Variation of Great Lakes Water Levels Derived From Geosat Altimetry

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Abstract

A technique for using satellite radar altimetry data to estimate the temporal variation of the water level in moderate to large inland bodies of water (lakes, in particular) is described. Great Lakes data from the first two years of the U. S. Navy's Geosat Exact Repeat Mission (November 1986- November 1988), for which there is an improved orbit, arc used to demonstrate the technique. The Geosat results arc compared to the lake level data collected by the Great Lakes Section, NOAA/National Ocean Service and arc found 10 reproduce the temporal variations of the five major lakes with root mean square error (RMS) ranging from 9.5 to 14.0 centimeters and a combined average of 11.3 centimeters. Geosat data arc also analyzed for Lake St. Clair, representing a moderate-sized lake, with a resulting RMS of 17.5 centimeters. During this study period, the waler level in the Great Lakes varied in a typical annual cycle of about 0.2 meters (0.5 meters for Lake Ontario) superimposed on a general decline of approximately half a meter. The altimeter data reproduced the general decline reasonably well for all the lakes, but the annual cycle was obscured in some lakes duc to systematic errors in the al timeter data. Current and future altimetry missions will have markedl y improved accuracy which will permit many moderate (25 kilometers) to large (> 100 kilometers) inland bodies of water to be routinely monitored,

Introduction

Monitoring the hydrologic cycle is of paramount importance to determining magnitude of global change and understanding the consequences of our changing environment (Dozier, 1992). It has direct implications on the Earth's energy budget, as well as agriculture and other aspects of mankind's quality of life. One aspect of the hydrologic cycle is the variation of inland bodies of (normally fresh) water. Typically these include lakes, rivers, marshes, and small seas. Variations in the level of inland waters reflect the amount of rain/snow melt, evaporation and even human intervention (such as pumping).

Over the past 20 years, a number of radar altimeters have been placed in orbit. Designed primarily for oceanographic research, these instruments measure the range between the satellite and the ocean surface. Because of limitations on the knowledge of the satellite's orbit, altimetric data could only be used in a relative sense to study transient features. The absolute measurement of sea level (relative to an ellipsoid) was limited by radial orbit error, which could be a meter or more. However, within the last few years, knowledge of the Earth's gravitational field has significantly improved, resulting in more accurate orbits. For the recently launched TOPEX/POSEIDON satellite, the orbit error is expected to bc less than ten centimeters.

Many inland bodies of water throughout the world are monitored with *in situ* measurement systems. However, satellite radar altimeters have the potential of providing an additional source of water level data with minimal effort and cost. For well-monitored bodies of water, altimeter data can supplement *in situ* data that may not be readily available to the global change researcher or for which the measurement technology and data quality may not be known. Altimeter observations can also benefit studies of those bodies of water for which the in *situ* data are not collected routinely or in dense enough networks to adequately provide average levels. In addition to water levels, altimeter data also provide statistics on wave height and have the potential to establish freeze/thaw dates. Unlike many other remote sensing systems, altimeter measurements arc not dependent on cloud cover. Distribution of altimeter data to researchers may occur as soon as a few weeks after the data are taken, depending on the policies of the specific mission.

In this paper we examine the potential for using altimetric data to monitor the water level variation of the Great Lakes and Lake St. Clair. These lakes were chosen because of their number, size and the fact that they are thoroughly monitored. The large size of the Great Lakes provides between five and ten satellite tracks over each lake. In addition, there are two tracks over Lake St. Clair, a moderate-sized lake. The size of the lakes permits the altimeter data to bc used without special reprocessing to eliminate interference from land. The six well-monitored lakes provide a reasonable sample to evaluate the performance of the altimeter. The altimeter data chosen is from the most recently completed mission -- the U. S. Navy's GEOdetic SATellite (Geosat).

Geosat

Mission Overview

Geosat radar altimeter satellite was launched by the US Navy in April of 1985 to map the Earth's geoid in what is referred to as the Geodetic Mission (GM). Most of the data from that mission arc still classified. Once the GM was completed, the satellite was placed into a 17.05 day exact repeat orbit - the same orbit as NASA's 1978 SEASAT satellite. The primary purpose of the Exact Repeat Mission (ERM) was to provide data for oceanographic analysis. The complete ERM data set from November 11, 1986 to December 31, 1989 is unclassified. The ocean data set, which includes the Great Lakes data used in this study, is available on CD-ROM from the National Oceanic and Atmospheric Administration (NOAA) and is summarized by *Cheney et al.* (1991). To date, the limiting factor on accuracy of satellite altimetry has always been the knowledge of the radial component of the satellite's orbit. Recently, the University of Texas has recomputed the orbit for the first 44 repeat cycles of the Geosat ERM (November 11, 1986 - November 24, 1988), using an improved TEG-2B gravity field (*Shum et al.*, 1993). These improved orbits were provided by *Shum* (1993). The resulting radial orbit error has been reduced by more than a factor of two. The remaining Geosat data arc significantly degraded because increased solar activity, which increases drag, increased the orbit error. The data used in this study is limited to the first 44 cycles of the ERM for which the improved orbit is available.

Discussion of Altimetry Observations

The basic quantity reported in the Geosat ERM ocean data set is the height of the ocean (lake) surface above an ellipsoid for a given location at a given time. This height estimate is derived by accurately knowing the satellite's orbital position and the distance from the satellite to the ocean (lake) surface, which is measured by the radar altimeter. The altimeter sends a 13.65 GHz chirp to the Earth's surface and the distance is estimated by timing the return signal. The altimeter includes an onboard tracker to estimate when the return pulse will arrive. The tracker assumes a slowly varying surface. When the tracker encounters a rapidly changing slope, such as is produced by land, it can become confused. When this occurs, the altimeter is said to be "out-of-lock" and the range estimates are lost. The tracker will then attempt to reestablish the proper range. When transitioning from land to water, the altimeter requires a certain amount of time to "lock-up." Unfortunately, Geosat, as compared with other satellite altimeters, was particularly poor at obtaining lock when coming off of land.

The time required to lock-up over inland bodies of water depends on the type of terrain being traversed prior to encountering water and the attitude of the spacecraft. The more rugged the terrain, the longer needed to find the proper range to the water. The situation is further complicated for Geosat because of the changing attitude of the spacecraft. The ability of the Geosat altimeter to lock-up as it transitioned from land to water was dependent on the off-nadir pointing of the altimeter (*Cheney et al.*, 1991). The larger the off-nadir pointing, the greater the data loss during the land-water transition. The attitude variation was primarily due to variations of solar radiation pressure on the satellite which produced short-term (period of about five hours) and long-term (11 -month period) variations in the satellite's attitude. The practical result is that for a repeat cycle, a given pass over the Great Lakes could include an extensive track of data while for the next cycle there may be little or no data for the same pass.

l'here are several corrections which must be applied to the radar altimeter range estimate. These arc documented in *Cheney et al, (1991).* Most of these corrections result from the radar pulse traveling through the Earth's atmosphere and tend to delay the return signal. Specifically y, these include the dry tropospheric, wet tropospheric (for water vapor) and the ionospheric corrections. The first two are estimated from meteorological models and the latter from an ionosphere model. Of these corrections, the ionosphere correction has the potential for the greatest error (see *Cheney et al., 1991).* For the latitude of the Great Lakes, the ionosphere correction is typically much smaller than at the equator, where the greatest errors occur, Nonetheless, there is the potential of several centimeters error in the altimeter range estimate because of uncertainties in these correct ions.

in addition to the atmospheric corrections, a correction also has to be made for the solid Earth tide. Unlike the oceans, the variations of Great lakes water levels due to direct tidal forcing are extremely small compared to the variations due to other sources. Thus, they are ignored for this application.

A detailed discussion of the radar altimeter measurement technique is given by *Chelton et al.* (1989).

Lake Level Data for the Great Lakes

Lake level data for these analyses were obtained from the Great Lakes Section, Ocean and Lake Levels Division, National Ocean Service (NOS). The Section is responsible for management of a permanent network of 49 lake level stations located throughout the Great Lakes Basin, including the connecting waterways and Lake St. Clair. Several stations have been in operation since the mid-1 800s. 'I'he data are used to support regulation, navigation and charting, river and harbor improvement, power generation, and scientific studies. All data are referenced to a common datum: International Great Lakes Datum (IGLD), which is also used by a comparable Canadian network of stations, Figure 1 shows the location of the NOAA stations and the **selected** stations used in this study.

