University of Southern Queensland
Faculty of Health, Engineering and Sciences

Measuring Changes in Sea Level Around Antarctica

A dissertation submitted by

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in fulfilment of the requirements of

ENG4111 and 4112 Research Project

towards the degree of

Bachelor of Spatial Science (Honours) (Surveying)

Submitted October, 2019

Abstract

This study focusses on the wharf mounted tidal gauge at Casey station in the Australian Antarctic Territory. The data collected from the gauge had largely remained unprocessed and survey data to the tidal gauge not collated. The main aim of the project was to process the data and ascertain a sea level record from around Casey station, whilst making corrections in the data for bedrock uplift (glacial isostatic adjustment (GIA)) which can be picked up on the Casey station GNSS receiver that forms part of the Australian Regional GNSS network.

The Australian Antarctic Division (AAD) has four stations as a part of Australia's Antarctic Territory, three of which are on the continent of Antarctica, Casey, Mawson and Davis and one sub-Antarctic station, Macquarie Island. Since approximately 1996 each station has been collecting sea level data via a variety of pressure sensors, which have been upgraded and improved over the years. At Casey pressure and temperature readings from top and bottom wharf mounted sensors are recorded and sent to an instrument cabinet where they are stored on a data logger. A barometer and temperature sensor inside the wharf hut also records data. The barometer is required to measure sea level pressure in order to be able to calculate the height of the water column. This wharf mounted gauge has been recording data since 2008, however minimal processing of data has occurred to date.

Raw CSV files provide by the AAD were stitched together with sea water density and water column height above the bottom pressure sensor calculated over a time series using Excel. Data was then processed to eliminate sea level variations due to tidal constituents and high frequency climatic fluctuations (Gharineiat & Deng, 2018) using MATLAB. Data was corrected for GIA, using the figures provided from the Casey Station GNSS receiver.

A costal sea level trend was calculated for Casey station over the period of approximately 11 years, and stability of the wharf was investigated, and found to have minimal movement providing assurance on the stability of the tidal gauge. A sea level rise of 4.2 mm/year was calculated, though it was identified that there was a high level of uncertainty associated with this rate, possibly due to too much 'noise' in the data.

The sea level history obtained from the tidal gauge at Casey station provides useful information, however for any conclusive outcomes to be drawn on whether there has been local sea level rise, a twenty year history would need to be obtained in order to remove the effects of decadal cycles, such as long period lunar effects. This length of data at Casey station is not yet available.

Acknowledgments

I would like to thank my supervisor Dr. Zahra Gharineiat for providing me with technical support and assistance, and my employer the Australian Antarctic Division, Department of Environment and Energy for providing the data and the opportunity to study whilst stationed at Casey Station, Antarctica during winter 2019. I'd particularly like to thank from the Australian Antarctic Division Ben Galton-Fenzi, Lloyd Symons and John French for helping to initiate this project and for technical assistance along the way.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Abbreviations

AAD	Australian Antarctic Division
ARGN	Australian Regional GNSS Network
GIA	Glacial Isostatic Adjustment
GLOSS	Global Sea Level Observing System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
MSL	Mean Sea Level
PSMSL	Permanent Service for Mean Sea Level
RLR	Revised Local Reference
TGRM	Tidal Gauge Reference Mark
VLM	Vertical Land Movement

Chapter 1 Introduction

Background Information and Scope

The Australian Antarctic Division (AAD) has four stations as a part of Australia's Antarctic Territory, three of which are on the continent of Antarctica, Casey, Mawson and Davis and one sub-Antarctic station, Macquarie Island. Since approximately 1996 each station has been collecting tidal data via a variety of pressure sensors, which have been upgraded and improved over the years. Various surveys to newer wharf mounted gauges have also been conducted over the years. Casey and Macquarie Island both have new wharf mounted gauges, while Davis and Mawson each have a single submerged pressure sensor. The data collected from all gauges has largely remained unprocessed, the survey data from nearby bench marks hasn't been collated, and the scope and magnitude of errors that influence the data are not quantified.

This project will focus on the tidal gauge data from Casey station and will aim to process the data such that a sea level record from around Casey station coastline can be ascertained. The steps developed to process the data may be used in future projects to process tidal gauge data from the other three stations. Processed data ideally should also be reviewed against available altimetry data, time permitting. The sea level record produced by this project may also be useful for some other research projects that the AAD is involved in, such as the TIDE project (Totten Glacier Ice Dynamics and Evolution) (Australian Antarctic Division, 2015), which is studying the increased thinning of the glacier.

Figure 1
Australia's Antarctic and Sub-Antarctic Stations (Australian Antarctic Division, 2019)

Aims

The aims of this project are as listed:

- Research background information relating to tidal gauge measurements, altimetry, identifying bedrock uplift in tidal gauge data, and previous work done in these fields in Antarctica by Australian and/or other countries. This research will form the basis of the literature review.
- Research via AAD Data Centre all previous surveying reports for the tidal gauge to understand if the wharf structure that the tidal gauge is connected to is stable.
- Clean up tidal gauge data, such as correcting time stamp errors, stitch all files together and process.
- Using spatial data from Casey's GNSS station from the Geoscience Australia's National Geospatial Reference System, identify bedrock uplift and apply to tidal gauge data.
- Analyse sea level history data to discern if there are any trends in sea level, such as sea level rise, and confirm any trends using altimetry, if available and time permits.
- Document the methodology for the above steps, such that it may be applied to tidal gauge data from Australia's other Antarctic research stations.
- If time permits, study sea level history data for changes and compare to findings from other studies in the Antarctic region.

History of Tidal Gauges and surveys at Casey Station

The history of the tidal gauges at Casey has been able to be pieced together using a set of electronic files that have been provided by the AAD. However, the history of Casey's tidal gauges, decisions on types of gauges deployed, surveys conducted, and what data would be collected is not well documented. The electronic file provided contains all of the raw data sets available, various surveying reports, text documents and excerpts of relevant emails and photographs. Along with email communication from Lloyd Symons, AAD Technical Services Manager, Electronics (Symons, 2019, pers. comms., 16 May) the history of the tidal gauge installations at Casey Station can be pieced together.

A gauge known as a 'Platypus' gauge was installed at Casey, approximately 50 meters off the wharf and submerged below sea level, during 1996. Figure 2 shows the approximate location of the Platypus gauge and the basic layout of Casey station. This gauge was a pressure transducer and it collected pressure readings of the sea water above, it also contained a thermocouple and collected temperature data. However, this gauge being submerged was never accurately surveyed for vertical height and it was unknown if it had moved overtime. To retrieve the data, personnel either had to reach the gauge by boat or walk over the sea ice and drill a hole above, then lower down an induction loop for information to be transferred.

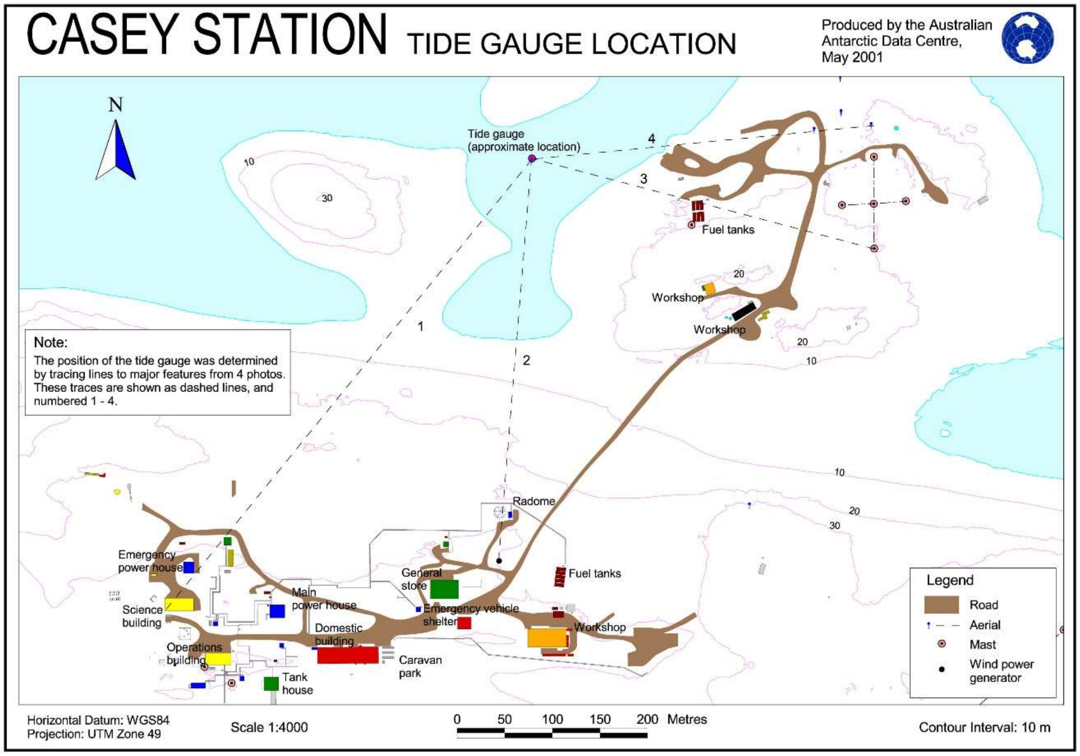

Figure 2
Casey Station and the approximate location of redundant Platypus tidal gauge (Han, 2009)

In order for the pressure data from the Platypus gauge to be more readily useable, sea level atmospheric pressure also needed to be collected. As the Platypus gauge never collected this information, in 2005 a barometer recording data in ten minute intervals was installed at the wharf hut, which is located adjacent to the fuel tanks near the tide gauge, as shown in Figure 2.

The Platypus tidal gauge and barometer set up was replaced in 2006 by a wharf mounted dual pressure sensor tidal gauge, however, only data from the start of 2008 is available, which is presumed when it was commissioned. The wharf mounted tidal gauge consists of a 250 mm diameter stainless steel tube that has a horizontal leg at the bottom to allow water in. The tube is insulated with foam and contains heating elements. There are two pressure sensors, a top mounted sensor and a bottom mounted sensor, which are 2.007 meters apart (Han, 2009). The pressure sensors are two digiquartz sensors that are in housings, which connect the sensors with sea water via oil columns. The two sensors are separated and held in place by a Monel rod, which has low thermal expansion. Figure 3 shows a the tidal gauge schematic and Figure 4 shows the top of the tidal gauge mounted on the wharf with the lid covering the tube and reference point (refer to Figure 3).

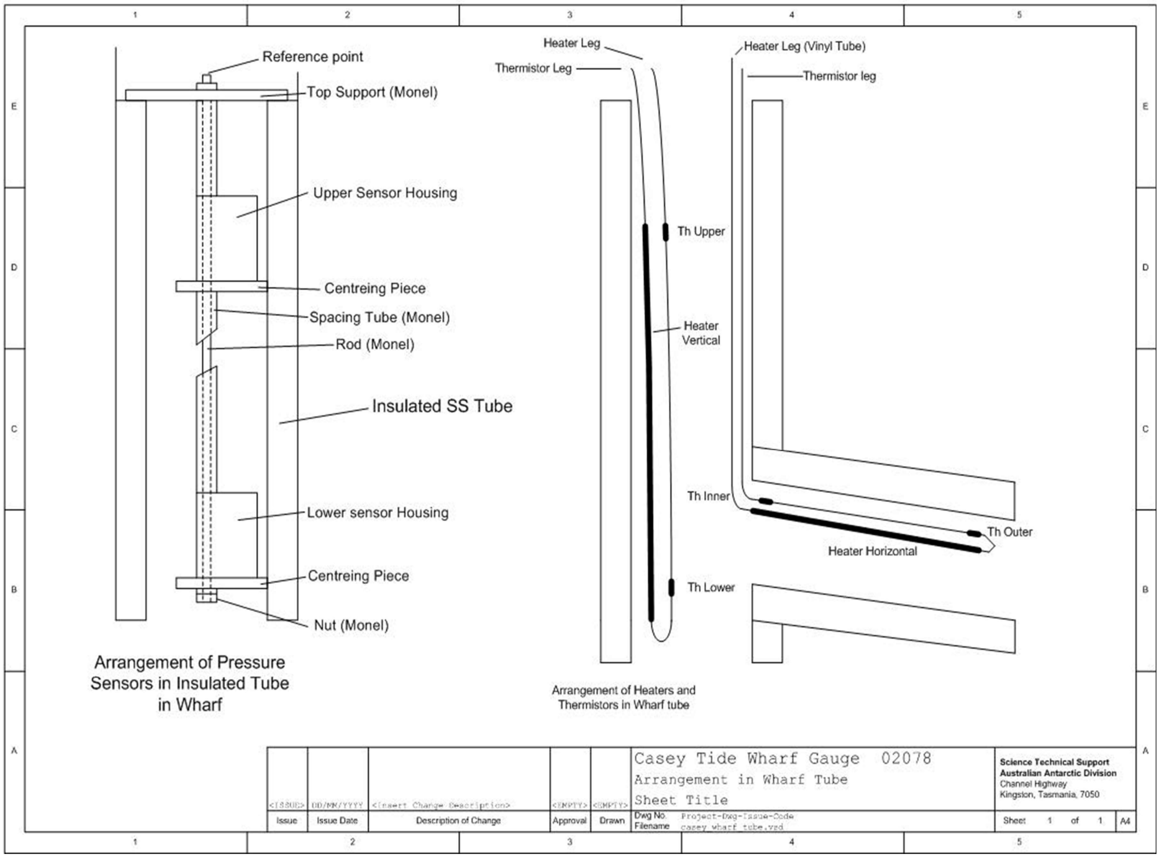

Figure 3
Current configuration of Casey Station wharf mounted tidal gauge (Han, 2009)

Figure 4
View of top of tidal gauge from Casey wharf (Han, 2009)

The wharf mounted tidal gauge is connected to an instrument cabinet, which is located in the wharf hut (a small building) adjacent to the wharf. Power and data cables to the tidal gauge run via a buried steel pipe from the hut to wharf. Pressure and temperature readings from the top and bottom mounted sensors are recorded and sent to the instrument cabinet where they are stored on a data logger. A barometer and temperature sensor inside the wharf hut also record data. The barometer is required to measure sea level pressure in order to be able to calculate the height of the water column.

