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Water levels and harbor response at Crescent City associated with the Great Chilean Earthquake tsunami of May 1960

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UNIVERSITY OF CALIFORNIA, SAN DIEGO

Water Levels and Harbor Response at Crescent City Associated with the Great Chilean Earthquake Tsunami of May 1960

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Oceanography

by

Linda Cheryl Holmes-Dean

Committee in charge:

Professor Myrl C. Hendershott, Chair
Professor Richard Salmon
Professor Clint Winant

2012

The Thesis of Linda Cheryl Holmes-Dean is approved and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego
2012

DEDICATION

I may have given up on this several times if it weren’t for the love and support of my family. Not only from my husband and children, who watched me work many hours before and after work and on the weekends, but also my immediate family.

Although Dad is no longer with us, I know he is beaming. My brothers and sisters are all proud for me. But, this thesis is dedicated especially to Mom and my brother Charlie who both lovingly kept asking, “How’s your thesis coming?” Without their constant prodding and caring, I may have actually given up!

I love them all …. “a bushel and a peck, with a hug around the neck” …

Thanks!

EPIGRAPH

Through Him all things are possible.

Matthew 19:26

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The staff at Docusure, San Diego worked patiently providing tedious test runs to determine optimum scan settings and to solve many other problems associated with the scanning. I am grateful as well to Junaid Fatehi of Scripps Institution of Oceanography who oversaw the digitizing process and patiently trained me in the procedure.

Chapter 1 is a Scripps Institution of Oceanography Technical Report, as uploaded to University of California's eScholarhip on January 27, 2010. The thesis author was primary investigator and author of this report.

Chapter 2, in part, is currently being prepared for submission for publication of the material. The thesis author was primary investigator and author of this material.

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PUBLICATIONS

1. With R. E. Flick, M. C. Hendershott, O. T. Magoon, P. D. Bromirski and T. R. Kendall, *Water Levels at Crescent City Associated with the Great Chilean Earthquake Tsunami of May 1960*, Scripps Institution of Oceanography Technical Report, November 2009.

2. With M. H. S. Elwany, A. Thum, and S. Aijaz, *1995 Inlet Channel Excavation and Maintenance Efforts at San Elijo Lagoon*, prepared for San Elijo Lagoon Conservancy, Encinitas, California by Coastal Environments, Encinitas, California, December 1995.

3. With M. H. S. Elwany, *Coastal Currents at San Onofre and Their Relationship to Currents in Southern California*, prepared for Southern California Edison Company, Rosemead, California by Coastal Environments, Encinitas, California, March 1993.

4. *Langmuir Circulations*, Science Applications International Corporation, Technical Memo, 1984.

5. With C. W. Winant, The Longshore Coherence of Currents on the Southern California Shelf During the Winter: A Data Report, Scripps Institution of Oceanography Reference 83-22, 1983.

6. Nearshore San Onofre Current Meter Program Quarterly Data Reports (Fall 1976 - Fall 1980), prepared for the Marine Review Committee, MRC Documents 81-01 (A–Q), 1980.

7. Wave Climate Data Analysis of Measurements Taken Near San Onofre Nuclear Generating Station Unit 1 During 1979 and 1980, prepared for the Marine Review Committee, MRC Document 80-03.

8. With D. L. Inman, C. E. Nordstrom, S. S. Pawka, and D. A. Aubrey, *Nearshore Processes Along the Silver Strand Littoral Cell*, prepared for the U. S. Army Corps of Engineers, L. A. District by Intersea Research Corporation, La Jolla.

9. With S. S. Pawka, D. L. Inman, and R. L. Lowe, *Wave Climate at Torrey Pines Beach, CA*, prepared for the U. S. Army Corps of Engineers Research Center, Technical Paper No. 76-5, May 1976.

10. University of California Master Thesis, *Water Levels and Harbor Response at Crescent City Associated with the Great Chilean Earthquake Tsunami of May 1960,* 2012.

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ABSTRACT OF THE THESIS

Water Levels and Harbor Response at Crescent City Associated with the Great Chilean Earthquake Tsunami of May 1960

by

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Master of Science in Oceanography

University of California, San Diego, 2012

Professor Myrl C. Hendershott, Chair

The Great Chilean Earthquake of 22 May1960 generated a tsunami that caused widespread damage along the Pacific Rim, including at Crescent City, CA. Coincidentally, the water level fluctuations at Crescent City were successfully recorded by two Stevens Type A-35 paper-chart water level recorders installed as part of a U.S. Army Corps of Engineers study of harbor seiche. Data is available on 35 paper rolls from each of two locations in the harbor, Citizen's and Dutton's docks.

Eleven rolls at each of the two docks were scanned and digitized covering the time period from 17:34, 20 May to 08:32, 31 May 1960 (PST). Digitization was performed at a sample rate of 1 Hz allowing high resolution analysis of the data.

Chapter 1 documents the procedures used to obtain the digital time series of water levels at the two docks.

A frequency domain investigation of the harbor response is presented in Chapter 2. Background data prior to the onset of the tsunami were used to estimate an admittance function at both docks, the result suggests the presence of edge wave resonances over the adjoining shelf as well as of individual harbor modes. Spectral ratios (of tsunami divided by background spectra) show amplification of the tsunami relative to the normal background. Frequency domain coherence and phase estimates as well as spectrograms at the two stations further show tidal modulation of the harbor response at frequencies at and somewhat above those characterizing the tsunami.

1. CHAPTER 1

The Scripps Institution of Oceanography Technical Report, Water Levels at Crescent City Associated with the Great Chilean Earthquake Tsunami of May 1960 was uploaded to University of California's eScholarhip on January 27, 2010. The report details methods used to prepare strip chart data of water levels taken at Citizen's and Dutton's Docks in the Crescent City Harbor during the tsunami generated by the Chilean Earthquake in May 1960 Of the 70 rolls, 22 were scanned and digitized, 11 at each of the two docks. The digitized data cover the time period from 17:34, 20 May to 08:32, 31 May 1960 (PST). Digitization was performed at a sample rate of 1 Hz allowing high resolution analysis of the data, in sharp contrast to the tide gage data available at the time with a typical sampling interval of 1 hour.

This report documents the procedures used to obtain the digital time series of water levels at the two docks. The original paper chart records are in the custody of the San Francisco District, U.S. Army Corps of Engineers.

Scripps Institution of Oceanography Technical Report

Water Levels at Crescent City Associated with the Great Chilean Earthquake Tsunami of May 1960

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1.1 Abstract

The Great Chilean Earthquake of 22 May1960 generated a tsunami that caused widespread damage along the Pacific Rim, including at Crescent City, CA. Coincidentally, the water level fluctuations at Crescent City were successfully recorded by two Stevens Type A-35 paper-chart water level recorders attached to float gauges in stilling wells that had been installed as part of a U.S. Army Corps of Engineers study of harbor seiche. Data from 11 May to 16 June 1960 is available on 35 paper rolls from each of two locations in the harbor, Citizen's and Dutton's docks.

Of the 70 available rolls, 22 were scanned and digitized, 11 at each of the two docks. The digitized data cover the time period from 17:34, 20 May to 08:32, 31 May 1960 (PST). Digitization was performed at a sample rate of 1 Hz allowing high resolution analysis of the data, in sharp contrast to the tide gage data available at the time with a typical sampling interval of 1 hour.

This report documents the procedures used to obtain the digital time series of water levels at the two docks. The original paper chart records are in the custody of the San Francisco District, U.S. Army Corps of Engineers.

1.2 Introduction

The U.S. Army Corps of Engineers, San Francisco District supported a harbor seiche measurement project at the Crescent City Harbor in the 1960's. Stevens Type A-35 strip chart water level recorders connected to floats inside 14-inch diameter stilling well pipes were employed at two docks in the harbor for the study. Having the foresight to consider the possibility of a tsunami reaching the harbor, the stilling wells were designed to measure such an event if one occurred (Magoon, 1962).

A circular opening on one side of each pipe provided a water inlet, while a variable triangular slot on the other side could be opened when needed to speed outflow allowing for less damping of non-tidal signals (Satake, *et al*., 1988). Measurements were made from 11 May to 16 June 1960 at two docks inside Crescent City Harbor. All in all, 70 strip chart rolls are available, 35 at each dock. No data exists at Citizen's Dock for 4 June 1960, and none exists at Dutton's Dock for 14 May 1960. Each roll covers approximately a 24-hour time period.

Ocean bottom topography offshore tends to amplify tsunami waves as they approach Crescent City making it a "sitting duck" (Lee, *et al*., 2008). This causes both near and far field tsunamis to cause larger waves and more damage at Crescent City than at nearby areas, even when Crescent City is farther from the earthquake source. Fatefully, the Chilean earthquake of 22 May 1960 created the opportunity to make relatively high-resolution measurements of the associated water level fluctuations.

The Chilean event generated one of the most destructive tsunamis in the Pacific basin during historic times (Lander, *et al*., 1993), with over $24 million in damage reported in Hawaii. Although the March 1964 Alaska tsunami did far more damage at Crescent City, including killing 11 people, its impact over the Pacific basin was not as great. In 1960, streets and structures flooded, boats sank, and approximately 12 feet of sediment was deposited in some areas of the harbor. In all, it was estimated that the tsunami caused a relatively modest approximately $30,000 in damages (Magoon, 1962), equivalent to about $220,000 in 2008.[1]

After partial hand-digitization and initial analysis and reporting by Magoon (1962), the 1960 Crescent City strip chart data were placed in storage. In early 2006, two boxes of chart rolls (Figure 1.1) containing the tsunami data were re-discovered in a Corps of Engineers records repository. The 1960 recordings were immediately recognized as an important contribution to the growing database needed to understand tsunami propagation and decay, and perhaps to help validate tsunami models. This interest was heightened by the devastating 2004 Indian Ocean tsunami caused by the great Sumatra earthquake.

All 70 strip chart rolls have been scanned and the data from 22 rolls, 11 at each of the two docks (the time period from 20-31 May 1960 spanning the tsunami), have been digitized (Kendall, *et al.*, 2008). The scanning and digitizing processes were carried out at the Scripps Institution of Oceanography and are detailed in this report, which is intended as a reference for those who wish to further analyze these data.

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[1] Adjusted according to the Consumer Price Index, which was 29.6 in 1960 and 215.3 in 2008.

The original chart data were recorded in feet, with annotations on the rolls also given in these units. For this reason, this report also presents the measurements in feet. Digitization was carried out at 1 Hz because the software was capable of this resolution, and not because the response of the float and stilling well systems or Stevens recorders could necessarily resolve signals at this frequency. The digitized records permit more convenient display as well as time series, spectral, statistical, and other analyses to be performed.

1.3 Background

Historically, the tsunami waves from distant earthquakes have resulted in larger and more destructive waves at Crescent City than waves from nearby earthquakes, and even than at locations considerably closer to the earthquake epicenters. For example, the tsunami of 1964 off Alaska (far source) caused an initial wave at Crescent City of 4.8 feet in height. However, the fourth wave was the largest at 20.8 feet (Lander, et al., 1993). On 25 April 1992, the magnitude 7.1 Cape Mendocino, California earthquake (near source, epicenter on land) did not produce observable waves at the nearby coast or at coastal locations south of the rupture, but waves about 2 feet high were observed at Crescent City 100 miles to the north.

The subject of this report is the magnitude 8.6 Chilean subduction zone earthquake that occurred on 22 May 1960 at 11:11 PST (19:11 GMT) off the coast of Chile at 39.5° S, 74.5° W. It produced an 82-foot runup in a coastal area close to the epicenter (Lander, *et al.*, 1993). The first tsunami waves from this event arrived at Crescent City on 23 May 1960 at 02:20 PST (10:20 GMT), over 15 hours later.

Lander, *et al*. (1993) reported that, “In Crescent City, California, three commercial fishing boats were sunk, and some damage was done to the dock facilities. A café and the Sea Scouts building were damaged, a wood piling was carried away and many tons of debris were left in the lower part of the harbor.” Oh and Rabinovich (1994) observed that, “A sad experience of the Chilean tsunami, May 22, 1960 showed that even distant tsunamis may be extremely dangerous, especially for regions with evident resonant topographic features.”

Tsunami propagation and topographic focusing are important for site-specific tsunami response modeling and warnings. Decay times of tsunami energy are also important so that an accurate “all clear” signal can be issued. “Identification and separation of seismically generated tsunami waves and atmospherically generated seiche oscillations (‘meteorological tsunamis‘) are important practical and scientific problems for the Canadian Hydrographic Service (CHS),” according to Rabinovich and Stephenson (2004).

1.4 Location and Instrumentation

Crescent City Harbor (41.3° N, 125.7° W) is located at the northern end of a crescent-shaped coastline, which is delineated by Point St. George to the north and Patrick’s Point to the south. The crescent shape is further defined by the narrowing of the continental shelf at both ends and the presence of a submerged reef at the northern end. The concave shape that approximates the coastline is 40 miles long and, as noted by Wilson and Torum (1968), forms a “semi-elliptic” basin with a depth profile that approximates a parabola to a depth of approximately 300 feet (Figure 1.2). It is this shape that presumably causes focusing of incoming waves and topographic trapping of edge waves (Horrillo, *et al.*, 2008).

Figure 1.3 shows the configuration of Crescent City Harbor in 1960, and the location of the stilling wells where the tsunami recordings were made. One stilling well was located in the inner harbor at Citizen's Dock, and the other at Dutton's Dock that was along the outer, western breakwater.[2] The stilling wells were 14 inches in diameter with a 3-inch circular, underwater inflow opening on one side. They were float-activated and included a "gate," or triangular slot that could be opened to increase the outflow of water, important to make the response of the stilling well system more sensitive to shorter period water level oscillations in the tsunami band (see Figure 1.4). Satake, *et al*. (1988) found that distortion of waves is minimal if the recovery time of the stilling well is less than the period of the wave. Most U.S. stilling well tide gauge systems, he noted, have outflows that are almost 20% faster than the inflow, and that the distorting effect is minor. Further discussion can be found in Kendall, *et al.* (2008).

Further work is certainly warranted to recover or reconstruct the precise frequency response characteristics of both the stilling well-float systems and the Stevens A-35 recorders used in the 1960 study. However, this is beyond the scope of the present report. For our purposes, we assume that the overall response is unity in

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[2] Most of Dutton's Dock was burned sometime before 1987, and the remainder was removed in 1988.

the relatively low frequency band below about 0.01 Hz (100-second period) that is of immediate interest in describing the tsunami fluctuations.

1.5 Overview of Strip Chart Rolls

In all, a total of 70 strip chart rolls are available, 35 at each dock, containing measurements from 11 May to 16 June 1960. Each roll contains approximately 24 hours of data, with 1 yard of chart paper representing 1 hour of recording. Thus, in general, each roll is 24 yards (72 feet) long, with a width of 11.5 inches. Approximately 1 hour of recording (3 feet of paper) is shown in Figure 1.5.

Before starting the scanning and digitizing, a detailed inventory was taken. Each roll was opened and information regarding the roll was logged. Rolls were identified using the convention “Lyymmddhhmm,” where “L” represents the location identifier (“C” for Citizen’s Dock and “D” for Dutton’s Dock), “yy” the year, “mm” the month, “dd” the day, “hh” the hour and “mm” the minute of the start time as noted on the roll. Many rolls were time stamped (mostly those from Citizen’s Dock) at the beginning and the end. Almost all the rolls from Dutton’s Dock had hand-written start and end times. Some rolls had either a start or an end-time missing.

In addition to logging the start and end times found on the rolls, a record was made of any notes or other information written on the rolls. Many rolls, especially those from Dutton’s Dock, had no notes or annotations. Others, especially those taken during the tsunami, were highly annotated, as illustrated in Figure 1.6. The complete log for all 70 strip chart rolls is presented in Appendix A.

This report focuses on the 11 rolls from each dock covering the period from 20-31 May 1960 that were digitized for analysis. It should be noted that initially only eight rolls were digitized, but preliminary study suggested that tsunami-related energy was still present, that is signal levels had not returned to background levels eight days after the initial tsunami wave arrival (that is, by the end of the eighth roll). Table 1 summarizes the start and end-time information retrieved from the 22 rolls considered here.

1.6 Scanning

In order to digitize the measurements on the strip chart rolls, they first had to be scanned into electronic image format. To accomplish this, the rolls were taken to *Docusure*, a commercial scanning service in San Diego, CA. At *Docusure*, a Contex FSS 4300 scanner was used to scan each roll at 400 dots per inch (dpi). Scanner settings were chosen to enhance the data trace and a straight “reference line” found at the bottom of each strip chart, and also to minimize the intensity levels of background grid lines, time-stamps, notes, and all other extraneous markings. This was done to minimize tracking errors in the digitization process described below (see Figure 1.7). Several test runs were required to determine appropriate scan settings.

During the testing it was discovered that the scanned image file size of an entire 72-foot long roll exceeded the software limits. Therefore, the scanned images were segmented into three sub-images of approximately 8 hours each.

The image files were output in TIF format. Files were named analogous to the source rolls, with segments represented by “_#.” Thus, “Lyymmddhhmm_1,” represents Segment 1 of File “Lyymmddhhmm.”

1.7 Digitizing

The *Matlab* based program *SeisDig* developed at Scripps Institution of Oceanography (Bromirski and Chuang, 2003) was used to digitize the tsunami-recording image files. *SeisDig* was designed to digitize once-per-day seismic record sheet scans, which are rectangular-shaped images. As such, the program required modifications to accommodate the much larger aspect ratio of the strip chart images.

SeisDig digitizing input parameters include the start and end times of the trace to be digitized, and the desired digitization sampling rate of the output. For the Crescent City strip chart roll images, a sampling rate of 1 Hz was selected. Start and end times marked on the rolls (when available) were used in conjunction with pixel counts in the (horizontal) time direction to calculate the time length of each segment, and to determine actual segment start and end times as accurately as possible (see Table 2).

SeisDig tracked the (vertical) distance in pixels between the reference line and the data trace at each sampling point. This was converted to millimeters and the values were stored in *Matlab* output files. Associated with each file is a header containing information such as the file start time, and the numbers of pixels and data points in the output time series.

On occasions when the trace on the roll was smudged, of poor quality, or erroneous (such as illustrated in Figure 1.8), the digitizing trace-tracking algorithm was ineffective and resulted in missing digital values. Prior to final export to the *Matlab* file, *SeisDig* employed a piecewise cubic spline interpolation function to fill in such missing-value gaps. However, some missing points identified as "NaN" in the *Matlab* files still occurred in the output.

The number of missing points was relatively very small, as can be seen in Figure 1.9. The largest number of data points (seconds) missing in an exported file was 153 (File D6005251053, the fourth day of the tsunami). File C6005241428 (third day) had 126 missing values, and D6005231054 (second day) had 112 missing points, almost all of which were non-consecutive. Most gaps were single missing points. The largest consecutive number of missing points was 13 and occurred in Files C6005221528 and C6005241428, from the first and third days of the tsunami, respectively. Before the data could be calibrated, the gaps in the *SeisDig* files were filled using Piecewise Cubic Hermite Interpolating Polynomial (PCHIP), a shape-preserving interpolation *Matlab* function. Results of this filling process for File C6005221528 are shown in Figure 1.10.

1.8 Calibrating

Data from *SeisDig* were converted from millimeters above the reference line to water level in feet above MLLW,[3] which was the reference elevation indicated in chart notations (see Figure 1.11), and regularly used in U.S. Army Corps of Engineers studies at the time.

As seen in Figure 1.11, the vertical scale indicated on the strip chart rolls is 1 inch or (25.4 millimeters) (chart) equals 2 feet (water elevation). The grid on the chart paper is 10 inches in height, implying a full-scale water level range of 20 feet. The range limits set during the time of the tsunami were -4 feet to +16 feet (Figure 1.11). *SeisDig* determines trace amplitudes relative to a reference datum. A baseline on the strip chart records, which was found on the grid usually at 0.3 feet above the -4 foot gridline at the bottom of the roll, or at a level of -3.7 feet (see Figure 1.12), was used as the digitizing reference datum.

The water elevation at each time step was obtained by converting the *SeisDig* value in millimeters between the reference datum and signal trace to feet, and then adding the elevation (in feet) of the reference datum as read off each strip chart. Once calibrated, the segments were concatenated and plotted.

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[3] We assume that MLLW in 1960 was referenced to the 1924-42 National Tidal Datum Epoch since values for the succeeding epoch (1960-78) were not published until at least 1961. Tide gauge measurements at Crescent City are available since May 1933. Examination of the history of annual mean tidal datum elevation values (MLLW, MSL, MHHW, for example) show that these decrease slowly over time, presumably because the area is being uplifted faster than sea level is rising, leading to a slow drop in relative mean sea level of about 0.5 cm per century (Flick, *et al*., 2003).

1.9 Gaps between Rolls

As shown in Table 3, gaps in the strip chart records resulted from the time needed to physically remove one roll and load another. Time gaps from roll changes range from 3 to 11 minutes. An attempt was made to fill gaps in the data at one dock using data from the other dock. The approach used was to take a 6-hour segment of data prior to every recording gap from each dock, thus forming 22, 6-hour segments. Estimates of the predominant period in each 6-hour record were made visually, and the time series low-pass filtered at that period. Cross correlation analysis then determined either the time lag or lead of data from one dock relative to the other. Corresponding data from the other dock was then used to fill each gap after adjusting for the respective lead or lag time.

1.10 Errors in Timing

Timing errors in the digitized data arose from a variety of sources. The times annotated on each roll are the only data-collection time information. Errors may have arisen from:

- Missing start or end time annotations;
- Watch or clock errors, potentially resulting from multiple persons involved in changing strip chart rolls and uncoordinated or inaccurately set clocks and watches;
- Mixed and inconsistent use of Pacific Standard Time (PST) and Pacific Daylight Time (PDT or PDST), which would have been in effect in May 1960;

- Inaccuracy or variation of the chart recorder drum speed from the nominal 1 yard per hour, which is equivalent to 1 inch per 100 seconds;
- Strip chart paper dimension changes due to stretching, shrinkage, or age.

A roll marked with a one minute-long scale is shown in Figure 1.13. These sources of timing errors and how they were resolved are discussed in the subsequent sections. There follows a discussion of how the timing errors may affect the determination of the frequencies of the water level signals.

1.10.1 Missing Time Annotations

The two rolls at Citizen’s Dock that recorded the main tsunami waves (C6005221528 and C6005231434) were well annotated sometime shortly after removal from the drum as shown in Figures 1.6, 1.11, and 1.14. Rolls C6005221528, D6005221035, and D6005231054 were digitized by hand and are discussed in Magoon (1962).

Not all the strip chart rolls were as well documented as these three. Two rolls from Citizen’s Dock (C6005241428 and C6005291522) were not marked with an end time, while one roll from Dutton’s Dock (D6005301010) did not have a start time. Missing times were initially determined using pixel count of the trace length using an image viewer (*IrfanView*) to obtain the pixel coordinates at the beginning and end of each trace.

Since the scans were done at 400 dpi, and 1 inch of chart paper equals 100 seconds (or 1 pixel represents 0.25 seconds), the pixel length of the trace could easily be converted to time length. The pixel time length of the trace was then used in conjunction with the given start or end time to calculate the missing value. Other ways of calculating time such as counting time off the time grid, or getting a physical measurement of the trace and converting to time (1 foot of paper = 20 minutes) were also employed (see Table 2).

As an example, Citizens Dock Roll 5 had no end-time stamp. Based on pixel measurements of the trace, the end time should be 25 May 1960 at 15:25; however, based on a physical measurement of the trace length on the chart paper, the end time was calculated to be 25 May 1960 at 15:12. The pixel-based end time of 25 May 1960 at 15:25 was used to produce the digitized data file. Potentially, the digitized times series length would need to be compressed by as much as 13 minutes.

1.10.2 Confusion of Standard and Daylight Time

The initial review and annotation logging of the strip chart rolls uncovered another problem: Time annotations, whether stamped or hand-written, were not always referred to a consistent time reference. In fact, times were found noted as “PST,” “PDT,” or “PDST” on the same roll. Presumably these stand, respectively, for “Pacific Standard Time,” and “Pacific Daylight Time” and its equivalent “Pacific Daylight Savings Time.”

Of the Citizen’s Dock rolls, only two (C6005221259 and C6005231434) have time marked as PST. These were rolls from the first and second day of the tsunami and had been well annotated. Rolls from Dutton’s Dock have beginning and end times labeled by hand; some included the annotation PDST or PDT, others did not. Of the 11 rolls per dock discussed in this report, Citizen's Dock times were generally marked in PST while Dutton's time was recorded in PDT. Exported digitized data from each dock were plotted to verify this finding. As needed, time for Dutton's Dock was shifted by one hour (-1) to correct from PDT to PST. For consistency, PST was chosen as the time base for this report.

However, this did not completely resolve the timing issue for Dutton's Dock rolls D6005240915 and D0605251058. Several methods were utilized to help sort out additional timing discrepancies. Table 2 compares total time length of the trace for each roll. For roll D6005240915, the time length of 24 hours, 45 minutes, 13 seconds using pixel calculations gives an end time of 25 May1960 at 10:00 PDT, which is 53 minutes earlier than the hand written end time marked on the roll from 25 May 1960, 10:53 PDT. Also, marking from the beginning yielded an end time of 09:52; nearly exactly 1 hour earlier than the marked end time of 10:53 PDT. This one-hour difference hints strongly at time zone confusion for that roll. Since the begin time of the roll was consistent with the end time of the previous roll, it was concluded that the end time of roll D6005240915 was likely incorrectly annotated. Changing the end time to 09:52 PDT was also more consistent with the start time of the next roll.

Perhaps after the tsunami, while personnel were reviewing and annotating the rolls, notice was made that Citizen's Dock times were recorded in PST while Dutton's Dock times were in PDT. It may have been decided to mark rolls at both docks in PST in an attempt to make the times consistent. It is conceivable, especially in the hectic days surrounding the tsunami, that one hour had inadvertently been added to PDT instead of subtracted when converting to PST. Finally, to make the times consistent, an end time of 09:52 PDT was used in exporting the trace file of roll D6005240915 from the *SeisDig* program.

Similarly, roll D6005251058 posed a problem. The time length of 23 hours, 56 minutes, 04 seconds using pixel calculations (see Table 2) gives an end time of 26 May 1960 at 10:54 PDT, 1 hour, 7 minutes later than the hand written end time given on the roll of 26 May 1960 at 09:47 PDT. The file was originally exported assuming the hand written time of 26 May 1960 at 09:47 PDT was given as PST and was meant to read "26 May 60 10:47 PDT," to be consistent with the pixel count and the start time. However, original plots of the exported data for Roll 6 at both docks (shown in Figure 1.15) indicated a problem still existed; Segment 3 appeared stretched and the end time now overlapped the beginning time of the next roll.

This time issue was resolved by low-pass filtering the data below 90 minutes (0.000185 Hz) and comparing the results with NOAA predicted and verified astronomical tides for Crescent City (Station 9419750[4]). The tide predictions for 1960 are available in intervals of 6 minutes and the verified water level observations in 1-hour intervals. After examining several possible time combinations on Dutton's Roll 6 (D6005251058), it was determined that the beginning time had the same error as the end time of the previous roll (Roll 5, D6005240915), discussed above. One hour had inadvertently been added to PDT instead of subtracted, when (possibly) trying to

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[4] See the NOAA NOS tides and currents website at http://tidesandcurrents.noaa.gov/.

convert to PST for consistency with Citizen's Dock time annotations. Comparison with the tide data indicated that the begin time was 2 hours ahead of PST, and the end time 1 hour ahead (given as PDT). Plots of Roll 6 at both docks reflecting the time corrections made for Dutton's Dock are shown in Figure 1.16.

This tidal data comparison check was performed on all rolls for both Citizen's and Dutton's docks. Based on these comparisons, it was determined that all Dutton's Dock rolls were in PDT except for the discovered mix of reference times on rolls D6005240915 and D6005251058 as discussed above. Final start and end times as determined in PST for each roll in the final digitized data are shown in Table 3.

1.10.3 Watch Error

Another source of timing problems is watch or clock error. Undoubtedly, several watches were used during the data recording, since a number of people were changing and annotating the strip chart rolls. The different watches may not have been regularly synchronized, or may have been set relative to inaccurate clocks, or not at all, and they likely gained or lost time, as is common with mechanical watches.[5] Finally, the watches were likely not read to the exact minute, let alone to the second, or were sometimes read inaccurately, as is also common with analog dial watches.