The NOAA stations are each generally configured with a primary digital float-driven electro-mechanical gauge providing punched-paper-tape output. These gauges collect data at 15-minute intervals with 0.01 foot resolution and with a backup analog float-driven mechanical gauge collecting data on a strip chart with 0.01 resolution. A station observer makes daily cheeks on the systems for correct time and to make independent water level measurements using an electric-tape-gauge (ETG). The ETG observations are used to complete the editing and processing of the data and to ensure the data are continuously referenced to datum. The gauges are located in heated walk-in enclosures sitting on top of wells or sumps located several feet from the shoreline. The wells are connected to the water with underground horizontal intake pipes located at sufficient depth to be below the expected ice thicknesses. These configurations act as stilling wells for the high-frequency wind waves while allowing full transmission of the lake variation frequencies.

Using hourly data, the daily, monthly, and annual average water levels are computed for each station as standard output products. Highest and lowest daily average water levels for each month and frequency distributions of the daily average water levels are also compiled. For purposes of this paper, average daily lake levels for each lake were estimated by averaging the daily lake levels from several strategical] y spaced stations from each lake. On] y one station was used (and in operation) for the Lake St, Clair analysis,

Figure 2 illustrates the range of consistency among stations on two of the lakes. In both examples, Lakes Ontario and Erie, a time series of daily lake levels are plotted for four stations. Although these lakes arc adjacent, the Lake Ontario stations display significantly better consistency. The brief, but significant, departures from the mean trend by some or all of the lake Erie stations is duc to wind-driven events (e.g., seiche). Lake Erie is extremely susceptible to seiche action in which the basin is set into periodic 'slosh' motion in response to meteorological forcing. Although the remaining lakes display some lack of consistency among stations, these periods are less extensive and of much smaller magnitude than those displayed by the Lake Erie data.

Data Analysis Methodology

In principle, monitoring temporal lake level variations, using Geosat *or* other spaceborne altimeter, is straightforward. For a given lake, the altimeter-derived lake level height variations arc evaluated as a function of time. Each overflight of the lake provides an estimate of the departure from the mean lake level. However, this estimate not only includes the lake level variation, but also the altimeter error. For convenience in these analyses, we have chosen to only look at the relative lake level variation and thus, the analyses are referenced to zero. It would be straightforward to reference the results to a specific point on the lake and present them in terms of a lake level datum.

in our analyses, we define one-half of an orbital revolution to be a *pass.* A given pass begins at either the northern-most or southern-most point in the satellites orbit and continues for 180 degrees of the orbit. Following the convention used by the Topex/Poseidon mission, ascending pass numbers, when the satellite is moving from the south to the north, are odd and the descending passes arc even. The passes are numbered consecutively from the beginning of the cycle. In its 17-day repeat cycle, Geosat has 244 orbits or 488 passes. Of these, only 21 passes actually cross the Great Lakes. The Geosat groundtracks that traverse the Great Lakes are shown in Figure 3. The number of passes across the lakes range from ten for Lake Superior to five for Lake Ontario. In addition, Lake St. Clair, a moderate-sized lake between Lakes Huron and Erie, also has two passes. Geosat pass 465 crosses every lake except Lake Ontario. Because the level of each lake may vary differently, each lake is analyzed separately.

The length an overflight over a lake or other inland body of water is very short when compared to a full pass. Thus, the determination of tilt in the altimeter orbital error is not a significant concern and does not need to be estimated. By ignoring the tilt in the orbit, the maximum increased error in the altimeter measurements across one of the Great Lakes is at most about one centimeter with the improved Geosat orbit.

For each pass across each lake, the satellite repeats approximately the same groundtrack (to within a kilometer or so) every 17.05 days, one repeat c ycle. The height estimates that the altimeter records as it traverses a lake will display variations that are primarily due to variations of the Earth's geoid, which the water level emulates. To evaluate the temporal change in lake level, the mean lake level, or the mean spatial variation of the water level along the pass, must be calculated so that it can be removed and the residuals studied, This is accomplished by binning all available data for the 44 repeat cycles as a function of latitude and averaging the data in each bin. Bins of 0.05 degrees or every 5.55 kilometers in a north-south direction were selected. Because the orbit of Geosat, which is retrograde, has an inclination of 108 degrees, it traverses the Great Lakes cast to west at an angle of roughly 30 degrees from north, corresponding to a ground track length of about 6.4 kilometers for each 0.05 degree latitude bin. The distance between one-second average Geosat height observations is 6.6 kilometers, resulting in one observation pcr bin pcr repeat cycle. The groundtrack angle varies somewhat with latitude over the region of interest, but this variation does not adversely affect the procedure adopted. If less than three observations (out of 44 possible overflights) fall into a bin, that bin is not used in the analysis.

After the spatial variation of the mean lake level is established for a given pass, residuals for each satellite overflight are calculated by subtracting each one-second altimeter observation from the average in the appropriate latitude bin. Each residual is corrected for location differences within the bin between the observation and average by using the known geoid difference. Thus, each residual for a given latitude bin is referenced to the location of the average value for the bin. The residual is assigned a weight equal to the total number of altimeter observations used to compute the bin's average lake level. The weighted average of the residuals for a single overflight over a lake provides an estimate of the departure from the mean lake level for that specific time. For the five Great lakes, any overflight with less than three valid one-second observations (in-lock footprints) over the lake were discarded from the analysis.

After the departure from the mean lake level is calculated for an overflight, it is then subtracted from the altimeter residuals. These corrected residuals are combined for all the overflights for that pass and examined for "trends" and "blunder points" or outliers. The blunder points typically occur near land and are the result of land contamination. For this study, these outliers were edited from the data if their corrected residuals were more than $\pm$ 30 centimeters. This limit was chosen because it is significantly greater than the observed cross-lake deviation from the average lake level variation. After data editing, the analysis procedure is repeated.

Trends, affecting one or more latitude bins, in the cross-lake corrected residuals can occur due to quirks in the data distribution among the latitude bins. The trends, when observed, arc usually near land where fewer observations are available and reflect errors in the average lake level for the latitude bins in question. The weighting procedure utilized minimizes the importance of these bins. However, it is possible to improve the lake level averages for each bin by using the information provided by the corrected residuals. In essence, the average value of the corrected residuals for each bin should be zero, if the average lake level for that bin is correctly determined. A non-zero mean for the corrected residuals implies that the average lake level is in error by that amount. By applying that correction to the average for the bin in question, an improved spatial variation along the satellite groundtrack is obtained. Figure 4 illustrates the typical improvement that is obtained using this procedure. The figure shows that, although the correction for most latitude bins is less than five centimeters, one bin requires a nine centimeter correction. The procedure gives a smoother variation of mean lake level which is consistent the Rapp geoid (Rapp and Pavlis, 1990). The entire analysis procedure is then repeated with the corrected average lake level values.

The final step in the analysis is to combine the results from the different passes for each lake.

‘l’his is done assuming that the temporal lake level variations are the same over the entire lake, an assumption which is consistent with the NOAA/NOS lake level measurements (eg., Figure 2). At this point, the time series of estimated departures from the mean lake level, for a given pass, are all referenced to zero and their sum equals zero; each estimate representing a combination of lake level change and altimeter error. All the lakes considered here have more than one pass. If the temporal distribution of overflights was the same for every pass, the passes could simply be combined. However in some cases, the distributions are significantly different and the. measurements are not random because they include lake level variation. Thus, to combine the different passes, all are referenced to the pass with the greatest number of overflights by interpolating and minimizing the sum of the squares. The resulting pass corrections to the bias estimates were typically less than five centimeters. However, a few corrections were greater than 10 centimeters.

Lake Level Variation

The Great Lakes

The largest of the Great Lakes also has the greatest number of Geosat passes. As indicated in Figure *3* and Table 1, Lake Superior is covered by a total of ten passes ranging from the short passes 207 and 340 at the west end of the lake to several long passes in the middle of the lake. These passes produced a total of 217 estimates of the relative lake level variation.

Figure 5 presents a comparison of the estimated relative lake level variation derived from the GEM-T2 orbit, which is distributed on the NOAA Geosat CD-ROMs, and the improved TEG-2B orbit. The improvement is dramatic. The root mean square (RMS) of the (Geosat - NOAA/NOS) lake level residuals decreases from 25.1 cm to 9.5 cm. The annual cycle of Lake Superior is visible, despite its small range (about 20 cm). However, close examination reveals that Geosat underestimates, particularly in 1987, and overestimates in 1988. This trend is apparent in the results for all the lakes. These systematic altimeter errors will be discussed later.

Figure 6 (a-d) presents the results for the other lakes. The number of passes, five to seven, for each of the remaining Great Lakes are displayed in Figure 2 and summarized in “l’able 1. It should be noted that pass 465 over Lake Huron and pass 149 over Lake Eric were too short to consistently provide the required minimum three footprints across the lake. These passes arc considered special cases and arc discussed in the section on Lake St. Clair.

