Chapter 5 : Calibration of Satellite Radar Altimeters

As with all scientific instruments, a calibration of the satellite altimeter needs to be performed to assess the error characteristics of the instrument. Calibrations are done by independently measuring the quantity to be measured and subsequently comparing the independent measurement to the measurement made by the instrument. Satellite altimeters perform internal calibrations on board the satellite to observe any relative altimeter range changes in the instrument; however, no absolute knowledge about the total corrected altimeter range can be ascertained from the internal calibration because of unknown biases and drifts external to the altimeter [Christensen et al. et al., 1994]. Therefore, the unknown biases and drifts can be observed and possibly understood by external calibration. Furthermore, proper calibration of multiple satellite altimeters allows for an intercomparison of scientific results which can span decades. Finally, calibration also allows for monitoring the instrument through its lifetime to observe anomalistic behavior of the altimeter system as a whole.

In this chapter, two types of calibration and associated error analysis will be discussed. First, the single point absolute calibration, where in situ tide gauge derived sea surface heights are compared to altimeter derived sea surface heights to compute the altimeter bias is described. Second, the relative calibration approach is discussed where it is assumed that one altimeter is properly calibrated and is used as a reference to calibrated the other altimeter. This relative calibration is discussed for global and local cases.

5.1 : Single point absolute calibration

In this research, the calibration of satellite altimeter over water surfaces will be discussed. However, the same procedure can be applied over non-ocean surfaces as well. The satellite altimeter calibration using tide gauges is illustrated in Figure 5-1. For the satellite altimeter calibration, the independent sea surface height measurement is made using one or more tide gauges. In this section, the single tide gauge calibration will be discussed first. Second, the multiple tide gauge case will be discussed for altimeter calibrations where the tide gauge is not near the satellite ground track.

In concept, the altimeter calibration follows from a simple linear relationship, called the closure equation (illustrated in Figure 5-1), which may be written as

$$h_{orbit} - h_{altcor} - bias = h_{anom} + h_{geoid} \tag{5.1}$$

where h_{orbit} is the center of mass of the satellite above the reference ellipsoid, h_{altcor} is the corrected altimeter range described in Chapter 1, h_{anom} is the instantaneous sea level anomaly from the geoid at the altimeter footprint

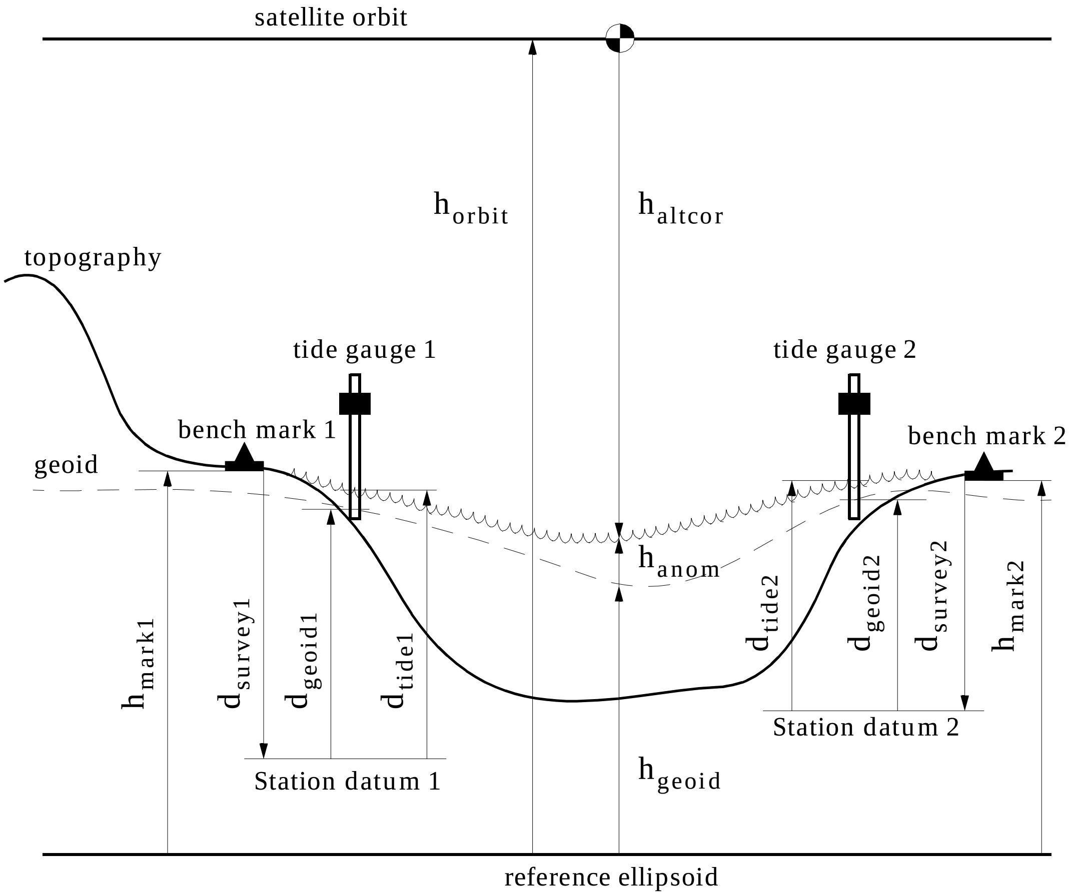

Figure 5-1 : Schematic overview of the closure equation for radar satellite altimetry

and h_{geoid} is the geoid height above the reference ellipsoid at the altimeter footprint. The bias in Eq. 5.1 is the altimeter bias and is defined to be positive if the true range is longer than the computed satellite measurement. If the altimeter is properly calibrated, the bias value is zero. In general, the satellite does not directly overfly the tide gauge position, and therefore, the closure equation needs to be rewritten in terms of the tide gauge measurement made at Station 1. Before Eq. 5.1 can be rewritten, the local in-situ tide gauge measurements need to be related to the global terrestrial reference frame used for the orbit determination of the radar altimeter satellite. In Figure 5-1, it can be seen that the tide gauge measurement d_{tide1} at Station 1 is related to the reference ellipsoid by

$$h_{tide1} = h_{mark1} - d_{survey1} + d_{tide1} \tag{5.2}$$

where h_{tide1} is the instantaneous sea surface height at Station 1 with respect to the reference ellipsoid, h_{mark1} is the height of the tide gauge bench mark at Station 1 above the reference ellipsoid and $d_{survey1}$ is height of the bench mark at Station 1 above the local station datum. Similarly, the geoid height above the reference ellipsoid h_{geoid1} at Station 1 can be computed according to

$$h_{geoid1} = h_{mark1} - d_{survey1} + d_{geoid1} \tag{5.3}$$

where d_{geoid1} is the long term mean of tide gauge observations above the local datum which is assumed to be the same as the geoid height. This assumption is only valid if the tide gauge is located in the open ocean or water bodies connected to the open ocean. Thus, the instantaneous sea level anomaly from the geoid for Station 1 can be written as

$$h_{anom1} = h_{tide1} - h_{geoid1} = d_{tide1} - d_{geoid1} \tag{5.4}$$

The result of substituting Eq. 5.2, Eq. 5.3 and Eq. 5.4 into Eq. 5.1 may then be written as

$$h_{orbit} - h_{altcor} - bias = h_{anom1} + h_{geoid1} + \Delta_{anom1} + \Delta_{geoid1} \tag{5.5}$$

where Δ_{anom1} and Δ_{geoid1} are the spatial differences in the sea level anomaly about the geoid and in the geoid itself, which can be written as

$$\begin{aligned} \Delta_{anom1} &= h_{anom} - h_{anom1} \\ \Delta_{geoid1} &= h_{geoid} - h_{geoid1} \end{aligned} \tag{5.6}$$

Most calibration sites have been chosen such that Δ_{anom1} and Δ_{geoid1} are minimized at the closest ground track approach and these terms are neglected or assumed to be linearly varying in the cross track direction [Martin et al., 1981; Kolenkiewicz et al., 1982; Francis et al. 1992; Christensen et al. 1994].

The closure equation Eq. 5.5 is evaluated at the closest approach of the satellite ground track to minimize the spatial variations in the sea surface anomaly and the geoid. However, for the tide gauge calibration case later described in this research, the closest approach is too far away from the tide gauge location to neglect or approximate Δ_{anom1} and Δ_{geoid1}. For this calibration type, additional tide gauges are used to determine the sea surface anomaly at the altimeter footprint. The geoid height at the altimeter footprint needs to be determined by other means, such that the total instantaneous surface height can be computed at the altimeter footprint. For more details see, Section 5.2.

The accuracy assessment of the bias determination follows directly from Eq. 5.5 by writing each quantity as

$$\tilde{h}_i = h_i + \varepsilon_i \tag{5.7}$$

where ε_i is the error in the h_i. Eq. 5.5 can then be written as

$$\begin{aligned} \text{bias} + \varepsilon_{bias} = {} & h_{orbit} - h_{altcor} - h_{anom1} - h_{geoid1} - \Delta_{anom1} - \Delta_{geoid1} + \\ & \varepsilon_{orbit} - \varepsilon_{altcor} - \varepsilon_{anom1} - \varepsilon_{geoid1} - \varepsilon_{\Delta anom1} - \varepsilon_{\Delta geoid1} \end{aligned} \tag{5.8}$$

where ε_{orbit} is the radial orbit error, ε_{altcor} is the sum of the altimeter error and all the associated corrections, ε_{anom1} is the measurement error in the sea level measurement at Station 1, ε_{geoid1} is the error in the geoid height above the reference ellipsoid at Station 1, $\varepsilon_{\Delta anom1}$ is the error in the spatial mapping of the sea surface anomaly of Station 1 to the altimeter footprint, and $\varepsilon_{\Delta geoid1}$ is the error in the spatial mapping to the geoid height above the reference ellipsoid at the altimeter footprint. In Chapter 1, ε_{altcor} was formulated as

$$\varepsilon_{altcor} = \varepsilon_{alt} + \varepsilon_{instr} + \varepsilon_{dry} + \varepsilon_{wet} + \varepsilon_{ion} + \varepsilon_{embias} + \varepsilon_{solid} \tag{5.9}$$

where ε_{alt}, ε_{instr}, ε_{dry}, ε_{wet}, ε_{ion}, ε_{embias} and ε_{solid} are the errors in the altimeter measurement, instrument correction, dry troposphere correction, wet troposphere correction, ionosphere correction, em bias correction and the solid Earth tide correction, respectively. It should be noted that the ocean tide correction is not included in Eq. 5.9, because this correction is directly measured by the tide gauge and has its own error associated with it. Another error term in Eq. 5.8 is the error in the geoid height above the reference ellipsoid at Station 1, ε_{geoid1}. Using Eq. 5.3 this error can be written as

$$\varepsilon_{geoid1} = \varepsilon_{mark1} - \varepsilon_{survey1} + \varepsilon_{dgeoid1} \tag{5.10}$$

where ε_{mark1} is the error in the bench mark height above the reference ellipsoid for Station 1, $\varepsilon_{survey1}$ is the error of the bench mark height above the station datum, and $\varepsilon_{dgeoid1}$ is the error in the mean tide gauge sea surface observations above the station datum.

In this research, each error will be considered to have fixed and variable components conforming to the error analysis in Christensen et al. 1994. The next subsection discusses all the satellite altimeter calibration campaigns in terms of the errors described above and the altimeter bias.

5.1.1 : Previous campaigns

Most satellite altimeter missions have had dedicated absolute calibration campaigns except for GEOSAT and ERS-2. Most calibration campaigns were of a short duration except for the Harvest Platform T/P campaign, which has lasted for several years and will be continued in the future [Born, personal communication,1996]. Unfortunately, the short campaigns do not allow for long term monitoring of the satellite altimeter system, which has major implications for long term studies like sea level rise. Furthermore, the short campaigns limit the accuracy of the bias estimates. In the next sections, each calibration site is described and the altimeter bias results and the error analysis are given. The results for the absolute campaigns will be later compared to the global relative calibration results using T/P as a reference.

5.1.2 : Bermuda

The island of Bermuda was used for the first two absolute altimeter calibration campaigns, e.g. GEOS-3 and SEASAT [Martin et al., 1981; Kolenkiewicz et al., 1982]. Bermuda was used because a SLR site on the island could measure nearly directly the orbital height above the tracking station, since both GEOS-3 and SEASAT flew nearly overhead of the SLR site.

The altimeter calibration for GEOS-3 is based on two overflights of GEOS-3 on 25 February 1976 and 30 April 1976 [Martin et al., 1981]. Only two overflights were available because GEOS-3 had no thrusters on board to maintain the ground track. The main error source for this calibration was the altimeter noise which was reported to be 20 cm [Martin et al., 1981]. Nevertheless, after smoothing the altimeter residuals, correcting for atmospheric,

Error Group	Error Source	Variable name	Fixed Error (mm)	Variable Error (mm)
Radial Orbit	Total	ε_{orbit}	-	30
Altimetry	altimeter noise	ε_{alt}	-	200
Altimetry	instrument	ε_{instr}	-	-
Altimetry	dry troposphere corr.	ε_{dry}	-	30
Altimetry	wet troposphere corr.	ε_{wet}	-	-
Altimetry	ionosphere corr.	ε_{ion}	-	20
Altimetry	em bias corr.	ε_{embias}	-	100
Altimetry	solid Earth tide	ε_{solid}	-	-
Altimetry	Total (RSS)	ε_{altcor}	-	226
In Situ	GPS survey bench mark	ε_{mark1}	-	-
In Situ	Tide gauge survey	$\varepsilon_{survey1}$	-	-
In Situ	Tide gauge noise	ε_{anom1}	-	30
In Situ	Tide gauge bias	$\varepsilon_{dgeoid1}$	-	-
In Situ	sea surface anomaly	$\varepsilon_{\Delta anom1}$	-	-
In Situ	geoid gradient	$\varepsilon_{\Delta geoid1}$	-	30
In Situ	Total (RSS)	-	-	42
Total error	-			231
RSS	fixed + variable			231
-	altimeter bias	bias	-5610	160

Table 5.1 : Error budget for GEOS-3 altimeter calibration and altimeter bias estimate from Martin, 1981

instrumental and sea state effects, the altimeter bias agreed to within 3 cm for both passes and was reported to be -5.61 ±0.16 m. The derived error budget for a single calibration pass can be found in Table 5.1. It should be noted that many of the error sources discussed in Section 5.1 were neglected or not reported because they were assumed to be small when compared to other errors in this calibration. Further, no distinction was made between fixed and variable errors.

The second altimeter calibration at Bermuda was for SEASAT. Although SEASAT only operated for four months, altimeter bias estimates from 4 pass of SEASAT were obtained during the 3 day repeat mission in September 1978 [Kolenkiewicz et al., 1982]. For these passes, the same SLR station as GEOS-3 was used for the altimeter calibration, but new tide gauge and reference benchmarks were installed [Diamante et al., 1982]. The calibration of SEASAT was based on the GEOS-3 experience and used the same technique to compute the altimeter bias. Based on these 4 passes, the altimeter bias was found to be 0 ±7 cm. The total error budget for a single SEASAT calibration pass can be found in Table 5.2. In this calibration, a more detailed description of the leveling of the tide gauge benchmark with respect to the SLR station benchmark is given and as well as the expected errors that could be introduced by the mapping of the tide gauge observations to the open ocean [Diamante et al., 1982]. It should be noted in Table 5.2 that no error

Error Group	Error Source	Variable name	Fixed Error (mm)	Variable Error (mm)
Radial Orbit	Total	ε_{orbit}	-	30
Altimetry	altimeter noise	ε_{alt}	-	50
Altimetry	instrument	ε_{instr}	-	20
Altimetry	dry troposphere corr.	ε_{dry}	-	20
Altimetry	wet troposphere corr.	ε_{wet}	-	20
Altimetry	ionosphere corr.	ε_{ion}	-	20
Altimetry	em bias corr.	ε_{embias}	-	50
Altimetry	solid Earth tide	ε_{solid}	-	-
Altimetry	Total (RSS)	ε_{altcor}	-	79
In Situ	GPS survey bench mark	ε_{mark1}	-	-
In Situ	Tide gauge survey	$\varepsilon_{survey1}$	-	10
In Situ	Tide gauge noise	ε_{anom1}	-	10
In Situ	Tide gauge bias	$\varepsilon_{dgeoid1}$	-	10
In Situ	sea surface anomaly	$\varepsilon_{\Delta anom1}$	-	37
In Situ	geoid gradient	$\varepsilon_{\Delta geoid1}$	-	25
In Situ	Total (RSS)	-	-	47
Total error	-			97
RSS	fixed + variable	97		
-	altimeter bias	bias	0	70

Table 5.2 : Error budget for SEASAT altimeter calibration and altimeter bias estimate from Kolenkiewicz 1982 and Diamante 1982

value is given for the GPS survey of the tide gauge bench mark. This fact illustrates the shortcoming of the altimeter calibration at Bermuda. For the calibration, the tide gauge measurements were related to the terrestrial reference frame through the SLR bench mark at Bermuda. The geodetic survey between these two marks, which are 6.6 km apart, is based on levelling, which is along a geoid-like surface referred to as a geodetic datum. The underlying assumption for the calibration at Bermuda is that the geoid height at the tide gauge is the same as at the SLR site. This, however, is probably not true. Kolenkiewicz et al.[1982] and Diamante et al.[1982] estimated this error to be 5 cm and reported that only improved knowledge of the geoid at Bermuda can improve the actual altimeter bias value for SEASAT and GEOS-3.

