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Faculty of Engineering, Al-Azhar University
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ABSTRACT

The principle of satellite altimetry is the determination of the distance between the altimetric satellite and sea surface, from which, when incorporated with altimetric satellite orbital geometry, the sea surface heights relative to a world geodetic reference ellipsoid (say WGS 84) can be determined. Usually, the global geoid which best fits WGS84 is adopted, for which the geoid undulation are known. The sea surface topography (SST) is the distance between the adopted geoid surface and the altimerically derived sea surface such as SST has several geodetic and geophysical practical applications. The basic objective of the present investigation is to perform a least squars adjustment of cross-over differences, in such a way to achieve the best estimated values for orbital bias and tilt unknown parameters for all used tracks, which in turn, are used to correct altimetric height measurements at all data points (other than the cross-over points), for the purpose of determining the sea surface topography (SST) over the Red Sea and the Mediterranean Sea areas. For this purpose, 35 days exact repeat mission (ERM) data set for the ERS-1 altimetric satellite is used.

The results of cross-over adjustment indicated that the OSU91A geoid model fits the sea surface, over the test area better than other currently used models, and hence, it is adopted in the current investigation, for the SST determination in Egypt. The OSU91A geoid model, being a global one, fits the WGS84 reference ellipsoid over the Red Sea area better than that of the Mediterranean Sea. The obtained results illustrates also that the SST value ranges between ± 1m. over the test area, and is positively increasing eastward and northward for both the Red Sea and Mediterranean Sea test areas. Further future investigations are still recommended to be performed for comparing the obtained results of SST from the analysis of ERS-1 satellite altimetric data, with other techniques of SST determination, like for instance, surface method of spectral analysis of Mean Sea Level (MSL) tide gauge records, and likewise.

KEYWORDS

Altimetry; track; bias, tilt, cross-over differences, sea surface topography.

INTRODUCTION

The purpose of Satellite radar altimetry, is measuring the height of a satellite above the earth's surface by means of a radar instrument carried by the satellite. These measurements may be used to determine the shape of the earth surface. The principle of satellite altimetry is the determination of the distance between the altimetric satellite and sea surface, due to its importance for several applications. The geodetic applications of altimetry include geoid and gravity field determination. Oceanographic applications comprise: sea surface time variations, ocean circulation and fishery while geophysical applications contain: bathymetric studies, sea mounts - ridges - fracture zone, isostatic behavior and loading of lithasphere. Our interest here in this paper is the sea surface topography. This sea surface topography is defined as the linear separation between stationary sea surface and the geoid surface. as shown in fig (1). The sea surface topography receives special interest from both oceanographers and geodesists, due to its practical importance. The required accuracy of this surface has been established to be in the order of a few centimeters (Schrama, 1989).

Oceanographers need the sea surface topography to evaluate geostrophic surface velocities of the oceans and the geostraphic velocities at any depth. Such velocities are essential for further investigation like, currents, sedimentation and so on.

Geodesists need the SST in order to establish a more accurate oceanic geoid which they currently identify with the mean sea surface. The ocean geoid, or as may be called marine geoid, has a multitude of geodetic applications. Such applications include: precise definition of vertical control datum, ocean loading, crustal movements, tidal effects and other earth dynamic activities. Of course, these geodetic activities will have its significant influences on precise geodetic measurements and associated geodetic computations. From the basic principle of altimetry, as mentioned before, it is possible to determine the range from the two way travel time of the pulse and because of the radar signal is emitted and received by the same radar dish. The reception of the returnal signal is only possible if at the same time the transmitter is not operating. As the altimeter has to supply a regular stream of observations, the receptions will take place in the intervals between the transmissions. Thus, the delay between transmission and reception is fairly constant, and the satellite should therefore be in a near circular orbit. So, a radar altimeter satellite has some limitations based on the parameters of its orbit. The altimeter satellite orbit, like any artificial satellite, is usually defined by the six keplerian orbital parameters, in the mean sense, (Hein, 1986).

The orbit should not be at a too low altitude approximately such that the atmospheric drag significantly perturbs the orbit and not too high altitude such that an extra ordinary amount of power is required by the altimeter. When the inclination is less than 90°, the rotation will be in clockwise direction and when it is greater than 90° the rotation will be unticlockwise. If the inclination is exactly 90°, that is the orbit pression is zero the satellite passes over both poles during every revolution, and this orbit will be exactly polar orbit. All the inclinations lead to orbits which are either prograde or retrograde. In the prograde type of orbit, the satellite moves around the polar axis in the same direction as the earth itself, which means that the inclination is between 0° and 90°. In the retrograde type the inclination is between 90° and 180°. The satellite orbit may also be nearly circular in which the eccentricity e is very small and also altimtry satellite are orbiting the earth in sun-synchronous mode. So, it is possible to choose an orbital inclination (equal 98.5° in case of ERS-1 satellite) for a given semi-major axis in such a way that as the precession has the same rate as the earth's rotation about the sun, (approximately 1° perday). It yields once per year the satellite will make exact one rotation around the earth. Of course, the altimetric measurements like any physical quantity, is expected to be exposed to some external influences, which result in certain errors. Some of these influences act on the altimetric satellite itself, like instrumetal effects and geophysical effects. However, a number of corrections must be done for meaningful application of the measurements; but it still exist to perform in flight back or calibration of the altimeter device itself. This calibration should be repeated several times during the mission, in order to detect any drift in these quantities. There are several ways, the satellite passes directly over a ground laser tracking stations which is able to determine the satellite height. The satellite is tracked simultaneously by several SLR sites mainly distributed in Europe. The Satellite passes directly over a research platform, located about 15-20 km offshore from Venice (Italy), on its ascending orbit. This platform is tower fixed to the sea. The refinement of the satellite ERS-1 orbit by using two satellites, either ERS-1 with Topex-Poseidon, due to the precise orbit of Topex-Poseidon, we can get the precise orbit for ERS-1 with accuracy of 3 cm (Zandbergen, 1990). Also by using ERS-2 because ERS-2 contains PRARE device so, it can give a precise information about its own position. The point on the earth's surface that is directly below the satellte is called the subsatellite point, and its trace as a function of time is called the ground track. The ground track pattern is a very important item for altimetry satellits, because it determines where the radar observations were made. After one day the ground track has developed into a network as shown in Fig (2).

The ground track of an altimetry satellite may eventually cover the entire surface of the earth between the extreme latitudes, but it may also be chosen such that it will repeat itself after a number of satellite revolutions, and this is known as a repeat orbit. This may be achieved by choosing suitable values for the semi-major axis **a** and the inclination **I** of the satellite orbit. Three motions determine whether the orbit is a repeat orbit, and if so, how long the repeat period will be. These motions are satellite motion, the earth's ratation; and orbital precession. After one orbital revolution (measured from the ascending node Ω) the earth will have rotated about its polar axis cover a certain angle. If the satellite arrived at exactly the same positiln, a one-day repeat orbit would be the result. The main objective of this paper is to analyzed the collected data from the ERS-1 satellite altimetry mission over 35 days, for the purpose of determining the SST over both the Red Sea and eastern part of the Mediterranean Sea areas. The basic concept of the soughts analysis, will be the least squars adjustment of the cross-over differences over the data points. In order to achieve such an objective, the definition of cross-over differences, along with the adopted methodology for their determination, will be given first. Then, the formulation and solution of the cross-over differences observation equation, will be presented. The analysis of obtained results, for the bias and tilt orbital parameters, for the purpose of evaluating of the SST, will be manipulated. Finally, the approperiate conclusion and recommendation will be drawn.

THE DEFINITION AND METHODOLOGY OF DETERMINING THE CROSS-OVER DIFFERENCES

Any satellite mission, likes ERS-1, provides its earth coverage in the form of ascending and descending tracks. The intersections of those two groups of tracks provide the so-called cross-over points. It has been found that, the best treatment, and hence corrections, to satellite altimetry data becomes possible after correcting or adjusting, those cross-over points. Of course, the number of cross-over points will depend upon the number of available ascending and descending tracks. In fact, the cross-over point location and height will have two approximate values, one from the ascending track and the other from the descending one. The difference between these two approximate values is called cross-over difference. The approximate position of cross-over point can be obtained from the intersection of two chords of the two great circles of ascending and descending tracks, within the vicinity of the allowable interpolation distance as shown in Fig (3) .

$$\phi_c = \phi_1 + \propto (\phi_2 - \phi_1) \tag{1}$$

$$\lambda_c = \lambda_1 + \propto (\lambda_2 - \lambda_1) \tag{2}$$

$$\text{and} \;\; h_{c_{12}} = h_1 + \propto (h_2 - h_1) \tag{3}$$

$$h_{c34} = h_3 + \beta(h_4 - h_3) \tag{4}$$

$$\Delta h_c = h_{c12} - h_{c34} \tag{5}$$

finally h_c which is defined as the difference between $h_{c_{12}}$ and $h_{c_{34}}$ can be evaluated as which after substituting in Eq. (5), we get :-

$$\Delta h_c = h_1 + \propto (h_2 - h_1) - h_3 + \beta(h_4 - h_3) \tag{6}$$

where

φ, λ the geodetic position in latitude and longitude
h is the height of the point
α, β are the constants.

RADIAL ERROR FUNCTION

The cross-over difference, Δh_c , consists of contribution due to the radial orbital error. Such orbital errors can be expressed as certain effects in several directions governing the satellite motion in its orbit, out of which the radial orbital error is the dominating ones. In order to model such radial errors, for the purpose of determining the sea surface topography SST, the most elementary error model may be taken as to provide a constant correction, of course, for each position. But this model would of course only be applicable to every short track. Therefore, the earliest implementations of this technique used a linear orbit error function, defined by two parameters as follows:

The bias model:

$$\Delta r_i(\mu) = a_i \tag{7}$$

the bias and tilt model:-

$$\Delta r_i(\mu) = a_i + b_i\,\mu \tag{8}$$

where $\Delta r_i(\mu)$ is the radial error function for ascending (or descending) track.

μ is known time parameter.

a_i bias parameter.

b_i tilt parameter.

finally, the obs. eq. for the cross-over diff. Δh_c takes the following form:-

$$\Delta h_{ij} = \Delta r_i(\mu_j) - \Delta r_j(\mu_i) \tag{9}$$

The bias and tilt parameters are generally different for each satellite track. The bias and tilt orbital errors appear in the altimetric measurement at resulting cross-over points, which are the intersections of ascending and descending tracks, as already defined in the previous section. Such cross-over errors appear as differences between altimetric measurement of ascending and descending tracks at the same cross-over points. In this case, the difference between the radial errors of any two ascending and descending tracks will be nothing else but the crresponding cross-over difference at the cross-over point under treatment. The approximate observation equation for the cross-over difference will be manipulated in the next section.

FORMULATION OF THE OBSERVATION EQUATION FOR CROSS-OVER DIFFERENCES

In order to estimate the bias and tilt parameters, for any ascending and descinding tracks, needed for the SST determination, a cross-over adjustment should be carried out. This means a least squars adjustment should be done for the corresponding cross-over differences observation equations. Such observation equation will be formulated as the difference between a radial error function of both ascending and descending tracks, as evaluated at each occur cross-over point. The observation equation for the cross-over differences Δh_c can be formulated in terms of either the bias or the bias and tilt radial error model, as merntioned in the previous section (Eq.7 and Eq 8) .

In this case, the observation equation for the bias and tilt model (from Eq.9) will be:

$$\Delta h_{ij} + v_{ij} = (a_i + b_i\mu_j) - (a_j - b_j\mu_i) \tag{10}$$

In which **a** represents the bias and **b** represent the tilt parameters of the track **i** or **j**, where **i** refers to the ascending track and **j** refers to the descending track.

which can be written as (using matrix notation)

$$L_{n,1} + V_{n,1} = A_{m,n} \quad X_{n,1} \tag{11}$$

where

L is the vector of the observed n cross-over diff. Δh_{ij}

V correction (or residuals) to the element of L

X is the vector of m unknown parameters, of bias and tilt.

