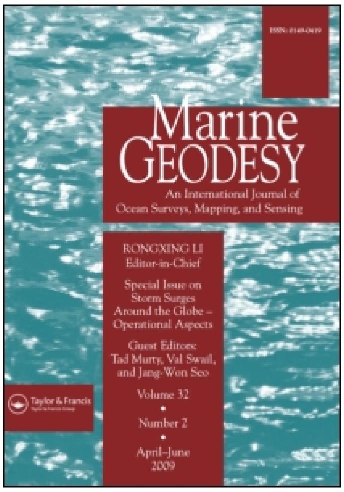
This article was downloaded by: *[Ardhuin, Fabrice]*
On: *17 February 2011*
Access details: *Access Details: [subscription number 933624544]*
Publisher *Taylor & Francis*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Marine Geodesy
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713657895

On the sea state dependence of sea level measurements at Platform Harvest

Michael E. Parke[a,b]; Stephen K. Gill[c]
[a] Colorado Center for Astrodynamics Research, University of Colorado, Boulder, Colorado, USA [b] Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO, USA [c] Ocean and Lake Levels Division, NOAA/National Ocean Service, Silver Spring, Maryland, USA

To cite this Article Parke, Michael E. and Gill, Stephen K.(1995) 'On the sea state dependence of sea level measurements at Platform Harvest', Marine Geodesy, 18: 1, 105 — 116
To link to this Article: DOI: 10.1080/15210609509379746
URL: http://dx.doi.org/10.1080/15210609509379746

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Marine Geodesy, Volume 18, pp. 105–116
Printed in the UK. All rights reserved.

0149-0419/95 $10.00 + .00
Copyright © 1995 Taylor & Francis

On the Sea State Dependence of Sea Level Measurements at Platform Harvest

MICHAEL E. PARKE

Colorado Center for Astrodynamics Research
University of Colorado
Boulder, Colorado, USA

STEPHEN K. GILL

NOAA/National Ocean Service
Ocean and Lake Levels Division
Silver Spring, Maryland, USA

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

This paper investigates correlations between sea level measurements and $H_{1/3}$ *at Texaco's Platform Harvest. In order to do so, a relationship is shown between the sample standard deviations of the 6-min NOAA acoustic system measurements and* $H_{1/3}$ *as estimated from CU Paros depth sensors. A transfer function for the NOAA acoustic system is developed by comparison between spectra of 2-s tsunami mode data with spectra from 1.1-s pressure data. Part of this transfer function is caused by the decay in pressure effects due to waves between the surface and the orifice of the protective well. The rest is due to damping characteristics of the protective well itself. The transfer function helps show the limitations of using the sample standard deviations of the NOAA acoustic system as a measure of* $H_{1/3}$.

Differences between sea level measurements show a distinct component related to $H_{1/3}$. *The effects related to* $H_{1/3}$, *low-frequency differences in the measurements, and wave effects are separated using an iterative procedure. If* $H_{1/3}$*-related effects are removed, then the sea level measurements agree to better than 1 cm rms for all three systems. The cause of the low-frequency differences is not understood. An estimate of the* $H_{1/3}$ *dependence of each individual system is found by removing a 1-year tidal prediction based on the NOAA acoustic system from sea level from each of the systems. It is assumed that real* $H_{1/3}$ *dependencies in sea level are small. The resulting residuals are iteratively separated as before. These results indicate that the greatest* $H_{1/3}$ *dependence is found in the NOAA Digibub system and the least in the NOAA acoustic system. It should be noted that the* $H_{1/3}$ *dependency found here occurs because of the harsh open ocean conditions at Platform Harvest and would not be expected to be observed under normal conditions in sheltered waters such as harbors, rivers, or lagoons.*

Keywords TOPEX, altimeter, calibration/validation, significant wave height, sea level, tide gauge

This work was performed at the Colorado Center for Astrodynamics Research, University of Colorado under contract 957388 with the Jet Propulsion Laboratory, California Institute of Technology, and at the National Ocean Service, Silver Spring, Maryland.

Address correspondence to Dr. Michael E. Parke, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO 80309, USA.

As has been described in Morris et al. (1995), Texaco's Platform Harvest was chosen to be the NASA calibration/verification site for the TOPEX/Poseidon altimetric mission. As part of the instrumentation of the platform, there were three tide gauge systems installed at Platform Harvest off the coast of southern California near Point Conception. The platform has been determined to be located at 34.470923 N and 120.685845 W using GPS measurements (Christensen et al., 1994) and is in approximately 200 m of water. Two of the tide gauge systems consisted of experimental modifications of the standard NOAA Next Generation water level management system (Gill et al., 1995), one employing a downward-looking acoustic sensor (acoustic system) and the other a "bubbler" pressure sensor (Digibub system). The third system consisted of two Paros depth sensors run by the University of Colorado (Kubitschek et al., 1995). The modifications to the standard NOAA system and the design of the CU system were governed by the need for long-term observations in the harsh open ocean environment found at Platform Harvest. Each of the tide gauge systems was mounted to Platform Harvest using a stainless steel riser. The NOAA acoustic system used its riser as a stilling well, the NOAA Digibub had its nitrogen gas orifice at the bottom of its riser, and the CU depth sensors were mounted in a cage that projected below the end of its riser. The data collection rates varied by system. Both NOAA systems collected data on 6-min centers based on averages of 3-min bursts of measurements taken 2 s apart. In addition to the averages, sample standard deviations were reported based on each 3 min of data. During many of the satellite overflights, 2-s data (Tsunami mode data) were also collected from the NOAA Next Generation acoustic system. The CU system collected data on 82.4-s centers (low-rate data) between overflights with 1.1-s data collected during the 2-h period surrounding most overflights (high-rate data).