The RMS of the lake level variation for the remaining four Great Lakes varies from 14.0 cm for Lake Erie to 9.5 cm for Lake Ontario. It is interesting to note that Lake Erie, with the worst RMS value of the five Great Lakes, is also the lake most affected by wind-driven events resulting in inconsistency in the lake level station data (Figure 2). Each of these lakes displays a general decline in water level which is detected by the altimeter. However, the annual cycles of Lakes Michigan, Huron, and Erie, which arc quite small, arc not convincingly shown. The failure of the altimeter to detect these annual cycles is a direct result of systematic errors that have a magnitude and period similar to the annual cycle of these lakes. Although Lake Ontario has only 59 estimates of temporal water level variation, it also has the greatest annual cycle (order of 50 cm). The altimeter-derived estimates accurately reflect the observed variation.

Lake St. Clair

The previous results were based on a minimum of three in-lock footprints across a lake for a given overflight. Clearly, the more footprints across a lake, the more accurate the lake level estimate. For very small lakes, where the altimeter fails to achieve lock, it may be possible to reprocess the altimeter returns to extract an estimate of the water level. *Koblinsky et al. (1993)* have demonstrated this technique for deriving the level of the Amazon River. However, reprocessing the waveforms requires a significant increase in effort. The question is how well can moderate-sized lakes be monitored using the available in-lock data? With two separate passes to evaluate, Lake St. Clair provides an interesting test. For Geosat, each pass has typically only one or two in-lock footprints over the lake.

In all, there are 37 estimates of lake level for Lake St. Clair. The resulting RMS is 17.5 cm, significantly higher than that observed for the other lakes (see Figure 6c). The altimeter does detect a downward trend in the lake level, but the very small annual cycle (10 cm) is totally missed. Once again, systematic errors in the altimeter data obscure the subtle changes.

Two other passes, pass 149 over Lake Erie and pass 465 over Lake Huron, failed to have three footprints over their respective lake and thus, provide additional tests for smaller bodies of water. Pass 149 provided only five water level estimates for Lake Erie with a surprising low RMS of 12.0 cm. However, pass 465, which included 10 estimates for lake Huron, had an RMS of 15.7 cm.

Clearly, the expected Geosat RMS for moderate-sized lakes will be perhaps 50 percent higher than that found for the larger lakes. This suggests that only significant water level changes will be detected.

Geosat Altimeter Error

With a known lake level variation, which then can be removed from the analysis, the Great Lakes altimeter data can be used to evaluate the Geosat altimeter error. Figure 7b displays the combined residuals, after removal of lake level variation, from the analyses of Lakes Superior, Michigan, Huron, Erie, and Ontario (Figures 4b, 5a-d). Ideally, these residuals should be random. However, it is obvious that there is a trend, a “discontinuity” and an “annual” cycle in the residuals.

The discontinuity, near day 860, begins with one Geosat orbit maneuver and ends with another. In all there were 25 such maneuvers, about once per month, during this phase of the ERM. Although the effect of other orbital maneuvers can be seen in the plotted residuals, these are short-lived effects and not of significance for deriving temporal lake level variation.

Of greater concern is the trend in the residuals, which amounts to 8.9 cm/year. The trend is much larger than would be expected from any known error source, except possibly drift in the orbit computation. The derived slope disagrees with the slight negative slope found by *Tapley et al.* (1992) using the TEG-2 orbit for the entire ocean, although the methodology used to derive the TEG-2B orbit is somewhat different. It is curious that using the same data over the same time period with the earlier GEM T2 orbit fails to show this trend, although a much larger annual cycle is evident (Figure 7a). Other than a drift in the orbit, the other logical possibility is that an error in processing produced the slope. In addition to providing the improved orbits, *Shum* (1993) also provided altimeter time bias corrections which were applied to the time on the geophysical data record. By changing the time, the orbital position of the satellite changes. This could introduce a temporal change in the results if the time bias systematically increased or decreased. However, this is not the case and analyzing the data with and without the time bias produces no significant changes in the slope of the residuals. A final possibility is that this is a regional effect which is not seen when a global data set is used.

When the trend in the residuals and the discontinuity are eliminated, the remaining residuals display an apparent annual cycle with an amplitude (peak-to-trough) of about eight centimeters and with maxima just after the beginning of the year (Figure 7c). The pattern of the residuals agrees extremely well with that found by *Tapley et al.* (1992, Figure 4b) in their analysis of the global mean sea surface variation (based on the TEG-2 orbit). They discuss in their paper possible sources of error that might contribute to a cyclic error. The annual cycle may represent an error in one or more corrections (dry and wet troposphere, ionosphere, etc.). Orbit error, which would be expected to have a period equal to or one half of the synodic period of the satellite, is another possibility. With the synodic period being about 11 months, it is impossible to distinguish between a true annual cycle and an 11 -month cycle with only two years of data. The agreement between the present study and that by *Tapley et al.* suggests that, whatever the cause of the periodic variation, it occurs over the Great Lakes as well as the ocean.

The effect of these altimeter errors is to obscure temporal lake level variations. For Geosat, it should be possible to remove many of these systematic errors for the study of other lakes based on the error analysis presented here. When the trend, discontinuity and annual cycle are removed from the Great Lakes data, the RMS error drops from 11.3 to 8.6 centimeters and the new residuals show no obvious trends. Data from future missions, in particular, Topex/Poseidon, should have no significant systematic errors.

Conclusions “

The Great Lakes, Lake St. Clair and the connecting rivers are well-monitored by NOAA/ National Ocean Service (NOS) and do not require additional monitoring. However, they do provide a useful test case to evaluate the potential use of satellite radar altimeters for worldwide monitoring of the variation of the levels of lakes and other inland bodies of water. Although man y of the world's lakes are monitored, the usc of satellite altimetry can provide a low-cost, readily available set of data to supplement existing data or provide data for lakes not currently monitored.

The results of the Geosat evaluation of the Great lakes is both encouraging for the use of altimeters in general and discouraging in that the Geosat data have systematic errors which, without correction, limit its usefulness for monitoring lakes and small seas. It is obvious that the altimetry errors, particularly orbit errors, are being reduced sufficiently so that centimeter accuracy (with averaging) in lake level variability can be achieved in the near future, Missions, such as the recently launched Topex/Poseidon mission, will produce data products with errors much smaller that the Geosat data used in the present study. These data, when combined with other satellite data sets (to identify changes in lake area), will permit the water volume of lakes to be monitored from space.

One drawback to using spaceborne radar altimeters for this purpose is that they only look at nadir. It is not possible to direct the satellite to look at specific lakes. Sampling of lakes is by chance only. Some of this problem is mitigated by the European's ERS- 1 mission launched in 1991, which is spending much of its time in a 35-day repeat orbit (as compared with the Topex/Poseidon 10-day repeat cycle). This repeat cycle provides denser spacing of the ground tracks and thus, a better opportunity to sample additional lakes. With several future altimeters currently under consideration, each with different repeat cycles and orbital inclinations, the prospects for lake coverage appears favorable.

We thank C. K. Shum for providing the TEG-2B orbits and for extensive discussions related to this paper. This work was performed, in part, at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Figure Captions

Figure 1 — Distribution of NOAA/NOS lake level stations (boxes) along the Great Lakes and Lake St. Clair. The subset of stations used in the analysis is denoted by an asterisk in the box.

Figure 2 — Examples of lake level measurement consistency: a) four stations on Lake Ontario, and b) four stations on Lake Erie. Values are referenced to the IGLD. Observed departures in the Lake Erie data result from wind-driven events.

Figure 3 — The distribution of Geosat data used in the study. Pass numbers are indicated. Significant breaks in the data typically indicate the presence of an island.

Figure 4 — Comparison of the variation of mean lake level for pass 235 over Lake Huron derived from Geosat and the Rapp geoid (Rapp and Pavlis, 1990).

Figure 5 — Comparison of the derived temporal lake level variation for Lake Superior from (a) the GEM T2 orbit and (b) the more recent TEG-2B orbit. Each point is derived by averaging three or more Geosat one-second observations (footprints) across the lake. The solid line is the NOAA/NOS-measured lake level variation.

Figure 6 — The derived temporal lake level variation for Lakes (a) Michigan, (b) Huron, (c) Erie, (d) Huron, and (e) St. Clair based on the TEG-2B orbit. For all the lakes, except Lake St, Clair, each point is derived by averaging three or more Geosat one-second observations (footprints) across the lake. The solid line is the NOAA/NOS-measured lake level variation. Lake St. Clair typically had only onc or two in-lock observations.

