The South African Tide Gauge Network and its Contribution to Maritime Safety.

by

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SUBMITTED TO THE UNIVERSITY OF CAPE TOWN
In fulfilment of the requirements for the degree

MSc by dissertation, Physical Oceanography

Faculty of Science

UNIVERSITY OF CAPE TOWN

Date of submission: 14 December 2020

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DECLARATION

I, *Ruth Elizabeth Farre*, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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ABSTRACT.

The use of tidal information and its application to, and value within, the study of climate change, sea-level rise and the tides effects on marine life is well known. However, little work has been done on the more technical aspects of tidal measurements and the use within maritime safety in accordance with international standards.

This thesis will address the key technical elements in the design and realisation of the national tide gauge network around the South African coastline and how the data collected can be used to increase maritime safety around the South African coast, as well as the additional benefits the data may have both nationally and internationally.

The South African Navy's national tide database, both actual records and predictions, as well as current and historical records, was used in order to establish the requirements for a sustainable tide gauge network. In addition, various case studies and data analysis were carried out, as were personal communications with various naval personnel. Establishing and maintaining a sustainable tide gauge network requires research and testing of various tide gauges. Identification of the correct locations to install the tide gauges is key to its success. Although the current South African Tide gauge network is not complete it does provide adequate coverage and is vitally important in the production of navigational products. The manner in which the raw collected tide data is processed and used for creating predictions meets international requirements and standards. Tidal predictions are a necessity for shallow water maritime operations and shallow water navigation, under keel and masthead clearances. The tide gauge network provides data to various organisations for storm surge and tsunami warnings while contributing to the "blue economy" through projects like Operation Phakisa.

This thesis provides a comprehensive overview of South Africa's tide gauge network, investigates and justifies the reasons behind the locations and gives in depth examples of the essential use of tidal information for maritime safety.

ACKNOWLEDGEMENTS.

This thesis was made possible through my work over the last 17 years as the Superintendent of Tidal Information at the South African Navy Hydrographic Office. It was additionally made possible with the support, co-operation, involvement, guidance, direction and encouragement of so many people. Therefore, I wish to express my gratitude and appreciation to them for contributing towards my thesis. I would like to specifically extend my deepest appreciation to the following people:

To my advisors Associate Professor Juliet Hermes, Emeritus Professor Geoff Brundrit and Professor Isabelle Ansorge for their unending guidance and assistance with my dissertation. I would like to specifically thank Emeritus Professor Geoff Brundrit for his mentorship, always having believed in me and his unwavering support throughout my career, also for coming out of retirement to be one of my supervisors.

Captain Theo Stokes, South African National Hydrographer, for supporting my application to study, his constant support and belief in my abilities to achieve whatever challenge is placed before me.

Captain (SAN) (Ret) Peter Louwrens, Navigational training instructor at the Maritime Warfare Training School (MWTS) for assisting me the Shallow water navigation information. Former Submarine Captain (SAN) Malcolm Farre for his assistance with the section on Submarine and Mine Counter Measures information.

And to Steven for your support, encouragement and constantly reminding me how to eat an elephant.

TABLE OF CONTENTS.

List of Figures.

List of Tables.

List of Equations.

List of Appendices.

Acronyms.

AWLR	Acoustic Water Level recorders
CD	Chart Datum
CGS	Council for Geoscience
COFUR	Cost of Fulfilling User Request
Coms	Communications
CP	Contact Point
CSIR	Council for Scientific Industrial Research
DEA	Department of Environmental Affairs
DOD	Department of Defence
DOT	Department of Transport
DPME	Department of Planning Monitoring and Evaluation
DU	Durban
ECDIS	Electronic Chart Display and Information System

EEZ	Exclusive Economic Zone
EL	East London
ELINT	Electronic Intelligence Surveillance Mission
ENC	electronic navigational charts
ETT	Equilibrium Tide Theory
FD	Fast Data
FMU	South African Naval Fleet Maintenance Unit
GB	Cape Town
GFZ	German Research Centre for Geoscience
GLOSS	Global Sea Level Observing System
GMDSS	Global Maritime Distress and Safety System
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System
GTS	Global Telecommunications System
GUI	Graphic User Interface
H	Height
HartRAO	Hartebeeshoek Radio and Astronomical Observatory
HAT	Highest Astronomical Tide
HI	Hydrographic Instruction
HM	Hermanus
HO	Hydrographic Office
HSV	Hydrographic Survey Vessel
HT	High Tide
ICASA	Independent Communications Authority of South Africa
IHAHINA	Mozambique Hydrographic Office
IHO	International Hydrographic Organisation
IMO	International Maritime Organisation
INT	International
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IOTWMC	Indian Ocean Tsunami Warning Monitoring Service
IPOS	Integrated Port Management/Operations System
JASL	Joint Archives for Sea Levels
JMA	Japanese Meteorological Agency
KN	Knysna
L	Length
LAT	Lowest Astronomical Tide
LB	Lamberts Bay

LLD	Land Levelling Datum (Ordinance Datum)
LT	Low Tide
LU	Lüderitz
MB	Mossel Bay
MBES	Multi-Beam Echo Sounder
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MSI	Maritime Safety Information
MSL	Mean Sea Level
NAMPORT	Namibian Ports Authority
NAVAREA	Navigational Area
NDMC	National Disaster Management Centre
NES	South African Naval Engineering Services
NGI	Department of National Geospatial Information
NOAA	United States of America's National Oceanic and Atmospheric Administration
NPU	South African Naval Publications Unit
NRC	National Research Council
NSRI	National Sea Rescue Institute
NTM	Notices to Mariners
OC	Officer Commanding
OCIMS	National Ocean and Coastal Information System
Ops Phakisa	Operation Phakisa
PCU12	Power Conversion Units (for tide gauges)
PE	Port Elizabeth
PETROSA	Petroleum Agency of South Africa
PHOTOKEN	Photo Reconnaissance Mission
PN	Port Nolloth
PRO	South African Navy Hydrographic Vessel SAS PROTEA
PSMSL	Permanent Service for Mean Sea Level
RB	Richards Bay
RD	Research Quality
Ret	Retired
RLS	Radar Level Sensor
ROPME	Regional Organization for the Protection of the Marine Environment

RSAHC	ROPME Sea Area Hydrographic Commission
SA	Saldanha
SADC	Southern African Development Community
SAIHC	IHO's Southern Africa and Islands Hydrographic Commission
SAL	Naval Unit SAS SALDANHA Training Unit (Saldanha Bay)
SAMSA	South African Maritime Safety Association
SAN	South African Navy
SANHO	South African Navy Hydrographic Office
SAPS	South African Police Services
SASDI	South African Spatial Data Infrastructure
SAWS	South African Weather Service
SB	Simon's Town
SBES	Single-Beam Echo Sounder
SITA	State Information Technology Agency
SOLAS	Safety of Life at Sea convention
SOSM	Senior Officer Submarines
STI	Superintendent Tidal Information
TG	Tide Gauge
TIGA	Tide Gauge Benchmark Monitoring Project
TNPA	Transnet National Ports Authority
TR	Technical Resolutions
TT	Tide Tables
TTA	Technical Tidal Assistant
TWCWG	IHO's Tides, Water level and Current Working Group
UK	United Kingdom
UKHO	United Kingdom Hydrographic Office
USA	United States of America
VARs	Value Added Retailers
VIMSA	Voluntary IMO Audit
VOIP	Voice Over Internet Protocol
Vol	Volume
W	Width
WB	Walvis Bay
Z_0	sensor offset/ tide gauge zero

The South African Tide Gauge Network and its Contribution to Maritime Safety

Chapter 1 – Introduction.

Throughout history tides have been perceived in many ways ranging from just the sea advancing and retreating to notions about the tides being breathing cycles of whales or other cultural beliefs. In some locations around the world the tide is negligible, often referred to as non-tidal, with a maximum range of less than 30 cm (IHO, 2010:61), thus something some of the ancient mariners never had any knowledge of. Simon (2013) states that the most comprehensive historical review has been written by David E. Cartwright in 1999. Cartwright (1999) outlines how the first recorded mention of tidal motion was by Aristotle in the 4th century BC with the very first tide tables having been compiled in the 13th century by an English monk. Cartwright (1999) further goes on to explain how it was not until the late 17th century that Sir Issac Newton's Universal Theory of Gravitation was published (1687) that an understanding of tides as an astronomical event came into being. Newton's Universal Theory of Gravitation defined the now well-known forces that drive the tides. Cartwright (1999) noted that during the late 18th and early 19th century, Pierre Simon, the Marquis de Laplace's work in hydrodynamics and the dynamics of fluid motion on the surface of a rotating earth in response to Newtonian tide stresses further increased tidal knowledge. Cartwright (1999) went on to note that from Laplace's work on tides, the analysis and prediction of tides using a series of harmonic oscillations, as well as the hydrodynamics of long waves gave rise to the accepted tide theory and tide equations are used to date. The fundamentals of tides are well established and recognised as being well documented.

1.1 Literature Review.

The first part of this literature review will focus on the science and definition of tides, following this the literature will focus on tides in a South African context. The scientific definition of a tide is the "*vertical movement of water on the Earth's surface"* (Great Britain Ministry of Defence (Navy), 2008) accompanied by a horizontal movement known as a Tidal Stream or Tidal Current. Tides are a complex dynamic system driven by gravitational and hydrodynamic forces. Harmonic analysis of collected tidal data is a methods used to extract the tide constituents for a specific area. These constituents or tidal terms indicate the relative importance of the diurnal and semidiurnal constituents (which are linked to one another) within a data time series and are used to calculate form factor. Form factor is defined by the sum of the amplitudes of O1 and K1 divided by the sum of the amplitudes of M2 and S2. A location with a form factor lower than 0.25 is normally considered to have a semidiurnal tidal regime (Pugh and Woodworth, 2014). Tides exhibit the following distinct patterns (Figure 1: Simon, 2013):

1. Diurnal tides: Having one high and one low tide approximately every 25 hours.
2. Semi diurnal tides: Having two high and two low tides approximately every 25 hours.
3. Mixed tides: Having characteristics of both diurnal and semi diurnal tides approximately every 25 hours. Mixed tides are often characterised by large diurnal inequalities, evident by a marked difference in either two successive high or low tides. The inequalities are influenced by the declination of the moon, as the declination increases so does the inequality (Bowditch, 1995).

