3820

SEA AND LAND LEVEL CHANGES IN HAWAI‘I

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Abstract

An overall rise in sea level has been recorded by all Hawaii tide gauges over the last century; however, the rates vary considerably between islands. In particular, the sea level rise rate is higher at Hilo (3.3 mm/yr) on the island of Hawaii at the southeast end of the island chain, than at Honolulu (1.4 mm/yr) on the island of Oahu about 335 km to the northwest. This difference has been attributed to island subsidence associated with active volcanism at the southeast end of the Hawaiian ridge. Continuous GPS measurements collected over the past 5 years are used to examine the relative vertical movements of the main Hawaiian Islands in an attempt to reconcile the observed difference in sea level rates. The rates of vertical crustal motion are estimated in a reference frame realized using a network of 30 GPS stations spread across the Pacific region. Although absolute vertical motion rates are not yet obtainable, the differential rates of vertical crustal motion are determined to within approximately ± 0.5 mm/yr at the 95% confidence level. The geodetic measurements indicate that vertical velocities within the main Hawaiian Islands are similar. Hilo is subsiding relative to Honolulu, but the difference in rates is only 0.5 mm/yr, considerably less than the 1.9 mm/yr difference suggested by tide gauge observations. Historical hydrographic data suggest that steric sea level trends since 1945 vary considerably along the Hawaiian Ridge, with rates increasing from the northwest to the southeast. It is suggested that the difference in Hilo-Honolulu sea level rise rate is due in part to upper ocean thermal variations. The notion that oceanographic effects influence differential rates of sea level rise at Hawaii challenges previous

interpretations based solely on variable crustal motion. The absolute rate of vertical crustal motion at Honolulu has been constrained by coral-age data to be less than 0.1 mm/yr since the last interglacial. A reanalysis of the age-depth relationship obtained from submerged Holocene corals recovered from the Hilo drill hole is consistent with an absolute rate of crustal subsidence anywhere between - 2.7 and 0 mm/yr. Given this wide range of velocities, the differential Holocene subsidence rates from coral data do not conflict with our reinterpretation of the tide gauge data.

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Chapter 1 Introduction

Tide gauges have recorded sea level variations at the Hawaiian Islands since the time of the Hawaiian monarchy in the late 1800s. The tide gauge time series from Honolulu Harbor is one of the longest continuous sea level records in the Pacific. Moore (1970) compared trends in tide gauge records throughout the northeast Pacific for the period 1905 to 1963. This comparison gave a sea level rise rate of approximately 2 mm/yr at the Honolulu tide gauge, which was found to be similar to sea level rates observed at other Pacific tide gauges, such as San Francisco, San Diego, and Seattle, as well as Boston and New York on the Atlantic coast. Because of this consistency, the 2 mm/yr Honolulu rate was considered to be representative of the global eustatic sea level rise rate (*e.g.* Gornitz *et al.*, 1982). Thus, Oahu was considered nearly stable in terms of vertical lithospheric motion. However, significantly different sea level rise rates were observed at other tide gauges within the Hawaiian Islands. In particular, the Hilo station data suggested that the island of Hawaii was subsiding relative to Oahu. Moore (1970) attributed the differential subsidence rates to loading and flexure of the lithosphere due to active volcanism on the island of Hawaii, resulting in subsidence southeast of Oahu and uplift northwest of Oahu. This model partially explained the observed differences in sea level rise between Hawaii and Oahu; however, Moore (1970) found that the subsidence inferred from the sea level rise rates for Hawaii did not agree with the subsidence rates predicted by volcanic loading.

Moore (1987) reanalyzed Hawaiian sea level change and subsidence scenarios using an additional seventeen years of tide gauge data and determined a sea level rise rate of 1.2 mm/yr at Honolulu. This revised figure was comparable to global sea level rise estimates of 1.0 mm/yr (Gornitz *et al.*, 1982) to 1.5 mm/yr (Barnett, 1983). Relative to the "stable" Honolulu station, a revised estimate for subsidence at Hilo was -2.4 mm/yr (Moore, 1987). An examination of tide gauge data including data through 2002 indicates a sea level rise rate difference closer to 1.9 mm/yr (here and other sources).

The island subsidence rates have been investigated on geologic time scales using isotopic dates for submerged corals and from corals recovered from cores drilled through a sedimentary sequence located near Hilo on the Island of Hawaii. The long term subsidence rate for the island of Hawaii is calculated to be approximately -2.5 mm/yr for the last 500 thousand years (Ka) based on coral dates and depths of drowned reefs located off the northwest coast of Hawaii (Moore and Clague, 1992). Given the motion of Hawaii relative to the Hawaiian hot spot and the related evolution in volcanic activity, it is possible that the vertical velocity field within and near the Big Island is laterally variable. Thus, it is not clear what the Moore and Clague (1992) study implies for the subsidence history near Hilo. Isotopic dates for coral fragments from the Hilo cores are more pertinent to this study. Based on these data, Moore *et al.* (1996) infer a mean subsidence rate of approximately -2.2 mm/yr over the past 10 Ka. We will argue that the observations are consistent with a wide range of possible subsidence rates.

Because Oahu has been characterized as tectonically stable, the island has been used as a local and global datum for sea level change (*e.g.* Ku *et al.*, 1974; Moore, 1987; Stearns, 1978; Veeh, 1966). However, in more recent analyses, geophysical and coral evidence have suggested that the island of Oahu has been rising slowly for the last 500 Ka (*e.g.* Jones, 1995; Jones *et al.*, 1993; Muhs and Szabo, 1994; Sherman *et al.*, 1999; Szabo *et al.*, 1994; Watts and ten Brink, 1989). Based on the dates of emerged corals, Sherman *et al.* (1999) have estimated an uplift rate of 0.05-0.06 mm/yr.

The Pacific GPS Facility (PGF) at the University of Hawaii at Manoa currently maintains a network of continuous GPS (CGPS) stations throughout the Hawaiian Islands. The time series are of sufficient duration to assess land motion differences between islands. The Honolulu CGPS and tide gauge are co-located. The Hilo CGPS, located ~500 m from the tide gauge, has been tied to the tide gauge benchmark array using campaign GPS and repeated spirit leveling. We have examined the relative land motion at these two sites to determine whether the tide gauge trend differences can be attributed to differential land motion (*i.e.*, Is the island of Hawaii sinking relative to Oahu?) or other causes. We find that the GPS rates do show that Hawaii is sinking relative to Oahu, but at a much lower rate than previous estimates based on tide gauges and the dating of corals.

Analyses that attribute the tide gauge rate differential between Hilo and Honolulu entirely to land motion imply that oceanographic contributions are negligible. Specifically, sea level changes due to thermal expansion are assumed to be similar at Hilo and Honolulu due to their proximity (335 km). However, World Ocean Atlas (WOA) data (Levitus *et al.*, 2000) for the Hawaii region suggests that local variations in steric sea level trends may be large enough to contribute to the observed sea level trend differences. Although the WOA data does not precisely differentiate between the locations of Hilo and Honolulu, there is a strong variation of the trend along the Hawaiian Ridge that is part of a larger-scale oceanic feature. This local gradient appeared in the recent WOA analysis by Cabanes *et al.* (2001) That considered the importance of steric trends on a global scale in relation to tide gauge measurements. The WOA data suggest that steric effects may have caused as much as a 0.7 mm/yr difference between the Hilo and Honolulu sites over the past 50 years, and thus relative steric effects should be included in the assessment of Hawaii tide gauge data.

We emphasize that rate differences between sites, and not the absolute rates themselves, are the focus of this study. For example, tide gauges measure relative rates of sea level change (ζ_{TG}), which can be expressed by:

$$\zeta_{TG} = \zeta_{steric} + \zeta_{eustatic} + \zeta_{land} \qquad \text{(Eq. 1)}$$

where ζ_{steric} represents volumetric changes primarily associated with thermal expansion, $\zeta_{eustatic}$ represents eustatic (regionally common mode) changes in ocean mass associated with storage of water on land versus the ocean, and ζ_{land} represents local land elevation changes associated with tectonic and other geophysical effects. We consider steric changes to represent the redistribution of heat owing to ocean circulation variations, as well as to changes in heat content due to surface heat fluxes. Eustatic effects are very nearly identical at Honolulu and Hilo and the rate difference can thus be expressed by:

$$\Delta\zeta_{Hilo-Hono} = \Delta\zeta_{steric} + \Delta\zeta_{land} \qquad \text{(Eq. 2)}$$

Quantifying the individual terms of equations 1 and 2 has proven to be difficult for a number of reasons, particularly because the magnitudes of these components are only marginally within the resolving power of historical measurement techniques and unknown and poorly constrained oceanographic and atmospheric signals occur at varying scales within the observed time series. While tectonic effects have previously been invoked as the primary component of $\Delta\zeta_{Hilo-Hono}$, we present evidence here that the steric contribution is of a comparable magnitude. We note that ζ_{land} at any location will include both a tectonic component and a component due to glacial isostatic adjustment (GIA), but given the proximity of Hilo and Honolulu the rates of GIA should be almost identical, and therefore $\Delta\zeta_{land}$ will generally be dominated by the spatial variability of tectonic vertical motion.

Chapter 2 Terminology: Absolute, Relative and Differential Motions

It is necessary to clarify the terminology used in this paper, especially with regard to the distinction (in our usage) between relative and differential rates of motion. The distinction between *absolute* and *relative* sea level change is now fairly well established in the literature (Bevis *et al.*, 2002). Absolute sea level (ASL) change refers to the vertical motion of the sea surface relative to the standard ellipsoid (our preference) or relative to the center of the earth (though some geodesists have referred to the earth's center of mass instead). Relative sea level (RSL) change refers to the motion of the sea surface relative to the underlying seafloor or immediately adjacent land surface. RSL is the quantity measured by tide gauges, which cannot distinguish between upward motion of the sea surface and downward motion of the land. Vertical crustal motion is assumed to refer to the motion of the surface of the solid earth relative to the ellipsoid, unless specified otherwise. In other words, vertical crustal motion refers to the absolute vertical motion of the solid earth surface. Local effects such as compaction of near-surface sediments due to changes in the water table may cause vertical motion measured at the surface to differ from the vertical crustal motion of the underlying lithosphere. Thus geodesists must select their sites with care and may have to make ancillary measurements in order to determine the precise significance of their measurements (Bevis *et al.*, 2002).

Broadly speaking, the difference in the magnitudes of absolute versus relative sea level change depends upon the time scale of measurement. Even if we ignore sea level variations associated with the tides and changes in atmospheric pressure, sea level can change by hundreds of millimeters over time scales of one year or less. Since a typical secular rate of vertical crustal motion (again ignoring tidal effects and high frequency atmospheric loading) is of order 1 mm/yr, it is clear that over short periods of time absolute rates of sea level change are vastly greater than vertical crustal velocities, and so absolute and relative rates of sea level rise are very nearly equivalent. (This may not be true in areas of intense tectonic activity, or in areas undergoing major subsidence due to fluid withdrawal). In contrast, when we consider secular rates of sea level change at the 50 – 100 year time scale, the rate of absolute sea level change is typically of the order of 1 mm/yr, which is comparable to secular rates of vertical crustal motion over much of the world. Therefore long term rates of inundation tend to be influenced roughly equally by the shifting levels of both the land and of the ocean.