General comparisons between sea level measurements from the different systems are given in Gill and Parke (this issue). The purpose of this paper is to explore the $H_{1/3}$ dependence of the sea level measurements. $H_{1/3}$ is defined to be the average of the highest one third of the waveheights (measured peak to trough) in a given region. The relationship between $H_{1/3}$ and more conventional statistics depends on the spectra but has been shown to be approximately 4.00 times the rms of the wavefield (Kinsman, 1965). For this paper we use 4.00 times the rms of the wave field to define $H_{1/3}$. Because high sampling rates occurred only around the times of the satellite overflights, there was no high resolution direct measure of $H_{1/3}$ at other times. Thus this paper begins with a comparison of $H_{1/3}$ estimates from the CU high-rate data and the sample standard deviation measurements from the NOAA acoustic system. A transfer function is developed for the NOAA acoustic system in order to explore the limitations of this relationship. Sea level measurements are then compared using the sample standard deviations of the NOAA acoustic system as a measure of $H_{1/3}$.

$H_{1/3}$ from NOAA Acoustic System Sample Standard Deviations

$H_{1/3}$ estimates were generated from CU 1.1-s high-rate data during the 2-h period around each TOPEX/Poseidon overflight. Each estimate was based on 6 min worth of data centered on the NOAA measurement times. Figure 1 shows a plot of these $H_{1/3}$ estimates vs. the sample standard deviation measurements of the NOAA acoustic system. As can be seen, there is a direct relationship between $H_{1/3}$ as estimated from the CU data and the sample standard deviations. Figure 1 also shows a line fit through the data using minimum absolute deviations (Press et al., 1992). The slope of the line is 0.1548 m/m. The standard

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

deviation about this line of $H_{1/3}$ estimates generated from the sample standard deviations is 0.41 *m*.

There appears to be a bimodal relationship between the $H_{1/3}$ estimates and the NOAA acoustic system sample standard deviations at low significant waveheights. This occurs because there tends to be a bimodal distribution in wave frequencies observed at the platform (Kubitschek et al., 1995). The lower branch in Figure 1 corresponds to relatively high wave frequencies. The upper branch corresponds to relatively low wave frequencies.

In order to investigate the frequency dependence of the NOAA acoustic system more fully, an estimate of the transfer function of the acoustic system was generated by comparison between spectra from tsunami mode data and CU high-rate data collected around the overflight times. In order to have the frequency content of the spectra match, the CU data were interpolated to the times of the NOAA data. The spectra of the CU pressure data were converted to spectra of surface waves using classical wave theory (Kinsman, 1965). The transfer function was then generated by dividing the spectra from the acoustic system by the equivalent estimated surface height spectra from the CU data. Estimates were only made for those frequencies for which the estimated surface wave spectrum was at least 0.05 m^2/s.

In all, 223 spectra were compared. The transfer functions from each of these cases were averaged whenever there were more than 10 values available. Except for the low frequency range between one cycle per 15 s and one cycle per 20 s, there were always at least 50 estimates. The results are shown in Figure 2.

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

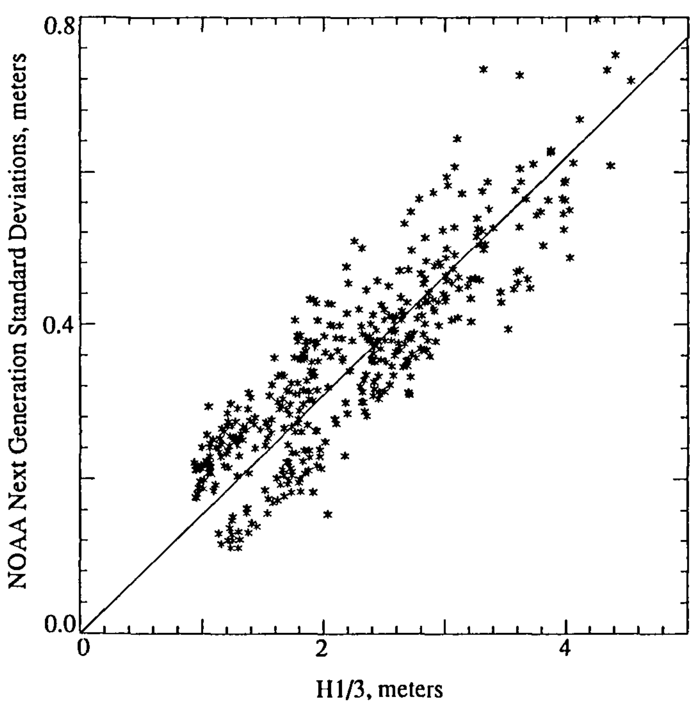


Figure 1. Comparison of NOAA Next Generation standard deviations with $H_{1/3}$ values from CU pressure gauges.