A is the coefficient matrix of the vector of unknown parameters X, which is usually terned as the design matrix of the observation equation.

m is the number of the unknown parameters.

n is the number of observation.

equation (11) can then be written in the form of reduced observation equations, or the so-called residual equation as:

$$V = AX - L \tag{12}$$

FORMULATION AND SOLUTION OF THE NORMAL EQUATIONS SYSTEM FOR ORBITAL BIAS AND TILT PARAMETERS

The system in equation (12) contains n equations into m + n unknowns, which is defined as an overdetermined mathematical model. This system is solved by applying the least squars principles which is :

$$v^t Q^{-1} v = Min. \tag{13}$$

In which Q represents the a priori relative variance covariance matrix of the observed cross-over differences, in. which its diagonal elements are the relative variances of the respective observed cross-over differences, while its off diagonal elements are the relative covariances among them. In fact, this Q matrix is related to the corresponding weight matrix W of the observed cross-over differences, before adjustment, that is a priori weight, through the following relationship (Nassar, 1984) :

$$W = \sigma_0^2 \, Q^{-1}$$

Where σ_0^2 is the a priori variance factor, that can be assigned any arbitrary chosen value, and then, will be checked after adjustment against its estimated a posteriori value. Usually, in many practical cases like the case in our hands, the observed cross-over differences can be treated as having equal weights, and uncorrelated, which yields both the W and Q matrices to be identity or unit matrices. Moreover, the a priori variance factor σ_0^2 can be taken to equal unity, just for simplicity.

The above minimization process will yield the following normal equations system for the vector X of unknowns bias and tilt parameters, as:

$$(A^t Q^{-1} A) X = A^t Q^{-1} L \tag{14}$$

This system can be rewritten in a more abreviated and simpler forms as:

$$N_{m,m} X_{m,1} = R_{m,1} \tag{15}$$

In which N is known as the normal equation matrix, and similary R is known as the absolute term of normal equation system.

The above system can be directly solved for the solution vector X, which is composed of bias and tilt unknown parameters for both ascending and descending tracks. That is

$$X = N^{-1} R \tag{16}$$

The measure of accuracy for such estimated parameter by its estimated covariance matrix as :

$$Q_x = \hat{\sigma}_0^2 N^{-1} \tag{17}$$

where $\hat{\sigma}_0^2$ is the posteriori variance factor given by :

$$\hat{\sigma}_0^2 = \frac{V^t Q^{-1} V}{n-m} \tag{18}$$

THE FIT OF THE SEA SURFACE TO THE ADOPTED GEOID MODEL

The altimetric observations are carried out and reduced relative to a prespacified geoid model, which is GRIM4-C2 geoid model in our case here. Some previous studies (Nassar et. al.,1993, Eltokhey 1993) have indicated that the geoid models OSU81 and OSU89B are much better for the Red Sea than the other models. In addition, similar investigations concerning the geoid determination for Saudi Arabia (Suenkel, 1993), have indicated that OSU91A geoid model fits better to the same area. Fig (4) shows the distribution of the ERS-1 altimeter data, in the form of tracks, covering the Red Sea and eastern part of Mediterranean Sea areas, for the 35 days repeat mission. 10 tracks where selected, on the bases of variable number of along track data points, and also including both ascending and descending tracks. Altimetric measurements of the sea surface height as well as the best fitted heights to the geoid models, for these 10 tracks, where transformed from the given GRIM4-C2 geoid model provided with the given data to each one of the three OSU geoid models. This has been performed using some programming facilities within the used software package CRosS-over ADJustment (CRSADJ). Then, the sea surface fit of those 10 tracks to each one of the three OSU models have been investigated. The obtained results indicated no significant difference between the three geoid models as far as the sea surface fitting is concerned, as can be seen from table (1). However, all of them gave better fit than the GRIM4-C2 geoid model. Therefore, Our discussion and presentation of results will be concentrated here only on the OSU91A geoid model.

As far as the representation of results here is concerned, three tracks where selected, as an example from the 35 days repeat mission. One of those three tracks is a long track, is numbered 7917, covers the Red Sea as well as the eastern area of the Mediterranean Sea. However, the other two tracks are short tracks, whose numbers are 8296 and 8339 respectively, are existing in the Red sea area only. Since, the separation between those two tracks is relatively large, it was possible to allocate them, as depicted in Fig(5).

The obtained results for the 35 days mission are illustrated in Fig.(6) for the eastern part of the Mediterranean sea, and Fig.(7) to (9) for the Red Sea area, related to the selected tracks. In each one of those 4 figures, the horizontal axis represents the longitude difference along the selected track, while the vertical axis represents the heights related to the adopted reference ellipsoid, which is WGS84 datum. In addition, three profiles are shown on each diagram. The first represents the geoid height (undulation) of the OSU geoid model. The second represents the sea surface height of the original sea surface data points along the selected track. The last profile gives the sea surface height, after its best fitting to the OSU91A geoid model. The investigation of the above diagrams indicates that the agreement of the fitted sea surface height and the OSU91A model is of varying quality. For instance, from figures (6) and (7) (results of 35 days ERM), it can be seen that, the maximum discrepancy occurs, generally, near the shore lines, which reaches for the selected long track number 7917, up to 1.8m in the Mediterranean Sea area and 0.8m in the Red Sea area. The examination of the maximum orthogonal distance between the track and the shore lines shows that its value in the Red Sea is less than one-half of the corresponding value in the Mediterranean sea. Accordingly, one can conclude that the absolute value of the discrepancies between the best fitted sea surface and the OSU91A geoid surface increases with the increase of the orthogonal distance of the track from the shore lines, perhaps according to a certain proportionals. Such a conclusion can be also verified through the examination of the long and short tracks behaviours over the Red Sea area, as illustrated in Figs (7) to (9), respectively. The same comments hold true for the original (measured) sea surface data points along the selected tracks, however, the maximum descrepancies of OSU91A geoid model will be about double its corresponding value for the best fitted sea surface, for such used data in our case.

ANALYSIS OF ORBITAL BIAS AND TILT PARAMETERS

The purpose of this section is to analyze the behaviour of bias and tilt parameters of ERS-1 satellite orbits from two main view points. Firstly, the comparison between the approximate values of bais and tilt parameters, as obtained from the regression analysis of each individual track Eq. (8), will be compared to their corresponding values, as obtained from the least squars solution with geoid fit technique. Note here that, if the number of cross-over points for a particualr track will be only one point, the tilt of this track will be assigned a zero value. Therefore, the error function of this track Eq. (7).

Starting with the 35 days ERM data satellite altimetry ERS-1, we find that we have 61 tracks for the test area, a total of 114 cross-over points, and a total of 4706 data points. The approximate values of bias and tilt parameters for the used 58 effective tracks, covering the test area of Red and Mediterranean seas, are computed through program called ALINE by using the least squars regression analysis of data points for each individual track separately. The obtained results of approximate bias and tilt, as well as, their corresponding RMS values are presented in table (2). This table containsmean longitude, the approximate value for bias, the RMS of bias, the approximate value for tilt and the RMS of tilt respectively. The normal equation system for both cross-over differences, as well as geoid fit, as produced by a program ALINE, is solved within another program called ABIAS, and the results are presented in both tabular and graphical forms. The estimated values of both bias and tilt parameters, for the used tracks, including the corresponding RMS of estimation by least squars, are given in table (3). Table (4) summarizes the mean values of the estimated bias and tilt parameters for ascending and descending tracks, as well as for all used tracks. In addition, the variation of the estimated bias and tilt parameters with revolution number of tracks are graphically depicted in Fig. (10). Moreover, Fig. (11) represents the histogram (bar diagram) of estimated bias as an example, while similar histogram can be shown for the tilt parameter.

The analysis of the orbital bias and tilt for 35 days ERM indicates the following remarks:

1. The adjusted bias and tilt parameters (table 3) are close enough to their corresponding approximate values (table 2). This means that the approximate values of bias and tilt, as obtained from regression analysis of geoid fit of each individual tracks, are of reliable quality that leads to a least squars conversion solution.
2. From Fig. (10) and Fig. (11), it can be seen that the estimated bias ranges between -200 cm to 40 cm with mean value equals -0.82 m while the estimated tilt ranges between -1.75m/km to 1.6 m/km with mean value equals to 0.014 m/100km. Such estimated values, although relatively small for the ERS-1 orbit, are statistically significant, since they attend, generally, a relatively smaller RMS.
3. The estimated bias and tilt parameters are more reliable than their corresponding approximate values, since the estimated RMS of the former is less than the RMS of the latter.
4. From Table (4) it can be seen that, the descending tracks have bias and tilt parameters smaller than their corresponding values as obtained for the ascending tracks, inbsolute values.
5. From table (3) and Fig. (11) it can be seen that more than 80% of the used effective tracks have biases distributed over the mean value ±1 standard deviation.

ANALYSIS OF CROSS-OVER DIFFERENCES

For the test area of the Red Sea and the eastern part of the Mediterranean Sea, with 35 days ERM data, 114 cross-over points were found 58 effective tracks (21 ascending and 37 descending tracks). Table (5) gives the number of cross-over differences per track, and the mean of cross-over differences per track as well as its RMS, as produced by program called ARCS before adjustment. Fig. (12) illustrates the histogram (bar diagram) of the mean value of cross-over differences per track, while (14) is the corresponding histogram of its RMS, for 58 used tracks before adjustment. In addition Fig. (16) shows the histogram of the cross-over differences before adjustment, for all determined 114 values.

The least squars adjustd values of mean cross-over differences per track along with its RMS, after being processed through program ABIAS, are shown in table (6). The corresponding histograms of adjusted mean cross-over differences per track and its RMS, are given in Figs. (13) and (15), respectively. However, Fig. (17) represents the histogram of estimated residuals (correction to the observed cross-over differences) as produced from the least squars adjustment performed within program ABIAS, for all usable 114 cross-over points.

The investigation and analysis of tables (5) to (6) and figures from (12) to (17), pertaining to 35 days ERM data, may reveal the following remarks:

1. From table (5), it can be seen that the number of cross-over points per track ranges between 1 and 9. The mean cross-over differences per track ranges between -0.4 cm and 5 cm, with mean value for all tracks equal 7 cm and RMS=4cm.
2. From table (6), one can find that the mean value of cross-over difference per

track ranges between -0.9 cm to 1.0 cm, after adjustment, with mean value for all tracks equals 0.1cm and RMS = 1.6 cm.

3. From results given in the above two items one and two, it is clear that the mean value of cross-over differences for all tracks is nearly eliminated after adjustment, while the sample RMS value is reduced from 4 cm to 1.6 cm after the least squars adjustment.
4. The mean cross-over difference per track is distributed over the two intervals zero and 1 dm before adjustment while all mean values for all tracks are concentrated around zero dm after adjustment, as can be seen from Figs. (12) and (13). This means that cross-over differences have gained considerable improvement after adjustment.
5. Similar comment, like number 4 above, can be stated for both sample RMS and cross-over difference after adjustment, as can be extracted from Figs. (14) and (15), and from Figs. (16) and (17), respectively.

THE SEA SURFACE TOPOGRAPHY FOR THE RED SEA AND THE EASTERN PART OF THE MEDITERRANEAN SEA

Recall that the SST is the deviation of the stationary sea surface from an adopted geoid surface. In otherwords the values of SST over a certain area will be directly depending on the adopted geoid model. In the present investigation, the OSU91A global geopotential model (which is complete to degree and order 360) has been adopted for the required geoid computation, which are characterized by the geoid undulation at any location over the globe. Such a location of our concern are the geographic position (latitude and longitude) of each altimetric satellite data subpoint. Those undulation can be further used, with an adopted accurate interpolation technique, for producing geoid undulation contour map.

Figs. (18) and (19) depict the geoid undulation (in meters) over the test area of Red Sea and Mediterranean Sea, respectively, based on the OSU91A model. From Fig. (18), it can be seen that the geoid undulation over the Red Sea ranges between -10m and 12m, with zero value at latitude about 18° N. In otherwords, the geoid undulation of the Red Sea is positively increasing northward. Similarly, from (19), one can find that the geoid undulation over the test area of the eastern part of the Meditarranean sea ranges between 3m and 27m. From both Figs (18) and (19), it can be visualized that the OSU91A geoid model fits the WGS84 reference ellipsoid over the Red Sea area better than the of the Medite4ranean Sea, in which the geoid undulation is positively increasing from south to the north. This can be also realised from the examination of Figs. (6) and (7). Of course, if one speaks about regional or local geoid, instead of using the global models, a better fit to the local reference ellipsoid could be easily achieved. In otherwords, the geoid undulation of the Mediterranean Sea is positively increasing eastward and also northward.