In this study we are interested in how vertical velocities vary within a region, from one tide gauge or GPS station to another. We will use the term *differential velocity* to refer to the difference in space between two absolute or relative vertical velocities. We use the term *differential sea level rise* to refer to the difference in the relative sea level rise recorded by two tide gauges. (Otherwise we will refer to differential rates of absolute sea level rise). In contrast, *differential crustal motion* or *differential crustal* *uplift (or subsidence)* will refer to the difference in the absolute vertical velocity at two points on the earth's surface. Horizontal velocities are of no interest in the context of this study.

Chapter 3 The Tide Gauges

The Honolulu Harbor tide station (21 18.4°N, 157 52.0°W) was built and maintained by the US Coast and Geodetic Survey from 1905-1972. It was then acquired and has been operated by the National Ocean Service (NOS) since 1973. The instrument type varied over the course of the record. According to NOS records, the sequence of gauge types were standard mechanical tape (1905-1974), analog-to-digital (ADR) recorder (1975-1990), and Aquatrak acoustic gauge, NOAA Next Generation Water Level Measuring System (NGWLMS) (1991-present).

All sea level measurements have been referenced to the primary benchmark (PBM) on land using USGS standards for vertical control. Thus, any movement of the pier relative to land has been corrected for, typically after each site maintenance visit based on the leveling data. While the standard mechanical or ADR instruments were the primary gauge, leveling calibration factors were applied monthly based on tide staff observations. Benchmark 8 (1913) is the PBM (see NOS website for location and details) for Honolulu.

The Hilo Bay tide station (19 44.0°N, 155 04.0°W) was built and maintained by the US Coast and Geodetic Survey from 1927-1972 and then acquired and maintained by NOS from 1973 to the present. According to NOS records, the gauge types were standard mechanical tape (1927-1974), ADR recorder (1975-1990), and Aquatrak acoustic gauge, NOAA NGWLMS (1991-present). Leveling to primary benchmarks was conducted at Hilo in the same manner as at Honolulu. Benchmark 4 is the PBM at Hilo. The tide gauge data are public domain and available from the NOS website, as well as from the University of Hawaii Sea Level Center.

To confirm that the sea level rise measured at Hilo and Honolulu is a natural phenomenon and not due to instrument instability, all of the records available of geodetic leveling surveys between each tide gauge and nearby benchmarks were examined. There was no evidence of significant local (engineering or soil) instability at the Hilo tide gauge. The Honolulu tide gauge is situated on a pier that is presently rising at about 0.1 mm/yr relative to the PBM (which appears to be stable). This motion, which is probably due to the swelling of the wooden piles supporting the pier, has been corrected for in the sea level time series.

The linear trend in sea level is estimated at Honolulu (1905-2002) and Hilo (1928-2002) using standard least squares analysis. If the entire time period of each record is considered, sea level is rising at Honolulu at a rate of 1.4 mm/yr and at Hilo at a rate of 3.3 mm/yr (Figure 1A). The 95% confidence intervals of the estimates are ± 0.52 and ± 1.52 mm/yr, respectively. These estimates are similar to those reported by Moore (1970; 1987) and Nerem and Mitchum (2001) using different record lengths. The differential sea level rise between Hilo and Honolulu is then 1.9 mm/yr ± 0.91 using all available data.

Figure 1. Map of Hawaii with GPS and Tide Gauge Data

A) Time series of annual mean sea level from the Hilo and Honolulu tide gauges with estimates of the linear trend. B) Estimates of vertical velocities, relative to the reference frame in 1C, at the Hawaiian CGPS stations (see also Table 1). 95% confidence intervals for the velocity estimates are depicted. C) Locations of the 30 CGPS stations used to establish a Pacific fixed reference frame (see also Table 1).

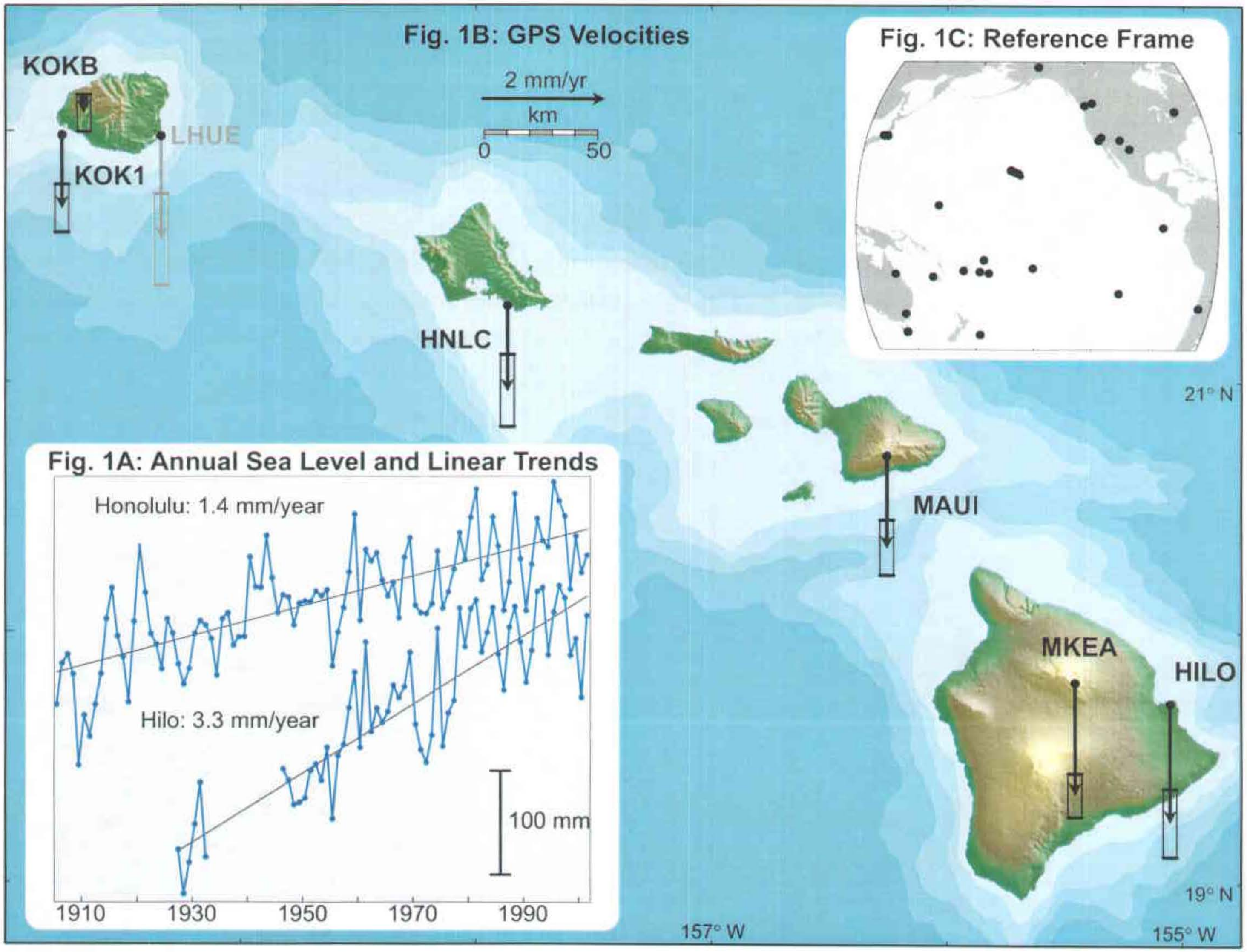


Fig. 1B: GPS Velocities
2 mm/yr
km
0
50
KOKB
KOK1
LHUE
HNLC
MAUI
MKEA
HILO
21° N
19° N
157° W
155° W
Fig. 1C: Reference Frame
Fig. 1A: Annual Sea Level and Linear Trends
Honolulu: 1.4 mm/year
Hilo: 3.3 mm/year
100 mm
1910
1930
1950
1970
1990

In chapter 7 this analysis will be revised so as to consider how the differential rate in sea level rise changes as a function of the time span under consideration. It will be shown that during recent decades the differential rate of sea level rise between Hilo and Honolulu has significantly declined. This rate change will be shown to be consistent with ocean rather than land effects.

Chapter 4 Geodetic Measurements

To determine whether the 1.9 mm/yr difference in the rate of sea level rise observed at Honolulu and Hilo can be explained in terms of differential land motion, the relative vertical velocity at these sites using the GPS stations HNLC (co-located at the Honolulu tide gauge) were measured and HILO (~500m away from the Hilo Bay tide gauge) (Table 1, Figure 1B). The absolute vertical velocity at each site was not determined. This is an important distinction for geodesists because absolute vertical motions (*i.e.*, vertical velocities defined in a global earth-fixed reference frame) are far more difficult to estimate than are relative vertical velocities within a region of moderate aperture, such as the Hawaiian archipelago. This is because: (*i*) although the vertical velocities of all the GPS stations tend to differ according to the specific reference frame in which these velocities are expressed (*e.g.* International Terrestrial Reference Frame, 1997 (ITRF-97) versus ITRF-2000), the differential vertical velocity of two or more stations separated by much less than 1,000 km is very nearly invariant under the transformation between modern reference frames, and (*ii*) defining or selecting a specific reference frame is different, in practice, from realizing that reference frame for the purpose of processing a new set of data and estimating station positions and velocities. Reference frame realization error is one of the major sources of velocity error at the global scale (Kendrick *et al.*, 2001). Much of this error is spatially coherent to the extent that it is nearly common mode within a small region, and therefore this error is largely cancelled as one forms estimates of relative velocity.

The PGF routinely analyzes continuous GPS datasets from a large number of geodetic GPS stations located in the Pacific and circum-Pacific region. Daily geodetic analysis is performed using GAMIT (King and Bock, 2000) and GLOBK (Herring, 2000) software and precise orbits computed by the Scripps Orbit and Permanent Array Center. Long time series of these daily solutions are analyzed using VSTACK software for the purpose of estimating station positions and velocities (Kendrick *et al.*, 2001). Our velocity solutions (Table 1) are presented in a reference frame that minimizes the vertical velocities of 30 stations in the Pacific and circum-Pacific region (Figure 1C). (We also minimize the horizontal velocities of the subset of these stations that are located within the rigid core of the Pacific plate, but this aspect of our reference frame is not important for our present analysis). These GPS stations were selected on the basis of their time spans, which fall in the range from 5 to 10 years. The root mean square (RMS) vertical motion of these stations is 1.55 mm/yr. The formal error estimates associated with the PGF solutions include a 'red noise' correction that is designed to account for the temporal correlation of GPS positioning errors in geodetic time series (Kendrick *et al.*, 2001; Zhang *et al.*, 1997). Having realized this reference frame over a very large region, we next focus on the relative vertical velocities of the stations located in Hawaii (Figure 1B, Table 2).

Table 1. Vertical Velocity Solutions

The vertical velocity solutions obtained by the Pacific GPS Facility (PGF) in a reference frame that minimizes the horizontal motion of all GPS stations located in the Pacific plate, and the vertical velocities of all GPS stations in the Pacific region. The table identifies each station by its four letter code, and lists its latitude and longitude, the total time span of observations in years, the number of daily solutions included in the velocity analysis, the vertical velocity of the station (upwards positive) and its formal error (2-sigma, nominally the semi-interval of 95% confidence) in mm/yr, and indicates whether or not that station is located in Hawaii.