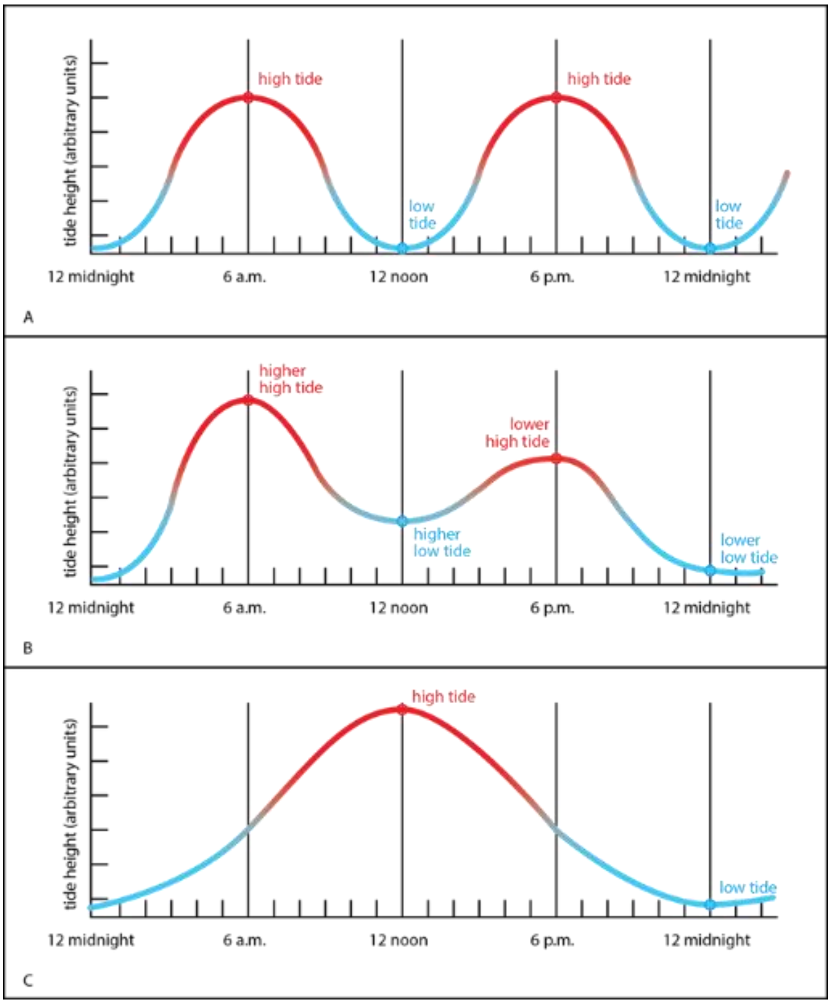

Figure 1 showing the most distinct types of tidal patterns: (**A**) semidiurnal, (**B**) mixed, and (**C**) diurnal (Inouye, nd) (https://manoa.hawaii.edu/exploringourfluidearth/physical/tides/tide-patterns-and-currents)

1.2 What drives the tides?

The gravitational attraction of both the moon and the sun are the two major astronomical factors that affect the tide with the moon's gravitational attraction being approximately twice that of the suns due to its closer proximity to the earth. As the moon rotates around the earth in its orbit it exerts a gravitational attraction, not only to the water on the earth's surface, but also on the solid earth itself. This attraction also applies to the gravitational effect of the sun, but due to its distance away from the earth it is less than that of the moon (Pugh, 1996 and Bowditch, 1995). The resultant effect is what is known as the ocean tides.

Newton's Universal Law of Gravitation, that states "*Two masses attract each other with a force proportional to the product of their masses and inversely proportional to the square of the distance"* and becomes of great importance in the understanding of basic tidal theory.

$$F=\frac{G\ m_1 m_2}{r^2} \qquad \text{Eq 1}$$

Where F is the calculated gravitational force, G is the universal gravitational constant, m_1 and m_2 represent the 2 masses and r represents the distance between m_1 and m_2. However, it is important to note that the tides are based on the change in gravity and not the gravity itself. This means that they drop off at the cube of the distance rather than the square of the distance like gravity does. Subsequently the celestial body with the greatest gravity does not necessarily cause the most tides. The net result is that r^2 now becomes r^3. Thus when calculating the ratio of the force exerted by the moon to that of the sun, it is found that the moon exerts a tide raising force twice that of the sun (Pugh and Woodworth, 2014).

In order to understand the fundamentals of tides, note needs also to be made of Newton's 3 laws of gravity.

1. Every body or object continues in a state of rest or uniform motion in a straight line until an external force acts upon it. Defining the basis for inertia.
2. When a body or object is acted upon by an external force, its acceleration (either positive or negative) is directly proportionate to the force applied and inversely proportionate to the mass of the body, with the acceleration will be in the direction in which the force acts (acceleration = Force/mass).

3. For every action there is an equal, but opposite reaction. The conservation of momentum.

1.3 The Equilibrium Tide Theory (ETT).

The Equilibrium tide theory (ETT) is the starting point in our ability to understand tides and the various factors that affect their type, timing of the tides and tidal patterns experienced around the earth (Pugh, 1996). In the ETT, an imaginary earth, which is completely round with no land masses, rotation or friction is considered. In the ETT the Moon's orbit is assumed to be circular as the point that the moon rotates around the earth, the common centre of gravity (the barycentre) is assumed to be the centre of the earth, this is similarly assumed of the earth-moon orbit around the sun (Pugh, 1996). In reality the barycentre is approximately 1700 km below the earth's surface thus giving the moon's orbit an almost egg like shape (Figure 2), similarly the earth-moon and sun rotate around a common centre of mass which is less than 500 km from the centre of the sun (Bowditch, 1995). Within the ETT, the earth has no tilt thus removing seasonal variation, declination[1] is simulated by "moving" the position of the moon around the earth and thus the effect that a change in latitude has on the creation of semidiurnal and diurnal tides (Bowditch, 1995).

The ETT is also an effective tool for understanding spring and neap tide generation as the gravitational effects of both the sun and the moon can be explored. During full or new moon, the sun and the moon's gravitational forces reinforce each other as they are in syzygy (when the right ascension of the sun and moon are co-incident to one another (Emiliani, 1987)) thus producing spring tides. In contrast, when the sun and moon are perpendicular to each other and thus the gravitational forces are working against each other neap tides form (Figure 3). In reality, due to water lag created by friction, spring and neap tides generally occur approximately 1 to 2 days after the relevant moon phase. This 1 to 2 days lag is called the Age of the Tide. (Pugh and Woodworth, 2014; Emiliani, 1987). In reality the tide continually gradually decreases in range from spring tide to neap tide, increasing in range back to spring tide approximately every 14 days (Hicks, 2006).

[1] Declination is used in the context of the earth's rotation/orbit around the sun as well as the moon's orbit around the earth. Declination is defined as "*the angular distance of an astronomical body north or south of the celestial equator, taken as positive when north and negative when south of the equator. The sun moves through a declination cycle once a year, and the moon moves through a cycle in 27.21 mean solar days. The solar declination varies between 23.5°N and 23.5°S. The cycles of the lunar declination varies in amplitude over an 18.61-year period from 28.5° to 18.5°."* (Pugh and Woodworth, 2014)

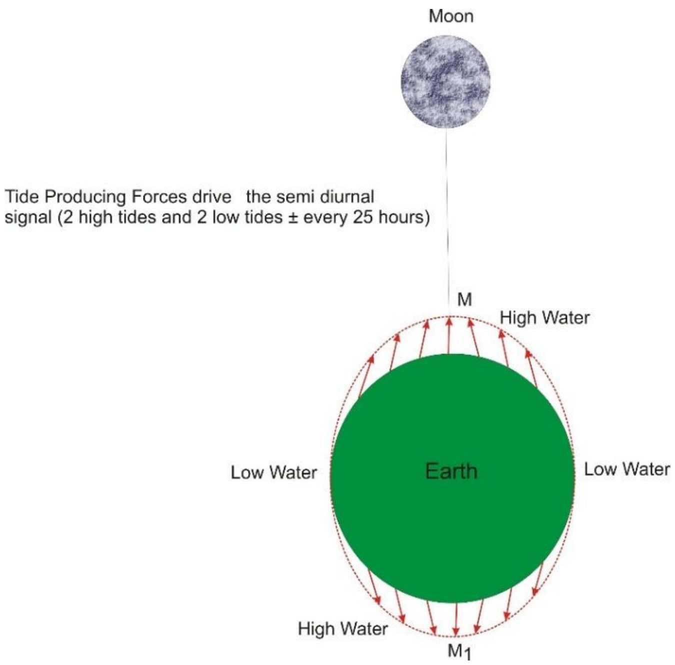

Figure 2 displaying an overhead view of the Moon's gravitational effect on the Earth and the Earth's water creating the "double bulge" effect and semi diurnal tides, in the Equilibrium Tide Theory (Farre, 2015).

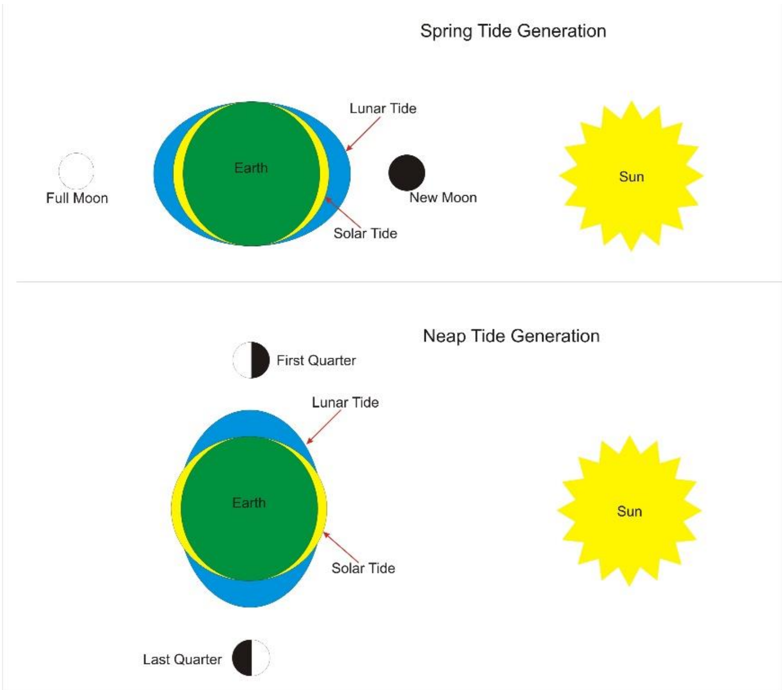

Figure 3 is a graphical representation of an overhead view of the Moon and the Sun's gravitational effect on the Earth and the Earth's water creating spring and neap semi diurnal tide, using the Southern Hemisphere moon symbols, in the Equilibrium Tide Theory (Farre, 2015).

1.4 Tides in reality.

Despite the importance of ETT, in reality, tides are complex, dynamic systems influenced by a non-spherical earth, which has tilt, rotation, land masses and ocean floors. The Admiralty Manual of Hydrographic Surveying NP134b (2) Volume 2, Chapter 2 - Tides and Tidal Streams, (United Kingdom, 1969) highlights that the real ocean basins have extremely complicated coastal and bottom topographies with varying depths and land masses with varying positions, thicknesses and depths of continental shelves, natural resonance, frictional effects and frictional drag and of course meteorological effects that all determine the specific natures and behaviours of tides.