On occasion, when time on a roll of interest was later marked along the chart time scale, annotations were found referring specifically to "watch error." For example, roll C6005231434 covering the second day of the tsunami, identifies a 3-

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[5] Inexpensive electronic watches with vastly better time-keeping properties and more fool-proof digital readouts than the mechanical watches of the 1950's and '60's were not available until the late 1970's.

minute watch error, as illustrated in Figure 1.14. Similarly, roll C6005221529 (Citizen's Dock start time 22 May 1960 at 15:29) is also well annotated because it was the "first day" of the tsunami (Figure 1.11). It had time marked off backwards from the end of the roll in 20-minute increments starting with the stamped end time. The vertical scale was also marked and labeled, and many notes were made. However, the stamped beginning time (15:25) did not match the physically calculated beginning time of 15:29, an error of 4 minutes.

A final example is roll C6005211540 (Citizen's Dock start time 21 May 1960 at 15:40) where someone had also counted time backwards from the end of the trace, which was stamped "1520 May 22 1960" to arrive at a start time of 15:54 on 22 May 1960. An annotation "1554 14 min off" was made at the beginning of the roll (Appendix A).

1.10.4 Drum Speed Errors

Time discrepancies may also be caused by inaccurate or variable drum speeds on the Stevens A-35 strip chart recorders, which may not have revolved at the constant nominal 1 yard-per-hour speed. To complicate matters further, the recorders at each dock operated independently of each other. Thus, drum speeds and chart positions at the Citizen's Dock recorder are unlikely to be exactly coordinated with those at Dutton's Dock.

Furthermore, there is the possibility that the paper stretched or shrank, including during installation, removal, or other handling, or because of changes in temperature or humidity, or as paper characteristics changed over time. Potentially the beginning and end of the rolls could have been stretched when installing a new roll. Rolls representing the first few days of the tsunami were handled more than others. At the time that Magoon (1962) presented some of the early findings, selected rolls were manually digitized, well annotated, and studied post-tsunami, as seen in Figure 1.6, which has an annotation, "start of digitizing."

Thus timing errors of 1-17 minutes may exist in the data from a variety of quantifiable and non-quantifiable sources. See Appendix A for annotations found on the rolls (these are given in quotes) and for additional notes regarding timing discrepancies.

1.10.5 Timing Errors and Frequency

Variable recorder speeds will cause shifts in the apparent frequency of the observed water level oscillations. Furthermore, differences in timing between the two docks will introduce errors in the phase relationship and coherence of the signals at each dock. Table 2 shows that timing errors over the digitized record typically are 1-10 minutes with a worst-case of approximately 17 minutes.

The resulting potential error in frequency is a function of the ratio of the total duration of the digitized record to the true duration of the record. Most strip chart rolls are 24 hours long, equal to 86,400 seconds. Assuming a uniform recorder speed throughout the record, an expansion or compression of 17 minutes (1,020 seconds) would alter a digitized frequency by 86,400/(86,400-1,020) for time compression and

86,400/(86,400+1020) for time expansion. Thus, an oscillation with actual period of 34 minutes (f = 0.0004861 Hz), if the record were expanded by 17 minutes, would become 34.7 minutes (f = 0.0004804 Hz), a frequency change of about 1%. A shorter oscillation with actual period of 1.5 minutes (f= 0.01111 Hz) would become 1.518 minutes (f = 0.01098 Hz) assuming the same time expansion, also a frequency error of about 1%.

For the periods of interest in this study, the frequency estimates in the spectral domain are not significantly adversely affected. The timing errors, however, could make determining phase, coherence, and correlations between the two docks less reliable.

1.11 Errors in Amplitude

Amplitude errors arose mainly from the smudging or complete absence of the reference line on the strip chart rolls, and from induced meandering related to the difficulty of feeding the nearly 72-foot long rolls squarely into the scanner. Figure 1.17 is an example of a smudged reference line from the Citizens Dock roll starting 27 May 1960 at 14:08 PST. The corresponding section of the trace from the Citizens Dock file C6005271408_2.tif is shown in Figure 1.18. A notation hand written above the water level trace says “0104 May 28 1960 oscillations still showing on tide gage”.

When digitizing, the *SeisDig* routine uses a linear fit to the reference line and outputs distances from this representation of the reference line to the trace. The linear fit is based on slope and intercept selected by the user. Care was taken to set the slope and intercept so as to best match the reference line on the image. However, as mentioned above, the actual reference line occasionally meandered to either side of the user-defined line from which distances were calculated.

A review was made of the reference lines in the scanned TIF files. Most of them were within 30 pixels of being straight (equivalent to less than 2 inches of water) and coincided well with the input (user given slope and intercept) reference line. A few reference lines were digitized and the error due to distortion in the reference line was calculated. The time series plots in Figure 1.19 show the calibrated water level and reference line for the first segment of file C6005211540 (Citizen's Dock 21 May 1960, 15:40 start), along with the reference line error and corrected water level. Comparing the spectra of the digitized data and the reference line error (Figure 1.20) shows that the error is at least two orders of magnitude below signal levels. Once the data were calibrated and plotted, amplitude variations determined to be caused by large deviations from the input reference line and a "distorted" reference line image were corrected.

Additional amplitude errors could be caused by the reference line (and/or trace) thickness. In the vertical, 10 inches of chart paper (4,000 pixels) represent 20 feet of water; therefore, each pixel equals 0.005 feet or 0.06 inches on the vertical scale of the chart paper. The typical thickness of the reference line and trace is between 10 and 20 pixels, or 0.6 to 1.2 inches of water. A value manually digitized off the chart may also vary by this amount. Although the *SeisDig* program is designed to stay in the middle of the trace, smudges, extraneous lines or notes, and trace wanderings sometimes caused *SeisDig* to fail to track the trace. In addition, File C6005231434 has two time periods where the trace is not tracked at all near the bottom of the chart; first from approximately 03:40-03:42, and again from 05:05-05:09 on 24 May 1960. Figure 1.21 shows a photograph of the roll at the second loss of trace. The broken line indicates data that were digitized interactively with the spline-fitting *SeisDig* function.

1.12 Reality-Check Comparisons

During the many times that the strip chart rolls were opened and examined, selected time and water levels were identified, or “digitized” manually, using the scale on the chart paper. These values were later used to “spot check” the data to compare timing and amplitudes between the chart trace, the scanned file (using pixel calculations), and the *SeisDig* data file. For example, the value of the trace on 23 May 60 at 14:28 as marked on the end of the roll pictured in Figure 1.22, which corresponds visually to the plot shown in Figure 1.23. The value of that point might be read from the roll as “2.0 feet at 14:28:00 PST on 23 May 1960.” The corresponding point in the digitized data is “2.08 feet at 14:28:05 PST on 23 May 1960.” The discrepancy is 0.08 feet (0.96 inches) in amplitude, and 5 seconds in time, which are well within the bounds of expected errors discussed above.

A final example is based on the discussion given by Magoon (1962) of the data that was manually digitized from the strip chart rolls:

> The first disturbance clearly associated with the tsunami was recorded (Citizens Dock) 23 May 1960 at 0220…… The maximum recorded

> water level occurred at 1110 (or nearly nine hours after the initial disturbance was observed) when a height of +12.5 was reached. The predicted tide at the time was 5.1. At the time of maximum water elevations, the period of the waves was about 20 minutes.

In Figure 1.24, the highest peak is approximately 12.75 feet, about 11:11:35 PST on 23 May 1960, which depending on the procedure, may have been lost in the lower resolution of the manual digitization. The same peak plots at 12.69 feet at 11:14:17 PST on 23 May 1960 with the high-resolution digitized data plotted in Figure 1.25. Additional analysis gives a zero-upcrossing period at this time of 27.5 minutes.

Other "spot checks" similarly found timing and amplitude errors to be within the stated observed and potential ranges. Total actual water level amplitude errors are believed to be less than 0.12-0.17 ft (1.5-2 inches), or less than 1% of full scale (20 feet), and less than about 2% of the maximum observed water level fluctuation (10 feet – see Figure 1.25). These errors are well within the error associated with manual digitization of the same traces, based on line thickness alone. On the whole, amplitude and timing errors are considered more than acceptable for the intended analyses.

1.13 Final Time Series

The goal of this report is to document the procedures used to derive the digital time series of water levels at Dutton's and Citizen's docks in Crescent City Harbor that were produced from strip chart recordings made before, during, and just after the tsunami triggered by the Great Chilean Earthquake of 22 May 1960. Of the 70 available strip chart rolls, 22 were scanned and digitized, 11 at each of the two docks. The 1-Hz sampled digital data span nearly 11 days, from 17:34, 20 May, to 08:32, 31

May 1960 (PST). The original paper strip chart records are in the custody of the U.S. Army Corps of Engineers, San Francisco District.

The 20-31 May 1960 data were scanned, digitized, adjusted and corrected, and are determined to be final. These data are plotted in 24-hour segments in Appendix B (Figures B1-B11). Also shown for comparison on each plot are the NOAA predicted tides at 6 minute intervals, and the NOAA verified water levels as measured at the Crescent City tide gauge at 1-hour intervals.

The digital data produced from scanning and digitizing the strip chart rolls discussed in this report exist in *Matlab* and ASCII format at Scripps Institution of Oceanography. The *Matlab* file contains start date, start time, sample rate, the water elevation, and channel names and channel units. The file is structured as a 4 by 917,880 element array, where Row 1 is seconds from start time (20 May 1960 17:34 PST); Row 2 is the *Matlab* serial representation of the date; and Rows 3 and 4 are Citizen’s Dock and Dutton’s Dock water elevation data in feet relative to MLLW (1924-42). The ASCII files are in a 917,880 line by 4 column array with similar structure.

1.14 Epilogue

Renewed interest in tsunami warning revived the “Dead Sea Scrolls,” as the 1960 strip chart rolls from Crescent City Harbor became affectionately known. It is hoped that this report will provide the background necessary to further use this unique and potentially important data set.

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Table 1.1: Start and End Time (PST) Information as Obtained from the Strip Chart Rolls

Citizen's Dock		Start Time Information Marked on Roll			End Time Information Marked on Roll			Time Between Roll Change
Roll #	Roll Name	Date & Time	Time Zone	Stamped or Hand Written	Date & Time	Time Zone	Stamped or Hand Written	(mm:ss)
Roll 1	C6005201734	5/20/60 17:34	none given	Stamped	5/21/1960 15:35	none given	Stamped	
								05:00
Roll 2	C6005211540	5/21/60 15:40	none given	Stamped	5/22/1960 15:20	none given	Stamped	
								09:00
Roll 3	C6005221529	5/22/60 15:29	PST	Stamped (15:25) & Hand written* (15:29)	5/23/1960 14:28	PST	Stamped & Hand Written*	
								06:00
Roll 4	C6005231434	5/23/60 14:34	PST	Stamped & Hand Written*	5/24/1960 14:17	PST	Stamped & Hand Written*	
								11:00
Roll 5	C6005241428	5/24/60 14:28	none given	Stamped	none	-	-	
								-
Roll 6	C6005251532	5/25/60 15:32	none given	Stamped	5/26/1960 15:30	none given	Stamped	
								04:00
Roll 7	C6005261534	5/26/60 15:34	none given	Stamped	5/27/1960 14:04	none given	Stamped	
								04:00
Roll 8	C6005271408	5/27/60 14:08	none given	Stamped	5/28/1960 15:00	none given	Stamped	
								03:00
Roll 9	C6005281503	5/28/60 15:03	none given	Stamped	5/29/1960 15:18	none given	Stamped	
								04:00
Roll 10	C6005291522	5/29/60 15:22	none given	Stamped	none	-	-	
								-
Roll 11	C6005301651	5/30/60 16:51	none given	Stamped	5/31/1960 15:12	none given	Stamped	

Dutton's Dock		Start Time Information Marked on Roll			End Time Information Marked on Roll			Time Between Roll Change
	Roll Name	Date & Time	Time Zone	Stamped or Hand Written	Date & Time	Time Zone	Stamped or Hand Written	(mm:ss)
Roll 1	D6005200920	5/20/60 9:20	PDT	Hand Written	5/21/1960 9:10	PDT	Hand Written	
								05:00.0
Roll 2	D6005210915	5/21/60 9:15	PDT	Hand Written	5/22/1960 10:30	PDT	Hand Written	
								05:00.0
Roll 3	D6005221035	5/22/60 10:35	PDT	Hand Written	5/23/1960 10:50	PDT	Hand Written	
								04:00.0
Roll 4	D6005231054	5/23/60 10:54	PDT	Hand Written	5/24/1960 9:10	PDT	Hand Written	
								05:00.0
Roll 5	D6005240915	5/24/60 9:15	PDT	Hand Written	5/25/1960 10:53	PDT	Hand Written	
								05:00.0
Roll 6	D6005251058	5/25/60 10:58	PDT	Hand Written	5/26/1960 9:47	PDT	Hand Written	
								05:00.0
Roll 7	D6005260952	5/26/60 9:52	PDT	Hand Written	5/27/1960 9:58	PDT	Hand Written	
								05:00.0
Roll 8	D6005271003	5/27/60 10:03	PDT	Hand Written	5/28/1960 9:35	PDT	Hand Written	
								05:00.0
Roll 9	D6005280940	5/28/60 9:40	PDT	Hand Written	5/29/60 9:40	PDT	Hand Written	
								05:00.0
Roll 10	D6005290945	5/29/60 9:45	PDT	Hand Written	5/30/60 10:05	PDT	Hand Written	
								-
Roll 11	D6005301010	none	-	-	5/31/1960 9:32	PDST	Hand Written	

Table 1.2: Length of Trace Calculations, Citizen’s Dock

File	Start Time	Pixel Length of Trace				End Time		Time Length of Trace			Physical Length of Trace			
Citizen's Dock		Pixels	Inches	Seconds	Hours	Calculated (using Pixel Length of Trace)	Marked on Roll	calculated (end-begin)	marked (end-begin)	Delta Time (hh:mm:ss) (Marked - Calculated) RED=>marked time earlier than calculated	feet (from pixel count)	feet (measured)	Delta Length feet (Pixel Count - Measured)	Delta Time (hh:mm:ss)
C6005201734	5/20/60 17:34	321278	803.195	80320	22.311	5/21/60 15:52	5/21/1960 15:35 stamped	22:18:38	22:01:00	0:17:38	66.933	66.480	0.453	0:09:04
C6005211540	5/21/60 15:40	339223	848.058	84806	23.5572	5/22/60 15:13	5/22/1960 15:20 stamped	23:33:25	23:40:00	0:06:35	70.671	70.286	0.385	0:07:42
C6005221529	5/22/60 15:29	332523	831.308	83131	23.0919	5/23/60 14:34	5/23/1960 14:28 stamped	23:05:30	22:59:00	0:06:30	69.276	68.875	0.401	0:08:00
C6005231434	5/23/60 14:34	342211	855.528	85553	23.7647	5/23/60 22:30	5/24/1960 14:17 stamped	23:45:52	23:43:00	0:02:52	71.294	70.958	0.336	0:06:42
C6005241428	5/24/60 14:28	359333	898.333	89833	24.9537	5/25/60 15:25	5/25/1960 15:12 none marked, measured out	24:57:12	24:44:00	0:13:12	74.861	74.375	0.486	0:09:43
C6005251532	5/25/60 15:32	347390	868.475	86848	24.1243	5/26/60 15:39	5/26/1960 15:30 stamped	24:07:26	23:58:00	0:09:26	72.373	71.875	0.498	0:09:57
C6005261534	5/26/60 15:34	325337	813.343	81334	22.5928	5/27/60 14:09	5/27/1960 14:04 stamped	22:35:33	22:30:00	0:05:33	67.779	67.396	0.383	0:07:39
C6005271408	5/27/60 14:08	359682	899.205	89921	24.9779	5/28/60 15:06	5/28/1960 15:00 stamped	24:58:39	24:52:00	0:06:39	74.934	74.385	0.548	0:10:58
C6005281503	5/28/60 15:03	349410	873.525	87353	24.2646	5/29/60 15:18	5/29/1960 15:18 stamped	24:15:52	24:15:00	0:00:52	72.794	72.354	0.440	0:08:47
C6005291522	5/29/60 15:22	361636	904.09	90409	25.1136	5/30/60 16:28	- no end time marked	25:06:47	no end time marked		75.341	74.833	0.508	0:10:09
C6005301651	5/30/60 16:51	320363	800.908	80091	22.2474	5/31/60 15:05	5/31/1960 15:12 stamped	22:14:49	22:21:00	0:06:11	66.742	66.313	0.430	0:08:35

Table 1.2 (continued): Length of Trace Calculations, Dutton’s Dock

File	Start Time	Pixel Length of Trace				End Time		Time Length of Trace			Physical Length of Trace			
Dutton's Dock		Pixels	Inches	Seconds	Hours	Calculated (using Pixel Length of Trace)	Marked on Roll	calculated (end-begin)	marked (end-begin)	Delta Time (hh:mm:ss) (Marked - Calculated) RED=>marked time earlier than calculated	feet (from pixel count)	feet (measured)	Delta Length feet (Pixel Count - Measured)	Delta Time (hh:mm:ss)
D6005200920	5/20/60 9:20	343112	857.78	85778	23.8272	5/21/60 9:09	5/21/1960 9:10 Hand-written	23:49:36	23:50:00	0:00:24	71.482	71.125	0.357	0:07:08
D6005210915	5/21/60 9:15	365010	912.525	91252.5	25.3479	5/22/60 10:35	5/22/1960 10:30 Hand-written	25:20:51	25:15:00	0:05:51	76.044	75.635	0.408	0:08:09
D6005221035	5/22/60 10:35	350361	875.903	87590.3	24.3306	5/23/60 10:54	5/23/1960 10:50 Hand-written	24:19:49	24:15:00	0:04:49	72.992	72.604	0.388	0:07:45
D6005231054	5/23/60 10:54	322196	805.49	80549	22.3747	5/24/60 9:16	5/24/1960 9:16 Hand-written	22:22:28	22:22:00	0:00:28	67.124	66.688	0.437	0:08:44
D6005240915	5/24/60 9:15	356452	891.13	89113	24.7536	5/25/60 10:00	5/25/1960 10:53 Hand-written; Note: get end time of 5/25/1960 09:52 when time marked from beginning	24:45:12 Note: ~ 1hour time difference determined to be incorrect labelling and conversion of end time (see text)	25:38:00	0:52:48	74.261	73.750	0.511	0:10:13
D6005251058 Note: get 5/25/1960 09:52 when time marked from beginning	5/25/60 10:58	344658	861.645	86164.5	23.9346	5/26/60 10:54	5/26/1960 9:47 Hand-written	23:56:04 Note: ~ 1hour time difference determined to be incorrect labelling and conversion of begin time (see text)	22:49:00	1:07:04	71.804	71.344	0.460	0:09:12
D6005260952	5/26/60 9:52	348246	870.615	87061.5	24.1838	5/26/60 17:50	5/27/1960 9:58 Hand-written	24:11:01	24:06:00	0:05:01	72.551	72.135	0.416	0:08:18
D6005271003	5/27/60 10:03	340524	851.31	85131	23.6475	5/28/60 9:41	5/28/1960 9:35 Hand-written	23:38:49	23:32:00	0:06:49	70.943	70.615	0.328	0:06:33
D6005280940	5/28/60 9:40	346667	866.668	86666.8	24.0741	5/29/60 9:44	5/29/1960 9:40 Hand-written	24:04:26	24:00:00	0:04:26	72.222	72.177	0.045	0:00:54
D6005290945	5/29/60 9:45	352698	881.745	88174.5	24.4929	5/30/60 10:14	5/30/1960 10:05 Hand-written	24:29:34	24:20:00	0:09:34	73.479	73.000	0.479	0:09:34
D6005301010	5/30/60 10:10	338128	845.32	84532	23.4811	5/31/60 9:38	5/31/1960 9:32 Hand-written	23:28:51	23:22:00	0:06:51	70.443	70.021	0.423	0:08:27

Table 1.3: Final Start and End Times (PST) Used for Digitization

Citizen's Dock	Start Time Used for Roll		End Time Used for Roll		Time Between Roll Change
Roll Name	Date & Time	Time Zone	Date & Time	Time Zone	(mm:ss)
C6005201734	5/20/60 17:34	PST	5/21/1960 15:35	PST	
					05:00
C6005211540	5/21/60 15:40	PST	5/22/1960 15:20	PST	
					09:00
C6005221529	5/22/60 15:29	PST	5/23/1960 14:28	PST	
					06:00
C6005231434	5/23/60 14:34	PST	5/24/1960 14:17	PST	
					11:00
C6005241428	5/24/60 14:28	PST	5/25/1960 15:25	PST	
					07:00
C6005251532	5/25/60 15:32	PST	5/26/1960 15:30	PST	
					04:00
C6005261534	5/26/60 15:34	PST	5/27/1960 14:04	PST	
					04:00
C6005271408	5/27/60 14:08	PST	5/28/1960 15:00	PST	
					03:00
C6005281503	5/28/60 15:03	PST	5/29/1960 15:18	PST	
C6005291522	5/29/60 15:22	PST	5/30/1960 16:28	PST	
					-
C6005301651	5/30/60 16:51	PST	5/31/1960 15:05	PST	

Dutton's Dock	Start Time Used for Roll		End Time Used for Roll		Time Between Roll Change
Roll Name	Date & Time	Time Zone	Date & Time	Time Zone	(mm:ss)
D6005200920	5/20/60 8:20	PST	5/21/1960 8:10	PST	
					05:00
D6005210915	5/21/60 8:15	PST	5/22/1960 9:30	PST	
					05:00
D6005221035	5/22/60 9:35	PST	5/23/1960 9:50	PST	
					04:00
D6005231054	5/23/60 9:54	PST	5/24/1960 8:10	PST	
					04:45
D6005240915	5/24/60 8:15	PST	5/25/1960 8:52	PST	
					06:00
D6005251058	5/25/60 8:58	PST	5/26/1960 8:47	PST	
					06:00
D6005260952	5/26/60 8:53	PST	5/27/1960 8:58	PST	
					05:00
D6005271003	5/27/60 9:03	PST	5/28/1960 8:35	PST	
					05:00
D6005280940	5/28/60 8:40	PST	5/29/60 8:40	PST	
					05:00
D6005290945	5/29/60 8:45	PST	5/30/60 9:07	PST	
					03:00
D6005301010	5/30/08 9:10	PST	5/31/1960 8:32	PST	

FIGURES

Figure 1.1: The two boxes of Crescent City study strip chart data rolls that were found in 2006 in an Army Corps of Engineers records repository in San Francisco.

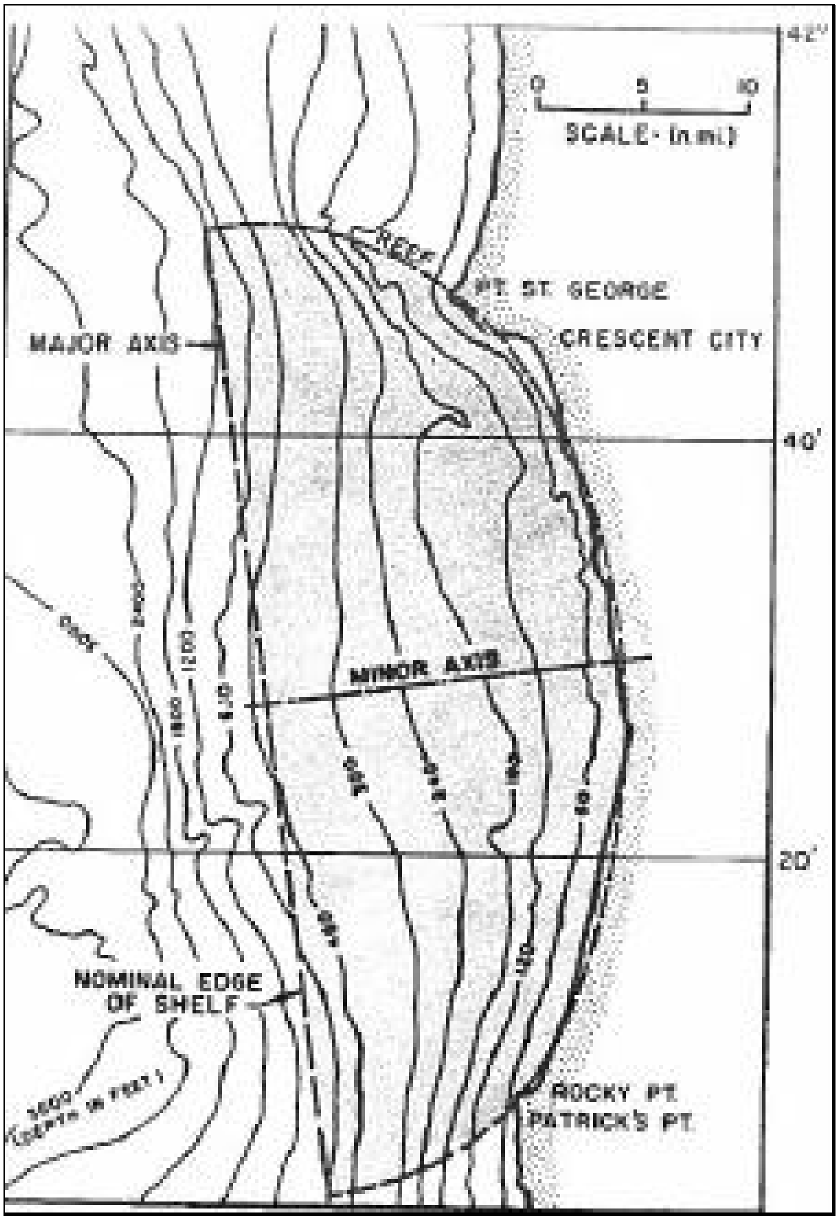

Figure 1.2: The shelf off Crescent City, CA approximates an ellipse (from Wilson and Torum, 1968).

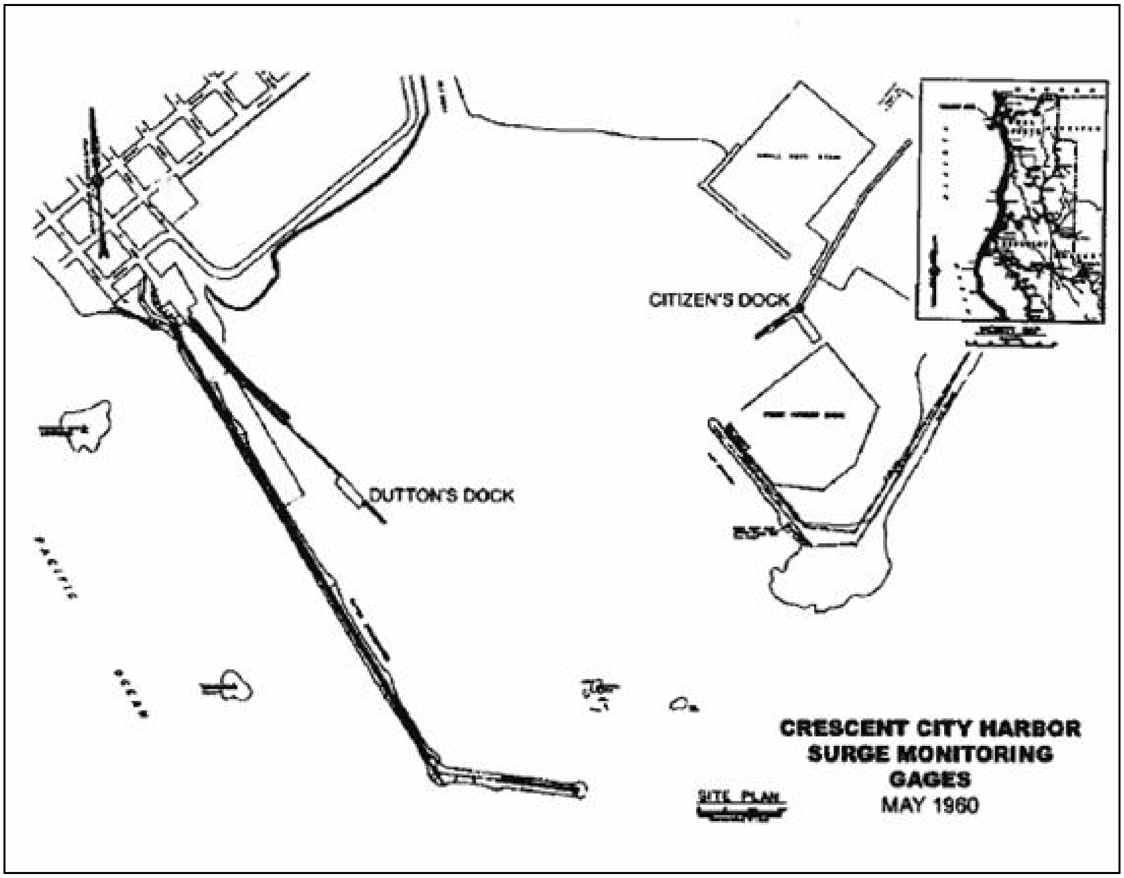

Figure 1.3: Stilling well stations at Citizen's and Dutton's Docks, Crescent City Harbor, 1960.