Chapter 2 Literature Review

Tidal gauges for measuring sea level in Antarctica

The Antarctic and sub-Antarctic seas have complex and influential interactions with the atmosphere and greatly influence the global climate. Increasing rates of the Antarctic ice sheet discharging fresh water into the Antarctic oceans effects global sea levels. One study found that from 1992 to 2011 the sea level rise along the Antarctic coast was at least 2 ± 0.8 mm/yr and for the Southern Ocean (south of 50 degrees) was greater than the regional mean (Rye, et al., 2014). Another study (Galassi & Spada, 2017) cited that the Antarctic ice sheet is currently the largest ice reservoir on Earth and that complete melting of it would cause a global sea level rise of approximately 58 m.

Galassi and Spada (2017) used tidal gauge data available from the Permanent Service for Mean Sea Level (https://www.psmsl.org) and produced two sea level curves from tidal gauges for the Antarctic Peninsula and West Antarctic. They averaged data from a period between 1958 and 2014, and once they had removed cyclic and non-cyclic components from the data such as Glacial Isostatic Adjustment (bedrock uplift due to glacial retreat) they were able to produce rates for sea level rise. For the Antarctic Peninsula a trend of 2.0 ± 0.1 mm/yr of sea level rise was calculated and for West Antarctica 1.8 ± 0.1 mm/yr (Galassi & Spada, 2017).

Various studies have investigated short term and long term sea levels histories around the Antarctic using various measurement systems for measuring sea level. Rye et al. (2014) analyses a sea level history from 1992 to 2011 using a combination of satellite sea surface height measurements, in situ hydrographic measurements and ocean model simulations to calculate a sea level trend across Antarctica. They acknowledge that the in situ hydrographic observations, which could be from tidal gauge data, are localised and temporarily sparse and that satellite data can only be used from summer months of the year when there is no sea ice present.

Other studies have used GPS or tidal gauges for short term measurements of sea level around Antarctica. In one study differential, GPS was deployed on the fast ice[1] to measure sea level over a period of eight hours (Aoki, et al., 2000). This data was then compared to pressure gauge observations, and at the time GPS accuracy was such that 2 cm accuracy could be achieved and sea level variations were able to be identified (Aoki, et al., 2000). However, this study is now considered quite old and with improvements in GPS accuracy, with more satellites available a greater level of accuracy is likely achievable. Given that we are interested in sea level trends, accuracy needs to be in the order of a few millimetres. In addition, GPS antenna floats or antennas deployed on the sea ice are unable to be deployed long term

[1] Fast ice is, ice that is fastened to the coast or shore. It can still move with the tides.

in Antarctica due to rapidly changing ice conditions throughout much of the year and the maintenance requirements for batteries to maintain continual running of equipment. Over the 2011/2012 summer season at Casey, the AAD deployed a GPS buoy in order to attempt to calibrate the tidal gauge (Cromarty, 2012). The next coming summer season 2019/2020 they also plan to deploy another GPS calibration buoy.

Another study that took place over the 2007/2008 Spanish Antarctic season by scientists from the University of Cádiz, deployed bottom pressure sensors at Deception and Livingston islands, which form part of the South Shetland islands located at the northern end of the Antarctic Peninsula (Vidal, et al., 2012). Tidal data was collected for a short period of over ten weeks, with the aim to study tidal characteristics. A geodetic network was used to provide a reference for the calculated sea levels, and they conducted geometric levelling that had an accuracy of 1 mm, to link the data to geodetic marks on both islands. In their article, they acknowledge the importance of conducting such surveying to tidal gauges and linking to permanent bench marks in order to successfully study mean sea level (MSL) variations over time (Vidal, et al., 2012). Similar work was then carried out by almost the same team of scientists two years later, examining two years' worth of data and with a focus on carrying out further geodetic levelling. MSL was calculated and more accurate values obtained for their reference bench marks (Jigena, et al., 2015).

Galassi and Spada (2017) carried out their study of sea level using a series of tidal gauge data, which was accessed via the PSMSL website. They cite that sea level data recorded from tidal gauges could be used to assess the changes in mass balance of ice sheets or glaciers and that as the Earth responds elastically to removal of ice load that there is local variation of sea level (Galassi & Spada, 2017). Therefore, tidal gauges in the vicinity of major ice sheets could be useful in recording their reduction in mass. However, it was also noted that in general around the late 1990s the state of tidal gauges around the polar regions was generally unsatisfactory, with interest in particularly Antarctic gauges having declined, leading to poor coverage and lack of continuous observations. (Galassi & Spada, 2017).

Galassi and Spada (2017) looked at all of the available tidal gauge data from Antarctica and with many not being related back to a Revised Local Reference (RLR). When comparing tidal gauge data from many locations time series data should be reference back to a RLR. The PSMSL website explains the RLR allows time series sea level data to be reduced to a common datum, with the calculation of the RLR being performed by PSMSL when provided with gauge datum history. It defines the RLR datum at each station to be approximately 7000 mm below mean sea level, with this arbitrary choice made years ago in order to avoid negative numbers in the resulting RLR monthly and annual mean values (Permanent Service for Mean Sea Level, 2019).

When Galassi and Spada (2017) reviewed the PSMSL database they found that of the 17 Antarctic stations, only six were RLR records with remained listed as 'Metric'. They also noted that East Antarctica at that time had no RLR tidal gauge stations and that the three Australian tidal gauges at Casey, Davis, and Mawson had fairly extended histories, but were affected by several recording problems (Galassi & Spada, 2017). They discuss that as sea level trends have decadal oscillations, and to avoid this influencing results for MSL trends, multi-decadal data was required. Other literature (Hannah, 2010) also concurs with Galassi and Spada (2017) in that 60 years of data is ideal in order to measure long term sea level changes.

Galassi and Spada (2017) found that the only station on Antarctica with substantial time spans of data was the RLR tidal gauge station on Argentine Island, with a time span of 54 years with 98% completeness, and the 'Metric' station of Syowa in East Antarctica with 37 years and 92% complete data (Galassi & Spada, 2017). Galassi and Spada (2017) also noted that all tidal gauge data in Antarctica should be adjusted for a glacial isostatic adjustment (GIA).

Tide gauges that use a pressure transducer system have been documented to provide a good form of data collection for sea level, especially in hostile environments, and these types of gauges already comprise much of the Global Sea Level Observing System (GLOSS) (Woodworth, et al., 1995). However, in order for the data from these gauges to be effective in measuring long term sea level changes, consistent and good datum control must be maintained (Hannah, 2010). Datum control is required in order to be able to discern the vertical movement of the gauge, whether that be from the structure it is mounted to moving over time, such as wharf subsidence, or the land itself moving from GIA or tectonic motion (Hannah, 2010).

The Geoscience Australia website (Geoscience Australia, 2019) discusses the importance of levelling connections between tide gauges and Global Navigation Satellite System (GNSS) sites. GNSS sites are able to pick up the vertical crustal motion of the land and then levelling to the tidal gauge can distinguish movement of the gauge itself, such as wharf subsidence. Being able to distinguish these types of movements is important otherwise relative sea level rise cannot be determined (Geoscience Australia, 2019).

Casey Station Tidal Gauge Surveys

The survey reports for the tidal gauges at Casey station appear to be sparse given the information file received. Casey station has a permanent geodetic quality GNSS receiver and antenna that forms part of the Australian Regional GNSS Network and is located approximately 100 m to the west of the Operations Building (refer to Figure 2). This network is intended to measure Earth's processes such as crustal dynamics and sea level rise (Geoscience Australia, 2019).

The Geoscience Australia website has levelling data from the ARGN station at Casey, known as AUS100, down to bench marks near the wharf and also to the reference mark on the newer wharf mounted tidal gauge. However, there is only levelling data available for the newer gauge from 2006, which would have been shortly after the installation of the tidal gauge, and 2009. Table 1 below shows the levelling data and Appendix B contains the full document from the website. (Geoscience Australia, 2019).

Geodetic Connections to Tide Gauge at Casey

	MSL HEIGHT (m) [1]						
BENCH MARK NAME	**1990/91 [2]**	**1993 [3]**	**1998/99 [4]**	**Oct 2001 [5]**	**Mar 2006[5]**	**Feb 2009[5]**	**COMMENTS**
AUS100		40.882		40.8798	-	40.8824	ARGN permanent GPS mark
AUS100 RM1		40.111		40.1098	40.1076	40.1115	ARGN permanent GPS mark, RM1
AUS100 RM2		39.783		39.7814	-	39.7837	ARGN permanent GPS mark, RM2
AUS100 RM3		41.561		41.5572	--	41.5604	ARGN permanent GPS mark, RM3
BM5		38.545		38.5491	38.5489	38.5497	
AUS396				26.8843	-	26.8830	
AUS394				29.3789	-	-	
AUS395				19.3345	19.3335	19.3327	
ISTS B052	20.469	20.464			-	20.4683	Casey Pageos mark
WHF1 [7]			2.269	2.2704	-	-	
HBM4			2.418	2.4247	2.4240	2.4242	
HBM1	7.171		7.171	7.1710	7.1710	7.1710	
HBM2	5.518			5.5172	5.5172	5.5171	
HBM3 [6]	1.968	1.968	1.968	1.9734	-	-	
AUS299 TGBM				2.0526	-	-	Tide gauge benchmark
TG RM					1.7261	1.7260	RM for Tide Gauge on Casey wharf
AUS2027					1.4615	-	Secondary TGBM
AUS2028					1.9401	-	Primary TGBM, replace AUS299
AUS2009						1.7500	Replaced AUS2027
AUS2010						2.2117	Replaced AUS2028

Table 1
Geodetic Connections to Tide Gauges at Casey (Geoscience Australia, 2019)

At the time of writing, available survey reports to the newer wharf mounted tidal gauge are as follows:

- 2006 Survey report conducted by AAD surveyors (Brolsma, et al., 2006) where a level run was conducted from AUS100 to TGRM (Tidal Gauge Reference Mark).
- 2012 Survey report conducted by AAD surveyors where a level run from HMB1 (a reference mark near tidal gauge) to TGRM was conducted and a tidal gauge calibration GPS buoy was deployed.
- 2018 Survey interim data provided by Naval hydrographers. Bench marks including HMB1 reoccupied with GPS and level runs conducted to TGRM. The final report still to be delivered to AAD Data Centre.

It should be noted that a survey, as shown in Table 1, was conducted during 2009, however, no report appears to be available for this survey work other than the results shown in Table 1.

HMB1 is a reference mark near the wharf that has been used in all surveys to the wharf tidal gauge, and Figure 5 and Appendix C show maps of Casey station bench marks that have been provided by the AAD Data Centre. Figure 6 shows a photo of the location of HMB1. HMB1 is in a location near the wharf that is not covered by multi-year snow and ice, unlike other bench marks such as AUS2009, and it is not in an area that is in a high traffic area often snow cleared using heavy machinery, such as AUS2028. Therefore, HMB1 appears to be in a good location that is undisturbed and accessible.

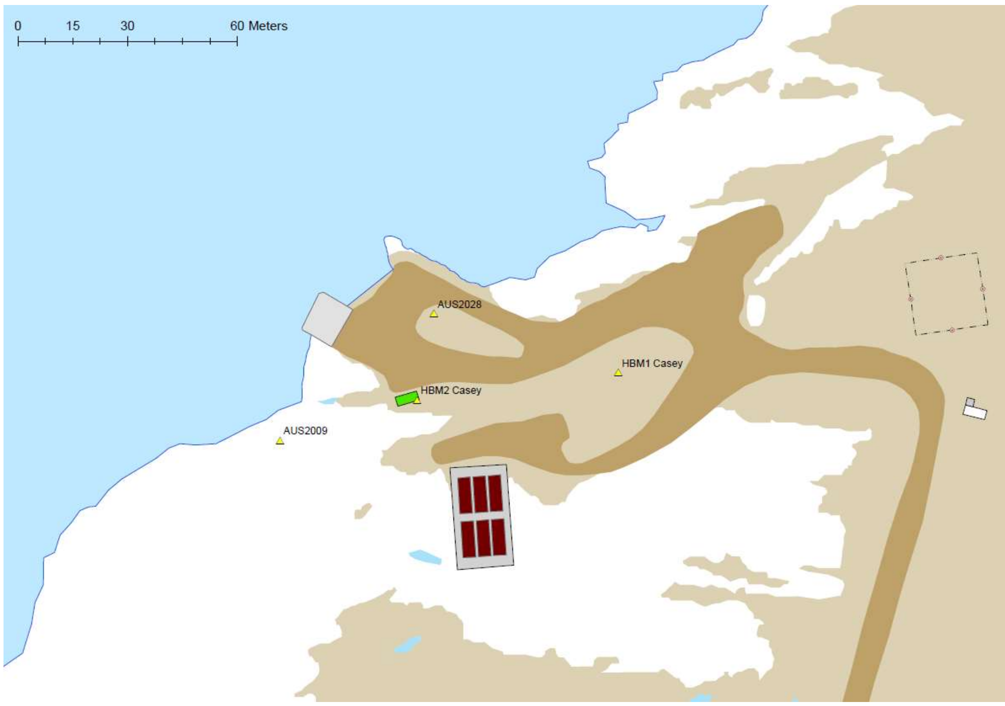

Figure 5
Survey control bench marks at Casey Station wharf area (Australian Antactic Division Data Centre, n.d.)