Figure 7 — a) Five point running mean of the Geosat residuals from the Great Lakes with the lake level variation removed based on the GEM-T2 orbit. b) Same as (a) except based on the improved TEG-2B orbit. c) Same as (b) with trend and discontinuity removed. Annual cycle of eight centimeter amplitude (peak-to-trough) is superimposed.

Table 1

Summary of Great Lakes Overflight Data

Pass	Lake Superior No. of Overflights*	Maximum No. of Latitude Bins
024	31/33	27
063	21/22	14
110	25/27	20
196	5/7	6
207	9/13	4
293	22/25	13
340	17/18	8
379	23/30	20
426	33/33	22
465	31/31	36
	21 7/239	

Pass	Lake Michigan No. of Overflights*	Maximum No. of Latitude Bins
196	26/26	41
207	7/7	16
282	30/30	27
293	12/14	20
379	13/1 6	7
465	7/15	5
	95/1 08	

Pass	Lake Huron No. of Overflights*	Maximum No. of Latitude Bins
052	25/28	15
063	31/32	42
149	25/27	15
235	18/22	16
368	19/19	8
454	27/28	25
465^{+}	0/10	2
	145/166	

Table 1 (cont.)

Summary of Great Lakes Overflight Data

Lake Erie

Pass	No. of Overflights*	Maximum No. of Latitude Bins
052	15/15	4
063	11/17	10
138	32/33	15
149+	1/10	3
224	14/14	8
465	9/11	6
	82/100	

Lake Ontario

Pass	No. of Overflights*	Maximum No. of Latitude Bins
224	11/15	7
235	3/9	3
310	9/11	7
321	22/24	10
407	14/20	9
	59/79	

Lake St. Clair

Pass	No. of Overflights*	Maximum No. of Latitude Bins
052	0/20	2
465	0/18	2
	0/38	

* Number of overflights (out of 44 possible) with valid data, First number includes only those overflights with valid data in three or more latitude bins. Second number includes all overflights.

+ Not used in general analysis.

Fig 2

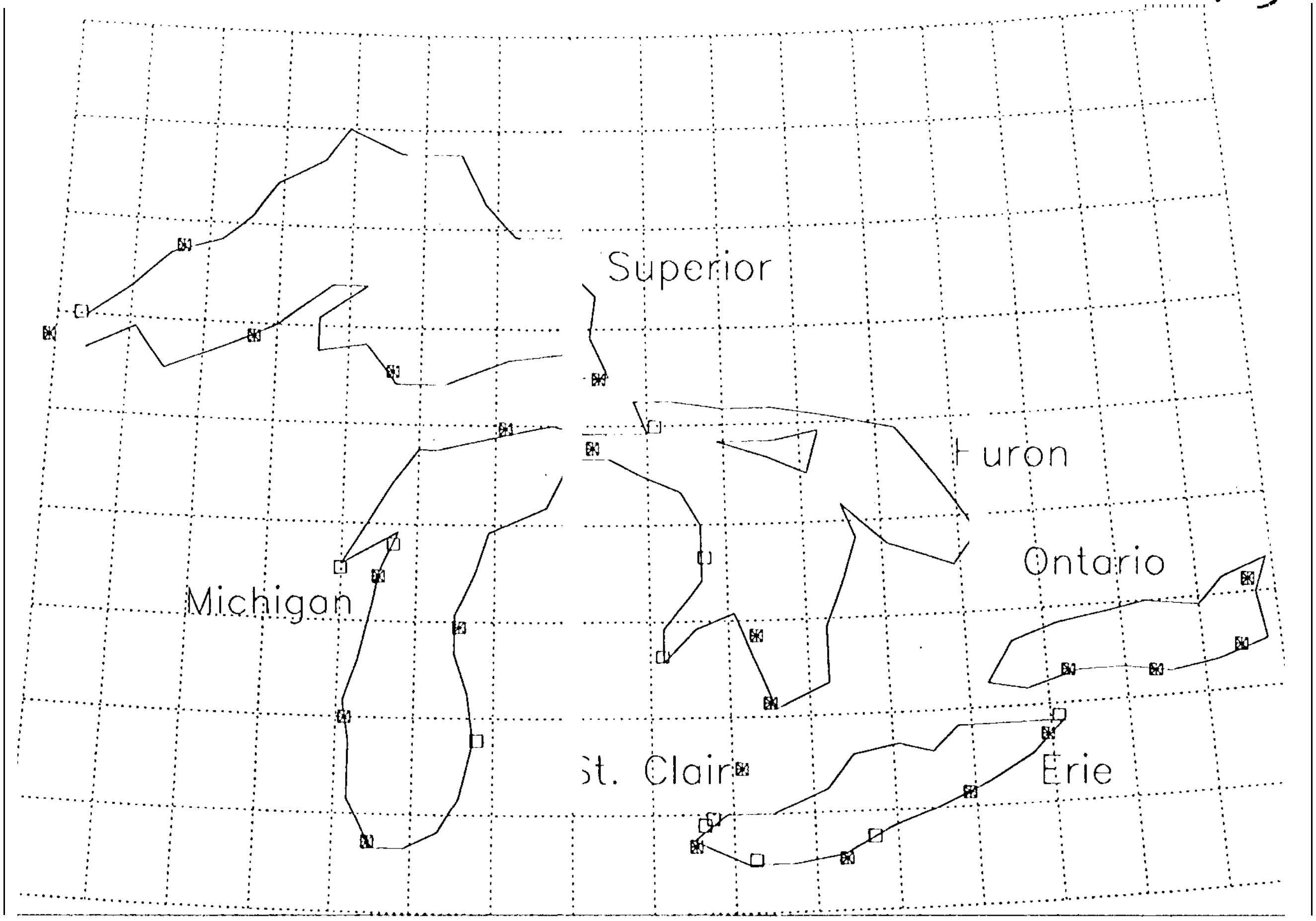
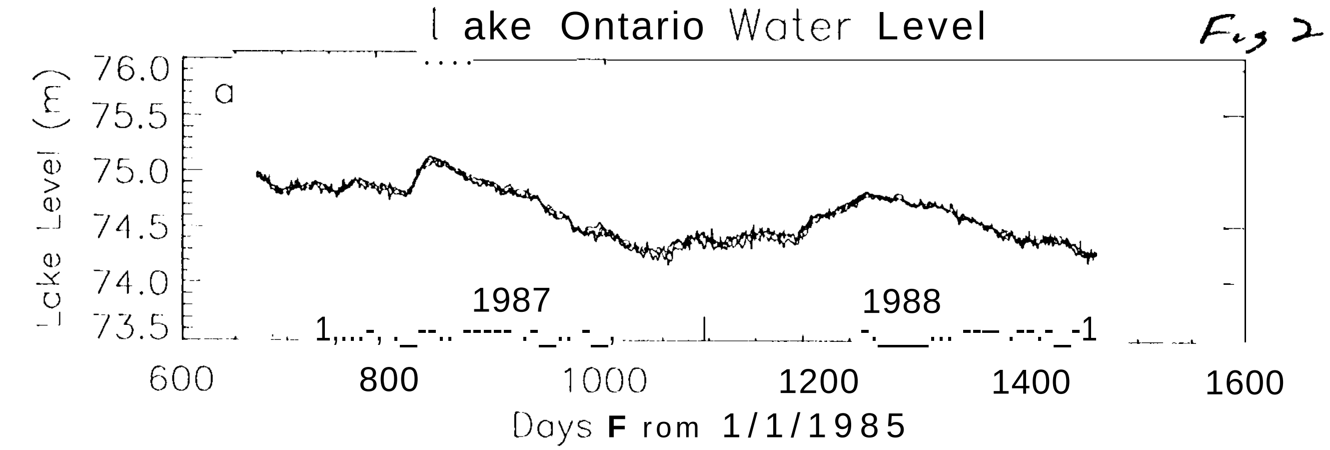
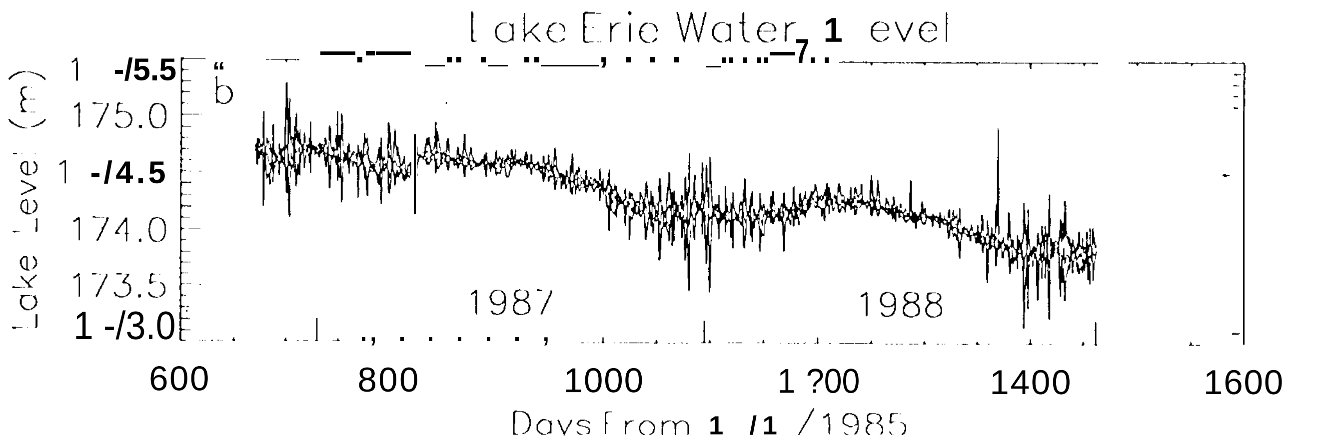