Table 1. Vertical Velocity Solutions

St Code	Lat	Long	Span	#Eps	Vup	Err	HI
ALBH	48.39	-123.49	9.82	3556	0.4	0.2	
ALGO	45.96	-78.07	9.82	3494	2.5	0.2	
CHAT	-43.96	-176.57	7.06	2549	0.6	0.3	
DRAO	49.32	-119.62	9.82	3354	0.2	0.2	
EISL	-27.15	-109.38	8.76	2489	-1.8	0.5	
FAIR	64.98	-147.50	9.82	3438	-2.5	0.3	
FALE	-13.83	-172.00	5.85	1901	-0.8	0.6	
GALA	-0.74	-90.30	6.73	1819	-0.1	0.6	
GOLD	35.43	-116.89	9.82	3496	-0.3	0.2	
HILO	19.72	-155.05	5.40	1675	-1.9	0.5	*
HNLC	21.30	-157.86	5.36	1805	-1.4	0.6	*
HOB2	-42.80	147.44	9.82	2953	-0.6	0.6	
JPLM	34.20	-118.17	9.82	3131	-1.2	0.2	
KOK1	21.98	-159.76	6.72	2240	-1.2	0.4	*
KOKB	22.13	-159.66	9.81	3266	-0.2	0.3	*
KOUC	-20.56	164.29	6.44	2235	-0.2	0.4	
KWJ1	8.72	167.73	6.35	1857	-2.9	0.7	
MAUI	20.71	-156.26	5.01	1700	-1.5	0.4	*
MDO1	30.68	-104.01	9.39	3314	0.1	0.2	
MKEA	19.80	-155.46	6.07	2103	-1.8	0.4	*
NIUC	-19.06	-169.93	5.77	1957	-0.1	0.5	
PIE1	34.30	-108.12	9.81	3525	2.5	0.2	
SANT	-33.15	-70.67	9.82	3171	0.2	0.3	
SUVA	-18.15	178.43	6.24	1701	0.1	0.5	
THTI	-17.58	-149.61	9.82	2140	2.9	0.4	
TIDB	-35.40	148.98	6.32	2297	0.5	0.3	
TOW2	-19.27	147.06	6.44	1878	-1.3	0.5	
TSKB	36.11	140.09	9.82	3181	-0.4	0.2	
USUD	36.13	138.36	9.82	3291	2.6	0.3	
VAVC	-18.59	-173.96	3.83	855	2.9	1.1	

Root Mean Square (RMS) vertical velocity = 1.55 mm/yr

Because geodesists do not yet understand in any great detail the nature of the noise contaminating their time series and their velocity estimates, formal error estimates are arrived at by a variety of essentially heuristic procedures that are rather difficult to defend. Therefore it is useful to supplement these internal measures of uncertainty with measures based on external comparisons. Our primary analysis is augmented by comparing the relative velocity estimates obtained by the PGF with those produced using different software, different orbital solutions and distinct processing methodologies. Unfortunately, the various global analysis centers contributing to the International GPS Service (IGS) have produced long time series for only one or two of the Hawaiian GPS stations (MKEA and/or KOKB). We have utilized the velocity solutions obtained for both of these stations by the Jet Propulsion Laboratory (JPL) whose GPS data processing software and procedures are different from those used in the PGF. This allows us to compare differential vertical velocity of MKEA and KOKB. For the purpose of making a much broader comparison, Mark Schenewerk analyzed a much larger subset of the PGF data set using the software package PAGES (Schenewerk, 2002). This analysis decimated the PGF dataset, using only one day in four. Orbital solutions were obtained from the National Geodetic Survey (developer of PAGES software). The daily positions and the velocity solutions were estimated in the reference frame ITRF-2000. The relative vertical velocity solutions within Hawaii produced by PGF, PAGES and JPL are compared in Table 2.

Table 2. Differential Velocity Solutions

A comparison of the differential vertical velocity solutions obtained for various pairs of GPS reference stations in Hawaii. The velocity described is the upward velocity of the first named station (STN1) relative to the second named station (STN2). We present velocity solutions obtained by the Pacific GPS Facility (PGF), by Mark Schenewerk (PAGES) and by the Jet Propulsion Laboratory (JPL). The numbers in each column represent the relative velocity and its formal (1-sigma) error stated in mm/yr.

STN1	STN2	PGF	PAGES	JPL
HILO	- HNLC	-0.51 ± 0.40	-0.35 ± 0.86	
KOK1	- HNLC	0.20 ± 0.36	0.76 ± 0.82	
KOKB	- HNLC	1.20 ± 0.34	2.72 ± 0.78	
MAUI	- HNLC	-0.04 ± 0.37	0.05 ± 0.79	
MKEA	- HNLC	-0.43 ± 0.34	1.00 ± 0.78	
KOKB	- MKEA	1.63 ± 0.24	1.72 ± 0.71	2.13 ± 0.26

The formal error estimates associated with JPL solutions are smaller than those associated with the PAGES solution and comparable to those estimated by PGF. All three solutions for the vertical velocity of KOKB relative to MKEA are consistent given their individual uncertainties. The same is true for all relative vertical velocities estimated by PGF and by PAGES. These intercomparisons provide us with additional confidence in the PGF solution (including its error estimates), which we now adopt as our preferred solution (Figure 1B). In addition to showing all Hawaiian stations involved in the realization of the reference frame, we show the vertical velocity of the station LHUE, which was not used to realize the frame because its antenna monument is known to undergo small tilts that are manifested as horizontal fluctuations in position. This instability probably does not affect the vertical position of the antenna (though we cannot be sure of this) and so we present its velocity in the figure. The velocity of KOKB seems to be anomalous when viewed in the regional context. We suspect that this GPS station, which is located in thick soils in an area of high rainfall, is subject to local vertical instability. Fig. 1B suggests that there is a tendency for subsidence rates to increase towards the southeast. Vertical velocities increase from -1.2 ± 0.4 mm/yr at Kauai (KOK1) to -1.9 ± 0.5 mm/yr at the island of Hawaii (HILO, Table 1, Figure 1B). The higher rate at Hawaii is consistent with the belief that active volcanic loading leads to higher subsidence at the youngest island (Moore, 1970; Moore, 1987; Moore and Clague, 1992). The GPS observations suggest that this rate is not as large as previous estimates that were based largely on the tide gauge data (Moore, 1987). It is interesting to note that loading models also suggest a smaller subsidence rate than indicated by the tide gauge sea level differential (Moore, 1970). The recent GPS results appear to support these modest loading rates.

For the purposes of this study, the primary result of the GPS analysis is that HILO is subsiding relative to HNLC at -0.5 ± 0.4 mm/yr (Table 2) over the past 6 years. The GPS station HNLC is located on the pier adjacent to the tide gauge, and this pier has been moving upwards at about 0.1 ± 0.05 mm/yr relative to the (stable) primary benchmark on land (Figure 2). Since the sea level time series has been referred to this benchmark one must refer the vertical motion of the ground relative to this benchmark too, which reduces our estimate of differential vertical crustal motion to -0.4 ± 0.4 mm/yr. Thus, vertical movements of the land cannot account for the difference in relative sea level rise of 1.9 mm/yr. Before considering the influence of steric effects in sea level, the geological literature that has previously been used to explain essentially all of the differential rate of sea level rise between Hilo and Honolulu in terms of crustal motion should be reviewed.