A natural frequency of oscillation is experienced by every body of water, which is dependent on its size and depth, this is the decisive factor in determining if an ocean basin will respond to diurnal, semi diurnal or mixed tide raising forces (Forrester, 1983 and Bowditch, 1995). As an example of this phenomenon, the Atlantic and Indian Oceans tend to be more semi diurnal in nature as they are more influenced by the phases of the moon than by declination of the earth, having their largest tides at springs near the equinoxes (spring equinoxial tides). While the Pacific Ocean tends to be more diurnal in nature with the largest tides occurring around the summer and winter solstices due to the declinations of the earth in relation to the sun and the moon. The size difference between the Indian, Atlantic and Pacific Ocean basins result in difference natural resonance properties (normal modes) and the normal mode of the Atlantic has a frequency not so different from 2 cycles/day. The Red Sea, the Baltic and Black Seas have a very small natural resonance period of only a few hours. The tides of the Red Sea, Baltic and Black Seas tend to be small because they themselves are small. The direct tide raising forces of the moon and sun are operating over a small area and there is little external source of tidal input (such as at Gibraltar for the Mediterranean) (Pugh and Woodworth, 2014). As a result they have a small maximum tidal range that is considered as inappreciable (less than 30 cm in total) (IHO, 2013:61). Semi diurnal tides are the most commonly occurring tides around the world (Bowditch, 1995) (Figure 4).

With the complex nature of the bottom topography, specifically in areas of shallowing water, the ocean floor sediments and the consequential water layer above it results in deceleration of the water, with the surface water moving faster than that near the ocean bed. The lower part of the water flow experiences frictional retardations, causing a lag of the tides in relation to the movement of the moon. The varying locations and shapes of land masses results in reflection and refraction of the moving water and affect the local tidal conditions (United Kingdom, 1969).

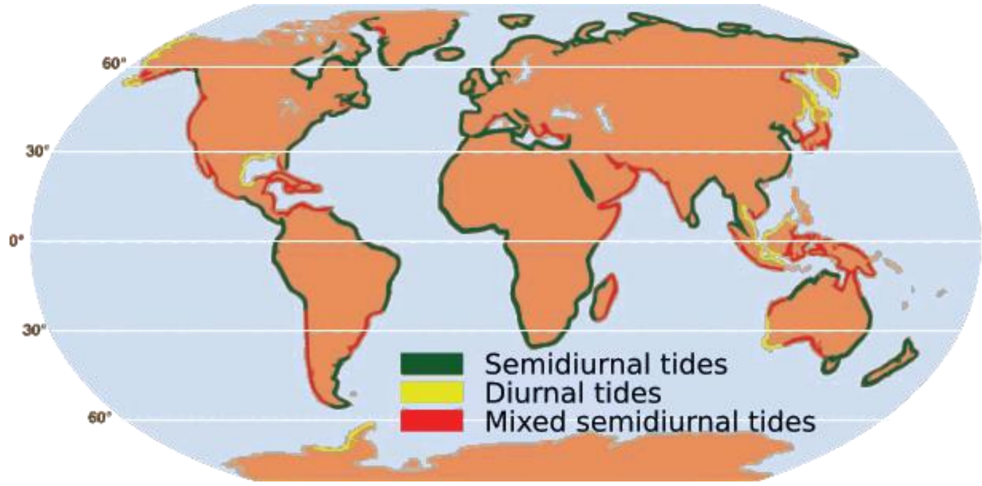

Figure 4 highlighting the distribution of semi diurnal, diurnal and mixed tides around the world (Pidwrirny, nd). https://manoa.hawaii.edu/exploringourfluidearth/physical/tides/tide-patterns-and-currents

Ocean basin geometry and the influence of the Coriolis force result in the development of amphidromic systems, in each system the crest of the tidal wave at high water circulates around an amphidromic or nodal point once during each tidal period, creating a rotating wave (Fairbridge, 1966). In each amphidromic system the crest of the tidal wave circulates around an amphidromic point once during each tidal period. The tidal range is zero at each amphidromic point, and increases outwards away from it (Wilson, 1966). Tidal stream is maximum at the amphidromic point and decreases away from it. Each amphidromic system has a series of co-tidal lines radiating outwards from the amphidromic point, cutting across the co-tidal lines, approximately at right angles to them, are co-range lines. Co-tidal lines link all the points where the tide is at the same stage (or phase) of its cycle, for example: all points along a particular line will experience high water at the same time. Co-range lines join places having equal tidal range (Rizal, 2002) (Figure 5).

As the moon is the main tide raising force its orbit around the earth has a repetitive pattern which makes tidal predictions possible. The angle between the plane of the earth's equatorial plane and the moon's orbit varies between 28.5° and 18.5° over an 18.6 year period. The orbits of the moon and sun are know from astronomy and their frequencies are those seen in the tides which lends itself to predictions. These frequencies from astronomy are those of constituents in the Equilibrium Tide and, although the real ocean tide has spatial variation very different from those expected from the ET (i.e. Figure 5), the frequencies are the same. The ocean is driven by the ideal tidal potential (i.e. the two bulges), but what comes out of this in reality is the complicated ocean response (Pugh and Woodworth, 2014). This variation is known as the lunar nodal regression which lends itself to tides being a predictable process (Bowditch, 1995). Subsequently, the more 18.6 years "parcels" of data that are recorded and analysed, the more accurate the predictions will become. However, international regulations state that 1 full years' worth of data is the acceptable minimum amount of data required to calculate predicted tide (IOC, 1985).

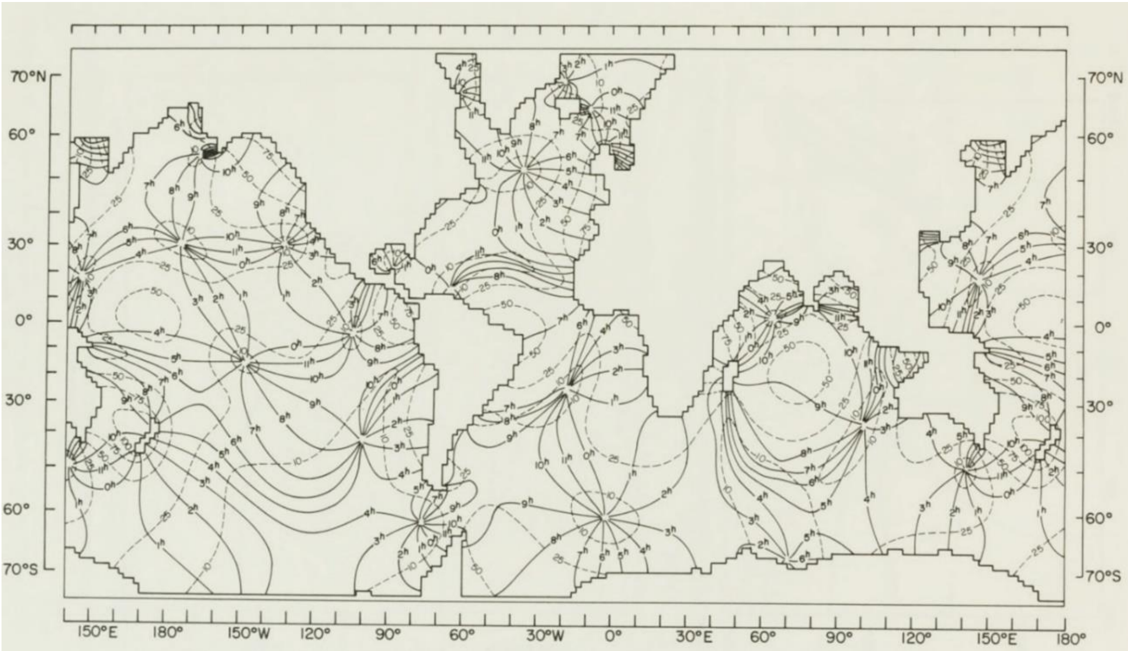

Figure 5 showing the M2 tide indicating the location of amphidromic points throughout the world's ocean on a 2° grid with a sloping shelf. The Solid lines are the Co-tidal lines (in GMT) and the dashed lines are the Co-Range lines (in cm) (Accad and Pekeris, 1978).

1.5 Harmonic Analysis of tides.

Pugh (1996) explains that the tide is a vector and has a vertical and a horizontal component. It is often referred to as a tidal wave (not to be confused with a tsunami, often incorrectly referred to as a tidal wave). The tidal wave is a resultant wave form consisting of each of the factors that affect the tides represented as its own sine curve or wave form, the resultant tide is created by the mixing of these wave forms (Pugh and Woodworth, 2014). These individual wave forms are known as tidal constituents. Once a complete data set of tide readings is collected, the tidal wave for each location is analysed by means of harmonic analysis in order to separate out the wave forms from the resultant wave.

A simplification of the tide equation is used in tide predictions and the calculations of the constituents (SAN, 2003),

$$Ht = Z_0 + SC + \Sigma\ [fH\ Cos\ \{(E+u) - g + nt\}] \qquad \text{Eq 2}$$

where Ht is the height of tide in a specific time zone, n is the speed of the constituent in ° per hour and t is the time in hours in time zone used for predictions. Z_0, SC, H and g are the port terms where Z_o is the mean sea level at a specific location, SC is the seasonal correction to mean sea level at that location, H is the amplitude of a particular constituent and is location specific and g is the phase lag of the tidal response for a particular constituent behind the tide raising force and includes a correction for time zones giving the results in the local time used for tidal predictions. The astronomical terms are f, E and u where f is the nodal factor that corrects for long period variations in the magnitude of the tide raising forces, E is the phase at Greenwich of the tide raising force, and u is the nodal correction that corrects for long period variations in the phase of the tide raising force (SAN, 2003).

During the harmonic analysis of the data recorded the astronomical and shallow water effects will be determined resulting in which constituents will be used for calculating the predicted tides. As each tide gauge station is located in a unique environment to the next, the constituents calculated for each location will vary for the minor constituents. RSA is classified as having a simple tide regime in comparison to the rest of the world, the SANHO typically uses less constituents to calculate the predicted tides than most other countries, using only 51 with [fH Cos {(E+u) – g + nt}] being calculated for each constituent (SAN, 2003).

1.6 Tidal Constituents.

The major tide constituents are created from the moon's and sun's orbits. These are the astronomical forces that give the tides their predictability. The ocean's response exhibits the following features:

1. the size of the tidal range,
2. the timings of high and low tides,
3. what type of tidal patterns will be experienced,
4. the speed and timing of tidal currents, and
5. the characteristics of the tides over horizontal distances.