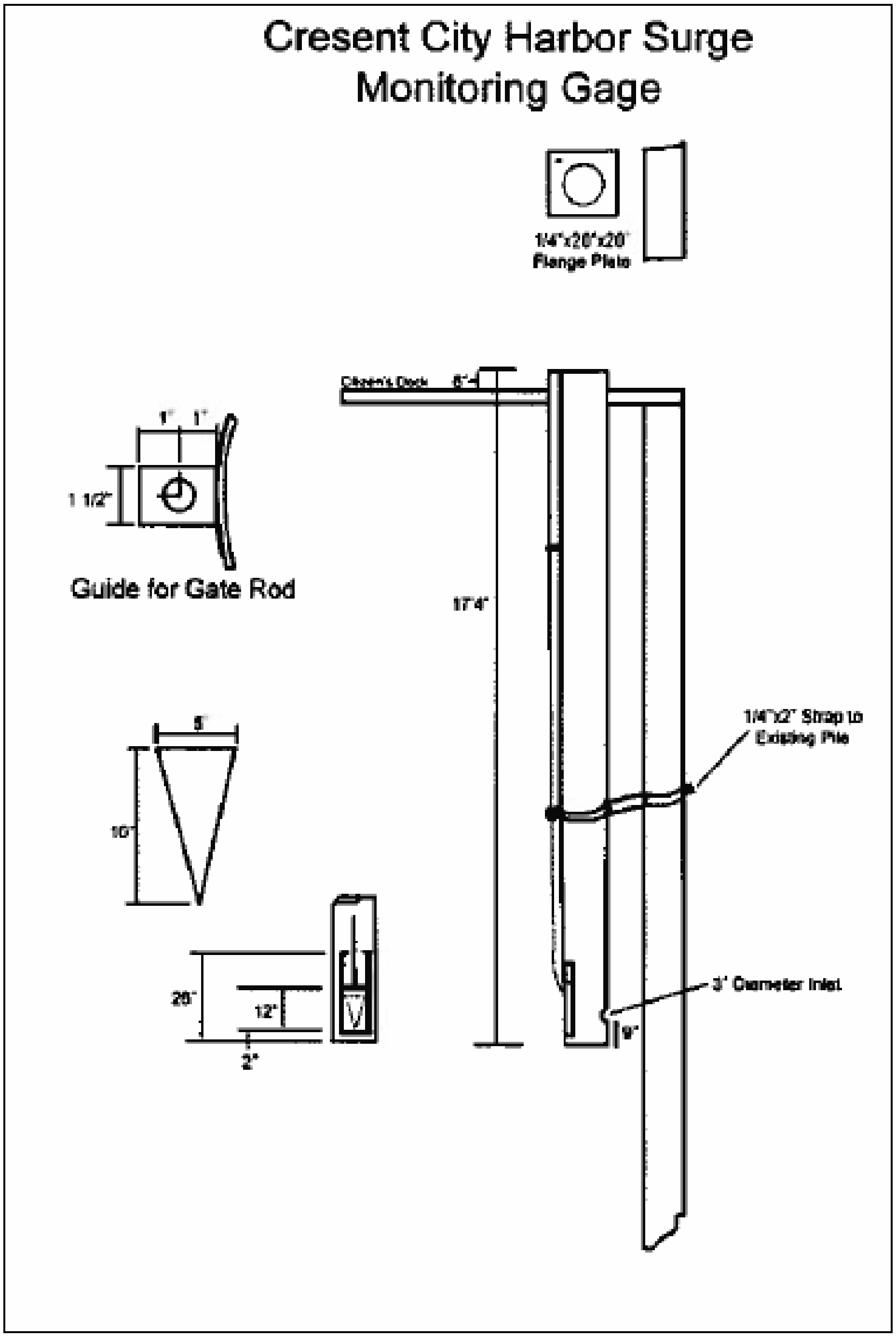

Figure 1.4: Illustration of stilling well gage as used in the 1960 Crescent City Harbor surge study.

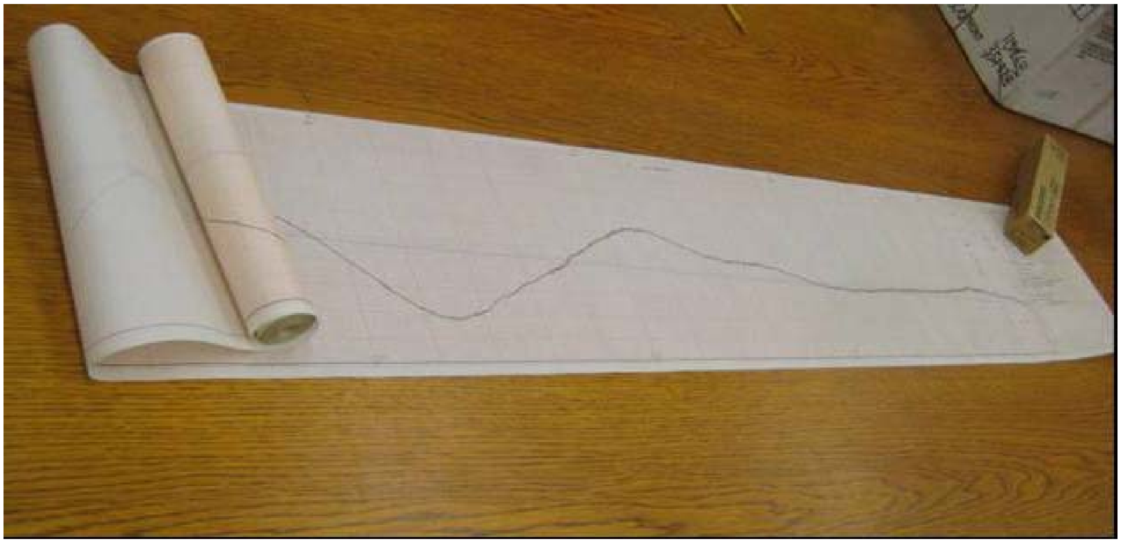

Figure 1.5: Approximately 3 feet of paper representing 1 hour of the record; rolls are about 72 feet long when completely unrolled.

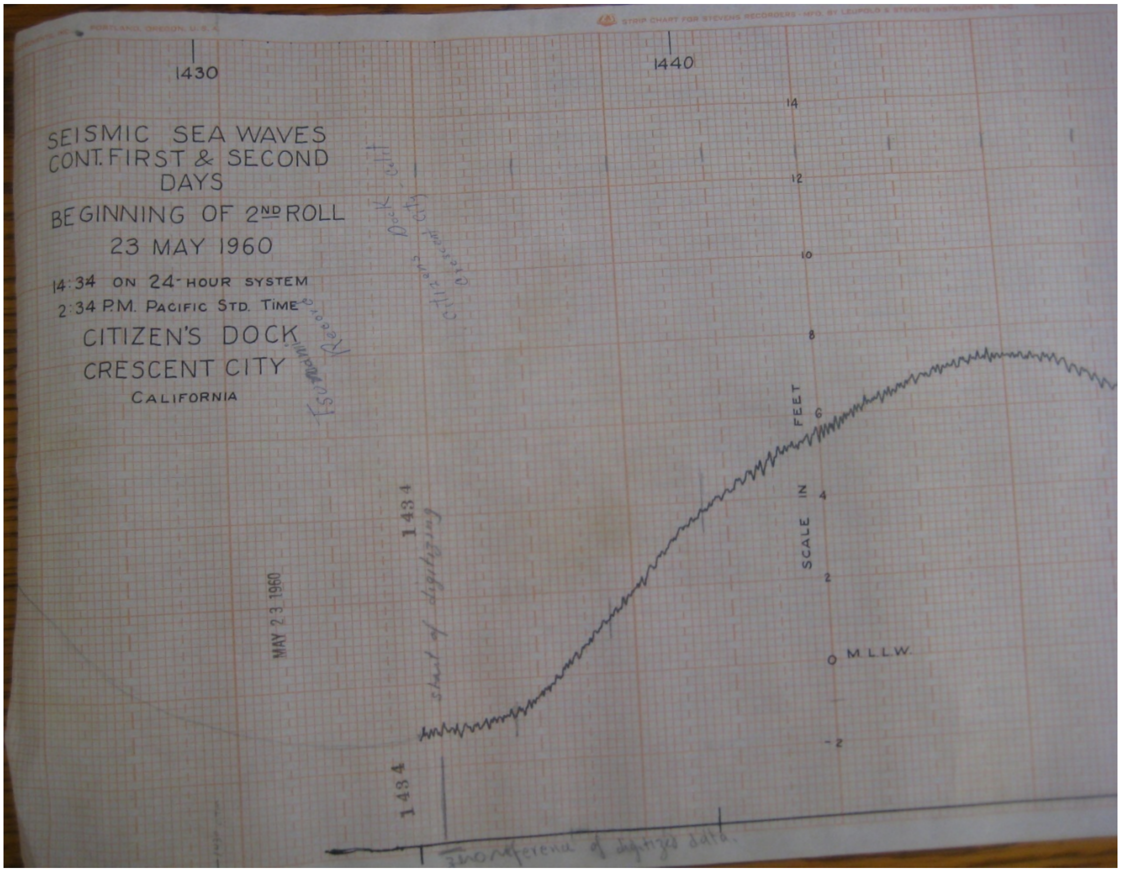

Figure 1.6: Some rolls are highly annotated, especially during the tsunami. All annotations are original markings.

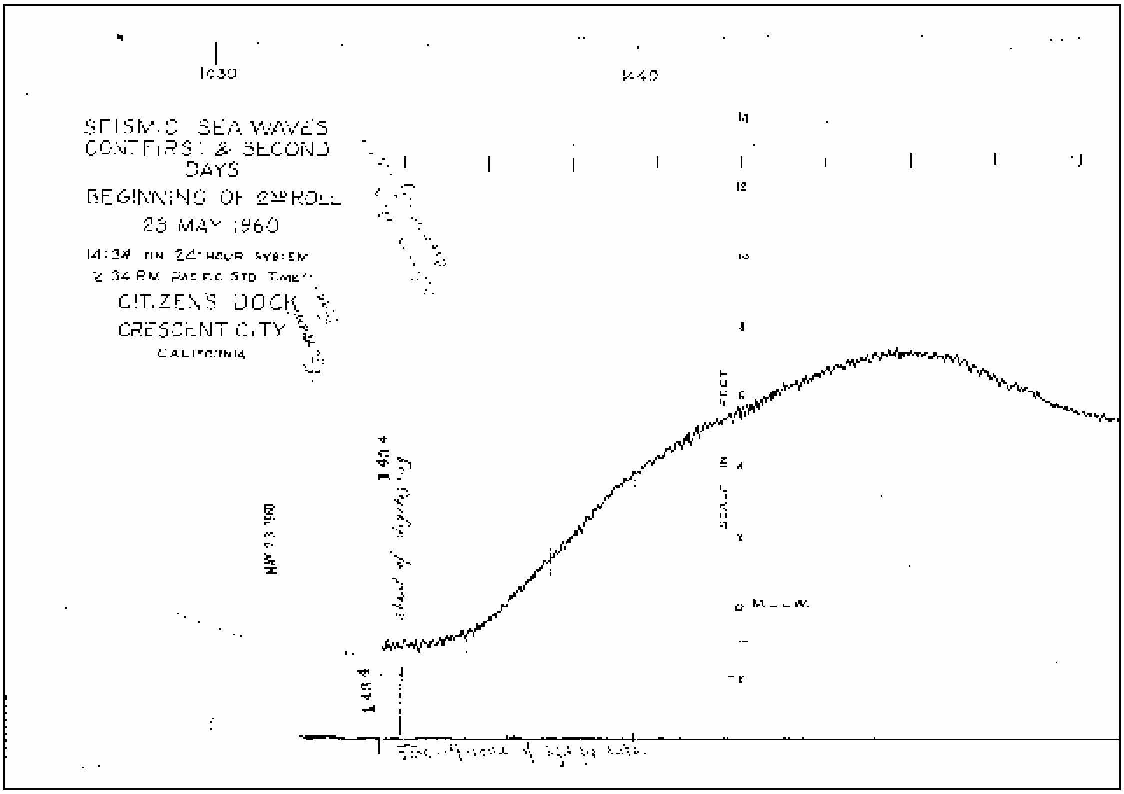

Figure 1.7: Segment of scanned C6005231434 corresponding to the section shown in Figure 1.6. Grid lines and other markings were minimized as much as possible during scanning to enable SeisDig's trace-tracking algorithm to effectively identify and track the data trace (see text).

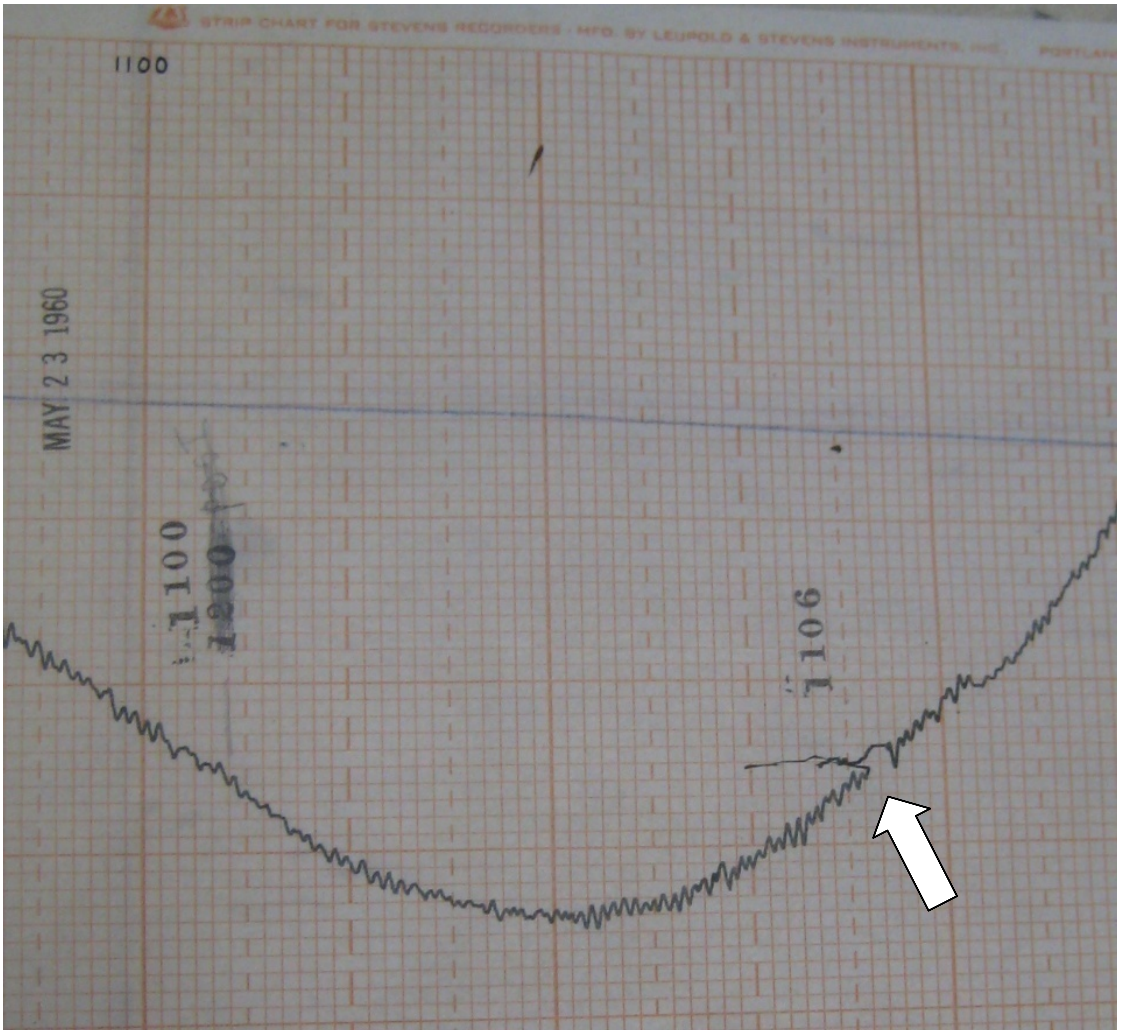

Figure 1.8: Example of a "wandering trace" error in the strip chart recording (arrow, lower right).

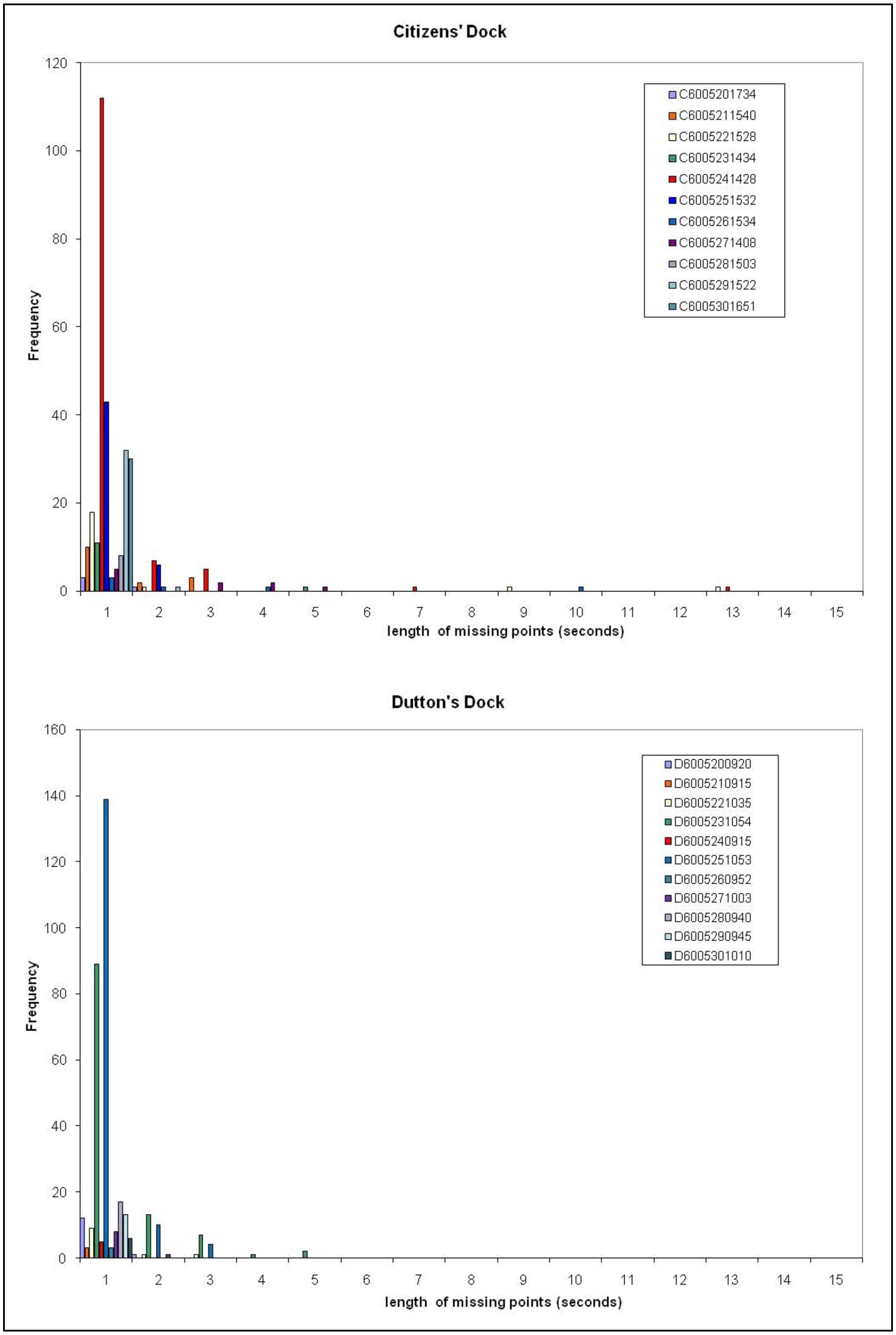

Figure 1.9: Number (Frequency) count of missing data points (seconds) for each digitized file.

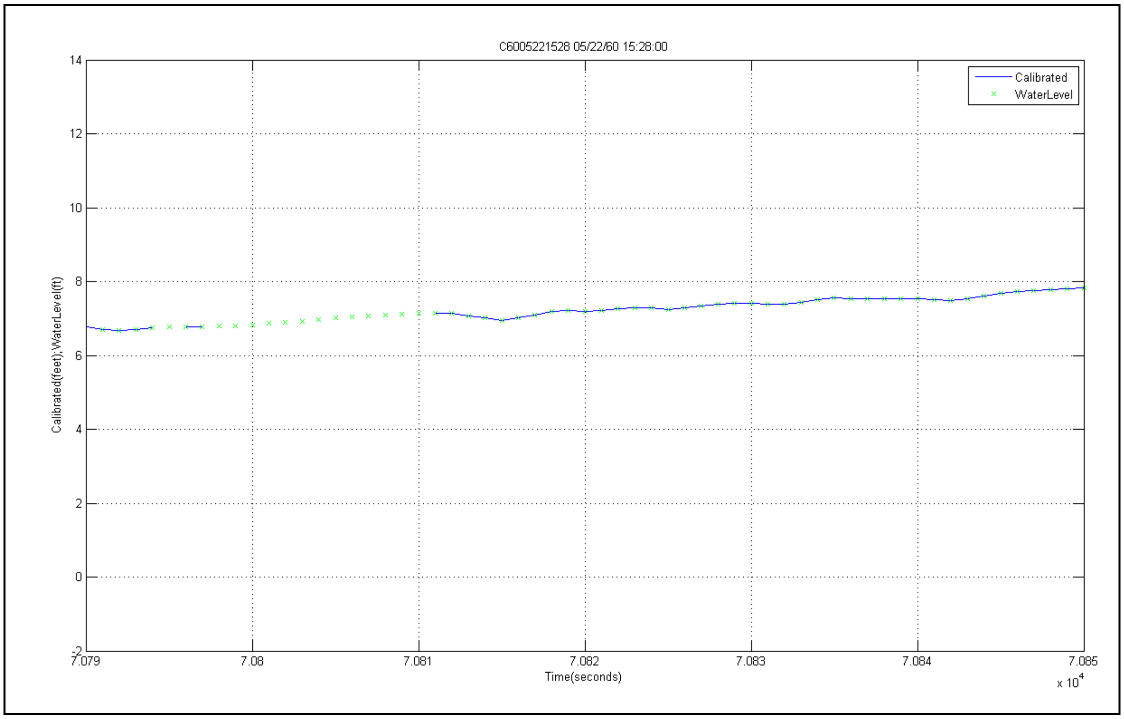

Figure 1.10: Calibrated data with missing points caused by trace image gaps are filled (small green x's) using a Matlab piecewise cubic spline interpolation function. Time is in seconds from start of file (22 May 1960 at 15:28).

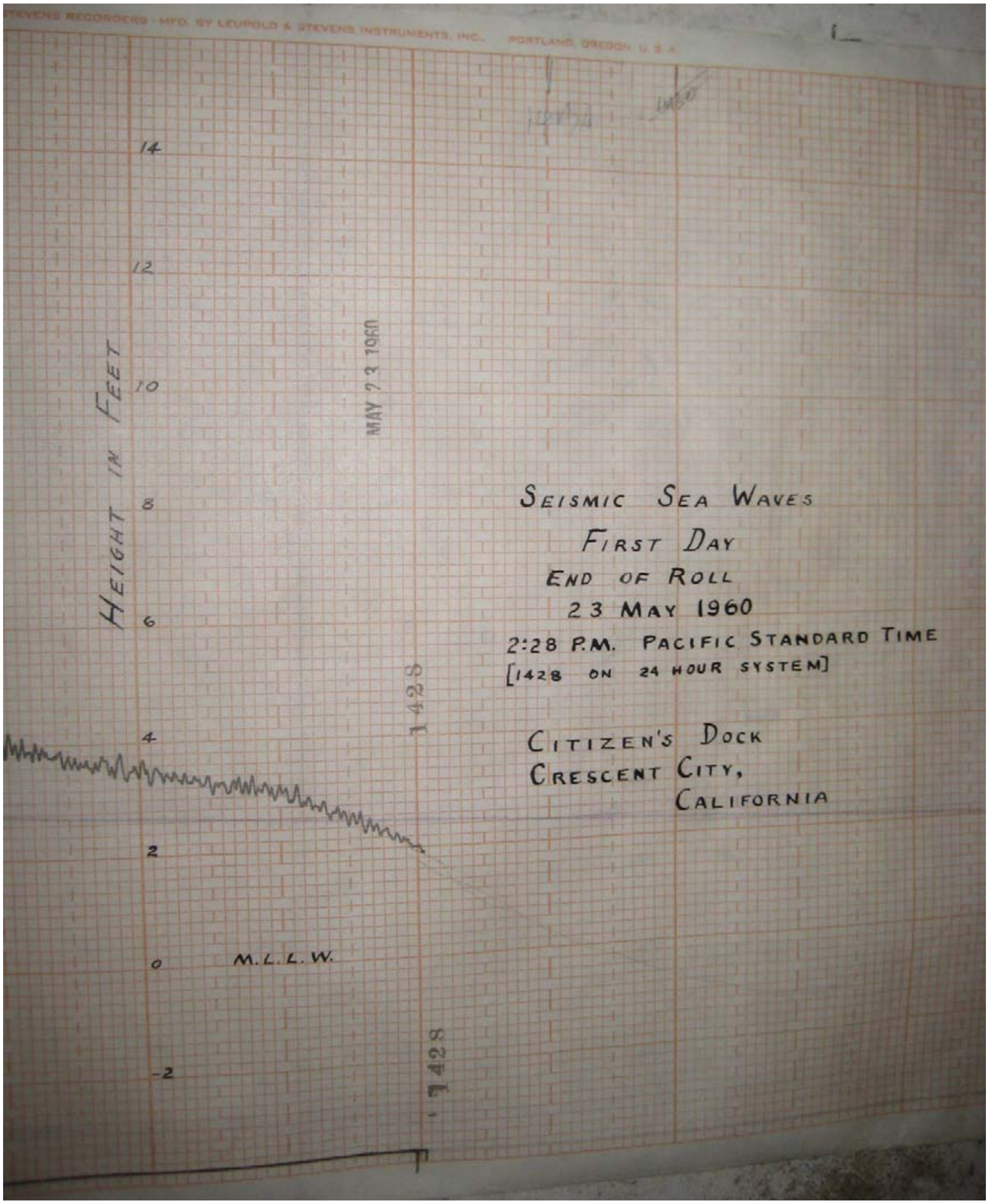

Figure 1.11: First two days (23-24 May 1960) of the tsunami were heavily annotated. Note time stamp and vertical scale marked as MLLW (in feet).