5.1.3 : Aqua Alta Tower

After the launch of ERS-1 on July 17, 1991, the radar altimeter on board was calibrated during the commissioning phase at the Aqua Alta Tower, an oil platform in the Adriatic Sea off the coast of Venice, Italy [Francis, 1992]. One advantage of using an oil platform is that there is no land in the altimeter footprint to corrupt the altimeter data. Furthermore, a tide gauge was mounted on the platform to measure sea level directly at the altimeter footprint. In contrast to the Bermuda calibration, no SLR station was available on the platform to measure the vertical orbit height. However, five SLR sites in Europe tracked ERS-1 before and after the overflight allowing for a short arc orbit solution during the overflight [Francis, 1992]. Besides the tide gauge measurement, a upward scanning Water Vapor Radiometer (WVR) and an atmospheric pressure sensor were deployed on the platform to measure the water vapor content and the surface atmospheric pressure used to model the wet and dry tropospheric correction for the altimeter measurement. On the platform, a GPS receiver was installed to relate the tide gauge measurements to the terrestrial reference frame used for the orbit determination. The GPS measurements and Faraday rotation measurements were used to infer the Total Electron Content (TEC) in the zenith direction at the platform. The TEC observations were then used to compute the ionospheric correction for the altimeter instrument. An error budget of the one calibration pass at Aqua Alto Tower and bias estimate can be found in Table 5.3. One of the disadvantages of the Aqua Alto Tower is that the tower is about 15 km from the coast. Because of this proximity, the Along Track Scanning Radiometer does not provide a reliable wet tropospheric correction during the overflight. Furthermore, the total length of the altimeter pass over the Adriatic Sea lasts only 25 seconds after coming from land about 140 km south of the platform. In this interval, the altimeter needs to lock on to the ocean surface. The process of locking on the ocean surface is highly variable

Error Group	Error Source	Variable name	Fixed Error (mm)	Variable Error (mm)
Radial Orbit	Total	ε_{orbit}	10	25
Altimetry	altimeter noise	ε_{alt}	-	15
Altimetry	instrument	ε_{instr}	-	-
Altimetry	dry troposphere corr.	ε_{dry}	-	20
Altimetry	wet troposphere corr.	ε_{wet}	-	-
Altimetry	ionosphere corr.	ε_{ion}	-	10
Altimetry	em bias corr.	ε_{embias}	-	-
Altimetry	solid Earth tide	ε_{solid}	10	-
Altimetry	Total (RSS)	ε_{altcor}	10	26
In Situ	GPS survey bench mark	ε_{mark1}	20	-
In Situ	Tide gauge survey	$\varepsilon_{survey1}$	10	-
In Situ	Tide gauge noise	ε_{anom1}	-	5
In Situ	Tide gauge bias	$\varepsilon_{dgeoid1}$	0	-
In Situ	sea surface anomaly	$\varepsilon_{\Delta anom1}$	-	-
In Situ	geoid gradient	$\varepsilon_{\Delta geoid1}$	-	20
In Situ	Total (RSS)	-	22	21
Total error	-		26	42
RSS	fixed + variable			49
-	altimeter bias	bias	-41.0	52

Table 5.3 : Error budget for ERS-1 altimeter calibration and altimeter bias estimate from Francis, 1992 and Francis 1993

and depends on the wave height. The waters in this part of the Adriatic are often calm, causing difficulties with the on board computer tracking the surface [Francis, 1992]. Therefore, the altimeter data was retracked, meaning that the altimeter waveform return was refitted to determine the range, Significant Wave Height (SWH), backscatter coefficient, skewness and pointing angle of the instrument. Finally, the platform is located at the end of the pass which means that the curve fit to determine the altimeter measurement at the platform is mainly determined by altimeter data before the overflight and relativity little after the overflight.

5.1.4 : Harvest Platform

The oil platform “Harvest” was chosen to be the NASA calibration site for the T/P altimeter satellite. The Harvest Platform is located about 12 km South of the Vandenberg Airforce Base in the Pacific Ocean of the coast of Southern California [Christensen et al., 1994]. Similar to the Venice Aqua Alto tower, the Harvest Platform is directly underneath an ascending T/P ground track, and the ground track crosses land 11 km after it passes the platform.

Harvest Platform is equipped with an array of instruments in support of the altimeter calibration campaign [Christensen et al. 1994]. There are three tide gauge systems which provide three independent measurements of sea level at the platform. A GPS receiver was permanently installed on the platform to tie the tide gauge observations to the terrestrial reference frame used for the orbit determination and to monitor the stability of the platform during the calibration campaign. The GPS observations were used also to infer the TEC in the zenith direction which is used to compute the ionospheric corrections. These ionospheric corrections were used to calibrate the ionospheric corrections derived from the T/P derived dual frequency altimeter. The platform also has a meteorological observation package which is used to compute the dry tropospheric correction. A WVR instrument was installed on the platform to infer the water vapor content in the zenith direction and hence determine the wet tropospheric correction. These observations were also used to calibrate the TMR instrument on board the T/P satellite [Ruf et al., 1994].

To date, the Harvest calibration campaign has been the longest calibration campaign. For the first time, the temporal behavior of the total altimeter bias could be observed. For the complete single pass error budget and latest TOPEX altimeter bias estimate, see Table 5.4. The time dependent behavior of the altimeter bias is very important for sea level rise studies, because of the perfect correlation between both signals and the fact that both signals are of the same order of magnitude. The latest results for the Harvest calibration differ from the one reported by Christensen et al. 1994 and Menard et al.

Error Group	Error Source	Variable name	Fixed Error (mm)	Variable Error (mm)
Radial Orbit	Total	ε_{orbit}	20	10
Altimetry	altimeter noise	ε_{alt}	-	10
Altimetry	instrument	ε_{instr}	-	20
Altimetry	dry troposphere corr.	ε_{dry}	0	7
Altimetry	wet troposphere corr.	ε_{wet}	5	5
Altimetry	ionosphere corr.	ε_{ion}	10	5
Altimetry	em bias corr.	ε_{embias}	14	14
Altimetry	solid Earth tide	ε_{solid}	-	-
Altimetry	Total (RSS)	ε_{altcor}	18	28
In Situ	GPS survey bench mark	ε_{mark1}	20	7
In Situ	Tide gauge survey	$\varepsilon_{survey1}$	5	10
In Situ	Tide gauge noise	ε_{anom1}	-	10
In Situ	Tide gauge bias	$\varepsilon_{dgeoid1}$	0	-
In Situ	sea surface anomaly	$\varepsilon_{\Delta anom1}$	0	20
In Situ	geoid gradient	$\varepsilon_{\Delta geoid1}$	0	5
In Situ	Total (RSS)	-	21	26
Total error	-		34	39
RSS	fixed + variable			52
-	altimeter bias	bias	2	52

Table 5.4 : Error budget for TOPEX altimeter calibration [Christensen,1994] and altimeter bias estimate from Haines personal communication

1994 because of a recently discovered error in the instrument correction for the TOPEX altimeter. The altimeter bias of approximately 13 cm was mainly caused by the fact that the oscillator drift error was applied with the wrong sign, introducing the formerly observed bias [P. Calahan, personal communication,1996]. The latest TOPEX altimeter bias at Harvest platform is reported to be 0.2 ±0.8 cm and with an altimeter bias drift of 2 ±4 mm/year [B. Haines, personal communication, 1996]. It should be noted that this estimate contains local effects that have not been modeled as well as the altimeter bias variations. To obtain the actual bias, several calibrations should be used to average out the unmodeled local effects. For the T/P satellite, two sites were used, one being Harvest platform and the second being Lampedusa Island, which will be discussed in the next section.

The POSEIDON altimeter was calibrated at Harvest Platform as well, and the altimeter bias is reported to be 2.9 cm with a reported drift of 3 ±3 mm/year [Haines, personal communication, 1997]. The uncertainties on these estimates is much larger because only 1 out of 10 passes is a POSEIDON pass.

One of the disadvantages at Harvest Platform is that it is very close to land. In general, very few altimeter observations were available after the satellite altimeter passed the platform, and sometimes the altimeter measurements needed to be extrapolated to the time of closest approach [Visser, 1993]. Furthermore, the average wave height at Harvest Platform is considerably larger than in the Adriatic Sea for the ERS-1 calibration. The higher SWH made retracking the waveforms unnecessary but caused biases in the three different tide gauge systems at Harvest platform which had to be modeled and removed [Gill, 1995, Parke 1995]. Another effect of the higher waves is that the Sea State Bias (SSB) correction becomes significant, and the choice for the SSB model affects the bias estimate at Harvest [Christensen et al., 1994]. Another important element in the Harvest calibration is that the SLR sites are not near Harvest Platform. Furthermore, the geographical distributions of the SLR sites was not as favorable as had been for the ERS-1 campaign. This disadvantage was not a major error source because of the unprecedented orbit accuracy of T/P and the close agreement of the three tracking systems [Marshall, 1995]. The orbit ultimately used for the altimeter calibration was the GPS orbit which is believed to be the most accurate [Christensen et al., 1994].

Finally, a GPS buoy was designed by the University of Colorado and floated at Harvest Platform in an attempt to measure sea level directly using GPS. The results of this buoy experiment yielded very encouraging results, and the bias determination disagreed by only 1.5 cm with the Harvest determination for that particular overflight [Born et al., 1994].

5.1.5 : Lampedusa Island

Lampedusa Island was the CNES altimeter calibration site for the T/P satellite. Lampedusa Island is located half way between Malta and Tunisia in the Straight of Sicily. The intensive campaign lasted from 11 September to 12 December 1994. For this period a SLR station was operating on Lampedusa Island, about 10 km from the T/P ground track at closest approach. Unfortunately, the SLR measurements were plagued by bad weather resulting in only a few overhead passes. This fact, however, did not impact the overall orbit determination [Menard, 1994]. One of the great advantages of Lampedusa Island was the fact that altimeter data is available before and after the overflight, allowing for an accurate interpolation to the point of closest approach. A disadvantage was the fact that retracking of the altimeter data was required because of the sometimes calm waters near Lampedusa.

The actual calibration point was a small rock called Lampione located about 16 km west of Lampedusa and on the T/P ground track. On this island, two tide gauges were installed with GPS receivers to tie the tide gauge measurements to the terrestrial reference frame used for the orbit determination. Furthermore, two GPS buoys were deployed near Lampione during the overflights. During the whole campaign nine overflights occurred, three passes with the TOPEX altimeter on and six with the

Error Group	Error Source	Variable name	Fixed Error (mm)	Variable Error (mm)
Radial Orbit	Total	ε_{orbit}	15	20
Altimetry	altimeter noise	ε_{alt}	-	12
Altimetry	instrument	ε_{instr}	-	-
Altimetry	dry troposphere corr.	ε_{dry}	-	5
Altimetry	wet troposphere corr.	ε_{wet}	-	20
Altimetry	ionosphere corr.	ε_{ion}	-	6
Altimetry	em bias corr.	ε_{embias}	-	7
Altimetry	solid Earth tide	ε_{solid}	-	-
Altimetry	Total (RSS)	ε_{altcor}	-	26
In Situ	GPS survey bench mark	ε_{mark1}	15	-
In Situ	Tide gauge survey	$\varepsilon_{survey1}$	-	-
In Situ	Tide gauge noise	ε_{anom1}	-	20
In Situ	Tide gauge bias	$\varepsilon_{dgeoid1}$	-	-
In Situ	sea surface anomaly	$\varepsilon_{\Delta anom1}$	-	-
In Situ	geoid gradient	$\varepsilon_{\Delta geoid1}$	-	-
In Situ	Total (RSS)	-	15	20
Total error	-		21	38
RSS	fixed + variable	44		
-	altimeter bias	bias	-185	34

Table 5.5 : Error budget for TOPEX altimeter calibration and altimeter bias estimate from Menard 1994 at Lampedusa Island

POSEIDON altimeter. Thus only three altimeter bias determinations for the TOPEX altimeter were available, limiting the accuracy of the estimates. Furthermore, no long term analysis of the TOPEX altimeter bias could be done. The single pass error budget for a TOPEX pass is shown in Table 5.5. The reported TOPEX altimeter bias (-18.5 cm) is based on the GDR data before the oscillator drift error was discovered. Correcting for this error yields a TOPEX altimeter bias of -5.5 ±3.4 cm. It should be noted that the emphasis of the altimeter calibration at Lampedusa was on calibrating the POSEIDON altimeter. The reported altimeter bias for POSEIDON is 0.7 ±3.3 cm based on 6 overflights.

5.2 : Galveston Bay campaign

In this section, the absolute calibration of the TOPEX altimeter using overflights of Galveston Bay will be discussed. The Galveston calibration campaign is an example of using GPS buoys with existing tide gauges, meteorological instrumentation and geodetic network to achieve altimeter calibrations. This is in contrast to the dedicated calibration campaigns previously described. These campaigns in general are expensive and require dedicated personnel to maintain the instrumentation [Menard, 1994]. It is for these reasons that most calibrations last only for a few months. The drawback of using existing instrumentation is that only instrumentation relatively near the T/P ground track is useful for calibration purposes. Additionally, error sources that are small for direct overflights like the geoid gradient and the sea level anomalies become major problems.

In the next sections, the TOPEX altimeter calibration at Galveston Bay will be discussed in detail. A discussion of the errors for each component contributing to the calibration is presented.

5.2.1 : Site description

Galveston Bay is located on the Texas Gulf of Mexico coast, southeast of Houston, Texas. The T/P ground track passes through the middle of the bay on a descending pass. The total pass over the bay lasts for four seconds,

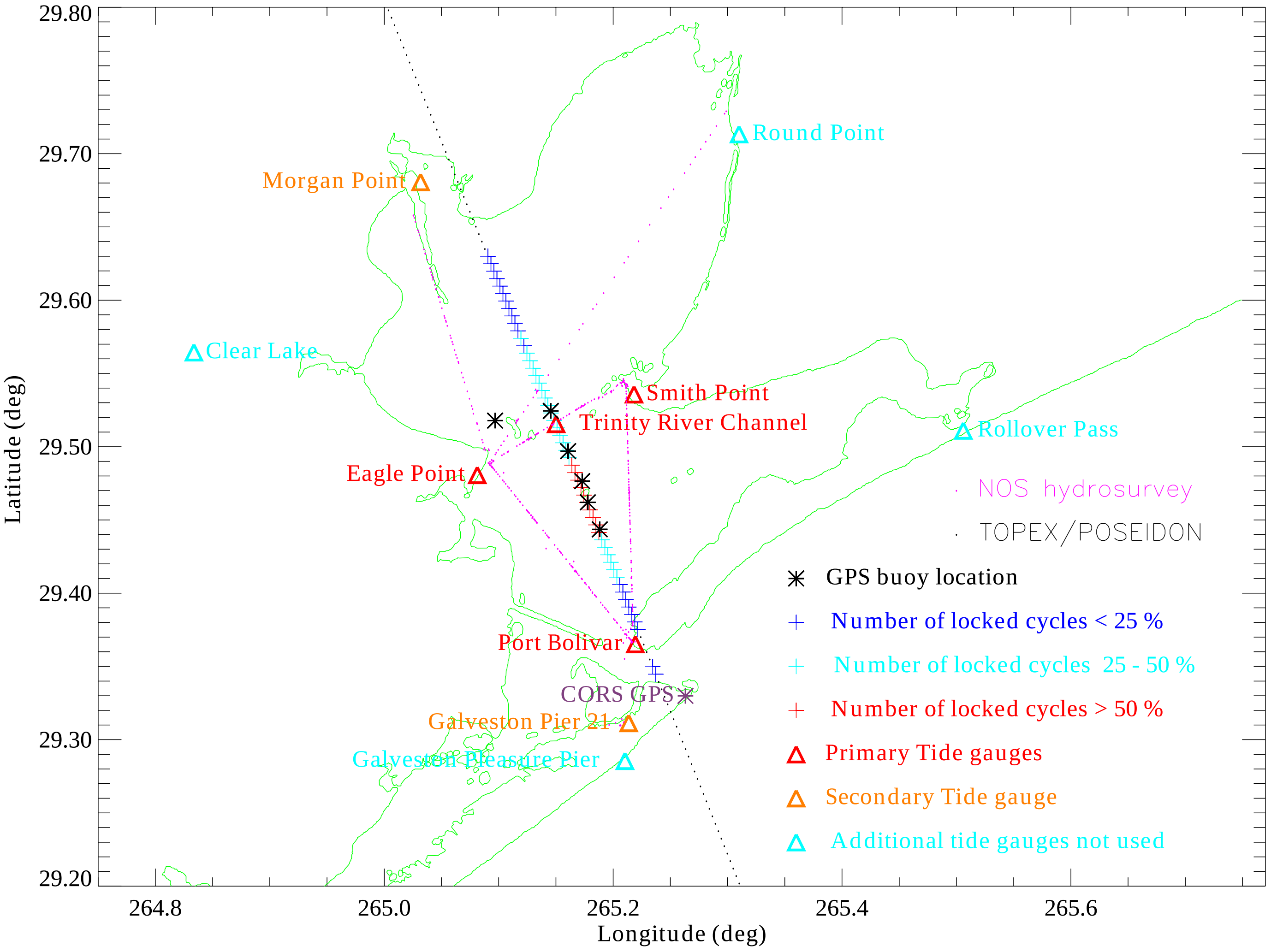

Figure 5-2 : Galveston Bay TOPEX / POSEIDON calibration site including tide gauge and GPS bench mark locations starting in the North near Texas City and ending at the city of Galveston in the South (see Figure 5-2).