NOAA/NOS Great Lakes Stations
Superior
Huron
Michigan
Ontario
St. Clair
Erie

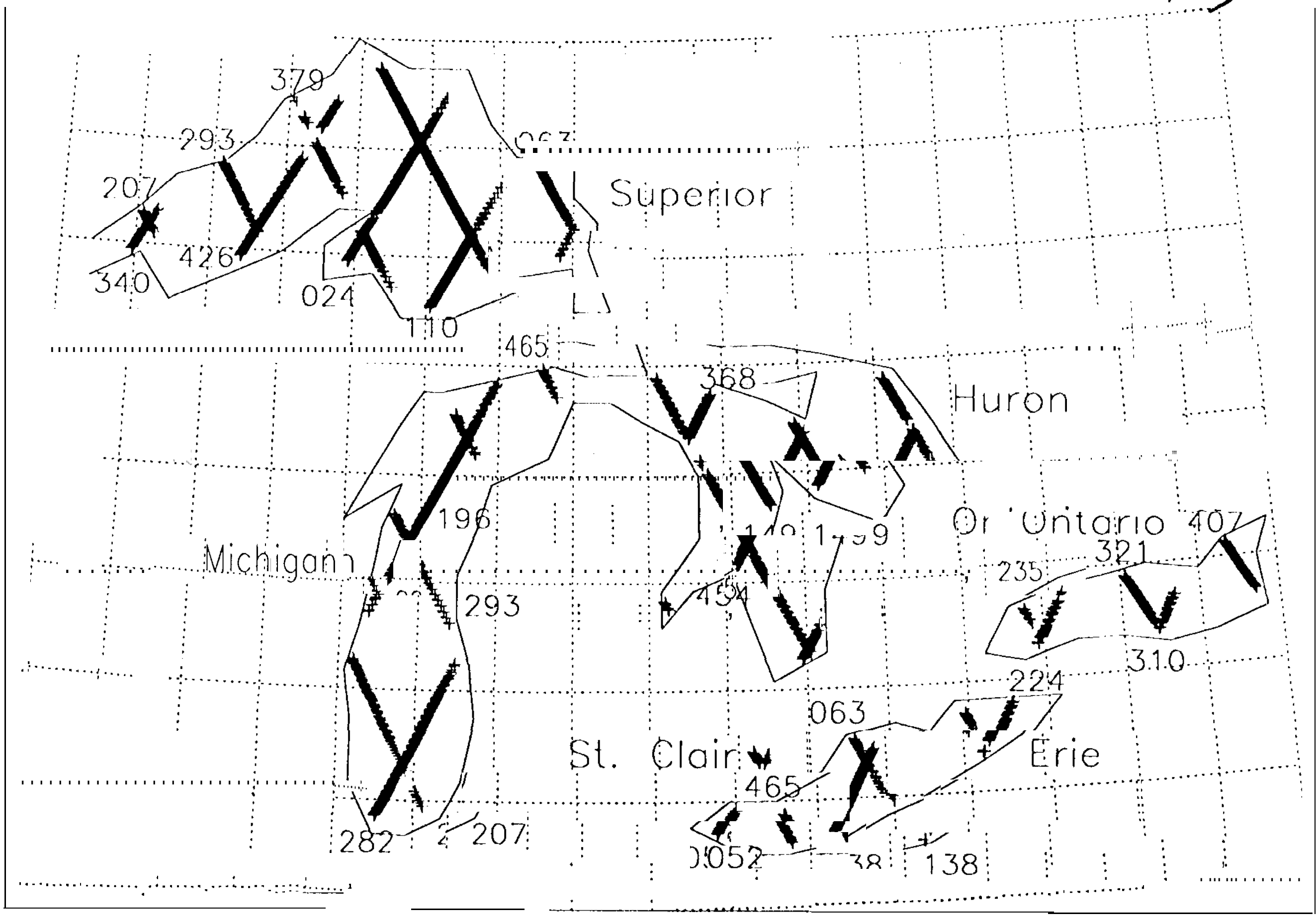
Fig 2


Lake Ontario Water Level
a
Lake Level (m)
76.0
75.5
75.0
74.5
74.0
73.5
1987
1988
600
800
1000
1200
1400
1600
Days From 1/1/1985


Lake Erie Water Level
b
Lake Level (m)
175.5
175.0
174.5
174.0
173.5
173.0
1987
1988
600
800
1000
1200
1400
1600
Days From 1/1/1985