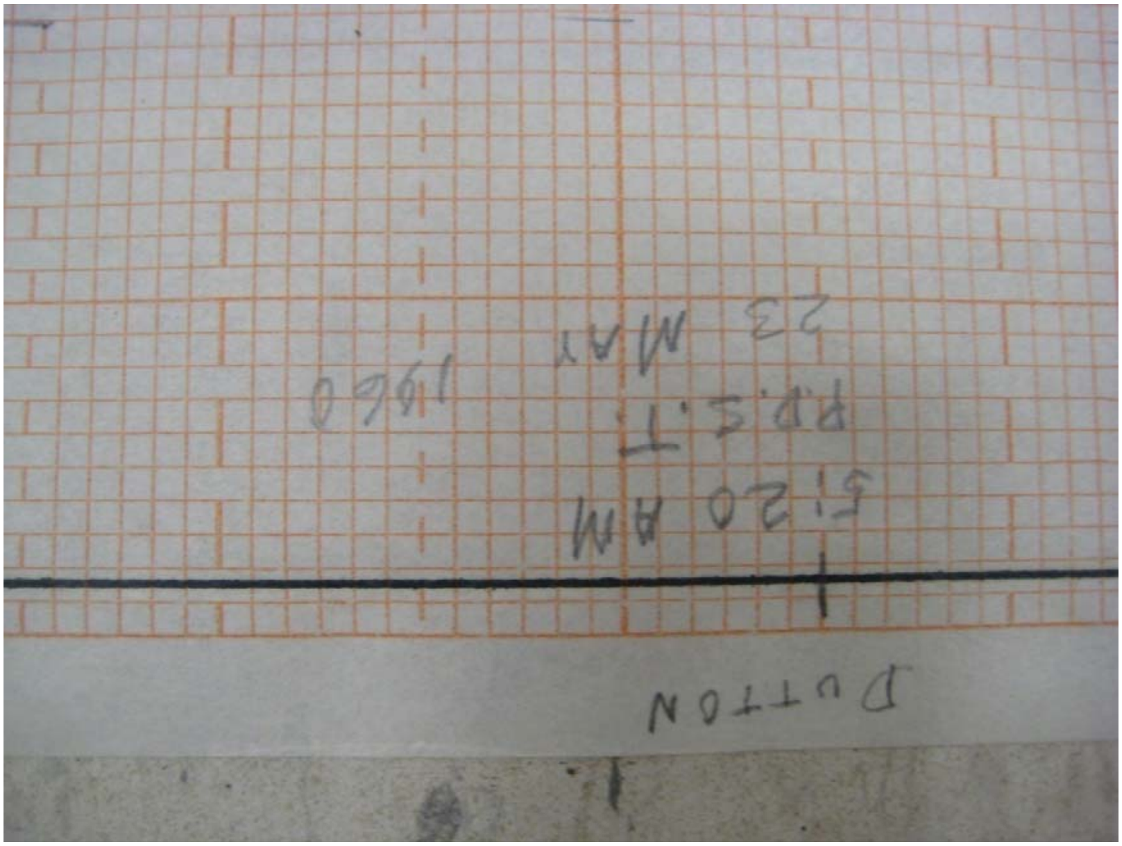

Figure 1.12: Reference line was typically located at a reading of -3.7 feet on the grid relative to digitized strip chart trace amplitudes (see text).

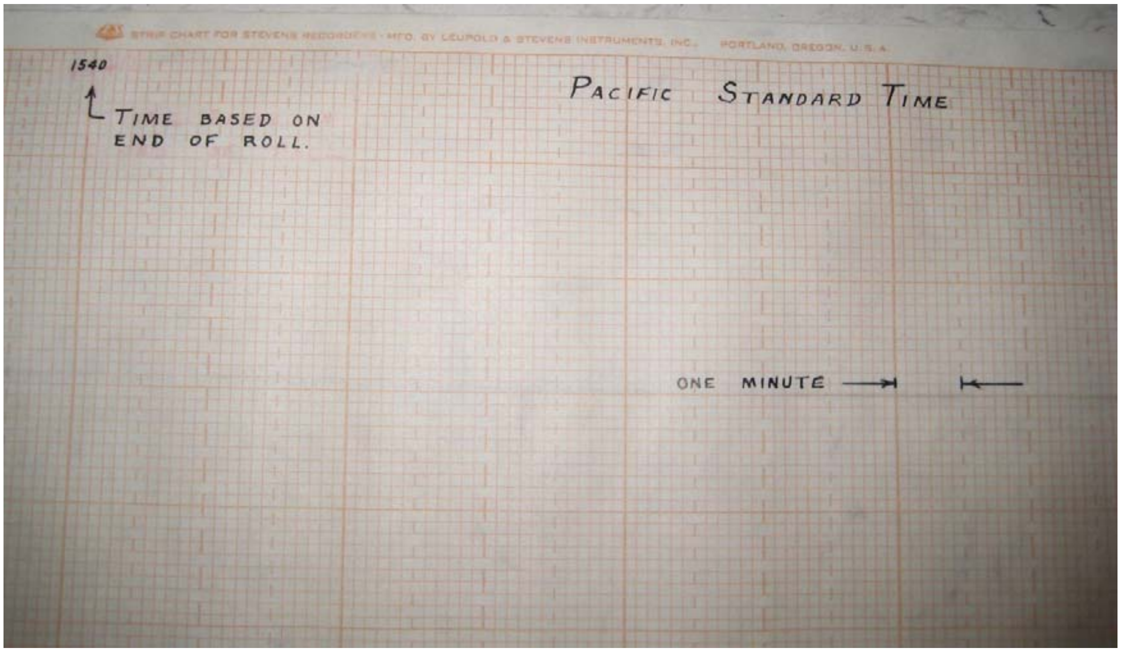

Figure 1.13: Detail from roll C6005211540 showing a reference to “Pacific Standard Time” and “ONE MINUTE” time interval marked on grid. The note “TIME BASED ON END OF ROLL.” is an original annotation referring to a time calculation based on the end-of-roll time stamp.

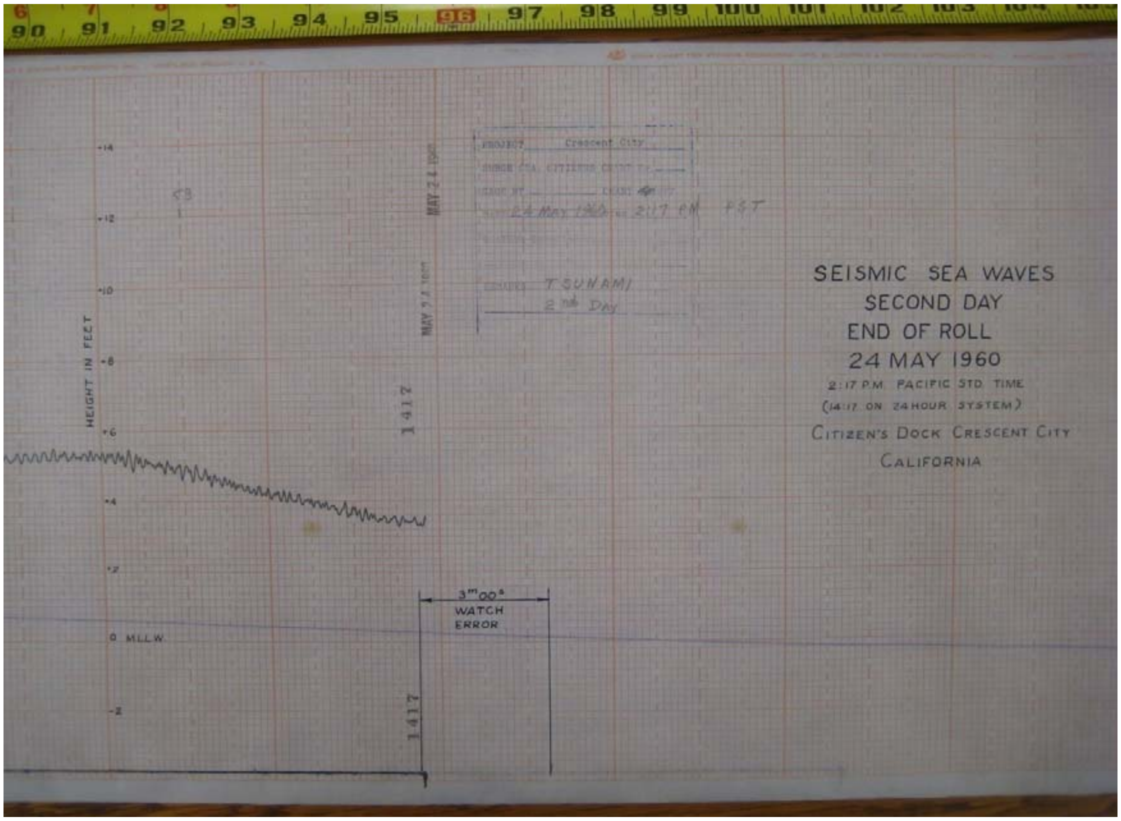

Figure 1.14: Watch errors were found and noted. This example is from a roll that was highly annotated shortly after the tsunami arrived.

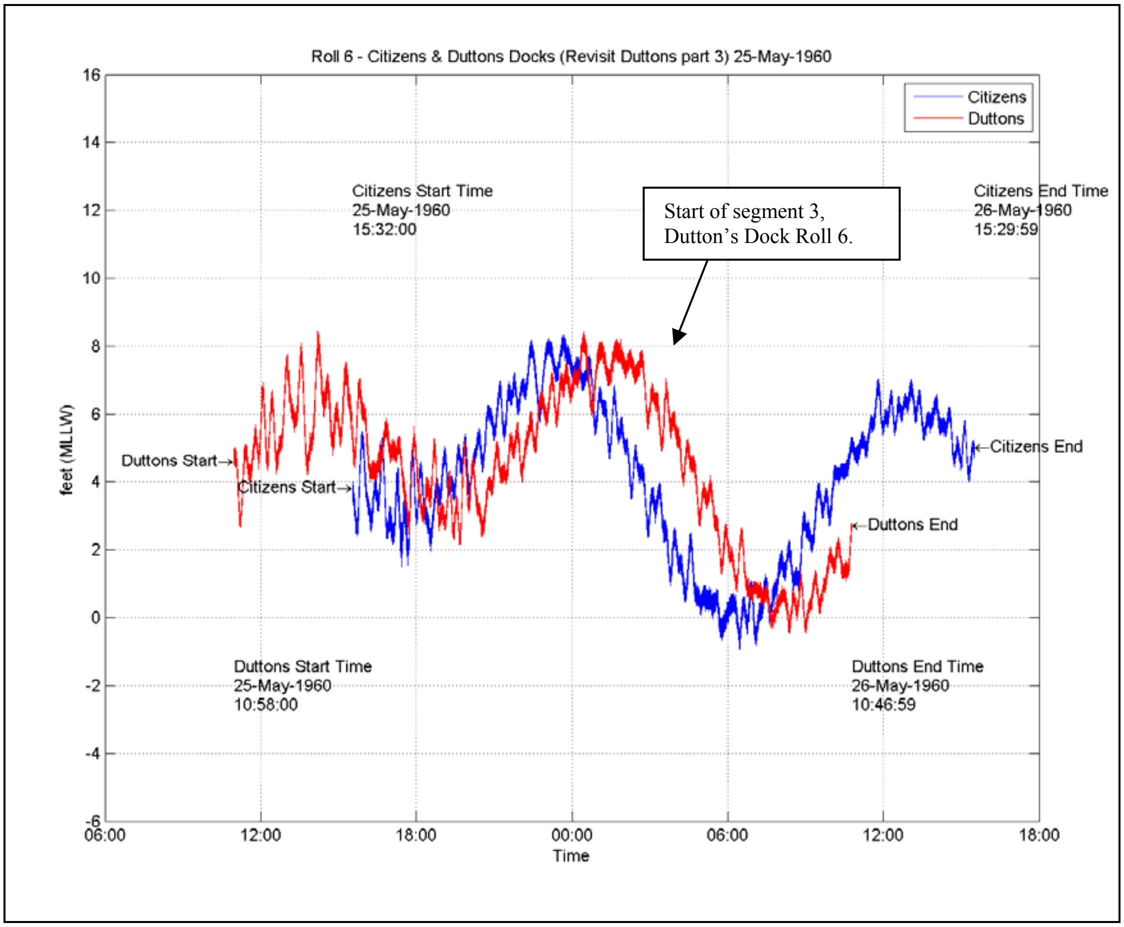

Figure 1.15: Plots of "first look" time series from Rolls 6 from Citizen's Dock (blue) and Dutton's Dock data (red). Segment 3 (D6005251058_3) was originally designated as 26 May 1960 at 02:53 to 10:47, based on the assumption that the annotated time was off by 1 hour in order to match pixel length of trace. See text for further explanation.

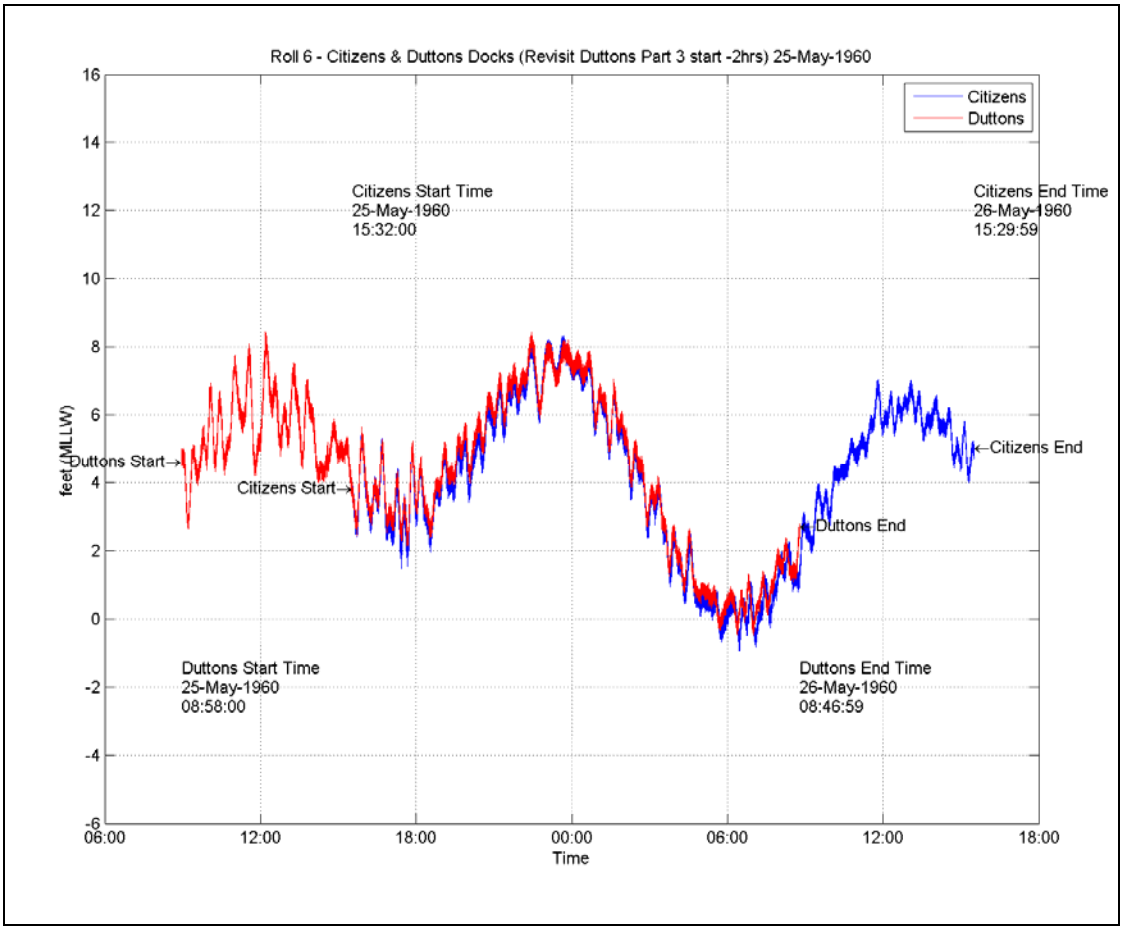

Figure 1.16: Plots of time series from Citizen's Dock (blue) and Dutton's Dock data (red) from Roll 6 showing close correspondence after the end time was corrected by shifting the trace time 2 hours to account for PST and PDT correction confusion (see text). Time annotations and horizontal scale are in PST.

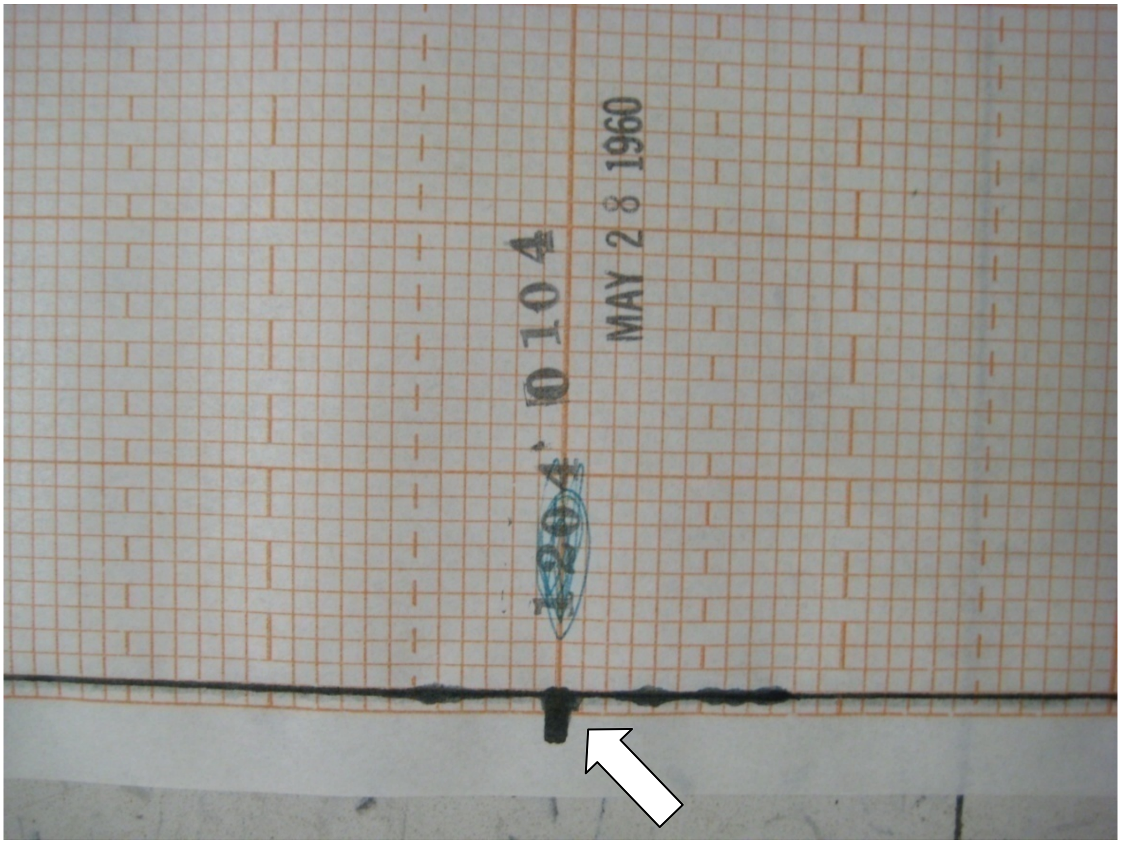

Figure 1.17: Example of smudged reference line (arrow, bottom center). Note the confusion of time (green cross-out, above smudge).

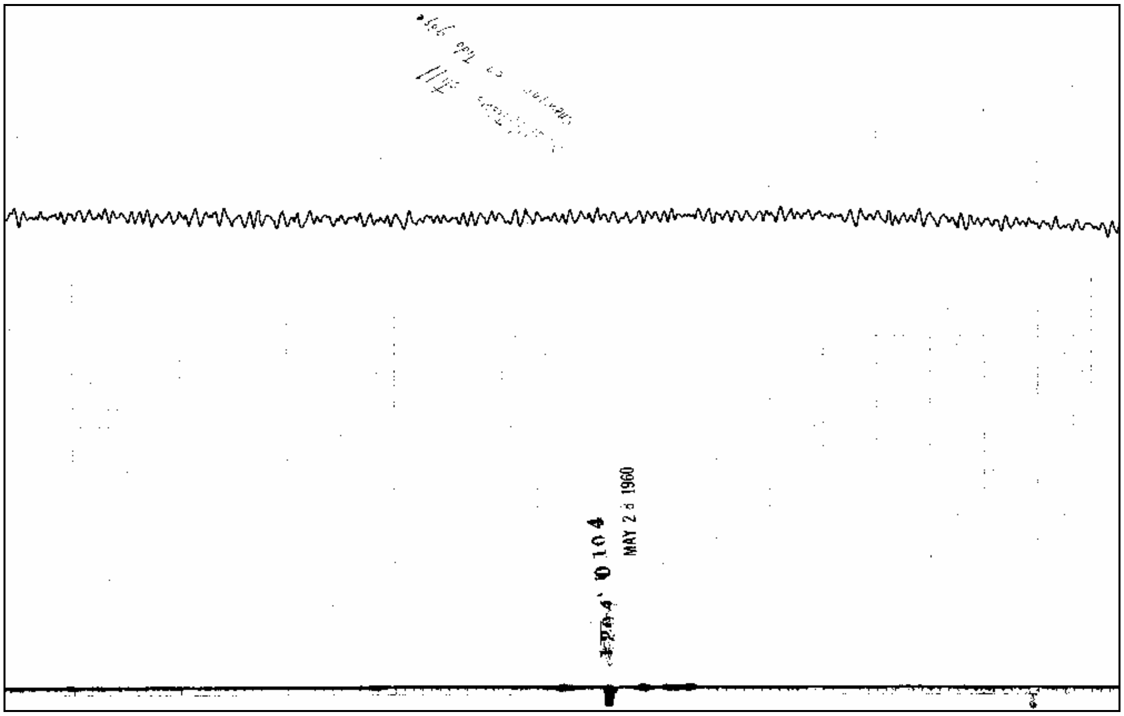

Figure 1.18: Scan from file C6005271408_2.tif showing area of photo in Figure 1.17. The annotation says “0104 May 28 1960 oscillations still showing on tide gage”.

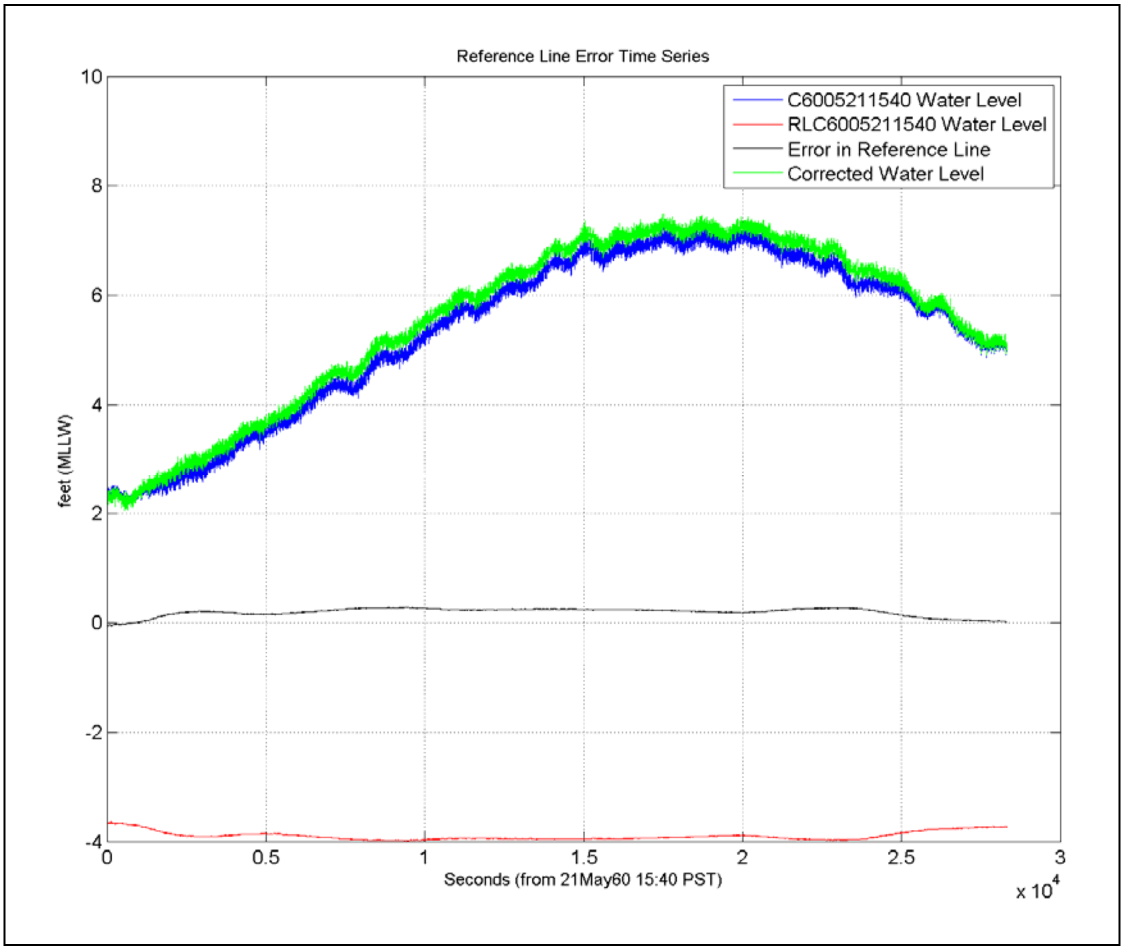

Figure 1.19: Segment 1 of file C6005211540 showing the calibrated water level (blue) and reference line (red). Error due to distortion of the reference line is shown in black.

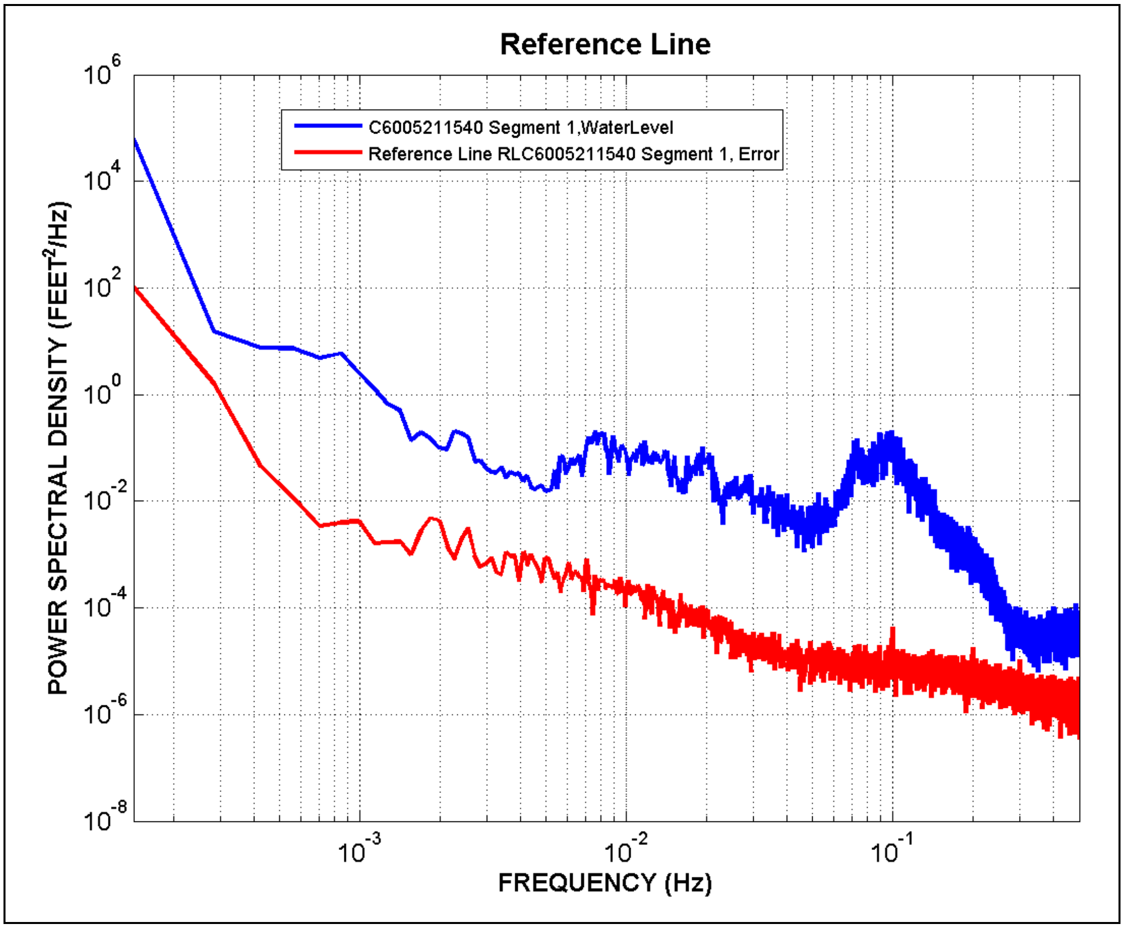

Figure 1.20: Spectra of error in reference line (red) compared to spectrum of the data (blue).