This transfer function is the product of an exponential decay down to the orifice of the protective well and the transfer function of the protective well. A description of the protective well is given in Gill et al. (1995). The equation for the solid line in Figure 2 is given by

$$t_{sw} = [\exp(-\ \omega z_o)]^2[\exp(-\ \omega z_s)]^2 \tag{1}$$

where ω is the angular wavenumber, z_o is the mean depth of the orifice below mean sea level (7.041 m), and z_s is 4.65 m. What this means is that on average there is less attenuation of surface wave energy inside the stilling well than occurs from the natural decay of wave pressures from the surface to the orifice depth.

The transfer function of Figure 2 shows some of the limitations of using sample standard deviations from the acoustic system data as a measure of $H_{1/3}$. Frequencies above one cycle/10 s are damped severely. Thus the standard deviations are much more sensitive to low-frequency waves than high-frequency waves. Thus in the presence of swell, $H_{1/3}$ should be overestimated by the relation given previously while in the presence of locally generated waves $H_{1/3}$ should be underestimated.

In addition, a few of the comparisons show the effects of resonances inside the stilling well. The worst of these cases occurred for the overflight of TOPEX/Poseidon cycle 22. The transfer function results are shown for all of the cycle 22 spectral comparisons in Figure 3. As can be seen, there is considerable enhancement of wave energy near one cycle/11 s.

Despite these limitations, the standard deviations of the NOAA acoustic system are a good first-order measure of $H_{1/3}$ and will be used as such for the rest of this paper.

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

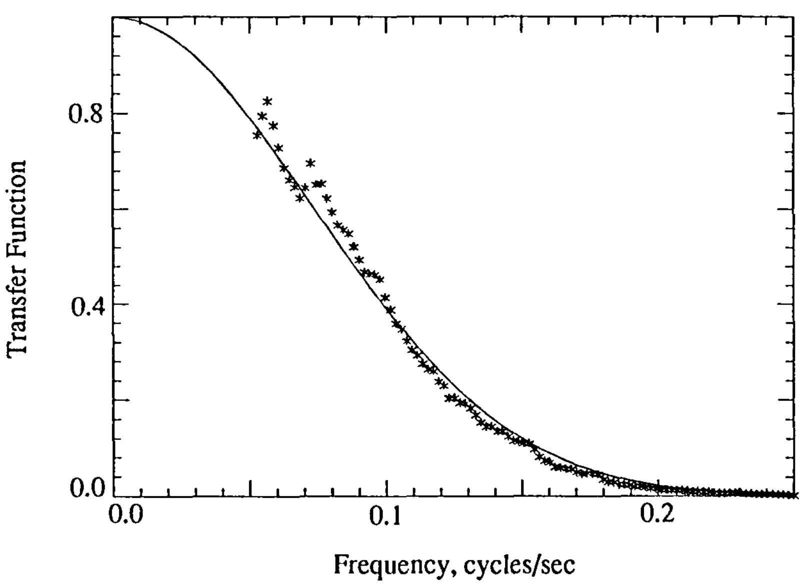


Figure 2. Transfer function between NOAA Next generation tsunami mode data and surface wave variations as determined by comparison with CU pressure data.

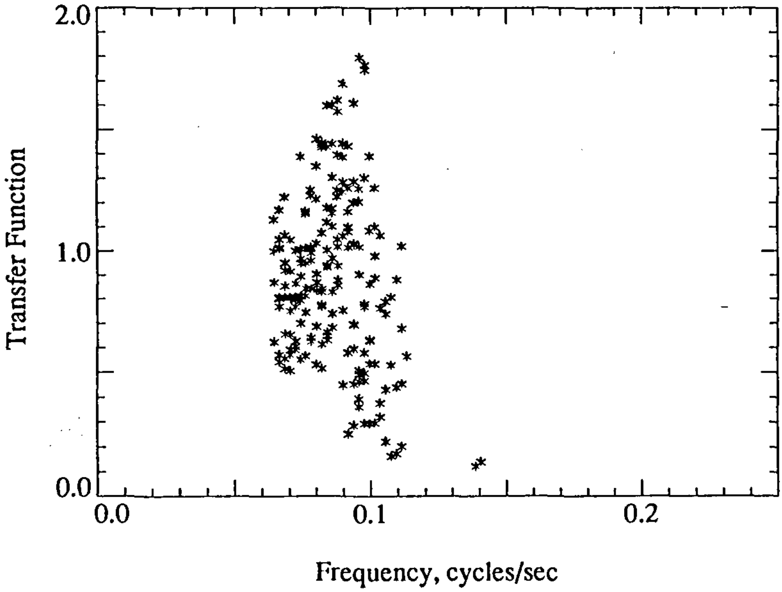


Figure 3. Transfer function as shown in Figure 2, except for cycle 22.

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

Sea Level Differences

The top three sections of Figure 4 show the difference between sea level measured by the three sea level systems, with the CU data averaged to the 6-min NOAA sampling times. The fourth section shows the sample standard deviations from the NOAA acoustic system. There is a very clear correlation between the sea level differences and the sample standard deviations.