Figure 6
HMB1 location around base of the scaffolding

In order to determine changes to mean sea level the effect of any land movement, such as GIA, and movement of the wharf or tidal gauge mount to the wharf needs to be taken into account. From levelling data shown in Figure 1 and the survey reports available, HMB1 is taken as a fixed point. Therefore, assuming it has relatively little movement compared to AUS100, other than the GIA, HMB1 could be considered as a good reference point to determine if the wharf is moving. Table 2 below shows the relative difference in heights between HMB1 and TGRM (Figure 7).

The figures in Table 2 show relatively little movement between HMB1 and TGRM, only varying over 3 mm, which is positive as it shows the wharf that the tidal gauge is mounted to is potentially stable. However, as there is only one data set for HMB1 relative to AUS100 it's difficult to tell if HMB1 can be considered as a stable bench mark. The Naval hydrographers who surveyed the tidal gauge in 2018 reoccupied HMB1 with GPS and will deliver post processed data for HMB1. This final report is yet to be delivered.

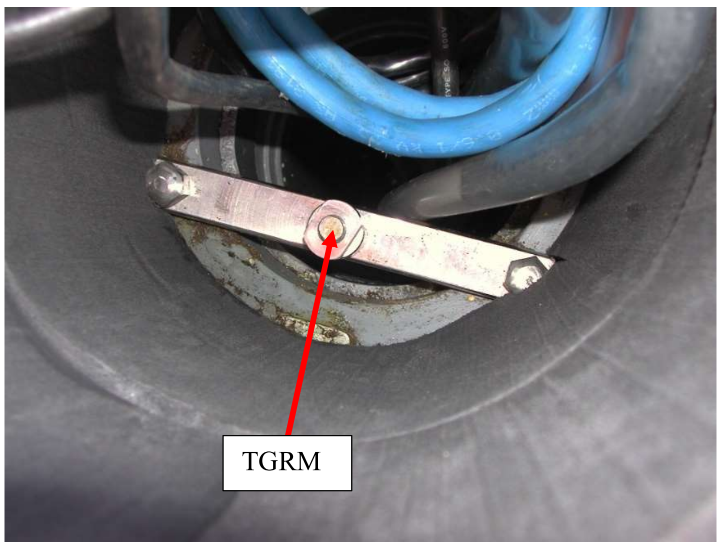

Figure 7
Top cap removed off tidal gauge showing the reference point (TGRM)

Survey Year	Recorded difference in height between HMB1 and TGRM (m)
2006	5.444
2009	5.445
2012	5.443 (1st run) 5.444 (2nd run)
2018	5.446

Table 2
Calculated height differences between HMB1 and TGRM

GNSS data from AUS100, which is available from either Geoscience Australia (Geoscience Australia, 2019) website or the Sonel website (Sonel, 2019) shows an upwards trend, which would be due to upward movement of the earth likely from GIA. Figure 8 shows a plot of GNSS data and the Sonel website quotes a vertical adjustment of 1.58 ± 1.90 mm/yr. The period of data from 1996 to 1997 is listed as an unknown offset and should be discounted (Sonel, 2019).

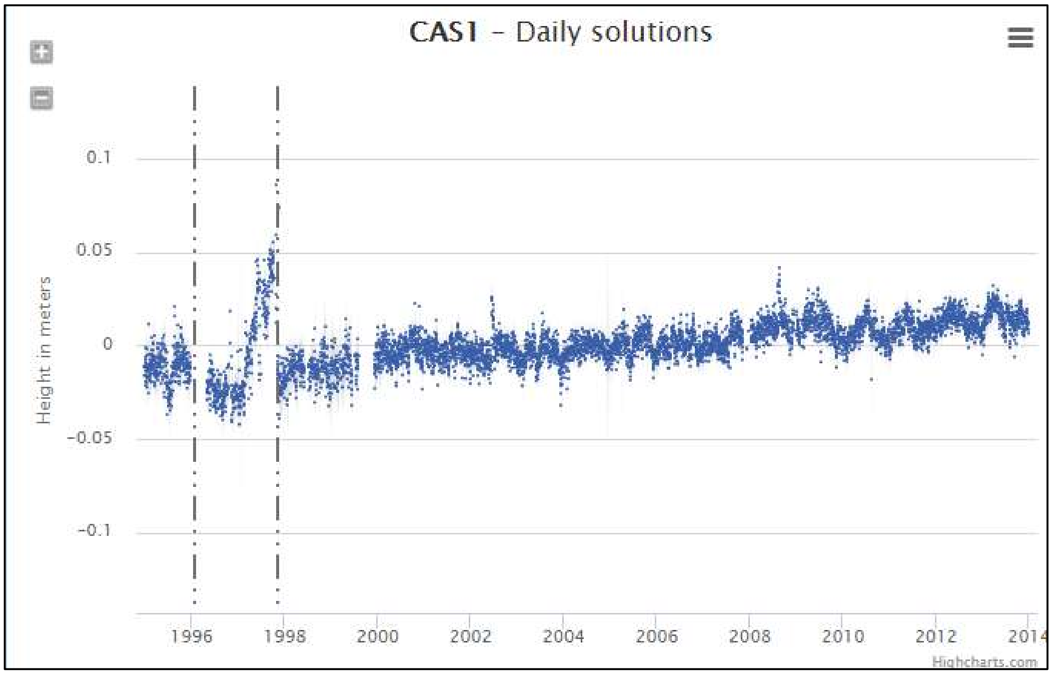

Figure 8
Plot of AGRN Point AUS100 showing relative upward movement over the years (Sonel, 2019)

Using Altimetry for Sea Level Measurements

Satellite altimetry is a method that can potentially be used to monitor long term sea levels and also the volume of the polar ice sheets (Yi, et al., 2000). Studies have also used costal tidal gauge data to calibrate altimeter data (Hannah, 2010). Sea-level trends derived from altimetry and tidal gauge data can provide regional sea level changes, which is important as in some regions the rate of sea level change is higher than the global average (Gharineiat & Deng, 2018).

Tidal gauge data and satellite sea surface height data have very different spatial and temporal sampling. For example, altimeters aboard satellites record data from a height of 1000 km above the earth, with ground tracks of 6 km, in a mesh that can be 100 to 300 km apart. The data may only be repeated every 10 to 35 days (Andersen, et al., 2015). While tidal gauge data is very regional to a particular point on the coast and is sampled frequently. The tidal gauge at Casey station records data every ten minutes. However, given the spatial and temporal differences in the data sampling, Gharineiat and Deng (2018) were able to show that there was a strong agreement between mean sea level trends from altimetry and tidal gauge data when exclusions for localised vertical land movement was made. Gharineiat and Deng (2018) also concur with Galassi and Spada (2017) that multi-decadal tidal gauge data is required to measure sea level trends and thus only used tidal gauge data that had a 20 year period available.

Chapter 3 Methodology for Data Processing

Calculation of Water Column Height from Tidal Gauge Data

Casey Station tidal gauge data has been provided by the AAD for both the old Platypus bottom mounted gauge and the newer wharf mounted gauge. Raw .dat files have been provided. For this project it has been decided to focus on processing data from the wharf mounted gauge, as this data simultaneously records from two below water pressure sensors, water temperature, and sea level atmospheric pressure. The equation to calculate the height of the column of water above the gauge is simple. Jigena et al. (2015) list the equation to convert a hydrostatic pressure into sea level as:

$$P = P_a + \rho g h \qquad \text{[Eqn 1]}$$

Where P = hydrostatic pressure (hPa)

P_a = sea level atmospheric pressure (hPa)

ρ = density of sea water (kg/m^3)

h = column height of sea water (m)

g = acceleration due to gravity, in the local area (m/s^2)

For the wharf mounted gauge, sea water density at that specific temperature and time can be calculated by rearranging Equation 1. Hydrostatic pressures P and P_a become the bottom and top pressure transducer readings PB and PT, and h is the separation distance between the top and bottom pressure transducer of 2.007 meters.

$$\rho = \frac{PB - PT}{10gh} \qquad \text{[Eqn 2]}$$

Once the sea water density has been calculated then Equation 2 can be rearranged again to find the height of sea water above the bottom gauge in meters.

$$h = \frac{PB - P}{10\rho g} \qquad \text{[Eqn 3]}$$

The figure for gravity varies with location and a figure of g = 9.823761905, which was provided by John French who works for the AAD as an Airglow and Climate Variation Physicist was used. The figure for gravity was calculated using the WGS 1984 Ellipsoidal Gravity Formula and a latitude for the wharf gauge of 66.27788802 degrees.

Data from the Platypus gauge only provided for one submerged pressure reading and no barometer readings at sea level. Although hourly sea level pressure data back to 1996 could be requested from the

Bureau of Meteorology and married up to the pressure data, an estimate of sea water density would have to be used. Though the effect of this would be minimal it does vary seasonally due to ice and snow melt over summer and it also introduces another source of error. Furthermore, the Platypus gauge could not be surveyed, thus providing no linkage geodetically, such that GIA effects can be removed, stability of the gauge confirmed, and the two data sets to be linked. Although data from this gauge has been used to produce prediction information for tide tables, the accuracy in the order of tens of millimetres is suitable for shipping information. Generally tide tables and sea level information for Casey station (available on the Bureau of Meteorology website) do not quote to millimetre accuracy and are supplied with caveats on accuracy (Bureau of Meteorology, 2019). However, in order to measure sea level changes over time, accuracy within a few millimetres is desired.

Processing of Tidal Gauge Data Files

The newer wharf mounted gauge data is downloaded remotely by the Science Technical Support section of the AAD and these files were provided for processing. The files come in a .dat file format (basic data file) with several months of data on the same file. Each data file was converted to a Microsoft Excel file, and water column height above bottom gauge calculated, as outlined in the section above. Each Excel file was then stitched together to form one tidal gauge history data file.

The tidal gauge takes simultaneous pressure and temperature readings and records them every ten minutes. The files provided have data first being recorded with a date time stamp of 13/2/2008 22:40 and the last data provided as 29/5/2019 23:20. There are periods of time missing from the data, and this has occurred when there were power outages at the wharf hut. The instrumentation in the wharf hut does have an uninterrupted power supply, however this only provides a short period of power. Therefore, any power outages of significant durations lead to loss of data. Table 3 provides a summary of the tidal gauge data available.

Date From	Date To	Total Days	Comment
25/05/2008	9/06/2008	15	Missing
24/09/2008	7/10/2008	13	Missing
23/03/2012	11/04/2012	19	Missing
17/12/2014	23/1/2015	37	Missing
23/02/2015	9/04/2015	45	Missing
30/04/2018	22/06/2018	53	Missing
13/02/2008	29/05/2019	4021 (11 yrs, 4 days)	Total data period
		3839	**Total days of data**

Table 3
Total tidal gauge data available

The 3839 days of data, with data recorded at 10 minute intervals equates to almost 548,000 rows of data in Excel. A graph of two years of raw data (2009 to 2010) is shown below in Figure 9.

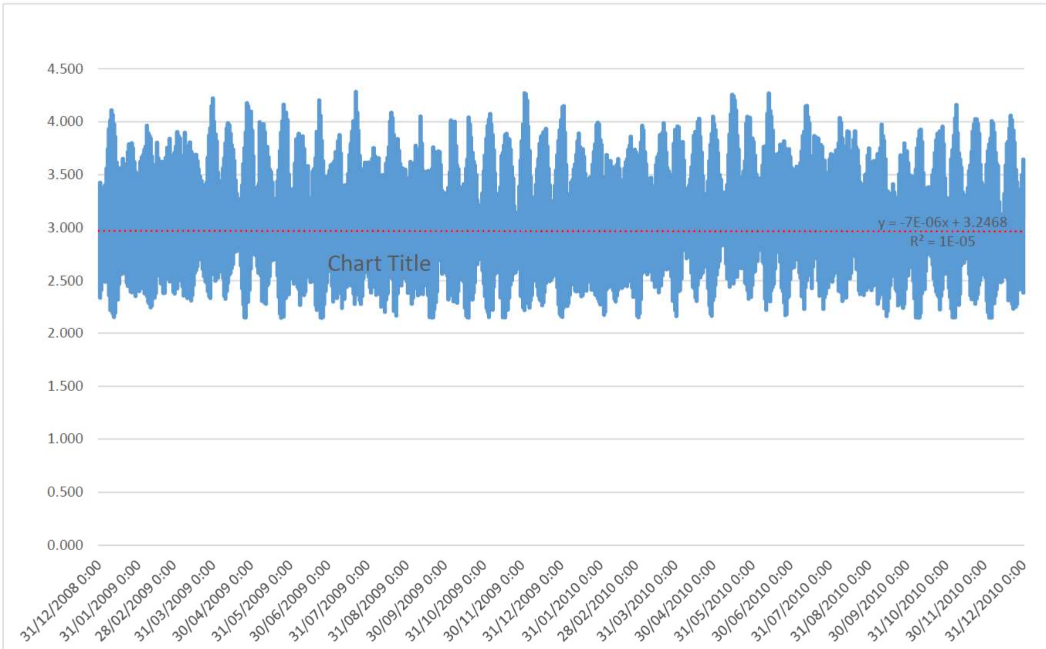

Figure 9
Time plot for height of sea water above bottom pressure sensor (m) for Casey Tidal gauge for years 2009 to 2010

Before any determinations on whether the local sea level at Casey station has been changing the data needed to be smoothed and have fluctuations, such as tides removed. It also needed to be adjusted for any land movement from GIA, and it confirmed that the tidal gauge mounting or wharf wasn't moving. The next sections discuss the methodology for each of these.

