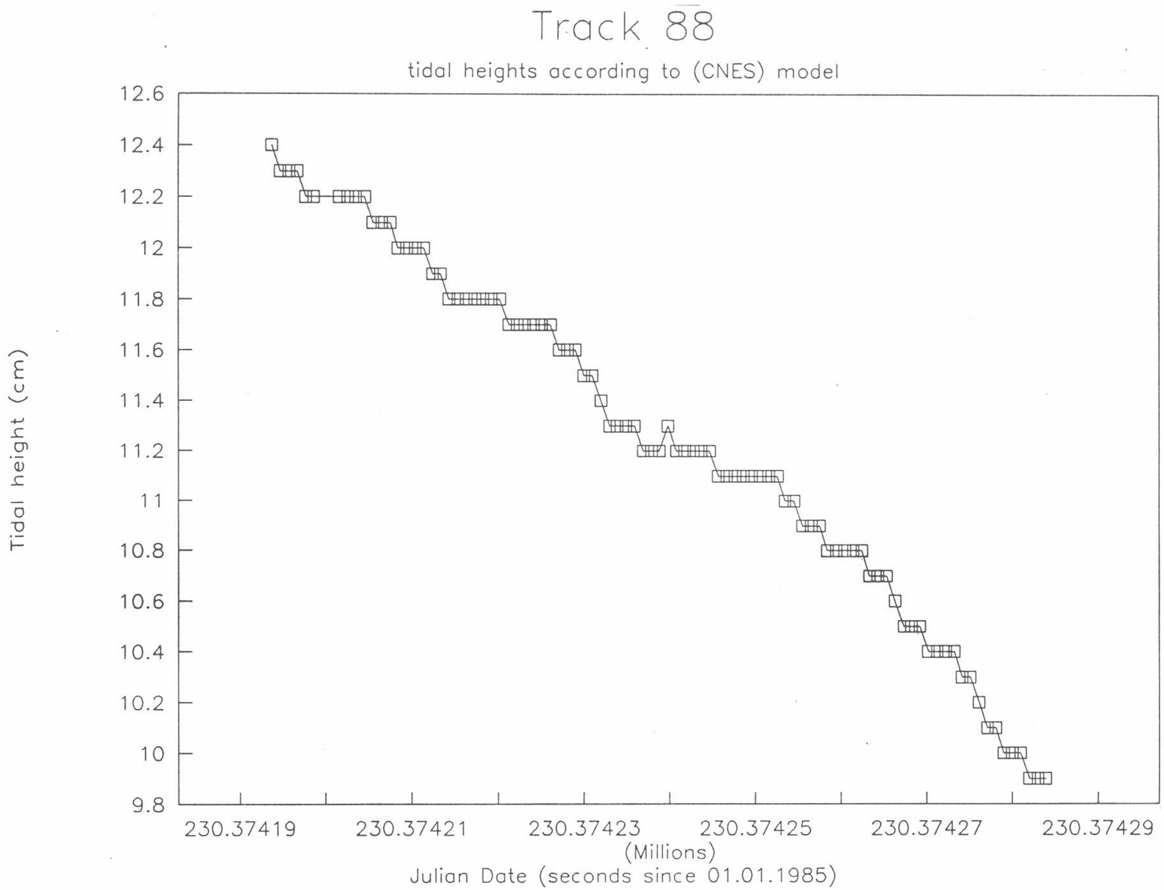

Fig. 9. Tidal heights along the track 88 according to (CNES) model. Unit is (cm).