Figure 5 shows a scatterplot of the difference between the NOAA acoustic and Digibub systems vs. the sample standard deviations from the acoustic data. There is a clear relationship between the two. A good description can be found by assuming that the $H_{1/3}$ dependence was zero up to a threshold and varied linearly thereafter. This is the functional dependence found by EG&G (1985) when comparing the NOAA acoustic system with wave staff measurements. This functional form will be assumed for the rest of this paper although the actual functional form may well be a function that is asymptotic to zero at low $H_{1/3}$ values and asymptotic to a straight line at high $H_{1/3}$ values. The data here are not sufficient to tell the difference. The EG&G measured values cannot be used to correct the acoustic data because the EG&G measurements were taken in shallow water and with a different orifice depth. Scatterplots using the differences between the CU sea level and the NOAA sea levels show a similar functional form and so are not presented here.

A first-order separation of the $H_{1/3}$ related effects, low-frequency differences, and wave effects was found iteratively by assuming the above functional form for the $H_{1/3}$ dependence (with NOAA acoustic sample standard deviations being used as a surrogate for $H_{1/3}$). This procedure consisted of an initial guess at the $H_{1/3}$ dependence. With the estimated $H_{1/3}$ dependence removed, the residual was filtered with a triangle filter of length 1 week to produce an estimate of the non–$H_{1/3}$-related long-period differences

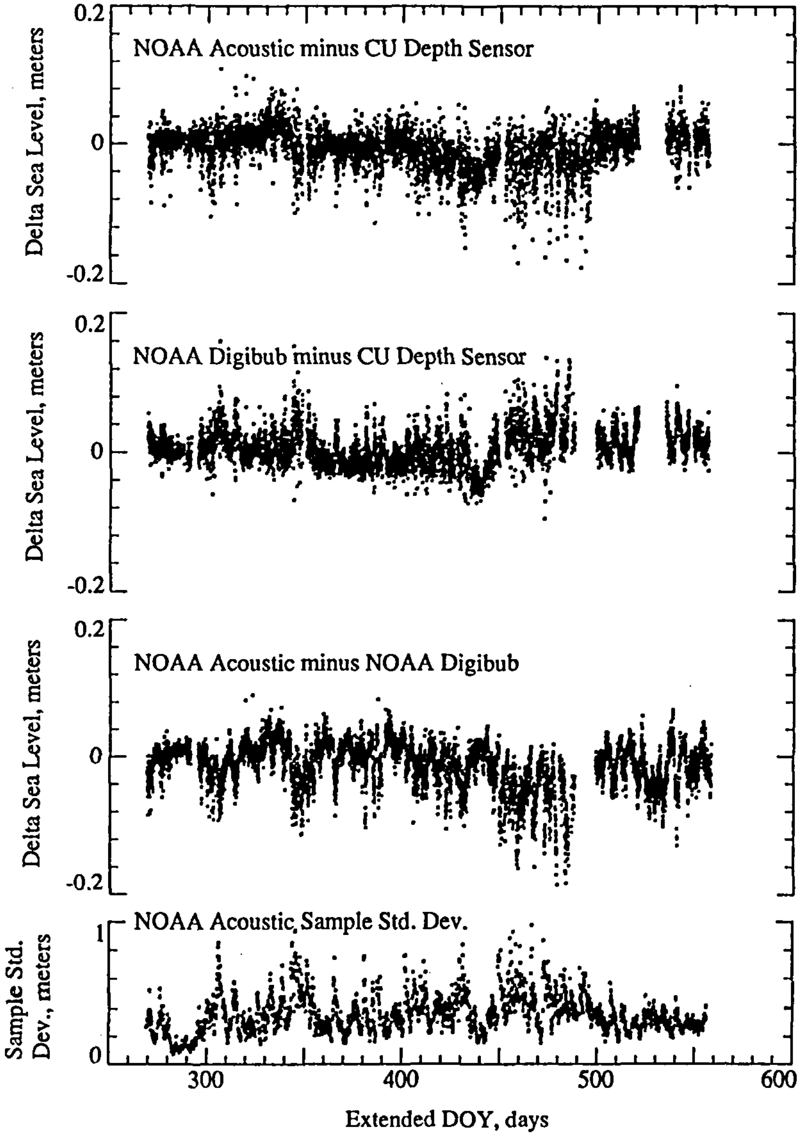


Figure 4. Comparison of sea level differences with the standard deviations from the NOAA acoustic system. Extended DOY is days after 0 h Dec. 31, 1991.

between the systems. The long-period differences were removed from the original data and an $H_{1/3}$ dependence was iteratively fit to the residuals. The $H_{1/3}$ dependence was found by assuming a threshold value of the NOAA acoustic sample standard deviation and fitting a line to the residual differences as a function of the sample standard deviations using the technique of minimum absolute deviations. The zero crossing of this line was used as a new threshold and a new fit produced. This was continued until the fit converged. Once a new $H_{1/3}$ dependence was generated, a new estimate of the non–$H_{1/3}$-related long-period differences was generated and so on.