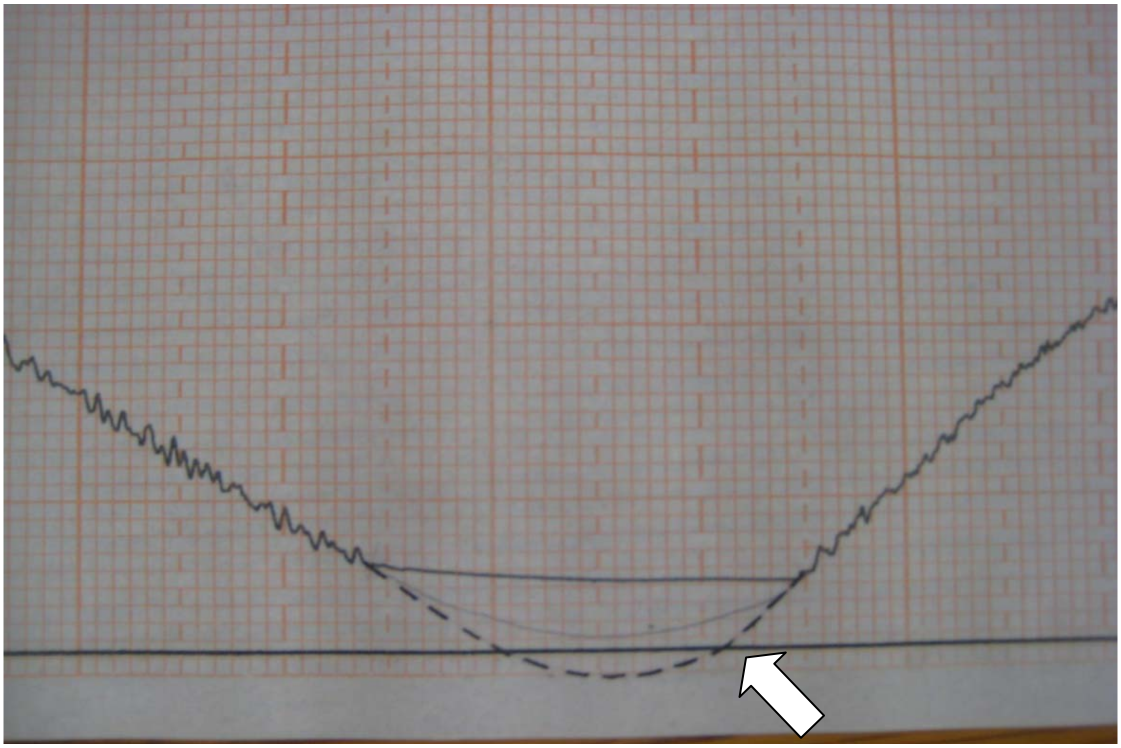

Figure 1.21: Loss of trace on roll C6005231434 from 05:05-05:09 PST on 24 May 1960. Data gap was filled with broken line (arrow, see text).

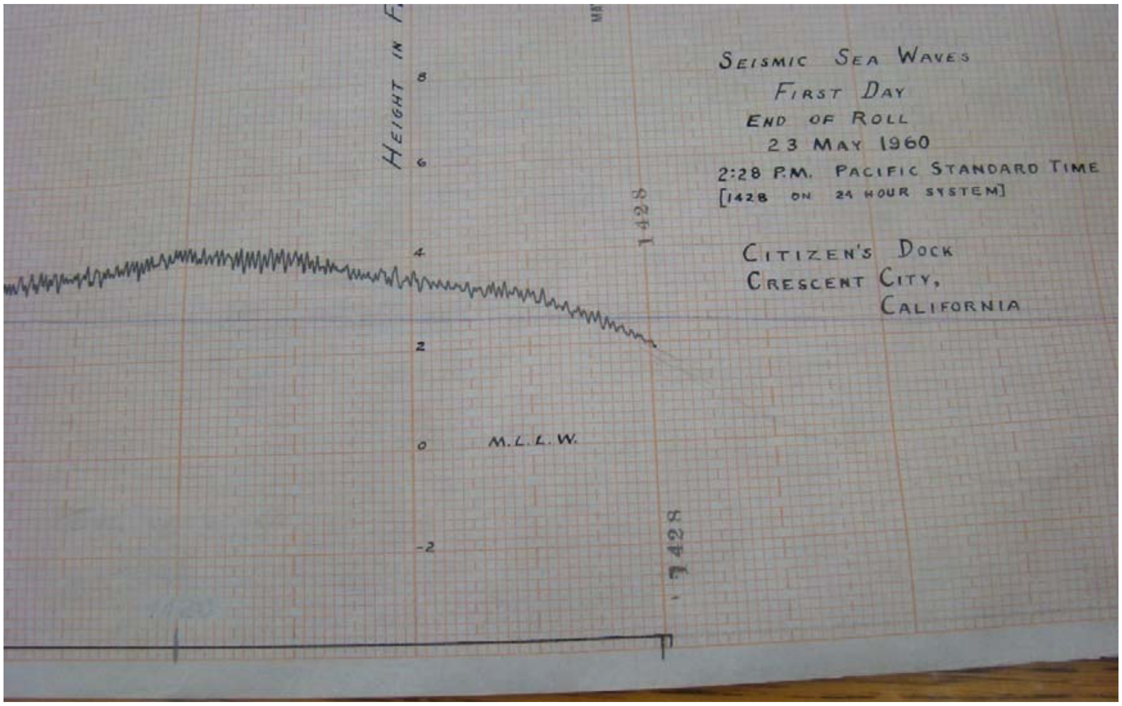

Figure 1.22: Photo showing trace on strip chart roll. Compare with plot of the same digitized data shown in Figure 1.23.

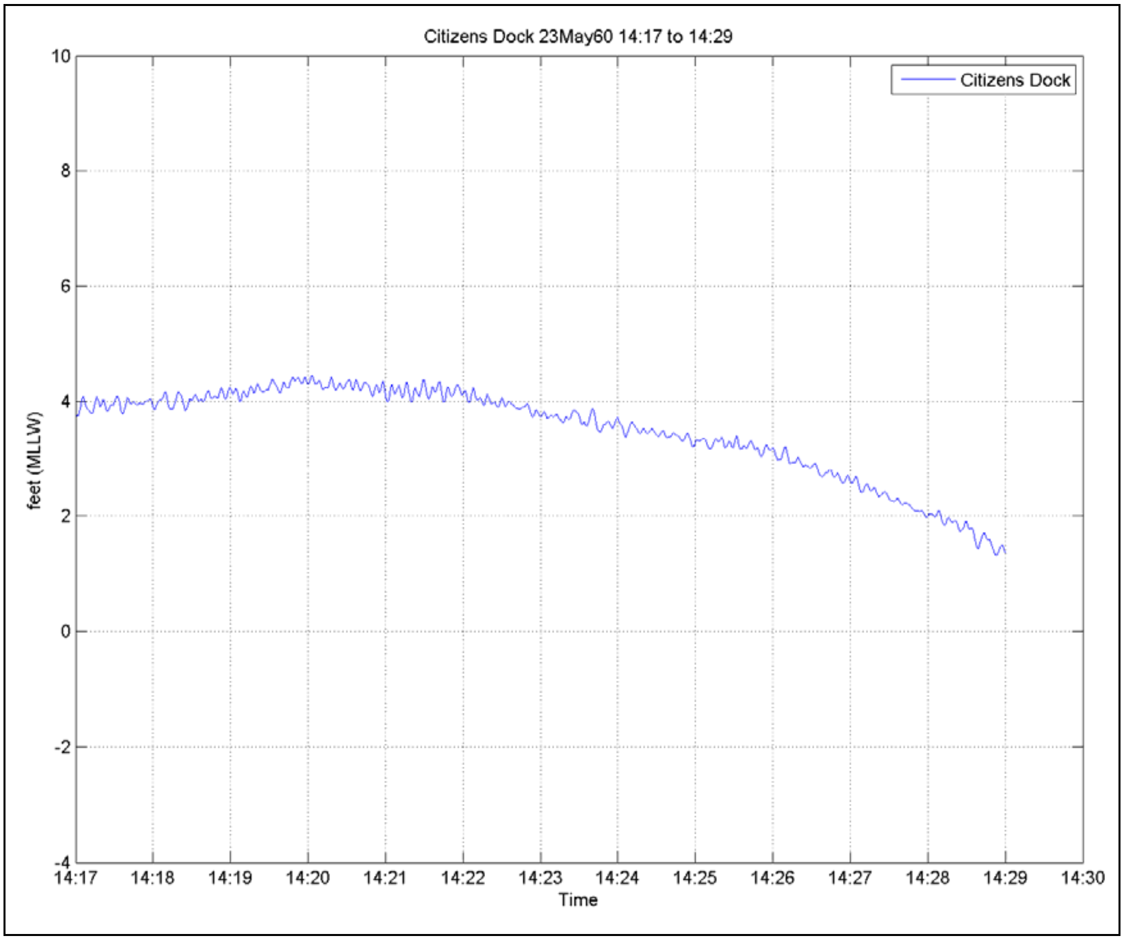

Figure 1.23: Plot of digitized data trace for the image shown in Figure 1.22. Time shown is PST.

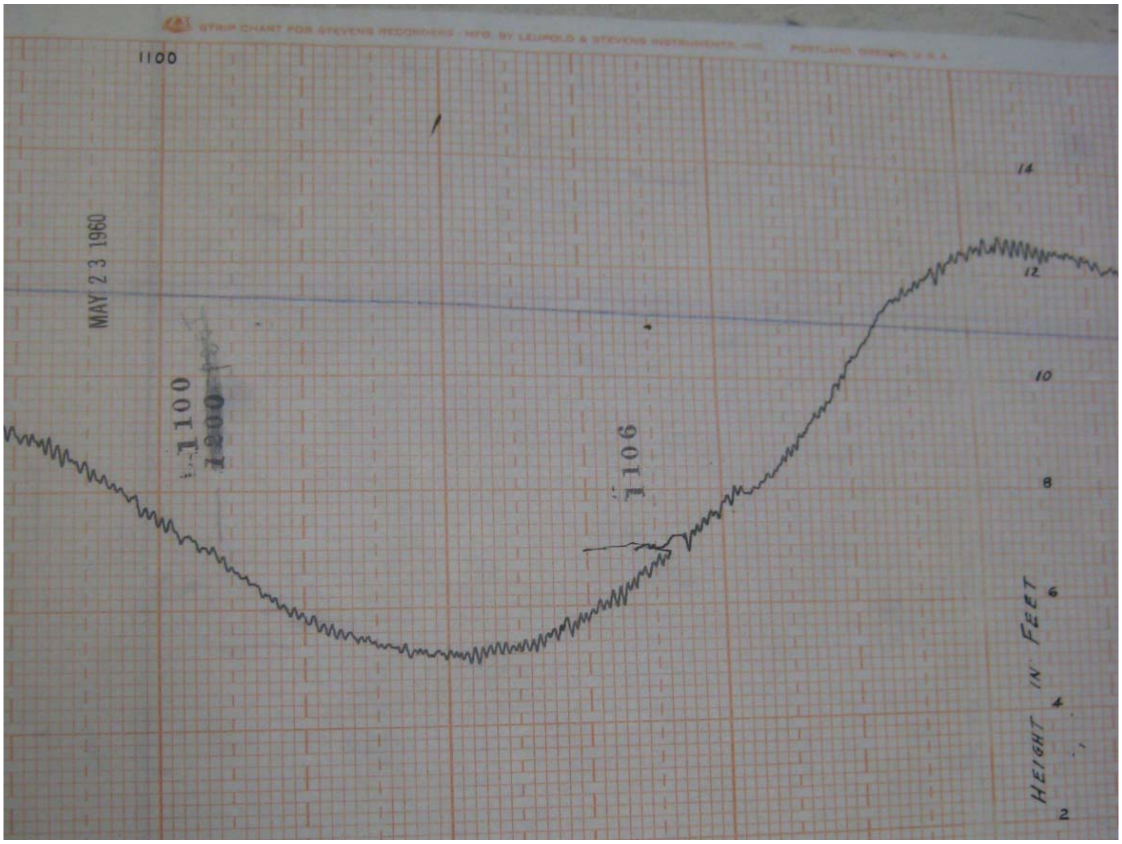

Figure 1.24: Citizen’s Dock strip chart roll showing trace from 23 May 1960 at time of highest tsunami waves (right). This section of trace was manually digitized and is discussed by Magoon (1962).

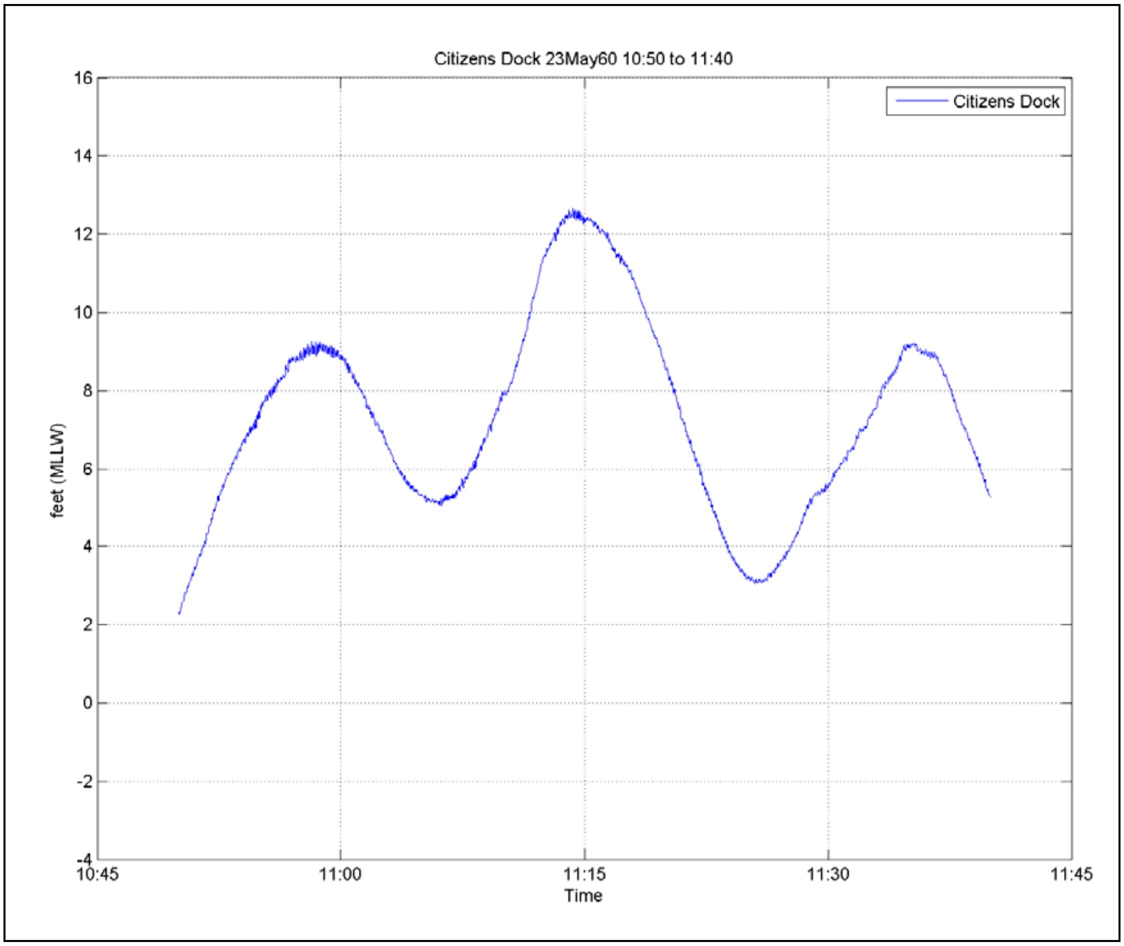

Figure 1.25: Citizen’s Dock digitized data from 23 May 1960, 10:50-11:40 PST. The beginning of this segment corresponds to the data shown in Figure 1.24 that was manually digitized by Magoon (1962).

Appendix A – Strip Chart Roll Log, Citizen's Dock & Dutton's Dock

Citizen's Dock		Start		End			
Label	Roll Number	Date	Time	Date	Time	Comments	Notes (approximate times given are calculated based on beginning time stamp)
	1	11-May-60	$08:30^{10s}$	11-May-60	$15:24^{55s}$	"May 11 1960, 1543, Citizen's Dock"	(test roll DocuSure)
			(Daylight)		(16:26 PDT	many "false" starts	
					4.1'	scale -2 to +8, black line @ -1.9	
						first notch @ 08:40; notches are 20 minutes apart	
						says daylight savings time @ 12:15 May 11, 1960	
						last labeled time stamp @ 15:20 pst"	
C6005111543	2	11-May-60	15:43	12-May-60	13:05		Time checks labeled "PDST"
			3.95'		6.8'	"opened slot @ 7:03 PM PDST"	
						"closed slot @ 7:16 PM ± PDST 11May60"	
						"reset to agree with tide tables 7:22 pm +3.0"	
						"raining hard now"	
						"testing gage 1^0 ft fluctuation	
						"New scale -4 to 16 "	~ 7:22 pm PDST 11May60
							has tide from tide tables line from ~7:55 PM to ~8:15 PM
						"MID-TIDE 4.9 from Table"	has tide from tide tables line from ~9:00 PM to ~9:27 PM
						"High-Tide 7.7' from Table"	
						settings"	
						"Tide ± 3' 1" by tables"	
						"slot opened"	
C6005121315	3	12-May-60	13:15	13-May-60	14:14	"loaded oil barge between end of jetty and gage"	
			PST		PST	"re-set to agree with tide table, RFW 7:00 pm PDST 12 May 60"	

Citizen's Dock		Start		End			
Label	Roll Number	Date	Time	Date	Time	Comments	Notes (approximate times given are calculated based on beginning time stamp)
C6005131430	4	13-May-60	14:30	14-May-60	14:42	"strong NW wind"	
			PST		PST	"wind N-NW 20-30 kts"	
C6005141405	5	14-May-60	14:05	15-May-60	14:35	"wind NW light"	
C6005151445	6	15-May-60	14:45	16-May-60	15:35	"12:40 closed gate"	
			PST				
C6005161540	7	16-May-60	15:40	17-May-60	15:20	"wind light NW"	minutes
C6005171526	8	17-May-60	15:26	18-May-60	15:15		
C6005181519	9	18-May-60	15:19				no end time stamp
C6005191630	10	19-May-60	16:30	20-May-60	17:27		
				PDST			
C6005201734	11	20-May-60	17:34	21-May-60	15:35	"1326 May 21 1960"	stamped
	read off roll	4.6'		2.3'			
	in file	4.8'		2.35'			
C6005211540	12	21-May-60	1540	22-May-60	15:20	"1554 14 min off"	hand written at begining of trace (time was calculated by counting backwards from end of roll)
	read off roll	2.1'		2.6'		"Tr" (for trough)	one of many starting 5/22/60 09:38
	in file	2.24'		2.53'		"crest"	one of many starting 5/22/60 09:47
						"3 waves in 54 min, T= 18 min"	5/22/60 10:10
						"1100"	5/22/60 10:52
						"gate open"	5/22/60 15:06
						"gate closed"	5/22/60 15:10

Citizen's Dock		Start		End			
Label	Roll Number	Date	Time	Date	Time	Comments	Notes (approximate times given are calculated based on beginning time stamp)
C6005221528	13	22-May-60	15:28	23-May-60	14:28	"Seismic Sea Waves First Day, Beginning of Roll 22 May 1960 Citizen's Dock Crescent City, CA"	
	read off roll	2.4'	PST	1.9'		"3:29 P.M. P.S.T [1529 on 24 hour system]" marked on roll (~ 1min from start of trace)	time was marked starting from end of roll every 20 minutes the 1529 mark was last time labelled (beginning of roll was stamped 1525)
						"gate open"	gate was opened from approximately 19:16 - 19:19 on May 22, 1960
						"watch error 2m 40s"	
						" May 22 2223 gate open"	for 14 minutes 46 sec
						"Seismic Sea Waves First Day, End of Roll 23 May 1960, 2:28 Pacific Standard Time [14:28 on 24 Hour System] Citizen's Dock, Crescent City, CA"	
C6005231434	14	23-May-60	14:34	24-May-60	1417	"Seismic Sea Waves Cont.First & Second Days Beginning of 2nd Roll, 23 May 1960 14:34 on 24-hour system 2:34 P.M. Pacific STD Time	times well annotated along top of roll
"Tsunami 2nd day" written on end of box						"start digitizing"	at beginning of roll
						"gate open ~ 1617 to 1625"	
						"30 sec. watch error"	written @ 23May60 19:49
						"1m 50s watch error"	written @ 23May60 23:20
							loss of trace ~ 03:40^{40s} - 03:42^{50s} (goes to ~-3.1 feet about 03:42)
							loss of trace 05:05^{20s} - 05:09^{30s} (~24May60 05:07 trace down to
						"3min. 00sec. Watch Error"	written at end of 14:17 time stamp, implying 14:17 as counted from beginning time stamp occurs 3 minutes after end time stamp
						"Seismic Sea Waves Second Day, End of Roll 24 May 1960, 2:17 Pacific Standard Time [14:17 on 24 Hour System] Citizen's Dock, Crescent City, CA"	

Citizen's Dock		Start		End			
Label	Roll Number	Date	Time	Date	Time	Comments	Notes (approximate times given are calculated based on beginning time stamp)
C6005241428	15	24-May-60	1428	25-May-60	non given	"open gate"	~07:53 25May60
"Tsunami 3rd day"						"3.6' from crest to trough"	
						"closed gate"	~07:59 25May60
						"Hard Southerly winds 35-40"	no end time marked
C6005251532	16	25-May-60	15:32	26-May-60	15:30	"closed gate "	approximately 25May60 17:40
"Tsunami 4th day"						"open gate"	
						" surge is giving boats trouble at dock"	
C6005261534	17	26-May-60	15:34	27-May-60	14:04		
"oscillations,							
C6005271408	18	27-May-60	14:08	28-May-60	15:00	"01:04 May 28 1960 oscillations still	reference line smudged starting ~00:10 28May60 and continues to end
C6005281503	19	28-May-60	15:03	29-May-60	15:18		
C6005291522	20	29-May-60	15:22				no end time stamp
							reference line smudged at end
C6005301651	21	30-May-60	16:51	31-May-60	15:12		reference line thick at beginning of roll and again from approximately 13:05 31May60 to end (15:05 31May60)
C6005311515	22	31-May-60	15:15				no end time stamp
C600601xxxx	23	1-Jun-60		2-Jun-60	15:05		no begin time stamp
C6006021508	24	2-Jun-60	15:08	3-Jun-60			no end time stamp
	no June 4th roll						
C6006051140	25	5-Jun-60	11:40	6-Jun-60	12:00	"no roll recorded for June 4"	
C6006061203	26	6-Jun-60	12:03	7-Jun-60	12:32		no reference line for part of record
C6006071236	27	7-Jun-60	12:36				reference line smudged at beginning, end of roll torn, no end time stamp

Citizen's Dock		Start		End			
Label	Roll Number	Date	Time	Date	Time	Comments	Notes (approximate times given are calculated based on beginning time stamp)
C6006081625	28	8-Jun-60	16:25	9-Jun-60	15:37		wide ink smudge at beginning
C6006091542	29	9-Jun-60	15:42	10-Jun-60	16:24		
C6006101630	30	10-Jun-60	16:30	11-Jun-60	16:57		
C6006111700	31	11-Jun-60	17:00	12-Jun-60	15:33		
C6006121537	32	12-Jun-60	15:37	13-Jun-60	14:53		
C6006131456	33	13-Jun-60	14:56	14-Jun-60	15:22		a test roll taken to Docusure
C6006141525	34	14-Jun-60	15:25	15-Jun-60	15:05		"note 'seiche' last hour or two, period ± 20 minutes"
							"11:20 PST 15 June 60 same watch used to set clock at Dutton's"
							"14:35 PST 15 June 1960 clear warm light breeze"
							"NNW 10 kts, higher than average seiche"
C6006151508	35	15-Jun-60	15:08	16-Jun-60	15:55		" NW 2-30 kts"

Dutton's Dock		Start		End			
Label	Roll Number	Date	Time	Date	Time	Comments	Notes (approximate times given are calculated based on beginning time stamp)
D6005111828	1	11-May-60	18:28	12-May-60	9:44	"slot open"	
			PDST?		PDST	"blowing and raining"	
						"low tide supposed to be 2.1 @ 6:25 pm 11 May 60"	
						"closed triangular slot at 6:30 pm PDST 11 May 60"	
						" A new scale now "	scale of -4 to 16 feet starts ~ 21:55 11 May 60
D6005120954	2	12-May-60	9:54	13-May-60	10:05	"09:30 am playing with sprocket"	
					PDST	"adjusting relay"	~ 09:00
					0.2'	"08:13 low tide =1.0"	
						"slot opened"	
						"Finally adjusted to agree with tide tables"	
						"dock elevation must be ~ 19"	
						"slot opened 12 inches"	
D6005131010	3	13-May-60	10:10	14-May-60	9:53		
					PDT		
missing 14-15 May 1960							
D6005150920	4	15-May-60	9:20	16-May-60	10:40		
			PDT		PDT		
D6005161647	5	16-May-60	16:47	17-May-60	9:09		
D6005171919	6	17-May-60	19:19	18-May-60	9:22		
D6005180928	7	18-May-60	9:28	19-May-60	9:31		
					PDT		
D6005190942	8	19-May-60	9:42	5/20/1960	9:16		

Dutton's Dock		Start		End			
Label	Roll Number	Date	Time	Date	Time	Comments	Notes (approximate times given are calculated based on beginning time stamp)
D6005200920	9	20-May-60	9:20	5/21/1960	9:09		as a check, starting at end of trace and marking time off towards beginning yields start of trace to be 20May60 at 09:27, 7 minutes after marked start time
D6005210915	10	21-May-60	9:15	5/22/1960	10:30		as a check, starting at beginning of trace and marking time off towards end yields end of trace to be 20May60 at 10:28, 2 minutes before marked end time
							reference line smudged at beginning
D6005221035	11	22-May-60	10:35	5/23/1960	10:51	"3:22 start of tsunmai	
"Tsunami first day" written on end of box			PDT		PDT	"note variation in period of seiche with change in depth"	~ 10:00 22May60
D6005231054	12	23-May-60	10:54	5/24/1960	9:10	"tidal wave, wind 20 MPH	written under beginning time
						"times at top of roll are way off, Tim"	reference line thick & smudgy at beginning and near end
D6005240915	13	24-May-60	9:15	5/25/1960	10:53		
			PDT	PDT			
D6005251058	14	25-May-60	10:58	5/26/1960	9:47	"heavy winds, chop"	written near beginning
						"opened gate 10"	note is written at 25May60 from ~15:33-15:36
							marking from end, get begin time = 09:27; 1 hour 1 minute earlier than marked begin time
D6005260952	15	26-May-60	9:52	5/27/1960	9:58		
D6005271003	16	27-May-60	10:03	5/28/1960	9:35		
D6005280940	17	28-May-60	9:40	5/29/1960	9:40		
D6005290945	18	29-May-60	9:45	5/30/1960	10:06		
D6005301010	19	30-May-60	10:10	5/31/1960	9:32		beginning time not marked; calculated from given end time

Dutton's Dock		Start		End			
Label	Roll Number	Date	Time	Date	Time	Comments	Notes (approximate times given are calculated based on beginning time stamp)
D6005310942	20	31-May-60	9:42	6/1/1960	9:32		
D6006010937	21	1-Jun-60	9:37	6/2/1960	10:12		
D6006021017	22	2-Jun-60	10:17	6/3/1960	10:32		
D6006031036	23	3-Jun-60	10:36	6/4/1960	15:45		
D6006041548	24	4-Jun-60	15:48	6/5/1960	16:47		
D6006051653	25	5-Jun-60	16:53	6/6/1960	17:21		
D6006061725	26	6-Jun-60	17:25	6/7/1960			
D6006071603	27	7-Jun-60	16:03	6/8/1960	18:17		
D6006081821	28	8-Jun-60	18:21	6/9/1960	14:15	"NW 15-20"	
D6006091415	29	9-Jun-60	14:15	6/10/1960	13:35		
D6006101345	30	10-Jun-60	13:45	6/11/1960	14:32		
D6006111437	31	11-Jun-60	14:37	6/12/1960	15:30		
D6006121535	32	12-Jun-60	15:35	6/13/1960	15:00		
D6006131505	33	13-Jun-60	15:05	6/14/1960	15:37		
D6006141542	34	14-Jun-60	15:42	6/15/1960	9:20		
D6006150926	35	15-Jun-60	9:26	6/16/1960	9:09	"Clear NW 15"	
						"Reset gage height 0.5 ft ~ 10:45 PST 15 Jun 60, RFW"	

Appendix B – Plots of Digitized Data

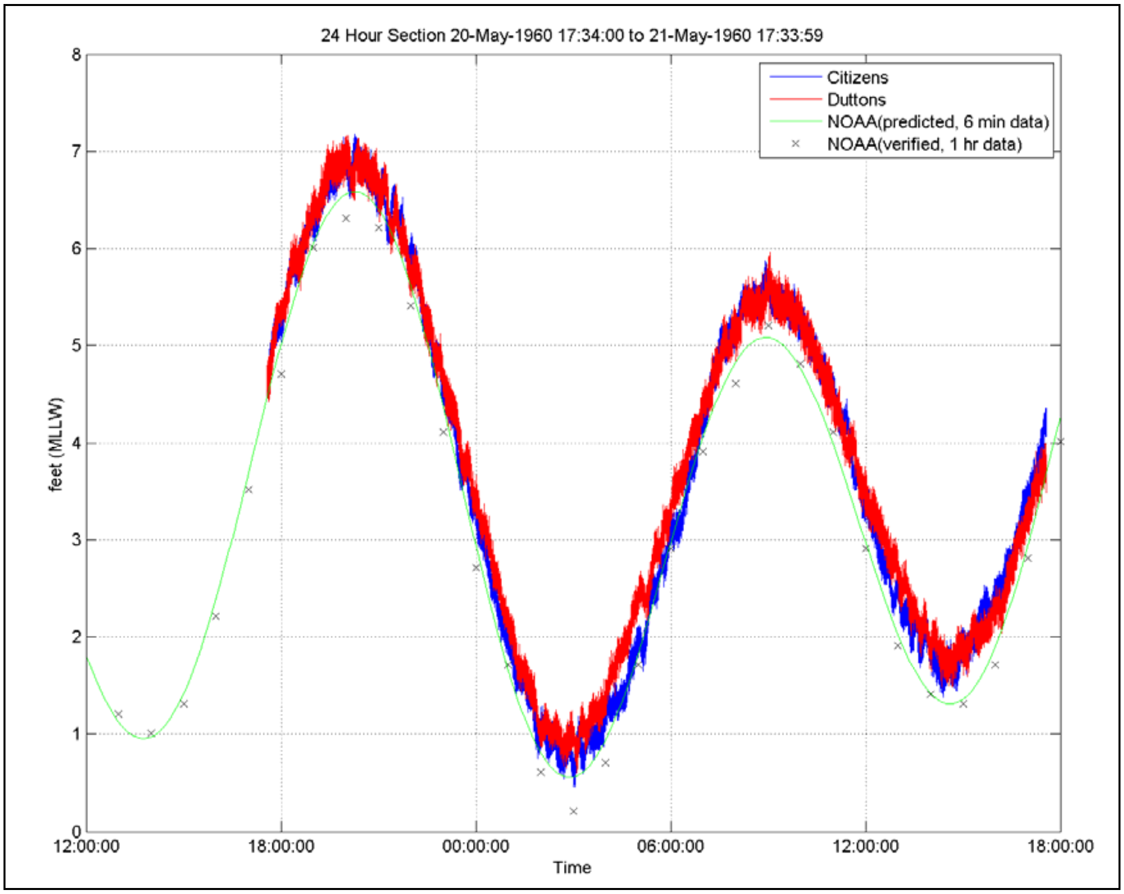

Figure B - 1: Plots of 20-21 May 1960 digitized strip chart data from Citizen's Dock (blue) and Dutton's Dock (red), NOAA 6-min tide prediction (green), and verified hourly water level observations at the Crescent City tide gauge (x's). Time is PST.