SST over the Red Sea

The least squars adjustment process of cross-over differences is performed (using the previously program mention ABIAS which yields both adjusted bias and tilt parameters of all used effective tracks as well as the adjusted values of the observed cross-over differences. Then, a program called ABCOR is activated to take the adjusted bias and tilt parameters of each track, and another program named ALINE to perform the necessary backward substitution to determine the adjusted values of the sea surface height (relative to WGS84) at each respective data point in each track. Further, the adjusted altimetric data (sea surface height) are combined with the OSU91A geoid undulations data point on each track. By subtracting the latter from the former, the net result is a data file containing the adjusted or corrected SST, at each altimetric data point as defined by its latitude and longitude. This file is further used,with a computer package known as GSPP (Suenkel,1980), for gridding and contour generation purposes, particularly here for the SST.

Fig. (20) illustrates the obtained SST, as a contour map over the Red Sea area, for 35 days ERM, while Fig. (21) is a three dimensional representation of such SST. From those two figures, it can be seen that the SST value ranges between -1.0m and 2.0m over the Red Sea area with a zero value at an average longitude of about 38° E. The examination of the SST contours of 35 days ERM, over the Red Sea, reveals that the major variation of SST over this area happens with a longitude rather than the latitude. In otherwords, the SST over the Red Sea is positively increasing eastward and also northward.

SST over the eastern part of Mediterranean Sea

For the selected test area for the eastern part of the Mediterranean Sea, 35 days ERM, the corresponding contour map of the SST is presented in Fig. (22). Also, the corresponding three dimensional view of this SST is presented in Fig. (23). In this case, the SST value ranges between -1.0m and 1.0m, with a zero value at an average latitude 32.5° N. The pattern of this SST, over the Mediterranean Sea slopes positively northwards and eastwards. This can be verified also, from Fig. (6).

Comparison with other techniques for the SST determination in Egypt

There are several techniques for determination and analysis of SST. The present study concentrates on the determination of the SST in Egypt, using the ERS-1 altimetric satellite data. Another interesting technique of SST determination, is the analysis of Mean Sea Level (MSL) records and its variation. Such variation of MSL are due to the local variations in the meteorological parameters, namely: temprature, pressure, wind speed, river discharge, salinity, currents, tides,... etc. A study (*El Shazly, 1995*) of MSL and SST variations, along the Egyptian shore lines at the existing tide gauges, has been carried out using actual data. Such investigation has applied a modified spectral analysis technique based on the zero response method. Due to the data availability at Alexandria, Port Said and Suez tide gauges, over certain short spans of time records, the influences of temprature, pressure and wind speed only were taken into account. It should be reminded here that, in our present study, the altimetric data used, and hence, the resulted SST over the Red Sea area has been taken along the Red Sea, excluding the Gulf of Suez. Consequently, we do not have an SST value at the location of Suez. However, we have obtained values of the SST at both Alexandria and Port Said locations. Therefore, a comparison may be performed here between our results, as obtained from the altimetry data, and the results of MSL spectral analysis at those two locations.

In order to make the comparison easier, and hence, meaningful, the local zero datum of the SST will be taken at Alexandria. Consequently, the SST value at Port Said will be calculated relative to such local zero datum. The spectral analysis results (ElShazly, 1995) indicated a local SST value at Port Said of about -9cm. On the other hand from Fig. (22), it can be seen that the altimetry results give a value of SST at Alexandria of about -75cm,and at Port Said -100cm. This means that the local SST at Port Said, relative to a local zero datum of SST at Alexandria, will be -25cm, as obtained from the ERS-1 altimetric data. The difference between altimetric results and MSL spectral analysis results is about 16 cm, in our case at Port Said. Such difference may be considered to be in the order of allowable orbital erros, before adjustment. In addition, such difference may be attributed to the existing unmodelled biases inherent existing in both altimetric and surface techniques for the SST determination. Finally, one can state that there are still further future investigation, which are needed to be carried out, for modelling such biases in order to improve the reliability of the obtained SST.

CONCLUSION

Based on the obtained results of our investigation, there will be a multitude of conclusions. It should be reminded here that, there are three principal investigations in the current research dealing with: main concepts of SST and satellite altimetry/ the sea surface fit to the adopted geoid model; and sea surface topography over the Red Sea and the eastern part of Mediterranean Sea areas. Accordingly, the main conclusions will be enumerated below following the same sequence, whenever, possible:

1. The sea surface fit of the used altimetric data to OSU91A geoid model was found to be better than the originally used geoid model of GRIM4-C2. In addition, the results indicated no significant practical difference between the surface fit related to OSU81, OSU89B, and OSU91A geoid models over the test area. Thus the OSU91A geoid model is adopted here.
2. The OSU91A geoid model fits the WGS84 reference ellipsoid over the Red Sea area better than that of the Mediterranean Sea.
3. Due to the topological structure of the Red Sea and loose connection between tracks, in case of 35 days ERM, the resulting number of cross-over points is small.
4. The least squars linear regression of each track to the geoid fit is a reliable technique since it provides approximate values for bias and tilt parameters that were found close enough to their final adjusted values.
5. The estimated bias and tilt parameters, of the used ERS-1 satellite altimetric tracks, are found in the order of few meters in absolute value, and in most of the cases attain submeters values only.
6. More than 80% of the used effective tracks, in case of 35 days ERM, have biases distributed over the mean value ± one standard deviation.
7. The RMS of cross-over differences before adjustment was found to be very small, in case of 35 days ERM data.
8. The SST value ranges between +2.0m and -1.0m, with a zero value at an average latitude 32.5° N. Here, the SST pattern is also sloping positively northwards. For instance, the SST over the Mediterranean Sea at Alexandria is -0.75m and at Port Said -1.00m.
9. The SST value is positively increasing eastward and northward, for both the Red Sea and Mediterranean Sea test areas, in case of the used two data

sets. The major trend of the SST pattern seems to be longitudewise in case of the Red Sea area, and latitudewise in case of Mediterranean Sea area.

10. The difference of local SST stationary surface, between the results of ERS-1 satellite altimetry and spectral analysis of MSL of meteorological parameters, at the location Port Said on the Mediterranean Sea of Egypt, was found to be less 15cm, which can be attributed to the inherent biases in both analyzed techniques.

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Table (1) : RMS values of geoid fit and cross-over difference for different OSU- geoid models (35 days)

OSU-Models	RMS Geoid fit (in meter)	RMS X-over (in cm)	
OSU91A	1.30	4.00	before
OSU89B	1.55	4.00	the
OSU81	1.45	4.00	adjustment
OSU91A	0.80	1.6	after
OSU89B	0.82	1.6	the
OSU81	1.21	2.8	adjustment

Table (2) : Approximate values for bias and tilt parameters as obtained from program ALINE (35 days ERM)

S. NO	REV. NO.	NO. OF D. POINTS	M. LONG.	BIAS	RMS	TILT	RMS
1	7910	81	33.376	-1.371	1.154	0.882	0.3
2	7917	202	35.536	-0.788	0.353	0.249	0.61
3	7924	79	38.024	-0.276	0.212	-0.74	0.185
4	7938	22	43.754	0.38	0.219	-3.49	0.135
5	7939	2	25.017	-2.275	1.275	3.51	0
6	7953	72	31.953	-1.478	1.581	0.8	0.478
7	7960	113	32.78	-0.433	0.221	0.863	1.268
8	7967	43	37.09	-0.482	0.217	0.208	0.184
9	7981	25	42.783	0.129	0.112	-2.06	0.102
10	7996	93	30.579	-1.312	1.142	1.714	0.153
11	8003	79	30.747	-1.186	1.317	-1.2	0.294
12	8010	54	36.011	-1.094	0.183	-1.08	0.372
13	8017	35	44.267	0.453	0.373	2.473	0.09
14	8024	37	41.703	0.286	0.25	-2.74	0.224
15	8039	84	29.037	-1.734	1.847	1.361	0.304
16	8046	90	29.253	-1.451	0.598	-1.29	0.31
17	8053	44	35.048	-0.182	0.156	1.913	0.206
18	8060	102	41.83	-0.076	0.022	0.907	0.337
19	8067	66	40.676	-0.456	0.226	0.558	0.213
20	8082	87	27.772	-1.77	1.856	1.033	0.311
21	8089	96	27.91	-2.044	1.079	-0.44	0.31
22	8096	15	34.4	1.771	2.658	-2.17	0.677
23	8103	175	38.642	-0.703	0.576	0.15	0.44
24	8110	60	39.526	-0.137	0.09	-2.03	0.608
25	8125	87	26.355	-1.824	0.877	-0.52	0.377
26	8132	90	26.408	-2.369	0.463	0.314	0.659
27	8139	95	34.09	-1.055	1.512	-0.44	1.055
28	8146	192	36.535	-0.624	0.321	0.306	0.47
29	8153	66	38.566	-0.435	0.2	-1.39	0.184
30	8167	41	44.432	0.267	0.13	-2.34	0.122
31	8163	35	25.427	-2.595	1.3	0.627	0.252
32	8175	40	25.343	-1.49	1	0.592	0.199
33	8182	64	32.597	-1.521	1.07	0.5	0.642
34	8189	152	34.1	-0.975	0.324	0.308	0.812
35	8196	49	37.608	-0.604	0.038	-0.7	0.149
36	8210	11	43.211	0.049	0.05	-1.33	0.167
37	8225	83	31.299	-1.318	1.1	1.213	0.14
38	8232	113	31.672	-0.361	0.03	0.964	1.45
39	8239	44	36.526	-0.46	0.1	-1.62	0.25
40	8246	21	44.842	0.02	0.02	2.748	0.057
41	8253	39	42.364	-0.134	0.135	-3.9	0.101
42	8268	102	29.849	-1.353	1.769	2.149	0.349
43	8275	79	30.023	-1.648	1.167	-0.39	0.673
44	8282	45	35.539	-0.909	0.7	-0.65	0.201
45	8289	97	42.694	-0.302	0.143	1.075	0.28
46	8296	49	41.218	-0.372	0.134	-1.27	0.113
47	8311	88	23.38	-1.659	1.04	1.493	0.249
48	8318	95	28.595	-1.983	1.09	0.8	0.25
49	8325	30	34.481	1.483	1.909	7.809	0.439
50	8332	108	40.232	-0.185	0.107	0.215	0.578