The harmonic analysis and least square estimation/fit is the most commonly used and proven method of extracting the phase and amplitude of the constituents to be used for tide predictions (The United Kingdom, 1962; Forrester, 1983; Pugh, 1996; Bowditch, 1996; Pugh and Woodworth, 2014), however newer methods are being tested for their viability. One such method is the least square estimation and inaction method, based on normal time-frequency (Li *et al.*, 2019). This method calculates the constituents directly from the recorded water levels and time–varying harmonics simultaneously. Li *et al.* (2019) state the results obtained showed a higher level of accuracy by 9-15 mm for predictions 2 months in advance than the more traditional harmonic method for the same 2 month period. This method may prove to be of great value to the scientific community for short term, high accuracy sea-level projects.

The rest of this chapter will now shift focus to that of South Africa and its tides, while looking at the South African Navy Hydrographic Office and its responsibilities.

Meteorological conditions that differ from the average can cause considerable variations between the observed sea level and the predicted tides. These variations are mainly caused by unusually high or low barometric pressures and their associated strong or prolonged winds, with most of these variations being predominantly due to wind. Onshore winds result in a raised sea level and can be seen in tide graphics as the high and low tides being higher than predicted and the tidal wave is less smooth, offshore winds will produce the opposite results by lowering the sea level (Figure 6). Over periods of a low atmospheric pressure, such as the passing of a cold front, the entire tidal wave is raised, conversely slow moving unusually high atmospheric pressure changes can be seen by the lowering of the sea surface and subsequently this is reflected in the tidal wave (Figure 7). van Ballegooyen (1995) noted that typically there is a 1 cm change in sea surface height for every 1 hPa change in atmospheric pressure however Bowditch (1995) states that this change seldom exceeds 30 cm. However the traditional harmonic analysis and least square estimation/fit method produces better quality long term predictions which is of more value to the maritime community. As per the IOC (1985) and the IHO (1994), as is the international standard, all tidal predictions are calculated for average meteorological conditions and any astronomical conditions.

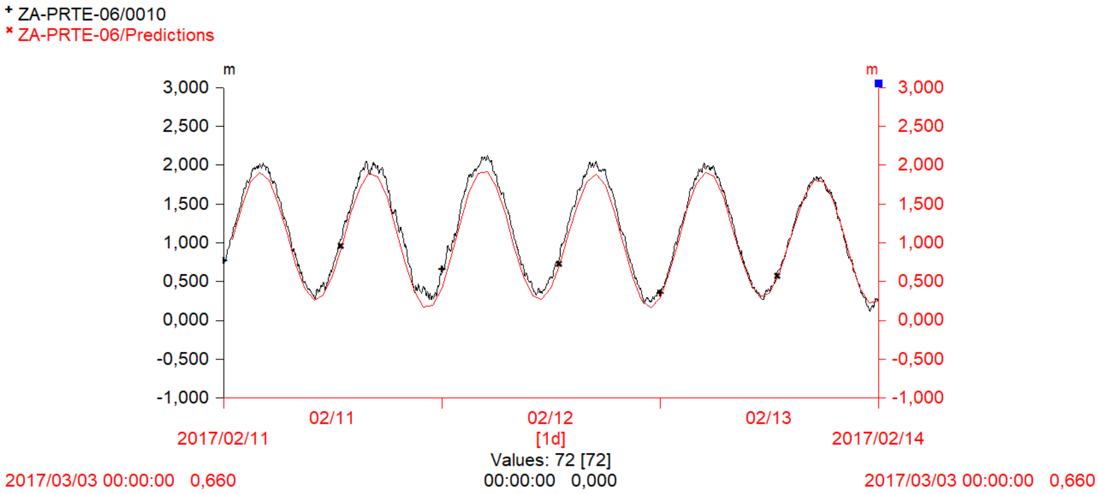

Figure 6 is graphic of tide gauge readings for Port Elizabeth, 11/02/2017 to 14/02/2017 showing the wind effect on the actual recorded tides (black wave) versus the predicted tides (red wave) (SANHO) (Farre, 2017).

A = area of low atmospheric pressure as the entire tidal curve has lifted above the predictions.
B = area of average atmospheric pressure as the predicted and actual tides sit on top of each other.
C = area of higher atmospheric pressure as the entire tidal curve has dropped below the predictions.

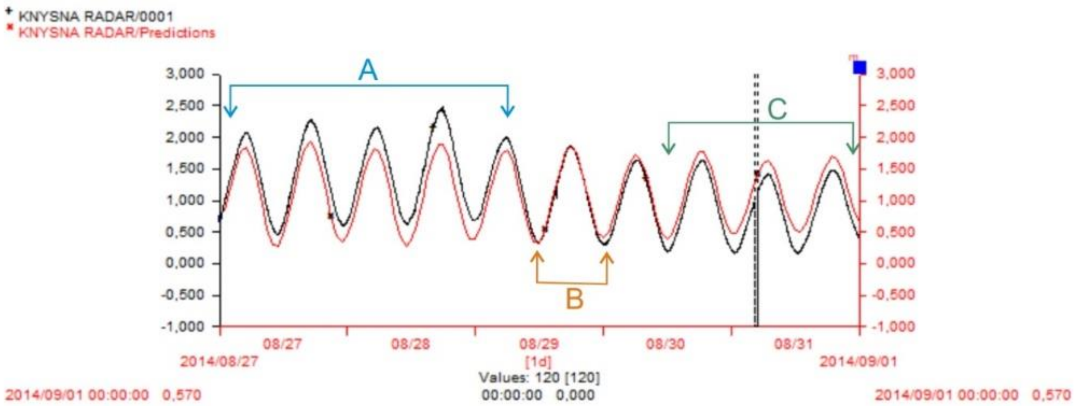

Figure 7 is a graph of tide gauge readings for Knysna 27/08/2014 to 01/09/2014 showing the effect of atmospheric pressure changes on the actual recorded tides (black wave) versus the predicted tides (red wave) (Farre, 2017).

1.7 Tides in South Africa.

In South Africa, tides are classified either as mesotidal[2] (Davies 1964) or upper mesotidal[3] (Hayes, 1967) (Scientific Committee on Oceanic Research, 2002) and exhibit an average range of 2,2m (SANHO, 2021). Around RSA, tidal stream is classified as being insignificant. The tides around the South African coastline occur with an approximate 30 minutes time

[2] Mesotidal is the cclassification of a tidal range between 2 m and 4 m.
[3] Upper mesotidal is the cclassification of a tidal range between 2 m and 3.5 m.

difference between the West/South West and East/South East sections of the coastline (Section 3.6). Whilst there is onshore and offshore tidal motion, there is little time for any appreciable longshore tidal flow. Tidal currents can be neglected except at the entrances of a few estuaries and bays, such as Saldanha Bay, Knysna Lagoon and Richards Bay. Offshore, the significant longshore currents are the Agulhas Current, on the East/South-East Coast of RSA, and the Benguela Current on the West Coast of RSA. Due to the strength and speed at which these currents flow, tidal current is inconsequential compared to them. Subsequently, there is no navigational requirement for tidal stream predictions to be calculated for South African waters.

The wider regions of the RSA continental shelf are considered to have greater changes in tidal water due to the changes in water depth (van Ballegooyen, 1995). An experiment carried out by Rautenbach, Barnes & de Vos (2019) for the SAWS Marine Unit as part of the validation of their storm surge model verified this. The aim of the experiment was to test the hypothesis that the semi-diurnal coastal resonance was the dominant cause for increased water levels associated with the wider continental shelf regions. This was achieved by comparing the amplitude and phase of the major tide constituents M2 and S2 calculated for the actual continental shelf with those calculated for a hypothetical smooth continental shelf showing the dependency M2 and S2 have on water depth (Rautenbach, Barnes & de Vos, 2019). The study confirmed the semi-diurnal tide dominance for South African waters while highlighting how the varying width of the continental shell could modified the phase lag, water level and timing of the tide (Rautenbach, Barnes & de Vos, 2019).

The South African coastline is an economic national asset spanning approximately 1 620 nm in length and extending to the 200 nm boundary of the exclusive economic zone (EEZ). The South African coastline has extensive mineral resources, 8 Commercial ports, 22 official commercial fishing industries (Turpie & Wilson, 2011), a wealth of subsistence fisheries and tourism opportunities that have resulted in a coastal population growth over the past few decades. It is estimated that over 30% of its current population of >58 million people live within 60 km of the coast (Statistics South Africa, 2019) (Figure 8). Naturally, these increasing numbers put pressure on coastal communities, in addition, dependence on sufficient resources to ensure safety of lives along the coastline and for those whose livelihoods are reliant on the sea.

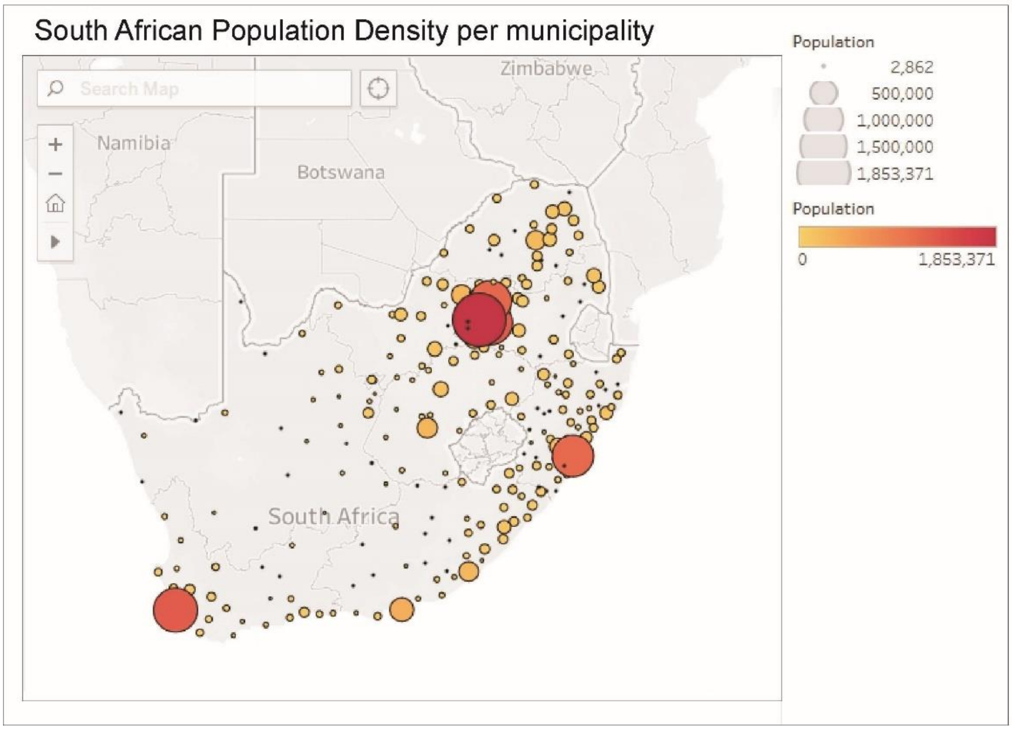

Figure 8 shows the South African population density by municipality for 2019 (South African Market Insight. 2019). The largest red circles indicate the highest population densities, the more orange dots show smaller population densities, many along the South African Coastline.