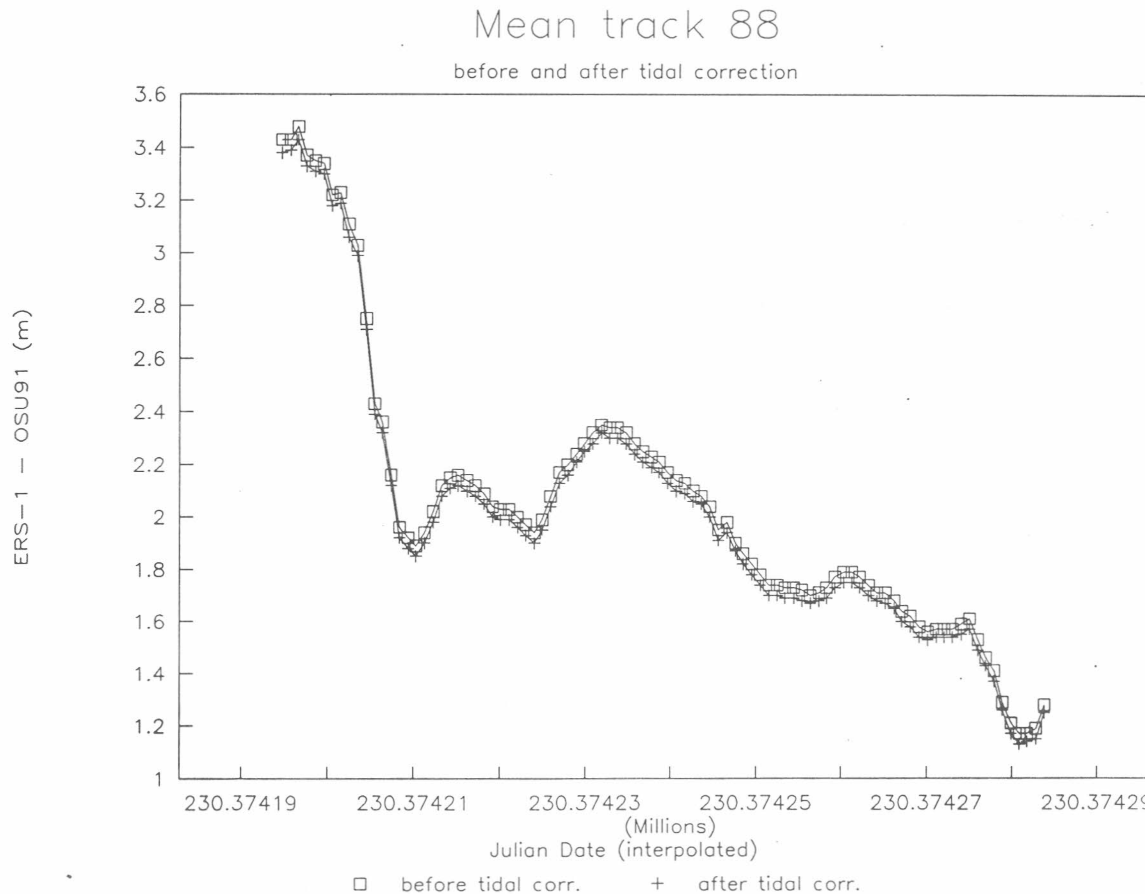

Fig. 10. Mean track (ERS1 - OSU91) after stacking of the descending tracks 88, 589, 1090, 1591, 2092, 3094, 3595 and 4096, before tidal correction (squares) and after tidal correction using the CNES model (crosses). Unit is (m).