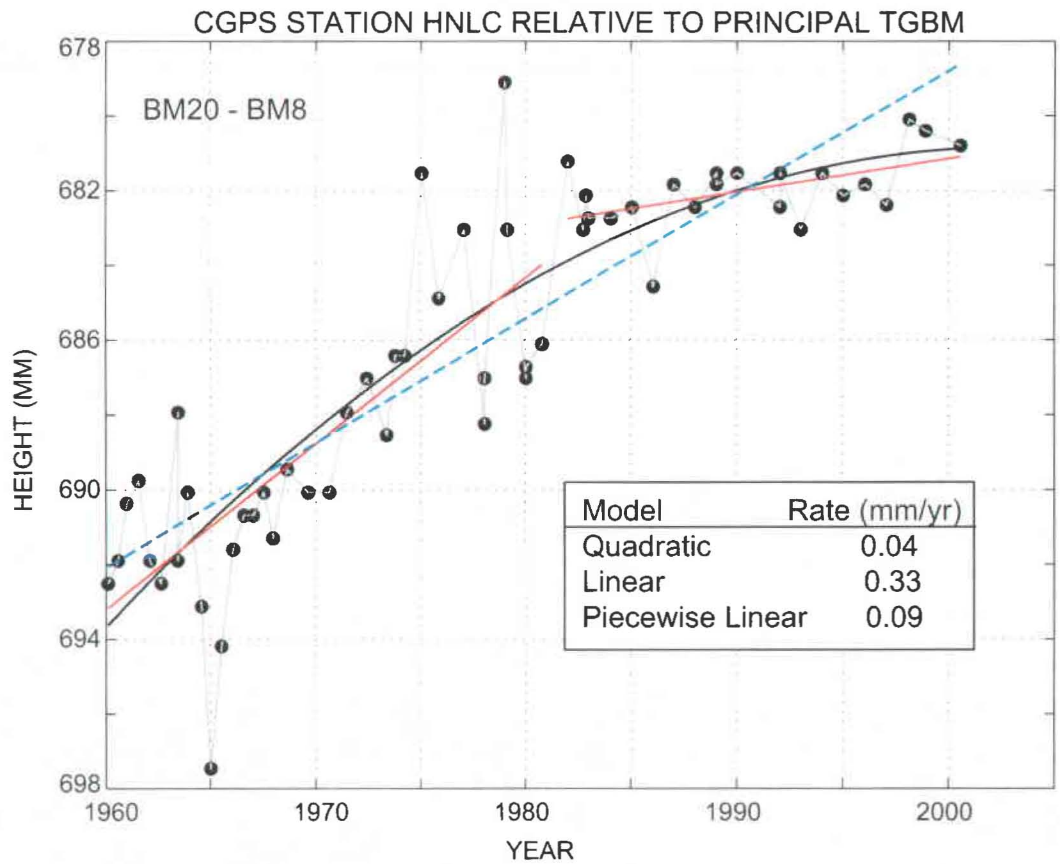


Figure 2. CGPS Relative to Primary TG Benchmark at Honolulu

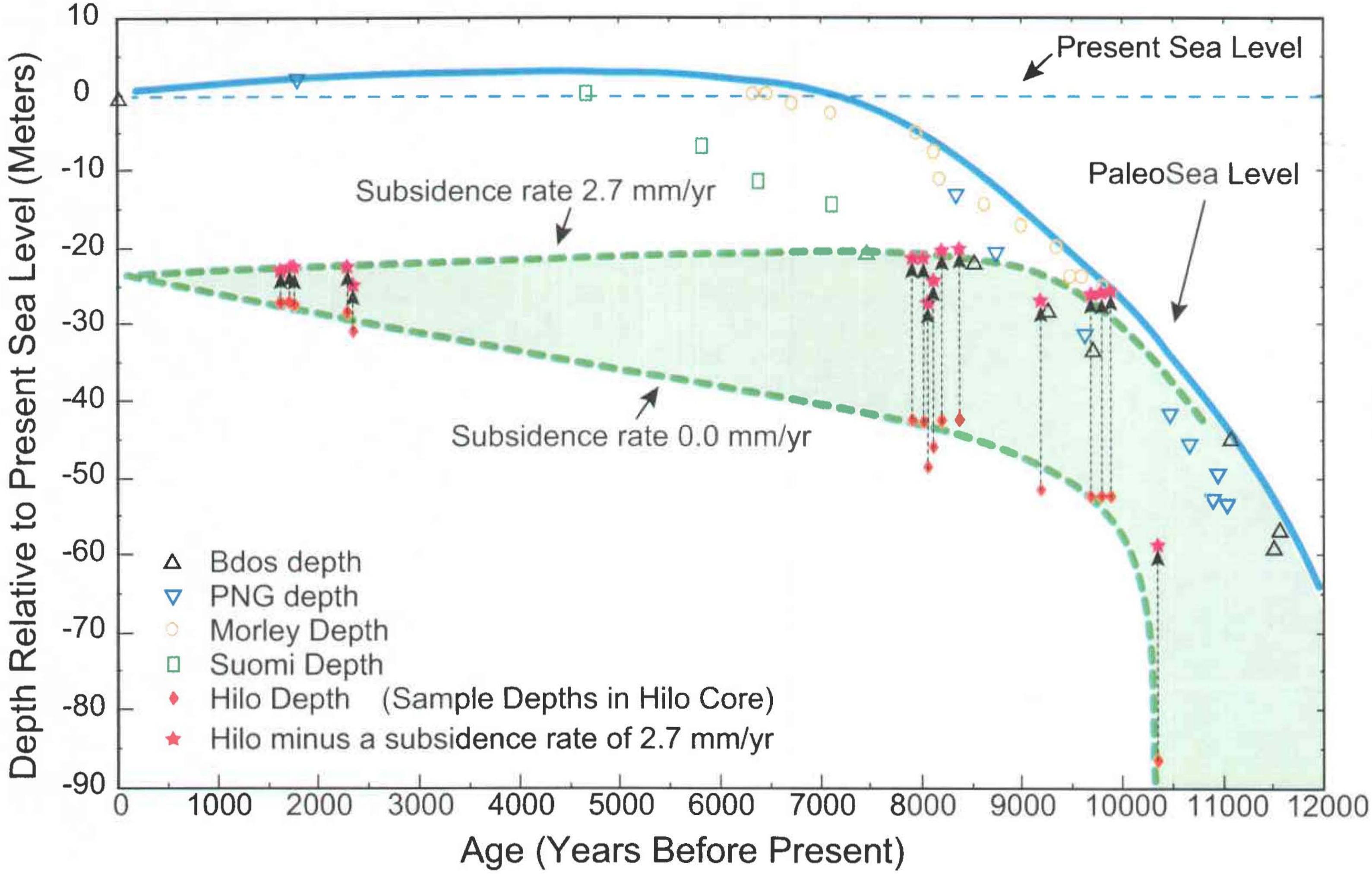
Chapter 5 Geological Observations

Coral reef deposits at 20-30 m above modern sea level on Oahu indicate slow net uplift on the order of 0.06 mm/yr since ~500 Ka (*e.g.* Ludwig *et al.*, 1991), although the uplift may be even slower if the reefs grew when sea level was higher than present. For example, Hearty *et al.* (1999) proposed that sea level during the Marine Isotope Stage 11 (MIS 11) (~400 Ka) may have been ~20 m higher than present. Mean uplift rates of 0.05 to 0.06 mm/yr have also been proposed for the interval ~125 Ka to present based on the emerged Waimanalo reef formation that reaches to ~8.7 m above present sea level (*e.g.* Sherman *et al.*, 1999). This uplift rate is based on the assumption that sea level during the last interglacial was ~6 m higher than present (*e.g.* Bloom *et al.*, 1974; Muhs and Szabo, 1994; Veeh, 1966). However, an error bar of at least several meters should be attached to the +6 m paleosea level because the height of the last interglacial maximum sea level cannot be precisely defined for the Pacific for the same reason that it is difficult to specify a single maximum height of Holocene sea level in the tropical oceans. For any time in the past, the Holocene paleosea level surface is distorted due to glacial hydroisostatic adjustments (*e.g.* Peltier, 1998). Today, we find that maximum heights of Holocene sea level indicators in the tropical Pacific range from present sea level to several meters higher (*e.g.* Grossman, 1998; Pirazzoli, 1991). Likewise, the last interglacial reef levels today are likely to vary in height by a few meters throughout the tropical oceans depending on the state of hydroisostatic adjustment. Thus, the Waimanalo reef heights neither confirm nor contradict uplift of Oahu since ~125 Ka because the last interglacial paleosea level for Hawaii is not known with sufficient accuracy. What can be said is that the net vertical motion since 125 Ka has been negligible.

Off the northwest side of the island of Hawaii, ^{14}C and $^{230}Th/^{234}U$ ages for coral samples obtained from drowned reefs at depths as great as 1650 m convincingly demonstrate that the mean subsidence rate since ~500 Ka is approximately -2.5 mm/yr (Ludwig *et al.*, 1991; Moore and Clague, 1992). However, the ages and depths of Holocene coral fragments recovered from cores drilled through a sedimentary sequence near Hilo are more relevant to contemporary vertical motion of the island of Hawaii near Hilo (Moore *et al.*, 1996). We can consider the maximum possible subsidence rate during the age range of the Hilo corals by comparing their present depths with paleosea level histories from other sites in the Pacific and Caribbean (*e.g.* Bard *et al.*, 1990; Collins *et al.*, 1993; Eisenhauer *et al.*, 1993). In Figure 3, the Hilo samples have been adjusted upward by subtracting their age x 2.7 mm/yr from their depths in the borehole. If the subsidence rate were to exceed -2.7 mm/yr, then some of the corals would have to have been deposited above sea level. The plot suggests that it is likely that most of the corals were deposited many meters below sea level. Thus the Hilo coral data neither confirm nor refute a rapid subsidence rate. The subsidence rate of -2.7 mm/yr is the extreme maximum subsidence rate allowed by the data. If the corals in the 10 Ka time range had been deposited well below sea level for example, then Hawaii could have been perfectly stable or even uplifting since 10 Ka. It is quite possible that the mean subsidence rate

Figure 3. Coral Age / Depth Comparisons

Isotopic ages for fossil corals representing post-glacial sea-level rise from various sites around the world compared to the Hilo coral data at their present depth below sea level. The blue dotted line represents present sea level. The solid blue line approximates paleosea level history based on the depths of coral data in the Atlantic and Pacific Oceans, corrected for land motion (Barbados (Bdos), Papua New Guinea (PNG), Morley, Suomi, see text for references). The dark red stars represent the depth and age of Hilo coral data relative to present sea level corrected assuming a subsidence rate of 2.7 mm/year. The green shaded region represents subsidence corrections ranging from 0 to -2.7 mm/year. Note that many of the fossil corals would have been deposited well below sea level at the time they lived even when their vertical position is adjusted using a subsidence rate of -2.7 mm/yr. If a subsidence rate greater than -2.7 mm/yr were applied then the 10 ka corals would have to have been deposited above paleosea level. Given that most of the corals must have been deposited well below sea level, it is possible that the 10 ka corals also were deposited well below sea level and that the subsidence rate is less to much less than 2.7 mm/yr. Since 10 Ka is substantially less than the mean subsidence rate of -2.5 mm/yr since 500 Ka.


Present Sea Level
PaleoSea Level
Subsidence rate 2.7 mm/yr
Subsidence rate 0.0 mm/yr
Depth Relative to Present Sea Level (Meters)
Age (Years Before Present)
Bdos depth
PNG depth
Morley Depth
Suomi Depth
Hilo Depth (Sample Depths in Hilo Core)
Hilo minus a subsidence rate of 2.7 mm/yr
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000

GPS measurements show that differential vertical motion between Oahu and Hawaii is continuing at much slower rates in the contemporary time frame than the mean rate difference of approximately -2.5 mm/yr over the past 500 Ka. Differential motion has either been reduced or it is not a continuous process. In either case, this observation offers insights into aspects of the interaction between volcanic loading, magma emplacement, and plate tectonics that have not been fully appreciated.

Fossil coral evidence from the Hilo drill core places only weak constraints on the average rates of Holocene vertical motion in this locale. The maximum mean rate of subsidence has been approximately -2.7 mm/yr during the Holocene, but it very likely was much slower, or even zero. None of the available data address the question of whether subsidence is a continuous or an episodic process. To assume that the process is continuous assumes that we fully understand the mechanism.

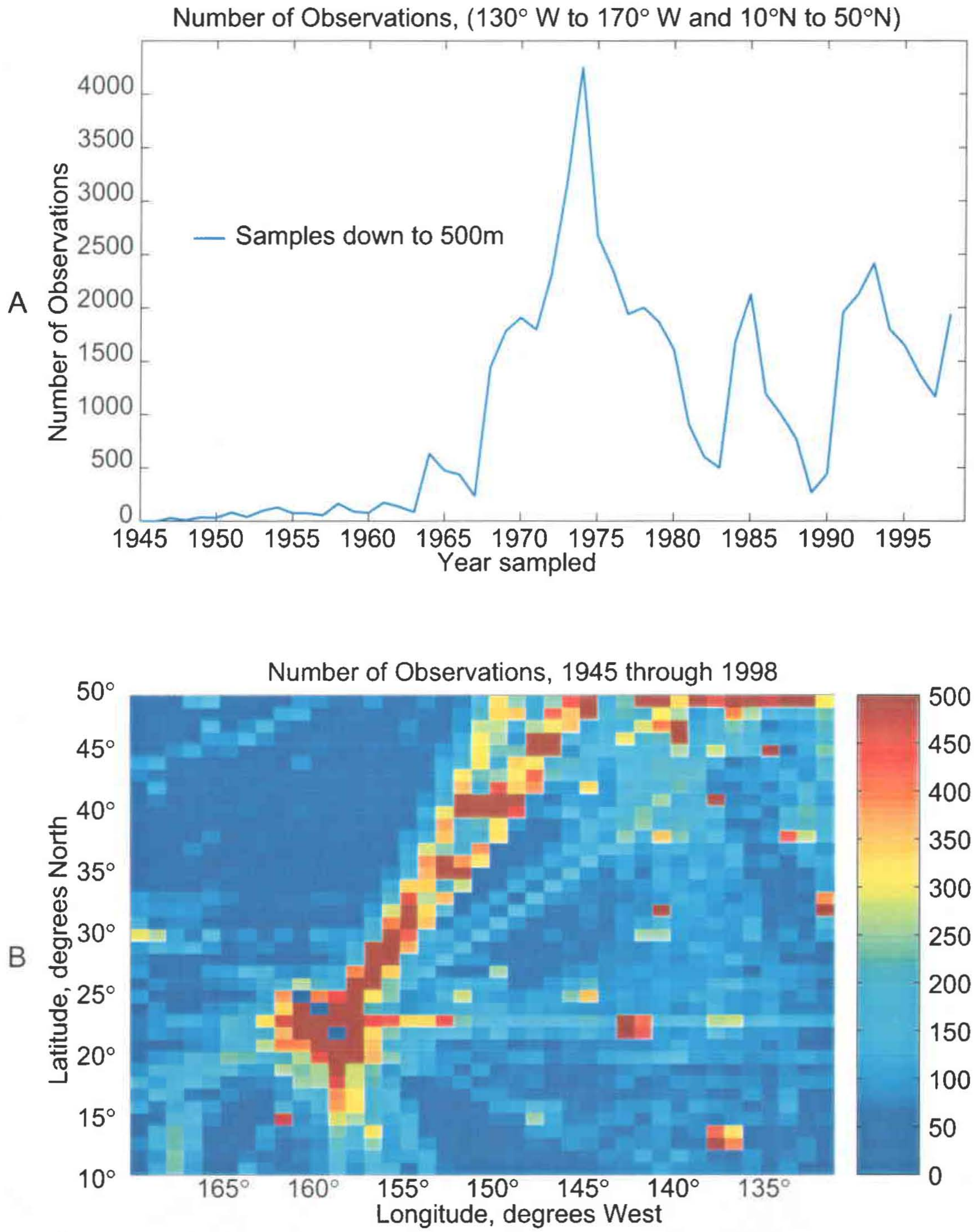
Chapter 6 Steric Contributions to Sea Level Change

The World Ocean Atlas (WOA) is a compilation of temperature and salinity measurements sampled throughout the global oceans. The focus of the WOA has been the depiction of time-averaged oceanographic fields; however, recently and in support of climate research, there has been an effort to document changes in the upper ocean (0-500 decibar pressure (db), nominally 500m depth) on a yearly basis dating to 1945. This ambitious data product is subject to sampling errors that increase significantly further back in time. For example, the amount of data available to describe conditions around Hawaii is considerably less prior to the mid-1960s (Figure 4A) Similarly, the spatial coverage is poor away from established shipping routes (*e.g.* Hawaii-San Francisco) (Figure 4B). Any attempt to infer details of the oceanographic fields and their variations over time must be treated cautiously given the sparse amount of data available, even in the most highly sampled years.