1.8 The South African Navy Hydrographic Office (SANHO).

A key protector of these communities is the South African Navy (SAN) and it is within this organisation that the South African Navy Hydrographic Office (SANHO) was founded in 1954. The SANHO is crucial for safety of life at sea (SOLAS) and is governed by the International SOLAS convention which is "*the most important of all international treaties concerning the safety of merchant ships". In addition, the main of the SOLAS Convention is to specify minimum standards for the construction, equipment and operation of ships, compatible with their safety"* (IMO, 2019). The SOLAS convention was initially created in 1914 as a response to the Titanic disaster and has subsequently been amended over the years. "*The main objective of the SOLAS Convention is to specify minimum standards for the construction, equipment and operation of ships, compatible with their safety"* (IMO, 2019). Chapter V of the convention is dedicated to the Safety of Navigation which applies to all vessels or ships irrespective of class or size, on all voyages. Chapter V identifies specific navigational safety services and requirements that must be supplied by maritime sovereign states. As a whole this chapter is the only one in the convention that applies to all vessels at all times which is in contrast to the rest of the convention which gives specific requirements for specific types of vessels embarking on international voyages. Although SOLAS is designed to apply to safety of life at sea, this includes safety of life in coastal environments, estuaries and navigable rivers as well (IMO, 2019). A tide gauge or water- level recorder is not only used for SOLAS requirements but also by many water affairs departments for dam/river level management.

South Africa has been an active member of the International Hydrographic Organisation (IHO) since 1951 and is solely responsible for the collection of tide, bathymetric and maritime safety information in order to produce accurate charts of the sea floor surrounding South Africa's coastline. In addition, the SANHO produces navigational publications (SANHO, 2020) aimed at the safety of all vessels sailing through South African waters. In order to achieve these critical responsibilities, the SANHO is mandated to maintain a tide gauge network around South Africa (Appendix A) and to create official national tide tables for both commercial and public use. The Ministerial Memorandum of 1954 made the SANHO responsible for the production of all navigational safety charts and publications, as well as the dissemination of all navigational warnings (DOD, 2019). As a result, the SANHO now works closely with the South African Maritime Safety Association (SAMSA) and the South African Weather Service (SAWS). The SANHO Archives was also made a part of the South African National Archives with all tide and hydrographic survey bathymetric data for South Africa being stored on its premises.

1.9 The SANHO tide gauge network.

Since 1938 South Africa has been producing accurate tidal data and prediction records with the installation of the first SANHO tide gauges in 1957. These first gauges were float and stilling well gauges. Over time the tide gauge network grew along South Africa's coastline with coastal towns such as Saldanha Bay, Simon's Town, Port Elizabeth and Walvis Bay being included and by 1989 a total of 12 tide stations were in operation (Figure 9). A key concern was the impact of wear and tear on these instruments and in 1995 the Council for Scientific Industrial Research's (CSIR) EMATEK Division was commissioned to design and construct Automatic Acoustic Water Level recorders (AWLRs) that incorporated additional barometer and temperature sensors. Unfortunately, in the 2002 report to the SAN Hydrographer (Thomson, 2002) it was noted that of the 8 AWLRs only the one installed in Walvis Bay operated successfully to produce an accurate dataset for the period 1997-1998. Despite several years of perseverance, the AWLRs were finally abandoned and replaced with 10 acoustic gauges (produced by a local company called SRD), which were installed between 1996 and 1997. Although these acoustic gauges were able to produce a continuous stream of tidal data their accuracy was extremely variable within the network (Thomson, 2002) and in 2002 a newly developed Radar tide gauge was put on trial in Simon's Town alongside a pressure sensor gauge and the existing acoustic gauge. The success of this trial resulted in the replacement of all 10 South African tide stations with these Radar gauges (Appendix B) (Gardener, 2002). Further improvements were made to the network in 2012/2013 when SANHO, in cooperation with the CSIR, began upgrading the communication systems on all their tide gauges to allow for 2G network (Archive port files). The historical information of the South African tide gauge network highlights the need for keeping up advances in technology in order to keep the network sustainable, creating an accurate long time series of data.

Figure 9 indicates the location of tide gauges in the South African and Namibia tide gauge network adapted from SAN 1 (with permission SANHO) (Farre, 2019).

1.10 The Hydrographic Act.

The Hydrographic Act no 35 of 2019 mandates the SANHO as the only legal authority responsible for the collection of sea level data as well as the installation and maintenance of a sustainable tide gauge network around South Africa's coastline and the publication and dissemination of all official tide predictions for South Africa (more details are found in Appendix C). As a result of this authority the SANHO is duty bound to collect, analyse, process, archive and disseminate all tide gauge data for South Africa (South Africa, 2018). Ensuring the information is collected, processed and archived in accordance with the International Hydrographic Organizations (IHO) guidelines, standards and resolutions (IHO, 2020). The IHO's resolution A6.3, 2/1947 states that

> “*In the general interests of navigation it is resolved that tidal predictions to be used for any important commercial port or approach areas within a country's territorial waters shall be those established by the appropriate authority in which the port or the approach area is situated or is being maintained. It may be necessary to establish the authority for predictions if such predictions are made on a regional co-operative basis where several narrow stretches of water separate States. In this connection, it is strongly recommended that Member States extend their tidal observations to those areas, and prepare and publish their predictions.*” (IHO, 2020:63)

The complexity and the subsequent importance of tides within the maritime community, in the form of Navigational products and maritime safety, has been described here. Although many countries have established tide gauge networks with long historical data sets, there is a large gap in the coastlines of developing countries where there is a strong need for them to develop and maintain their own tide gauge networks. The remainder of this thesis will explore how to design/develop and implement a sustainable tide gauge network and explain how the data is analysed and used to create tidal predictions and how that information is used within maritime safety while complying with international standards.

1.11 Key Questions.

The overall aim of this study is to investigate the requirements of designing a sustainable tide gauge network in order to obtain adequate coverage around the South African coastline and how to ensure the data is used in compliance with SOLAS regulations.

The two main research questions under investigation are:

1. What are the key technical elements in the design and realisation of the national tide gauge network around the South African coastline? and,

2. How can the national tide gauge network be used to increase maritime safety around the South African coast and does the data have any additional value?

1.12 Thesis overview.

A key aspect of this thesis is the design of the tide gauge network and the data collection. In order to answer question 1 the emphasis is placed on the key technical elements in the design and the coverage of the observational network of tide gauges for South Africa. The investigation into the answer for question 2 will look at the processing of the collected data and how it can be used to increase maritime (and coastal terrestrial) safety around the South African coastline. The value and dissemination of calibrated, measured sea level data and predictions and the benefits of tides to coastal cities, local maritime industries, national/ international initiatives is also investigated.

Chapter 2 will focus on the technical scene, in particular the design of an observational tide gauge network and the requirements for a successful installation to yield accurate data for collections. The technical details of the current equipment in use will be investigated supported by Appendix E. Chapter 3 will focus on the installation and maintenance of a tide gauge network along with the problems experienced and the solutions or possible solutions implemented. This chapter will also look at possible existing gaps within the current tide gauge network and the feasibility of closing these gaps.

Chapter 4 will be used to discuss how the data obtained from a tide gauge is quality controlled, analysed and used to create the annual predictions. The methodology and accuracy of the in-house software used by the SANHO will be investigated in the two case studies within this chapter.

Chapters 5 and 6 look at the value of the collected data and calculated predictions. Chapter 5 focuses on the importance of the collection of accurate data to result in accurate predicted tides and the importance thereof in the naval and wider maritime community. Chapter 6 focuses on the added value that the raw collected, analysed tide data and predicted tides has to the national and international organisations and SANHO collaborations.

Finally, Chapter 7 will provide an overview of the thesis and investigations undertaken and the data analysis and conclusions throughout this thesis, while seeking to answer the main questions posed by this thesis.

CHAPTER 2 – Designing a tide gauge network.

2.1 Design of the observational network of tide gauges.

From the author's experiences of working with the South African tide gauge Network over the past 19 years, the key to designing and executing an observational network of tide gauges is effective planning, cooperation and field reconnaissance. It should be noted that the Intergovernmental Oceanographic Commission (IOC) has published several manuals on recommended methods of how to design an operational tide gauge network. This chapter focuses on how to design a tide gauge network in South Africa and the methods needed to achieve this. The current positions/ locations of the tide gauges in relation to the length of the coast line will be discussed in order to determine if the current locations provide adequate tidal coverage. Points of consideration in selection of a tide gauge location are supported by Case Study 1. Technical details of the tide gauge instrumentation and methods of data collection employed by the SANHO will also be covered.

2.1.1 Location of a Tide Gauge Network.

Given that the main purpose of a national tide gauge network is to gather sea level readings for the creation of accurate tide tables for the safe navigation of shallow waters and the creation of accurate navigational charts, the possible locations for the tide gauges needs to be identified and investigated. The majority of permanent tide stations are located in strategic major harbours around the coastline of the maritime state. Often, due to coastline length or lack of permanent infrastructure, temporary tide stations are included to gain a better understanding of the relationships between a primary (permanent tide gauge) and secondary (temporary tide gauge) location. In South Africa, an example of this is the temporary tide gauge stations that were installed in Gordon's Bay and Hermanus in False Bay, and Robben Island in Table Bay. Due to the simplicity of the nature of the tides around South Africa the permanent tide gauge in Simon's Town was giving adequate information to cover Hermanus and Gordon's Bay, while Cape Town covered Robben Island and surrounds sufficiently.

The current primary tide gauge locations of Port Nolloth, Saldanha Bay, Cape Town, Simon's Town, Mossel Bay, Knysna, Port Elizabeth, East London, Durban and Richards Bay were considered based on the shape of the coastline, as well as their latitude and longitude (Appendix D). The continental shelf, bottom topography/bathymetric information for the specific internal waters, territorial waters and contiguous zones, as well as currents within the area should also be considered (Figure 10 and Figure 11.). The Maritime Zones Act, no 15 of 1994 says that the baseline for South Africa and its territories will be the low water line with straight "lines" used to join the lowest points across bays and capes. The internal waters are all the waters landward of the coastal baseline, the territorial waters being the ocean within 12 nm seaward of the baseline and the contiguous zone being within 24 nm seaward from the baseline (RSA, 1994). This additional information can be used to determine the minimum distance between tide gauge stations and areas of oceanographic or navigational importance where additional tide gauge may be required.