Galveston Bay is a shallow subtropical bay with an average depth between 2-3 meters with the exception of the shipping channels, the main channel being the Houston Shipping Channel (HSC) connecting the entrance of Galveston Bay with Houston Harbor. Galveston Bay is subject to the tide influence from the adjacent Gulf of Mexico, which are mainly diurnal. The tides range from 0.3 to 0.5 m, and the phase lag can be as much as 6 hours with respect to the tide in the Gulf, resulting from the shallowness of the bay and its small opening to the Gulf [Schmalz, 1996]. The water level in the bay is also strongly influenced by meteorological forcing due to the shallowness of the bay and the small astronomical tide amplitudes. Another factor affecting the water level is the fresh water inflow from the Trinity River and San Jacinto River, which together contribute 92%. Both rivers empty into in the northern part of the bay and affect the water level throughout the bay. The fresh water flow varies throughout the year, creating salinity gradients which cause buoyancy-driven currents affecting the water level.

Because of the complex nature of the water level in Galveston Bay, a partnership was formed by the National Ocean Service (NOS) at the National Oceanic and Atmospheric Administration (NOAA) to improve the water level modeling of the bay. The following three components of the project proved to be useful for altimeter calibration [Schmalz, 1996]:

- A hydrographic survey using kinematic differential Global Positioning Systems during May 1995
- GPS survey of tide gauge bench marks to tie the tide gauge measurements to the terrestrial reference frame
- Installation of permanent and temporary tide gauge systems to supplement the existing tide gauge network. Some systems were also equipped with meteorological packages.

In order to complement the GPS survey done by NOS, several GPS bench marks were reoccupied by the Center for Space Research [Schutz, 1995], to assess the long term stability of the geodetic network used for the altimeter calibration. For the complete bay, seven tide gauges were available during some part or all the T/P mission (see Table 5.8 and Figure 5-2). Furthermore, the US Coast Guard installed a permanent GPS receiver in October 1995 near Galveston as part of the CORS network. This site proved to be useful in the assessment of the stability of the tide gauge stations (see Figure 5-2).

5.2.2 : Geoid gradient

From Figure 5-2, it can be seen that the T/P ground track directly crosses over two tide gauge positions: the Trinity River Platform and Port Bolivar. The Trinity River Platform station was in operation only several months, allowing only a few calibration passes. The Port Bolivar station is at the southern end of the Galveston Bay pass, and, in general, no reliable altimeter measurements were available within 2 km of this station. In order to calibrate the altimeter using the other tide gauges, a mapping is necessary to account for the change in geoid height at the tide gauge station and a position on the ground track. This section describes how the absolute geoid height along the ground track was determined and how the associated error budget was determined.

The geoid surface at Galveston Bay shown in Figure 5-3 is based on the National Geodetic Survey Geoid93 [Milbert, 1993]. The geoid surface slopes up from North to South by 30 cm for the extent of the T/P pass. Most of the gradient is in the along-track direction, which is favorable for the calibration because the along track geoid gradient can be modeled very well by the repeat track analysis. The cross track gradient is very poorly determined by the repeat track analysis. However, an estimate of the cross track gradient error can be obtained by evaluating the NGS Geoid93 in the cross track direction of the ground track.

For the absolute geoid height along the ground track the following four data sources were considered:

- TOPEX Altimeter repeat track analysis over Galveston Bay
- GPS buoy survey of five points on the T/P ground track during TOPEX

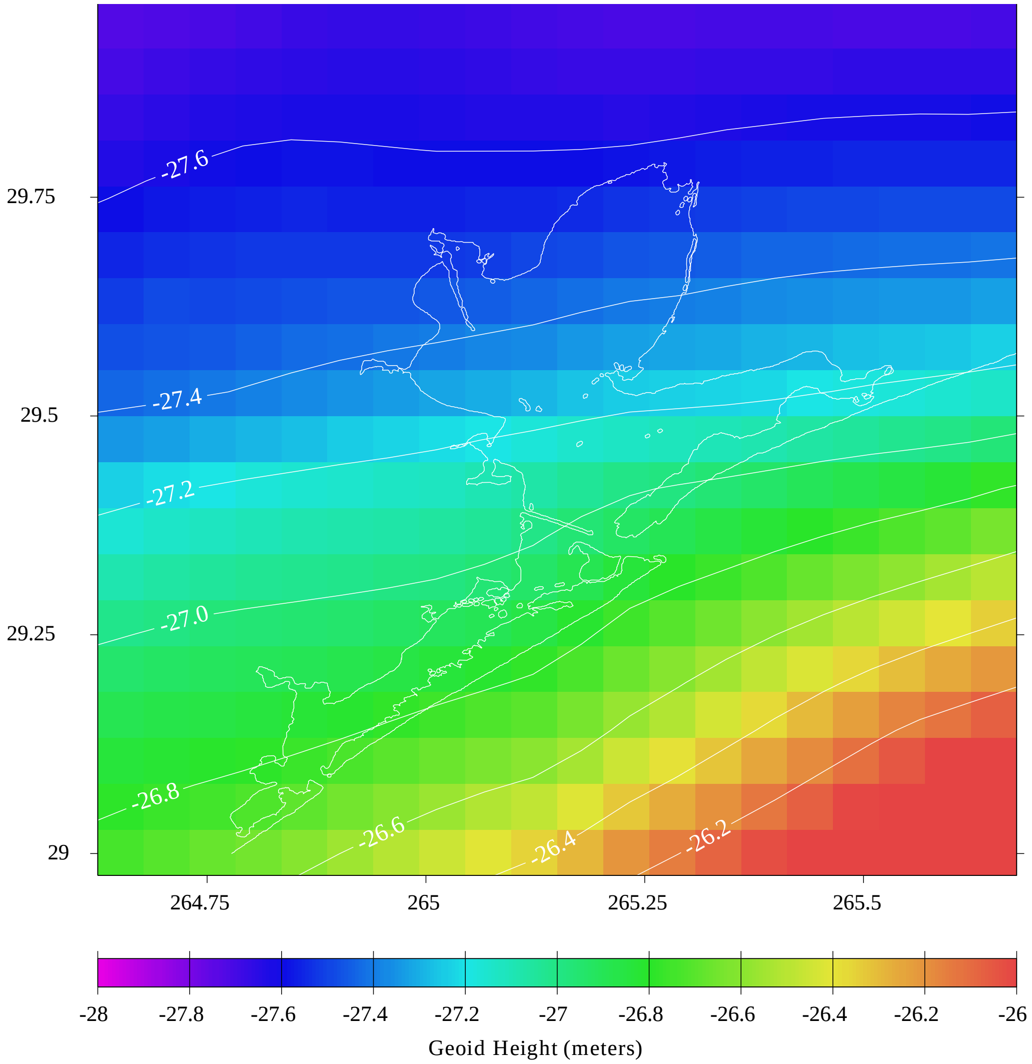

Figure 5-3 : Galveston Bay Geoid93 surface with respect to the reference ellipsoid based on OSU91A amended with surface gravity data

outreach campaign in May 1996 (see Figure 5-2 for locations)

- Hydrographic survey done by NOS in May 1995
- Geoid height determination from tide gauge data from Trinity River Platform

The shape of the geoid profile along the ground track is determined by the repeat track analysis described in Chapter 2. The assumption for the determination of the profile is that, after averaging 152 repeat cycles of the T/P data, the mean sea surface height has an accuracy of 0.8 cm RMS (based on the global crossover analysis of the mean sea surface heights described in Chapters 2 and 4). This mean sea surface profile, however, may still be offset because of the altimeter bias. The geoid profile determined by the repeat track analysis is then adjusted by using the absolute water level determination from the GPS buoys. The absolute hydrosurvey data was not used because of a 1.4 m bias in the data. Most likely this error was introduced when the data was converted from the standard reference ellipsoid to the T/P reference ellipsoid [Benada, 1993]. The difference between these two ellipsoids is 70 cm; correction in the wrong direction yields a 1.4 m bias in the data.

Unfortunately, the GPS buoys measure the instantaneous water level and not the geoid height. Therefore, the GPS buoy water levels need to be corrected first for atmospheric and astronomical tides at that particular location. The GPS buoy heights were also corrected for cross-track geoid gradients because the GPS buoys were not positioned exactly on the T/P ground track.

The Trinity River Platform tide gauge operated for several months and is located on the T/P ground track. The mean water level at this site is interpreted as the geoid, though height is not the actual geoid because long period tides have not averaged out. The short term mean was corrected by determining the same short term mean at Eagle Point and then comparing this with a 4 year mean at Eagle Point. The difference in the short term mean and long term mean was then used to correct the mean height at Trinity River Platform. This is the same procedure used by Schmalz [1996] to determine long term mean tide water levels at short time operating tide gauges.

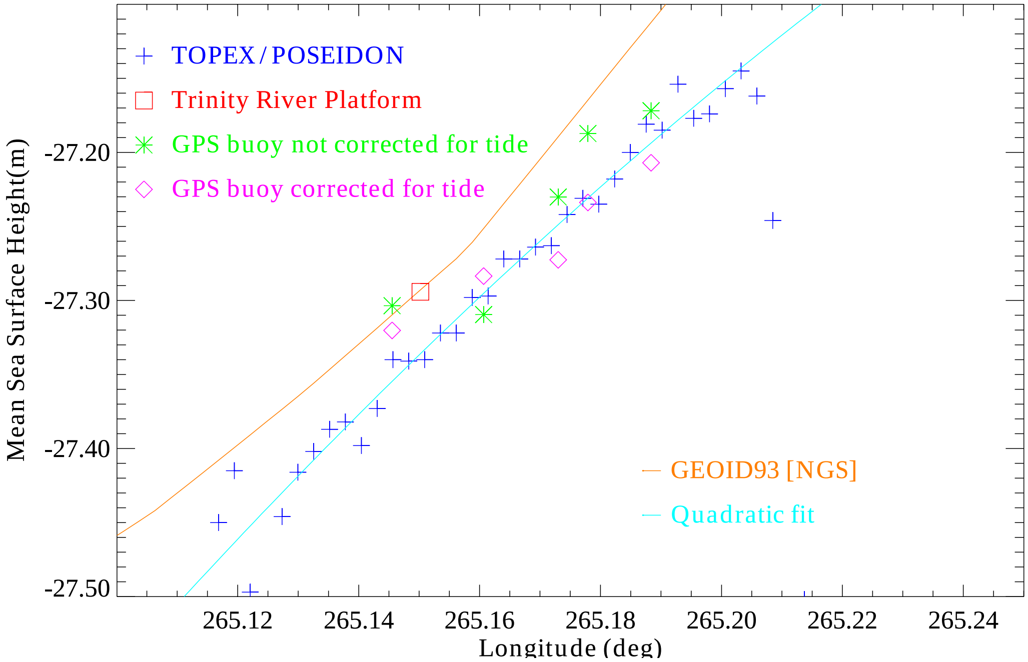

Figure 5-4 : Absolute geoid height along the TOPEX / POSEIDON ground track for Galveston Bay with respect to the NGS Geoid93

The result of the absolute geoid height along the ground track is shown in Figure 5-4. In this figure, the absolute geoid heights derived from the GPS buoys and the geoid height determination at Trinity River Platform are shown. The altimeter profile was adjusted by 1.0 mm up which translates into an overall constant altimeter bias of 1.0 mm during cycles 1-152.

The following error sources were considered in the fixed error assessment for the geoid height profile:

- constant geoid error in T/P mean sea surface height profile due to repeat track analysis. This error was estimated to be 0.8 cm based on global crossover analysis of the mean sea surface
- fixed errors in the GPS height determinations of the GPS buoy. The fixed error in the GPS height determination of the GPS buoy is estimated to be 1.4- 2.8 cm [Key, personal communication, 1997] (See Section 5.2.7) and the fixed error in the height determination of the phase center of the GPS antenna on the buoy with respect to the water surface is assumed to be less than 0.2 cm
- bias introduced due to retracking, which affects the altimeter range and sea state bias correction, which are based on the new SWH and sigma0 estimates. This error is estimated to be 1.1 cm based on analysis of the same retracking process used on the same descending pass off the coast of Galveston in the Gulf of Mexico (See Section 5.2.6)

The variable error in the geoid gradient is due to fact that the ground track does not exactly repeat but has a ±1 km variation in the cross-track direction. The mean cross track gradients based on the NGS-Geoid93 model at the GPS buoy positions on the ground track are shown in Table 5.6 to illustrate the magnitude of the variable geoid gradient error.

In summary, the geoid gradient correction can be computed with a 3.1 cm RSS fixed error and 0.5 cm RMS variable error.

latitude (degrees)	cross track gradient (micro radians)	distance to ground track (m)	sea surface height correction (mm)
29.443568	7.0	305.9	-2.2
29.462028	3.6	53.3	-0.2
29.476505	6.7	146.1	-1.0
29.496966	6.4	164.6	-1.0
29.524387	6.9	81.7	-0.5

Table 5.6 : Geoid cross track gradients estimated from Geoid93 model at GPS buoy locations

5.2.3 : Tidal correction

The tide correction is complicated by the nature of the water level variation in Galveston Bay. The water level variations in the bay can be separated into two components. The first component is referred to as the astronomical tide and is forced by the changes in the gravitational potential due to the relative motions of the Sun, Earth and Moon. The second component is referred to as the atmospheric tide which is the response of the water level to atmospheric forcing, e.g. winds and atmospheric pressure gradients. In this section, the interpolation of the sum of the water level anomalies of produced by these components to the T/P data will be discussed. The error analysis for this correction will be based on a verification of the interpolation technique at the Trinity River Platform, which is situated on the T/P ground track.

The atmospheric and astronomical tides in Galveston Bay are of the same order of magnitude, and the atmospheric tide often exceeds the astronomical tide in size. This is illustrated for a 15-day time span of tide gauge data at Eagle Point in Figure 5-5. An attempt to separate the atmospheric tide and astronomical tide was made by using the same Kalman filter described in Chapter 4. In Table 5.7 all the tidal frequencies are listed with

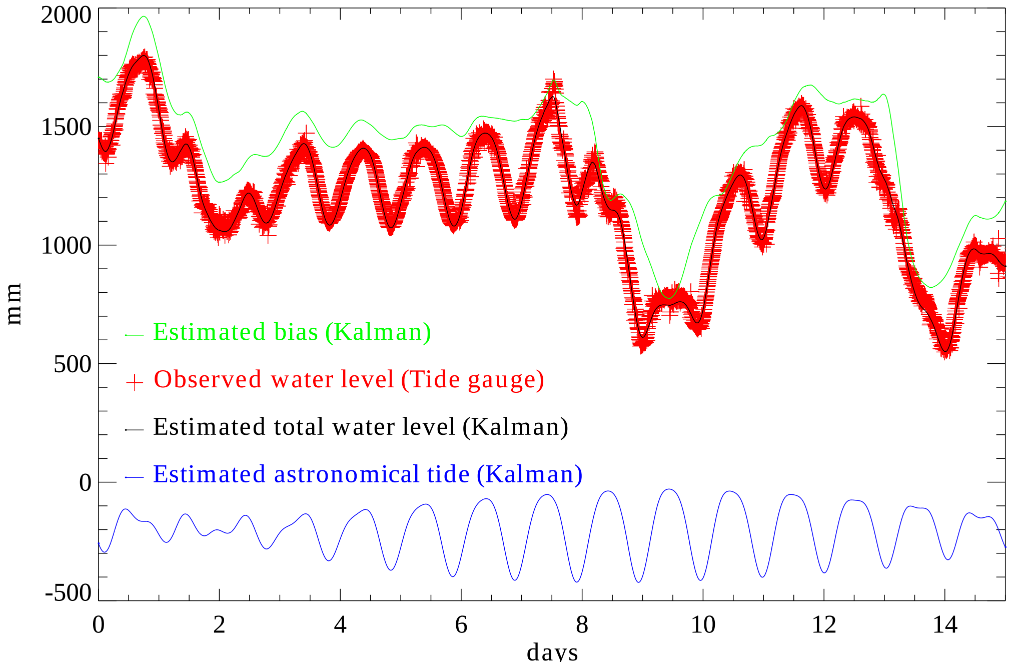

Figure 5-5 : Kalman filtering of Eagle Point tide gauge measurements

Tide name	Frequency (cycles / day)	q
Q1	0.893244033	1.0e-2
S1	1.000000104	1.0e-2
K2	2.005475765	1.0e-2
O1	0.929535680	1.0e-2
N2	1.895981915	1.0e-2
M2	1.932273562	1.0e-2
P1	0.997262064	1.0e-2
K1	1.002737883	1.0e-2
S2	1.999999946	1.0e-2
MM	0.036291647	1.0e-3
MF	0.073202203	1.0e-3
SA	0.002737779	1.0e-5
SAA	0.005475819	1.0e-5

Table 5.7 : Estimated tidal harmonics for Galveston bay and Kalman filter process noise parameters

their associated process noise parameters used in the estimation. With the large amount of parameters estimated, no physically meaningful estimates for each tidal constituent can be obtained, and the filter needs to be constrained to prevent divergence. Therefore, the total sum of the water level estimate is used which is illustrated in Figure 5-5. The filter has been used as an optimal smoother on the observed water level.