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

This iterative process was continued for four iterations. Figure 6 shows an equivalent scatterplot to Figure 5 with the estimated long-period differences removed. If the separation were perfect, all that would be left would be the $H_{1/3}$ effects and wave energy. The change from Figure 5 is not dramatic because the sea level differences between the systems appear to be dominated by the $H_{1/3}$ dependence. The fit to the difference between the acoustic system and CU system vs. the NOAA acoustic sample standard deviations produced a threshold of 0.167 m and a slope of -0.06547 m/m. The fit to the difference between the NOAA Digibub system and the CU system produced a threshold of 0.241 m and a slope of 0.08256 m/m. The fit to the difference between the NOAA Next Generation acoustic system and the NOAA Digibub system produced a threshold of 0.223 m and a slope of -0.14894 m/m.

Figure 7 shows the resulting estimate of the non-$H_{1/3}$-related differences between the systems. As can be seen, there are long-term variations between the systems of approximately ± 2 cm. The source of these variations is not well understood. By comparing the three plots, one can determine which of the instruments is different than the others at a given time. Around day 340 there is a positive departure in the differences between the NOAA acoustic sea level and the sea levels from the other two systems, indicating that during this period the acoustic system differed from both the Digibub and CU systems.

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

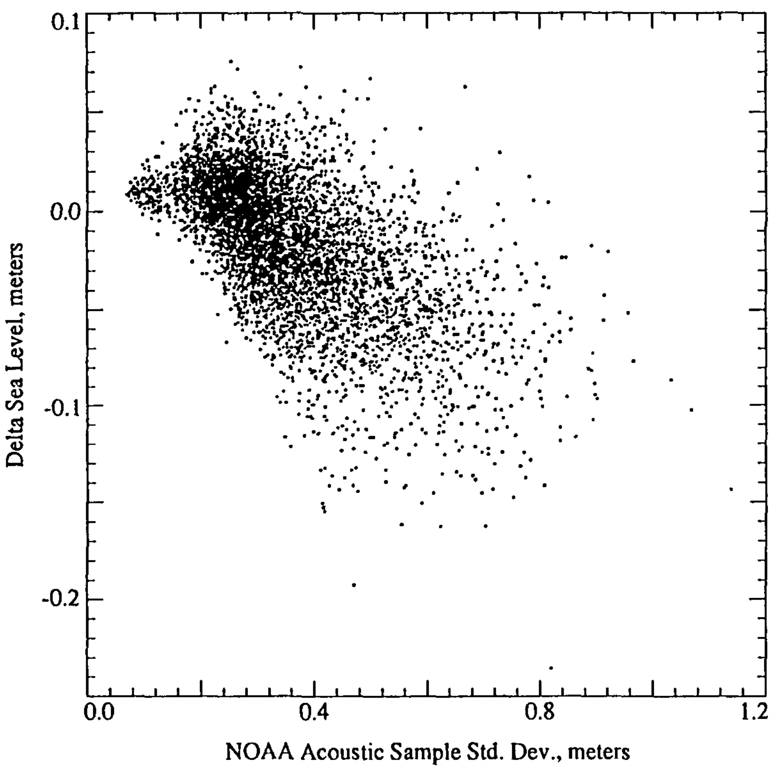


Figure 5. Scatterplot of sea level difference between NOAA acoustic and NOAA Digibub data with the standard deviations of the NOAA acoustic system.

Around day 440 there is a negative departure between the CU sea level and the other two, indicating that during this period the CU system differed from both the NOAA acoustic and Digibub systems.

Raw sea level differences between the acoustic and Digibub systems have a mean of −1.5 cm and a standard deviation of 3.4 cm, the differences between the acoustic and CU systems have a mean of −0.8 cm and a standard deviation of 2.9 cm, while the differences between the Digibub and CU systems have a mean of 0.5 cm and a standard deviation of 2.7 cm. Upon removal of the estimated $H_{1/3}$ effects and surface gravity waves, these become 0.4 cm and 1.6 cm, 0.4 cm and 1.4 cm, and −0.2 cm and 1.5 cm, respectively. It is encouraging that with the $H_{1/3}$-dependent effects and waves removed the systems agree to better than 0.5 cm in the mean and the differences have standard deviations on the order of 1.5 cm.

Absolute Sea Level

As was seen in the previous section, there is a strong $H_{1/3}$ dependence in the differences between sea level measurements from the different systems at Platform Harvest. In the sea level differences, sea level changes due to tides and other oceanographic effects cancel