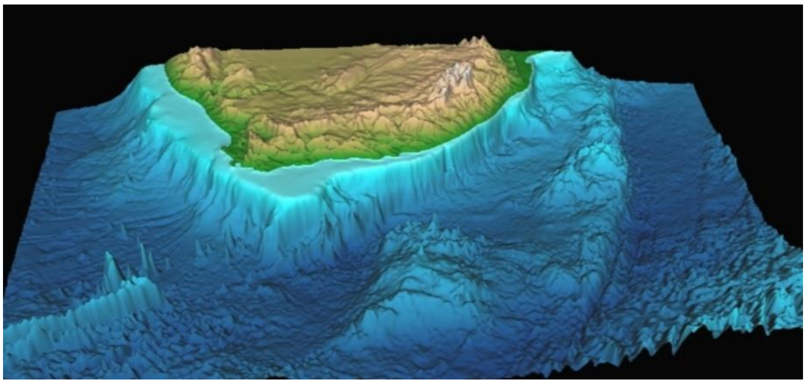

Figure 10 is a 3D rendering of a bathymetric survey done for the Extended Continental Shelf Project showing the coastline of South Africa and the width of the continental shelf around the coastline (courtesy of PETROSA).

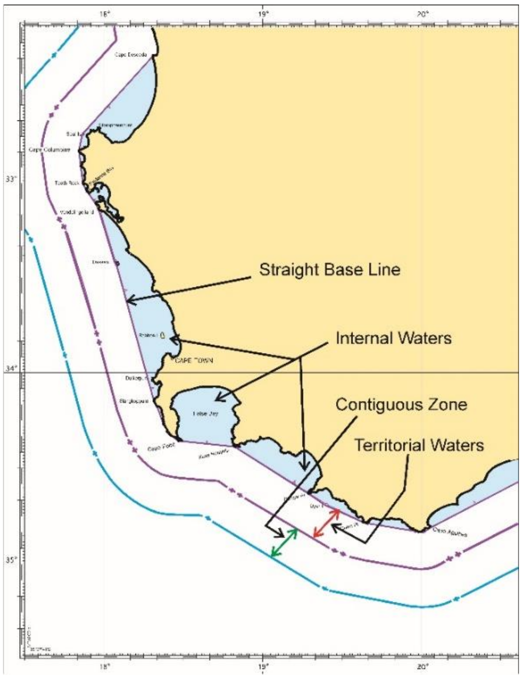

Figure 11 is an adaptation from SAN MZ1 informational chart showing the positions of the baseline, internal waters, territorial waters and contiguous zones around the South African coastline. These zones also apply to the Marion and Prince Edward Islands (with permission of the SANHO) (Farre, 2020).

South Africa's main objective for a sustainable tide gauge network is safety of life at sea and safe shallow water navigation. Archived historical files kept at the SANHO indicate that in accordance with these objectives major ports (Cape Town, Mossel Bay, Port Elizabeth, East London, Durban and Richards Bay, with the addition of Simon's Town and Saldanha as Naval Ports) were the priority for tide gauge locations. An additional influence was that a large amount of South Africa's, and Southern Africa's economic wealth passes through its major ports. Due to the large expanses of coastline between these major ports additional stations were situated, approximately 200-300 km apart to close the gaps between ports and produce better tidal coverage. To date two sections of the coastline are considered inadequately represented (Figure 12) - the stretch between East London and Durban on the East Coast, and between Saldanha Bay and Port Nolloth on the West coast. This will be discussed in Chapter 3, Case Study 2: Do the Current tide gauge Locations Sufficiently Cover the South Africa Coastline? Various attempts to close these gaps have been unsuccessful due to lack of adequate infrastructure and security. East London is a unique location within the tide gauge network as it is the only river port in South Africa.

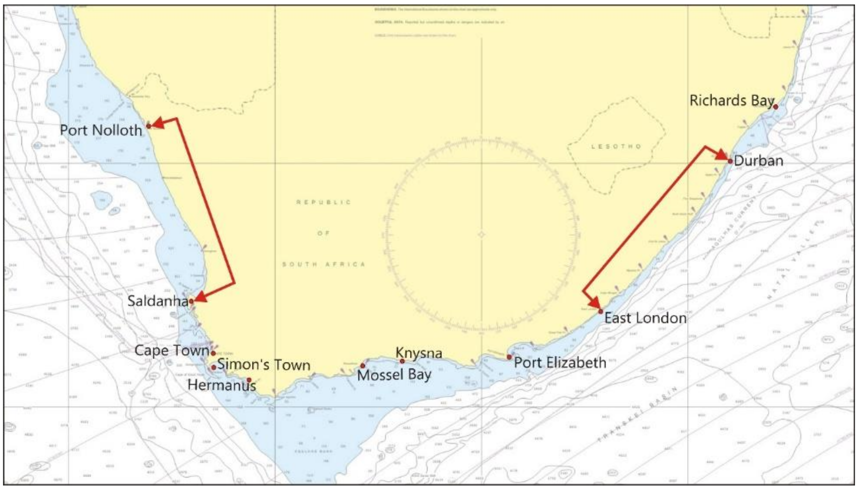

Figure 12 is an adaptation, a cropped section, of SANHO navigational chart SAN 27 (with permission SANHO) showing the 2 sections of the South African coastline considered inadequately covered by tide gauges (Farre, 2019).

Using the South African tide gauge network as an example, when either establishing a completely new tide gauge network, supplementing an existing network or relocating a tide gauge, various factors need to be considered and processes will need to be completed before the actual installation of new tide gauges can be initiated. Having established where the tide gauges are to be located, permissions need to be obtained to gain access to the desired areas and carry out site investigations. Upon gaining access in a specific port or location, a site visit is the best means to determine the most appropriate location to place a tide gauge. The closer to the harbour entrance the better so as to obtain the most accurate tides without too many harbour related influences. The following are general factors within the physical environment to consider when choosing a potential tide gauge site.

2.2 What to consider when selecting a Tide Gauge Site within the South African Context.

2.2.1. Is there harbour basin oscillations?

Harbours can be considered as a series of basins within an ocean basin. Natural resonance is already present within the ocean basin and will subsequently be present within the harbour and each of its basins (created by the quays.) Each of these basins within the harbour is subject to 'bathtub swash' and their own amphidromic systems. Thus the closer the tide gauge is located to the harbour entrance, the less these additional effects will have on the measured data, giving a truer reflection of the tidal influence.

2.2.2. Is there a benchmark network or will one need to be established?

Each tide gauge that is installed needs to be linked to a reference framework in order to carry out effective analysis of the data over large areas and across tide gauges. Ideally the data received from the tide gauge should be linked to some national reference framework. In South Africa the tide gauges are all linked to the National Geodetic System as recommended by the IOC (IOC, 1985). This is a national reference framework, consisting of triangulation Station (Trig Beacons) and benchmarks that use the coastline as its Z_0 or zero reference level (Land Levelling Datum - LLD). Everything above LLD is a height and everything below LLD is a depth. LLD is often incorrectly referred to as Mean Sea Level (MSL) and this may be due to the fact that the zero for LLD is nominally at mean sea level.

2.2.3. Availability of benchmark data.

All South African national benchmark data is gathered and held by the Department of National Geospatial Information (NGI) in Mowbray, Cape Town. It is part of their national mandate to install and maintain these benchmarks for South Africa. Each benchmark is surveyed back to a Trig beacon. Should there be no national benchmarks close to the tide gauge location, it can be requested that NGI install benchmarks close to the proposed tide gauge site. The SANHO may install their own benchmarks however they would still have to have the height checked by NGI to for the benchmark to be included in the national benchmark network. In 2016 a project was embarked on by the NGI and SANHO whereby the benchmarks near the tide gauges were resurveyed and GPS coordinates were established. Where no benchmarks were located very near the tide gauges, new national benchmarks were installed. Alternatively a land or quantity surveyor can be contracted to install benchmarks, as long as they are linked to the national benchmark network.

2.2.4. Are there existing structures that can be used or will these need to be built?

It is preferable to have a small building in which to house the electronics for the tide gauge. Although the electronics can be ordered from the supplier to be housed in a watertight cabinet, additional protection from the elements is often required. When considering South Africa, only Durban, Port Elizabeth, Simon's Town and Port Nolloth have their electronics housed in buildings or permanent structures provided by the respective ports. Examples of how environmental factors have affected the tide gauge electronics and how they were overcome will be discussed at a later stage.

2.2.5. Is there power available?

Previously, power supplies from the national power grids have always been a requirement and an easily available resource, as well as a necessary consideration when investigating a tide gauge installation site. The stability of the power grid should also be considered as spikes within the supply can often lead to electrical fires causing damage to expensive equipment. Should there be no power available or prevalence for load shedding/ rolling blackouts, consideration of solar or alternative sustainable power needs to be investigated.

2.2.6. How will data be retrieved?

In the past, with the old manual tide gauges, collaboration with local contacts was essential to replace the data charts twice a week and then have the charts mailed (in the case of South Africa) to the SANHO. However, with the introduction of electronic tide gauges the methods of data retrieval have evolved from manually downloading on site to downloading via 56k modems and analogue landlines. This has evolved to data retrieval via cellular communications (2G/3G/4G data transmissions to an FTP site.) Dependent on the chosen location and means of data retrieval, communication signals and possible interferences that could degrade these signal need to be considered.

2.2.7. Security of the equipment and the data.

When selecting the ideal tide gauge location for installation it is important to look for a location where there is restricted or limited access to the equipment. General or open access may lead to the equipment being tampered with or even stolen. Even with limited access, the tide gauge and its associated components may be damaged or rendered inoperable. A good working relationship with the relevant role-players for each specific location will aid in avoiding these issues.

It is important to ensure that a logical and precise process be undertaken before creating an observational tide gauge network that will yield accurate and valuable information. Non facilitation of this process could result in useless and wasteful expenditure, loss of man hours and valuable information.

Often, for various reasons, a tide gauge might need to be moved. A South African example of this was an occurrence in Saldanha whereby an investigation into a new tide gauge location was completed in November 2017. This example serves as an ideal, recent case study to address factors which could possibly influence the choice of location of a tide gauge.

2.3 CASE STUDY 1: Relocation of the Saldanha Tide Gauge.

2.3.1 Introduction.

This case study was carried out by the author in their position of as the SANHO Superintendent Tidal Information. The former tide gauge in Saldanha was located in the TNPA Small Craft Harbour for over 30 years (Labelled as *Current Location* in Figure 14.) In April 2004, the acoustic tide gauge was removed from its stilling well and upgraded to a Kalesto Radar Sensor extending over the water on a davit. This system worked extremely well, without incident until it succumbed to age and was upgraded to a newer Radar Level Sensor (RLS) in April 2016.

In May 2016, it became apparent that the tide gauge was not sending information to the FTP site and the SANHO's local contact was requested to go and reboot the system. Upon arrival it was discovered that the transducer was severely damaged. From the manner in which the Stainless-steel bracket was bent it was evident that a large force had been required to cause this level of damage (Figure 13).