S. NO.	ASC./DESC.	REV. NO.	BIAS	ST. DV.	TILT	ST. DV.	MEAN	RMS
1	N	7917	-0.729	0.406	0.084	0.02	-0.006	0.011
2	N	7960	-0.844	0.576	0.054	0.04	0.006	0.019
3	N	8003	-1.657	0.64	0.529	0.527	-0.001	0.001
4	N	8017-	0.319	6.436	0	0.032	0	0
5	N	8046	-1.685	0.592	0.071	0.04	-0.01	0.021
6	N	8060	0.254	0.078	-0.209	0.06	0.011	0.023
7	N	8089	-1.787	0.816	0.342	0.1	0.004	0.009
8	N	8103	0.364	0.197	0.327	0.09	0	0.002
9	N	8132	-1.977	0.824	0.217	0.08	-0.002	0.007
10	N	8146	-0.704	0.416	0.178	0.067	0.002	0.009
11	N	8175	-1.838	0.998	-0.285	0.12	0	0
12	N	8189	-0.579	0.473	0.304	0.26	0.003	0.009
13	N	8232	-1.216	0.558	0.788	0.591	-0.012	0.042
14	N	8275	-1.751	0.58	0.231	0.112	0.012	0.02
15	N	8289	0.177	0.117	0.141	0.078	0	0
16	N	8318	-1.701	0.694	0.246	0.023	-0.004	0.01
17	N	8332	0.131	0.11	0.331	0.29	-0.009	0.19
18	N	8361	-1.916	0.87	0.311	0.21	0.003	0.007
19	N	8375	-0.524	0.208	0.265	0.21	-0.002	0.016
20	N	8404	-1.948	0.904	-0.055	0.011	0.001	0.002
21	N	8418	-0.735	0.402	0.081	0.02	-0.003	0.013
1	S	7910	-0.87	0.462	-0.064	0.033	0.004	0.01
2	S	7924	-0.433	0.4	0.244	0.12	0.001	0.001
3	S	7938-	0.278	0.15	0	0.032	0	0
4	S	7953	-1.184	0.511	0.234	0.124	0.02	0.04
5	S	7967-	-0.594	0.467	0	0.032	0	0
6	S	7981-	0.175	0.133	0	0.034	0	0
7	S	7996	-1.688	0.648	-0.071	0.01	0	0.008
8	S	8010	-0.592	0.467	-1.698	0.98	0	0.001
9	S	8024	0.347	0.3	-0.777	0.23	0	0.001
10	S	8039	-1.681	0.857	-0.229	0.11	0.003	0.031
11	S	8053-	-0.313	0.23	0	0.032	0	0
12	S	8067	0.285	0.19	0.285	0.118	0	0.003
13	S	8082	-1.814	0.825	0.012	0.002	-0.001	0.004
14	S	8096-	-0.33	0.2	0	0.032	0	0
15	S	8110	-0.055	0.01	0.185	0.09	0	0
16	S	8125	-1.993	0.823	-0.104	0.087	0.001	0.007
17	S	8139	-0.993	0.513	-0.575	0.45	-0.001	0.025
18	S	8153	-0.329	0.08	0.168	0.098	0.005	0.024
19	S	8167-	0.319	6.436	0	0.032	0	0
20	S	8168	-2.003	0.994	-0.533	0.034	0	0
21	S	8182	-0.939	0.495	-0.051	0.009	-0.001	0.032
22	S	8196-	-0.518	0.47	0.147	0.089	0	0
23	S	8210-	0.232	0.19	0	0.032	0	0
24	S	8225	-1.434	0.579	0.274	0.19	-0.006	0.013
25	S	8239	-0.655	0.475	-0.004	0.001	0	0.002
26	S	8253	0.152	0.05	-0.156	0.08	0	0
27	S	8268	-1.735	0.572	-0.315	0.087	-0.001	0.003
28	S	8282	-0.472	0.39	-1.453	1.02	0	0.001
29	S	8296-	0.377	0.2	0	0.032	-0.004	0.042
30	S	8311	-1.707	0.744	-0.007	0.004	0	0.007
31	S	8325-	-0.166	0.09	0	0.032	0	0
32	S	8339	0.093	0.08	0.253	0.01	-0.001	0.002
33	S	8354	-1.913	0.877	-0.057	0.009	-0.002	0.01
34	S	8368	-1.161	0.664	-0.56	0.4	0	0.001
35	S	8382	-0.185	0.09	0.129	0.09	0	0
36	S	8397	-1.961	0.813	-0.321	0.089	-0.001	0.003
37	S	8411	-0.879	0.461	-0.131	0.05	0	0.011

Table (3) : Adjusted values for bias and tilt parameters as derived from program ABIAS (35 days ERM)

	Ascending	Descending	All
Mean bias(m)	-1.004	-0.712	-0.818
Mean tilt(m/100km)	0.207	-0.140	0.014

Table (4) : average values of tilt and bias parameters as resulted from cross-over adjustment of the ERS-1 altimeter data for 35 days ERM

Table (5) : Mean cross-over difference and its RMS, for each track before adjustment, as obtained from program ARCS for 35 days ERM

S. NO.	ASC /DESC	REV. NO.	NO. CRS	M. LONG.	MEAN	RMS
1	N	7917	9	35.54	0.001	0.013
2	N	7960	7	32.78	0	0.001
3	N	8003	4	30.75	0.001	0.002
4	N	8017-	1	44.27	0.001	0.001
5	N	8046	5	29.25	0.014	0.033
6	N	8060	4	41.83	0	0.001
7	N	8089	5	27.91	0	0.001
8	N	8103	6	38.64	0.001	0.001
9	N	8132	5	26.41	-0.008	0.011
10	N	8146	9	36.54	-0.054	0.114
11	N	8175	2	25.34	-0.004	0.006
12	N	8189	8	34.1	-0.005	0.014
13	N	8232	6	31.67	0.003	0.003
14	N	8275	4	30.02	0.001	0.002
15	N	8289	5	42.89	0.019	0.043
16	N	8318	5	28.6	0.009	0.021
17	N	8332	4	40.23	0	0.001
18	N	8361	5	27.13	0.001	0.007
19	N	8375	8	37.69	0	0.002
20	N	8404	4	25.75	-0.026	0.055
21	N	8418	8	35.49	0.006	0.017
1	S	7910	5	33.38	0.058	0.124
2	S	7924	3	38.02	0	0.002
3	S	7938-	1	43.75	0	0
4	S	7953	4	31.95	0.002	0.006
5	S	7967-	1	37.09	0.001	0.001
6	S	7981-	1	42.78	-0.001	0.001
7	S	7996	4	30.58	-0.001	0.002
8	S	8010	3	36.01	0.002	0.003
9	S	8024	3	41.7	-0.031	0.056
10	S	8039	4	29.04	0.001	0.001
11	S	8053-	1	35.05	-0.007	0.007
12	S	8067	3	40.68	0	0.001
13	S	8082	5	27.77	-0.012	0.033
14	S	8096-	1	24.4	-0.001	0.001
15	S	8110	3	39.53	0	0
16	S	8125	5	26.36	0.002	0.004
17	S	8139	6	34.09	0.007	0.015
18	S	8153	3	38.57	-0.002	0.002
19	S	8167-	1	44.43	-0.001	0.001
20	S	8168	2	25.43	0.003	0.012
21	S	8182	5	32.6	-0.018	0.027
22	S	8196-	2	37.61	-0.001	0.001
23	S	8210-	1	43.21	0.005	0.005
24	S	8225	4	31.3	-0.002	0.002
25	S	8239	3	36.53	0.003	0.003
26	S	8253	2	42.38	-0.001	0.001
27	S	8268	5	29.85	-0.001	0.002
28	S	8282	3	35.54	0.001	0.002
29	S	8296-	2	41.22	-0.001	0.001
30	S	8311	4	28.38	0.003	0.003
31	S	8325-	1	34.48	0.002	0.002
32	S	8339	3	40.04	0	0.001
33	S	8354	5	27.07	0.016	0.054
34	S	8368	3	34.85	0.001	0.002
35	S	8382	2	39.02	0	0.001
36	S	8397	4	25.72	-0.002	0.008
37	S	8411	5	33.36	0.042	0.091

Mean value of cross-over difference for all tracks (before adjustment) =7.0 cm and Sample RMS (before adjustment) = 4.0 cm

Table (6) : Mean cross-over difference and its RMS, for each track after adjustment, as obtained from program ARCS for 35 days ERM

S. NO.	ASC./DESC.	REV. NO.	NO. CRS	M. LONG.	MEAN	RMS
1	N	7917	9	35.54	-0.006	0.011
2	N	7960	7	32.78	0.006	0.019
3	N	8003	4	30.75	-0.001	0.001
4	N	8017-	1	44.27	0	0
5	N	8046	5	29.25	-0.01	0.021
6	N	8060	4	41.83	0.011	0.002
7	N	8089	5	27.91	0.004	0
8	N	8103	6	38.64	0	0.001
9	N	8132	5	26.41	-0.002	0.007
10	N	8146	9	36.54	0.002	0.009
11	N	8175	2	25.34	0	0
12	N	8189	8	34.1	0.003	0.009
13	N	8232	6	31.67	-0.012	0.003
14	N	8275	4	30.02	0.012	0.002
15	N	8289	5	42.89	0	0
16	N	8318	5	28.6	-0.004	0.001
17	N	8332	4	40.23	-0.009	0.001
18	N	8361	5	27.13	0.003	0.007
19	N	8375	8	37.69	-0.002	0.001
20	N	8404	4	25.75	0.001	0.002
21	N	8418	8	35.49	-0.003	0.013
1	S	7910	5	33.38	0.004	0.01
2	S	7924	3	38.02	0.001	0.002
3	S	7938-	1	43.75	0	0
4	S	7953	4	31.95	0.02	0.004
5	S	7967-	1	37.09	0	0
6	S	7981-	1	42.78	0	0
7	S	7996	4	30.58	0	0
8	S	8010	3	36.01	0	0.001
9	S	8024	3	41.7	0	0.001
10	S	8039	4	29.04	0.003	0.001
11	S	8053-	1	35.05	0	0
12	S	8067	3	40.68	0	0.001
13	S	8082	5	27.77	-0.001	0.004
14	S	8096-	1	24.4	0	0
15	S	8110	3	39.53	0	0
16	S	8125	5	26.36	0.001	0.002
17	S	8139	6	34.09	-0.001	0.003
18	S	8153	3	38.57	0.005	0.002
19	S	8167-	1	44.43	0	0
20	S	8168	2	25.43	0	0
21	S	8182	5	32.6	-0.001	0.01
22	S	8196-	2	37.61	0	0
23	S	8210-	1	43.21	0	0
24	S	8225	4	31.3	-0.006	0
25	S	8239	3	36.53	0	0.001
26	S	8253	2	42.36	0	0
27	S	8268	5	29.85	-0.001	0.002
28	S	8282	3	35.54	0	0.001
29	S	8296-	2	41.22	-0.004	0
30	S	8311	4	28.38	0	0
31	S	8325-	1	34.48	0	0
32	S	8339	3	40.04	-0.001	0.001
33	S	8354	5	27.07	-0.002	0.01
34	S	8368	3	34.85	0	0.001
35	S	8382	2	39.02	0	0
36	S	8397	4	25.72	-0.001	0.003
37	S	8411	5	33.36	0	0.001

Mean value of cross-over difference for all tracks (after adjustment) =0.1 cm and Sample RMS (after adjustment) = 1.6 cm

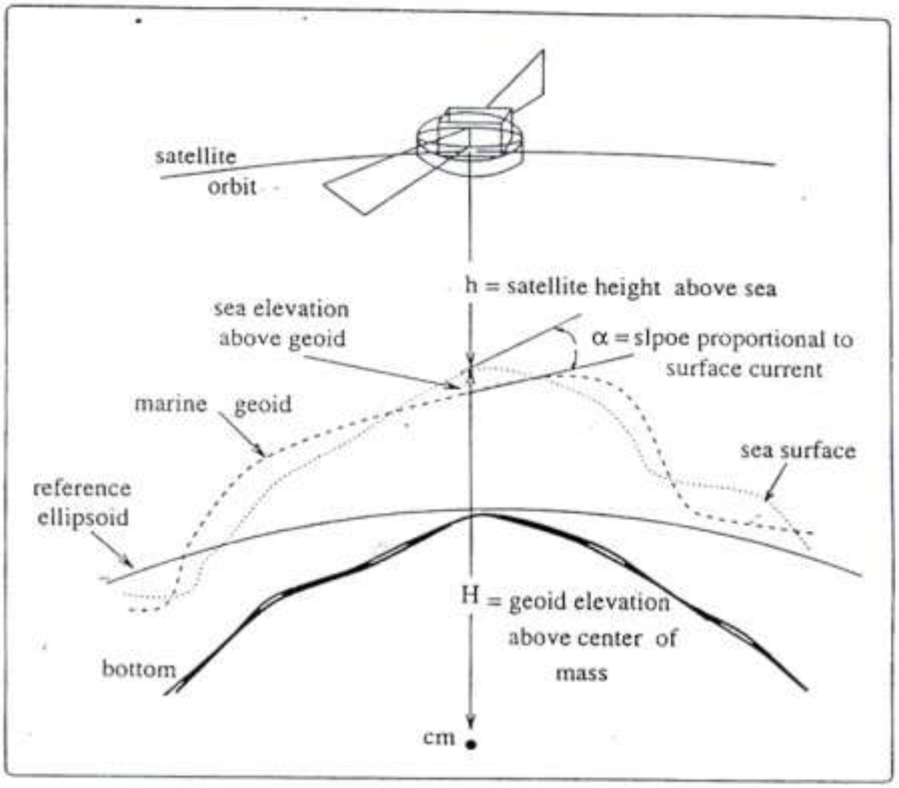


Fig. (1) The geometry of an altimeter satellite measuring its height above the sea surface