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

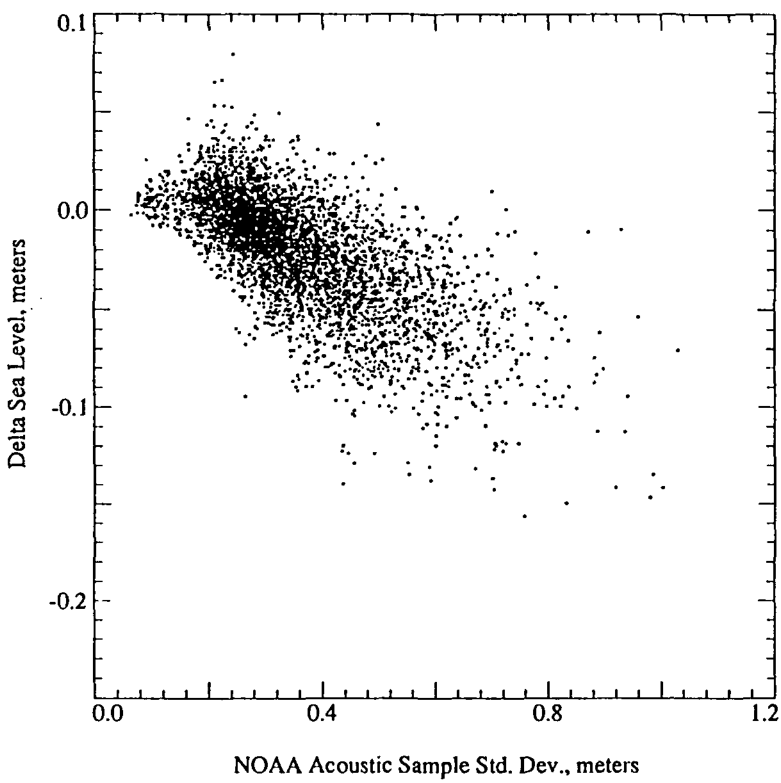


Figure 6. Scatterplot of sea level difference between NOAA Next Generation and NOAA Digibub data with low-frequency component removed vs. the standard deviations of the NOAA Next Generation system.

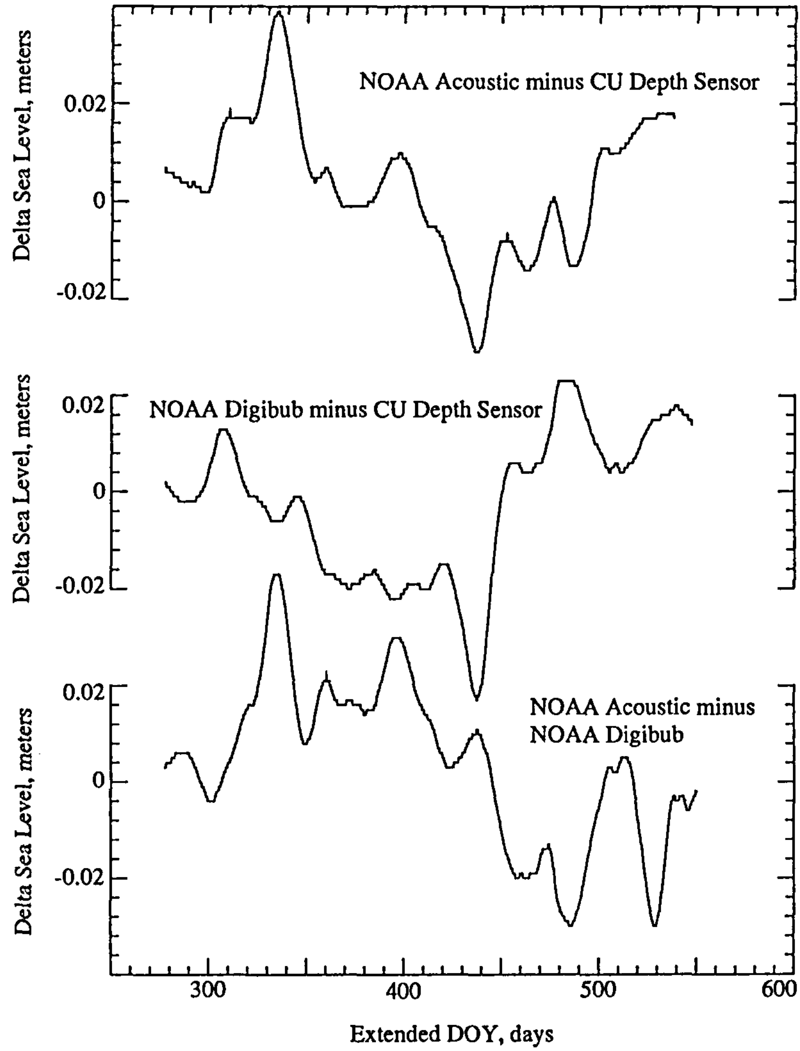


Figure 7. Low-frequency non–$H_{1/3}$-related component of sea level differences shown in Figure 4. Extended DOY is days after 0 h Dec. 31, 1991.

out, and so $H_{1/3}$ dependence is easier to detect. This section explores estimating the $H_{1/3}$ dependence from the sea level data itself by removing a tidal prediction based on a year of acoustic system data (Gill and Parke, 1995). In doing this, it is assumed that the natural $H_{1/3}$ dependence of sea level is smaller than the instrument effects.

Figure 8 shows the residuals for each of the systems when the tidal prediction is removed. In each case there is a lot of background variation and the $H_{1/3}$ dependence is hard to detect visually (although the dependence does show up in scatterplots of residual vs. the NOAA acoustic sample standard deviations for the Digibub and CU systems). The iterative procedure of the previous section was used to provide a first-order separation between $H_{1/3}$ effects, long-period non–$H_{1/3}$-related variations, and waves.

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

After six iterations, the estimate of the long period non-$H_{1/3}$-related variations is given in Figure 9. This dominantly represents nontidal oceanographic changes at the platform. Gill and Parke (1995) show that these sea level changes are dominantly a response to atmospheric pressure.