Data Smoothing and Removal of Tidal Fluctuations

The sea level, or column of water above the lower tidal gauge sensor varies continuously throughout the day due to tides, and the recorded data may have short term changes in sea level due to changes in atmospheric pressure from storms and wave action. Mean Sea Level (MSL) is considered as a tidal datum half way between low and high tides (Consoli, et al., 2013), but is somewhat conceptual given that the sea is always moving due to tides and weather. The Australian Hydrographic Office defines MSL as a tidal datum, which is the arithmetic mean of hourly heights of the sea at a tidal station, observed over a period of time (preferably 19 years) (Australian Hydrographic Office, 2019). Consoli et al. (2013) considers that any instantaneous sea level observation is actually the sum of the MSL and levels due to tides and meteorological actions. Therefore, before a MSL can be calculated from observed results both tidal and meteorological actions, such as waves, need to be removed from the observation (Consoli, et al., 2013).

The daily fluctuations from tides needs to be identified in the data and removed before analysis of long term changes can be determined. Tides are the sea level rising and falling due to gravitational forces from the moon, sun and rotation of the earth. Most areas on earth have predominate semi-diurnal tides (low and high tides that occur twice a day) and some areas only have a predominate diurnal tide (low and high tide occurring once a day) (Consoli, et al., 2013).

Tidal modelling and forecasting uses tidal constituents, which are sets of sinusoids at specific frequencies, with each constituent representing a periodic change in relative positions of the earth, moon and sun (NOAA, 2019). George Darwin's work, which derived and established tidal harmonic analysis and tidal constituents in the late 1800's, is still used today. He also formulated a least squares method for tidal harmonic analysis (Consoli, et al., 2013).

There are a range of standard tidal constituents identified, with each constituent having its own specific speed (in degrees per hour) and period (hours). A Darwin Symbol identifies each constituent and Table 4 lists the most dominate standard tidal constituents.

The data was processed in MATLAB using the Tidal Fitting Toolbox (Grindsted, 2014) open source code developed by Aslak Grinsted, which can be downloaded from the MathWorks website at https://au.mathworks.com. A copy of the code can be found in Appendix D. The Tidal Fitting Toolbox uses the Ordinary Least Squares method to fit data to the known tidal constituents. An explanation of the maths involved in the Ordinary Least Squares method can also be found on the MathWorks website at https://au.mathworks.com/help/curvefit/least-squares-fitting.html, but it basically is a method of fitting response data to that of predicted data for a parametric model (MathWorks, 2019)

The output provided by the Tidal Fitting Toolbox identified what tidal constituents are dominate in the data, by providing an amplitude against standard tidal constituents. Most of the tidal constituents don't have an amplitude greater than a few millimetres, indicating they are not a tidal influence, with others in the order of hundreds of millimetres indicating that these tidal components are present in the data. The Tidal Toolbox then provided a 'de-trended' output with these daily tidal influences removed from the raw sea level data.

Species	**Darwin Symbol**	**Period (hr)**	**Speed** (°/hr)
Semi-diurnal			
Principal lunar semidiurnal	M_2	12.4206012	28.9841042
Principal solar semidiurnal	S_2	12	30
Larger lunar elliptic semidiurnal	N_2	12.65834751	28.4397295
Larger lunar evectional	v_2	12.62600509	28.5125831
Variational	MU_2	12.8717576	27.9682084
Lunar elliptical semidiurnal second-order	2"N_2	12.90537297	27.8953548
Smaller lunar evectional	λ_2	12.22177348	29.4556253
Larger solar elliptic	T_2	12.01644934	29.9589333
Smaller solar elliptic	R_2	11.98359564	30.0410667
Shallow water semidiurnal	$2SM_2$	11.60695157	31.0158958
Smaller lunar elliptic semidiurnal	L_2	12.19162085	29.5284789
Lunisolar semidiurnal	K_2	11.96723606	30.0821373
Diurnal			
Luni-solar diurnal	K1	23.93447213	15.0410686
Principal lunar diurnal	O1	25.81933871	13.9430356
Lunar diurnal	OO1	22.30608083	16.1391017
Solar diurnal	S1	24	15
Smaller lunar elliptic diurnal	M1	24.84120241	14.4920521
Smaller lunar elliptic diurnal	J1	23.09848146	15.5854433
Larger lunar evectional diurnal	ρ	26.72305326	13.4715145
Larger lunar elliptic diurnal	Q1	26.868350	13.3986609
Larger elliptic diurnal	2Q1	28.00621204	12.8542862
Solar diurnal	P1	24.06588766	14.9589314
Long Period			
Lunar monthly	M_m	661.3111655	0.5443747
Solar semiannual	S_{sa}	4383.076325	0.0821373
Solar annual	S_a	8766.15265	0.0410686
Lunisolar synodic fortnightly	M_{sf}	354.3670666	1.0158958
Lunisolar fortnightly	M_f	327.8599387	1.0980331
Short Period			
Shallow water overtides of principal lunar	M4	6.210300601	57.9682084
Shallow water overtides of principal lunar	M6	4.140200401	86.9523127
Shallow water terdiurnal	MK3	8.177140247	44.0251729
Shallow water overtides of principal solar	S4	6	60
Shallow water quarter diurnal	MN4	6.269173724	57.4238337
Shallow water overtides of principal solar	S6	4	90
Lunar terdiurnal	M3	8.280400802	43.4761563
Shallow water terdiurnal	2"MK3	8.38630265	42.9271398
Shallow water eighth diurnal	M8	3.105150301	115.9364166
Shallow water quarter diurnal	MS4	6.103339275	58.9841042

Table 4
Standard Tidal Constituents

Once the tidal information was removed from the data, it could be filtered (or ‘smoothed’) to remove other fluctuations, such as wave action. This was done by calculating a monthly moving average using the MOVMEAN function in MATLAB (MathWorks, 2019). A moving average can be considered as a low pass FIR (Finite-duration Impulse Response) filter, which removes short term fluctuations and allows longer term trends to be identified. The moving average filter is like a window that moves along the data, where the central element of window is replaced with average of all the elements in the window (Consoli, et al., 2013).

Data Processing for Glacial Isostatic Adjustment

The data was also processed for GIA in order for the tidal gauge data not to be contaminated by land movement. The Sonel website quotes a vertical adjustment of 1.58 ± 1.90 mm/yr for bedrock recoil as measured on the Casey Station GNSS receiver. Figure 10 clearly shows that in Antarctica and areas in Patagonia and Northern America most of the landmass is recoiling and moving in an upwards direction, though there are some areas that are experiencing a downwards motion (Paulson, et al., 2007). As the land is moving upwards the adjustment needs to be added to the smoothed tidal gauge data.

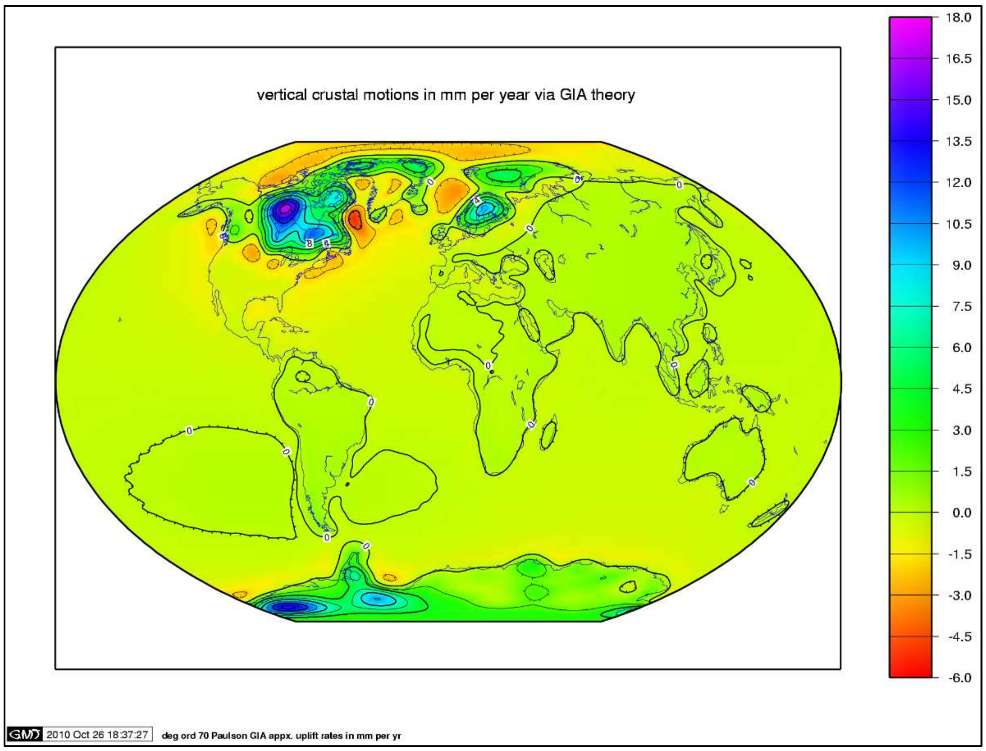

Figure 10
A model of present-day mass change due to post-glacial rebound and the reloading of the ocean basins with seawater

The adjustment needs to be added to the data, in order not to falsely skew it as showing a decrease in mean sea level. In other words, imagine if mean sea level is at a constant level, but the bedrock and seabed beneath the gauge is moving upwards, therefore the column of water above the pressure sensor would effectively be getting shorter, thus showing a decrease in sea level.

White et al (2014) designates observed land movement rates at GPS receivers adjacent to tidal gauges as Vertical Land Movement (VLM), and notes that not all VLM maybe from GIA. He notes that other land movement due to earthquakes, or local subsidence from groundwater could contribute to the VLM. The GPS data in his study is from receivers sparsely located, up to 100 km from the tidal gauge sites, and he derives figures from GIA from models (White, et al., 2014). However, at Casey station the GPS receiver is located approximately less than 1 km from the wharf, and as it is a part of the Australian Regional GNSS Network it has foundations that have been embedded into the bedrock and are considered very stable. Also, White et al.'s (2014) study was conducted for tidal gauges around Australia, and when referring to Figure 10, it can be seen that Antarctica is subject to much more GIA than what Australia is. Therefore, for the purposes of this study all land movement recorded at the Casey Station GNSS receiver is considered as, and designated as GIA.

To apply the GIA to the tidal gauge data, Excel was used to calculate accumulative GIA for each row of 'de-tided' averaged data at the rate of 1.58 mm/yr. The accumulative GIA was then added to each 'de-tided' averaged data point. It should be noted at this point that the standard error of ± 1.90 mm/yr associated with the quoted GIA is considerably large, however, with no alternative measure of land movement the figure of 1.58 mm/yr has been applied. The resultant mean sea level data was then plotted against years (calculated in decimal years) and a trend line for mean sea level produced.

Confirmation of Wharf Stability

Local subsidence or movement of the tidal gauge also needed to be taken into account, with the biggest concern for local land movement being stability of the wharf. The wharf is constructed from piling sheets driven into the sea bed, and is pulled together with tie rods and filled-in with rocks and soil. So it's was possible that this structure had moved or subsided between when the wharf mounted gauge was constructed in 2006 and present day. Levelling survey data was plotted against year to see if there was an upward trend, and additional research was conducted to try and find more information on the surveys that have been conducted over the years. Some additional comments on the accuracy of these surveys have been included in the following section.

Chapter 4 Results and Discussion

This sections presents the raw data and the data step by step as its processed. It also discusses the results observed and issues that affect the data.

Tidal Gauge Data and De-Tided Data Results

As mentioned in Chapter 3 the tidal gauge data was sampled every 10 minutes for just over 11 years, and height of the water column above the bottom pressure sensor calculated for each observation in Excel. An example of the raw data in Excel can be found in Appendix E, and Figures 11 and 12 below show examples of plotted daily and monthly raw data.

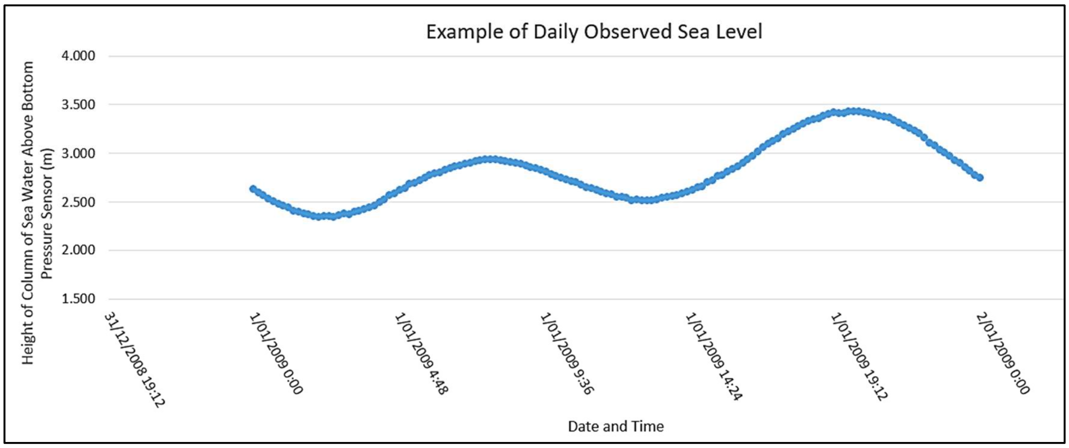

Figure 11
One day of tidal gauge observed sea level data

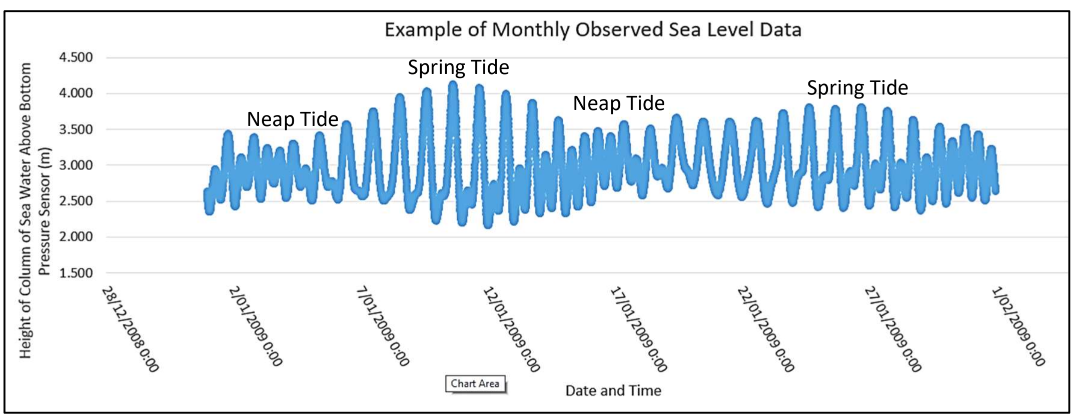

Figure 12
One month of tidal gauge observed sea level data

Figure 11 clearly shows two daily (semi-diurnal) low and high tides, with the height of high tides varying by 0.5 m, and the low tides being approximately the same heights. While Figure 12 clearly shows the harmonic nature of the tides, with a clear addition of various harmonic (tidal) functions. Spring and neap tides can also be observed in Figure 12. A spring tide is where there is the largest difference in tides, and these occur at a new and full moon. A neap tide is where there is the least difference between high and low tides, and these occur after the first and third quarters of the moon, when the moon is at right angles to the sun (National Ocean Service, 2019).