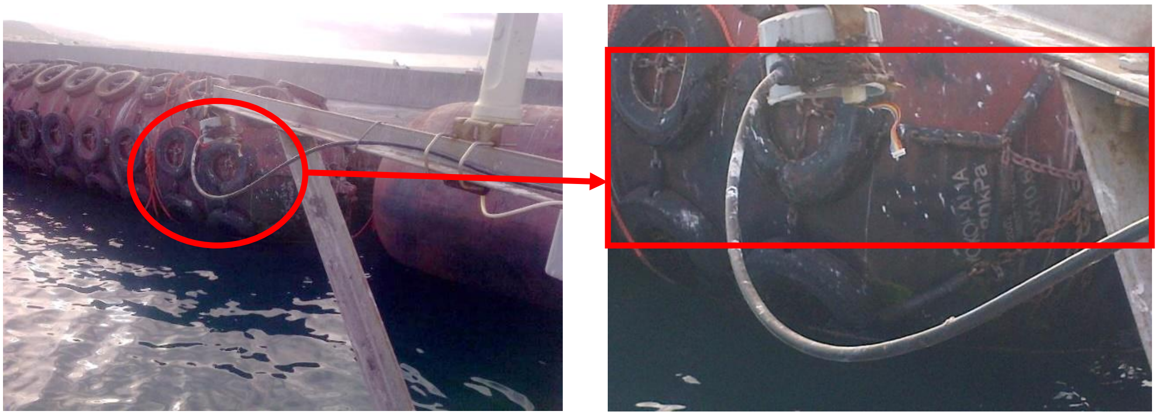

Figure 13 is a severely damaged RLS transducer. The sensor face has been smashed off from the electronics “tower’ (Bouwer, 2016).

No security footage was available for the tide gauge area, hence it was impossible to determine what had caused the damage. Due to budgetary constraints and a long procurement process a new RLS was installed, levelled and calibrated just over a year later, in July 2017. However, the system stopped transmitting data once again, as the new transducer had been damaged in the same fashion as its predecessor. Again, it was difficult to determine the cause.

At the end of July 2017, an older Kalesto sensor was re-installed at the Saldanha location as it was assumed that the transducers had possibly been hit by a vessel that did not see the new less visible RLS sensor (grey compared to the Kalesto’s copper colour). Once again this transducer was severely damaged in the same manner as the previous two transducers. A site visit and feasibility study was carried out to investigate the possibility of relocating the Saldanha tide gauge to another location within the Saldanha Bay area.

Prior to the commencement of the site visit and based on the historical tidal files for Saldanha, navigational charts (SAN 1010 and SAN 1011) and conversations with key stakeholders in the area, the following assumptions were made:

a. Deductions based on the relevant charts indicate large amounts of possible basin oscillation, reverberation or bathtub swash would make the Navy Jetty at SAS SALDANHA (SAL) unsuitable.

b. There would be no access to electricity at the SAL Jetty.

c. The jetty next to Sea Harvest, across from the Navies SAL Jetty, would cause deflection of the tide due to its proximity. (Labelled as *Quay of Concern* in Figure 14.)

d. The Iron Ore Quay belonging to ArcelorMittal South Africa, Saldanha Steel Works might be a better location to use. (Labelled as *Saldanha Steel* in Figure 14.)

2.3.2 Site visit and investigation of issues.

Prior to the site visit, the SANHO historical port file for SA was investigated and there was no explanation as to why the tide gauge was moved from SAL and installed in the Saldanha TNPA Small craft basin in 1986.

A study of the charts of the area gave rise to concern that the original relocation from the *SAL Jetty* to the TNPA Small Craft basin (*Current Location*) (as labelled in Figure 14) was done due to basin oscillation, reverberation with a large bathtub swash effect within the area, as well as the proximity of the newer quays that had been constructed over time near to the SAL jetty. The ArcelorMittal South Africa, Saldanha Steel Works Ore Jetty seemed to be the best option for the new tide gauge location (Figure 14).

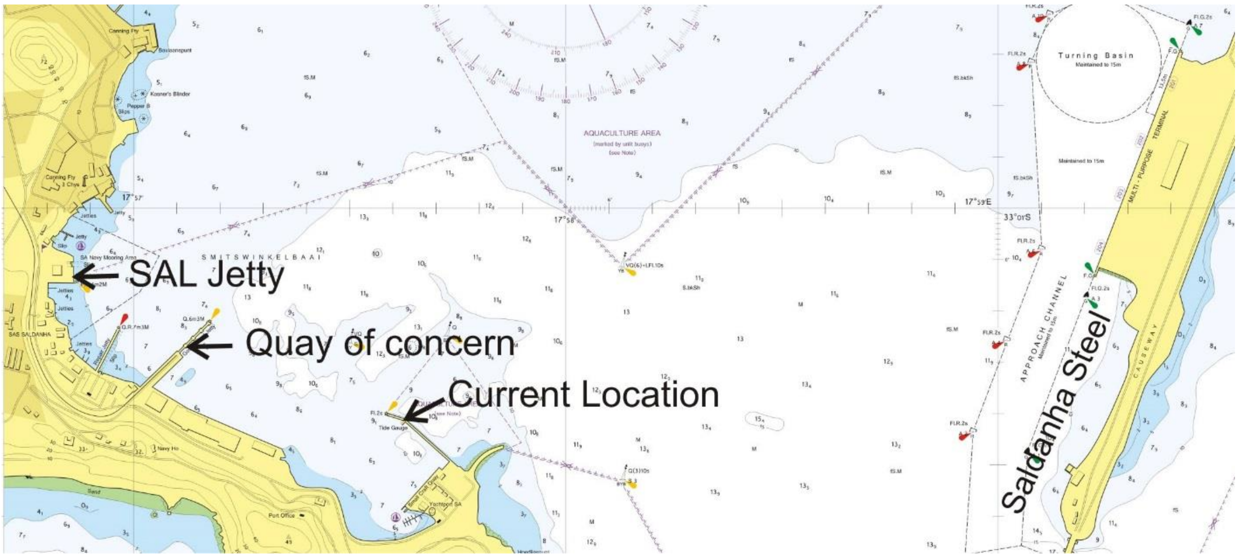

Figure 14 is adapted from SAN 1012 (with permission of SANHO) this chart shows the areas of interest within Saldanha Bay Harbour during the transfer of the tide gauge from its current location at the Small Craft Basin to the Navy jetty, marked as the "SAL Jetty" (SAS SALDANHA) (Farre, 2017).

Upon arrival at the SAL jetty it became clear that the ArcelorMittal South Africa, Saldanha Steel Works Jetty would not be an appropriate location for the tide gauge. Although there would be excellent security, the extremely large vessels moored where the tide gauge would need to be located were of great concern. From the charts, the jetty and vessels that were originally a source of concern were found to be a lot further away from the SAL jetty than thought. This concern was dispelled immediately as it was evident that the location of the quays was not creating or contributing reverberation or swash effects.

The original tide gauge at the SAL jetty was relocated to the TNPA Small Craft Basin when Sea Rescue and the T-Craft (small patrol vessel) moved out of the area meaning there was nobody to take over the role of local tide gauge custodian in 1986 (personal communications). Hence possible poor quality of the data that was being recorded in this location was not the reason for moving the tide gauge. This location (SAL jetty) had working and accessible power available for the tide gauge and was safe from vessels bumping into the transducer. The area also does not dry at spring lows.

It was concluded that the SAL jetty was the ideal location to move the tide gauge back to as there was power, security and assistance from the SAN Electrical Workshop if required. The only disadvantage was the lack of benchmarks in the area and none on the jetty itself. The tide gauge location at the TNPA small craft harbour, although closer to the harbour entrance, was believed to have too much swash and suffer from the bathtub effect, although it was more sheltered from the wind than the SAL jetty that resulted in it not really being an ideal location.

From visual observation during the site visit a string of large vessel anchorage buoys, that were not secured, were surmised to be the cause of the damage to the transducers. As the tide went out the buoys drifted out with the tide and when it came in they drifted back. At spring tides, the buoys would have been at the correct height to hit and subsequently severely damage the transducers.

Based on the site visit and investigation, the following recommendations were made.

a. The Saldanha tide gauge should be relocated to the SAL Jetty.

b. A survey team would need to be sent up to install a bench mark at the new tide gauge location.

c. Official permission would need to be requested from the Officer Commanding (OC) SAL to carry out the relocation of the Tide Gauge.

d. Official permission would need to be requested from the OC SAL to obtain assistance from his staff to assist with rebooting the system when required.

2.3.3 Conclusion.

In late February 2018, after the relevant permissions were obtained, the tide gauge in Saldanha was successfully relocated from the small craft harbour to the SAL jetty. In order for a special Hydrographic Instruction (HI) to be issued to have a benchmark installed on the SAL jetty, discussions were held with the Assistant Hydrographer. He indicated that a benchmark was already surveyed in and installed within metres of the new location. However upon arrival on site, it was discovered that the aforementioned benchmark had been removed in order to place railings on the edge of the quay. A temporary benchmark was surveyed in so that installation could continue, the tide gauge could be levelled and the reference level set. The new benchmark was installed by a remote survey team, from the hydrographic survey branch of the SAN, in 2019 having the same level as the temporary Benchmark.

The mains power to be supplied to the tide gauge was to be taken directly from the light on the quay. It was established that this light was not a navigation "flashing" light so a repeat of the Cape Town Power issues would not occur again (section 3.4.2, page 59). The Saldanha tide gauge relocation was successful with good quality data being received

Case study 1 highlights the various factors to be considered when relocating or installing a new tide gauge. Both a theoretical investigation and a site visit were conducted in order to establish the most desirable new location for the Saldanha tide gauge, after several instances of severe damage were caused to the tide gauge in its existing location. To date the Saldanha tide gauge, after relocation, is producing high quality data.

2.4 Technical details of the tide gauge instrumentation.

The choice of the best type of tide gauge equipment to be used can only be made after comparative research of the specifications of different equipment. It is important not only to factor in initial cost of the equipment, installation and maintenance and repairs but also the knowledge and skill levels required to carry out these functions.

Over the years technological advancements across all spheres have led to improved tide gauges being produced, each with its own unique set of specific requirements, not only for installation but maintenance and durability.

As most tide gauges are designed and developed in Europe or the United States of America (USA)/Canada, the environmental requirements for many equatorial and Southern Hemisphere countries are not taken into account. Research into the various types of tide gauges on the market and the individual specific requirements is of paramount importance. To address this, the IHO's Tides, Water Level and Currents Working Group (TWCWG) has created a document in which the contributing member states have listed the equipment in use (https://iho.int/en/miscellaneous-6). Appendix E gives the technical specifications of the tide gauges in use in South Africa. However, equipment should still undergo bench testing before selection.

By the mid 1990's the SANHO was using acoustic tide gauges that were installed in PVC stilling wells as per the manufacturer's recommendations. From the onset the data acquired from these tide gauges was erratic. An independent study (Gardner and Matsapola, 1999) on these gauges showed that transducers housed in tubes/stilling wells produced large errors due to temperature gradients that formed within the tube. The solution to this was to remove or modify the existing tubes to maintain a thermally well mixed air column around the transducer.