Not all tide gauges were available throughout the T/P mission. The primary tide gauge for the calibration campaign was Eagle Point, which became available in April of 1993. Eagle Point was chosen as the primary tide gauge site because of its long time series and its relative location to the T/P ground track. Furthermore, the tide interpolation into the bay could be verified by temporary tide gauges near Eagle Point. The Trinity River Platform tide gauge operated for 4 months and was directly within ±1 km of the ground track. The tide gauge at Smith Point operated for about 6 months and complemented the surveyed triangle from Eagle Point, to Smith Point, to Port Bolivar (see Figure 5-2). In Table 5.8, a complete overview is given of all the tide gauges used in the calibration and the period for which they were operational

Station ID	Station name	Start Date	Final Date
8770631	Morgan’s Point	01/01/1993	12/31/1996
8770931	Smith Point	05/19/1995	12/07/1995
8771013	Eagle Point	04/19/1993	12/31/1996
8771021	Trinity River Platform	05/20/1995	09/11/1995
8771328	Port Bolivar	06/01/1994	12/31/1996
8771459	Pier21	01/01/1993	12/31/1996

Table 5.8 : Tide gauges used for altimeter calibration in Galveston Bay up to 31 December 1996

The spatial interpolation of the observed water levels is done in terms of the water level anomaly at each tide gauge. For each tide gauge, the long period mean water level is assumed to be the geoid height. The water level anomaly is then computed by subtracting the mean water level from the actual observation. Strictly speaking, the long term mean is not the geoid height because long period tides were not considered. NOS uses 19 years (approximately the nodal period of the moon) of tide gauge data to determine the mean water level [Schmalz, 1996]. In Galveston Bay, the longest time series used in this calibration is four years. This long term bias, however, should more or less cancel in the calibration because the altimeter will sense the same biased water level. The same problem occurs for tide gauges that only operated for a few months. In this case, the long period tides have a contribution to the altimeter bias and need to be corrected (see Section 5.2.2).

The water level anomalies are interpolated along the T/P groundtrack assuming that Port Bolivar, Trinity River Channel and Morgan's Point are located on the ground track and separated by their respective great circle distances. Unfortunately, only three anomalies are available for interpolation. Using a second order polynomial interpolation introduced unrealistically large anomalies. Therefore, a cubic spline was used for the Bolivar - Trinity River Platform and Trinity River Platform - Morgan's Point segments (see Figure 5-6). For a cubic spline, however, a surface slope of the water level anomalies is required. The surface slope at each tide gauge was approximated by using the water-level height rate of change at each tide

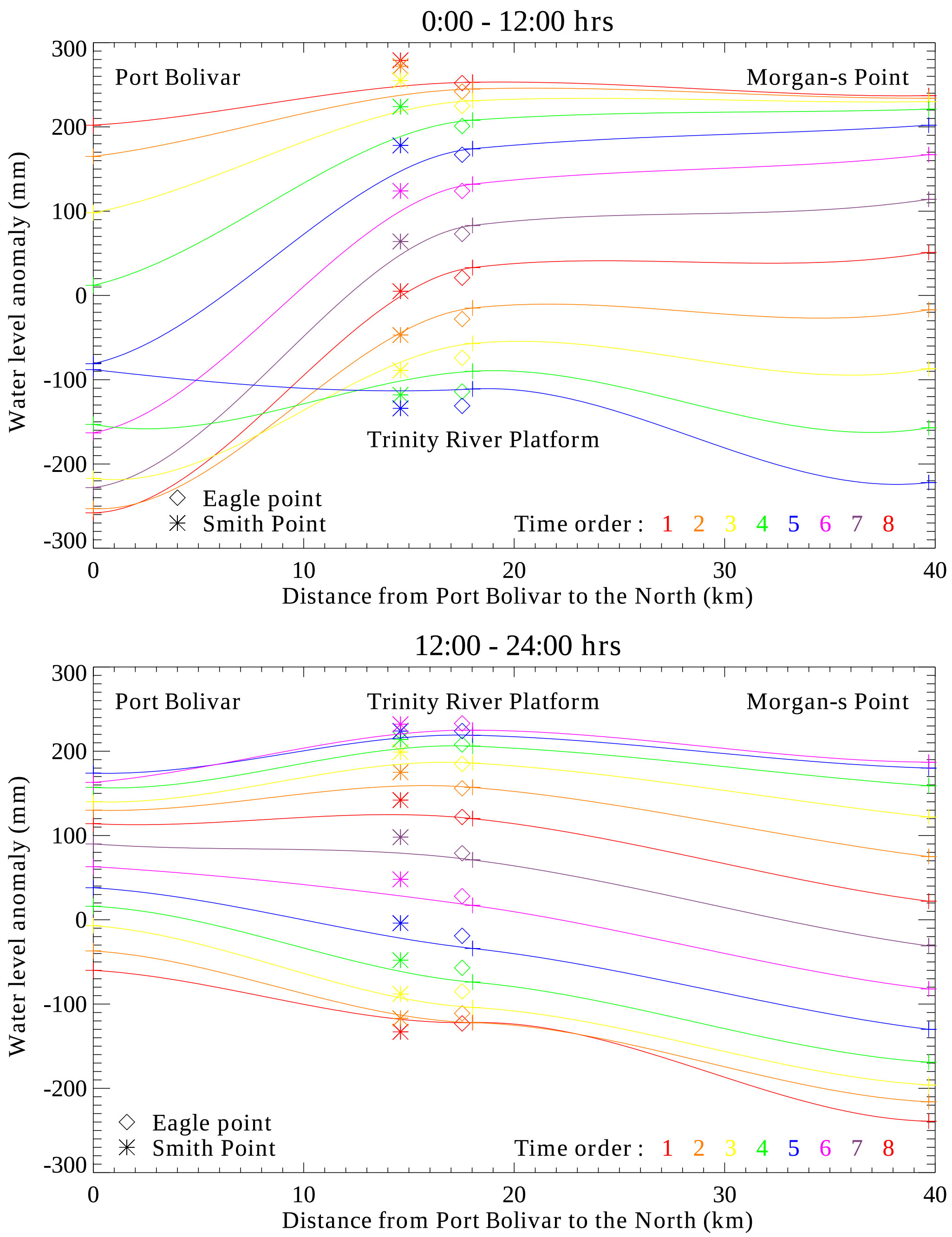

Figure 5-6 : Tide anomaly interpolation at Galveston Bay Tide gauges along the TOPEX / POSEIDON ground track using a cubic spline gauge. The height rate of change $\partial h/\partial t$ can be related to the surface slope using the wave equation and assuming a free moving wave [Boyce and DiPrima, 1976]

$$\frac{\partial h}{\partial t} = -V\frac{\partial h}{\partial x} \qquad (5.11)$$

where h is water level anomaly, t is time, V is the wave speed and x is the space coordinate in the direction of the wave movement. To compute the slope at the tide gauges, the following assumptions were made:

- The surface slope with respect to the geoid is caused by the tidal wave; this, in general, is not true.
- The tidal wave is moving parallel to the T/P ground track. While not necessarily true, the shape of Galveston Bay lends itself to this assumption.
- The wave speed is based on the wave speed for long wave length waves in shallow water, calculated according to [Pond, 1995]

  $$V = \sqrt{gd} \qquad (5.12)$$

  where g is the gravitational constant and d is the depth of the bay.
- The average bay depth of 2.0 m is used for the wave speed computation [Schmalz, 1996].

The height rate $\frac{\partial h}{\partial t}$ is directly determined from the tide gauge measurements, and the surface slope is then computed from Eq. 5.11. The results for this spatial interpolation are shown in Figure 5-6, which shows the water level anomalies for a 24 hour period based on water level anomalies for Port Bolivar, Eagle Point and Morgan's Point.

Tide gauges at Eagle Point and Smith Point have been repositioned to equivalent positions on the T/P ground track. The equivalent position is defined to be the location on the ground track for which the time cross-correlation with a particular station is zero. These positions were found in two steps. First, the time cross-correlation of all tide gauge stations with respect to Port Bolivar is computed and listed in Table 5.9. The table contains all time correlations with respect to Port Bolivar, the residual RMS after correction for the time lag, and the derived equivalent position. A positive value of the time correlation means that high water occurred after high water at Port

Station name	Time correlation (minutes)	Residual RMS (mm)	Equivalent ground track position (km)
Morgan's Point	240	77	39.689
Smith Point	132	50	14.598
Eagle Point	162	53	17.526
Trinity River Platform	168	50	18.022
Pier21	-6	27	0.0

Table 5.9 : Time correlation for Galveston Bay tide gauges with respect to Port Bolivar tide gauge

Bolivar. Second, the equivalent position is adjusted such that the Trinity River platform residual is minimized. This adjustment process is illustrated for Eagle Point. The equivalent ground track position for Eagle Point based on the time crossover-correlation is compute according to

$$\text{distance} = \frac{162}{168} \times 18.022 = 17.378 \tag{5.13}$$

where 162 is the time lag for Eagle Point and 168 is the time lag for Trinity River Platform (considered to be on the ground track) and 18.022 is the great circle distance between Port Bolivar and Trinity River Platform in km. This distance is then used to initialize an iterative process to adjust the equivalent ground track position. The spatial water level anomaly interpolation is then performed using Eagle Point on the equivalent ground track position and the water level residual is computed at Trinity River Platform during the four months it operated. The final adjusted equivalent ground track position is reported in Table 5.9 and is in close agreement with the time cross-correlation derived position. The mean after adjustment for the Trinity River Platform residual is 1 mm and the RMS about the mean is 19 mm. Hence Eagle Point can be used as a substitute for Trinity River Platform but with an increased error of 19 mm RMS, which is caused by cross track spatial tidal variability. This variability has a diurnal character and can be observed in Figure 5-6. The same is true for Smith Point, which is also shown in Figure 5-

6 at its equivalent position. However, for Smith Point a 14 mm bias was introduced in the Trinity River Platform residual, and the RMS about the mean increased to 27 mm. Smith Point was not used in the altimeter calibration.

The error in the spatial interpolation of water level anomalies is based on the adjustment process described above, because most altimeter data were acquired near the equivalent ground track positions for Eagle Point and Smith Point (see Figure 5-2). Based on the adjustment process above, the variable error for the spatial water is believed to be 25 mm RMS, with a mean error of 15 mm.

5.2.4 : Dry and Wet tropospheric correction

In this section, the tropospheric correction used in the TOPEX altimeter calibration will be discussed, including an error analysis.

The Merge Geophysical Data Records (MGDR) [Benada, 1993] dry tropospheric correction was used for the altimeter calibration. The local surface pressure observations were not used because they were not available throughout the T/P mission. For consistency purposes, the MGDR dry tropospheric was used. This dry correction is in close agreement with local pressure measurements, as has been shown in Chapter 3. The mean error for this correction at 30 degrees North is believed to be 2.2 mm and the variable error is 2.2 mm RMS.

Unfortunately, the TMR derived wet tropospheric correction is not reliable over Galveston Bay due to land influences on the instrument [Christensen, 1994]. Therefore, the wet tropospheric correction is extrapolated from TMR derived wet tropospheric corrections off the Galveston Coast in the Gulf of Mexico up to a 100 km offshore. One year of GPS data was processed for the Galveston CORS site to investigate the validity of the extrapolation. The Galveston CORS site is located on the tip of Galveston Island and nearly on the T/P ground track (see Figure 5-2). The wet zenith delay was estimated from double-differenced GPS data with the IGS sites at McDonald Observatory (TX), Pie Town (NM) and Richmond (FL) according to a procedure described in Nam, 1996. Surface pressures from the Port Bolivar and Eagle Point tide gauges were used to compute the wet zenith delay at the Galveston CORS site. The wet zenith delay was estimated every hour. The comparison of the TMR and GPS derived wet tropospheric correction is shown in Figure 5-7. It can be seen that the two wet corrections are biased with respect to each other by 30 mm. The RMS about the mean for the comparison is 18 mm which is a measure of the variability in water vapor between the Gulf of Mexico and Galveston Bay. The 30 mm bias existing between the two systems is unfortunate. This bias is most likely caused by the conical raydome shape used at the Galveston CORS site and the simulta-

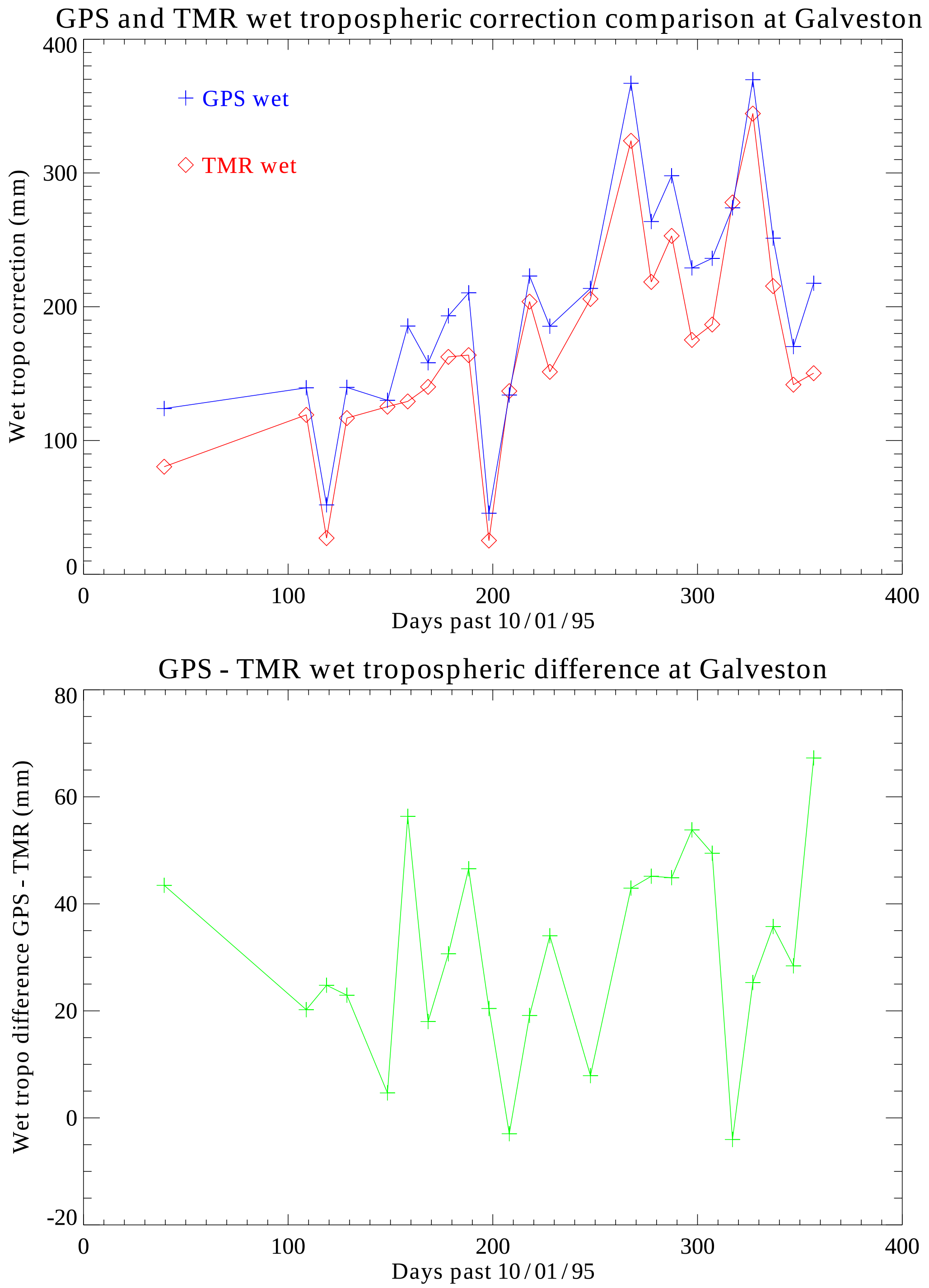

Figure 5-7 : GPS and TMR derived wet tropospheric correction comparison at Galveston October 1, 1995 to November 30, 1996 neous estimation of the position and zenith delay. Tests at the University Navstar Consortium (UNAVCO) revealed up to 25 mm biases in the vertical position due to the conical antenna raydome and the simultaneously estimation of position and zenith delay [Meertens, personal communication, 1996]

Because of the relative bias between the TMR and GPS derived wet tropospheric corrections, the systematic error in the extrapolated TMR wet tropospheric correction is difficult to assess. Therefore, the mean error used for Harvest Platform will be used which is reported to be 5 mm [Christensen, 1994]. The variable error based on the comparison is 18 mm RMS.