Table 5 below shows the output results of the Tidal Fitting Toolbox function in MATLAB, and 37 tidal constituents were identified. However, only four of them are significant. These are identified by their higher amplitudes, in the order of 100 to almost 300 millimetres, compared to the other constituents that have amplitudes of only a few millimetres.

The four dominate tidal constituents are identified as M_2 (principal lunar semidiurnal), S_2 (principal solar semidiurnal), and K1 and O1, two lunar diurnal components. Although these four tidal constituents are identified as the dominate constituents, various references identify that in order for long period tides associated with the moon's change of orbit around Earth, 19 years of data is required as a minimum (University of Washington, 2019) (Australian Hydrographic Office, 2019). However, the four main tidal constituents identified for Casey station also are generally the four largest amplitude tides in most locations (University of Washington, 2019).

It should be noted that potentially as the long period lunar tides cannot be removed from the data, as only 11 years' worth of surveyed tidal gauge data for Casey Station exists, that this could possibly effect the smoothed data and final calculated mean sea level trend. Other references such Galassi and Spada (2017) also indicate that in order to avoid decadal oscillations in the calculated sea level trend that several decades of data is required.

Figure 13 shows the de-tided data after processing using the Tidal Fitting Toolbox in MATLAB. It can be seen that although the predominate tides have been removed from the data, that there is still a lot of 'noise' in the data. This is likely from wave action and other weather events such storms, which in Antarctica are generally blizzards from low pressure systems moving over the station, and other long term cyclic events.

Name	Speed	Period	Amp (m)	Phase
'M2'	28.9841	0.517525	0.291216	-1.040788991
'S2'	30	0.5	0.166171	-2.809192286
'N2'	28.43973	0.527431	0.073604	-2.554327843
'K1'	15.04107	0.99727	0.252157	-2.23742129
'M4'	57.96821	0.258763	0.001988	1.363725207
'O1'	13.94304	1.075806	0.242423	0.782001242
'M6'	86.95231	0.172508	0.000492	1.334174558
'MK3'	44.02517	0.340714	0.000217	-2.036445238
'S4'	60	0.25	7.98E-05	2.692153314
'MN4'	57.42383	0.261216	0.000287	-0.973744952
'NU2'	28.51258	0.526084	0.013674	2.550712935
'S6'	90	0.166667	0.001213	1.13706884
'MU2'	27.96821	0.536323	0.013999	1.265318313
'2N2'	27.89535	0.537724	0.013069	1.948965199
'OO1'	16.1391	0.92942	0.003817	-2.552349154
'LAM2'	29.45563	0.509241	0.003655	-2.009109847
'S1'	15	1	0.001458	2.650244702
'M1'	14.49669	1.034719	0.015256	2.807278975
'J1'	15.58544	0.962437	0.009986	-1.091122268
'MM'	0.544375	27.55455	0.018637	-1.898089496
'SSA'	0.082137	182.6211	0.021761	2.980681816
'SA'	0.041069	365.2422	0.035085	1.884419673
'MSF'	1.015896	14.76529	0.004876	1.873284908
'MF'	1.098033	13.66079	0.013971	-2.766774573
'RHO'	13.47151	1.113461	0.01078	-1.695338741
'Q1'	13.39866	1.119515	0.055827	-0.518302827
'T2'	29.95893	0.500685	0.012055	-2.286625949
'R2'	30.04107	0.499316	0.002136	-2.29605873
'2Q1'	12.85429	1.166926	0.008398	-1.877926337
'P1'	14.95893	1.002745	0.084369	-1.934928722
'2SM2'	31.0159	0.483623	0.005284	-2.894423414
'M3'	43.47616	0.345017	0.005084	-0.452886213
'L2'	29.52848	0.507984	0.010703	-2.810662465
'2MK3'	42.92714	0.349429	0.000896	-1.440890111
'K2'	30.08214	0.498635	0.039245	-0.077657396
'M8'	115.9364	0.129381	0.000545	0.025002102
'MS4'	58.9841	0.254306	0.004243	-2.550256279

Table 5
Casey Station tidal gauge resultant Tidal Constituents

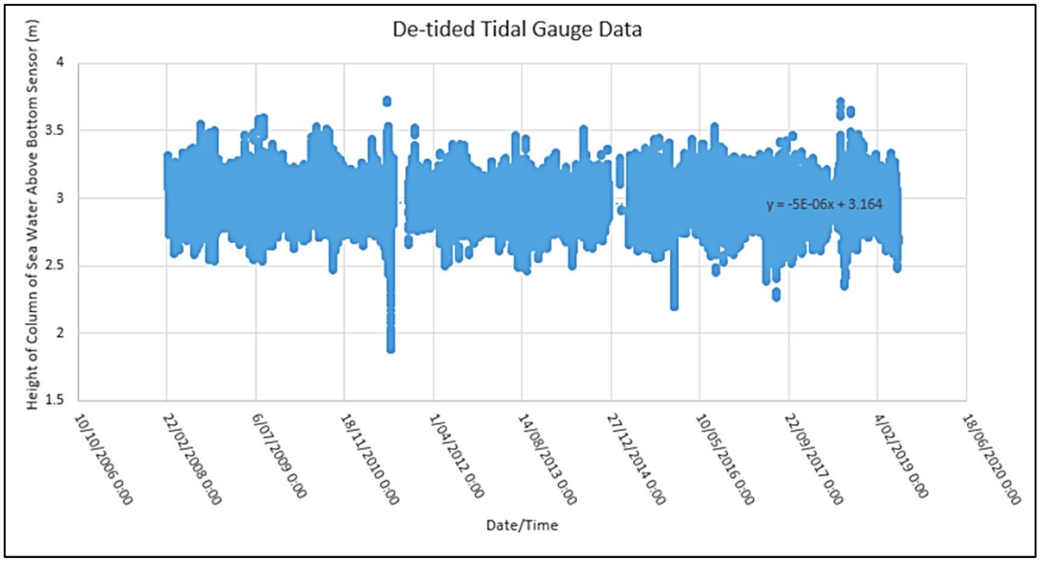

Figure 13
De-tided Tidal Gauge Data

Figure 14 shows the filtered (or smoothed) 'de-tided' data. By the application of the monthly moving average acting as a low pass filter, it can be seen that high frequency events or 'noise' has been removed only leaving other annual or seasonal cyclic events. Basic probing of the data in Figure 14 shows the maximum difference in the sea level in the order of 250 mm, and with many of the higher levels approximating to later February early March annually.

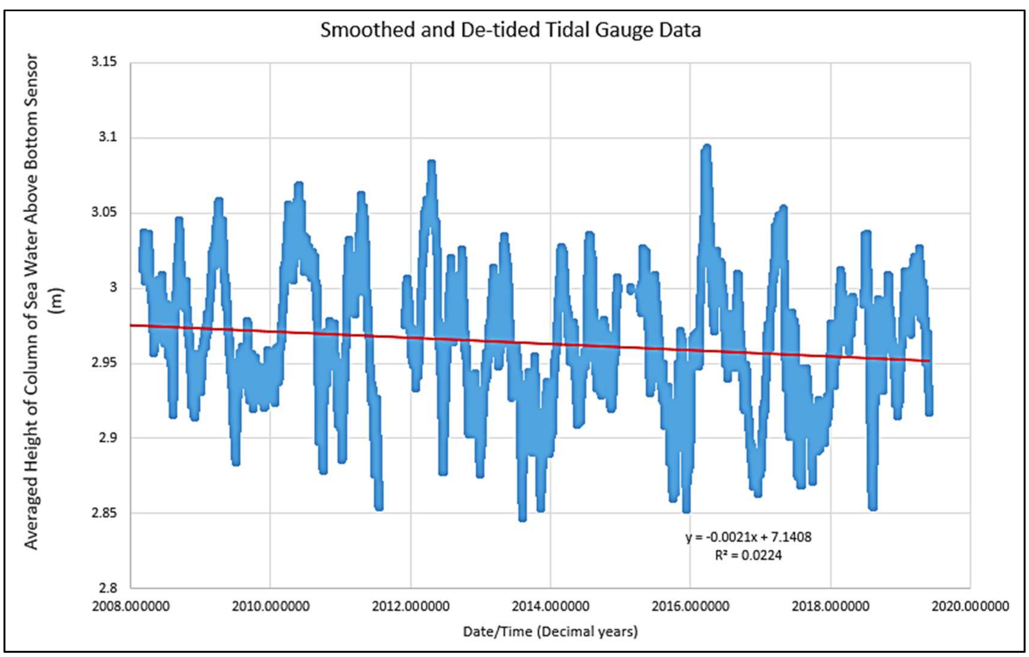

Figure 14
Smoothed and De-tided Tidal Gauge Data

Annually during the summer months at Casey, particularly through January there is usually a large melt. This is where land based ice and snow rapidly melts and runs off into the ocean, therefore, it is possible that these highly monthly averages are due to melt run off, albeit with a slight lag.

Some other peaks in the data approximately in the 3.025 m range coincide with winter months of June, July and August. A periodic ocean/weather event that is well documented for the Antarctic region is the Semi-Annual Oscillation (Meehl, et al., 2017). The Semi-Annual Oscillation is where around Antarctica the pressure trough minima occurs twice a year annually during February, March and April and again in August, September, October as the circumpolar trough contracts (Meehl, et al., 2017) (Broeke, 2000). It is possible that observed peaks in the tidal gauge data around late summer and winter could be influenced by the lower barometric pressures due to the Semi-Annual Oscillation.

Again with very basic probing of the data shown in Figure 14 the two greatest peaks for the average monthly figures are in March 2012 and February 2016. Various references, such as Simmonds (2013) Memin et. al (2015) document another periodic event call the Antarctic Circumpolar Wave. The Antarctic Circumpolar Wave is a wave that propagates eastward around Antarctica with a period in the range of 4 to 5 years (Simmonds, 2003), and influences sea level atmospheric pressure, wind and sea surface temperatures (Galassi & Spada, 2017) (Mémin, et al., 2015). Memin et. al (2015) also makes connections between temporary sea level rise and presence of the Antarctic Circumpolar Wave.

Although the data presented in Figure 14 is too 'noisy' to clearly discern these periodic semi-annual and inter-annual climatic events, with more complex filtering applied to the data and if more data were available it is likely that they would be evident. Gharineiat & Deng (2018) demonstrated in their research of tidal gauges and altimetry data from around the Austrlian coastline that with a 12 month moving average low pass filter, El Niño and La Niña (Gharineiat & Deng, 2018) climatic events were clearly evident. The variation between the troughs in their sea level data for El Niño and La Niña for the 12 month moving average only varied between approximately 100 mm to 150 mm, which is commensurate with the troughs and peaks in the monthly moving average data presented in Figure 14. This again highlights that with further filtering it is likely that Semi-Annual Oscillation and Antarctic Circumpolar Wave are likely to be evident in the tidal gauge data collected at Casey Station.

Glacial Isostatic Adjusted Data and Sea Level Trend

The final adjustment made to the data was a linear adjustment for GIA of 1.58 mm/yr, which for the final data point in the data period of 11 years and 4 days yielded a total upward adjustment of 17.4 mm. Once this adjustment was applied, the data was graphed plotting height of column of water above bottom sensor against decimal years, and a trend line applied. Although this data has not been adjusted onto another datum such as LAT, as the gauge is stable any change in the height of column of water above the bottom sensor can be considered as a relative sea level change.

The trend line equation calculated by Excel, with the R^2 value is as below:

$$y = 0.0041x - 5.2307 \quad \text{[Eqn 4]}$$

$$R^2 = 0.0024$$

Using the above trend line equation y was calculated for the total data period of 11 years and 4 days, and this yielded a total increase of 46.1 mm over the period. This equates to 4.2 mm of relative sea level rise per year. Although this figure should be used very cautiously. due to various caveats discussed below, it is in the range of sea level rise for other areas around Antarctica. Galassi and Spada (2017) conducted a study of many tidal gauges around Antarctica and quoted final figure of +4.0 mm of sea level rise for both the West Antarctic Shelf and the Antarctic Peninsula. More broadly the rate of sea level rise indicated for Casey is well within the range observed around other parts of the globe, with Gharineiat & Deng (2018) quoting 6.3 ± 1.4 mm/yr for the coastline of Northern Australia. A Global Mean Sea Level (GMSL) rate of change of 3.2 ± 0.4 mm/year for the period between1992 to 2016 has also been quoted by CSIRO (CSIRO, 2019).