GEOSAT Great lakes Data

Fig 3



Mean Lake Level Variation – Pass 235 Lake Huron

Fig 4

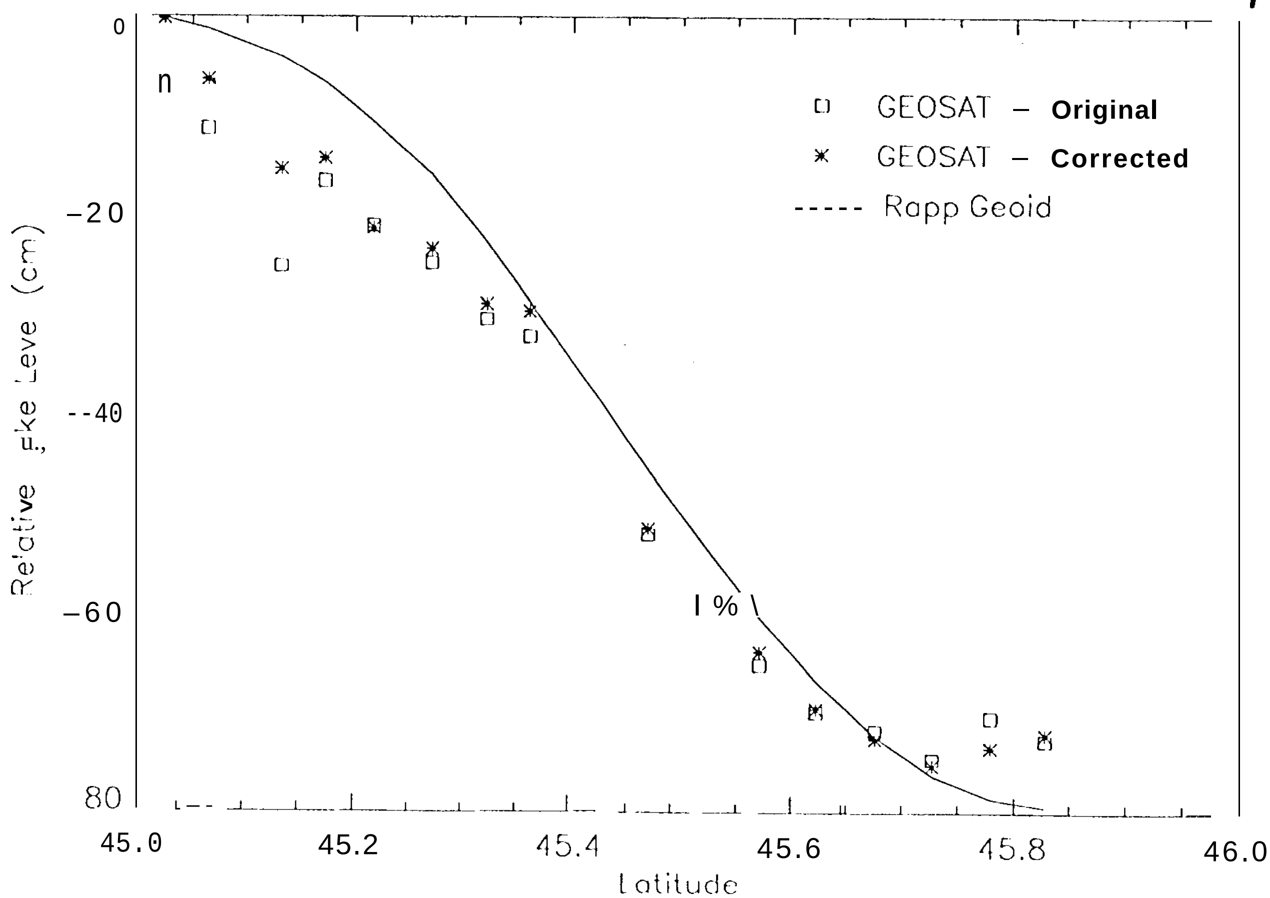


Fig 5

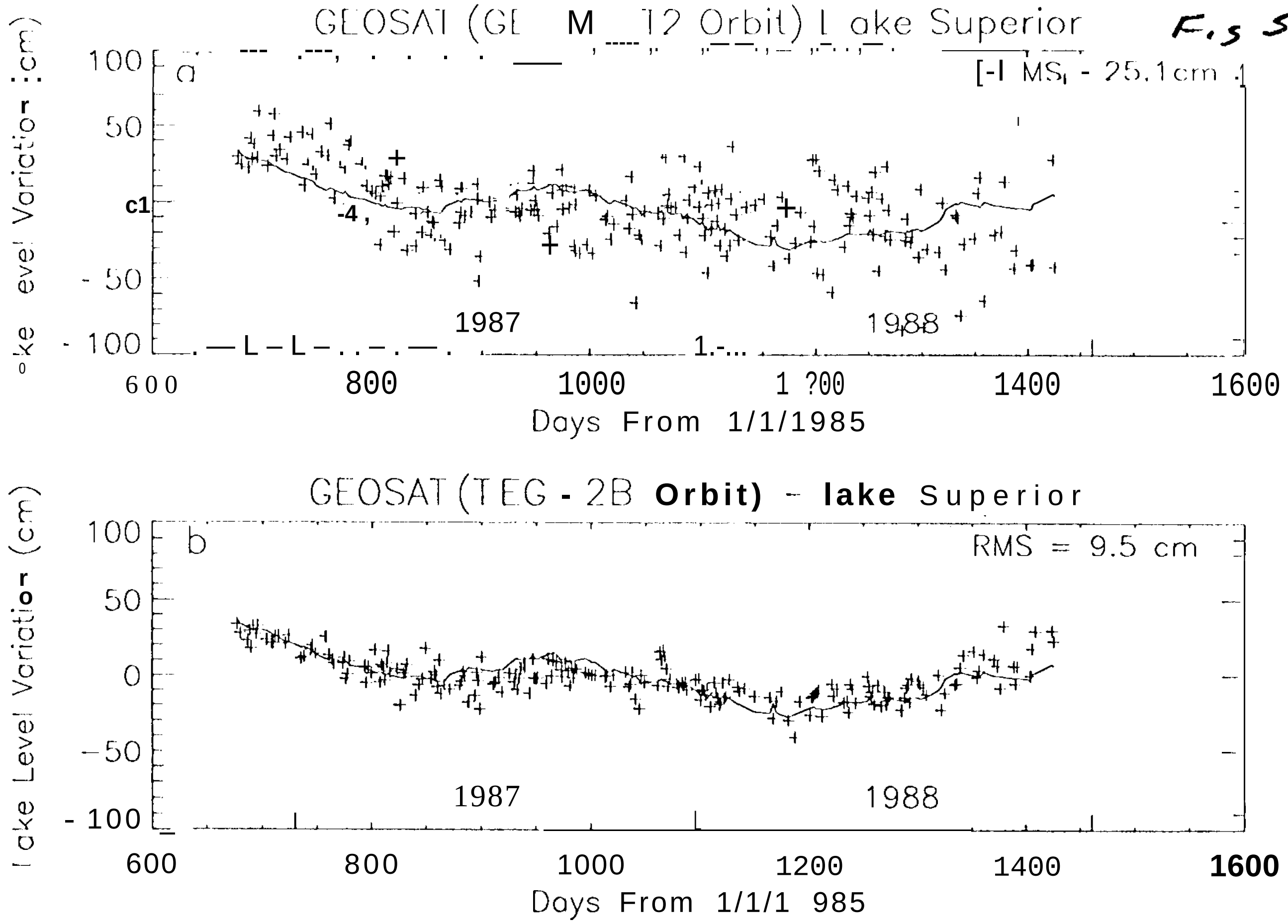

GEOSAT (GEM T2 Orbit) Lake Superior
a
RMS = 25.1 cm
1987
1988
Lake Level Variation (cm)
Days From 1/1/1985
GEOSAT (TEG-2B Orbit) - lake Superior
b
RMS = 9.5 cm
1987
1988
Lake Level Variation (cm)
600
800
1000
1200
1400
1600
Days From 1/1/1985