Fig. (2) Global ERS-1 Track Pattern

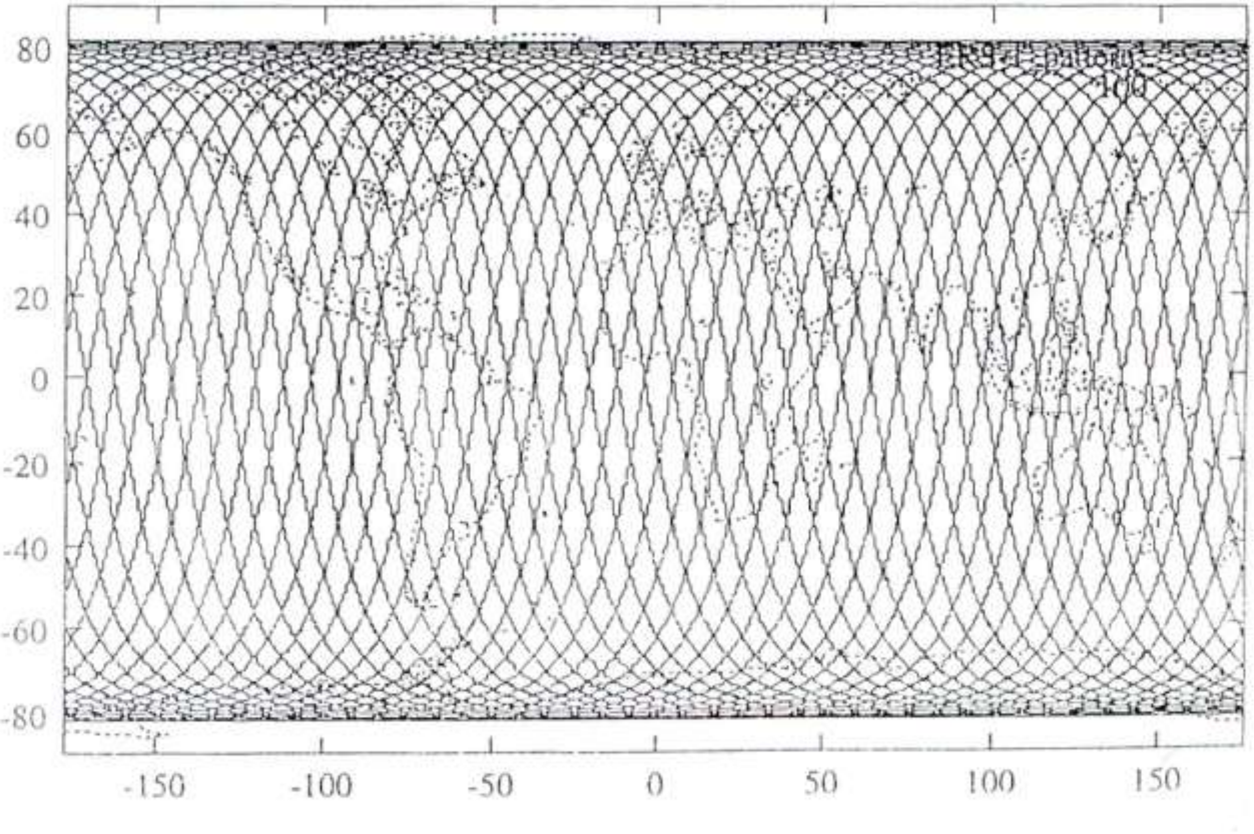


Fig. (3) Local cross-over area

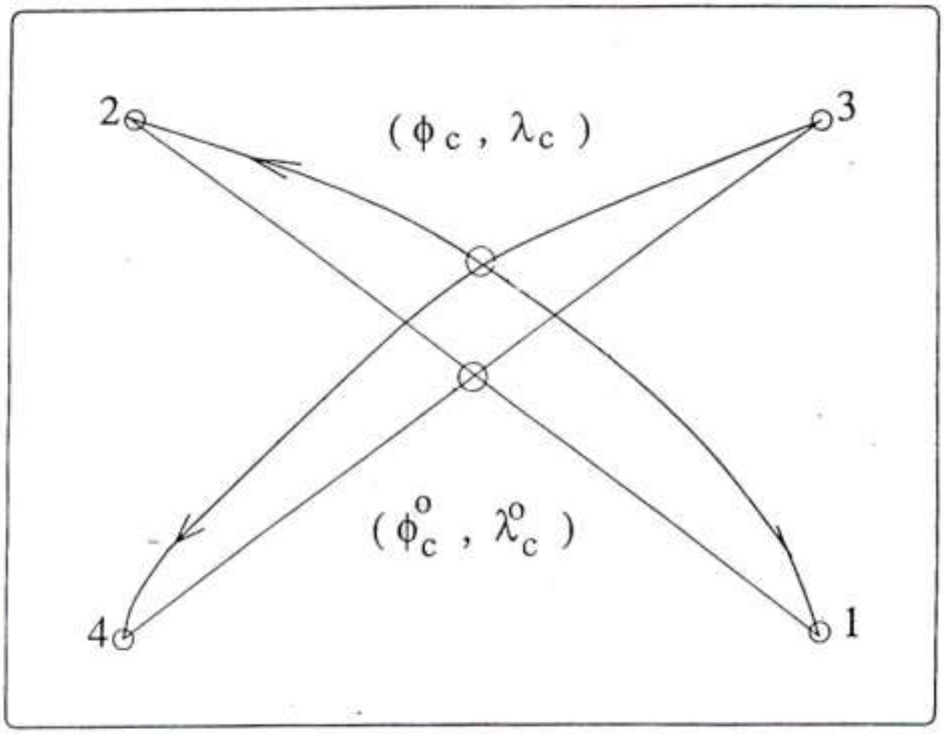
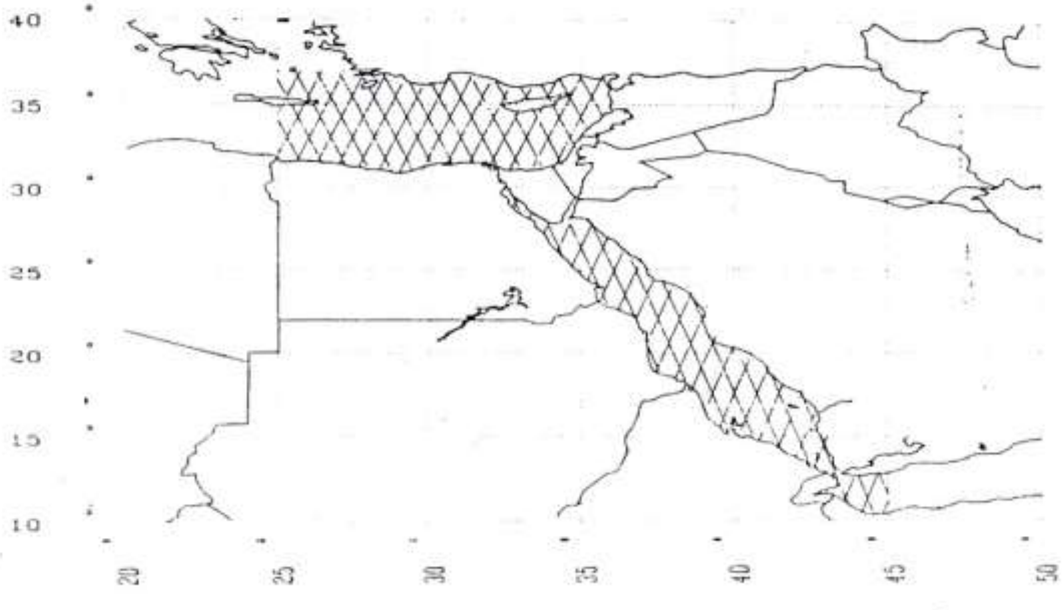


Fig. (4) The distribution of ERS-1 altimeter data (35 days) in the test area



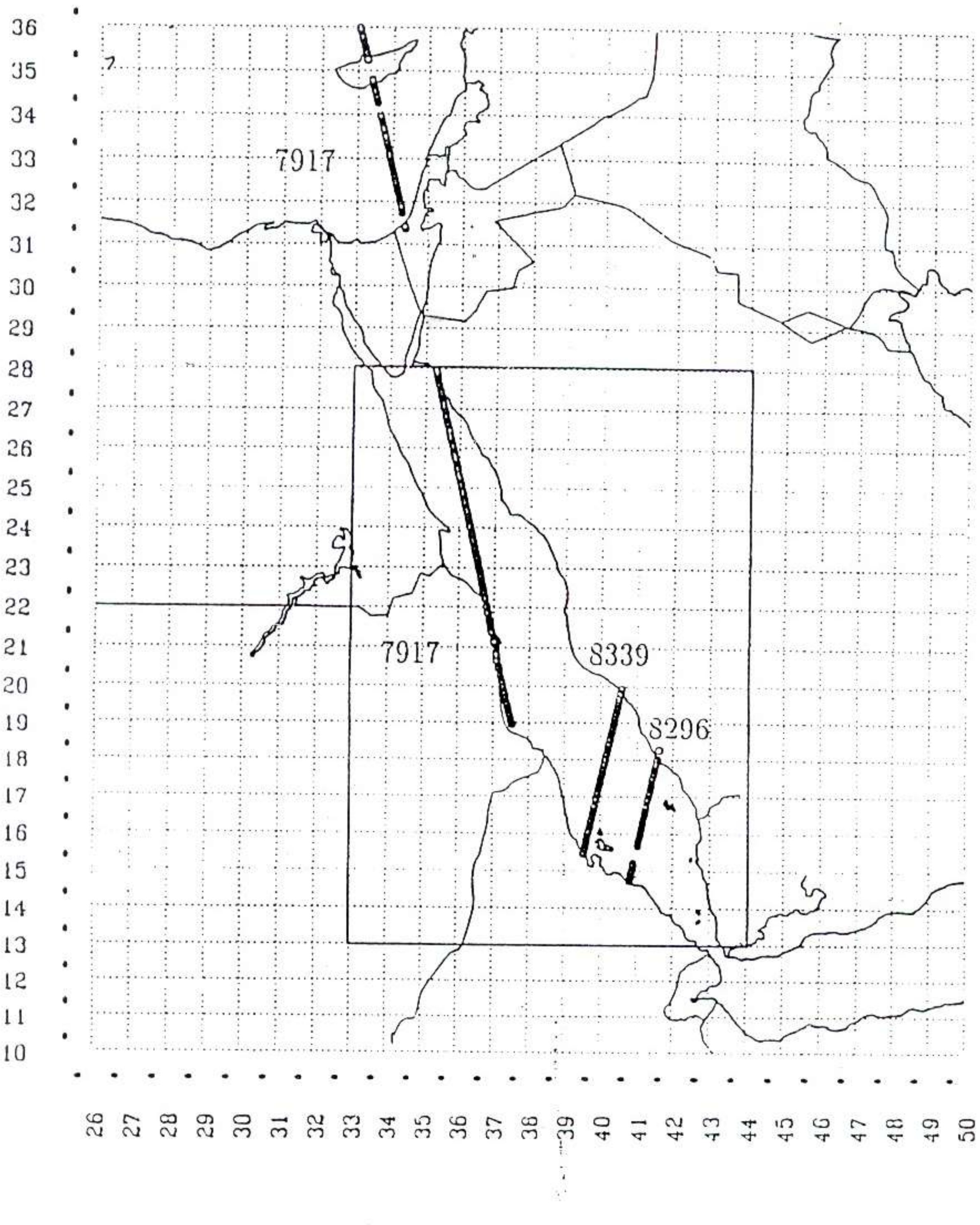


Fig. (5) Location of the 3 selected tracks for the 35 days

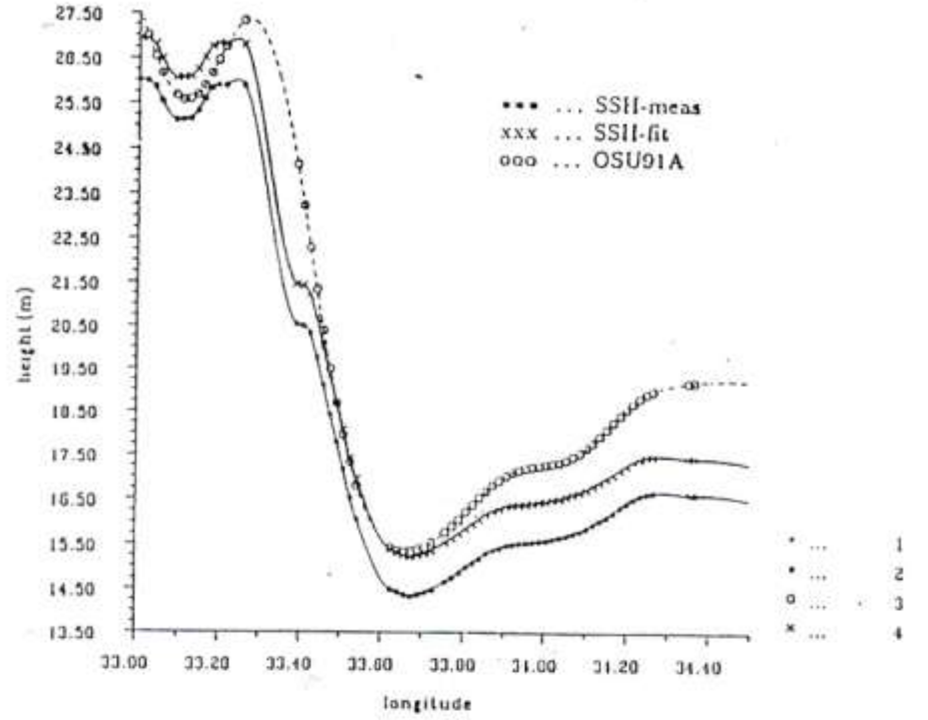


Fig. (6) Height profiles along the selected long north-going track 7917 (over the eastern part Mediterranean Sea 35 days)