5.2.5 : Ionospheric correction

The ionospheric correction for the TOPEX altimeter is derived from two altimeter measurements in the Ku and C bands at the same location [Imel, 1994]. On the MGDR, the ionospheric correction is reported every second, and most ionospheric corrections over Galveston Bay have been corrupted due to the inclusion of corrupted altimeter ranges in the ionospheric correction calculation. Over Galveston Bay, many waveforms have non-ocean waveform shapes or the altimeter has not locked onto the surface. Therefore, the ionospheric correction is extrapolated from ionospheric corrections off the coast from Galveston in the Gulf of Mexico up to 100 km offshore. It has been recommended to average the ionospheric correction over 140 km (20 seconds) to minimize the noise without loss of accuracy (Imel, 1994). The extrapolation described above is even less than the recommended smoothing interval. Therefore it is assumed that extrapolation can predict accurately the ionospheric correction over Galveston Bay within the systematic and variable errors reported for Harvest Platform. The variable error for Harvest Platform is reported to be 10 mm and the systematic error is 5 mm [Christensen, 1994].

5.2.6 : Altimeter waveform retracking

The MGDR reports altimeter ranges at 10 Hz, but all corrections and waveform associated quantities have been computed or derived based on 1 Hz averages. This process turned out to be a problem over Galveston Bay when accurate 10hz altimeter measurements were needed. The T/P altimeter system needs time to acquire the water surface, in general this takes about one second after the satellite travels from land to water. For Galveston Bay only two seconds were available to obtain reliable altimeter ranges. Due to the once per second averaging on the MGDR, many quantities and instrumental corrections were corrupted due to the inclusion of non-ocean altimeter waveforms.

After examination of the Altimeter Sensor Data Records (SDR) [JPL, 1992], it was found that many good altimeter waveforms existed over

Galveston Bay, in contrast to the MGDR where all the data were flagged suspicious. An example of altimeter waveforms over Galveston Bay is shown in Figure 5-8, which shows the altimeter waveforms and their location in the Galveston Bay Region. The pass shown in Figure 5-8 is one of the best passes because of the large number of good altimeter waveforms over the Bay.

The good altimeter waveforms over Galveston Bay were retracked, meaning that the altimeter waveform data is refit to a theoretical waveform shape in a least squares sense to determine the waveform parameters. The retracking software used for this research was developed by Van Nuth at the Center for Space Research. The theoretical mean waveform over water surfaces can be expressed by the following convolution

$$W(t) = P_{FS}(t) \bullet q_s(t) \bullet p_t(t) \tag{5.14}$$

where W(t) is the mean received power, $P_{FS}(t)$ is the flat surface impulse response (Brown model, 1977), $q_s(t)$ is the radar-observed surface elevation probability density function, which is modeled as a skewed Gaussian, and $p_t(t)$ is the radar system point-target response which has been modeled as a sinc^2 function [Hayne, 1980]. For each waveform, the following parameters were estimated [Hayne, 1994]:

- Waveform amplitude scale
- Range correction

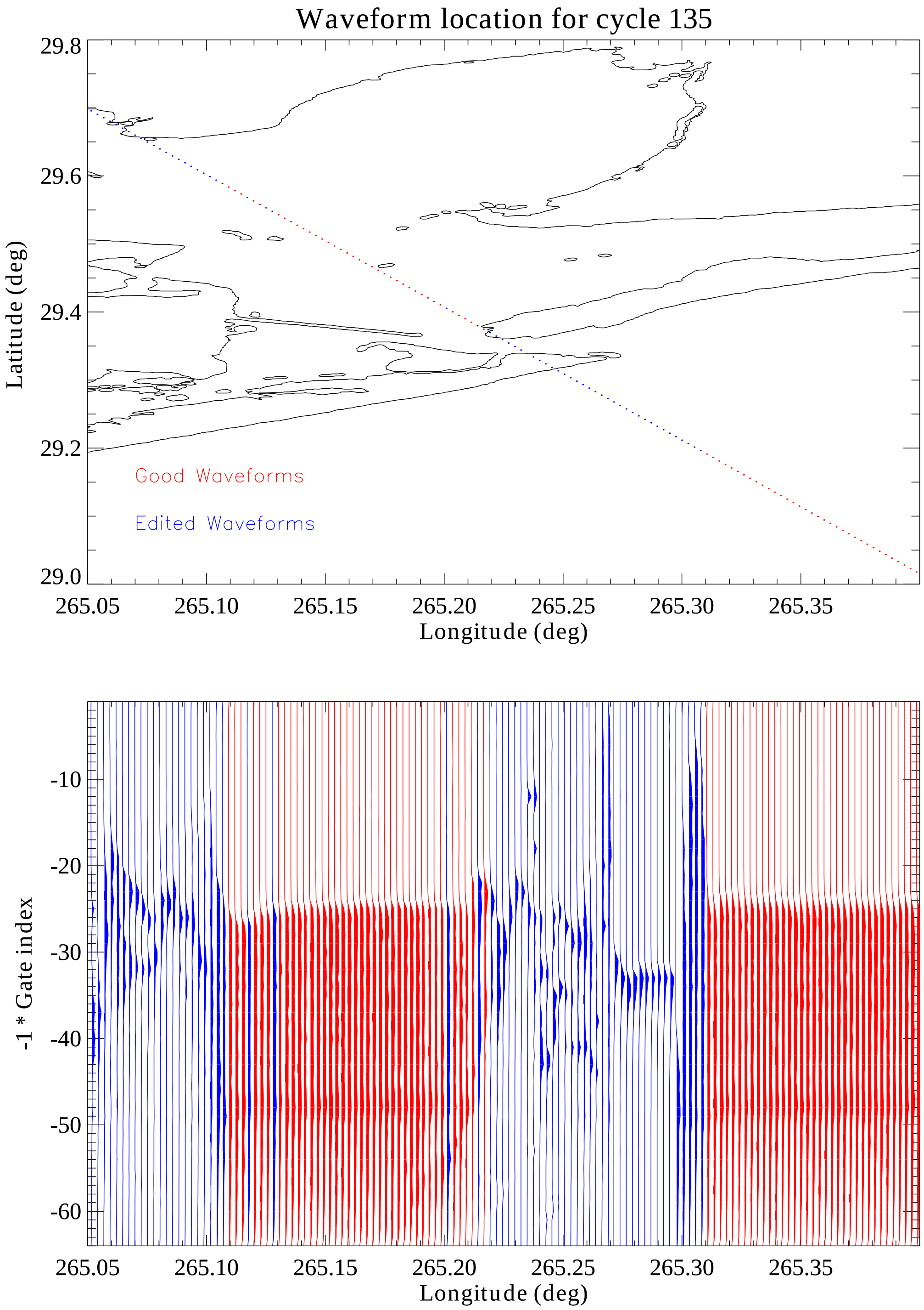

Figure 5-8 : TOPEX altimeter waveforms (vertical) over Galveston Bay and the Gulf of Mexico for cycle 135

- Surface Significant Wave Height (SWH)
- Off nadir angle
- Thermal noise

It should be noted that the surface skewness was not estimated but set to 0.1 [Hayne, personal communication, 1996]. One important parameter for the sea state bias computation is the σ_0 or backscattering cross section. This parameter was computed from the Automatic Gain Control (AGC) and the retracked waveform amplitude scale with a modified formulation of the TOPEX σ_0 computation [Calahan, 1991] provided by Hayne, 1996 [Nuth, personal communication].

The edit criteria used to select good altimeter waveforms are based on the 64 telemetry waveform samples reported on the SDR. The actual TOPEX altimeter observes 128 waveforms but only 64 unevenly sampled waveforms are stored on board and later telemetered down to Earth [Hayne, 1994]. The altimeter waveform on the SDR is a scaled version (range 0-255) of the actual waveform. The edit criteria will be discussed in terms of telemetry sample number and the scaled amplitude. The edit criteria are:

- The maximum slope does not occur at telemetry waveform sample 24 also known as the range gate. This checks if the altimeter is locked. If the altimeter is not locked then the telemetry waveform sample with the maximum slope is assumed to be the range gate and the waveform will be checked against the remainder of the edit criteria with the offset applied to telemetry waveform sample numbers.

- The mean slope for telemetry samples 5-20 is greater than 1.0.
- The RMS about mean slope for telemetry samples is greater than 3.5.
- The mean of the scaled waveform for telemetry samples 26-40 is larger than the waveform amplitude at telemetry sample 25.

The result of these edit criteria is seen in Figure 5-8, which shows the waveforms deemed good (red) and the edited waveforms (blue).

As mentioned before, the MGDR reports only the 1 Hz the average waveform parameters (SWH, σ_0, AGC). In general, these corrections were corrupted over Galveston Bay due to the inclusion of non-ocean altimeter waveforms, which made retracking of the waveform a necessity. Another reason for retracking was the recalculation of the net Ku range instrumental correction which is the lumped sum of the

- Oscillator drift
- Center of gravity correction
- Acceleration correction
- Altimeter pointing angle / sea-state correction
- Doppler shift correction
- Altimeter track mode correction

- Altimeter calibration correction

The Doppler correction and the acceleration correction are based on three second windows of altimeter ranges to determine the surface height velocity and acceleration with respect to the satellite [Calahan, 1991]. Because many ranges over Galveston Bay were incorrect or invalid, many doppler and acceleration corrections were not computed or corrupted due to the inclusion of bad ranges. Furthermore, the altimeter pointing angle / sea state correction, which corrects for improper tracking of the altimeter waveform by TOPEX altimeter due to pointing and seastate effects, was not computed either. By retracking the data, the acceleration correction and altimeter point angle / sea-state correction are not necessary because retracking will compensate for these errors introduced by the TOPEX altimeter [Hayne, 1994]. Unfortunately, not all individual corrections in the net Ku range correction were reported on the MGDR. For Galveston Bay, the net Ku range correction was computed by taking the net Ku range correction over land (North of Galveston Bay) which was found to be the sum of the oscillator drift, center of gravity correction, altimeter track mode correction and the altimeter calibration correction. The only correction that needed to be recomputed was the Doppler shift correction, which was done with the retracked ranges over Galveston Bay [See Calahan, 1991 for Doppler shift computation]. Adding the new Doppler shift correction to the land net Ku range correction completed the new Ku range correction over Galveston Bay.

To evaluate the systematic and variable error of the CSR retracking software including the recomputation of the net Ku range correction, a six second segment on the same descending pass through Galveston Bay was retracked over the Gulf of Mexico. Since no retracking is required for the Gulf of Mexico, an assessment can be made to the effect of retracking on the altimeter bias. The mean sea surface height from repeat track analysis is compared for retracked and GDR data in Figure 5-9. It can be seen that retracking of the altimeter data introduced a 1.5 cm height bias such that the retracked mean sea surface is 1.5 cm lower than the GDR data. For compari-

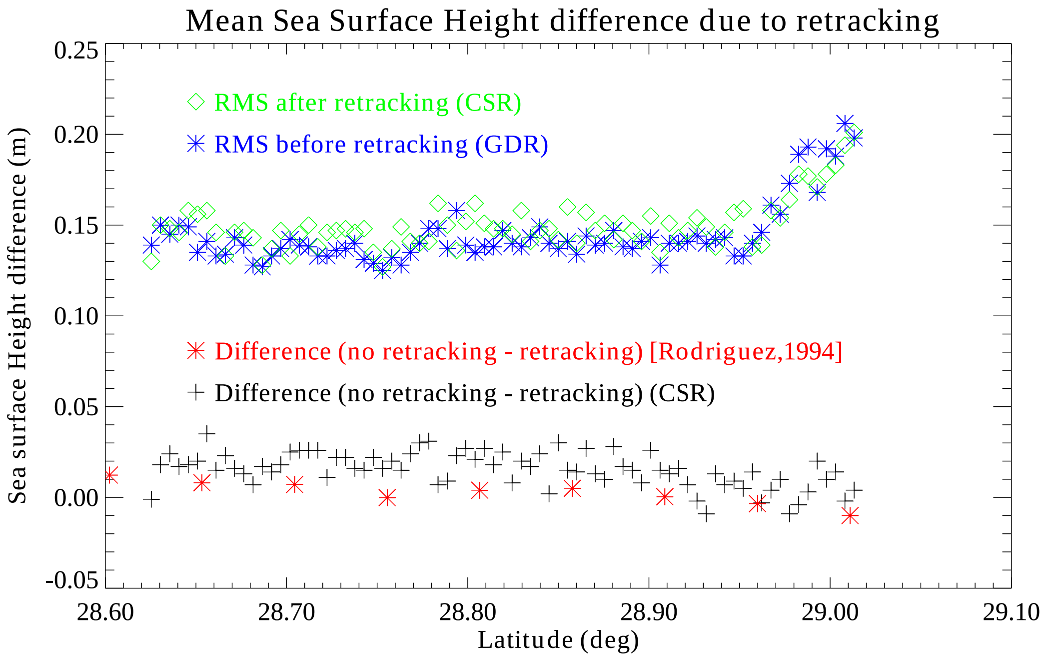

Figure 5-9 : Mean sea surface height comparison between retracked and GDR altimeter data over the Gulf of Mexico son the retracking result provided by Rodriguez and Martin is also shown, which introduced a 0.4 cm bias in the same direction. The 0.4 cm is consistent with the value reported in Rodriguez and Martin, 1994, which reports an mean offset for the TOPEX altimeter of 0.5 cm for descending passes at 30 degrees North. Hence, the CSR retracking and the recomputation of the net Ku range correction introduces a 1.1 cm bias over the Gulf of Mexico. This bias also includes the recomputation of the sea state bias according to the TOPEX algorithm [Calahan, 1992] (See Chapter 1). Finally, it can also be seen in Figure 5-9 that the RMS about the mean slightly increased, which is expected due to estimation error (Rodriguez, 1994).

In conclusion, the fixed error of the overall retracking process and derived corrections may be as much as 1.1 cm, and an additional variable error of 4.5 cm based on the power difference of the RMS about mean of the mean sea surface before and after retracking.

5.2.7 : Benchmark survey of tide gauge network using GPS

The tide gauge observations have been tied to the terrestrial reference frame using GPS during 5 campaigns. The first two campaigns were conducted by NOS in March and May of 1995, and the GPS data were provided to CSR by NOS [Doug Martin, personal communication, 1997]. The next two campaigns were conducted by CSR in March and November of 1995. The

Tide gauge name	NGS bench mark	month / year of occu- pation	Height above the TOPEX reference ellipsoid (m)	Repeat- ability (cm)	Number of sur- vey days
Morgan's Point	BM 10 1975	03 / 95	-24.183	-	-
Round Point	BM 0559F	03 / 95 05 / 95	-26.8268	0.43	13
Round Point	BM 0559F	11 / 95	-26.836	0.40	2
Eagle Point	LUB 1031A	03 / 95	-25.983	0.54	9
Eagle Point	LUB 1031A	11 / 95	-25.973	0.76	3
Eagle Point	LUB 1031A	05 / 96	-25.975	0.77	3
Eagle Point	LUB 1031A	04 / 97	-25.984	1.16	7
Trinity River Palfrey	BM 1021 A	05 / 95	-22.717	1.03	3
Smith Point	BM 5 1973	05 / 95	-26.635	0.32	3
Smith Point	BM 5 1973	11 / 95	-26.629	0.89	3
Port Bolivar	LUB 1450 A	-	-25.016	0.47	3
Port Bolivar	LUB 1450 A	-	-25.017	0.00	1
Pier 21	LUB 1328 F	03 / 95	-26.401	-	-

Table 5.10 : GPS survey results for Galveston Bay tide gauges

latest campaign was a collaboration between CSR and the Colorado Center for Astrodynamics Research (CCAR), which included a static survey of Eagle Point and GPS buoys for direct altimeter calibration.

All position solutions for the static survey were computed using the Multiple Satellite Orbit Determination Program (MSODP) at the CSR except for Morgan's Point and Pier 21. The position solutions were computed from the double-differenced ionospheric-free GPS measurements with McDonald observatory on a daily basis where the position of McDonald Observatory was kept fixed. The daily solutions were parameterized as follows:

- Hourly zenith delay estimates
- Station position
- Ambiguity parameters

The orbits for the GPS satellites were computed at CSR and used for these solutions. The results for all GPS surveys have been listed for each tide gauge in Table 5.10 including the repeatability of the height solutions, which is a measure of the variable error in the height solutions. The fixed error in the height solution is believed to be 1.0 cm based on JPL IGS McDonald Observatory position analysis [Heflen, personal communication 1997], with a variable error of 1 cm RMS [Nam, personal communication, 1997].