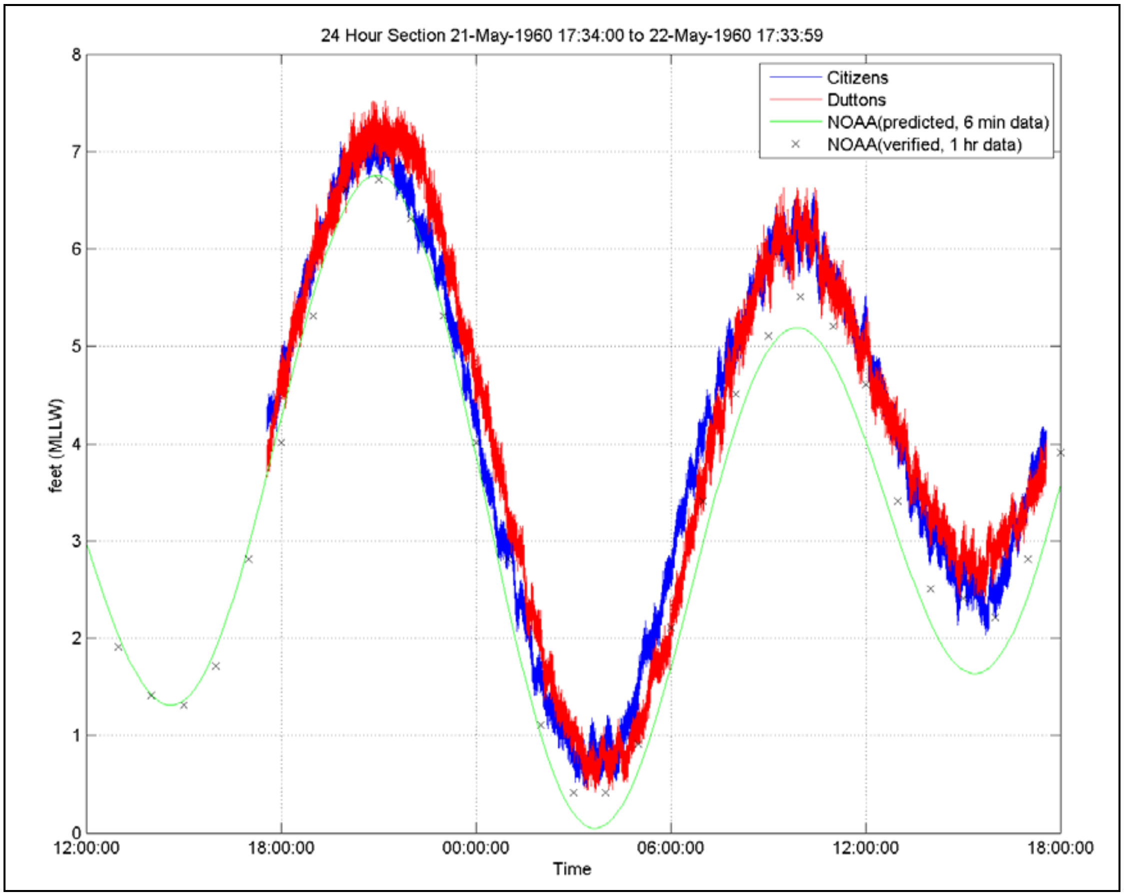

Figure B - 2: Same as Figure B - 1 for 21-22 May 1960.

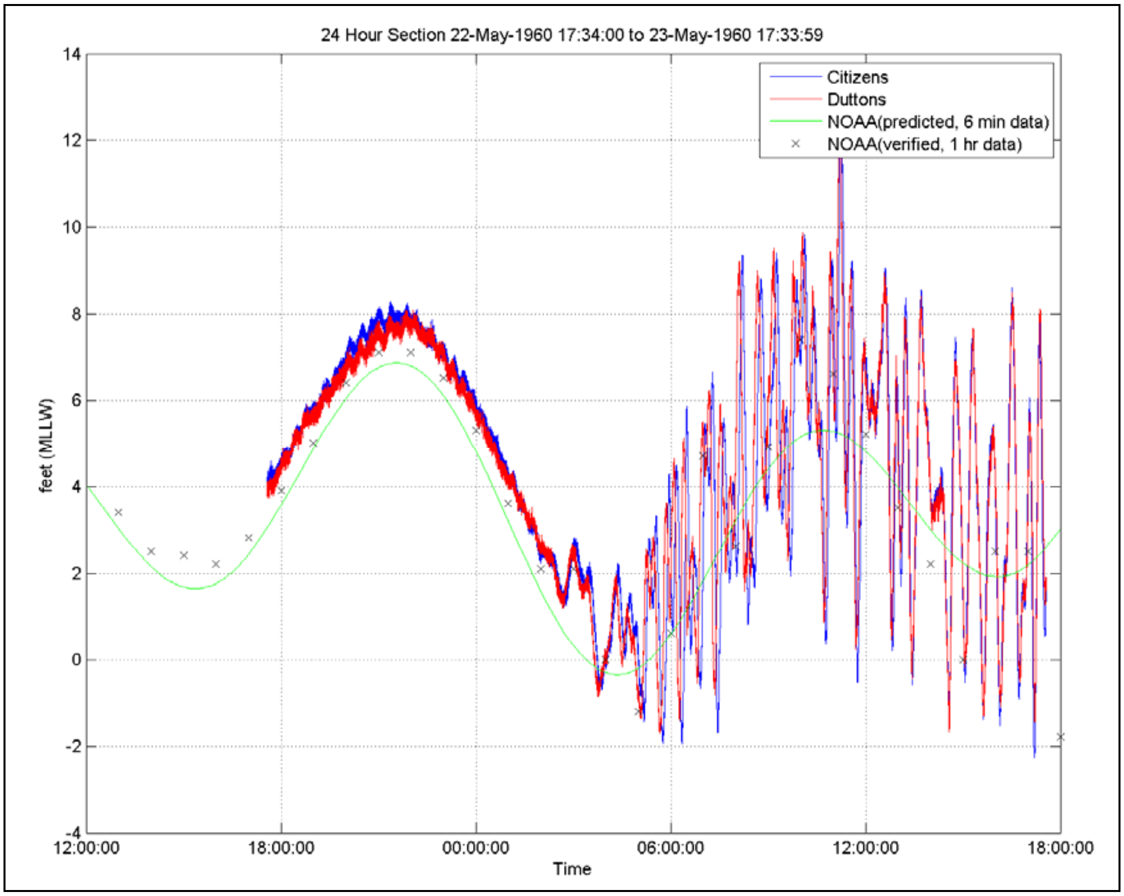

Figure B - 3: Same as Figure B - 1 for 22-23 May 1960. Note onset of tsunami waves at 02:20 PST, 23 May 1960.

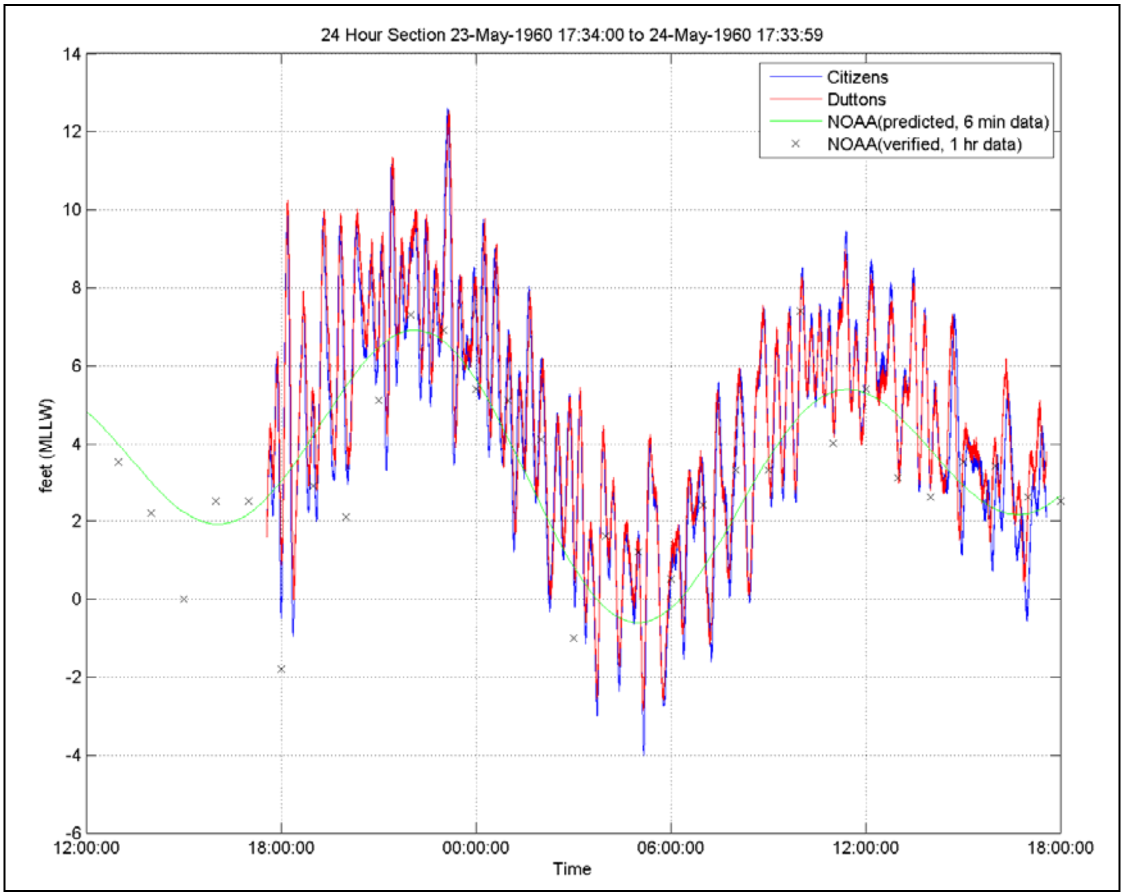

Figure B - 4: Same as Figure B - 1 for 23-24 May 1960.

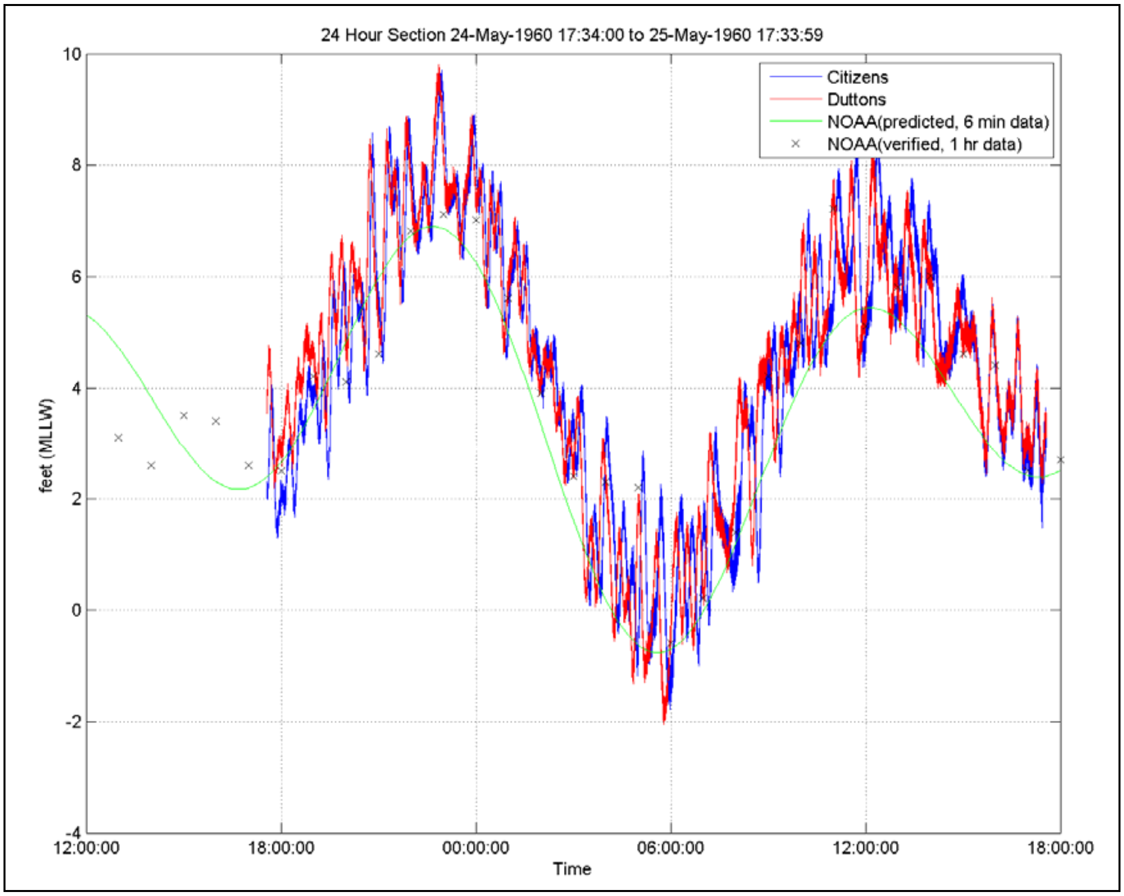

Figure B - 5: Same as Figure B - 1 for 24-25 May 1960.

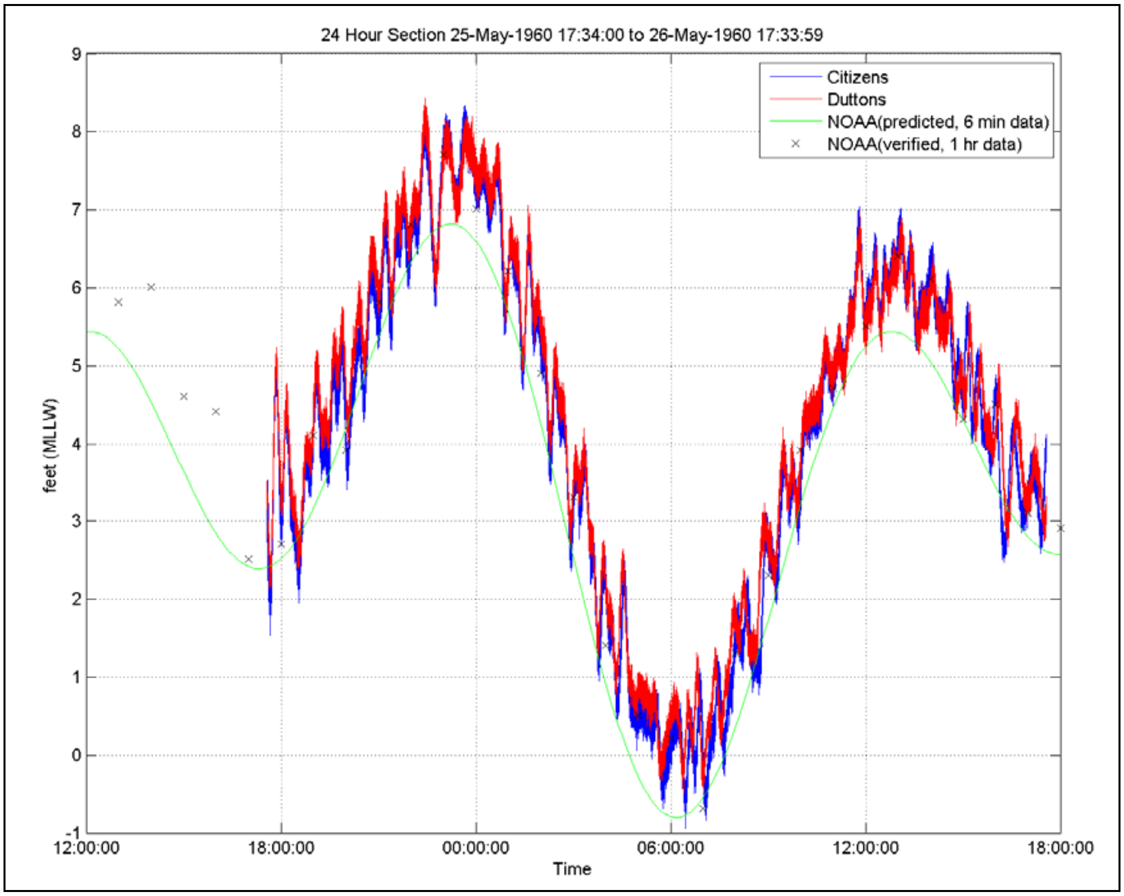

Figure B- 6: Same as Figure B - 1 for 25-26 May 1960.

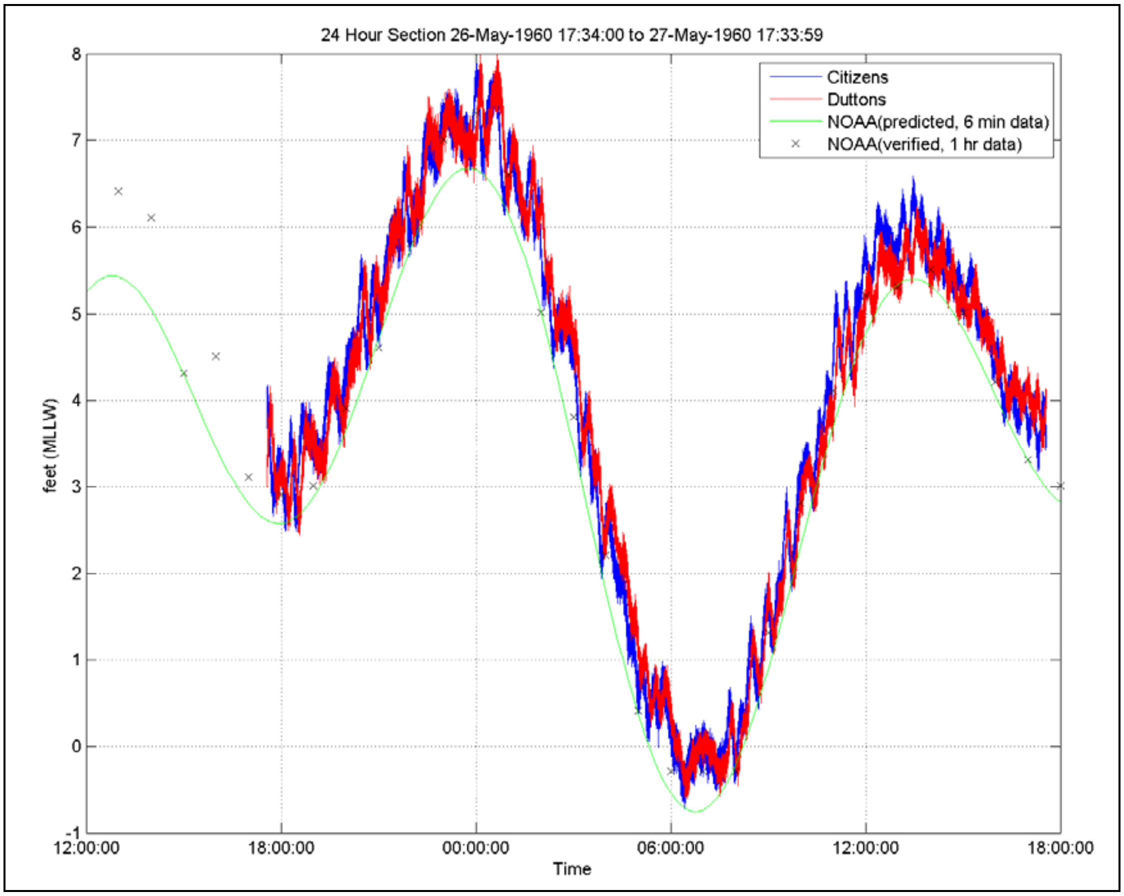

Figure B - 7: Same as Figure B - 1 for 26-27 May 1960.

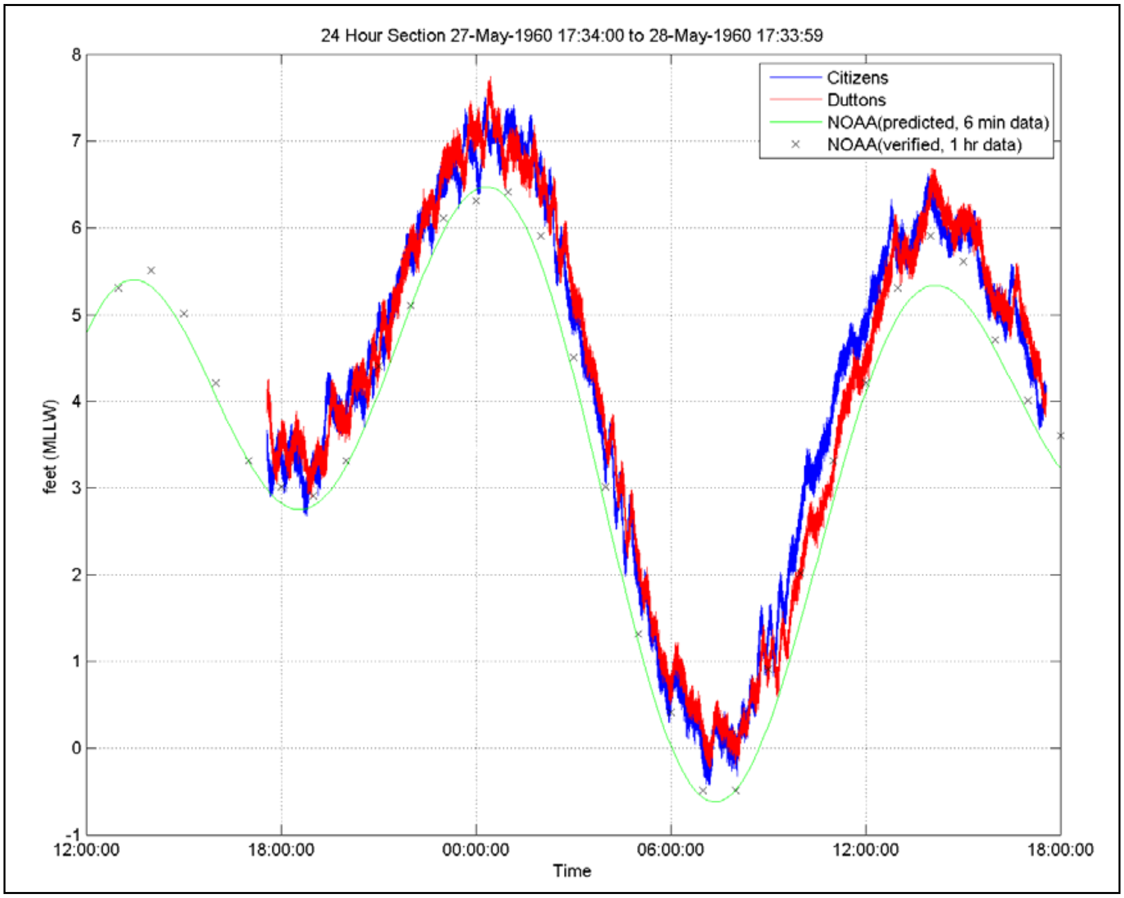

Figure B - 8: Same as Figure B - 1 for 27-28 May 1960.

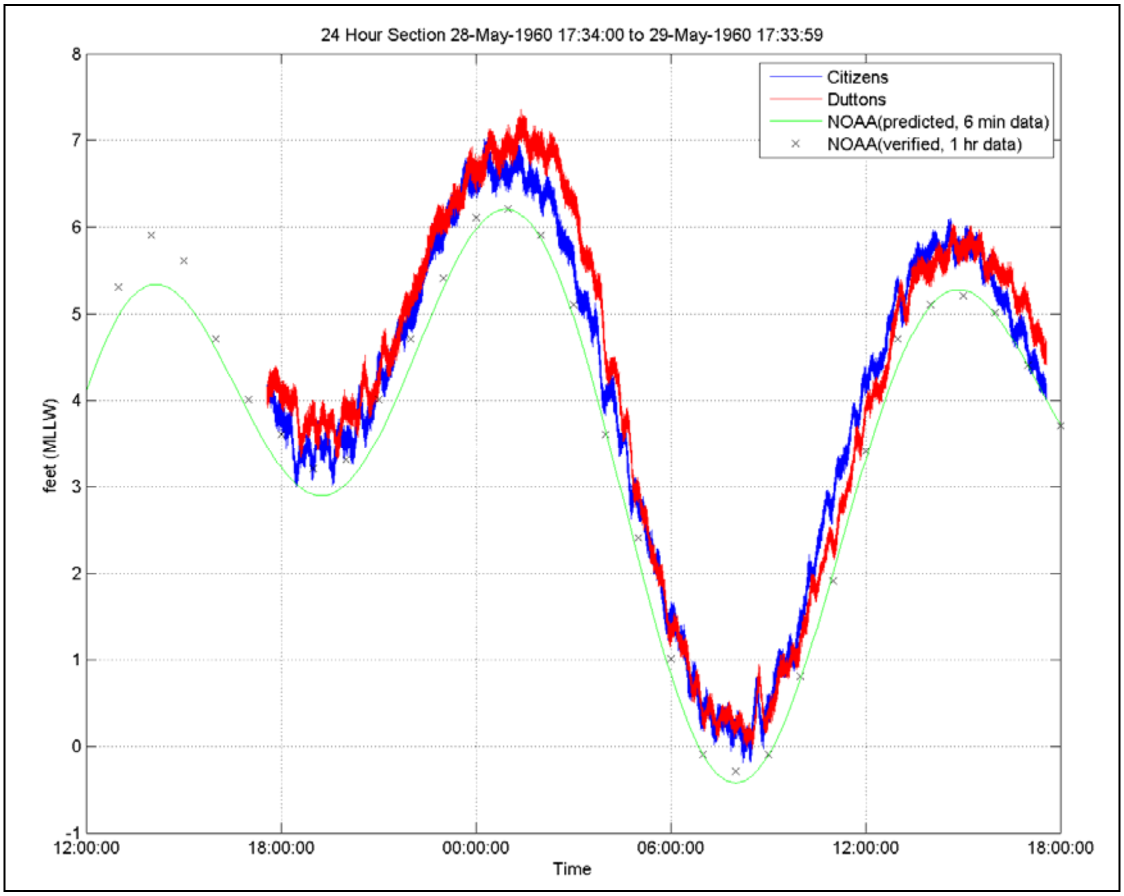

Figure B - 9: Same as Figure B - 1 for 28-29 May 1960.