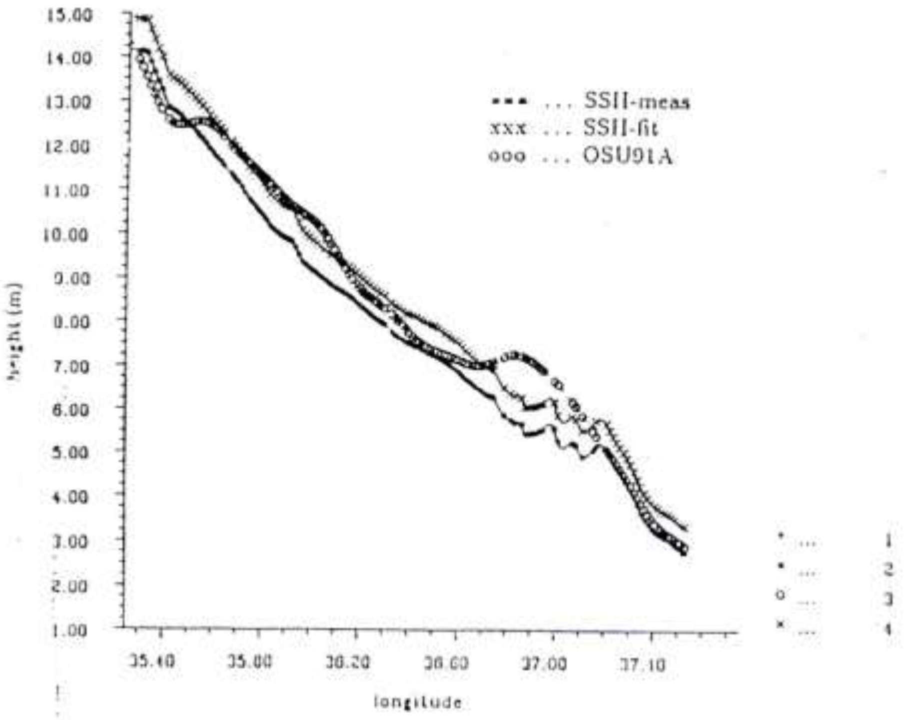


Fig. (7) Height profiles along the selected long north-going track 7917 (over the Red Sea 35 days)

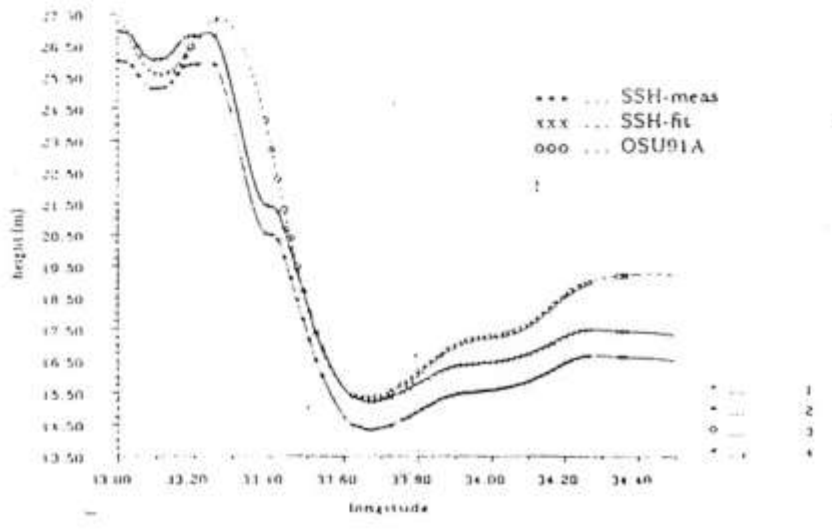


Fig. (8) Height profiles along the selected short south-going track 8296 (over the Red Sea 35 days)

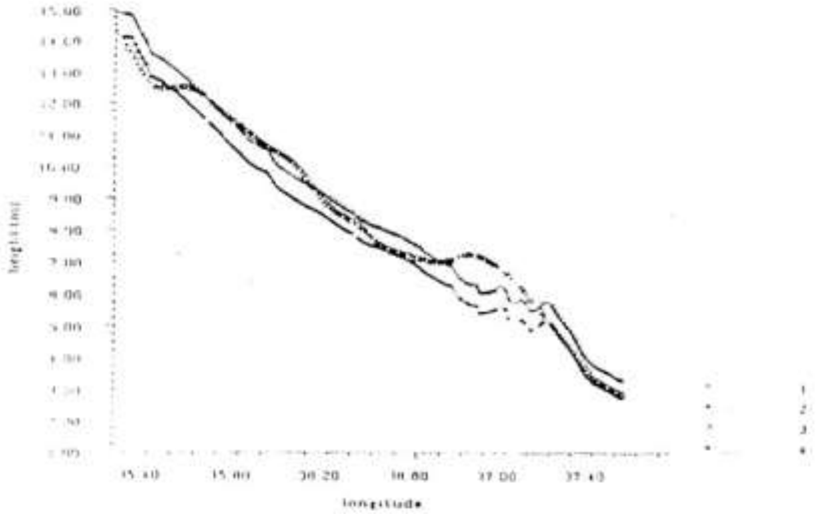


Fig. (9) Height profiles along the selected short south -going track 8339 (over the Red Sea 35 days)

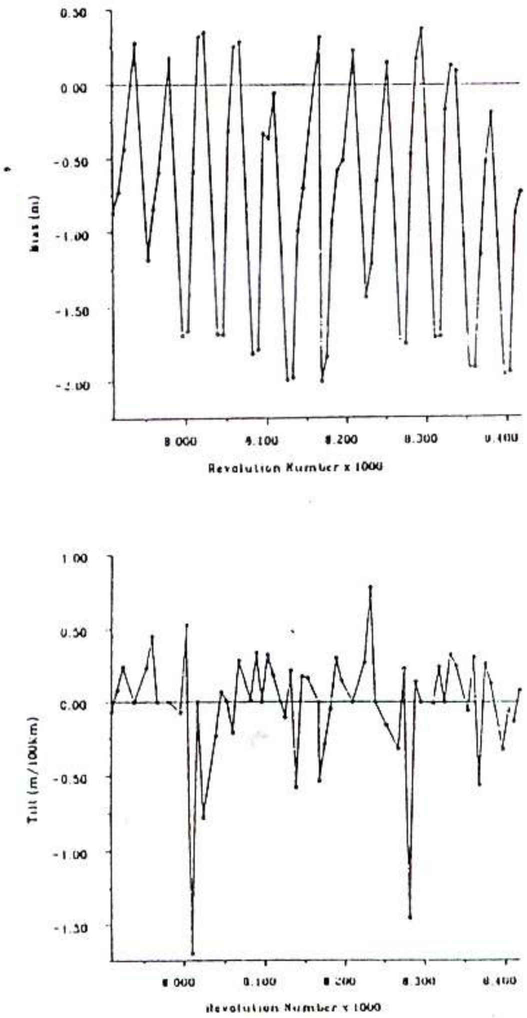


Fig. (10) Variation of adjusted bias and tilt for the used 58 tracks for 35 days ERM

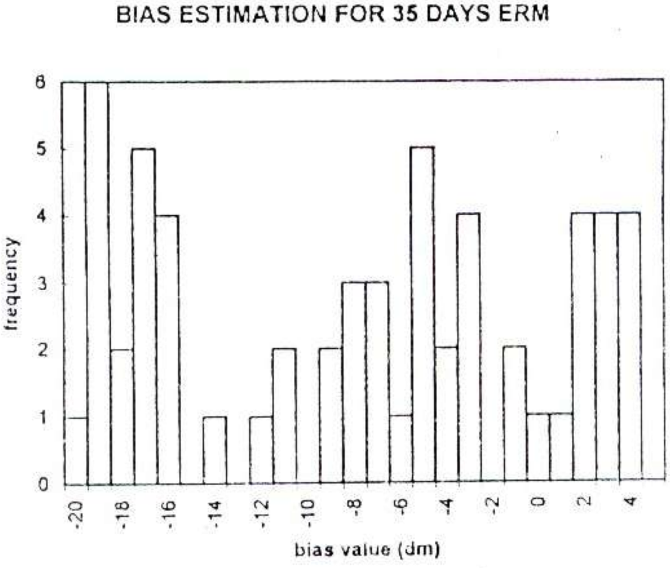


Fig. (11) Histogram of estimated bias parameter (for 35 days ERM)

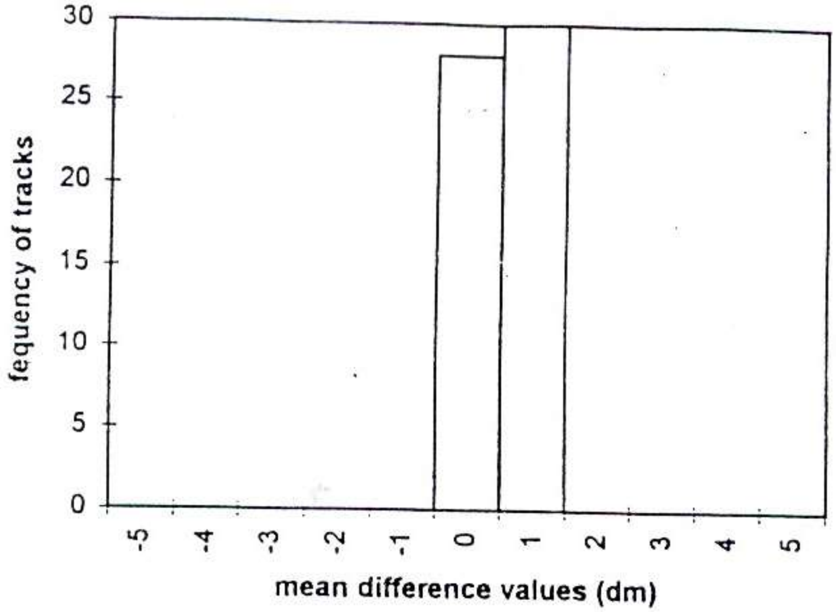


Fig. (12) Histogram of mean cross-over difference per track before adjustment for 35 days ERM