5.2.8 : Geoid mapping using GPS buoys

An attempt was made to observe the absolute geoid height along the T/

P ground track using GPS buoys because the T/P altimeter locks on a different location for each overflight, which introduces the need to map to geoid in order to combine the results for each overflight. For this purpose, GPS buoys designed by CCAR were floated at 5 positions along the T/P ground track in May 1996 as part of the T/P Outreach project (see Figure 5-2 for locations). Eagle Point served as the base station during the kinematic survey. The GPS buoys were floated on each location for 30 minutes and one of the deployments was commensurate with an overflight of T/P, which was used as a direct calibration by measuring the instantaneous water level at the time of overflight.

The GPS solutions for the GPS buoys were computed by CCAR using the KIN program [Key, personal communication, 1996] which is based on the Kinematic and Rapid Static (K&RS) software developed by Mader, [1986]. The solution procedure for the GPS solution was identical to Born et al., [1994], where a GPS buoy was floated at Harvest Platform for an independent determination of the altimeter bias. The result of the mapping are shown in Figure 5-4, which show a good agreement with the geoid profile observed with the TOPEX altimeter. For a complete discussion see Section 5.2.2.

5.2.9 : Stability of tide gauge network from tide gauge time series and GPS

In order to monitor the long term stability of the T/P altimeter, very stringent requirements are necessary for the long term stability in the tide gauge measurements and their reference benchmarks. In this section, the stability of the total tide gauge system, the reference benchmarks and an assessment of local vertical crustal motion will be discussed.

The long term stability of the total tide gauge system was assessed using two methods. First, the absolute tide gauge measurements were averaged into monthly values, and the secular trend was determined for each tide gauge which observed for at least two years. Second, all tide gauge measurements were differenced with the Eagle Point tide gauge, and a relative secular trend was determined. The advantage of the second method is that all signals common to all tide gauges (e.g. sea level rise, vertical crustal motion, long period signals) will cancel. However, local secular trends as well as instrument drifts will be present in the difference. The results for all tide gauges are listed in Table 5.11. It should be noted that in Galveston Bay large annual and semi-annual signals (10-20 cm amplitude) exist with time varying amplitudes, which limits the accurate determination in the absolute drift in the total system. This is illustrated by the large drifts observed in the total system measurements. The differenced tide gauge observations are more accurate because the large common signals have been canceled. Nevertheless, annual and semi-annual differences do exist between the tide

Tide gauge name	NGS bench mark	Absolute drift (mm / year)	Relative drift with respect to Eagle Point (mm / year)	Inferred absolute drift (mm / year)
Morgan's Point	BM 10 1975	-19.4	-1.7	-6.3
Eagle Point	LUB 1031A	-4.6	-	-
Port Bolivar	LUB 1450 A	-26.7	-12.9	-17.5
Pier 21	LUB 1328 F	-16.7	-	-

Table 5.11 : Absolute and relative drift of the total tide gauge system for Galveston Bay tide gauges.

gauges which limits the relative drift determination to ±3.6 mm / year. It can be seen in Table 5.11 that relative drifts as large as -13 mm / year exist. The inferred absolute drifts, assuming the Eagle Point drift is accurate, show a relative drift between Morgan's Point and Port Bolivar of -11 mm / year. This drift is in close agreement with the relative drift of -9 mm / year by directly differencing the tide gauges measurements. Therefore, it is reasonable to assume that drifts as large as 20 mm / year may exist in the current tide gauges at Galveston Bay. Longer time spans will be required to obtain more accurate determination of the absolute drift in the tide gauges.

To assess the stability of the bench marks at the tide gauges, multiple occupations of the bench marks by GPS are required, spaced out over a least

5 to 10 years. Unfortunately, no long term GPS observations were available. The only tide gauge data spanning more than one year with more than 2 occupations is Eagle Point (see Table 5.10). Based on these results, no drift conclusion can be drawn. However, the data suggest a small uplift which is in the same direction based on the overall tide gauge drifts discussed earlier.

An inference about the local vertical crustal motion was made from one year of continuous GPS data observed at the CORS site in Galveston. The result for the vertical of the GPS solution is shown in Figure 5-10. The drift in height of 1.5 ±2 mm/year is in the direction observed in the total tide gauge system. The annual variation is most likely an artifact of the conical ray-

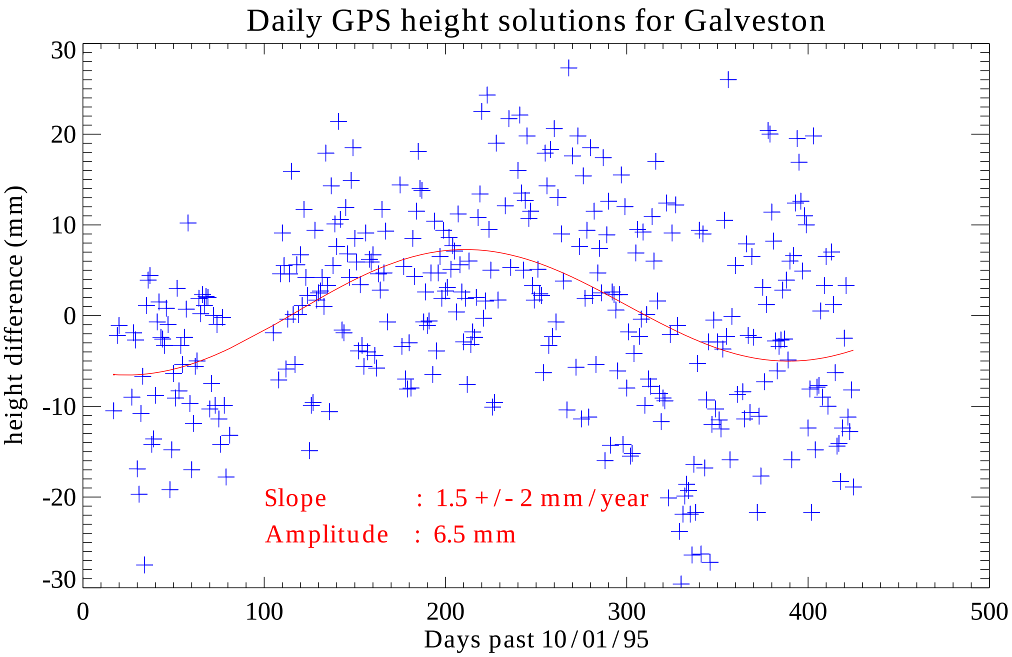

Figure 5-10 : Daily height variation from continuous GPS observation at Galveston CORS site dome used at the Galveston CORS site [Meertens, UNAVCO, personal communication,1996]. The annual variation may be introduced because of the fact that the GPS constellation repeats twice per sidereal day. The difference of four minutes between the sidereal and solar day may cause the different average refraction pattern inside the antenna raydome since the GPS solution is computed each solar day [Schutz, personal communication,1996]. Therefore, an annual signal may be introduced because the same average refraction pattern would occur once per year. The annual signal was also observed in the North, and to a lesser extent, in the East component of the daily GPS solutions.

In conclusion, drifts, up to 20 mm / year may exist in the total tide gauge system. These large drifts were not observed in the GPS survey for Eagle Point and the continuous operation GPS CORS site at Galveston. These results do not agree with the general belief that subsidence is occurring in the Galveston Bay region with rates from 0.1 to 2.4 mm year [Sharp, 1991]. This discrepancy is probably due to fact that only very short time intervals of tide gauge data were available to determine drifts.

5.2.10 : Results

In this section, the results of the absolute calibration of the TOPEX altimeter over Galveston Bay will be discussed. First, a short description is given of the two calibration procedures used at Galveston Bay. Second, the error budget for the calibration is presented based on the discussion in the previous sections. Finally, the calibration result and its limitations will be discussed.

Two types of calibrations were performed at Galveston Bay. The first, the direct calibration, involves a direct overflight occurred of a tide gauge or GPS buoy. In total, three direct overflights occurred, two over Trinity River Platform and one over a GPS buoy. For all other passes the spatial interpolation of the water level anomalies and geoid was used.

The following steps in the calibration procedure are identical for both calibration types, which are for each individual T/P pass over Galveston Bay:

- Smoothing of all tide gauge measurements using a Kalman filter (Chapter 4 and Section 5.2.3)
- extraction of waveform data from SDR and retracking of good altimeter waveforms over Galveston Bay (Section 5.2.6)
- extraction of altimeter data from MGDR for which good altimeter waveforms exist.
- postprocessing of selected MGDR data which includes orbit replacement, application of altimeter, instrumental and geophysical corrections

(Chapter 1, Sections 5.2.4, 5.2.5, 5.2.6) except for the ocean tide

- Sea surface height computation

For the direct overflight calibration, a fifth-order polynomial is fit to the derived sea surface heights and evaluated at the over flight location. The altimeter bias is then computed using the resulting sea surface height, and the independently determined sea surface height from GPS buoy or tide gauge according to Eq. 5.1.

For non-direct overflights, the altimeter derived sea surface heights are related to a common reference to compute the altimeter bias according to the following steps:

- remove absolute geoid profile from sea surface heights (Section 5.2.2)
- compute water level anomalies along the T/P ground track and correct residual sea surface heights from previous step (Section 5.2.3)
- Average the residual from the previous step using a three sigma editing criteria to remove the outliers. The resulting average is the estimate of the altimeter bias with the opposite sign, since the difference computations is a difference in sea surface heights.

The error budget for the Galveston Bay calibration is summarized in Table 5.12. This error budget is based on all previous discussion of

corrections and the error budget at Harvest Platform [Christensen, 1994].

Error Group	Error Source	Variable name	Fixed Error (mm)	Variable Error (mm)
Radial Orbit	Total	ε_{orbit}	20	10
Altimetry	altimeter noise	ε_{alt}	-	20
Altimetry	instrument	ε_{instr}	11	20
Altimetry	dry troposphere corr.	ε_{dry}	2	7
Altimetry	wet troposphere corr.	ε_{wet}	5	18
Altimetry	ionosphere corr.	ε_{ion}	10	5
Altimetry	em bias corr.	ε_{embias}	10	14
Altimetry	solid Earth tide	ε_{solid}	-	-
Altimetry	Total (RSS)	ε_{altcor}	27	38
In Situ	GPS survey bench mark	ε_{mark1}	20	10
In Situ	Tide gauge survey	$\varepsilon_{survey1}$	5	5
In Situ	Tide gauge noise	ε_{anom1}	-	10
In Situ	Tide gauge bias	$\varepsilon_{dgeoid1}$	0	-
In Situ	sea surface anomaly	$\varepsilon_{\Delta anom1}$	15	25
In Situ	geoid gradient	$\varepsilon_{\Delta geoid1}$	29	5
In Situ	Total (RSS)	-	38	29
Total error	-		46	47
RSS	fixed + variable			65
-	altimeter bias	bias	1	65

Table 5.12 : Error budget for TOPEX altimeter calibration and altimeter bias estimate for Galveston Bay (all units in mm)

The total uncertainty is 6.5 cm, which is mainly due to the spatial interpolation of the water level anomaly, the uncertainty in the absolute geoid profile and uncertainty due to retracking of the altimeter waveform.

The results of the direct and non-direct overflights are shown in Figure 5-11. From this figure, a large drift in the altimeter bias can be observed for the Galveston Bay estimate compared to the results at Harvest Platform. As mentioned before, large drifts in the tide gauges at Galveston bay may exist (see Section 5.2.9) and the observed large drift is drifting in the same direction as the tide gauges. By applying the internal calibration [Hayne, 1994a], the altimeter drift increases even further, from 8 to 9 mm / year. The reported uncertainties for the biases and drifts in Figure 5-11 are formal errors based

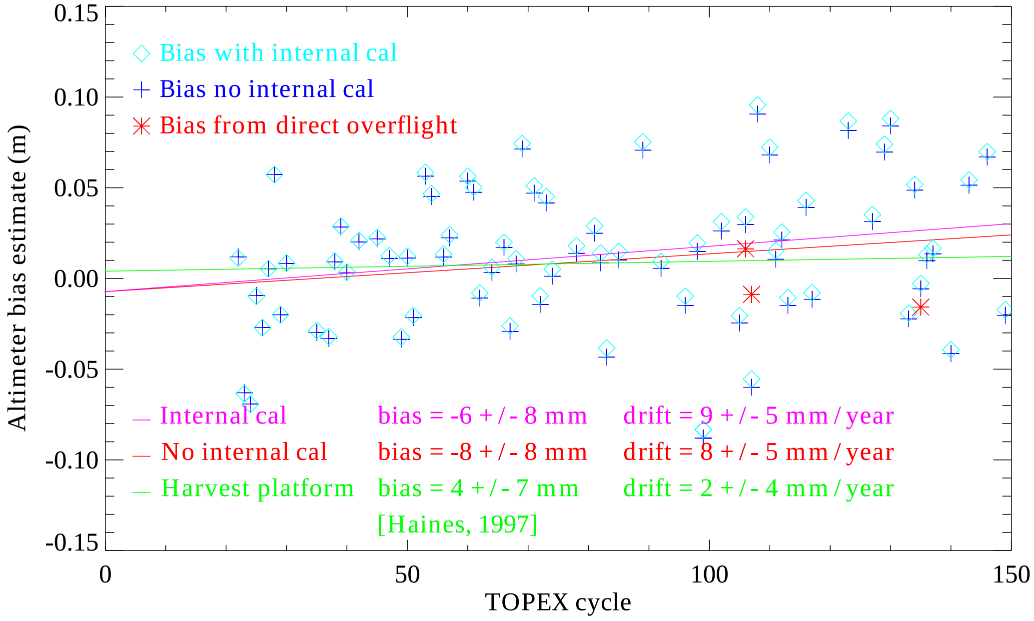

Figure 5-11 : TOPEX altimeter bias estimate over Galveston bay for cycles 22-152 (April 1993 - August 1996) on the covariance of the straight line fit to the bias estimates scale with an RMS about the mean of 4.5 cm. The overall mean estimate of 1 mm is within the uncertainty of the bias reported from Harvest platform [Haines, personal communication, 1997]. Another measure of the accuracy of the altimeter bias estimate is illustrated by the comparison of the direct overflight estimates and the non-direct estimate. From Figure 5-11, it is clear that difference between the two procedures can be as much as 5 cm (cycle 106). The direct overflight is considered more accurate, which is corroborated by Figure 5-11 as well.

In conclusion, the TOPEX altimeter can be calibrated over Galveston Bay using direct overflights. For non-direct overflights, the uncertainty of the altimeter bias is 6.5 cm, which is insufficient for cm level calibration. Furthermore, long term monitoring of the altimeter system over Galveston Bay is limited by possible large drifts in the tide gauge systems used at Galveston Bay.

5.3 : Relative Calibration from global dual crossovers

Once the absolute bias has been determined for one satellite altimeter, the relative bias can be computed for other altimeters using dual-satellite crossover measurements. In this section, the relative calibration for the satellite altimeters GEOS-3, SEASAT, GEOSAT, ERS-1 and ERS-2 will be discussed.

The dual crossover measurements for each satellite were computed using the mean T/P mean sea surface (for details see Chapter 4). Next, the dual crossover measurements were averaged into 120 second intervals. The noise on the dual crossover measurements was reduced, and a more even distribution was created by this averaging process. This was especially necessary at high latitudes, where a clustering of dual crossover measurements occurs due to the ground track pattern of T/P. Using the Kalman filter described in Chapter 4, the relative altimeter bias was then estimated simultaneously with a once per revolution radial orbit error. Finally, the estimated relative biases were averaged into daily values, which will be reported in the next subsections. It should be noted that the relative bias estimates do include secular trends (i.e. sea level rise) and inter annual oceanographic signals.

In the next section, a short description will be given of the altimeter data used, and the relative calibration result will be translated into an absolute altimeter bias assuming an absolute altimeter bias of 0.4 cm for the TOPEX altimeter [B. Haines, personal communication,1996]. The uncertainty reported is based on the RMS of the daily estimates of the relative bias over time life span of each altimeter mission.