Fig 6

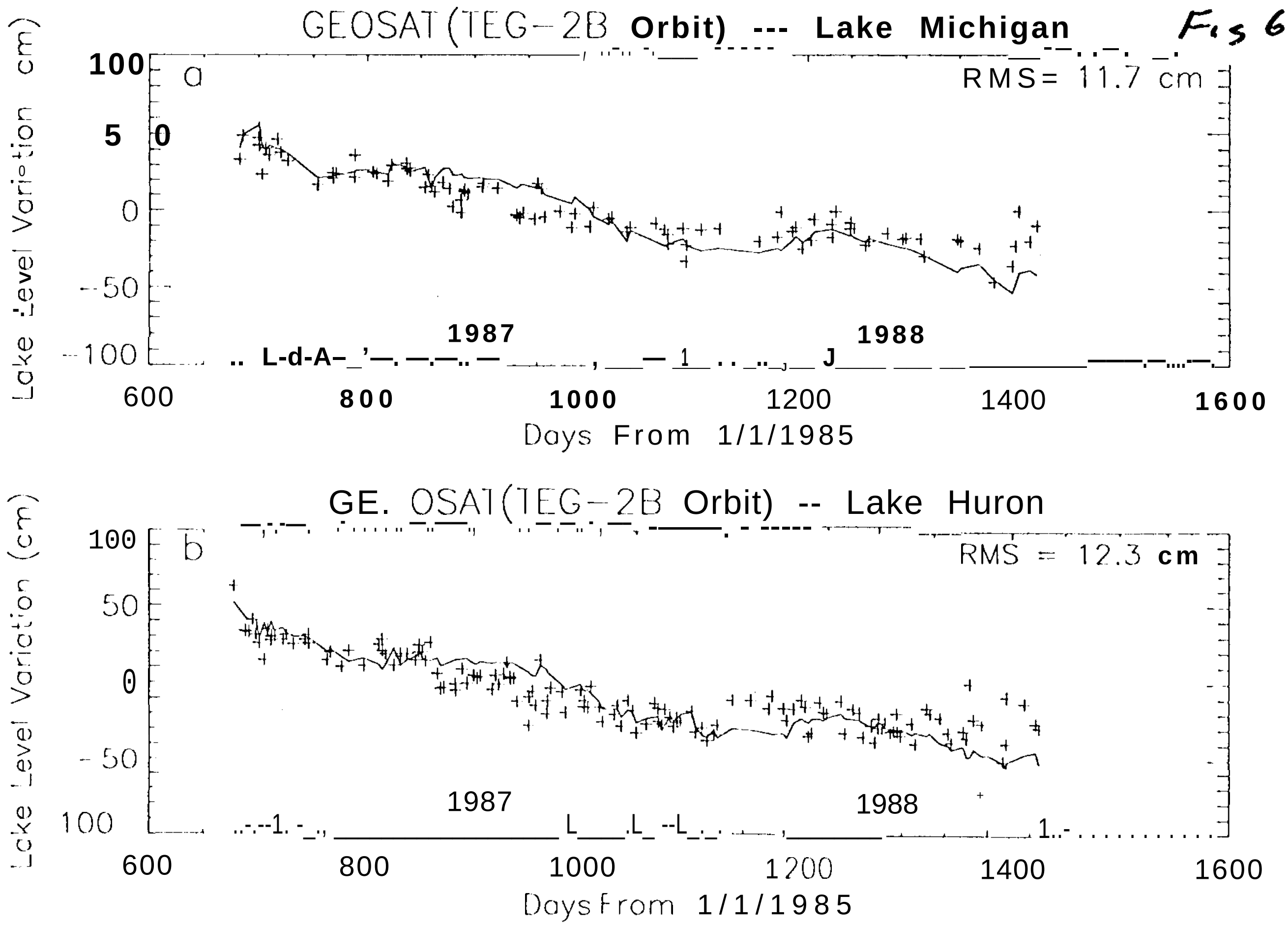
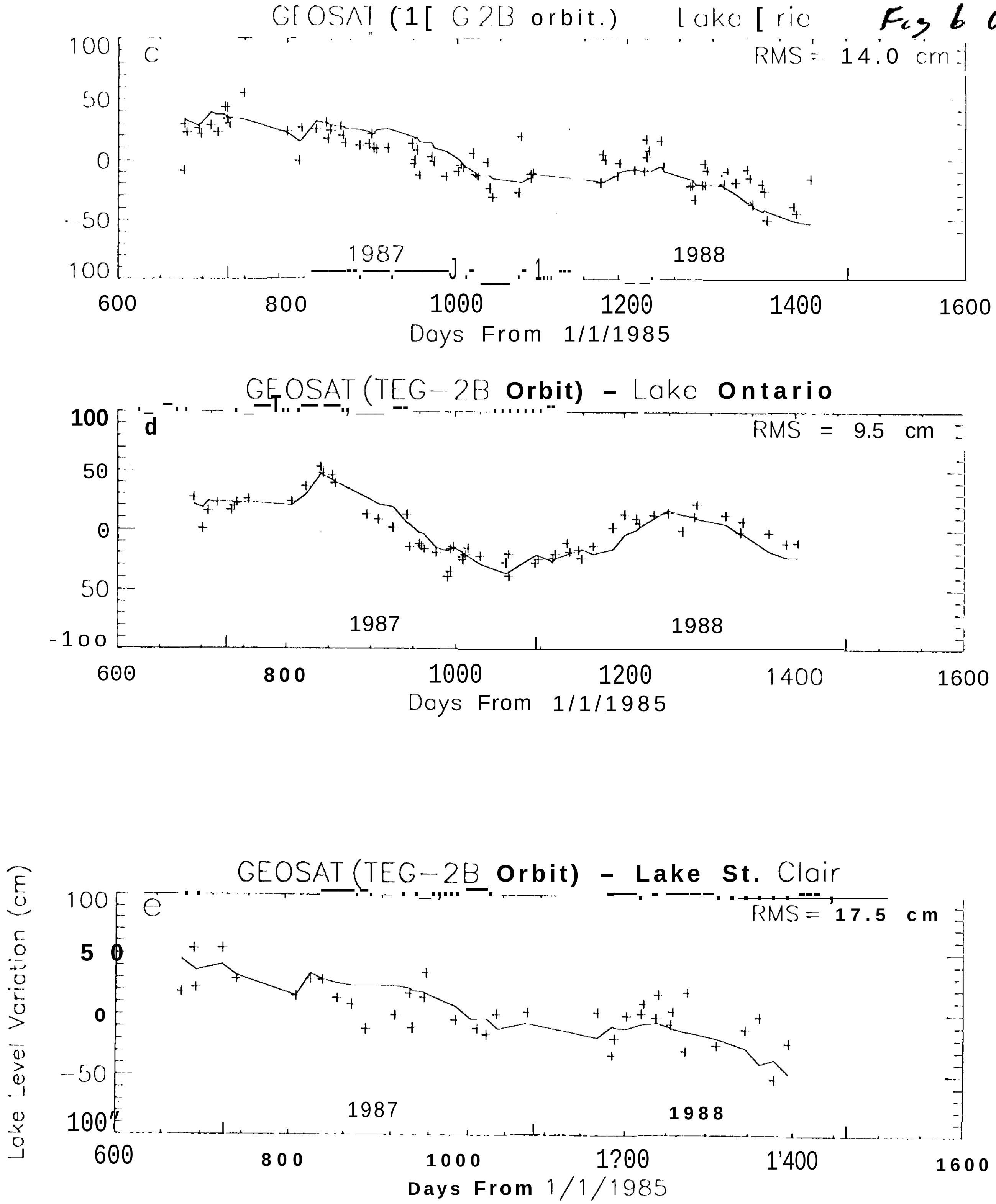
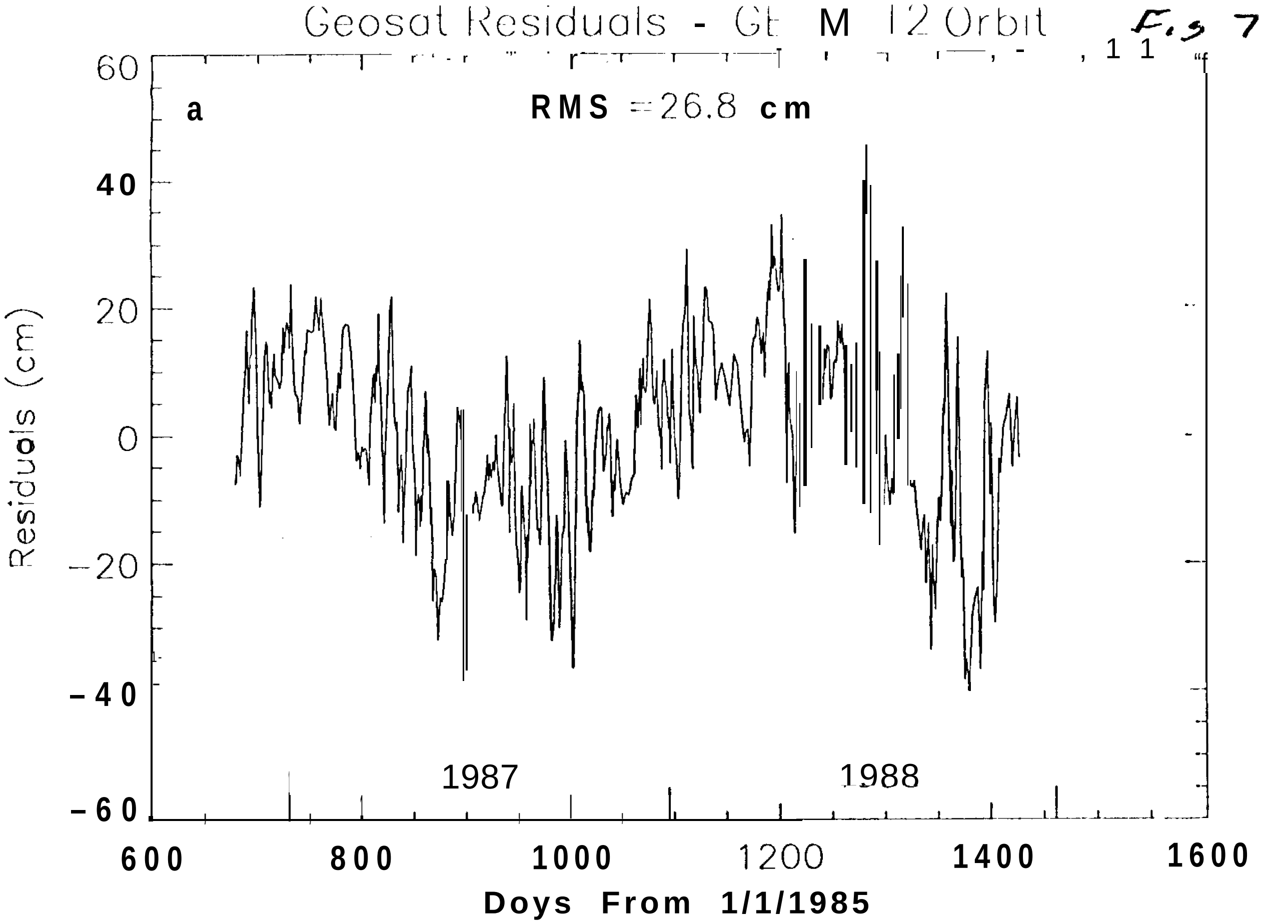

GEOSAT (TEG-2B Orbit) --- Lake Michigan
a
RMS= 11.7 cm
1987
1988
Lake Level Variation (cm)
600
800
1000
1200
1400
1600
Days From 1/1/1985
GEOSAT (TEG-2B Orbit) -- Lake Huron
b
RMS = 12.3 cm
1987
1988
Lake Level Variation (cm)
600
800
1000
1200
1400
1600
Days From 1/1/1985

Fig 6 (cont)