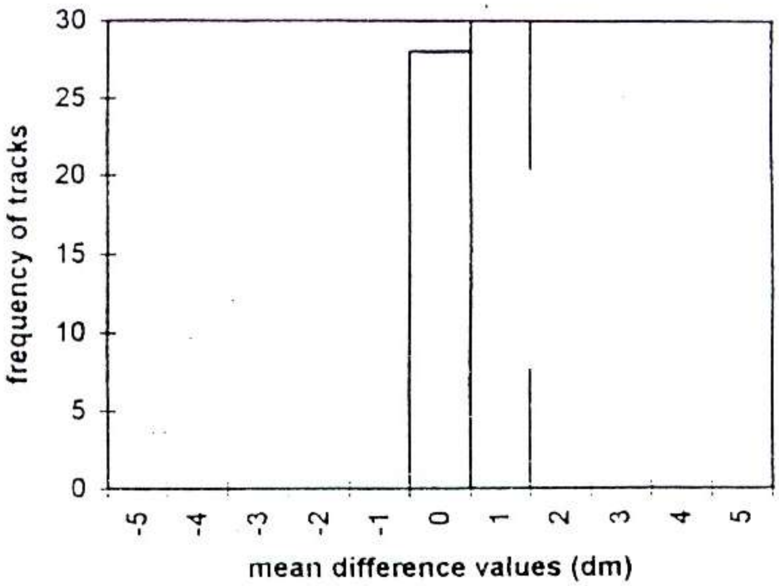


Fig. (13) Histogram of mean cross-over difference per track after adjustment for 35 days ERM

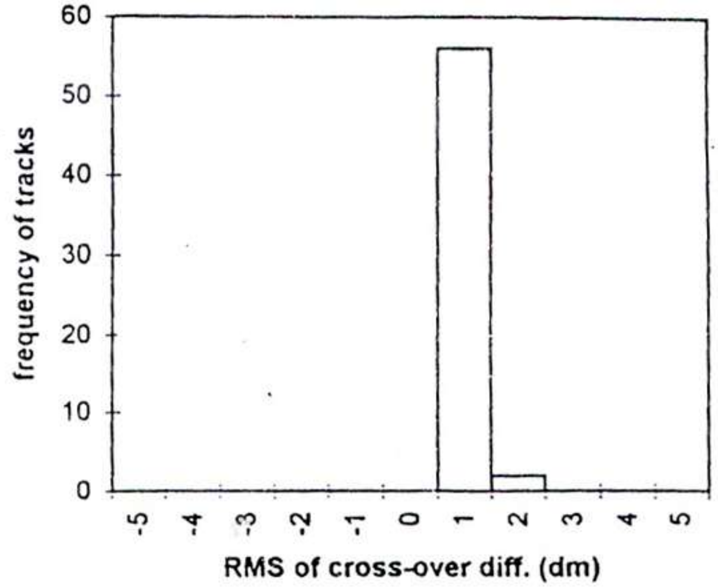


Fig. (14) Histogram of RMS of the cross-over difference per track before adjustment for 35 days ERM

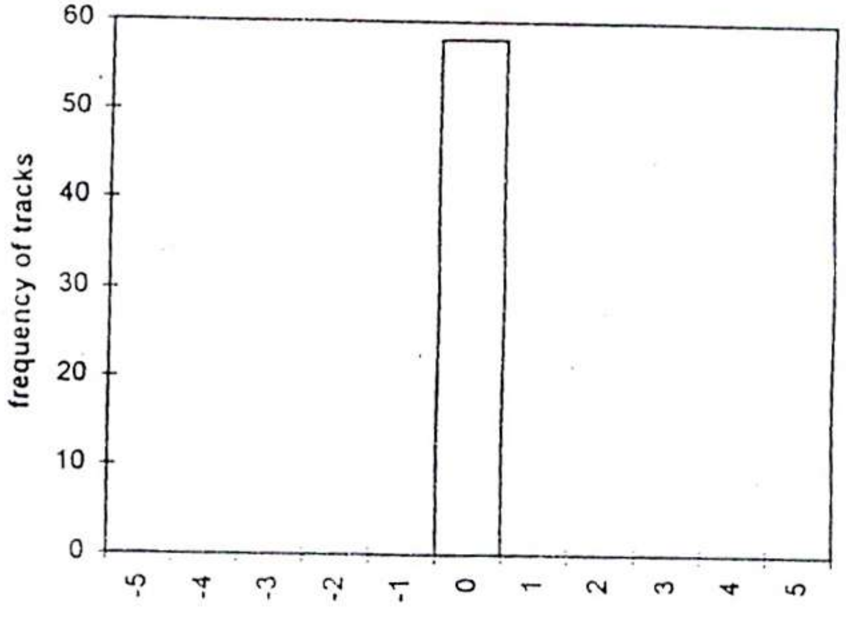


Fig. (15) Histogram of RMS of the cross-over difference per track after adjustment for 35 days ERM

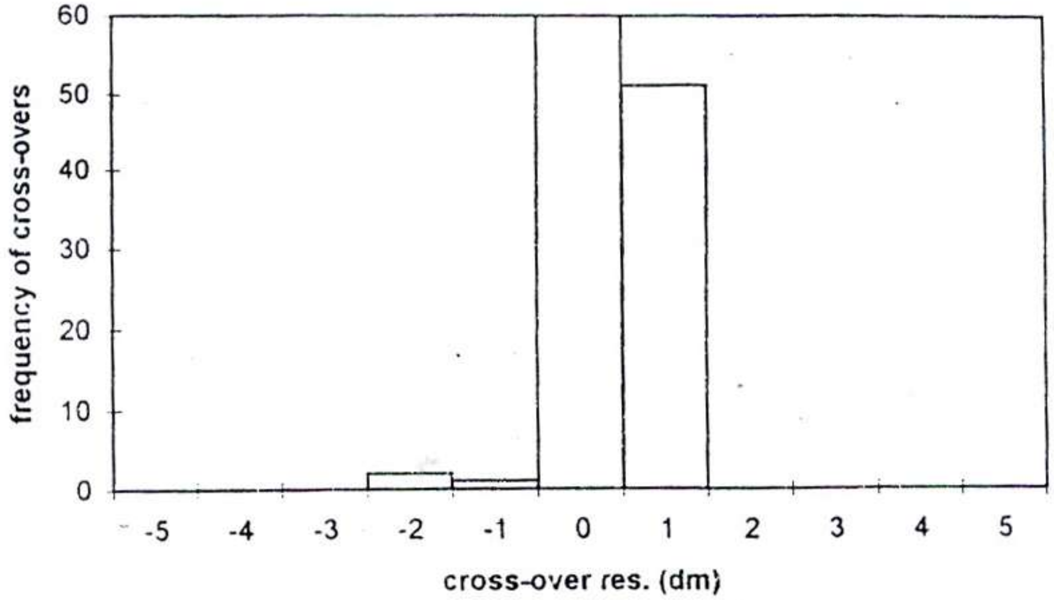


Fig. (16) Histogram of cross-over difference before adjustment for 35 days ERM

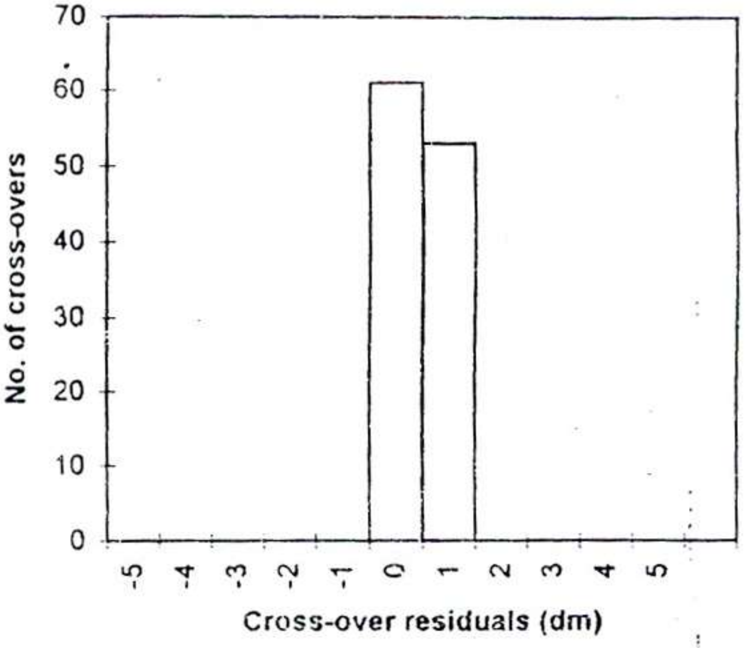


Fig. (17) Histogram of cross-over difference after adjustment for 35 days ERM

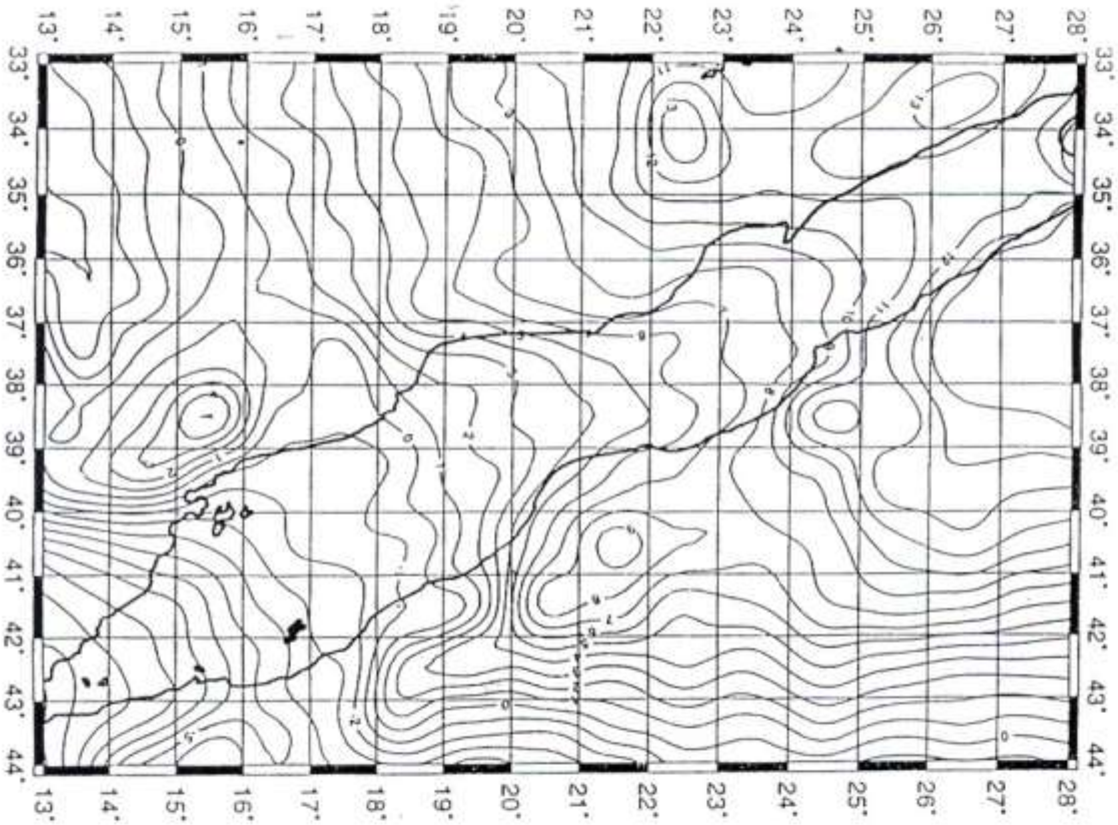


Fig. (18) The geoid undulation over the Red Sea area, as derived from OSU91A geopotential model. Contour interval: 1m