5.3.1 : GEOS-3

The relative bias for GEOS-3 was calculated for the period April 1977 to December 1977. The altimeter data was extracted from the 3.5 year GEOS-3 altimeter data set [Agreen, 1980]. Unfortunately, the ionospheric and tropospheric corrections were not provided on this data but applied to the altimeter data. Hence, these corrections could not be replaced on the data. Otherwise, the following models and corrections were applied to the ocean data:

- CSR JGM-3 orbit
- TOPEX/POSEIDON solid earth tide [Cartwright, 1971, Cartwright, 1973]
- TOPEX/POSEIDON pole tide [Wahr, 1985]
- CSR3.0 tide model [Eanes, 1995b]
- Sea State Bias (SSB) correction according to: $SSB = 0.050 \times SWH$

The result of the relative altimeter calibration for GEOS-3 is shown in Figure 5-12. The relative bias of GEOS-3 shows a periodicity of about 109 days with an amplitude of 30 cm. This period is half the nodal period of the

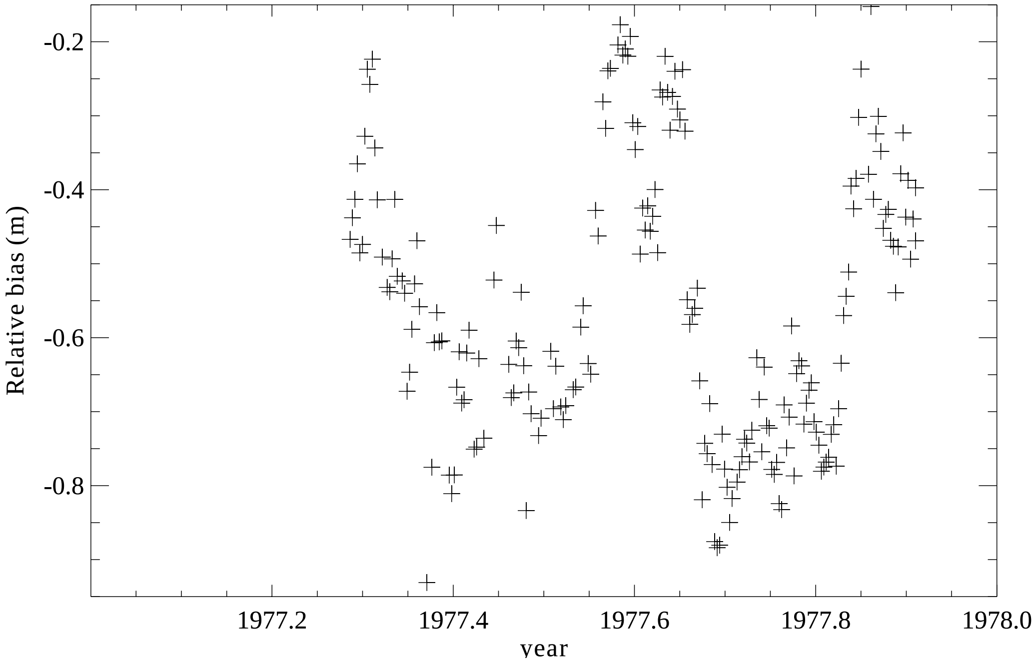

Figure 5-12 : GEOS-3 relative bias with respect to TOPEX/POSEIDON for April 1977 to December1977

orbital plane of GEOS-3 with respect to the sun. One explanation for this periodicity in the relative bias may be the temperature changes due to the eclipsing of the satellite on the satellite altimeter. The overall mean of the relative bias is -55.0 ±19.0 cm, which means that the altimeter is measuring long with respect to T/P. The absolute calibration suggested an altimeter bias of -5.61 ±0.16 m [Martin, 1981]. The data used in this research already had a bias applied of -5.3 meters [Martin, 1981]. Hence, the new altimeter bias for GEOS-3 can be calculated by adding the relative bias to -5.3 m, which results in -5.85 m. Correcting for TOPEX altimeter bias results into an altimeter bias of -5.81 ±0.19 m.

5.3.2 : SEASAT

The relative bias for SEASAT was computed during the 17 day repeat mission from dual crossover measurements over the ocean. The SEASAT altimeter data were extracted from the SEASAT GDR [Lorell, 1980] and the following models and corrections were applied to the uncorrected altimeter data:

- CSR JGM-3 orbit
- IRI90 ionospheric model [Bilitza, 1990]
- TOPEX/POSEIDON solid earth tide [Cartwright, 1971, Cartwright, 1973]
- TOPEX/POSEIDON pole tide [Wahr, 1985]
- CSR3.0 tide model [Eanes, 1995b]
- SSB correction according to: $SSB = 0.0 \times SWH$
- Dry and wet tropospheric correction from GDR [Lorell, 1980]

The very short time series of the relative bias is shown in Figure 5-13. The average relative altimeter bias is 34 ± 3 cm, which means that the SEASAT altimeter is measuring long compared to the T/P. This result does not agree with the absolute calibration over Bermuda, which reported an absolute bias of 0 ± 7 cm [Kolenkiewicz et al., 1982]. The relative result seems to agree over the Caspian Sea but further study is necessary to validate the observed relative bias. Based on this result the SEASAT absolute altimeter bias would

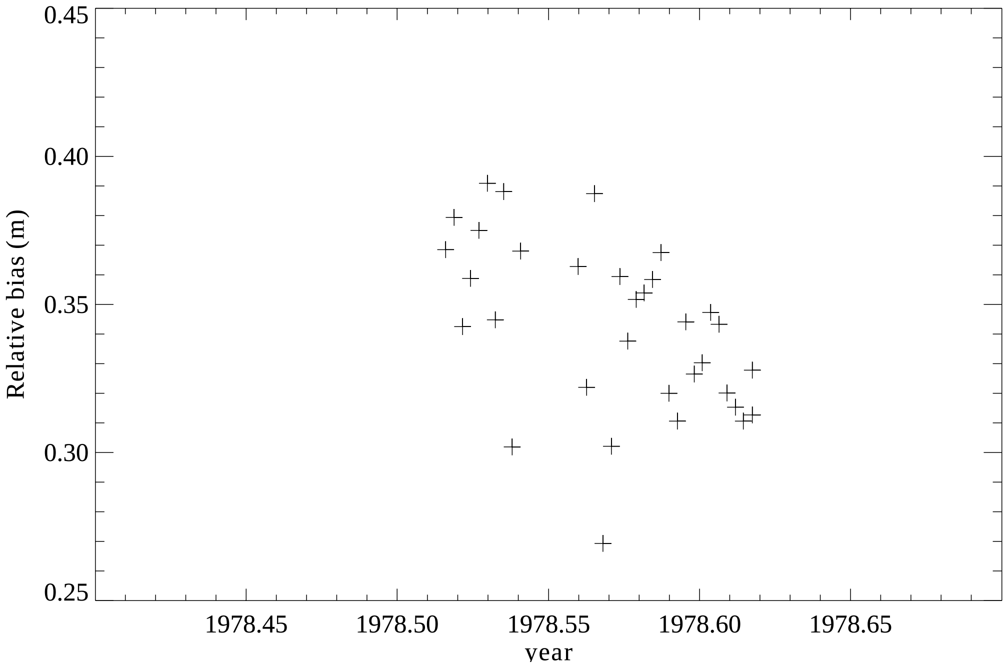

Figure 5-13 : SEASAT relative bias with respect to TOPEX for August 1978

be 34 ±3 cm.

5.3.3 : GEOSAT

The relative bias is computed for the GM and ERM missions separately. The ERM GEOSAT altimeter data were extracted from the TEG-2 GDR distribution [Cheney, 1991]. The following models and corrections were applied to the uncorrected altimeter data

- CSR JGM-3 orbit [Gabor, 1995]
- IRI90 ionospheric model [Bilitza, 1990]
- ECMWF Dry and Wet tropospheric correction, (see Chapter 3)
- TOPEX/POSEIDON solid earth tide [Cartwright, 1971, Cartwright, 1973]

- TOPEX/POSEIDON pole tide [Wahr, 1985]
- CSR3.0 tide model [Eanes, 1995b]
- SSB correction according to: $SSB = 0.025 \times SWH$ [Gabor,1995]
- Constant altimeter time tag bias of 4.75 msec [Gabor, 1995]

The GM GDR altimeter data was provided by NOAA [Lillibridge, personal communication,1997]. All corrections and models, described above for the ERM mission, were applied, except for the orbit which was calculated with the JGM-3 gravity field by Goddard Space Flight Center. Furthermore, no altimeter time tag bias was applied.

The result for the relative bias is shown in Figure 5-14. In the figure is also shown the internal calibration and oscillator drift [Wagner, 1992] adjusted relative to the time series such that it overlays the series. From Figure 5-14, it is clear that the relative bias series agrees very well with the internal calibration for the ERM mission but not for the GM mission. More research is necessary for the GM data to investigate the discrepancy. The mean relative altimeter bias for the GM mission is 12.2 ±1.6 cm, and for the ERM mission 12.0 ±1.4 cm, which means the altimeter is measuring long. Corrected for the TOPEX absolute bias, the altimeter bias for the GM mission is 11.8 ±1.6 cm, and for the ERM mission, 11.6 ±1.4 cm. This result is in

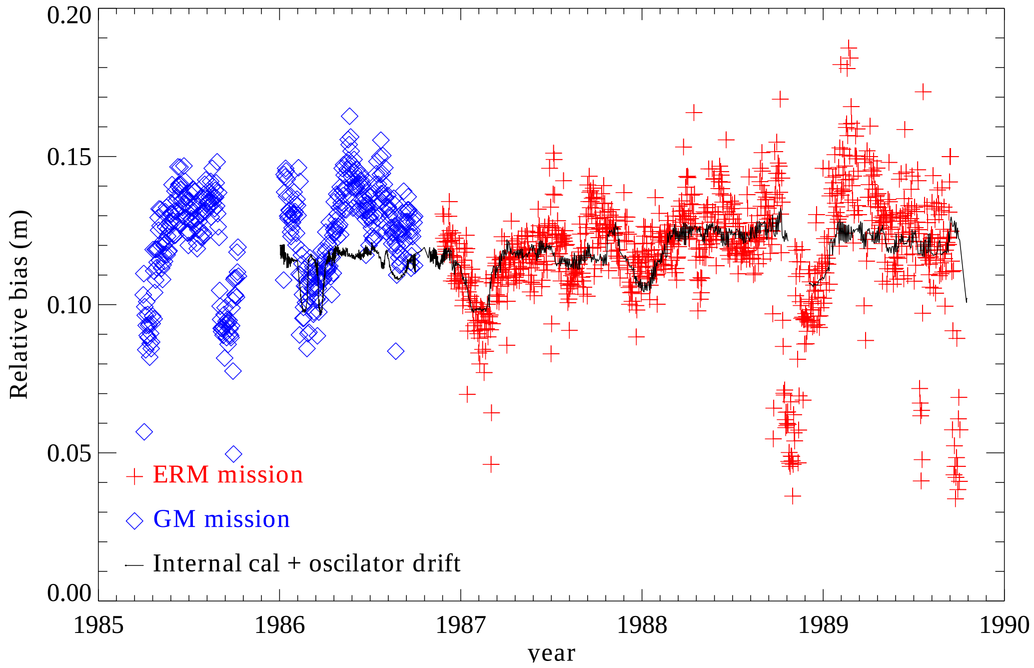

Figure 5-14 : GEOSAT relative bias with respect to TOPEX for GM and ERM missions

close agreement with the altimeter bias computed for the ERM mission by Guman, [1997]

5.3.4 : ERS-1

The relative bias for ERS-1 was computed for phases A, B, C, D, E, F and part of phase G. The altimeter data were extracted from OPR files distributed by CERSAT [CLS, 1994]. The following models and corrections were applied to the uncorrected altimeter data

- OPR orbit [CLS, 1994]
- IRI95 ionospheric model [Bilitza, 1995]

- ECMWF Dry tropospheric correction, (see Chapter 3)
- Calibrated ATSR wet tropospheric correction [CLS, 1993, Eymard, 1995] if not available, ECMWF wet tropospheric correction, (see Chapter 3)
- TOPEX/POSEIDON solid earth tide [Cartwright, 1971, Cartwright, 1973]
- TOPEX/POSEIDON pole tide [Wahr, 1985]
- CSR3.0 tide model [Eanes, 1995b]
- SSB correction according to: $SSB = 0.035 \times SWH$ in addition to the SSB on OPR [CLS, 1994]

The OPR orbits were used because of consistency considerations. The result for the relative bias for all phase is shown in Figure 5-15. In this plot is also

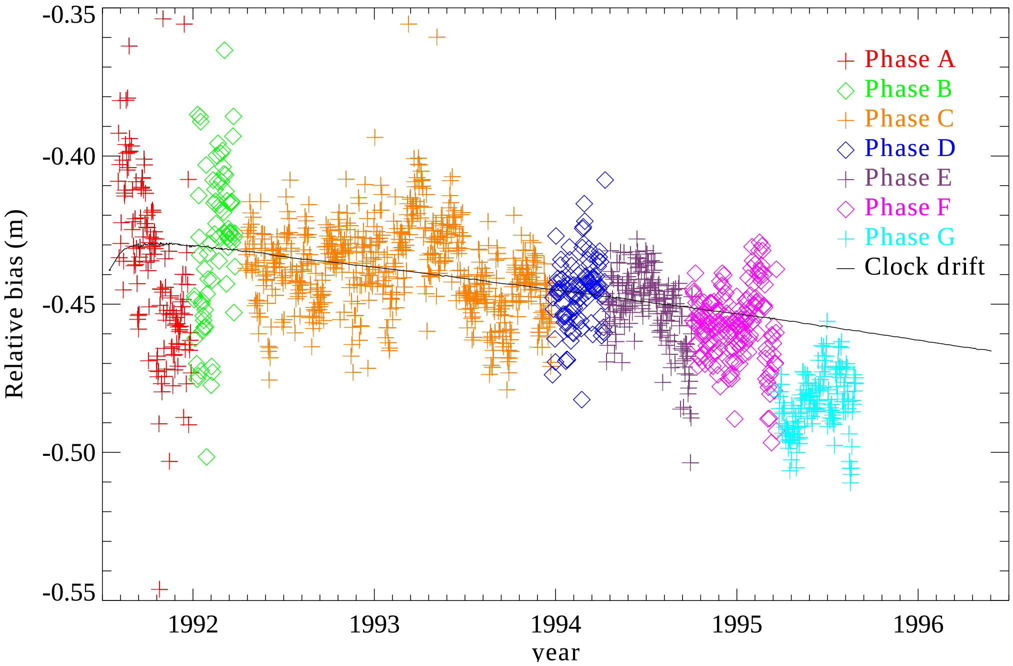

Figure 5-15 : ERS-1 relative bias with respect to TOPEX/POSEIDON for phases A, B, C, D, E, F and G shown the resulting altimeter drift due to the Ultra Stable Oscillator (USO) drift [Loial, 1997], adjusted such that it overlays the relative bias estimates. From this plot, it is clear that a large part of the secular trend in the relative bias estimate can be explained by the USO drift. The documentation, however, suggests that this correction was applied to the altimeter data [CLS, 1994]. Phases A and B show anomalistic behavior which may be explained because of the meter level radial orbit errors in the OPR orbit for these Phases. The offset in phase G was introduced because the additional em bias correction estimated from UTOPIA was not applied to the altimeter data. Inclusion of this correction would line up this phase with the other phases. The average relative altimeter bias for ERS-1 is -44.8 ±2 cm, which means the altimeter is measuring short with respect to T/P. Corrected for the TOPEX altimeter bias this would result in an absolute bias for ERS-1 of -44.4 ±2 cm. This number is in close agreement with the absolute calibration -41.0 ±5 cm [Francis, 1993]. It should be noted that the absolute bias estimate includes the USO, drift which could explain the difference.

5.3.5 : ERS-2

The relative bias for ERS-2 was computed for the first six 35-day repeat cycles of the ERS-2 mission. The altimeter data were extracted from the ERS-2 OPR distributed by CERSAT [CLS, 1995]. The following models and cor-

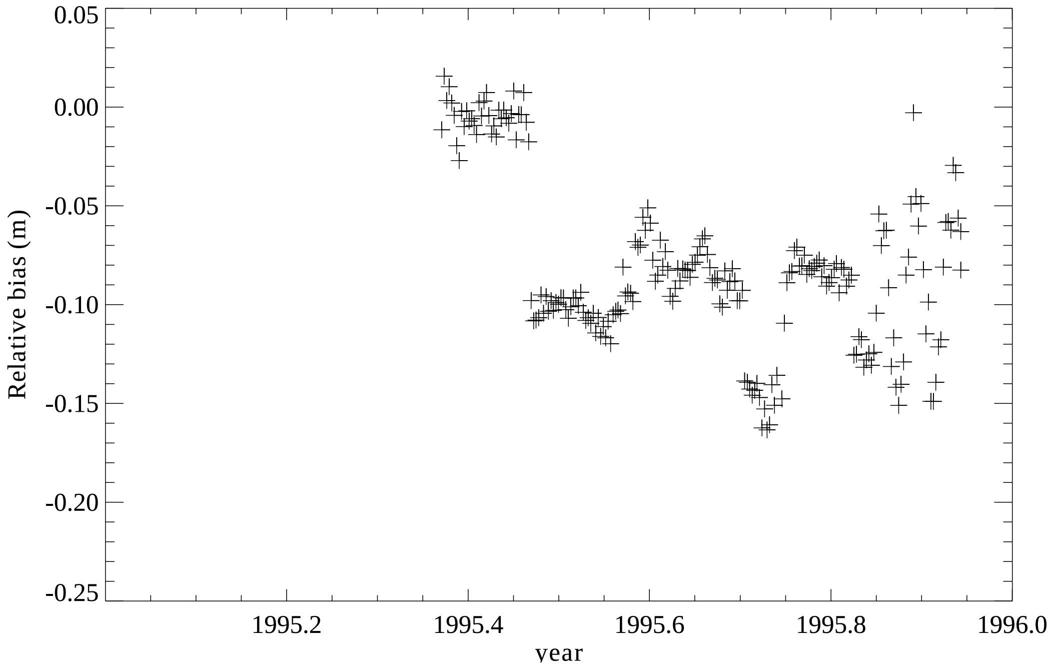

Figure 5-16 : ERS-2 relative bias with respect to TOPEX/POSEIDON for cycles 1-6 of the 35-day repeat mission

rections were applied to the uncorrected altimeter data

- OPR orbit [CLS, 1995]
- IRI95 ionospheric model [Bilitza, 1995]
- ECMWF Dry tropospheric correction, (see Chapter 3)
- Calibrated ATSR wet tropospheric correction [CLS, 1995] if not available, ECMWF wet tropospheric correction, see (Chapter 3)
- TOPEX/POSEIDON solid earth tide [Cartwright, 1971, Cartwright, 1973]
- TOPEX/POSEIDON pole tide [Wahr, 1985]
- CSR3.0 tide model [Eanes, 1995b]
- OPR SSB correction [CLS, 1995]

The result for the relative bias is shown in Figure 5-16. From this plot it is clear that different populations exist, which coincide with different releases of the data. Hopefully, more consistent results will be obtained with future releases of the data. Based on these results, the mean relative bias is 8.0 ±4 cm.