Nevertheless, Cabanes *et al.* (2001) considered changes in steric height over the past 40 years for the global ocean using the WOA dataset. It was found there was considerable spatial variation in the linear steric rates, with amplitudes similar to tide gauge estimates of relative sea level rates. A comparison of recent steric trends with those computed from the TOPEX/POSEIDON altimeter shows a surprising

Figure 4. Density of Hydrographic Observations

A) The number of hydrographic observations, for the region shown in Figure 4B, used to form WOA annual temperature data. The blue line indicates casts made to 500 db pressure. B) The total number of WOA hydrographic observations to 500db for 1945 to 1998 obtained within 1° x 1° boxes around Hawaii.

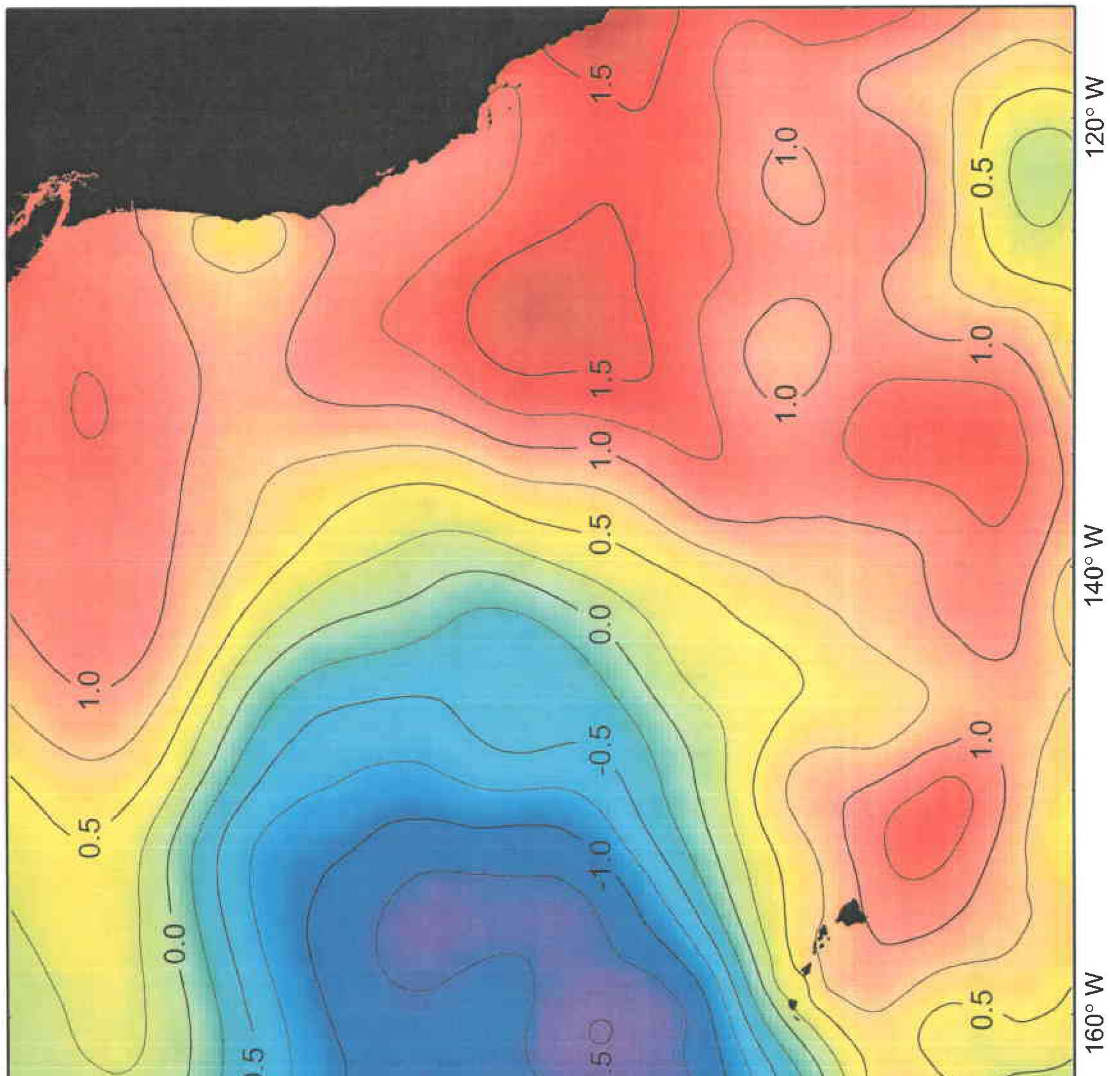

Number of Observations, (130° W to 170° W and 10°N to 50°N)
A
Number of Observations
4000
3500
3000
2500
2000
1500
1000
500
0
Samples down to 500m
1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995
Year sampled
Number of Observations, 1945 through 1998
B
Latitude, degrees North
50° 45° 40° 35° 30° 25° 20° 15° 10°
165° 160° 155° 150° 145° 140° 135°
Longitude, degrees West
500 450 400 350 300 250 200 150 100 50 0

correspondence. Their analysis suggested that global sea level trend estimates obtained from tide gauges may suffer from bias errors associated with the distribution of gauges relative to the steric field. In general, the data are insufficient to explore this issue at individual tide gauges.

The analysis of Cabanes is repeated for the northeast Pacific Ocean with a focus on the Hawaii region (Figure 5). The data indicate that Hawaii is located in a region of relatively weak steric changes that separates large areas to the northwest and southeast where the upper ocean has apparently cooled/warmed significantly, causing steric sea level to decrease/increase over time. We will not attempt to judge the statistical confidence of this feature, except to emphasize that the data coverage is poor, particularly to the northwest and southeast of the Hawaiian Islands (Figure 4B). We do note, however, that the spatial pattern of linear trend is similar to patterns associated with reported interdecadal oceanographic variations such as the Pacific Decadal Oscillation (PDO) (Mantua and Hare, 1997) and the Pacific North American (PNA) index (Deser *et al.*, 1996; Firing, 2003; Mantua and Hare, 1997). It seems likely then that steric sea level changes over the past 50 years are strongly influenced by interdecadal variations, and that the trend pattern may in fact be a robust feature in this region. If so, its expression in the vicinity of Hawaii is a strong variation in trend, with increasing values to the southeast. The causes of interdecadal sea level fluctuations in the North Pacific are under investigation; however, it appears

Figure 5. Steric Sea Level Change (1945-1998) mm/yr (500m Depth)

Estimate of the linear trend in steric sea level relative to 500db obtained using WOA data. A positive value indicates rising sea level.


40° N
20° N
160° W
140° W
120° W
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5

likely that wind-forced redistributions of heat content play a major role (Firing et al., 2003).

The difference in steric height trends (1945-1998) between the islands of Oahu and Hawaii is investigated by computing averages over 2°x2° areas near each island (Table 3). At Oahu, the steric trend is 0.6 or 0.8 mm/yr relative to 500db and 3000db, respectively, compared to the sea level trend of 1.4 mm/yr. At Hawaii, the trend is 1.3 mm/yr compared to a sea level trend of 3.3 mm/yr. The difference in steric trend between the islands is 0.5-0.7 mm/yr compared to the sea level rate difference of 1.9 mm/yr. Correcting for the GPS estimates of differential vertical trends at the Hilo and Honolulu tide gauges lowers the differential sea level rate to 1.4 mm/yr, nearly twice the difference in steric trend.

Because the steric trends around the Hawaiian Islands vary strongly over short distances, any estimate of trend differences between the islands is sensitive to how the data are selected. For example, moving the averaging area by 1° out (Table 3) changes the steric rate difference to 1.3 or 1.6 mm/yr, similar to the GPS-corrected sea level difference of 1.4 mm/yr. The under-sampled WOA data are not sufficient for determining the steric difference in detail; however, it appears that the gradients in trend are such that steric effects could arguably account for the entire observed sea level rate difference between Hilo and Honolulu.

Table 3. Steric Sea Level Trends

Steric sea level trends from WOA data averaged over the regions bounded by the specified latitude and longitude ranges. Rates are given relative to the 500-db and 3000-db isobar. The difference values represent the estimated trend difference between Oahu and the island of Hawaii.

Original region

Lat (Deg)	Long (Deg)	0/500 db	0/3000 db
157.5 to 159.5	20.5 to 22.5	0.6 mm/yr	0.8 mm/yr
154.5 to 156.5	18.5 to 20.5	1.3 mm/yr	1.3 mm/yr
Difference:		0.7 mm/yr	0.5 mm/yr