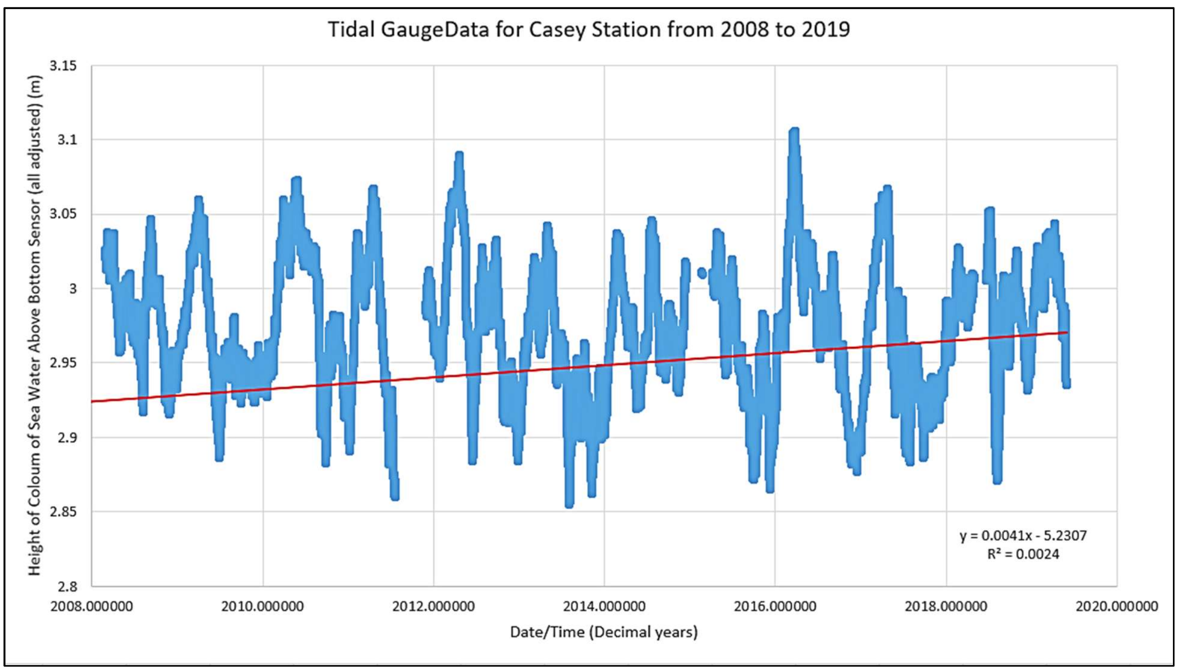

Figure 15
De-tided, filtered and GIA applied data for Casey Station tidal gauge with sea level change trend line

As previously mentioned the figure quoted GIA from the Sonel website (Sonel, 2019) of 1.58 ± 1.90 mm/yr has a large uncertainty of ± 1.90 mm associated with it. Also, the R^2 value for the trend line applied to the data in Figure 15 is very small (0.0024) indicating a poor fit for the resulting trend line.

A standard error for the quoted sea level rise figure of 4.2 mm for Casey Station was attempted to be calculated using the STEYX function in Excel and R^2 figure. However, the error calculated for the trend line was ± 270.26 mm, which is too large for the quoted sea level rise figure to be considered very meaningful. The error should be in the order of several millimetres. A larger data set and further filtering of the data, such as applying a 12 month moving average filter, might yield a trend line with a better resultant fit.

Also, ideally this calculated rate for sea level change should be compared against altimetry data, which the author had intended to do, if time allowed. Gharineiat & Deng's (2018) study showed that there was good correlation between the sea level change rates derived from altimetry and tidal gauges with the tidal gauges for Northern Australia indicating an overall rise of 6.3 ± 1.4 mm/yr and altimetry 6.1 ± 1.3 mm/yr.

Discussion of Wharf Levelling Results

Further research was done through AAD records to try and find more information on levelling surveying of the tidal gauge. Further reading found a few extra notes, which have been recorded in Table 6 below.

Survey Year	Recorded difference in height between HMB1 and TGRM (m)	Comment's
2006	5.444	Comments from surveyor's report is that the misclose of the level run was within L0 (Zero) order specifications (2√k) where k is in km.
2009	5.445	
2012	5.443 (1st run) 5.444 (2nd run)	Comments from surveyor's report mention changes in height from 2006 being 1 mm, as negligible.
2018	5.446	Comments from surveyor's logging sheets, were allowable misclose 12√k (km), equals 6 mm, and actual misclose was 0 mm.

Table 6
Calculated height differences between HMB1 and TGRM with comments

As can be observed from the comments in Table 6, level runs conducted were well within the allowable tolerances for misclose, and the surveyor from 2012 only noted 1mm of height difference between TGRM and HMB1 and the 2006 survey. Figure 16 shows the plot of difference in height between TGRM and HMB1 for various surveys. Assuming bench mark HMB1 is fixed and using the trend line equation, a rate of change of height of 1.2 mm between years 2006 and 2018 was calculated, indicating that the wharf is stable. Confirmation levelling surveys should be conducted perhaps every two years during the summer to ensure the wharf is stable and tidal gauge data is not contaminated. Level runs from the GNSS receiver should also be conducted every few years to maintain the connection between the two, and to also ensure that bench mark HMB1 remains stable. The last level run from the GNSS receiver to the tidal gauge was carried out over ten years ago now in 2009.

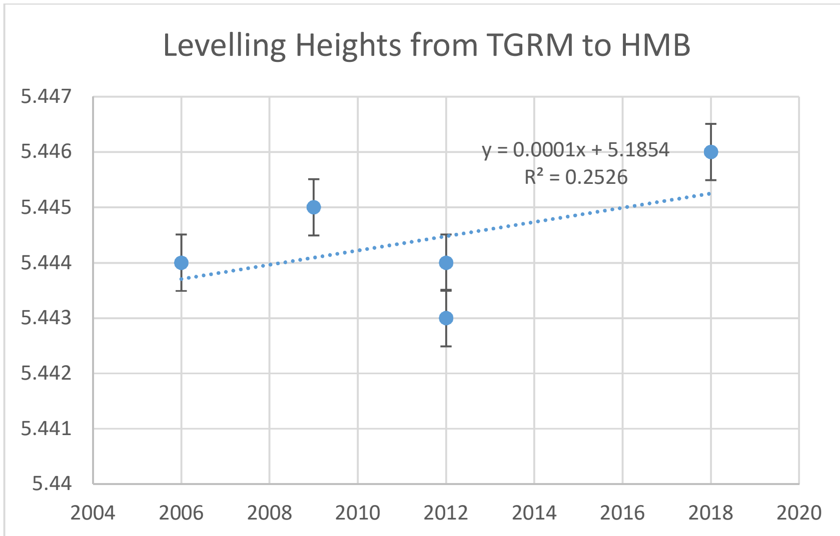

Figure 16
Calculated height differences between HMB1 and TGRM with comments

Effects of Sea Ice and Sea Water Density on Tidal Gauge Data

It is also worthy to mention in this section the difficulties of maintaining and collecting tidal gauge data in Antarctica. The tidal gauge requires constant heat, particularly over winter months in order for the sea water inside the tube to remain liquid as the sea ice freezes around the gauge. Should this heating fail due to a power outage or other reasons, and sea water freezes inside the tube, it is possible to damage components in the tidal gauge. Power outages on station do, and have occurred from time to time, hence the gaps in the tidal gauge data in this study.

The density of sea water also varies during the seasons in Antarctica. During the melt over summer as a great volume of fresh water runs into the ocean, the salinity is reduced and density varies. Also as the sea ice initially freezes, salt is rejected making the resultant sea water higher in salinity and density. With the newer tidal gauge at Casey station having two pressure gauges, this allows for variations in density to be calculated (refer to equation 2). For the data analysis in this study, sea water density varied between 1010 to 1030 kg/m^3.

$$\rho = \frac{PB - PT}{10gh} \qquad \text{[Eqn 2]}$$

The older type Platypus gauges do not allow for this calculation in density, and although the effect on the final calculated height of water is small, only using an estimation for density in the calculations is just another source of error.

Chapter 5 Conclusions

Conclusions

The Casey Station tidal gauge data had remained largely unused until this project, where all available files were downloaded, stitched together and height of column of sea water above the bottom gauge was calculated. It was also determined early on in the project that as the tidal gauge at Casey station had changed from a submerged Platypus gauge (that ran from about 1996 to 2006) to a newer wharf mounted gauge that the two data sets could not be used together as the Platypus gauge could not be surveyed for height/depth. Therefore, only a smaller data set of 11 years from the newer gauge could be used for this study.

The data was analysed for tidal constituents and these tidal responses removed, however due to the data set being less than 19 years, it could not be fully analysed for lunar cycles. The most common tidal constituents were identified (M_2, S_2, K1 and O1) and in total 37 were identified and removed from the data. The data was then 'smoothed' using a basic monthly moving average low pass filter, and GIA was applied. It is very evident at Casey Station that the land mass is moving vertically and enough to be able to effect tidal gauge readings and should be taken into account for any further tidal gauge studies.

Once the data had all the required various adjustments made, a trend line was calculated and a rate of sea level change was determined. The value calculated was 4.2 mm/yr of sea level rise, and although the regression analysis shows that the trend line may not be an ideal fit, the value derived is commensurate with what has previously been reported for recent sea level rise in Antarctica and around Australia. It was also identified that with further filtering of the data, more 'noise' many be removed from the data and a better fitting trend line achieved. It may then also be possible to identify bi-annual and inter-annual climatic/ocean events, such as the Semi-Annual Oscillation and the Antarctic Circumpolar Wave. Ideally, this derived sea level rate of change and any future ones calculated from this data should be compared against altimetry data to confirm any findings. This was one of the original aims of the project, but due to time delays was not completed.

As the research around this project developed, it has also become very evident the need for maintaining good, long, consistent and accurate tidal gauge readings in order to be able to support climate change research. Data records in excess of two decades are required to be able to filter out all tidal effects and analyse trends. It has also been documented in various references that local sea level changes may be effected by local climatic changes and thus the need for projects such as the TIDE project (Totten Glacier Ice Dynamics and Evolution) to have access to good sea level records is essential.

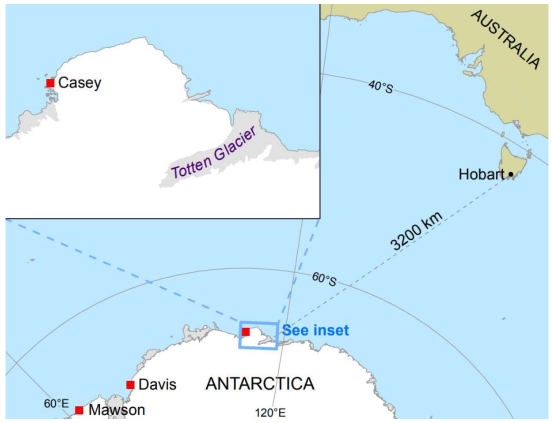

Figure 16
Location of Totten Glacier in relation to Casey Station (Australian Antarctic Data Centre, 2015)

It was also evident to the author of this report that using Excel with the laptop computer available on station that they are not adequate to manage 500,000 plus rows of data. Calculations in Excel became laborious and graphing difficult. For any future works alternative software and hardware needs to be identified and used.

Future Work

Whilst working on this project many areas have been identified where future works are required. For the Casey Station tidal gauge data already worked on, further filtering and regression analysis of the data needs to be performed in order to achieve a sea level rate of change with an acceptable level of uncertainty. This data should then be compared to altimetry data from the over the same time period of 2008 to 2019.

For the actual tidal gauge at Casey station a GPS buoy should be used to calibrate the readings from the gauge, and it is believed that this will occur in the next summer season. A level run from the GNSS station to TGRM should occur, and then ongoing regular, at least every two years, levelling from local bench mark HMB1 and GNSS station.

Tidal gauge data from Mawson, Davis and Macquarie Island should also be downloaded and processed. For the newer wharf mounted gauge at Macquarie Island a similar methodology to the one described in this report can be followed. For the older submerged Platypus gauges at Davis and Mawson, estimations of sea water density will need to be used, and hourly mean sea level atmospheric pressure records will need to be matched to the tidal gauge data. Although this is more time consuming and potentially may introduce small errors, tidal gauge records for Davis and Mawson have all been operating since approximately 1996, and therefore provide the multi-decadal data required to create robust sea level histories.

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Appendix A – Project Specification V2

ENG4111/4112 Research Project

Project Specification

For: Amy Hobbs

Title: Measuring changes in sea level around Antarctica

Major: Surveying

Supervisors: Dr. Zahra Gharineiat, USQ
Dr. Ben Galton-Fenzi, Australian Antarctic Division
Aaron Read, Australian Antarctic Division

Enrolment: ENG4111 – EXT S1, 2019
ENG4112 – EXT S2, 2019

Intellectual Property: All data and processes developed will remain IP of Australian Antarctic Division.

Project Aim: To provide a sea level record for the coast line at Casey Station that is useable and verifiable such that it can be used for significant Australian Antarctic Division research projects. Develop data processing process can then be extended to the tidal gauge data collected at Mawson and Davis stations.

Programme: Version 1, 20th April 2019

1. Research background information relating to tidal gauge measurements, altimetry, identifying bedrock uplift in tidal gauge data (short-term viscoelastic deformation) and previous work done in these fields in Antarctica by Australian and/or other countries. This research will form the basis of the literature review.
2. Research via AAD Data Centre all previous surveying reports of tidal gauge and request altimetry data.
3. Clean up tidal gauge data, such as correcting time stamp errors, and shift all data onto the same datum. Write MATLAB script as required to do this.
4. Stitch all corrected data together to form a sea level history for Casey Station and using spatial data from Casey's GNSS station from the Geo Science Australia's National

Geospatial Reference System, identify bedrock uplift and apply to tidal gauge data. Write MATLAB script as required to do this.