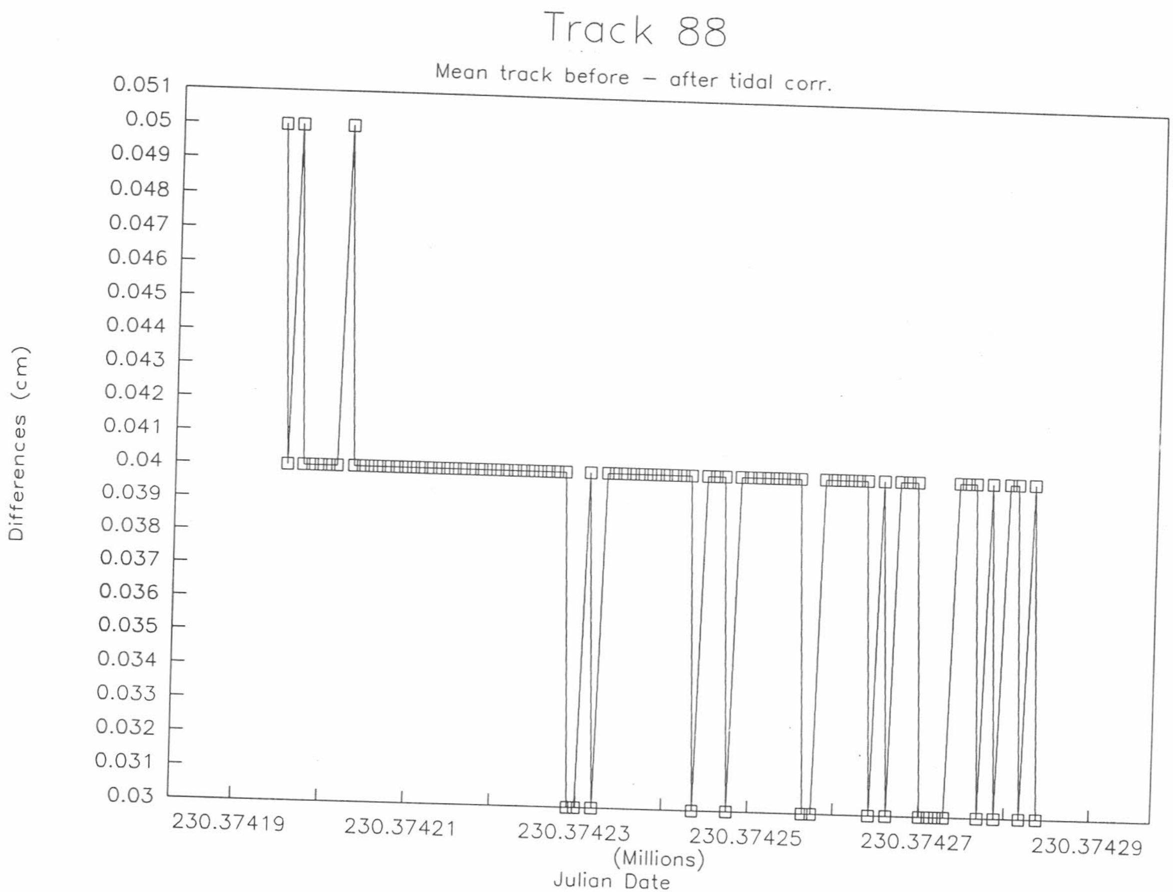

Fig. 11. Differences between the mean tracks of Figure 10. Unit is (m).