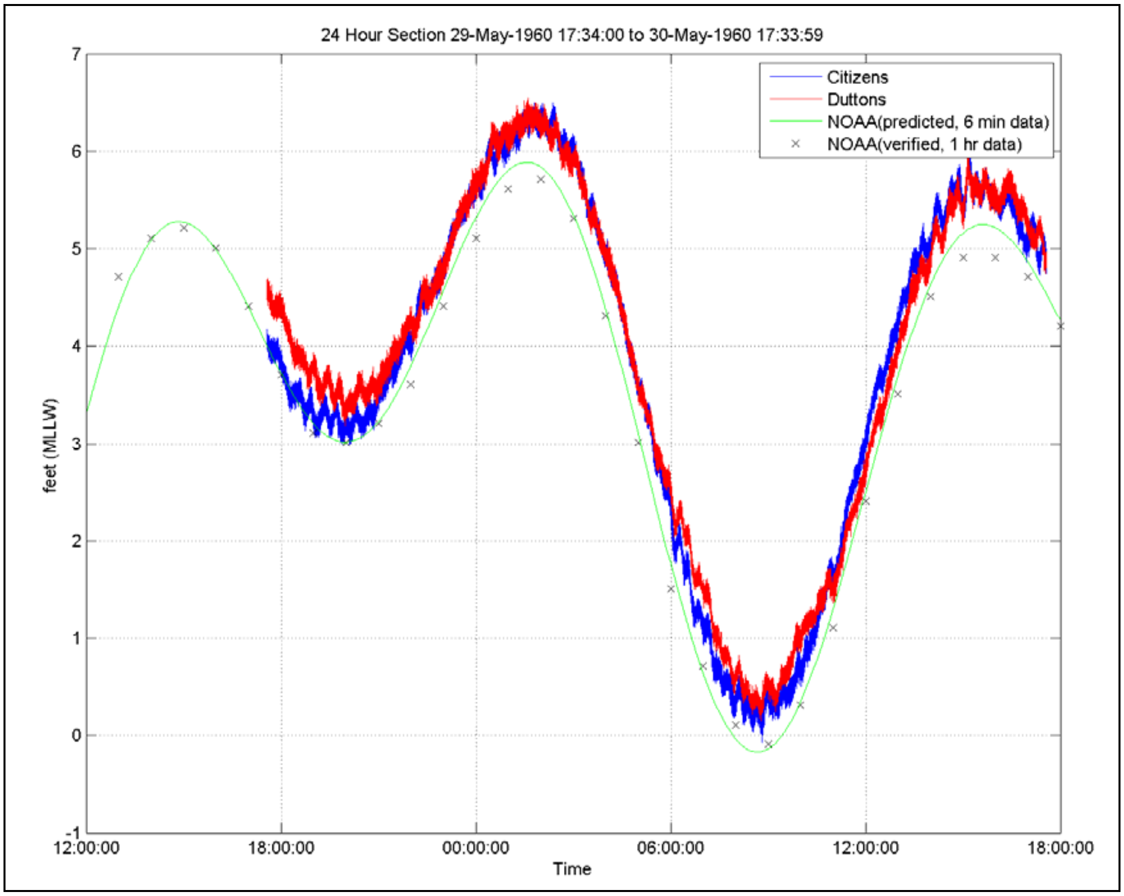

Figure B - 10: Same as Figure B - 1 for 29-30 May 1960.

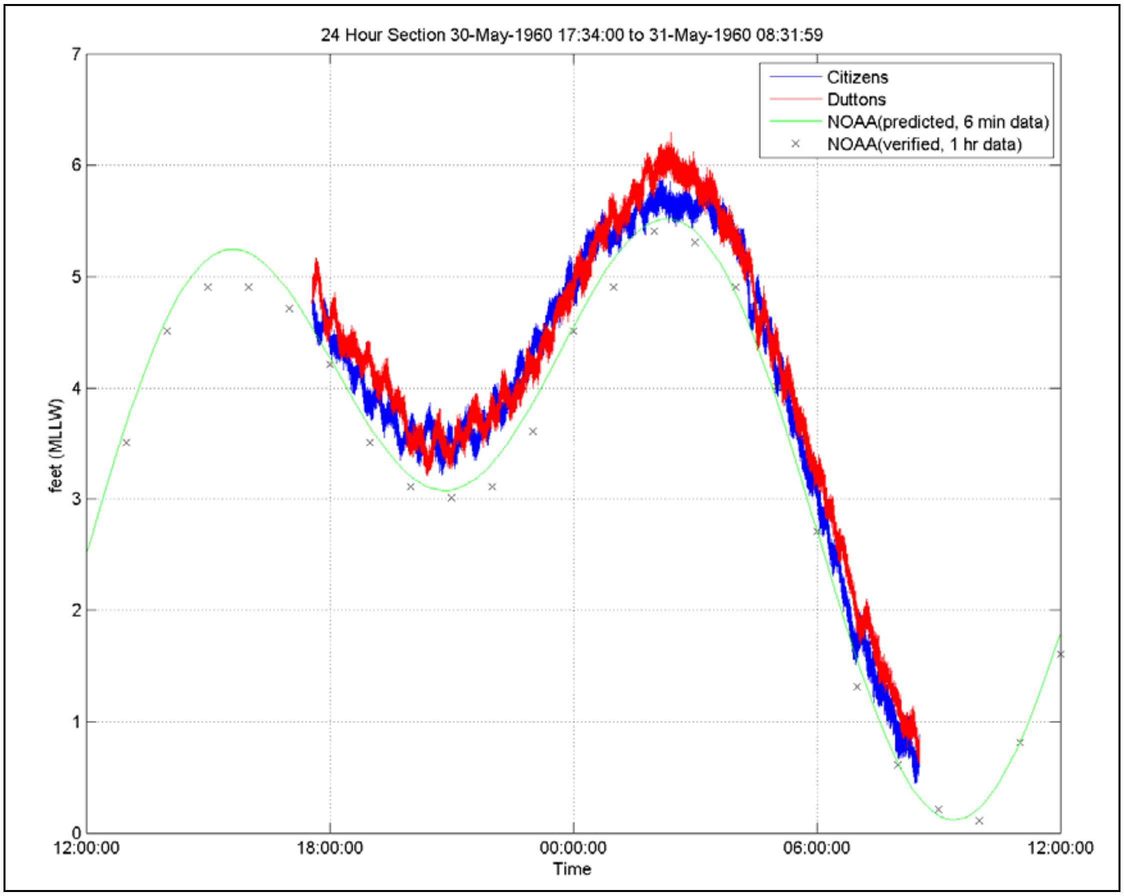

Figure B - 11: Same as Figure B - 1 for 30-31 May 1960.

2. CHAPTER 2

Chapter 2 presents analysis of the data digitized as discussed in Chapter 1 in order to characterize the tsunami in the harbor and the harbor response. Data from two stations in the harbor plus the high digitization rate makes possible a frequency domain investigation of the harbor response. Admittance function estimates at both docks are presented as are spectral ratios (of tsunami divided by background spectra) which show amplification of the tsunami relative to the normal background. Coherence and phase estimates as well as spectrograms at the two stations further show tidal modulation of the harbor response for frequencies at and somewhat above those characterizing the tsunami.

Crescent City Harbor Response to the 1960 Tsunami at Crescent City, CA

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2.1 Abstract

Recently discovered strip chart scrolls of stilling well water levels recorded at two docks in the harbor at Crescent City, California in May 1960 have made possible a study of the 1960 Chilean Earthquake Tsunami as manifested in the Crescent City harbor. A portion of the strip chart data covering a period before and after the tsunami hit the harbor was digitized at 1 Hz sampling rate. The availability of data from two stations in the harbor plus the high rate of digitization makes possible a frequency domain investigation of the harbor response. Background data prior to the onset of the tsunami were used to estimate an admittance function at both docks, the result suggests the presence of edge wave resonances over the adjoining shelf as well as of individual harbor modes. Spectral ratios (of tsunami divided by background spectra)

correspondingly show relative amplification of the tsunami relative to the normal background. Frequency domain coherence and phase estimates as well as spectrograms at the two stations further show tidal modulation of the harbor response at frequencies at and somewhat above those characterizing the tsunami.

2.2 Introduction

The port of Crescent City, located on the California coast about half way between Cape Mendocino and Cape Blanco, has been unusually vulnerable to tsunamis (e.g. Lander *et al.*, 1993). Historically, waves from both far and near tsunami sources are larger and more destructive at Crescent City than at nearby locations.

Figure 2.1 shows the coastline and bottom relief in the vicinity of Crescent City and Figure 2.2 is a plan-view sketch of the harbor in 1960. The purposes of this paper are i) to document sea level variation within Crescent City harbor during the 1960 tsunami associated with the Chilean earthquake of 22 May 1960, and ii) to attempt to elucidate the local topographic and harbor resonances. The analysis suggests that the heightened susceptibility of Crescent City to tsunami energy is primarily due to the specific adjacent shelf topography that is conducive to the trapping of edge waves that amplify energy near resonant periods of the shelf.

The impetus for revisiting this historical event is the recent discovery (Kendall *et al.*, 2008) of two boxes of virtually continuous strip chart data over the time interval 11 May 1960 to 16 June 1960 from pressure gauges at two locations in the harbor. The locations of the two pressure gauges, at Dutton’s Dock and at Citizen’s Dock, are shown in Figure 2.2. Magoon (1962) digitized and analyzed a small portion of this record, Holmes-Dean *et al.* (2009) have digitized the nearly eleven day interval 20 May 1960 to 31 May 1960 that captures the onset of the tsunami and its decay. The data and digitization procedures are documented fully in Holmes-Dean *et al.* (2009). This paper analyzes the resulting pressure (hereafter called sea level) time series.

2.3 Sea Level Spectra and Spectral Ratio

All spectra S(f) discussed below are estimates of one-sided power spectra having the property that the variance in the demeaned record is $\int_o^\infty S(f)df$.

Rabinovich (1997) suggests that the background (pre-tsunami) sea level spectrum $S_{bay}^{back}(f)$ in a bay or a harbor may be regarded as the product of the open ocean background sea level spectrum $S_{ocean}^{back}(f)$ and an admittance function A(f): $S_{bay}^{back}(f) = A(f)\, S_{ocean}^{back}(f)$. On the basis of the few measurements available in the North Pacific, Kulikov *et al.* (1983) and Filloux *et al.* (1991) suggest that S_{ocean}^{back} (f) is smooth and may be fit by the form $S_{ocean}^{back}(f) = E_o f^{-2}$ in the typical tsunami frequency band (about 10^{-4} to 10^{-2} Hz) where E_o is of order 6.45×10^{-5} to 6.45×10^{-6} ft^2Hz^{-1}. Again in the North Pacific, Rabinovich *et al.* (2011) found very similar pre-tsunami sea level spectral variation over the typical tsunami frequency band. After Rabinovich (1997), we thus estimate A(f) as $S_{bay}^{back}/S_{ocean}^{back}$ with $S_{ocean}^{back}(f) = E_o f^{-2}$, using the value $E_o = 6.45 \times 10^{-5}$ ft^2Hz^{-1}.

Subject to various assumptions stated in e.g. Rabinovich (1997), the sea level spectrum during a tsunami in a bay or a harbor $S_{bay}^{tsu}(f)$ may correspondingly be written as the product of the open ocean sea level spectrum S_{ocean}^{tsu} during the tsunami and the same admittance function A(f); S_{bay}^{tsu} (f) = A(f) S_{ocean}^{tsu} (f). The form of the admittance A(f) thus has no effect on the spectral ratio R(f) defined as $S_{bay}^{tsu}(f)/S_{bay}^{back}(f)$. Indeed, from this point of view, the spectral ratio could also be estimated as $S_{ocean}^{tsu}(f)/S_{ocean}^{back}(f)$, but in practice the necessary spectra are only rarely available.

The admittance function A(f) summarizes the effects of shelf and/or bay and harbor resonances on sea level in a bay or a harbor, whereas the spectral ratio R(f) characterizes the tsunami in a manner that is, under the assumptions of Rabinovich (1997) in principle independent of local shelf and/or harbor resonances.

2.4 Background Sea Level Spectra

Figure 2.3 shows sea level at the two pressure gauges as well as the NOAA predicted tide for Crescent City from the beginning of digitization to several hours after the onset of the tsunami (at about 02:20 PST, 23 May 1960; Magoon, 1962). The same pressure gauge records, but de-tided (by linearly interpolating the NOAA tide prediction at six minute intervals for this time and location) are shown in Figure 2.4.

The very highest frequency variations cause the time series plots at this scale to have a ”fuzzy” appearance before arrival; plotting at shorter time scales (not shown) reveals this to be due to the existence of fluctuations at time scales the order of a few tens of seconds at both gauges, never appreciably correlated in time at any lag. Before the arrival of the tsunami, broadband fluctuations at time scales roughly the order of about 2000 seconds are also visible and are generally visually highly correlated between the two gauges.

Estimates of the background spectrum $S_{bay}^{back}(f)$ of de-tided sea level and of the admittance function $A(f) = S_{bay}^{back}(f)/ (E_o f^{-2})$ at both gauges are shown in Figure 2.5. The spectrum $S_{bay}^{back}(f)$ was estimated at each gauge from the first 204,827 seconds (2 days, 8 hours, 53 minutes and 47 seconds) of data comprising the digitized period prior to the start of the tsunami. Segments of 86,400 seconds were extracted and overlapped by 50%, yielding an elemental frequency of 0.00001157 Hz. The spectra are in substantial agreement at the two gauges over the range of frequencies 10^{-5} Hz to slightly above 10^{-3} Hz. Both additionally show a distinct peak at about $2.5x10^{-3}$ Hz, albeit more distinctly at Citizen's (most distant from the harbor mouth) than at Dutton's (nearest the harbor mouth). At still higher frequencies (roughly $3x10^{-3}$ Hz to roughly $3x10^{-2}$ Hz) the spectra at Dutton's and Citizen's differ markedly in a manner that will be elucidated below. Finally, a broad peak centered at about 10^{-1} Hz (10 second period) corresponds to incoming swell (see also Figure 2.9).

The broad upward ramp in admittance (with a sharp dip at $6x10^{-4}$ Hz), over about 10^{-4} Hz to 10^{-3} Hz, identical at both gauges, followed by a much more rapid falloff towards yet higher frequencies of order $1.1x10^{-3}$ Hz, corresponds to a period range of about 2.8 hours to 15.2 minutes. Distinct higher frequency peaks are visible in the spectra at Citizen's at about $2.5x10^{-3}$ Hz and $8x10^{-3}$ Hz. These peaks correspond to periods of about 6.7 minutes and 2.1 minutes. The former is also visible at Dutton's but the latter is not; the latter appears more clearly in Figure 2.10 on account of more extensive averaging. We compare these various peak frequencies with the literature estimates, cited below, for the frequencies of resonances over the shelf adjacent to Crescent City and within Crescent City harbor.

Wilson and Torum (1968) suggest that the continental shelf between Pt. St Georges and Patrick's Point is "a responsive echo chamber" for great tsunamis since their periods will always be capable of exciting full or partial resonances. Horillo *et al.* (2008) estimate the spatial shapes and periods of shallow water normal modes in a domain consisting of the coast and shelf between Pt. St Georges and Patrick's Point shown in Figure 2.1 augmented by the region between straight boundaries extending westward from each of the two points about 30 km and terminating at the 200 m isobath; the boundary conditions were no normal flow at the coast and no sea level variation (a node) at the other three boundaries. For the modes discussed in Horillo *et al.* (2008), periods of free oscillation range from 67-18 minutes; many modes have maximum amplitude at the coast but some have maximum amplitude offshore. Except for the shortest period modes, the spatial shapes and periods are in qualitative accord with what one would estimate using the mean bottom slope over this region for mode zero or mode one edge waves that are standing between Pt. St Georges and Patrick's Point. This domain no doubt also supports shorter period modes. They would correspond to shorter wavelength and/or higher mode edge waves, but on this account are unlikely to be strongly excited by large-scale forcing of distant origin.

Horillo *et al.* (2008) also use a shallow water numerical model of Crescent City harbor to calculate the frequencies of the first four harbor normal modes, finding 14.45, 7.68, 7.28 and 5.68 minutes at MHHW, and 15.68, 9.01, 6.38 and 4.71 minutes at MLLW. In their calculations sea level is held fixed at the mouth of the harbor so that, if the true harbor modes are radiatively coupled to shelf modes or to the open ocean, these estimates of harbor normal mode frequencies are likely to be too low (just as are the normal mode frequencies of a closed organ pipe relative to those of an open organ pipe of the same length (J. S. Bach, 1735)).

By the foregoing estimates, there are many more shelf and harbor resonances than there are significant peaks in our spectra. It is however noteworthy that the foregoing estimates of the longest period shelf resonant periods are almost all of significantly longer period than the foregoing estimates of the longest period harbor resonant periods. On this basis, the observed upward ramp in admittance (Figure 2.5b), over about 10^{-4} Hz to 10^{-3} Hz (2.8 hours to 16.7 minutes) probably reflects excitation of a number of edge wave resonances outside the harbor, while the isolated peaks in admittance at the higher frequencies $2.5\text{x}10^{-3}$ Hz and $8\text{x}10^{-3}$ Hz (6.7 and 2.1 minute period) likely correspond to harbor modes. Some support for these suggestions will be found in the analysis of frequency domain correlations between sea level at the two gauges, as shown below.

2.5 The Tsunami

At the scale of Figure 2.3, the tsunami appears identical at the two gauges, yet an overlay of the two de-tided sea level series (Figure 2.4) reveals time variation apparently associated with timing errors in one or the other of the two records, in some instances clearly associated with a shift from one strip chart roll to another but in others not so clearly localized. The origins of this error are fully discussed in Holmes-

Dean *et al.* (2009); no objective improvement over their attempts to minimize this error has been found. This circumstance effectively vitiates attempts to compare the time evolution of sea level at the two pressure gauges, but it will be shown below that some information about the difference in sea level at the two gauges may nonetheless be obtained in the frequency domain because of the rapid rate of digitization.

The evolution of the tsunami is in general accord with that for other tsunamis in the same harbor (Lander *et al.* 1993, Kowalik *et al.* 2008, Horillo *et al.* 2008). The highest arrival is not the first, rather the amplitude of resurgences associated with the tsunami increases steadily over the first six or so hours of the record, with the greatest amplitude at about 8.7 hours after the onset of the tsunami (Figure 2.4). Accordingly, a plot (Figure 2.6) of variance of each of the two de-tided records rises by three orders of magnitude over the first half day or so of the tsunami, and then settles into decay with a (least square fit to exponential) decay time of about 23 hours at Dutton's and 23.5 hours at Citizens. The variance returns to pre-tsunami levels only after about six to seven days. Departures from strict exponential decay the order of half an order of magnitude over several days occur simultaneously at both gauges.

Figure 2.7 shows ten successive estimates of the spectral ratio at both pressure sensors constructed from three successive 65,536 second segments of the pre-onset part of each record and from ten successive 65,536 second segments of the post-onset part of each record. At both stations the spectral ratio rises from unity at low frequencies (about 10^{-4} Hz, 166 minute period) to a maximum (of order 1,000) at a frequency of about $5\text{x}10^{-4}$ Hz (33 minute period), and then decays more slowly towards higher frequencies, reaching unity at frequencies the order of 10^{-2} Hz (1.7 minute period). The spectral ratios at the two stations are virtually identical for lower frequencies in the tsunami band, as expected from the discussion above, but differ significantly in that the ratio at Dutton's shows a well defined peak at about $2.5\text{x}10^{-3}$ Hz that is not as visible in the ratio at Citizen's. This means that the admittance at Dutton's is not the same as the admittance at Citizen's in the vicinity of this peak, and suggests that this peak is, as suggested above, associated with a harbor mode whose amplitude at Dutton's is greater than that at Citizen's, and not with longer period edge-wave shelf modes, for which the response at Dutton's and Citizen's should be nearly identical.

Figure 2.8, left panels, shows sea level spectra S_{bay}^{tsu} and the admittance estimate $S_{bay}^{tsu}/S_{bay}^{back}$ for both gauges, and the frequency domain coherence and phase between the two gauges all averaged over four successive 65,536 second segments of the records starting at the onset of the tsunami. Figure 2.8, right panels, shows the same quantities but averaged over 24 successive 10,800 second segments of the records starting at the onset of the tsunami.

The segment lengths are somewhat arbitrarily chosen, but the salient features of the correlation and the phase are not sensitive to the choice. The correlation is very high over the range of frequencies 10^{-4} Hz to 10^{-3} Hz (Figure 2.8, left panels) corresponding to the ramp in the admittance function (Figure 2.5b). The phase difference between the two gauges in this frequency range has been made nearly zero by lagging one record relative to the other by the order of 100 seconds, a lag well within the range of timing errors estimated by Holmes-Dean *et al.* (2009). For neighboring choices of lag the phase difference varies nearly linearly across this band, as would be the case if the motions in this band were indeed in phase. Further averaging (Figure 2.8, right panels) uncovers a secondary peak in correlation at about $2.5\text{x}10^{-3}$ Hz corresponding to the peak noted above in the admittance (Figure 2.5b) at this same frequency; the relative phase varies smoothly across this peak but the phase difference itself depends so sensitively on the choice of lag that it cannot be reliably estimated.

Experiments with differently lagged subsections of the record sometimes suggest peaks in correlation at higher frequencies, but the timing errors seem to be sufficiently large that no stable results may be obtained. Nonetheless there is reason to believe that at least one shorter period mode may be identified.

2.6 Tidal Modulation

Figure 2.9 shows spectrograms of nearly the entire sea level record at the two gauges over the frequency range $2.5\text{x}10^{-3}$ Hz to 10^{-1} Hz together with time series of energy at each gauge within two specified frequency bands $6.4\text{x}10^{-3}$ Hz to $9.2\text{x}10^{-3}$Hz and $1.66\text{x}10^{-2}$ Hz to $3.46\text{x}10^{-2}$ Hz. Salient features are (i) the arrival of the tsunami itself, (ii) the arrival of dispersive swell particularly evident about halfway through the record, well after the onset of the tsunami, and (iii) tidal modulation of spectral levels, most readily visible at Dutton's but also present at Citizen's. (Care has been taken to assure that the tidal modulation apparent in the spectrograms is *not* an artifact of the choice of intervals into which the record is decomposed for spectrogram estimation.)

The tidal modulation is most strikingly displayed in Figure 2.10, which shows spectra of sea level at Citizen's and Dutton's averaged over three hour intervals centered first at high tide and then at low tide. At Citizen's (Figure 2.10, top panel) there is little if any systematic difference between the spectra at high and low tide, but at Dutton's the entire spectrum over the frequency range about $6x10^{-3}$ Hz to about $4x10^{-2}$ Hz shifts towards higher frequencies at high tide with but little change in shape. This behavior is in qualitative accord with what would be expected from the upward shift in harbor resonant frequencies between MHHW and MLLW estimated by Horillo *et al.* (2008).

The spectra at Citizen's (Figure 2.10, top panel) also show a peak at about $8x10^{-3}$ Hz (2.1 minute period) at both high and low tide. The absence of a corresponding peak at Dutton's suggests that this peak may correspond to a harbor mode refractively trapped near the shoal eastern side of the harbor, but having negligible amplitude nearer the western side of the harbor. Similarly trapped modes along the south wall of north-facing Kahului harbor (Maui, Hawaii) but of negligible amplitude near the harbor mouth were found in a model study by Okihiro *et al.* 1994, (their Figures 8, 9).

2.7 Summary and Discussion

Analog records of sea level data taken at two locations in the harbor at Crescent City in northern California recorded the tsunami generated by the May 1960

Chilean earthquake. Records from 20 May 1960 to 31 May 1960 were digitized at 1 Hz and have been used in this paper to examine sea level variation associated with that tsunami in Crescent City harbor.

Tsunami energy persists detectably in the harbor for six to seven days after onset as evidenced in both the decay of variance (Figure 2.6) and the spectral ratios (ratio of sea level spectrum during tsunami to sea level spectra before tsunami, Figure 2.7). Departures from strict exponential decay of up to an order of magnitude are evident near 0.57 day (13.7 hours), 1.11 days (26.6 hours), 2.41 days (57.8 hours) and perhaps even later at 5.49 days (131.8 hours) and 6.24 days (149.8 hours) before pre-tsunami levels are attained. These departures, evident in Figure 2.6, are similar to those observed by Oh and Rabinovich (1994) in data taken along the coast of Korea during the tsunami of 12 July 1993 and attributed by them to "multiple reflections of tsunami waves from the coasts of Korea and the Sea of Japan." Similarly, the departures of the Crescent City harbor data may be due to open ocean bathymetry (ridges, seamounts - in particular Koko Guyot and Hess Rise) that redirect tsunami energy, creating sources of scattered and reflected energy. The redirecting and refocusing of tsunami energy by distant bathymetric features as it relates to the response at Crescent City during the Kuril Islands tsunami of 2006 is discussed by Kowalik *et al.* (2008). This suggestion is in agreement with Miller *et al.* (1962) who noted that energy due to the 1960 Chilean tsunami remained for approximately five days in records taken off La Jolla, with waves having the form of trapped edge waves propagating along the South -North American coast for more than a week.

Spectral ratios (of tsunami event spectra divided by background spectra) show relative amplification of the event in comparison with the pre tsunami background situation. Spectral ratios at Dutton's and Citizen's docks (Figure 2.7) show that initially, tsunami energy is one to three orders of magnitude larger than the background; amplification is largest at the lower frequency end with maximum amplification at a frequency near $5x10^{-4}$ Hz (33 minute period). As time progresses, the ratios decrease, becoming essentially unity in the typical tsunami frequency band for the segment from 29 May 1960, 22:10 PST to 30 May 1960, 16:22 PST, meaning the tsunami-related energy in the harbor, whether direct or indirect, is reduced to background levels after about seven days.

Miller (1972) and Rabinovich and Stephenson (2004) suggest that tsunami spectral characteristics common to adjacent stations are attributable to the characteristics of the source event and/or effects of distant relief, while characteristics specific to an individual station are attributed to the local topography. Results at Crescent City harbor are consistent with these ideas. At the two docks in Crescent City harbor, admittance functions (ratio of sea level spectrum at the station during tsunami to the empirically determined spectrum of open ocean sea level before tsunami) are nearly identical from 10^{-4} Hz to about $3x10^{-3}$ Hz, with broad upward ramp from 10^{-4} Hz to 10^{-3} Hz followed by an abrupt drop towards a minimum at about $2x10^{-3}$ Hz, but the admittance functions differ significantly between docks for higher frequencies, particularly in the range $3x10^{-3}$ Hz to $8x10^{-3}$ Hz (Figure 2.5b).

Horillo *et al.* (2008), estimate periods of free edge wave oscillation over the adjacent shelf from 67 minutes to 18 minutes (2.5×10^{-4} Hz to 9.3×10^{-4} Hz). Shorter period edge wave solutions probably exist in this domain, but on account of their relatively short scales they are not likely to be excited directly by the tsunami arriving from the open sea. Horillo *et al.* (2008), also use a shallow water numerical model of Crescent City harbor to calculate the frequencies of the first four normal modes, finding the grave period to be 14.45 minutes (1.2×10^{-3} Hz) at MHHW and 15.68 minutes (1.1×10^{-3} Hz) at MLLW.

On this basis of these estimates we would expect the admittance ratios at the two docks to start to differ appreciably at frequencies above that of the grave harbor mode, about 1.1×10^{-3} Hz. In fact they remain similar up to about 1×10^{-3} Hz and display a common peak at about 2.5×10^{-3} Hz but differ appreciably at still higher frequencies (Figure 2.5b). As noted above, the peak at 2.5×10^{-3} Hz may correspond to the grave harbor mode of Horillo *et al.* 2008, after allowance for the condition of fixed sea level employed by Horillo *et al*. 2008, at the harbor mouth.