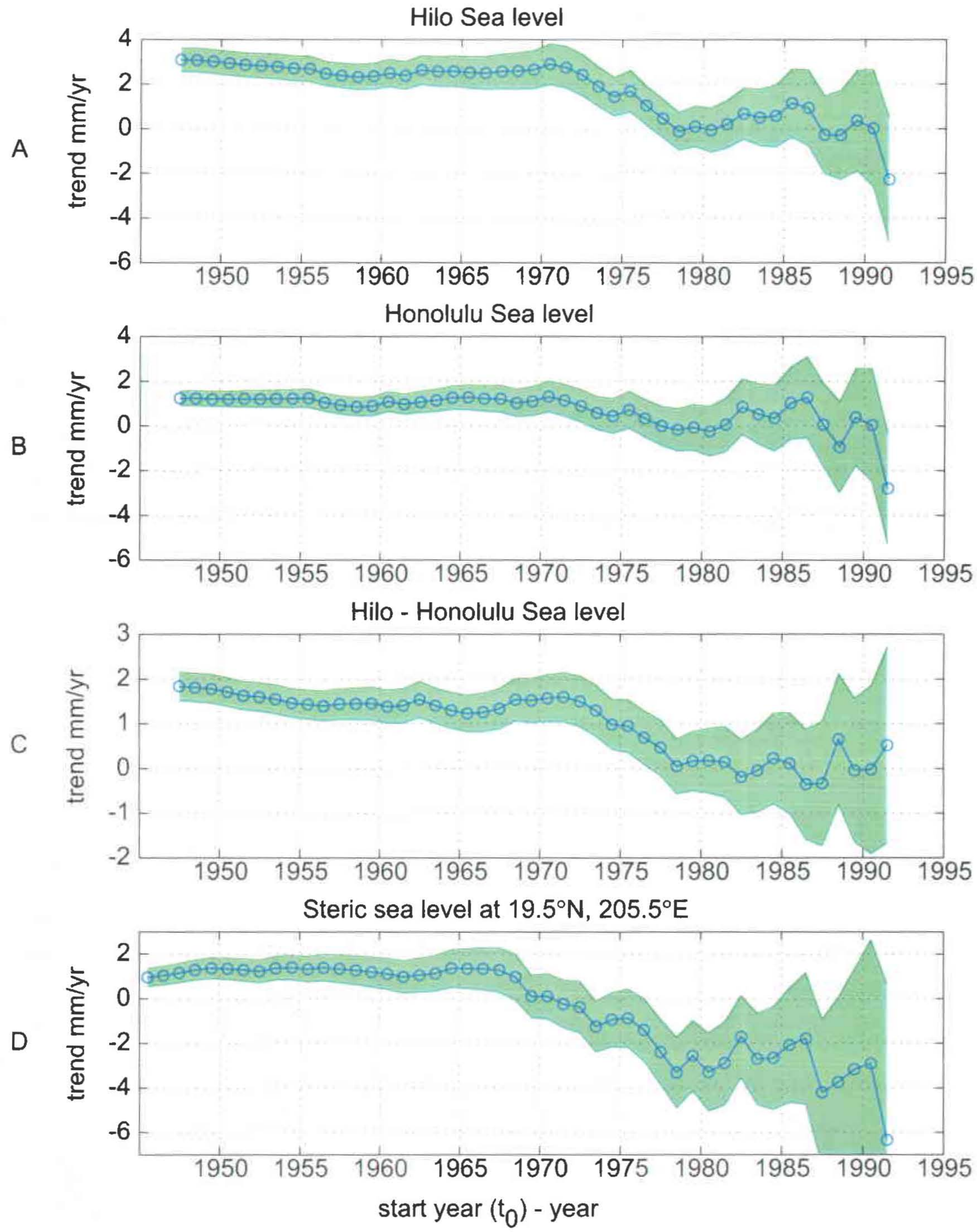
Offset region

-158.5 to -160.5	-21.5 to -23.5	0.1 mm/yr	0.2 mm/yr
-153.5 to -155.5	-17.5 to -19.5	1.6 mm/yr	1.5 mm/yr
Difference:		1.6 mm/yr	1.3 mm/yr

The importance of upper ocean heat content in determining sea level trends near Hawaii is also reflected in the nonlinear components of the trend. The sea level rise rate measured at the Hilo tide gauge appears to have decreased since the 1970s (Figure 1A; also discussed by Moore, (1987)). To better quantify this rate change over time, the linear trend is computed as a function of the start year (t_0) of the record considered (Figure 6). For example, the trend at Hilo is computed for t_0 to 2002 and plotted versus t_0 (Figure 6A), with t_0 ranging from 1945-1992. The Hilo sea level trend of 3.3 mm/yr decreases beginning in the 1970s to a value near zero (Figure 6A).

Figure 6. Hilo-Honolulu Sea Level Comparison

Estimates of the linear trend for A) Hilo sea level, B) Honolulu sea level, C) the difference in Hilo and Honolulu sea levels, and D) the steric sea level from WOA data, relative to 500db, at a location near the island of Hawaii. The trends are computed for progressively shorter lengths of time by truncating the start of the original time series. The x axis represents the start date (to) of the sub-record used to compute the trend (to through 2002). For example, the first point in panel A represents the linear trend at Hilo for the time period 1945-2002; the last point shown in panel A is the Hilo trend for 1992-2002. The green shaded region represents the 95% confidence interval.

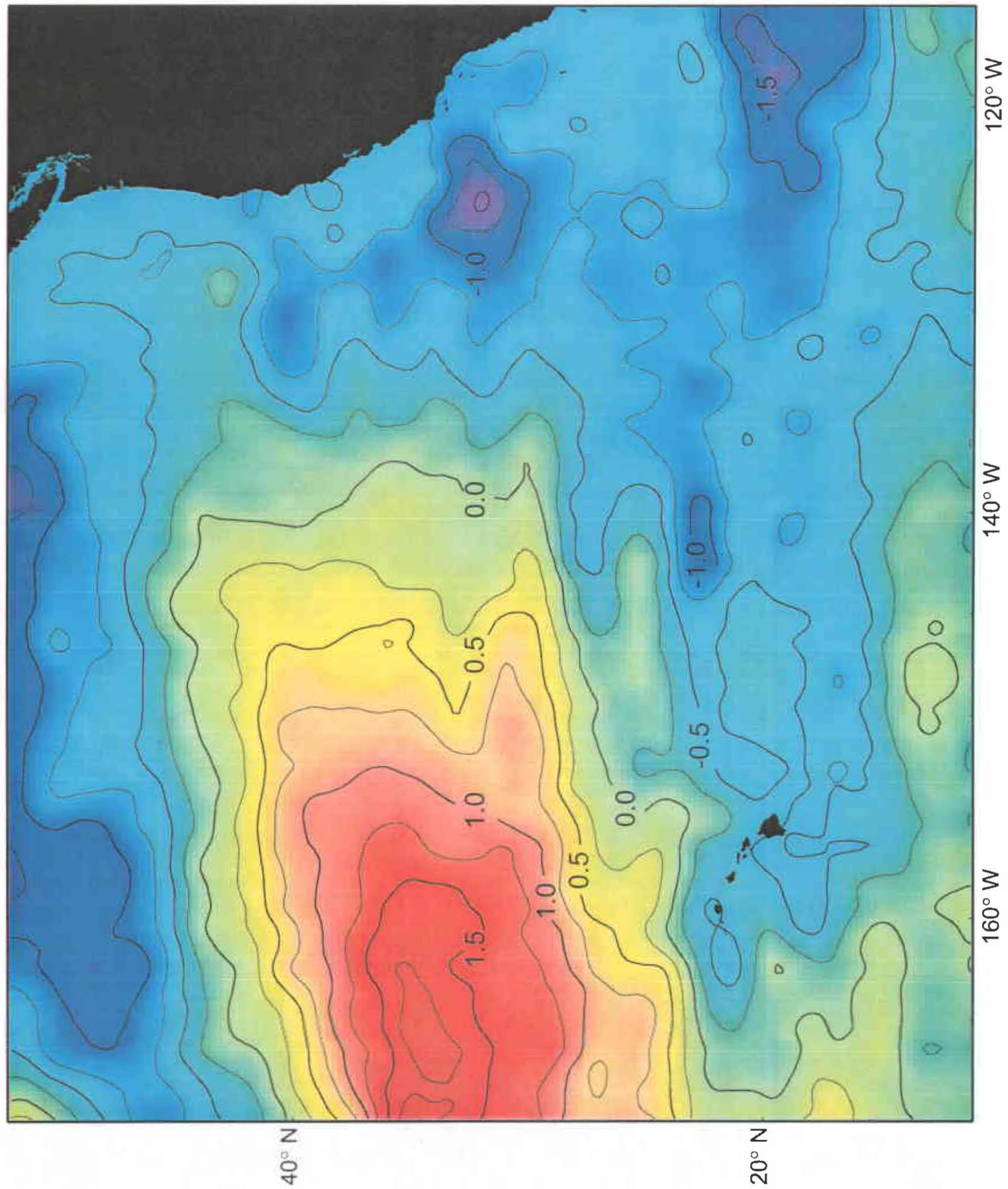

Hilo Sea level
A
trend mm/yr
Honolulu Sea level
B
trend mm/yr
Hilo - Honolulu Sea level
C
trend mm/yr
Steric sea level at 19.5°N, 205.5°E
D
trend mm/yr
1950 1955 1960 1965 1970 1975 1980 1985 1990 1995
start year (t0) - year

A similar change to near zero trend occurs at Honolulu (Figure 6B), and in the Hilo-Honolulu trend difference (Figure 6C). An analysis of WOA steric height near Hilo (19.5°N, 205.5°E) shows a similar trend change (Figure 6D). The amplitude of this change weakens to the northwest, consistent with the difference seen in the Hilo-Honolulu trends (Figure 6C). These results emphasize the importance of interdecadal heat content fluctuations in determining Hawaii sea level trends. The changes evident in the more recent epochs shown in Figure 6 are not simply the result of a decrease in sampling as we approach the end of the time series. Rather, these variations are expressions of real changes in the ocean dynamics. Figure 7 shows a linear trend in sea surface height obtained from the TOPEX/Poseidon data for the time span 1993-2002. The TOPEX/Poseidon results in Figure 7 are consistent with the recent trends discussed here. These results emphasize the difficulty in resolving secular trends from interdecadal fluctuations in tide gauge records of 50-100 years duration.

We believe the reduction in trend is most likely due to oceanographic phenomena; however, episodic tectonic and/or volcanic activity may strongly affect short-term vertical land rates. This is most evident at active regions such as faults or larger-scale plate boundaries. For example, direct estimates of land motion at Socorro Island, Mexico, show a strong non-linear component (Cazenave *et al.*, 1999). We are not aware of any specific geological events or changes at Hawaii that may account for the reduction in relative sea level trend measured by the tide gauges, although the

Figure 7. Linear Trend from TOPEX/Poseidon (1993-2002)

Linear trend in sea surface height obtained from TOPEX/Poseidon data for the time span 1993-2002. The weak to negative sea level rates near Hawaii are consistent with the recent sea level trend change depicted in Figure 6.


120° W
140° W
160° W
40° N
20° N
-1.5
-1.0
-1.0
-0.5
0.0
0.0
0.5
0.5
1.0
1.0
1.5

possibility cannot be discounted. Given the striking similarities between the tide gauge and steric trend changes, we believe that recent geological effects are minimal.

Finally, we note that WOA data (Figure 5) suggest that steric sea level has been falling northwest of the main Hawaiian Islands. The tide gauge on Midway Island (28.22°N, 177.37°W) has recorded a sea level trend of 0.4 mm/year for the period 1947-2002. Thus, the relative sea level trend is smaller at Midway than at the main Hawaiian Islands. A similar result is found for Tern Island (23.87°N, 166.28°W), although the record length is relatively short for a significant trend analysis. The rate differences between the northwest and main islands are consistent with the gradient in steric sea level depicted in Figure 5. We believe that this is further evidence for the importance of steric effects for the region. Longer CGPS time series are needed at Midway (currently < 2 years of data) to resolve differential land motion along the Hawaiian Ridge.

Chapter 7 Summary

In this study, we have tried to reconcile the sea level trend differences between the Hawaiian Islands. We have focused on the long time series available at Honolulu Harbor on Oahu, and Hilo Bay on the island of Hawaii. The sea level trend difference between Hilo and Honolulu is 1.9 mm/yr, with Hilo sea level rising faster than Honolulu sea level.