The fit to the $H_{1/3}$ dependence (with the NOAA acoustic sample standard deviations once again being used as a surrogate for $H_{1/3}$) produced a threshold of 0.130 m and a slope of 0.0060 m/m for the NOAA acoustic system data. A fit to the NOAA Digibub data produced a threshold of 0.217 m and a slope of 0.1141 m/m. A fit to the CU data produced a threshold of 0.251 m and a slope of 0.0766 m/m. This suggests that the strongest $H_{1/3}$ dependence is in the Digibub system while the smallest is in the acoustic system. The mechanism for the Digibub system $H_{1/3}$ dependence is probably that during

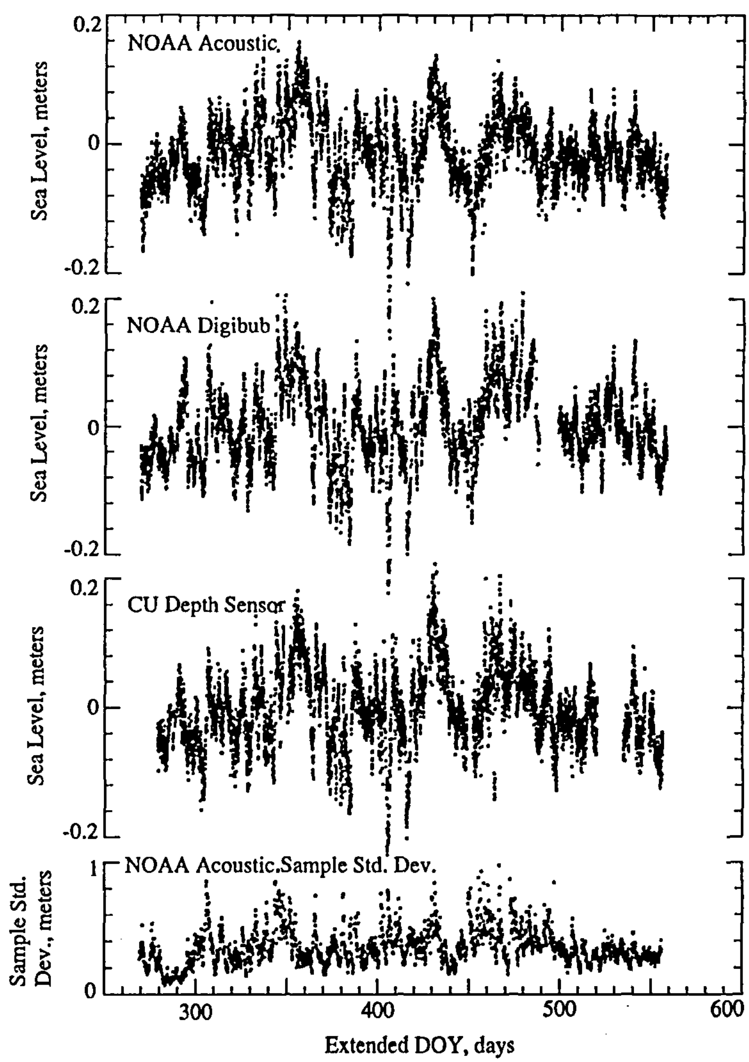


Figure 8. Sea level data with a 1-year tidal prediction based on NOAA acoustic data removed. Extended DOY is days after 0 h Dec. 31, 1991.