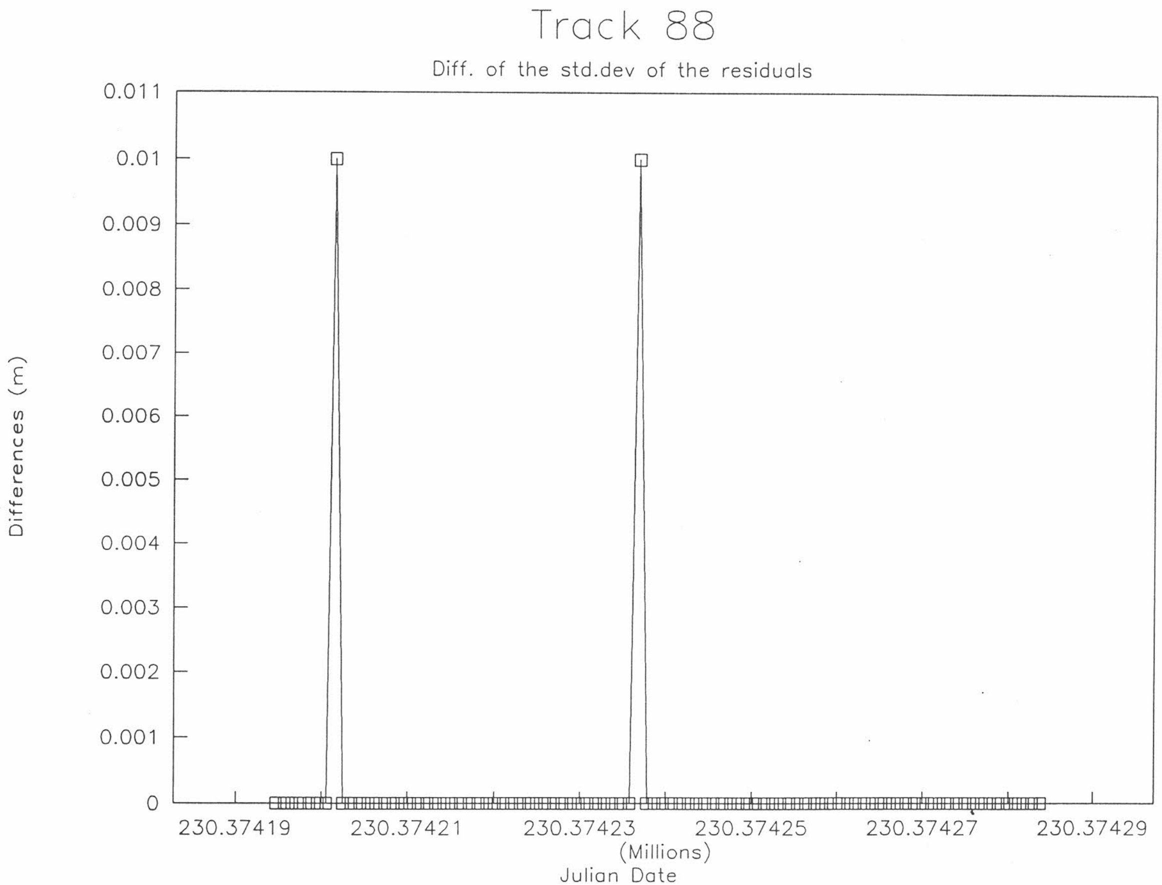

Fig. 12. Differences between the sd of the residuals with respect to the mean tracks of Figure 10. Unit is (m).

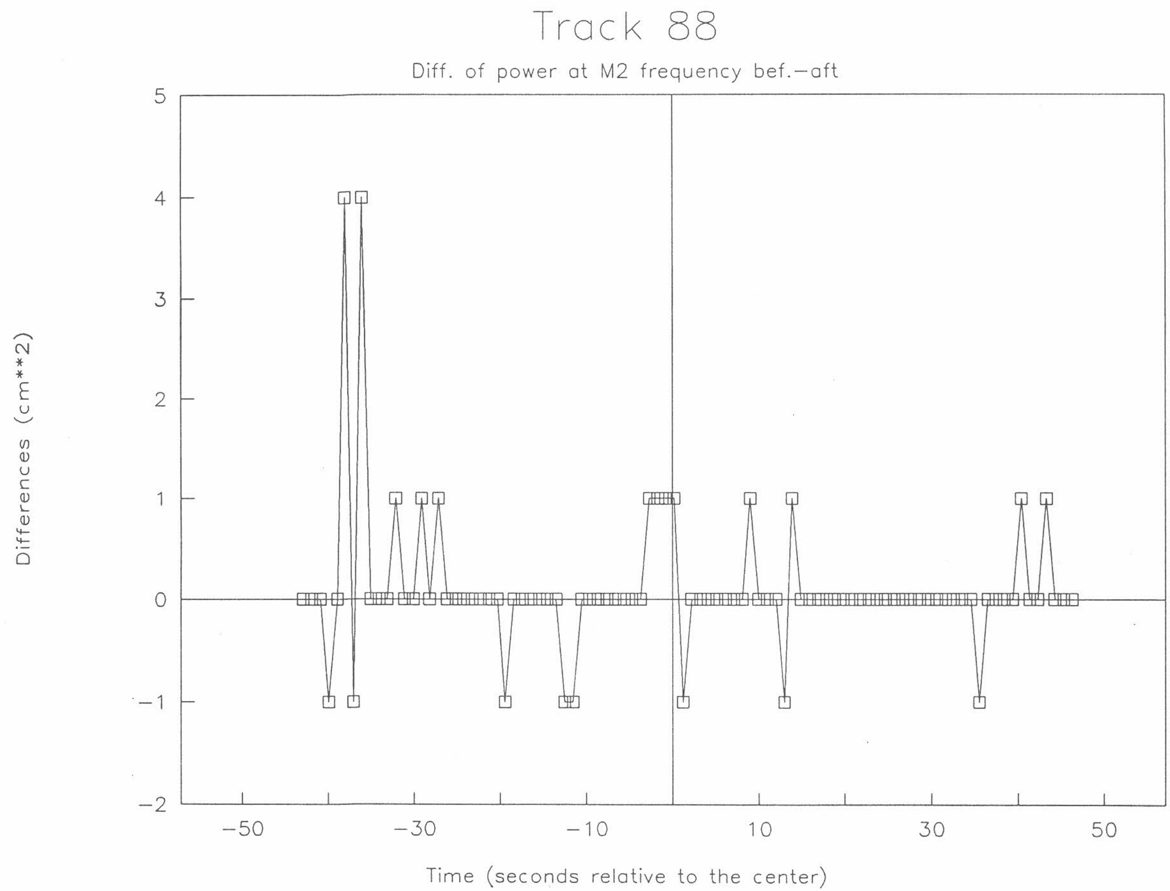

Fig. 13. Differences between the power at the frequency of M2 waves in the case of mean tracks of Figure 10. Unit is (cm^2).