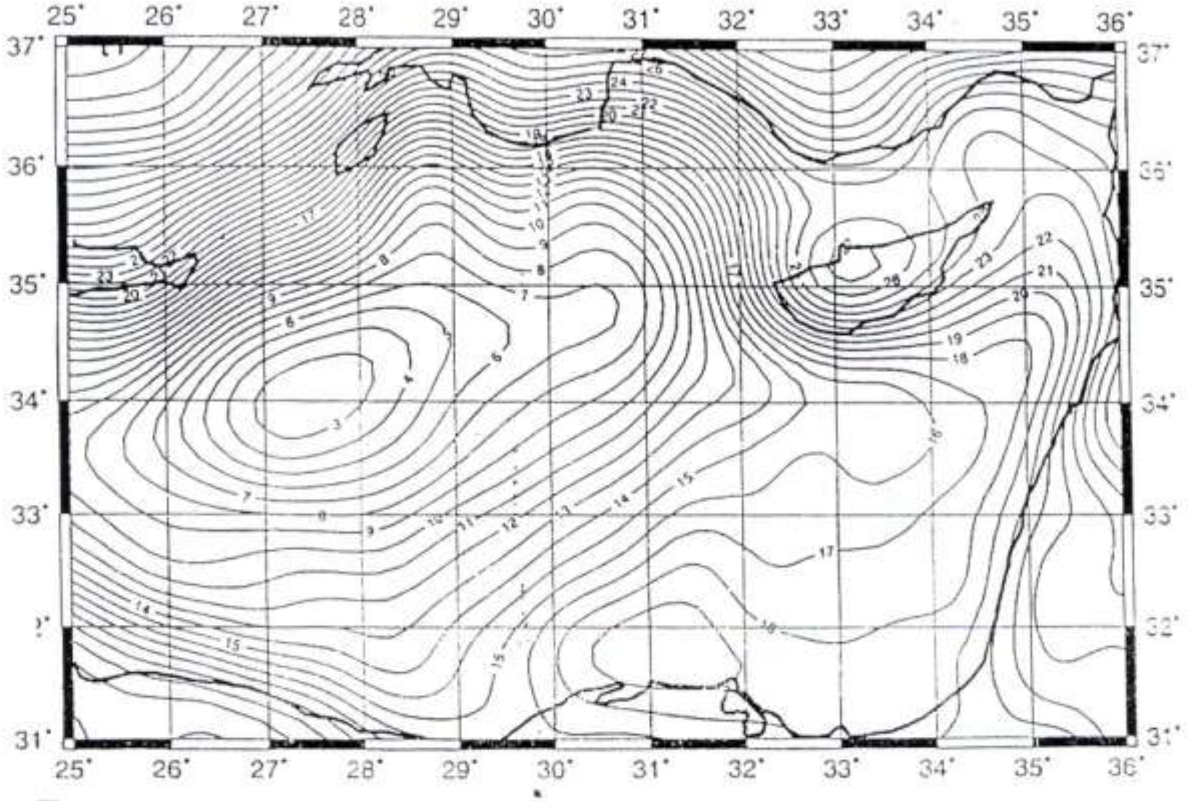


Fig. (19) The geoid undulation over the eastern part of the Mediterranean Sea area, as derived from OSU91A geopotential model. Contour interval: 1m

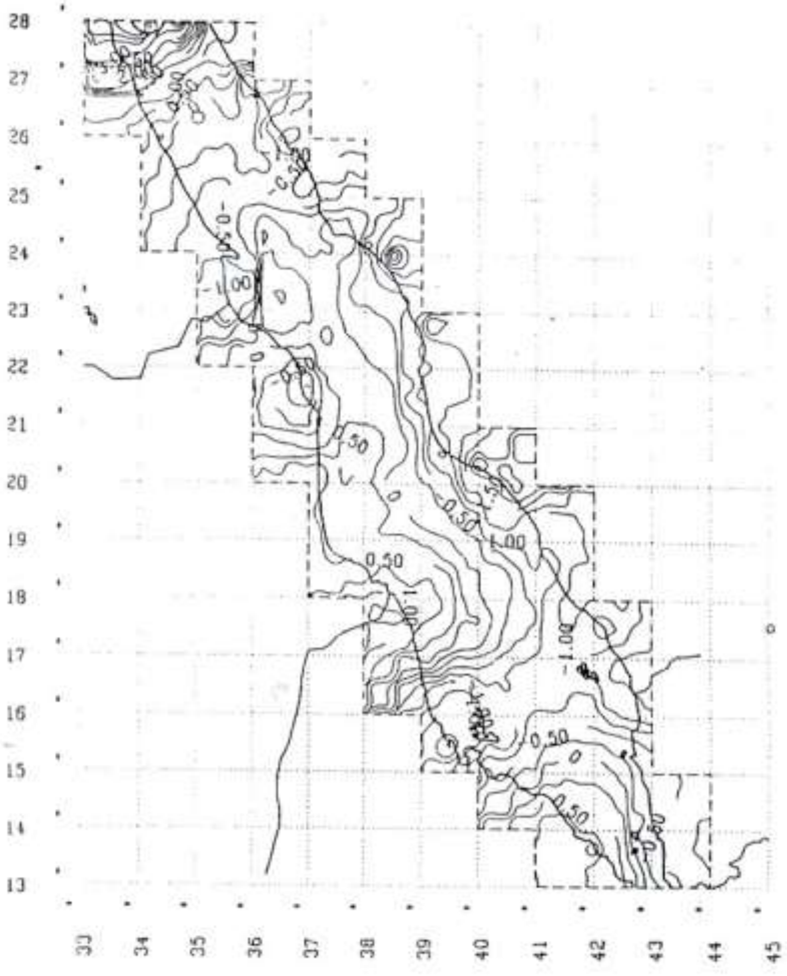


Fig. (20) Countour map of sea surface topography (SST) of the Red Sea related to OSU91A global geoid, as derived from the ERS-1 altimetric data of 35 days ERM. Contour interval 0.25 m

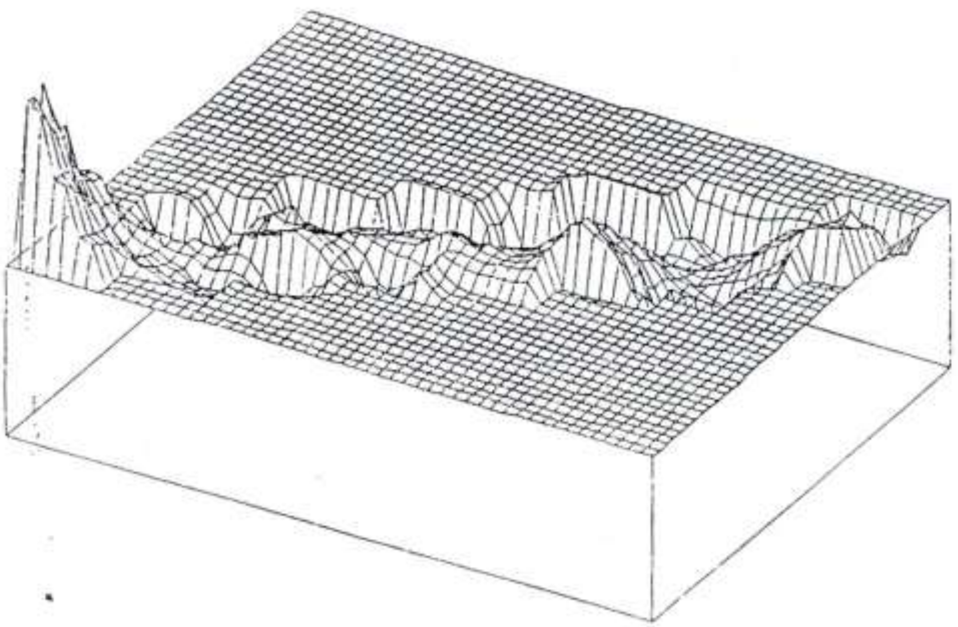


Fig. (21) 3-dimensional view of the SST of the Red Sea area related to OSU91A global geoid, as derived from the ERS-1 altimetric data of 35 days ERM

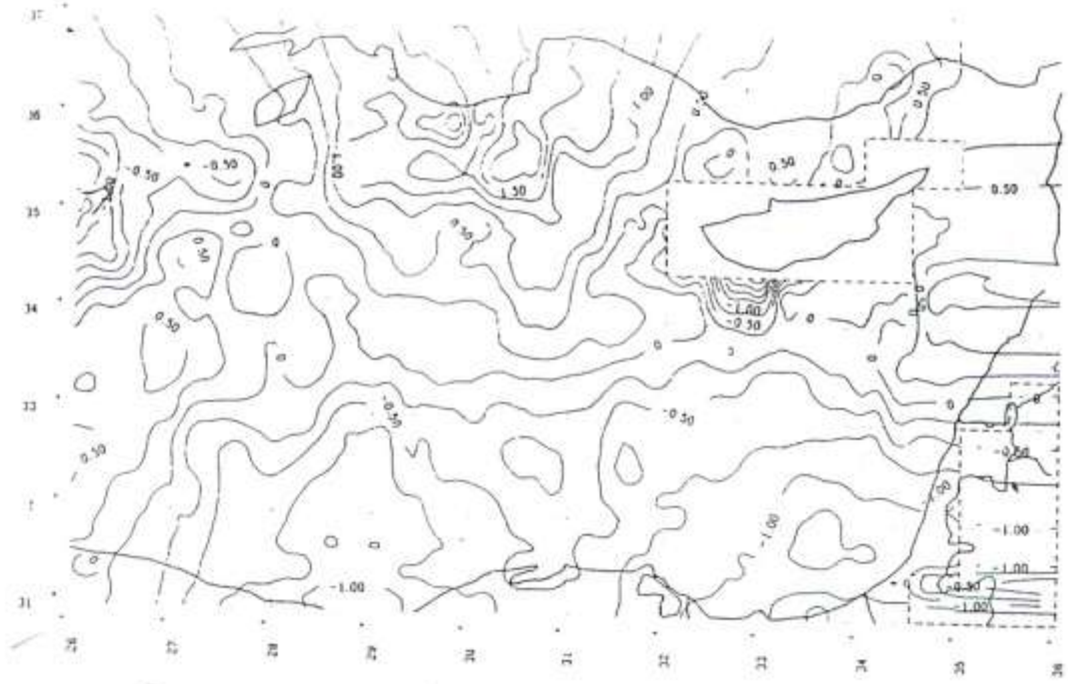


Fig. (22) Countour map of sea surface topography (SST) of the Mediterranean Sea related to OSU91A global geoid, as derived from the ERS-1 altimetric data of 35 days ERM. Contour interval 0.25 m

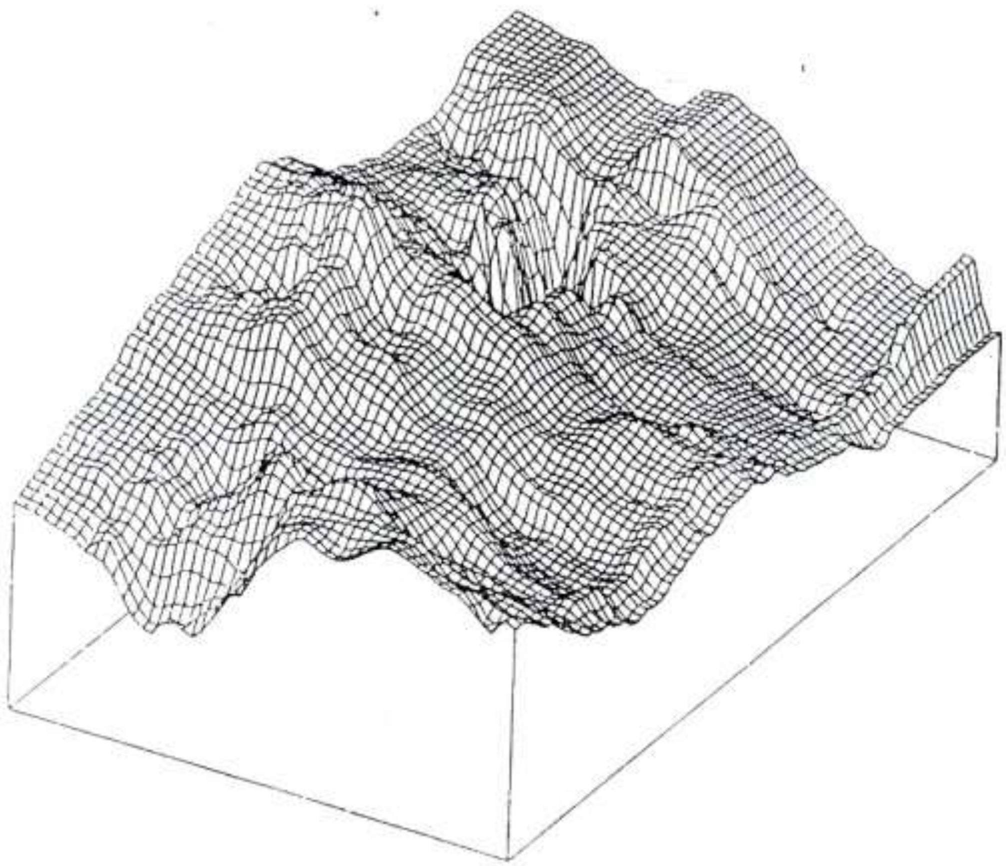


Fig. (23) 3-dimensional view of the SST of the Mediterranean Sea area related to OSU91A global geoid, as derived from the ERS-1 altimetric data of 35 days ERM