The main results of this study are:

- Continuous GPS measurements over the past 5-10 years show that the relative subsidence rate between the island of Hawaii and the other Hawaiian Islands is approximately -0.4 ± 0.4 mm/yr. Trend differences between the remaining islands are relatively small (Figure 1B, Table 2). Thus, recent island subsidence rates cannot account for the observed sea level trend difference.
- Our GPS estimates of differential land subsidence are smaller than those obtained from geological datasets (*e.g.*, ~2.5 mm/yr, (Moore and Clague, 1992). A reevaluation of the geological data, however, suggests that the reported 2.5 mm/yr differential vertical velocity between Oahu and Hawaii is an upper bound. Slower rates can be inferred from the available data and thus the GPS rate is not inconsistent with the geologic datasets.
- WOA data have been used to compute trends in steric height relative to 500db over the Northeast Pacific. The strongest spatial gradient in the linear trend occurs at the Hawaiian Islands. This gradient is such that even over the 335

km separation between Oahu and Hawaii, a steric rate difference of 0.7 mm/yr may have occurred over the last 50 years. This suggests that steric effects probably contribute as much or more to the tide gauge trend differences than does differential land motion. Midway Island located at the northern end of the Hawaiian Ridge also suggests similar results.

- A further indication of the significance of the steric contribution to sea level is the finding that the rate of increase at the Hilo tide gauge has decreased over the last 35 years compared to the long-term rate. To a lesser extent, Honolulu has also shown a decrease in rate of sea level rise (Figure 6A, B). The Hilo-Honolulu sea level rise difference has also decreased (Figure 6C). A similar nonlinear rate change is observed in the WOA steric estimates. We know of no geological explanation for this recent change in trend.

Steric effects, in extreme cases, can account for differential rates of sea level rise as high as 1 mm/yr deduced from tide gauge records several decades in length, even when these tide gauges are located as close as 350 km from each other. In the presence of such laterally variable oceanographic signals, the use of tide gauge observations can introduce significant errors into differential rates of vertical crustal motion.

Appendix A Case Study in Establishing a Network of CGPS and TG Stations

Introduction

The Pacific GPS Facility (PGF) and the University of Hawaii Sea Level Center (UHSLC) began installing continuous Global Positioning System (CGPS) reference stations at Tide Gauge (TG) sites throughout the world in 1998. As demonstrated in this thesis, colocated CGPS stations and tide gauges can provide significant insights into sea level change. By precisely measuring the vertical offset between a tide gauge and a colocated CGPS station, sea level measurements can be directly compared within a global datum. This section provides an overview of the CGPS-TG sites that we have installed to date (listed in Table A1) and includes a detailed look at the particularly challenging installation at Valparaiso, Chile.

Table A1. PGF / UHSLC Operated CGPS-TG Site List

GPS Site	Location	Monument Type	Installed
BMHA	Freeport, Bahamas	Aluminum Fixture Pole	06-05-2002
HNLC	Honolulu, Hawaii	Steel mast, flange	06-19-1997
MALD	Male, Maldives	Aluminum Fixture Pole	08-12-1999
MANZ	Manzanillo, Mexico	Aluminum Fixture Pole	04-13-1999
PALA	Malakal, Palau	Aluminum Fixture Pole	07-01-2001
TGCV	Sal, Cabo Verde	Aluminum Fixture Pole	04-29-2000
VALP	Valparaiso, Chile	Aluminum Tower	11-25-1998

CGPS Components and PGF Installation Guidelines

The CGPS consists of three primary components: a GPS antenna, a GPS receiver and a data logger (PC computer). The Pacific GPS Facility has installed and maintains dozens of CGPS stations around the world. Our installation procedures are rigorous and require that numerous physical and practical conditions be met. The primary physical requirements are: (*i*) a solid substrate in which to install the GPS antenna monument, preferably solid rock, (*ii*) an unobstructed sky view to allow maximum satellite coverage, and (*iii*) a low multipath environment, such as avoiding sites near large metallic surfaces. Practical necessities for the site include: (*i*) a continuous and reliable power supply, (*ii*) a dependable means of downloading the data, often a telephone modem or internet connection for automated downloads, and (*iii*) a secure site to prevent vandalism and theft. In the real world, these requirements are sometimes mutually exclusive and finding a suitable location for a CGPS installation can be a difficult and time-consuming exercise.

GPS Antenna Monuments and Antenna Reference Point (ARP)

The GPS antenna is installed on a specially designed monument. Most CGPS-TG sites use the Aluminum Fixture Pole, which was designed with TG installations in mind (Figure A1.a). The two exceptions are HNLC, which uses a steel flanged pole with support arms (Figure A.1.b), and VALP, which uses a framed aluminum tower with flanged aluminum coupling (Figure A4.b). Physical factors generally prevent the GPS antenna from being installed directly on the tide gauge itself.

Figure A1. PGF GPS Antenna Monuments

a. Aluminum Fixture Pole (left) b. Steel Flanged Pole with supports (right)

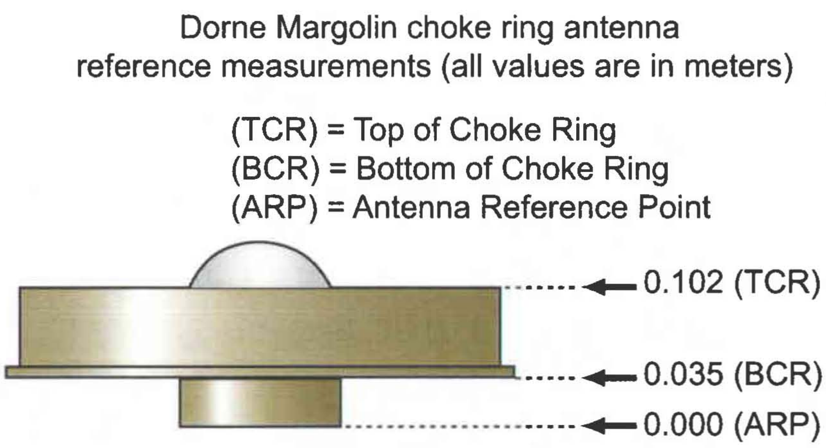


Figure A2. Measurement Reference Point Locations on the GPS Antenna

Table A2. Vertical Offsets Between GPS and TG Reference Points.

(GPS-SRP) = GPS Survey Reference Point; (TG-SRP) = Tide Gauge Survey Reference Point; (BCR) = Bottom of Choke Ring (GPS antenna); (ARP) = GPS Antenna Reference Point; (TS) = Tide Staff Reference Point; (GSL-Aqua) = Electronic Tide Gauge Reference Point.

SITE	GPS-SRP	TG-SRP	GPS-SRP Vertical Offset (m)	GPS-ARP Vertical Offset (m)	Date of Survey	Surveying Agency
BMHA	BCR	TS	1.832	1.797	06-05-2002	UHSLC
HNLC	ARP	GSL-Aqua	2.475	2.475	07-24-2000	NOAA
MALD	BCR	TS	4.262	4.227	09-13-2002	UHSLC
MANZ	BCR	TS	2.744	2.709	11-15-2001	CICESE
PALA	BCR	TS	2.416	2.381	06-13-2002	UHSLC
TGCV	BCR	TS	2.888	2.853	12-08-2002	UHSLC
VALP	ARP	TS	8.784	8.784	03-15-2002	SHOA

The GPS antenna should be situated close to the tide gauge so as to allow accurate determination of the offsets between the antenna reference point (ARP), the tide gauge reference point (*i.e.* tide staff if one exists), and a network of reference benchmarks (Bevis *et al*, 2002). The ARP is described in Figure A2. The vertical offsets of each CGPS-TG site are provided in Table A2.

Valparaiso, Chile: An Example of Adapting to Difficult Circumstances

A continuous GPS station was installed near the tide gauge at Valparaiso, Chile, in November 1998 as part of an effort to monitor global sea level change. The installation was performed by the Pacific GPS Facility (PGF) with support from the

University of Hawaii Sea Level Center (UHSLC) and the Servicio Hidrografico y Oceanografico de la Armada de Chile (SHOA). The Valparaiso tide gauge features a substantial time series of more than fifty years. The location of the tide gauge, however, presented numerous challenges for a reference quality CGPS installation. Major concerns included deformation of the CGPS/tide gauge observation platform (a concrete pier) as well as significant sky view obstructions and multipath sources (a tall lighthouse and nearby naval vessels). To overcome these physical limitations while ensuring geodetic integrity of the CGPS station, the following steps were implemented: (*i*) frequent leveling surveys are performed between the CGPS antenna, the tide gauge, and the reference benchmark network to monitor deformation of the pier and any resulting instrument offsets, and (*ii*) a non-standard monument was used to position the CGPS antenna more than 3 meters above the pier surface in order to achieve greater sky view and to minimize multipath effects. While this configuration differs somewhat from typical CGPS installations, it provides the desired level of positioning correlation between the CGPS station and the tide gauge, and thus provides enhanced sea level monitoring at Valparaiso.

Valparaiso Tide Gauge Description

The Armada de Chile pier is an L-shaped concrete structure dedicated to naval operations. The pier is actually composed of numerous concrete blocks supporting an asphalt surface that accommodates vehicular and pedestrian traffic. The tide gauge is situated at the bend of the "L" on the inboard side (Figure A3). A lighthouse (called

“El Faro”) approximately 16 m tall is situated on the outside bend of the "L", about 10 meters northeast of the tide gauge. The tide gauge was moved to its current location in 1984 (Figure A3). This location is quite well-suited for the tide gauge because the gauge is in quiet water, it is generally protected from accidental damage from marine craft, and it is easily accessible by SHOA personnel. Routine leveling surveys are performed by SHOA personnel to monitor any movement of the tide gauge relative to onshore reference points (bench marks). A detailed description of the Valparaiso tide gauge including instrumentation, history, and survey network details can be found at:

http://www.bodc.ac.uk/services/glosshb/stations/gloss175.htm

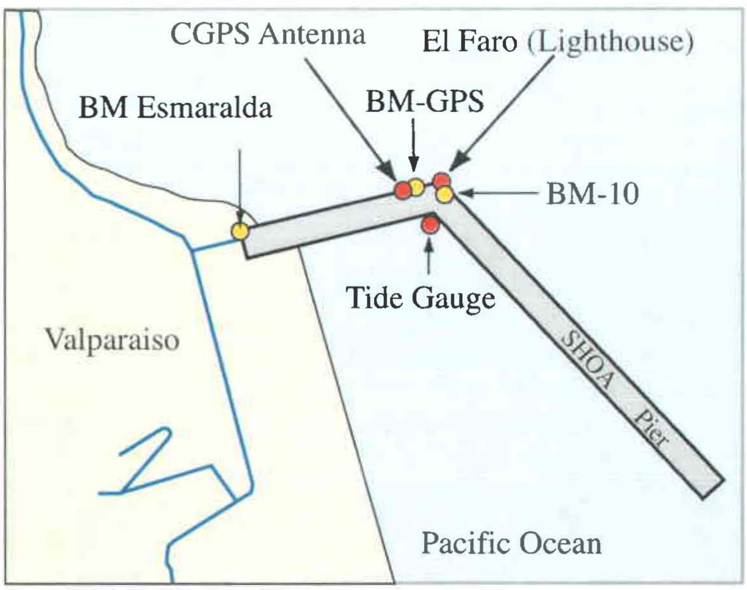


Figure A3. Valparaiso Pier Location Map

Installation Challenges and Solutions

Pier Deformation

The SHOA pier at Valparaiso, upon which the tide gauge is situated, is an artificial structure. Generally, we avoid artificial structures because they are subject to deformation through time and it is difficult to differentiate this structural deformation from ground surface deformation due to plate tectonics or other natural phenomena. Moreover, the Navy pier does not consist of a single structure. Rather, it is made up of many individual segments that are likely to move and deform independently of one another. SHOA leveling surveys indicate that the pier segment supporting the tide gauge subsided by more than 28 cm between 1941 and 1985.