5. Using the tidal gauge sea level history data, compare this to altimetry data in order to understand the variations and potential deficiencies of costal altimetry data for measuring sea levels. In order to compare data all data will be shifted to the same datum.
6. Write up a process for the above steps, such that it can be applied to tidal gauge data from Davis and Mawson research stations (Australia's other two research stations situated in Antarctica).
7. If time permits, study sea level history data for changes and compare to findings from other studies in the Antarctic region.
8. Write up formal dissertation.

Resource Plan

Tidal Gauge Data: Tidal gauge data files for Casey Station have been provide by the Future Climate and Sea Level Change department at the Australian Antarctic Division. Raw data files have been provided in Excel format.

Survey Reports for Tidal Gauge: Various old surveying reports have been provided Future Climate and Sea Level Change department AAD. The most recent survey of the tidal gauge was conducted over summer 2018/2019 at Casey Station by Naval Hydrographers. The report for this survey works has yet to have been provided to the AAD Data Centre. This report will be made available as soon as it is delivered.

Data Processing Software: Excel and a student version of MATLAB software will be used to process the data. MATLAB software can be purchased and downloaded via the internet.

Altimetry Data: Altimetry data will be downloaded from https://www.aviso.altimetry.fr and some may be available via the AAD data centre.

Peer Reviewed Papers: Peer reviewed papers will be downloaded from online database available via the USQ Library website

Appendix B – Geodetic Connections to Casey Tidal Gauges

Australian Government

Geoscience Australia

Geodetic Connections to Tide Gauge at Casey

	MSL HEIGHT (m) [1]						
BENCH MARK NAME	**1990/91 [2]**	**1993 [3]**	**1998/99 [4]**	**Oct 2001 [5]**	**Mar 2006[5]**	**Feb 2009[5]**	**COMMENTS**
AUS100		40.882		40.8798	-	40.8824	ARGN permanent GPS mark
AUS100 RM1		40.111		40.1098	40.1076	40.1115	ARGN permanent GPS mark, RM1
AUS100 RM2		39.783		39.7814	-	39.7837	ARGN permanent GPS mark, RM2
AUS100 RM3		41.561		41.5572	--	41.5604	ARGN permanent GPS mark, RM3
BM5		38.545		38.5491	38.5489	38.5497	
AUS396				26.8843	-	26.8830	
AUS394				29.3789	-	-	
AUS395				19.3345	19.3335	19.3327	
ISTS B052	20.469	20.464			-	20.4683	Casey Pageos mark
WHF1 [7]			2.269	2.2704	-	-	
HBM4			2.418	2.4247	2.4240	2.4242	
HBM1	7.171		7.171	7.1710	7.1710	7.1710	
HBM2	5.518			5.5172	5.5172	5.5171	
HBM3 [6]	1.968	1.968	1.968	1.9734	-	-	
AUS299 TGBM				2.0526	-	-	Tide gauge benchmark
TG RM					1.7261	1.7260	RM for Tide Gauge on Casey wharf
AUS2027					1.4615	-	Secondary TGBM
AUS2028					1.9401	-	Primary TGBM, replace AUS299
AUS2009						1.7500	Replaced AUS2027
AUS2010						2.2117	Replaced AUS2028

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A number of survey marks in the Casey area are used to connect the tide gauge bench mark to the permanent Casey GPS tracker (AUS100), using both GPS and conventional optical levelling techniques. Connections from the tide gauge benchmark to the tide gauge are held by Antarctic Division.

Notes:
[1] The MSL heights are based on a MSL height for HBM1 as shown on the RAN Hydrographic Service Bench Mark Report (5 February 1991).

[2] Class LC* optical levelling, using Aluminium staves, by Lt Slade (RAN). All values corrected for thermal expansion/contraction of the staves (King 2000).

[3] Class LC* optical levelling, using Aluminium staves and Sokkisha B2 Level, by John Hyslop (AUSLIG) (see fieldbook W0010).

[4] Class LC* optical levelling, using Aluminium staves, by King & Manson (Antarctic Division). All values corrected for thermal expansion/contraction of the staves (King 2000).

[5] Class L2A* levelling, using the "Leap-Frog" EDM Height Traversing., by Gary Johnston (Geoscience Australia) using a Leica TC2003 Total Station - see Technical Report 5.

[6] In October 2001, HBM3 was found leaning, and the height cannot be reliably compared to previous results.

[7] Although the mark connected to in October 2001 is probably WHF1, it was not positively identified.

[8] In October 2001, GPS observations were made between AUS100 and AUS299. The resulting difference in height, corrected for geoid ellipsoid separation, was 38.8251 metres, compared to 38.8272 from the Total Station levelling - a difference of only 2 mm from the two independent techniques. See Technical Report 8 for more details.

[9] During the 1995/96 Antarctic Summer, a Platypus Engineering bottom-mounted tide gauge was installed in the previously placed tide gauge mooring

- See ICSM Special Publication 1, "Standard Practice for Control Surveys" for an explanation of optical levelling standards.

- King, M (2000), "Report on Temperature Corrections for Levelling Observations made at Australia's Antarctic Bases", An internal report prepared for the Australian Antarctic Division. Prepared June 2000, Revised November 2000.

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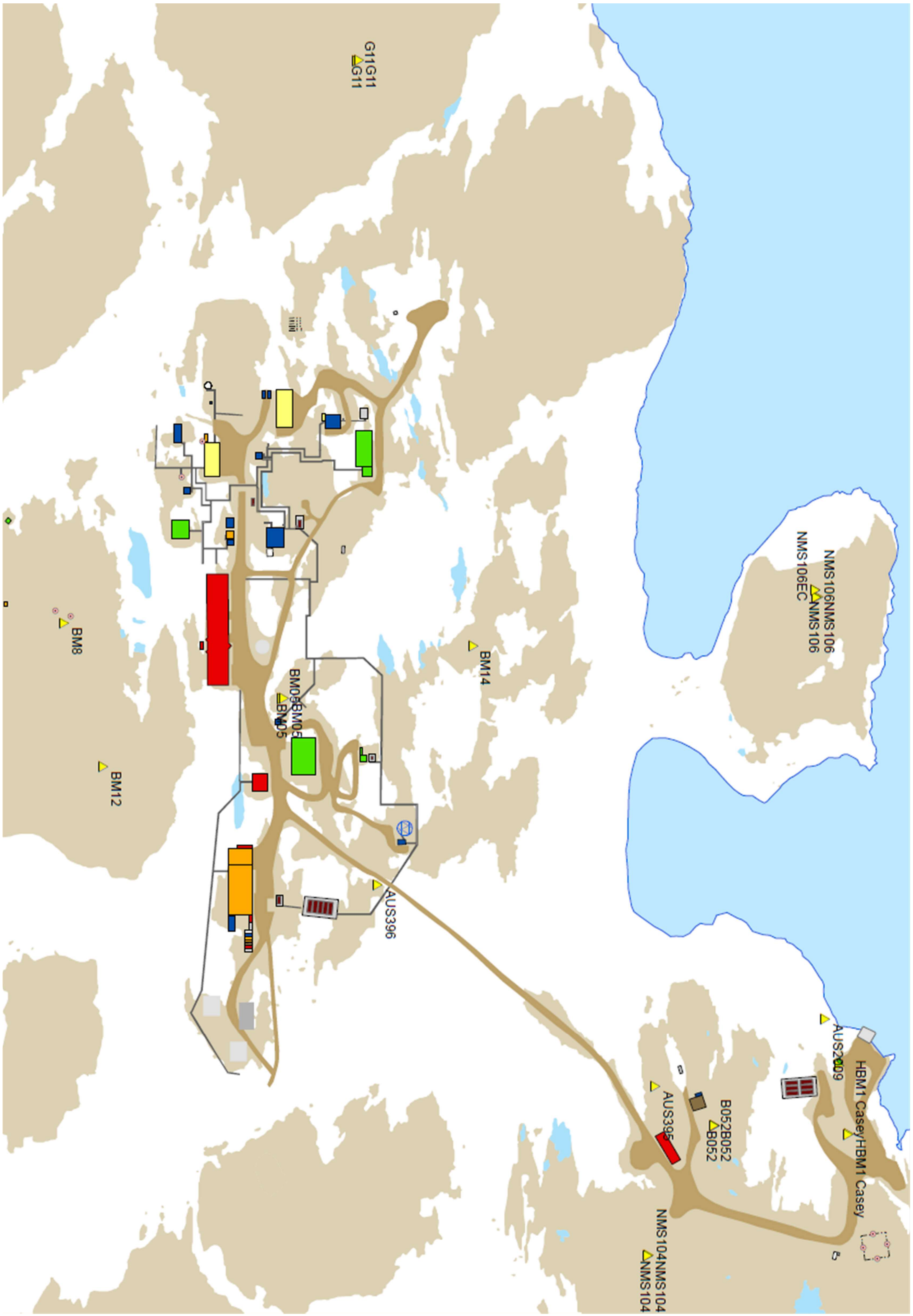
Appendix C – Casey Station Bench Marks


G1G11
G11
BM8
BM12
BM05BM05
BM05
BM14
AUS396
NMS106NMS106
NMS106
NMS106EC
AUS2009
HBM1 Casey/HBM1 Casey
B052B052
B052
AUS395
NMS104NMS104
NMS104