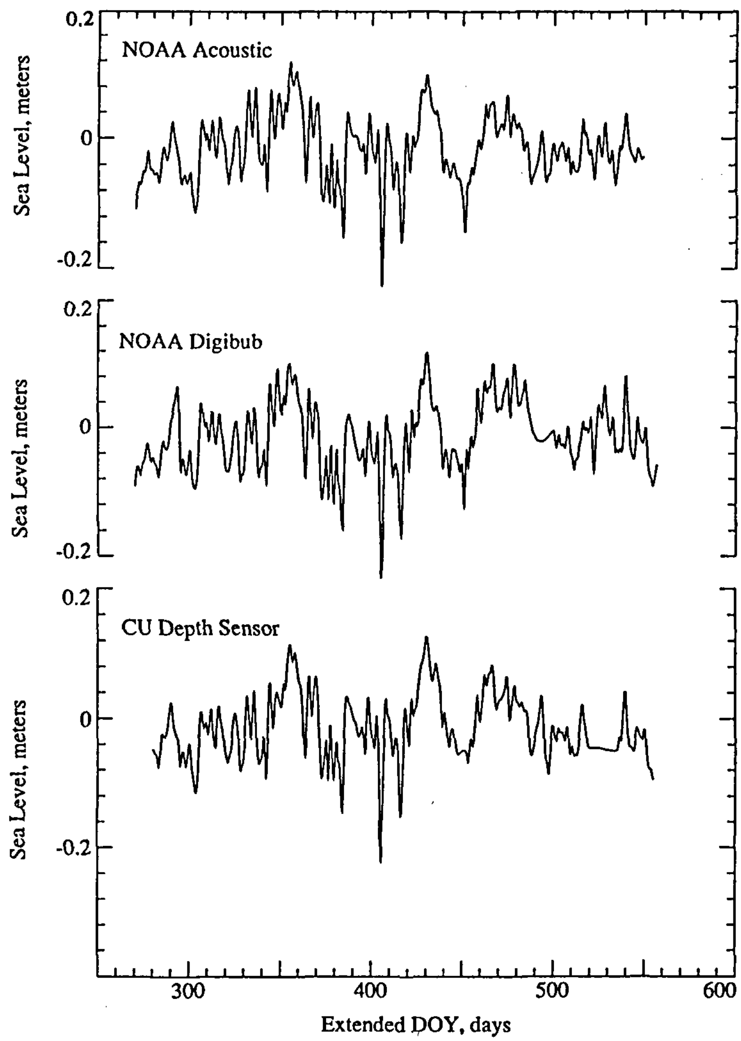


Figure 9. Low-frequency non-$H_{1/3}$-related component of sea levels shown in Figure 8. Extended DOY is days after 0 h Dec. 31, 1991.

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

times of high $H_{1/3}$ the effective measurement point of the system is driven up into the orifice chamber producing a bias in the measurement. The mechanism for the $H_{1/3}$ dependence of the CU system is not known but may be related to the design of the cage in which the depth sensors are located.

Discussion

It has been shown that the standard deviations of the NOAA acoustic system can be used as a first-order measure of $H_{1/3}$ at Platform Harvest. There is a clear relationship between these standard deviations and the differences in sea level between the systems. This implies that there is an $H_{1/3}$ dependence in at least two of the systems. However, there is no way to use the differences between the systems to determine the $H_{1/3}$ dependence of each individual system.

It is encouraging that when an $H_{1/3}$ adjustment is made to the sea level differences and waves are filtered out, the sea level systems agree in the mean to better than 0.5 cm and the differences have a standard deviation of about 1.5 cm. It is also encouraging that there is no evidence of drift between the systems.

A first-order estimate of the $H_{1/3}$ dependence was found by removing a 1-year tidal prediction from each of the sets of measurements and seeking an $H_{1/3}$ dependence in the residuals. This approach is limited by the fact that there will be in general real $H_{1/3}$-related changes in sea level. It is assumed that the real-world $H_{1/3}$ dependence is much smaller than the instrument dependences. The $H_{1/3}$ dependence presented here was used in a TOPEX/Poseidon closure analysis (Christensen et al., 1994). It should be noted that the algorithm for altimeter $H_{1/3}$ estimates is empirically determined and may also incorporate real-world $H_{1/3}$ dependencies.

The $H_{1/3}$ dependence found here occurs only above a threshold value of $H_{1/3}$. Because of this, it would not be expected to observe any $H_{1/3}$ dependence in sheltered waters such as harbors, rivers, or lagoons. It is only in the harsh open ocean environment, such as that in the EG&G (1985) study or at Platform Harvest, that sufficiently high sea states routinely occur. The $H_{1/3}$ dependence of the instruments should be revisited in the future when there are at least data from one complete seasonal cycle. With enough data, the natural $H_{1/3}$ dependence of sea level can be investigated. For example, $H_{1/3}$ is correlated with atmospheric pressure and atmospheric pressure is correlated with sea level. If these relationships can be sufficiently understood, then the above estimates of the instrument corrections can be repeated with a realistic natural $H_{1/3}$ dependence for sea level rather than assuming that there is effectively none.

Downloaded By: [Ardhuin, Fabrice] At: 08:20 17 February 2011

References

Christensen, E. J., B. J. Haines, S. J. Kheim, C. S. Morris, R. A. Norman, G. H. Purcell, B. G. Williams, B. C. Wilson, G. H. Born, M. E. Parke, S. K. Gill, C. K. Shum, B. D. Tapley, R. Kolenkiewicz, and R. S. Nerem. 1994. Calibration of TOPEX/Poseidon at platform Harvest. *Journal of Geophysical Research* 99:24465–24485.

EG&G. 1985. Stilling/Protective Well Study Results and Analysis of a Field Experiment at Duck, North Carolina. Report to Ocean Systems Development Group, National Ocean Service, NOAA, Silver Spring, Maryland.

Gill, S. K., R. F. Edwing, D. F. Jones, T. N. Mero, M. K. Moss, M. Samant, H. H. Shih, and W. M. Stoney. 1995. NOAA/National Ocean Service Platform Harvest instrumentation. *Marine Geodesy* 95:49–67.

Gill, S. K., and M. E. Parke. 1995. Platform Harvest sea level measurement comparisons. *Marine Geodesy* 95:85–95.

Kinsman, B. 1965. *Wind Waves: Their Generation and Propagation on the Ocean Surface.* Englewood Cliffs, N.J.: Prentice Hall.

Kubitschek, D. G., M. E. Parke, G. H. Born, J. Johnson, and C. McLaughlin. 1995. CU sea level system at Platform Harvest. *Marine Geodesy* 95:69–83.

Morris, C. S., S. J. DiNardo, and E. J. Christensen. 1995. Overview of the TOPEX/Poseidon Platform Harvest verification experiment. *Marine Geodesy* 95:25–37.

Press, W. H., S. A. Teukolsky, W. T. Vettering, and B. P. Flannery. 1992. *Numerical Recipes in FORTRAN: The Art of Scientific Computing,* 2nd ed. Cambridge, Cambridge University Press.