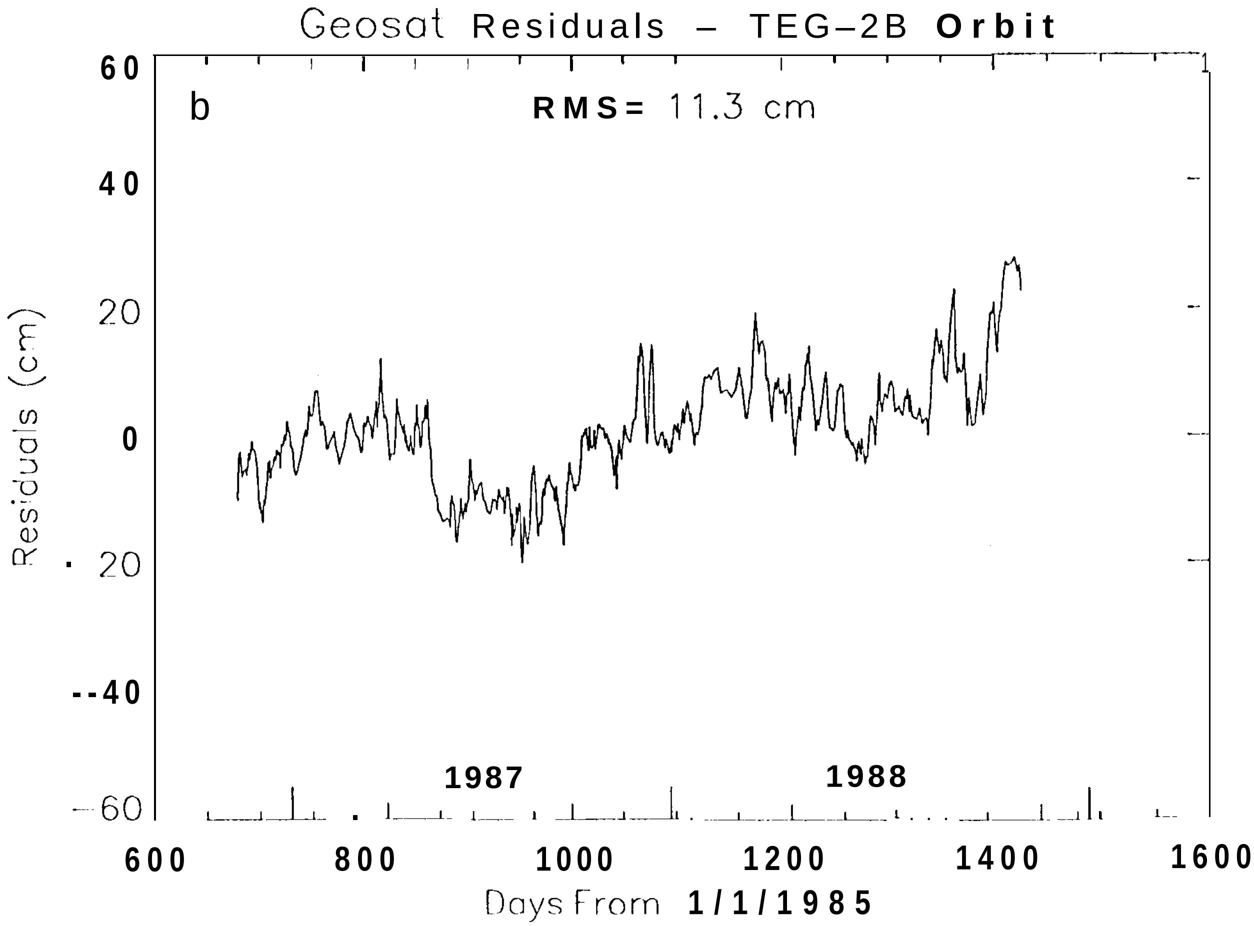


GEOSAT (TEG-2B orbit.) Lake Erie
c
RMS = 14.0 cm
100
50
0
-50
-100
1987
1988
600
800
1000
1200
1400
1600
Days From 1/1/1985
GEOSAT (TEG-2B Orbit) – Lake Ontario
d
RMS = 9.5 cm
1987
1988
Days From 1/1/1985
GEOSAT (TEG-2B Orbit) – Lake St. Clair
e
RMS = 17.5 cm
Lake Level Variation (cm)
1987
1988
Days From 1/1/1985

Fig 7

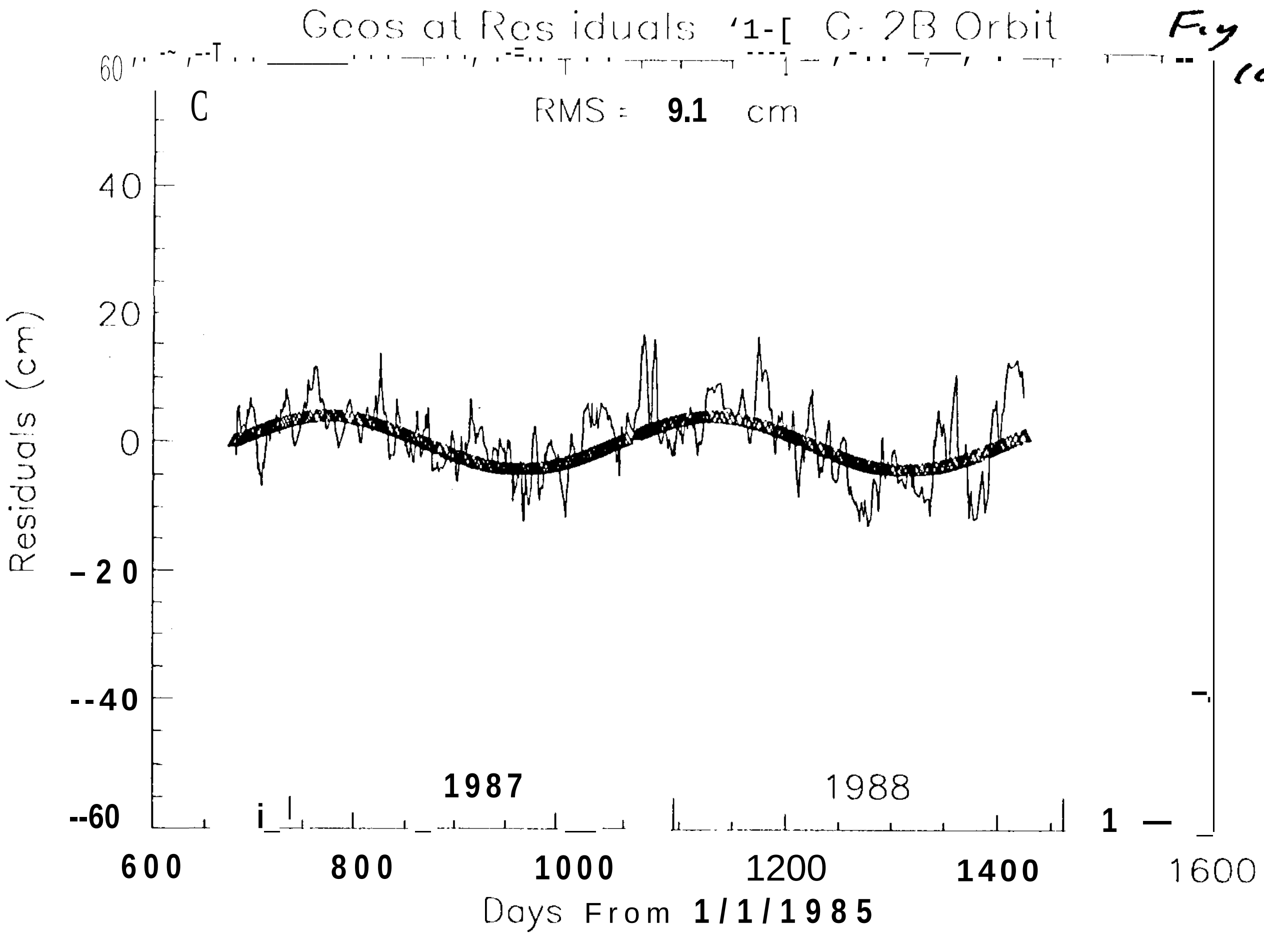


Geosat Residuals - GE M T2 Orbit
a
RMS =26.8 cm
Residuals (cm)
60
40
20
0
-20
-40
-60
1987
1988
600
800
1000
1200
1400
1600
Days From 1/1/1985



Geosat Residuals – TEG–2B Orbit
b
RMS= 11.3 cm
Residuals (cm)
60
40
20
0
-20
-40
-60
1987
1988
600
800
1000
1200
1400
1600
Days From 1/1/1985

Fig 7 (cont)


Geosat Residuals C-2B Orbit
C
RMS = 9.1 cm
Residuals (cm)
60
40
20
0
-20
-40
-60
1987
1988
600
800
1000
1200
1400
1600
Days From 1/1/1985