Tidal modulation of spectral levels is observed at both docks over a wide frequency range (Figure 2.9) and is particularly strong at Dutton's dock in the frequency range 6×10^{-3} Hz to about 4×10^{-2} Hz (Figure 2.10). Tidal modulation of the intensity of infragravity waves has been observed by Okihiro and Guza (1995) on the inner shelf, possibly associated with tidal variations of the surf zone width and beach slope. Such processes might be at least in part responsible for the tidal modulation of spectral intensity over the broad range of frequencies of the spectrograms of Figure

2.9. Additionally, in this instance, the tidal modulation is of the frequency of short period spectral peaks within the harbor, and corresponds to that expected from estimates of Horillo *et al.* 2008 based on a shallow water numerical model of the normal modes of Crescent City harbor in which the depth varies parametrically from low to high tide.

2.8 Acknowledgements

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FIGURES

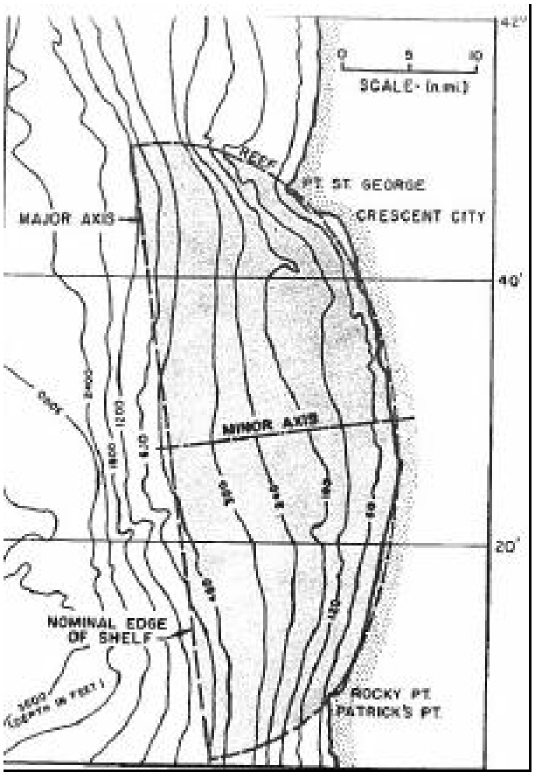

Figure 2.1: The continental shelf offshore of Crescent City, after Wilson and Torum, 1968.

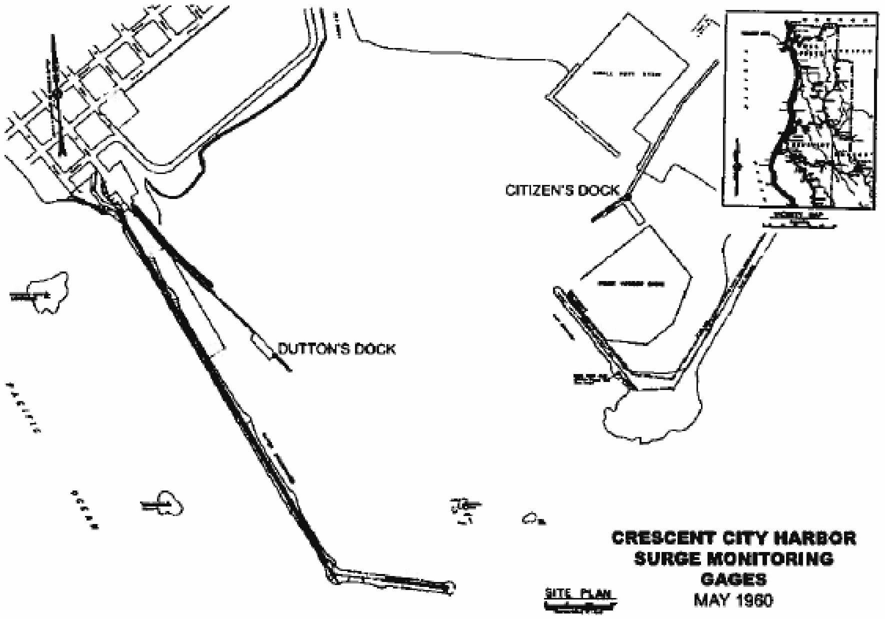

Figure 2.2: Crescent City Harbor, May 1960, with locations of pressure gauges at Dutton’s Dock and Citizen’s Dock (Holmes-Dean et al., 2009).

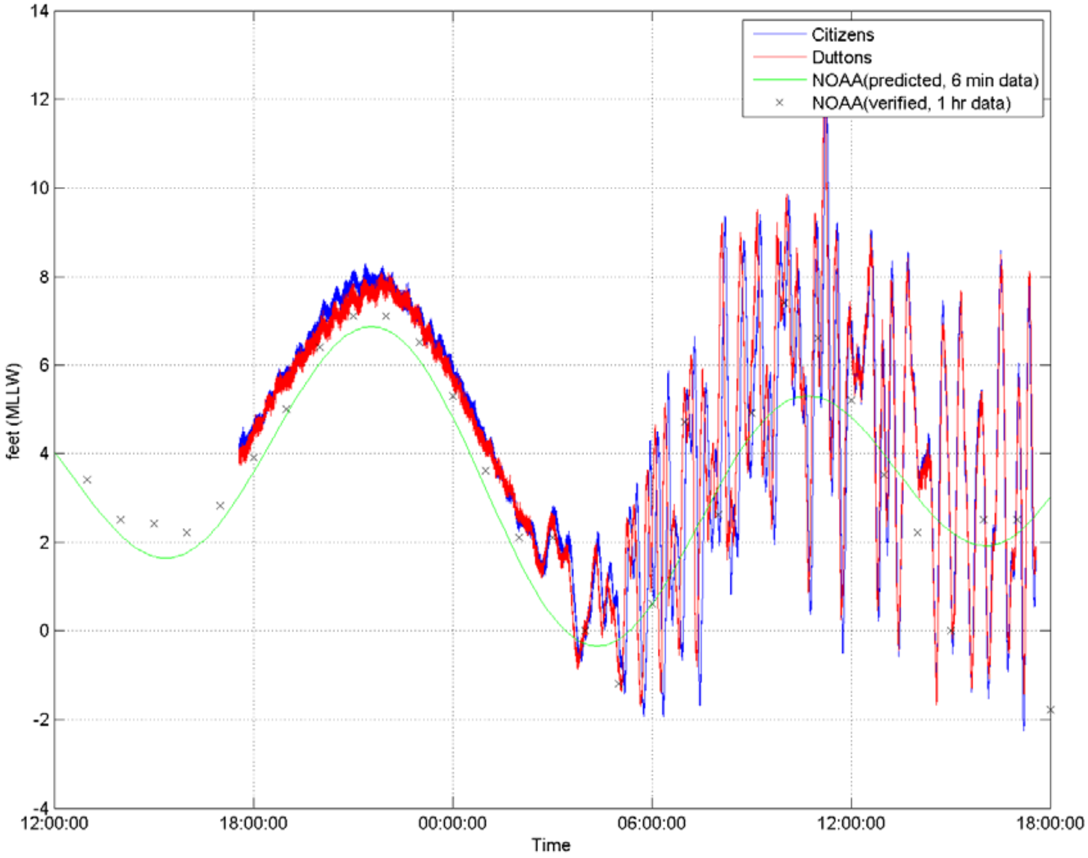

Figure 2.3: Sea level at Citizen's dock (blue) and at Dutton's dock (red) from May 22, 1960 at 17:34 PST through May 23, 1960 at 17:34 PST. Solid green line is NOAA predicted tide.

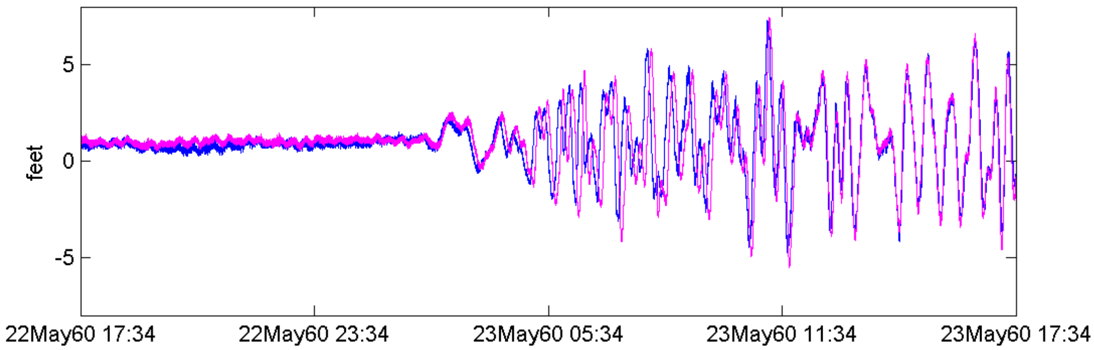

Figure 2.4: De-tided sea level at Citizen’s (magenta) and Dutton’s (blue) docks.

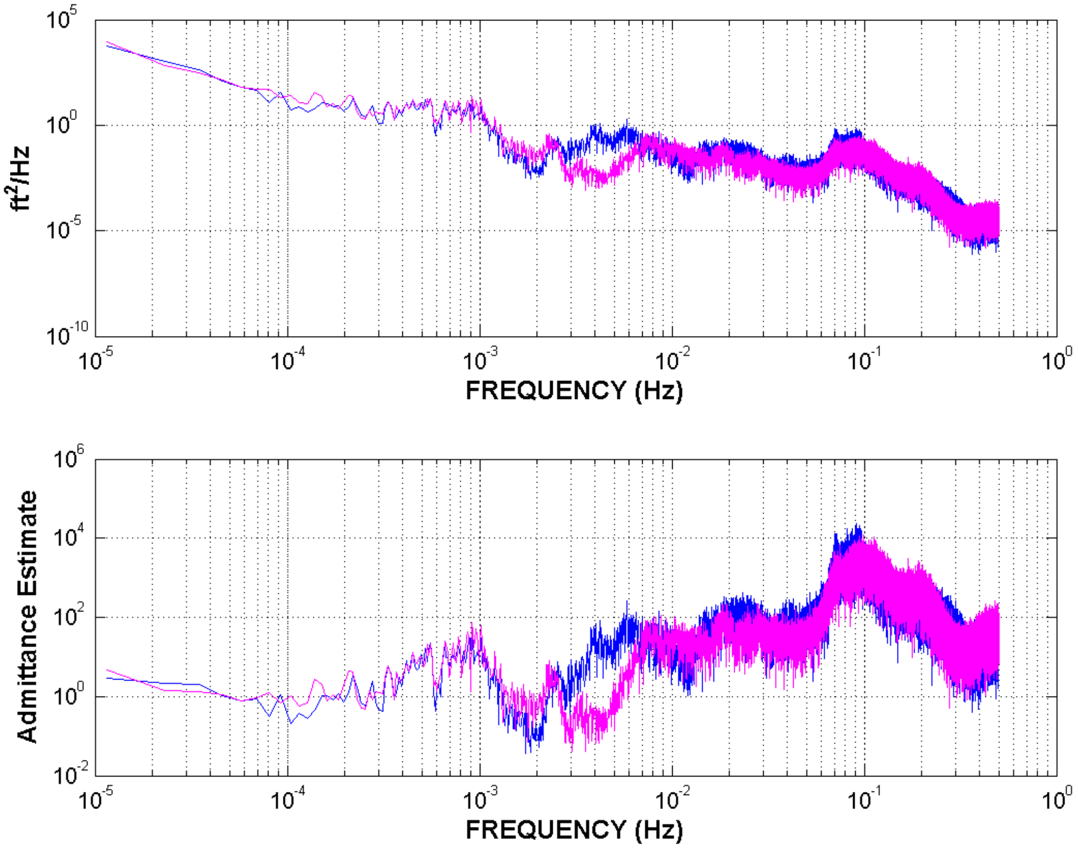

Figure 2.5: (a) Sea level background spectra of de-tided signals at Dutton's dock (blue) and Citizen's Dock (magenta) before onset of tsunami. (b) Admittance function estimate: sea level spectra at Dutton's Dock and Citizen's Dock divided by $E_o f^{-2}$.

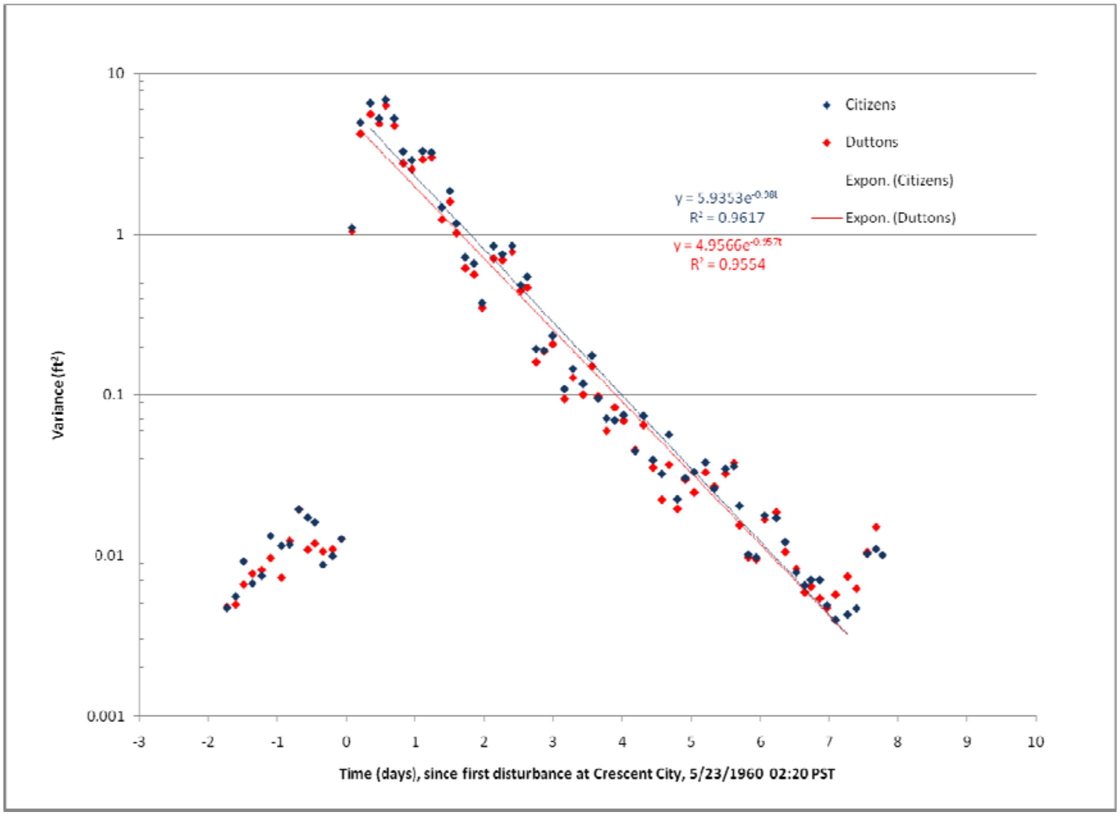

Figure 2.6: Decay of variance with time after onset of tsunami at Citizen’s and Dutton’s docks.

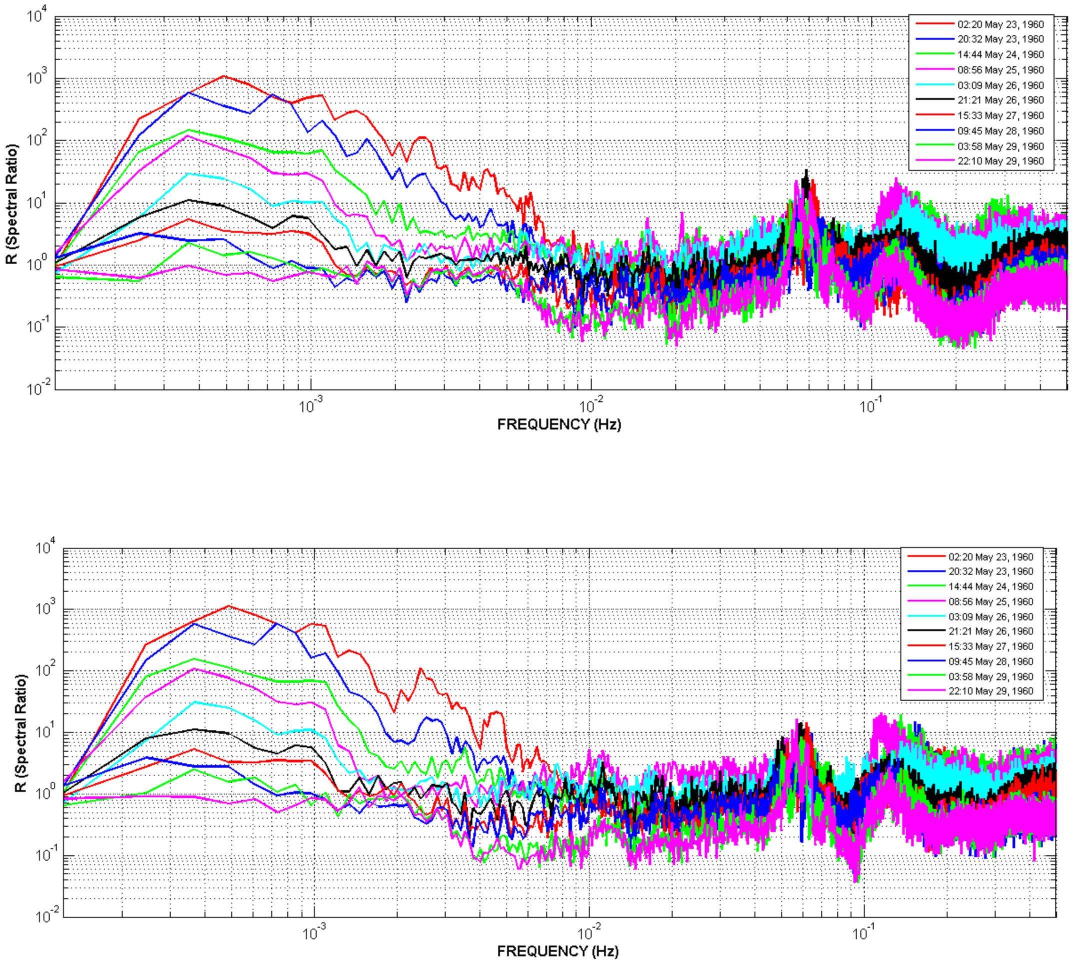

Figure 2.7: Top panel: spectral ratio at Citizen’s dock for 10 successive 65,536 second segments of sea level record after onset of tsunami. Bottom panel: same but for Dutton’s dock.

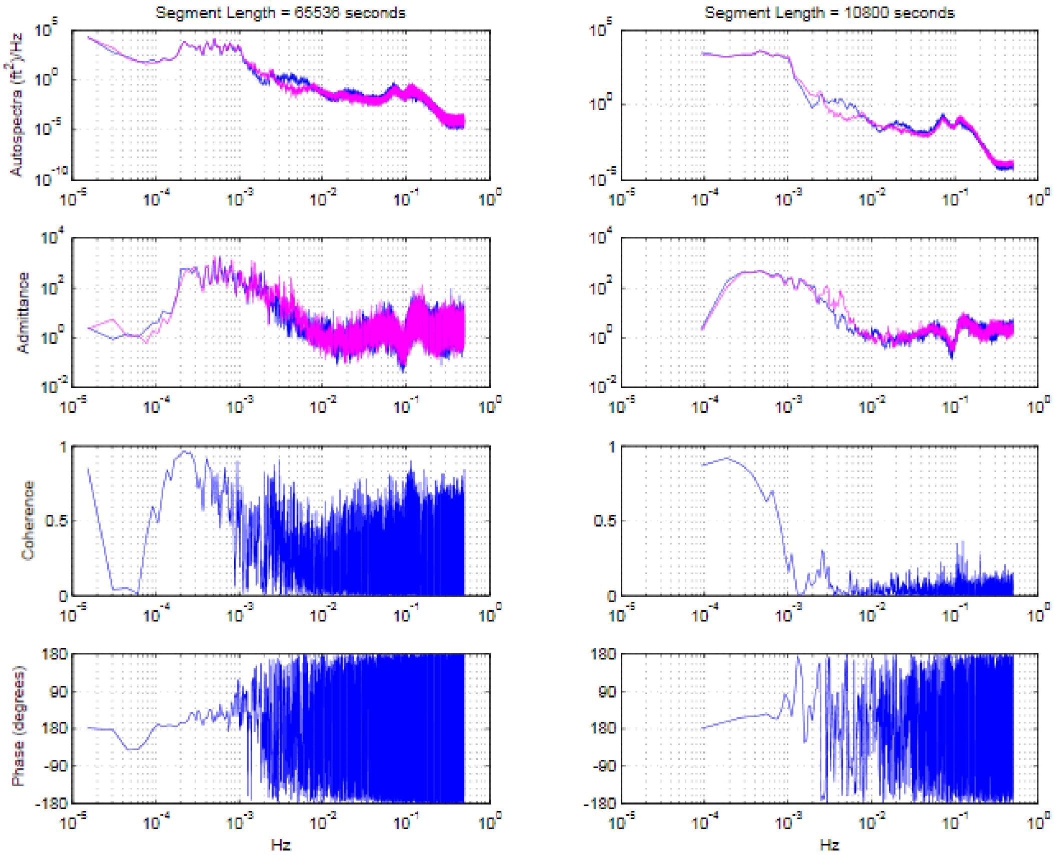

Figure 2.8: Top panels; sea level spectra at Citizen's (magenta) and Dutton's (blue) docks; next-to-top panels admittance estimates at Citizen's (magenta) and Dutton's (blue) docks; next-to-bottom panels frequency band coherence between sea level at Dutton's dock and Citizen's dock; bottom panels, frequency band phase difference between sea level at Dutton's dock and Citizen's dock. Left column: averages over first four 65,536 second segments of sea level record after onset of tsunami. Right column: averages over first twenty four 10,800 second segments of sea level record after onset of tsunami.

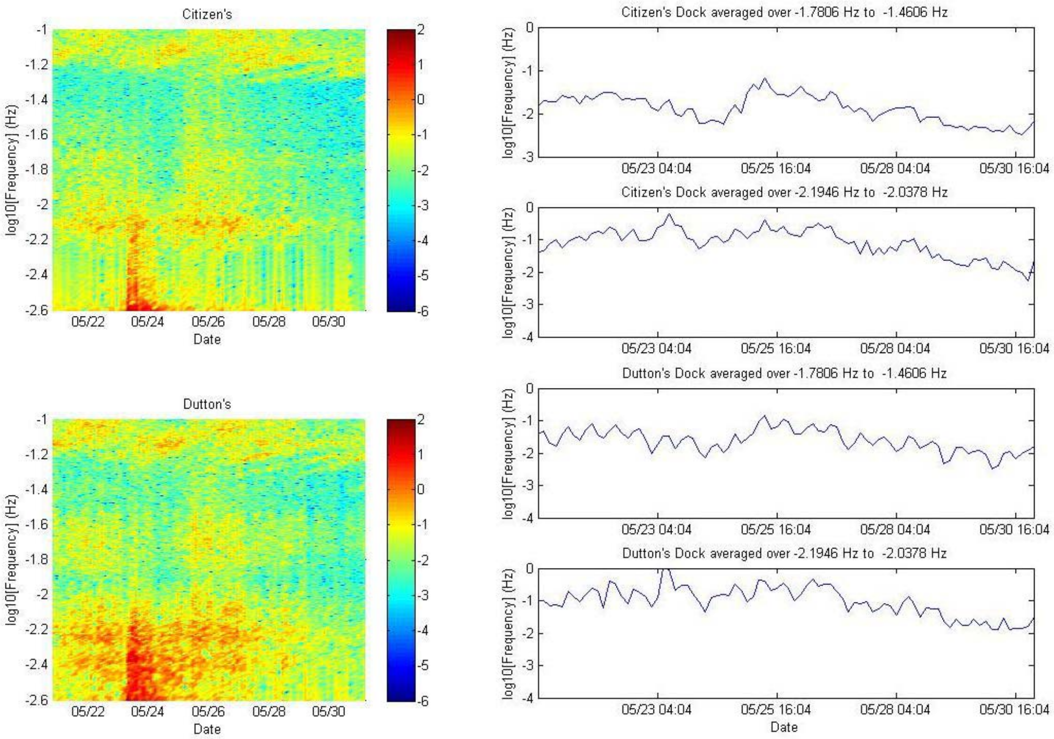

Figure 2.9: Left column: spectrograms of sea level record at Citizen’s dock (top), Dutton’s dock (bottom) for entire duration of digitized record. Right column: spectral density averaged over stated frequency bands for Citizen’s dock (top) and Dutton’s dock (bottom). Note strong tidal modulation of high frequency spectral intensity at Dutton’s dock (lower two right panels).

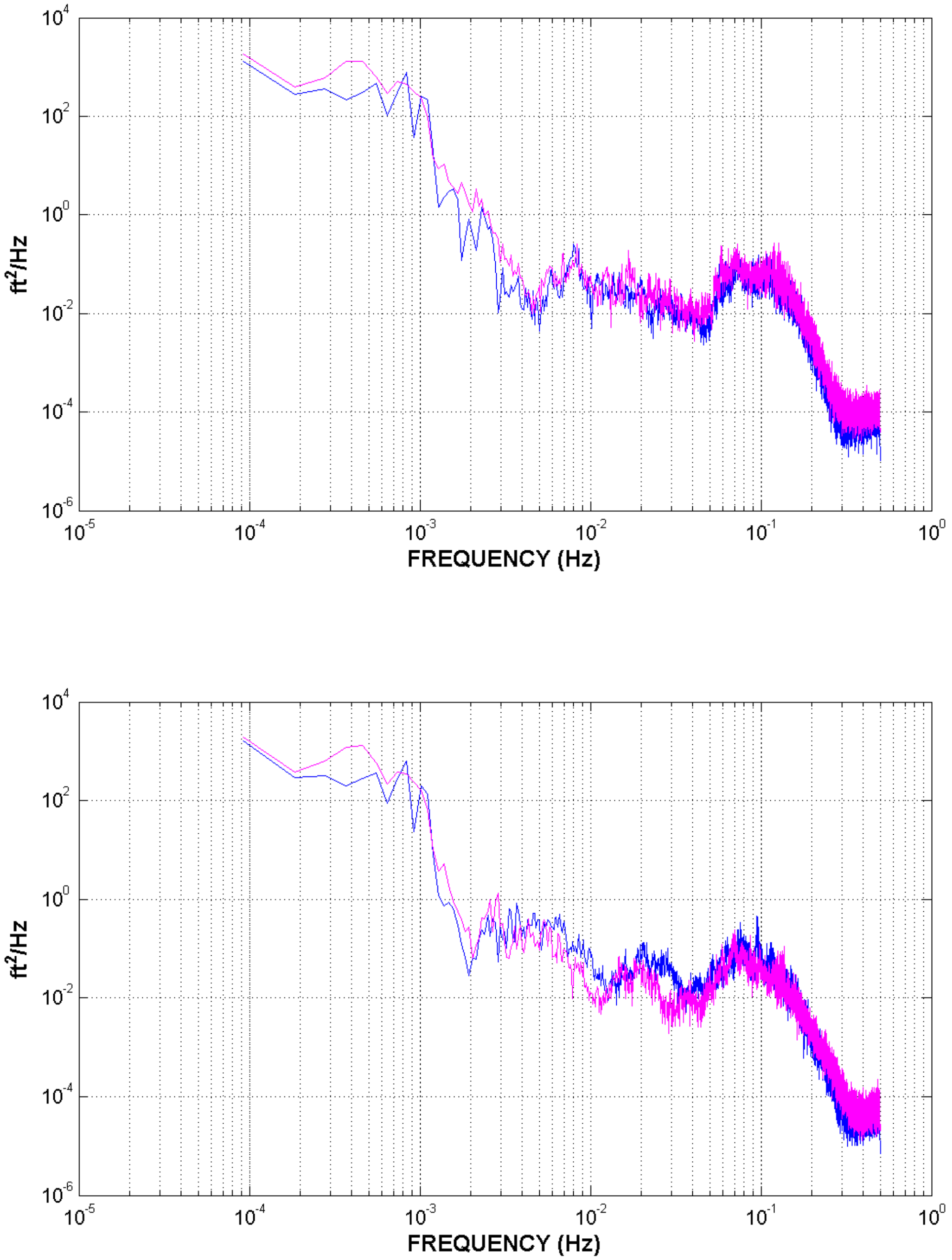

Figure 2.10: Top panel: Eleven sea level spectra at Citizen's dock averaged over 10, 800 second (3 hour) intervals centered at high tide (blue) and low tide (magenta). Bottom panel: same as top panel but for Dutton's dock. Note shift of spectral shape over frequency range 0.006 Hz to 0.04 Hz from high to low tide visible at Dutton's Dock but not at Citizen's.