Appendix D – Tidal Fitting Code for MATLAB

```
function tidal=tidalfit(data,varargin)
%% TIDALFIT: Fits a tidal model to data
%
% tidalfit uses the HAMELS (ordinary least squares)
% technique to fit tidal components to the detrended data. Additionally it
% can also do robust fitting.
%
% Please include an acknowledgement to Aslak Grinsted if you use this code.
%
% USAGE: tidal=tidalfit(data[,parameter,value])
%
% INPUT:
% ------
% data:  A two column vector.
% \       - first column should be a serial date number (See help datenum)
% \       - second column should be the y-values (i.e. sea level)
% \       (missing values and nans are OK.)
%
% OPTIONAL PARAMETERS:
% --------------------
% Components: cell-array of strings with names of the which
% \           components should be included in the fit? (ALL is default)
% \           Note: The routine will only attempt to fit components
% \           that have period<data_timespan/4 and period>dt*2.
% FittingMethod: 'OLS' for ordinary least squares or 'ROBUST' for robustfitting.
% \           (default=OLS)
% RobustFitOptions: cell of options for robustfit. (See help robustfit.)
% \           only used if FittingMethod='ROBUST'. (default={})
% DetrendData: should the data be detrended prior to fitting? (default=true)
%
% Note: optional parameters can be specified using abbreviations. e.g. RFO for
RobustFitOptions.
%
% OUTPUT:
% -------
% If no output arguments are specified the routine will display the results
% visually.
%
% tidal: A struct-array containing the fitted model parameters.
% \     .name:  name of tidal component (see e.g.
http://www.mhl.nsw.gov.au/www/tide_glossary.htmlx)
% \     .period:period of tidal component in days
% \     .speed: frequency of tidal component in degrees per solar hour
% \     .amp:   amplitude of fitted component
% \     .phase: phase of fitted component
%
% Components that are not included in the fit will have NaN in .amp and .phase.
%
%
%
% EXAMPLE:
%  data=datenum(1971,1,1):datenum(2008,1,1);
%  data=[data;randn(size(data))]';
%  tidal=tidalfit(data,'fm','robust');
%  future=[datenum(2008,1,1):datenum(2009,1,1)'];
%  plot(future,tidalval(tidal,future));
%
%
```

```
%%  Copyright (C) 2008, Aslak Grinsted
%   This software may be used, copied, or redistributed as long as it is not
%   sold and this copyright notice is reproduced on each copy made.  This
%   routine is provided as is without any express or implied warranties
%   whatsoever.
if nargin<1
    error('no input data specified!')
end
if size(data,2)~=2
    warning('TIDALFIT:DATASHAPE','tidalfit needs a two column data matrix.')
end
Args=struct('Components',[],'FittingMethod','OLS','RobustFitOptions',[],'DetrendData',
true,'NumericArguments',[]);
Args=parseArgs(varargin,Args);
if (Args.DetrendData)
    p=polyfit(data(~isnan(data(:,2)),1),data(~isnan(data(:,2)),2),1);
    data(:,2)=data(:,2)-polyval(p,data(:,1));
else
    data(:,2)=data(:,2)-nanmean(data(:,2)); %center
end
tminmax=[min(data(:,1)) max(data(:,1))];
dt=min(diff(sortrows(data(:,1)))); %SLOW but robust. dt needed for nyquist
if dt==0
    error('dt==0!')
end
isOLS=false;
switch upper(Args.FittingMethod)
    case {'OLS','ORDINARY LEAST SQUARES'}
        isOLS=true;
    case {'ROBUST','ROBUSTFIT'}
        if isempty(Args.RobustFitOptions)
            Args.RobustFitOptions={};
        end
    otherwise
        error('Unknown FittingMethod specified')
end
T=15;
s=0.54901653;
h=0.04106864;
p=0.00464183;
p1=0.00000196;
%good high precision table:
%http://www.mhl.nsw.gov.au/www/tide_glossary.htmlx
%key west:
%http://tidesandcurrents.noaa.gov/cgi-bin/co-ops_qry.cgi?stn=8724580 Key West,
FL&dcp=1&ssid=WL&pc=P2&datum=NULL&unit=0&bdate=20080306&edate=20080307&date=1&shift=0&
level=-4&form=0&data_type=har&format=View+Data
%initialize struct to avoid dynamic re-allocation.
tidal=struct('name','.','speed',num2cell(nan(38,1)),'period',nan,'amp',nan,'phase',nan
);
ix= 1; tidal(ix).name='M2';       tidal(ix).speed     =     2*T - 2*s + 2*h ;
ix= 2; tidal(ix).name='S2';       tidal(ix).speed     =     2*T;
ix= 3; tidal(ix).name='N2';       tidal(ix).speed     =     2*T - 3*s + 2*h + p;
ix= 4; tidal(ix).name='K1';       tidal(ix).speed     =     15.0410686;
ix= 5; tidal(ix).name='M4';       tidal(ix).speed     =     4*(T - s + h) ;
ix= 6; tidal(ix).name='O1';       tidal(ix).speed     =     T - 2*s + h;
ix= 7; tidal(ix).name='M6';       tidal(ix).speed     =     6*(T - s + h);
ix= 8; tidal(ix).name='MK3';      tidal(ix).speed     =     44.0251729;
ix= 9; tidal(ix).name='S4';       tidal(ix).speed     =     4*T;
ix=10; tidal(ix).name='MN4';      tidal(ix).speed     =     57.4238337;
ix=11; tidal(ix).name='NU2';      tidal(ix).speed     =     28.5125831;
ix=12; tidal(ix).name='S6';       tidal(ix).speed     =     6*T;
```

```
ix=13; tidal(ix).name='MU2';      tidal(ix).speed     =     27.9682084;
ix=14; tidal(ix).name='2N2';      tidal(ix).speed     =     2*T - 4*s + 2*h + 2*p;
ix=15; tidal(ix).name='OO1';      tidal(ix).speed     =     T + 2*s + h;
ix=16; tidal(ix).name='LAM2';     tidal(ix).speed     =     29.4556253;
ix=17; tidal(ix).name='S1';       tidal(ix).speed     =     T;
ix=18; tidal(ix).name='M1';       tidal(ix).speed     =     T - s + h + p ;
ix=19; tidal(ix).name='J1';       tidal(ix).speed     =     15.5854433;
ix=20; tidal(ix).name='MM';       tidal(ix).speed     =     s-p;
ix=21; tidal(ix).name='SSA';      tidal(ix).speed     =     2*h;
ix=22; tidal(ix).name='SA';       tidal(ix).speed     =     h;
ix=23; tidal(ix).name='MSF';      tidal(ix).speed     =     2*s-2*h;
ix=24; tidal(ix).name='MF';       tidal(ix).speed     =     2*s;
ix=25; tidal(ix).name='RHO';      tidal(ix).speed     =     T - 3*s + 3*h - p;
ix=26; tidal(ix).name='Q1';       tidal(ix).speed     =     T - 3*s + h + p;
ix=27; tidal(ix).name='T2';       tidal(ix).speed     =     2*T - h + p1 ;
ix=28; tidal(ix).name='R2';       tidal(ix).speed     =     2*T + h - p1;
ix=29; tidal(ix).name='2Q1';      tidal(ix).speed     =     T - 4*s + h + 2*p ;
ix=30; tidal(ix).name='P1';       tidal(ix).speed     =     T-h;
ix=31; tidal(ix).name='2SM2';     tidal(ix).speed     =     31.0158958;
ix=32; tidal(ix).name='M3';       tidal(ix).speed     =     3*T - 3*s + 3*h ;
ix=33; tidal(ix).name='L2';       tidal(ix).speed     =     29.5284789;
ix=34; tidal(ix).name='2MK3';     tidal(ix).speed     =     42.9271398;
ix=35; tidal(ix).name='K2';       tidal(ix).speed     =     30.0821373;
ix=36; tidal(ix).name='M8';       tidal(ix).speed     =     8*(T - s + h);
ix=37; tidal(ix).name='MS4';      tidal(ix).speed     =     58.9841042;
%-------------------------------
ix=38; tidal(ix).name='N';        tidal(ix).speed     =     0.00220641;
% for sn=3:8 %y1&y2 are the same as sa & ssa
%     ix=39-3+sn;
%     tidal(ix).name=['S' num2str(sn) 'A']; tidal(ix).speed=360*sn/(365.24237*24);
% end
%DO NOT ADD ANY MORE COMPONENTS AFTER HERE:
%-----------------------------------------
for ii=1:length(tidal)
    tidal(ii).period=(360/tidal(ii).speed)/24;
end
if isempty(Args.Components)
    keep=(1:length(tidal))';
else
    components={tidal.name};
    keep=nan(length(Args.Components),1);
    for ii=1:length(Args.Components)
        ix=strmatch(upper(Args.Components{ii}),components,'exact');
        if isempty(ix)
            error(['Unknown component: ' upper(Args.Components{ii})]);
        end
        keep(ii)=strmatch(upper(Args.Components{ii}),components,'exact');
    end
    keep=unique(keep);
end
%Check nyquist and long period:
ix=([tidal(keep).period]'>=2*dt)&([tidal(keep).period]'<=diff(tminmax)/3);
keep=keep(ix);
%---------------------------------
data(any(isnan(data),2),:)=[];
N=size(data,1);
Np=length(keep);
if Np==0
    error('No predictors kept. Too little data?')
end
predictors=ones(N,Np*2+isOLS);
for ii=1:Np
```

```
    period=tidal(keep(ii)).period;
    predictors(:,ii)=cos(data(:,1)*2*pi/period);
    predictors(:,ii+Np)=sin(data(:,1)*2*pi/period);
end
if isOLS
    if length(data)>5000
        reg=lsqr(predictors,data(:,2));
    else
        reg=predictors\data(:,2);
    end
else
    reg=robustfit(predictors,data(:,2),Args.RobustFitOptions{:});
    reg=reg([2:end 1]);
end
for ii=1:Np
    q=reg([ii ii+Np]);
    if all(isnan(q))
        tidal(keep(ii)).amp=nan;
        tidal(keep(ii)).phase=nan;
    else
        tidal(keep(ii)).amp=sqrt(nansum(q.^2));
        q(isnan(q))=0;
        tidal(keep(ii)).phase=atan2(q(2),q(1));
    end
end
% Visualize the output if the user doesn't want it as an output.
if nargout==0
    %yp=predictors*reg;
    yp=tidalval(tidal,data(:,1));
    plot(data(:,1),data(:,2),data(:,1),data(:,2)-yp,data(:,1),yp);
    legend('data','residuals','model','location','best')

    fprintf('\n\n')
    v=[tidal.amp;tidal.phase;tidal.speed;tidal.period]';
    v=v(keep,:);
    v(:,2)=mod(v(:,2)*180/pi,360);

    dispmtx(v,'%7.3f',{'amp' 'phase' 'speed' 'period'},{tidal(keep).name})

    xlabel('serial date')
    fprintf('\ntidalmodel accounts for %.1f%% of the
variance.\n',var(yp)*100/var(data(:,2)))
    clear tidal
end
```

Appendix E – Sample of Raw Data and Height of Water Column Calculations

TOA5	Casey_Pre	CR1000	6771	CR1000.Std.1	CPU:Casey_1.	935	AvgTable							
TIMESTAMP	RECORD	Press10m(1)	Press10m(2)	Press10m(3)	Temp10m(1)	Temp10m(2)	Temp10m(3)	b3min	Top Pressure	Bottom	Density	Temp C	Bottom Pr	height
TS	RN								corrected	corrected	average	average	-baro	above TGZbot
		Press10m(1)	Press10m(2)	Press10m(3)	Temp10m(1)	Temp10m(2)	Temp10m(3)	b3min	sub 12.34	sub 12.00				metre
13/02/2008 22:40	0	1055.936	1258.264	980.7466	2.038792	0.6575478	32.15376	13.76	1043.596	1246.264	1.027922	0.690622	277.5174	2.753
13/02/2008 22:50	1	1053.489	1255.817	980.8354	2.047443	0.6518779	32.13208	13.76	1041.149	1243.817	1.027922	0.697783	274.9816	2.728
13/02/2008 23:00	2	1053.493	1255.799	980.9586	2.059059	0.6364757	32.0162	13.75	1041.153	1243.799	1.02781	0.711292	274.8404	2.727
13/02/2008 23:10	3	1051.059	1253.373	981.0698	2.077515	0.6110459	31.79327	13.76	1038.719	1241.373	1.027851	0.733235	272.3032	2.702
13/02/2008 23:20	4	1051.062	1253.363	981.0808	2.099854	0.5784406	31.52859	13.76	1038.722	1241.363	1.027785	0.760707	272.2822	2.702
13/02/2008 23:30	5	1048.163	1250.466	981.1172	2.126489	0.5428185	31.28043	13.76	1035.823	1238.466	1.027795	0.791835	269.3488	2.672
13/02/2008 23:40	6	1046.385	1248.674	981.1738	2.155631	0.508799	31.02267	13.76	1034.045	1236.674	1.027724	0.823416	267.5002	2.654
13/02/2008 23:50	7	1043.807	1246.107	981.1418	2.185924	0.477398	30.76157	13.75	1031.467	1234.107	1.02778	0.854263	264.9652	2.629
14/02/2008 0:00	8	1042.297	1244.589	981.1511	2.21652	0.4494945	30.53992	13.76	1029.957	1232.589	1.027739	0.883513	263.4379	2.614
14/02/2008 0:10	9	1040.635	1242.925	981.1572	2.248567	0.4245542	30.33039	13.75	1028.295	1230.925	1.027729	0.912006	261.7678	2.597
14/02/2008 0:20	10	1038.92	1241.205	981.1497	2.279934	0.4023377	30.10733	13.75	1026.58	1229.205	1.027703	0.938798	260.0553	2.580
14/02/2008 0:30	11	1035.842	1238.125	981.2123	2.31015	0.3821679	29.90512	13.75	1023.502	1226.125	1.027693	0.963991	256.9127	2.549
14/02/2008 0:40	12	1033.703	1235.991	981.1809	2.340266	0.3640325	29.74154	13.75	1021.363	1223.991	1.027719	0.988117	254.8101	2.528
14/02/2008 0:50	13	1031.439	1233.724	981.1702	2.369408	0.3481632	29.57162	13.75	1019.099	1221.724	1.027703	1.010622	252.5538	2.506
14/02/2008 1:00	14	1029.029	1231.31	981.2051	2.397402	0.3354669	29.39337	13.75	1016.689	1219.31	1.027683	1.030968	250.1049	2.482
14/02/2008 1:10	15	1027.217	1229.502	981.1927	2.423342	0.3252559	29.22994	13.75	1014.877	1217.502	1.027703	1.049043	248.3093	2.464
14/02/2008 1:20	16	1023.54	1225.821	981.1924	2.448369	0.3166355	29.1091	13.75	1011.2	1213.821	1.027683	1.065867	244.6286	2.427
14/02/2008 1:30	17	1021.684	1223.979	981.2039	2.474578	0.3100621	28.9837	13.75	1009.344	1211.979	1.027754	1.082258	242.7751	2.409
14/02/2008 1:40	18	1021.339	1223.634	981.2122	2.500133	0.3057472	28.83908	13.75	1008.999	1211.634	1.027754	1.097193	242.4218	2.405
14/02/2008 1:50	19	1020.049	1222.349	981.2053	2.523868	0.3025815	28.67691	13.75	1007.709	1210.349	1.02778	1.110643	241.1437	2.393
14/02/2008 2:00	20	1019.247	1221.531	981.2189	2.544845	0.3000961	28.42957	13.75	1006.907	1209.531	1.027698	1.122374	240.3121	2.385
14/02/2008 2:10	21	1019.893	1222.187	981.3259	2.566497	0.2994096	28.18411	13.75	1007.553	1210.187	1.027749	1.133544	240.8611	2.390
14/02/2008 2:20	22	1020.988	1223.28	981.3358	2.58838	0.2980458	27.93344	13.76	1008.648	1211.28	1.027739	1.145167	241.9442	2.401
14/02/2008 2:30	23	1020.831	1223.119	981.356	2.609341	0.2960108	27.48735	13.75	1008.491	1211.119	1.027719	1.156665	241.763	2.399
14/02/2008 2:40	24	1022.536	1224.826	981.3945	2.62857	0.2934978	26.90454	13.75	1010.196	1212.826	1.027729	1.167536	243.4315	2.415
14/02/2008 2:50	25	1022.296	1224.589	981.4109	2.643806	0.2891921	26.40033	13.75	1009.956	1212.589	1.027744	1.177307	243.1781	2.413
14/02/2008 3:00	26	1024.422	1226.715	981.4615	2.658819	0.2835228	26.08846	13.76	1012.082	1214.715	1.027744	1.187648	245.2535	2.433
14/02/2008 3:10	27	1025.601	1227.885	981.4182	2.672922	0.2744458	25.94168	13.76	1013.261	1215.885	1.027698	1.199238	246.4668	2.446
14/02/2008 3:20	28	1028.025	1230.322	981.3945	2.686121	0.2626507	25.92339	13.76	1015.685	1218.322	1.027764	1.211735	248.9275	2.470
14/02/2008 3:30	29	1029.297	1231.583	981.3539	2.697043	0.2488177	26.01802	13.76	1016.957	1219.583	1.027709	1.224113	250.2291	2.483
14/02/2008 3:40	30	1031.245	1233.544	981.3773	2.704103	0.2327043	26.21935	13.76	1018.905	1221.544	1.027774	1.235699	252.1667	2.502
14/02/2008 3:50	31	1033.083	1235.368	981.4153	2.711399	0.2160066	26.53161	13.76	1020.743	1223.368	1.027703	1.247696	253.9527	2.520
14/02/2008 4:00	32	1036.226	1238.529	981.3773	2.718224	0.1992224	26.87336	13.76	1023.886	1226.529	1.027795	1.259501	257.1517	2.551