5.4 : Relative Calibration over the Great Lakes from dual crossovers for GEOSAT

In order to separate the sea level rise signal and the true relative altimeter bias, an independent determination of the relative altimeter bias is necessary over non-ocean water surfaces with measured water level variations. This independent determination of the relative altimeter bias is illustrated for GEOSAT over the Great Lakes by using dual crossover measurements with the T/P mean sea surface.

The Great Lakes were chosen because the surface area is large enough for altimeters to lock on, and long term tide gauge data exists for the GEOSAT and T/P mission intervals. Unfortunately, systematic biases and drifts [Chambers, 1997] exist in tide gauge data which corrupt the determination of the relative bias between GEOSAT and T/P over the Great Lakes. The data coverage for T/P and GEOSAT is shown in Figure 5-17. For most lakes except Lake Huron, the dual crossover locations between T/P and GEOSAT are not favorable because most locations are near the coast or at the end of a data pass over the lake.

The ERM GEOSAT altimeter data were extracted from the TEG-2 GDR distribution [Cheney, 1991]. For this research, the 10hz data was used instead of the 1hz data. The following models and corrections were applied to the uncorrected altimeter data

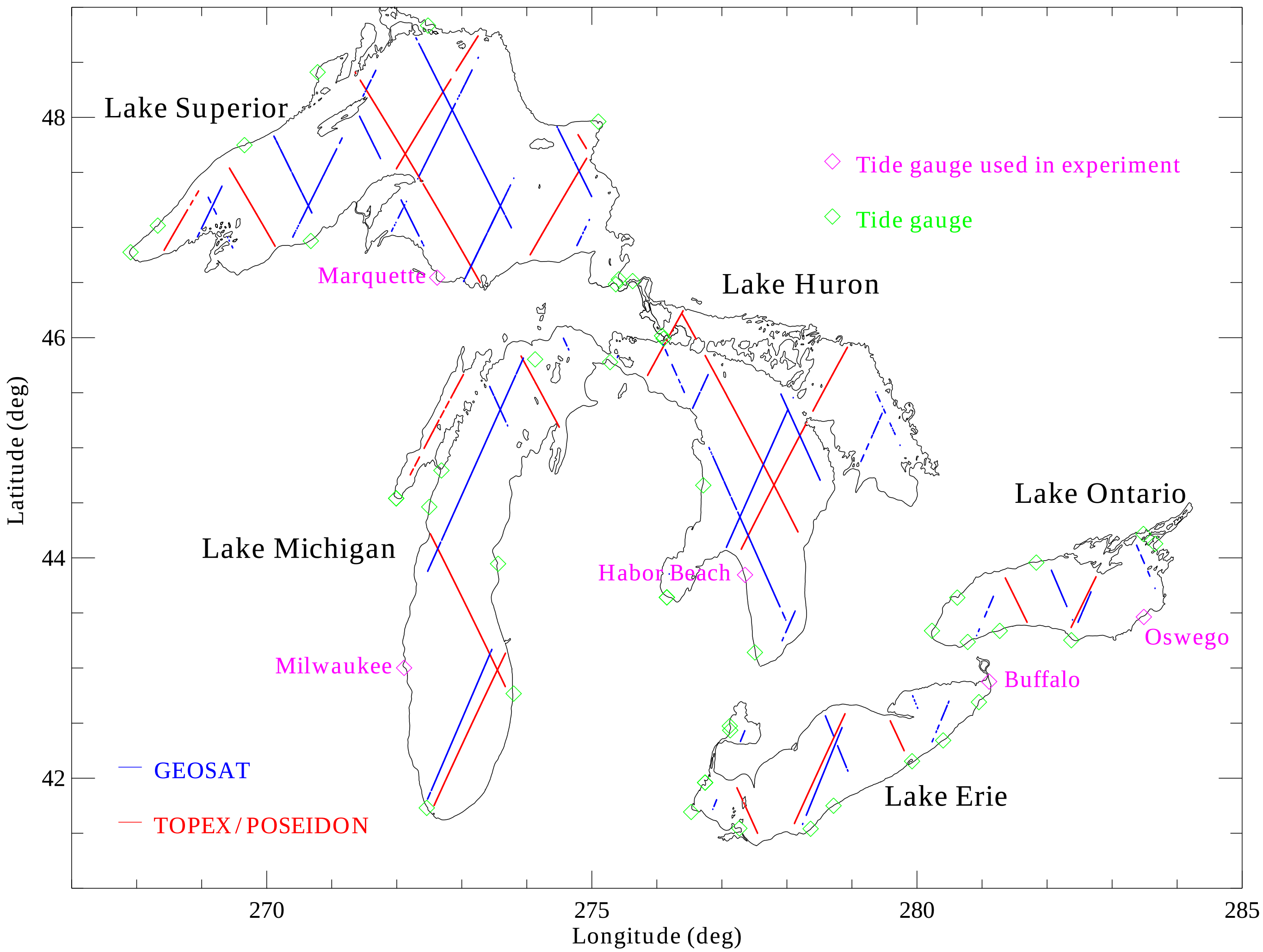

Figure 5-17 : Altimeter data coverage for TOPEX/POSEIDON and GEOSAT over the Great Lakes including tide gauge locations

- CSR JGM-3 orbit [Gabor, 1995]
- IRI90 ionospheric model [Bilitza, 1990]
- ECMWF Dry and Wet tropospheric correction, (see Chapter 3)
- TOPEX/POSEIDON solid earth tide [Cartwright, 1971, Cartwright, 1973]
- TOPEX/POSEIDON pole tide [Wahr, 1985]
- em bias correction according to: $embias = 0.025 \times SWH$ [Gabor,1995]
- Constant altimeter time tag bias of 4.75 msec [Gabor, 1995]
- Empirical determined radial orbit error correction, (see Chapter 4)

The GM GDR altimeter data was provided by NOAA [Lillibridge, personal communication, 1997] and the 10 Hz altimeter data was also used in the analysis. All corrections and models, described above for the ERM mission, were applied except for the orbit which was calculated with the JGM-3 gravity field by Goddard Space Flight Center. Furthermore, no altimeter time tag bias was applied.

The T/P altimeter data was extracted from the Merged GDR (MGDR) [Benada, 1993]. As with GEOSAT, the 10 Hz altimeter data was used instead of the 1 Hz data. All recommended corrections on the MGDR were applied to the uncorrected altimeter measurements, except for the ocean tide and inverted barometer. The wet tropospheric and the ionospheric correction were extrapolated from the middle of the lakes to the coast because many wet tropospheric and ionospheric corrections were not reliable in the coastal regions. The orbit was replaced with CSR's JGM-3 orbit instead of the MGDR orbit, and a correction was made for the erroneous oscillator drift applied to the MGDR data [Calahan, personal communication, 1996].

For the dual crossover computation, the mean lake surface height was computed from T/P data which had been corrected with the lakes levels observed by one tide gauge for each lake. The lake level data were obtained from the Great Lakes Section, Ocean and Lake Levels Division, NOS. All tide gauge data are referenced to one common datum: the International Great Lakes datum [Morris, 1994b]. This datum will serve as the reference for the relative altimeter bias determination instead of the reference ellipsoid. Only one tide gauge per lake was used to insure that no additional systematic errors would be introduced by the combination of multiple tide gauges for one lake. The disadvantage of this approach is that lake level variations near the coast do not represent the mean lake level variation and additional noise is added to the residuals. However, it is assumed that these variations are random and not systematic. The tide gauges used for this research are shown in Figure 5-17. Lake Ontario and Lake Erie were excluded from this analysis because not enough data for GEOSAT were available to obtain statistically significant results.

The relative bias was computed in two ways. First, the mean profile was computed for the GEOSAT data, corrected with the same tide gauge data as T/P. Subsequently, the mean GEOSAT-profile was crossed with the mean TOPEX-profile and the relative bias was determined. The advantage of this method is that most random errors have averaged out. For the second approach, all available data for GEOSAT (GM + ERM) corrected with the same tide gauge data as T/P was crossed with the mean TOPEX profile. After computation of all the dual crossover measurements, the average relative bias was determined per lake. Unfortunately, only very few dual crossover measurements were available, which ruled out an analysis of the crossover residual time series. The results of the relative calibration have been summarized in Table 5.13.The first observation that can be made from this table is that the relative bias for Lake Superior does not agree with the results for lake Huron and Michigan. The inconsistent result was obtained for all tide gauges available in Lake Superior, which suggest a systematic change in the tide gauges between 1989 and 1992, although no direct evidence could be found to support this supposition. Therefore, the results for Lake Superior were excluded from the analysis.

The results for Lake Huron and Lake Michigan are consistent with the relative bias analysis over the open ocean (see Section 5.3.3) and also agree with the relative bias determination by Guman, [1997]. The uncertainties reported in the Table 5.13 are one sigma values based on the RMS of all the

Lake	Relative bias mean profiles crossovers (mm)	Relative bias individual crossovers (mm)
Huron	127.6 ±10	135.0 ±118
Michigan	130.6 ±24	112.0 ±205
Superior	222.5 ±4	202.0 ±182
Combined (Superior excluded)	129.0 ±16	126.0 ±157

Table 5.13 : Relative altimeter bias results for GEOSAT with respect to TOPEX/POSEIDON over the Great Lakes

relative bias estimates. No formal uncertainties were computed due to the small number of samples on which the relative bias estimates are based.

The effect of postglacial rebound was neglected because the total effect over 5 years (mean time interval between T/P and GEOSAT) for the tide gauges of Lake Huron and Lake Michigan is less than 1.5 mm. For postglacial rebound rate see the next section.

5.5 : Altimeter drift determination over the Great Lakes for the TOPEX altimeter

In this section, the determination of the relative drift of the TOPEX altimeter bias will be illustrated over the Great Lakes. The Great Lakes provide an independent determination of the overall system drift without the effect of sea level rise. However, other natural drifts do occur in the Great

Lake (e.g. postglacial rebound) which need to be taken into account for the TOPEX altimeter bias drift determination. Furthermore, the same TOPEX altimeter and tide gauge data was used as in Section 5.4. For a complete description of all corrections to the altimeter data, see Section 5.4 as well. Finally, the effect of post glacial rebound on the relative bias will be considered and a comparison with the TOPEX internal calibration [Hayne, 1994a] will be made.

The relative altimeter bias drift is computed per pass by subtracting the mean sea surface determined from colinear track analysis, from each individual overflight for that pass. The bias residual is then averaged along the ground track for each overflight. All average bias residuals with an RMS about the mean greater than 20 cm and overflights with less than 20 good altimeter data points were edited. In the next step, all altimeter biases are averaged per cycle for all available passes per lake. Finally, the altimeter bias residuals for all lakes are combined per cycle. Lake Erie was not included because of the large relative drift observed which is due to large spatial variations of water levels in Lake Erie [Morris, 1994b]

The result of the combined altimeter bias residuals is shown in Figure 5-18. In this figure, two altimeter bias residual time series are shown. The first time series has no postglacial rebound correction, and the second time series has the postglacial rebound applied. The postglacial rebound values used

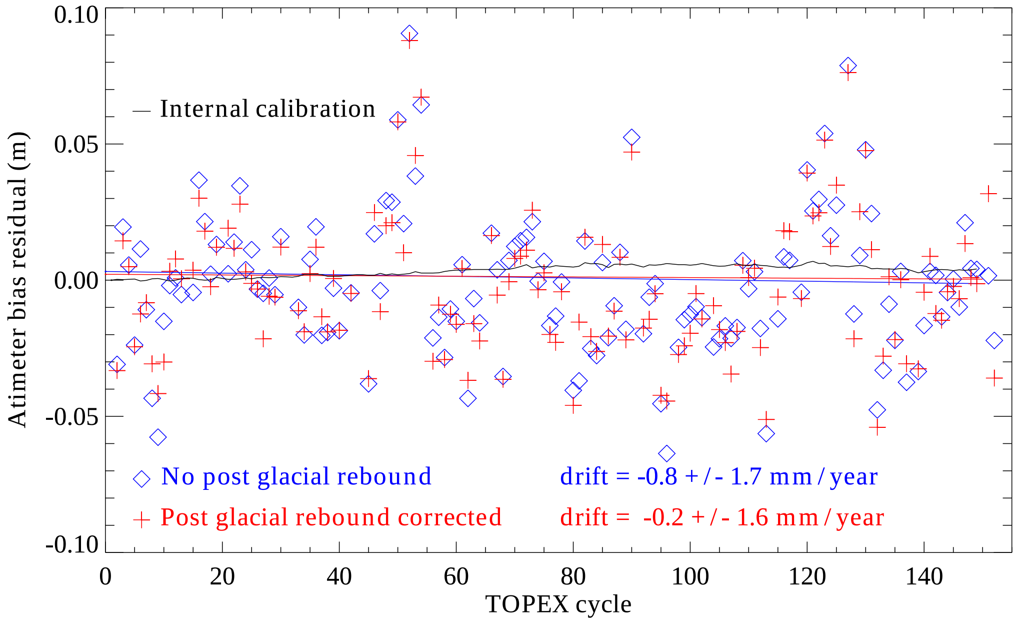

Figure 5-18 : TOPEX altimeter drift over the Great Lakes for cycles 1-155

for the Great Lakes were based on the ICE4G model [Peltier, 1994; Peltier, 1995] and have been tabulated for each tide gauge in Table 5.14. The altime-

Lake	Tide gauge location	radial crust drift (mm/year)	Effect on water level including geoid change (mm/year)
Ontario	Oswego, NY	0.0213	0.0798
Erie	Buffalo, NY	-0.3574	0.4137
Huron	Harbor Beach, MI	0.2539	-0.1308
Michigan	Milwaukee, WI	-0.2536	0.3427
Superior	Marquette, MI	1.0322	-0.7679

Table 5.14 : Post glacial rebound drifts for tide gauges in the Great lakes based on Peltier, 1994 and Peltier,1995

ter bias residuals were corrected by subtracting for each lake the last column of this table from the uncorrected altimeter bias residuals. After this correction, all altimeter bias residuals were once again combined for all lakes except Lake Erie. The individual TOPEX altimeter bias drift results for each lake have been tabulated in Table 5.15. From this table it is clear that applying post glacial rebound affects the altimeter bias drift by 0.6 mm/year, reducing the drift to -0.2 mm year and the formal uncertainty marginally improved. Another observation can be made that the postglacial rebound effect on water level (last column Table 5.14), which has the opposite effect on the altimeter bias, has the same drift direction of the observed drift in the altimeter (Table 5.15).

Lake	TOPEX altimeter bias drift with no correction (mm/year)	TOPEX altimeter bias drift with post glacial rebound correction (mm/year)
Ontario	-0.1 ±2.9	-0.0 ±2.9
Erie	-10.9 ±6.7	-10.5 ±6.7
Huron	3.2 ±2.5	3.1 ±2.5
Michigan	-3.4 ±2.9	-3.0 ±2.9
Superior	1.1 ±2.7	0.3 ±2.7
combined (Erie excluded)	-0.8 ±1.7	-0.2 ±1.6

Table 5.15 : TOPEX altimeter bias drifts over the Great Lakes for repeat cycles 1-155

The overall result for the altimeter drift over the Great Lakes of -0.2 mm/year is consistent with the reported altimeter bias drift by Chambers, [1997] of 1-2 ±1.5 mm/year, from a similar analysis using Pacific tide gauges. Applying the internal calibration [Hayne, 1994a] (see Figure 5-18) would increase the altimeter bias drift to 1.1 mm/year.