Because this environment was not ideal on first inspection, we began searching for a suitable location on shore. Valparaiso is famous for the steep cliffs of its shoreline, and these cliffs effectively block much of the sky along the coast and thus make any shoreline site near the pier a poor choice for a CGPS. Several acceptable sites for the CGPS were identified on top of the high cliffs but these sites were impractical because they were too far away from the tide gauge. It was ultimately concluded that we had no choice but to install the GPS on the pier.

Due to the unstable nature of the pier at geodetic scales, it is critical to monitor any deformation of the pier segments containing the GPS antenna and the tide gauge relative to the reference network on shore. As long as any structural deformations are properly measured, their effects on the GPS/tide gauge relationship can be compensated for and thus mitigated. It was decided that geodetic leveling surveys would be conducted between the GPS antenna, the tide gauge, and shore-based reference points on a regular basis. Through frequent leveling surveys, we are confident that we can observe and compensate for any significant movements of the GPS due to deformation of the pier.

Sky View and Multipath

We decided to install the CGPS on the pier, although the height of the lighthouse and the superstructure of docked Navy ships effectively obstructed the site's sky view. The solution to the sky view problem due to the GPS antenna's proximity to the lighthouse was twofold. First, we positioned the antenna so that it was as far away from the lighthouse as practical, in this case approximately 30 meters. Second, we raised the antenna up as high as practical. The GPS antenna was installed atop a tower monument approximately 3 meters above the pier surface. The monument was bolted to the surface of the outer pier wall rather than being buried and cemented into place beneath the surface (Figure A4.a).

Figure A4. GPS Antenna on Pier

a. GPS Antenna in the shadow of the Lighthouse (Left). b. GPS antenna mounted on custom mount (Right).

Monument Installation Details

We used a commercially available aluminum tower designed for antennas and meteorological instruments manufactured by Glen Martin Engineering. The RT-832 "roof tower" has a height of 9.0 feet (2.7 meters) and is constructed of corrosion-resistant aluminum with stainless steel fastening hardware. We designed a custom adapter plate to couple the GPS antenna to this tower (Figure A4.b). A useful feature was that the adapter plate could be leveled independently of the tower to ensure that the GPS antenna was perfectly horizontal. Once leveled in this way the entire structure was "locked" into a rigid unit.

The tower was easy to install. We used a masonry hammer drill to bore four holes in the concrete pier surface. Each hole was approximately 20 cm deep. Threaded steel rods (3/4" diameter) were then inserted into the holes and permanently emplaced using epoxy. The tower foundation was then bolted to the rods. Positioning the antenna approximately 3 meters above the surface of the pier at a distance of approximately 30 meters from the lighthouse significantly improved the sky view. From the height of the antenna, the lighthouse reaches a maximum elevation of 25° over an area spanning 5° along an azimuth centered on 080°. A nearby lamppost produces a minimal obstruction of approximately 10° elevation at an azimuth of 250 degrees. Sky view is sub-optimal, however, for this specific location it will prove adequate.

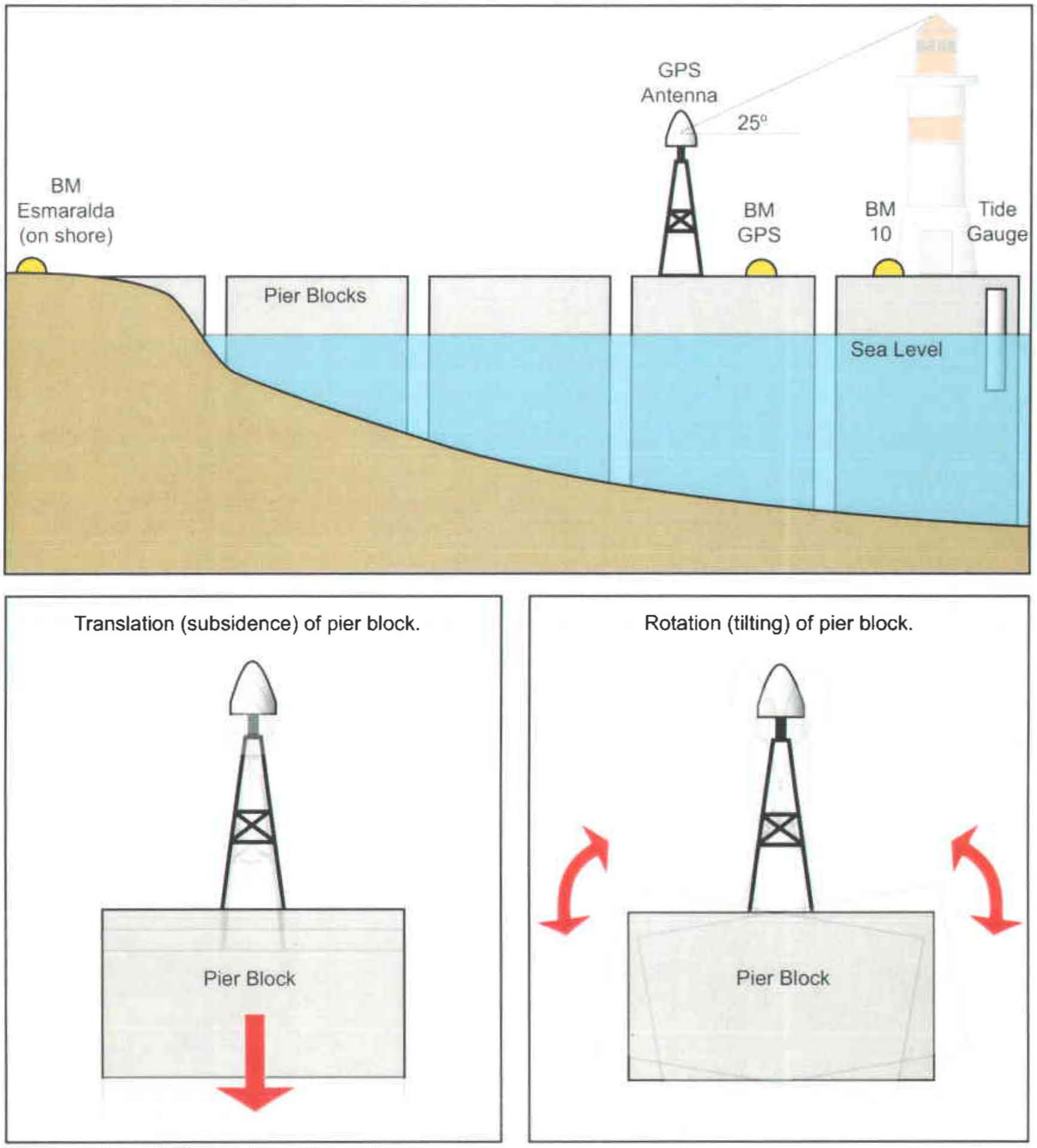


Figure A5. Valparaiso Pier Construction

The pier is constructed from several giant concrete blocks. These blocks undergo translation (subsidence) or rotation (tilt) with time, where each block deforms independently from the other blocks. Instruments and reference benchmarks must be surveyed on a regular basis to monitor offsets due to deformation of the pier.

Regular leveling surveys thus provide a means of determining the height offset between the tide gauge and the GPS through time. No vertical displacement between the tide gauge and the GPS was measured between December 1998 and March 2002.

A benchmark was installed at the base of the GPS antenna tower to provide a pier surface reference point for measuring the height of the GPS antenna reference point (ARP) above the pier. This benchmark is called "B.M. GPS" or "BM-GPS". The ARP is located in the plane of the GPS antenna's lower mounting surface, beneath the preamplifier housing (see Figure A2). The offset between BM-GPS and the ARP is 3.041 m as determined by leveling surveys conducted by SHOA. Leveling surveys conducted by SHOA and UHSLC show that BM-GPS is positioned 3.331 m above NOAA's standard tide gauge reference mark (BM-10). However, because BM-GPS and BM-10 are situated on different blocks of the pier, the elevation between them will likely vary with time due to tilting and subsidence of the various pier blocks as shown in Figure A5. BM-10 is located approximately 10 m NE of the tide gauge and is situated on the same pier block as the tide gauge. Surveys show that BM-10 is situated 2.412 m above the UHSLC reference point on the tide gauge (UH@). Total offset between the tide gauge reference point (UH@) and the ARP is thus 8.784 m, as shown in Figure A6.

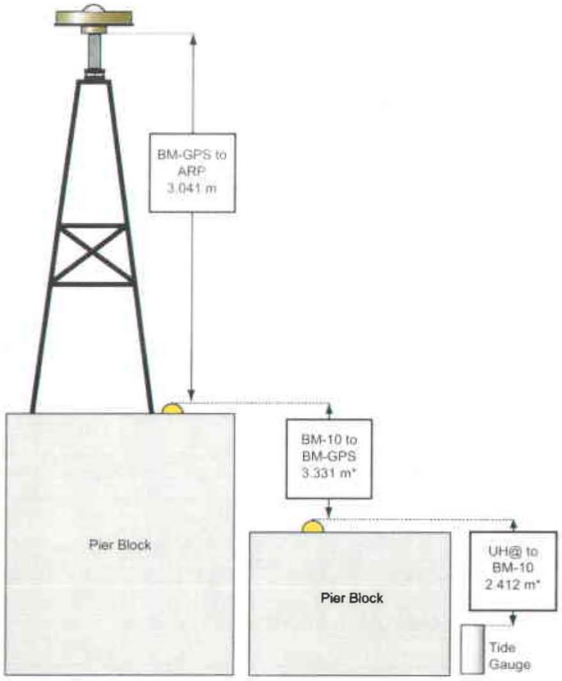


Figure A6. Vertical Offsets Between TG and GPS

GPS Receiver and Power Supply

The GPS receiver and peripherals were installed inside the lighthouse. This location provided security, protection from the elements and reliable AC power. A line-conditioner/voltage regulator was installed to help protect the system from electrical spikes and brownouts. A 12-volt, 70 Ah gel-cell battery was also installed to provide reserve power in case of an AC power failure.

Data Acquisition

SHOA personnel visit the site weekly to download the data manually (the GPS receiver's memory can store a maximum of 10-14 days of data). Although labor intensive, this approach has the added benefit of having people regularly visit the site and visually inspect the instruments. During a manual download, a laptop PC is connected to the GPS receiver; data files are downloaded to the computer and subsequently deleted from the receiver. The data are then archived at the SHOA office and are transferred electronically to the PGF archive at the University of Hawaii. GPS data processing is performed by the PGF.

Conclusion

The technical, logistical and environmental aspects of CGPS installations can differ significantly from those of tide gauge installations. When colocated CGPS stations and tide gauges are installed at the same time, these issues can generally be addressed and a suitable site can be identified that allows both instruments to perform optimally. However, when a CGPS reference station is installed at an existing tide gauge site, there may be few (if any) ideal locations for the CGPS. It is important to recognize that non-standard installation techniques and monitoring procedures may be necessary to maintain the integrity of the GPS data quality in these situations. The installation of the CGPS near the tide gauge at Valparaiso illustrates some of the issues faced by workers integrating the needs of GPS geodesy with sea level monitoring, and serves as an example of how such challenges can be resolved.

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