Additionally, within the Gardner and Matsapola (1999) study the accuracy of the two types of acoustic gauges was tested. One was found to have a systematic error of about 6 mm per metre in addition to a fixed offset of about 24 mm. The other was found to have a systematic error of approximately 10 mm per metre with a fixed offset of about 36 mm. This accuracy problem was addressed with the manufacturers to establish why the claimed accuracy of 0.05% over the 2 to 10 m working range could not be achieved with the units under test (Gardner and Matsapola, 1999). The manufacturer could not solve the problem and a method of post-data-processing was devised to improve the absolute accuracy of the data back to the claimed 0.05%. This post-data-processing could, however, only be carried out once all tide gauges in the network had been calibrated in situ to establish their individual calibration factors.

A refined method for *in situ* calibration was devised as a quality control tool, allowing absolute accuracy, measurement repeatability and sensor offset/ tide gauge zero (Z_0) to be reliably established in the field (Thomson, 1999). Between 2000 and 2008, the acoustic tide gauges in the SAN tide gauge Network were calibrated every six months, using carbon graphite poles of known length and a stainless steel target suspended below the sensor (Farre, 2006). This method of *in situ* calibration will be discussed in Chapter 3.

Between 2000 and 2008 average quality data was collected however it was degrading and often large portions of the data were unusable (Farre, 2006). The stability of the readings became erratic and the anomalies within the data increased exponentially. The anomalous data or spikes had to be edited out of the data in order to make the data usable for creating the annual tide predictions. Table 1 shows the means of the calibration results for the acoustic tide gauges. Investigations into the possible cause of the increasingly poor quality data being received showed that the extremely corrosive coastal environment was causing the tide gauges to rust and this may have impacted the data quality. The transducers that had little or no rust produced less anomalous data then their rustier counterparts.

Table 1: Acoustic Tide Gauge Mean Calibration Results

PORT	**MEAN CALIBRATION READING (cm)**	**ACTUAL VALUE (cm)**	**ERROR (cm High H or Low L**	**AVERAGE ST. DEV^{N}**	**STD DEV^{N} OF THE MEAN READINGS**	**REMARKS**
PN	1791	1786	5H	4.6	5.15	
SA	1243	1246	3L	1.46	3.63	
CT	1069	1076	7L	4.87	1.4	Only 2 calibrations
SB	Now too erratic to obtain results					
MB	1355	1363	8L	2.47	11.9	
KN	1519	1520	1L	2.16	2.4	
PE	1110	1113	3L	1.86	7.4	
EL	2252	2250	2H	3.63	2.74	
DN	1343	1341	2H	3.98	8.79	
RB	2370	2361	9H	2.22	3.77	

Given these examples of issues in tide gauges depending on their location, it became evident that more modern, reliable equipment needed to be sourced in order to better suit the South African coastal environment and gather a far superior quality of data.

During 2002 two newly designed transducers that fitted within budgetary constraints, were lent to the SANHO to test before possible purchase. An OTT “Kalesto” Radar actuated gauge and a float type OTT “Thalidimes” were successfully installed in Simon’s Town, with the Kalesto producing the best results (Appendix B). An independent study to check-calibrate the Kalesto radar tide gauge (Gardner, 2002) showed that, during the calibration period, the Kalesto performed consistently within the manufacturer’s claimed accuracy parameters over the 2–7 m range. The absolute accuracy of the gauge under test had a standard deviation of better than 3 mm over the 2–7 m range. The independent study confirmed the results achieved by the SANHO.

The refined method for *in situ* calibration, devised for the acoustic tide gauge as a quality control tool, is used to calibrate the Kalesto gauge annually. The data received from these gauges has very little ‘spiking’ due to the look angle and measuring interval. The low spike density is evident in the graphics and there is very little editing of the data before the predictions can be produced, thus improving on the accuracy of the Hydrographic Office’s predictions. The quality of data being sent to the GLOSS as Fast Data (Chapter 3) has also increased, not only in quality but also in frequency of data transfer.

To date (2020), the SANHO has two Kalesto radar gauge sensors still in use producing good quality data.

2.5 The Radar Level Sensor (RLS).

The investigation into the current South African tide gauge network, by delving into the history of the network, ascertained the key elements that were used in designing and the realisation of a tide gauge network. Within the design phase, Case Study 1 showed the importance of carrying out a theoretical investigation into the proposed installation sites followed up by a site visit before any installations were carried out.

The RLS (Radar Level Sensor) was launched by OTT Hydrometry as the replacement/upgrade to the Kalesto Radar sensor in early 2008. By late 2011 the SANHO had procured the new RLS sensors to systematically replace the non-functioning Kalesto sensors. Where possible, to tie in with budgetary constraints and long procurement procedures, the Kalesto’s would be left installed, however as a upgrade to the tide gauge network new NetDL loggers would be installed. These new loggers have integrated GPRS/2G modems that would allow for data transmissions to be sent, via a cellular or mobile network, to an FTP site. Table 8 (Appendix E) is a summary of the technical specification of the Kalesto, the two types of RLS and the NetDL Logger. It is envisioned that the 1 remaining gauge in South Africa, still on dial-up communications will be upgraded to GPRS/2G network and subsequently the FTP site before the end of 2020. Due to the Corona Virus pandemic, this is now been postponed to be completed in 2021.

2.6 Methods/ means of communication.

Between 1996 and 2003, the SANHO tide gauges were connected to 56k modems that allowed the Tidal Department (TD) to manually dial into the logger and download the stored data on a bi-weekly basis. With the rapid advances in technology, towards the end of 2008 the telephone lines throughout South Africa were being changed over from the old analogue (copper) to digital (fibre optic) and VOIP (voice over internet protocol) lines. This created a problem with connecting to the tide gauges as the 56k analogue modems were not compatible with these new lines. In some areas, older lines that were either stolen for the copper or damaged were not being replaced by the national telecommunications carriers and this became increasingly problematic.

Investigations on alternative methods of communicating with the loggers were undertaken. At the end of 2012 and the beginning 2013, the SANHO, with the co-operation of the Council for Scientific Industrial Research (CSIR), began upgrading the communication systems on the tide gauges from the outdated 56k analogue modems to 2G/GPRS cellular communications. New loggers with built-in 2G modems (OTT NetDL) have been installed in 8 of the 10 South African tide stations. The data now streams directly to a secure FTP site for near real time access. With the rapid developments within the cellular communications world, 2G/GPRS communications are becoming obsolete (with many first world countries already using 5G) and South African cellular providers will no longer support the 2G by the end of 2024. The SANHO is embarking on a project to upgrade the existing 2G communications with 3G/4G communications.

2.7. Conclusion.

When creating a new tide gauge network, the location and environmental factors surrounding the possible location for the placement of the equipment, as well as the type of equipment needs to be considered carefully. This chapter has looked at various types of equipment. The best practices, supported by Case Study 1 (section 2.3) in properly investigating the locations when moving or supplementing a network. The South African tide gauge network was initially designed and implemented, in some cases as far back as 1937. This network has been used as a platform to show how a network can be designed, developed and made sustainable into the future.

<u>Chapter 3</u> - Installing and Maintaining a Tide Gauge Network.

Having identified the most suitable location of the tide gauges, after consideration of possible constraints as discussed in Chapter 2, the next step is to commence with the installation phase. This chapter will focus on the realisation of a national tide gauge network with a focus on the method used by the SANHO to obtain the sensor offset or tide gauge reference level of the tide gauge as well as to calibrate the tide gauge *in situ*, highlighting the importance of linking the tide gauges into the national geodetic system. Additionally, several problems and possible solutions will be examined in order to achieve a robust tide gauge resulting in good quality observations recorded by the tide gauges. Case Study 2 will look at the current positions/ locations of the tide gauges in the SANHO network in relation to the length of the coast line. The time and height differences between ports will be evaluated and discussed in order to determine if the current SANHO tide gauge network locations provide adequate tidal coverage to South Africa.

3.1 Tide Gauge installation.

During the installation of a tide gauge the reference level, tide gauge zero or sensor offset (Z_0) is required to be established in the field and programmed into the data logger. In order to obtain an accurate Z_0 the relationship between the tide gauge and Chart Datum (CD) must be established and subsequently the relationship to Land Levelling Datum (LLD) /Ordinance Datum can be established. The South African Tide Tables define CD as "*…the Datum to which all soundings on the largest scale navigational chart of the area have been reduced*" (SANHO, 2022). The IHO defines CD as "*1222* ***datum: chart.*** *A permanently established surface from which soundings or tide heights are referenced, usually low water*…" (IHO, 2020). How soundings and CD are relevant will be discussed in section 5.1. In accordance with the TWCWG technical resolutions A2.5 - Datums and Benchmarks 3/2019 as amended 10/2017 paragraph 6 "…*It is resolved that the Lowest Astronomical Tide (LAT), or a datum as closely equivalent to this level as is practical and acceptable to Hydrographic Offices, be adopted as chart datum…*" (IHO, 2020), where LAT is "…*the lowest tide level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions*" (IHO, 1994).

To accurately establish these relationships the tide gauge is surveyed or levelled into the national geodetic system via land survey benchmarks in the vicinity of the tide gauge. The SANHO uses the stirrup method to obtain the reference level/ tide gauge zero to be input into the data loggers on installation, as well as to calibrate the tide gauges (Figure 15).

Figure 15 is a set of calibrating stirrups deployed under a radar tide gauge sensor in Lüderitz, Namibia (2008).

3.2 Use of a Stirrup to obtain the Z_0 of a Radar Sensor.

The “stirrup” target method (Thomson, 1999) is used to calibrate an altimeter or radar type gauge with an unknown Z_0. This method was originally devised as an *in situ* calibration quality control tool for the acoustic tide gauge. Other methods (IOC, 2017) for determining the Z_0 are now well documented and used prevalently in developed countries. Unlike the simplistic “stirrup” target method, these alternate methods require specialist knowledge and skills to use. However, to underline the probability of range measurements provided by a newly-purchased sensor being biased by having a non-zero Z_0, calibration of the sensor is essential. The SANHO regularly calibrates the tide gauges *in situ*. This calibration method is used to confirm the accuracy of the reference level and the actual sensor.

In this section the relationships between the various levels and the procedure for using the stirrup is described. In order to understand the relationships between levels, the set-up of the gauge and the benchmark needs to be considered. The stirrup target is suspended beneath a sensor with its metal plate target attached to the ends of rods of known length (G) (Figure 16). The rods and plate are suspended from a 5 mm thick supporting plate that rests on top of the sensor.

The tide gauge sensor and its logger are set up to provide sea level (positive upwards). The tide gauge is required to report sea level relative to Chart Datum (CD) which is a distance B below Land Levelling datum (LLD) (Figure 16).

Using the following diagram a basic idea of what the reference level should be can be calculated

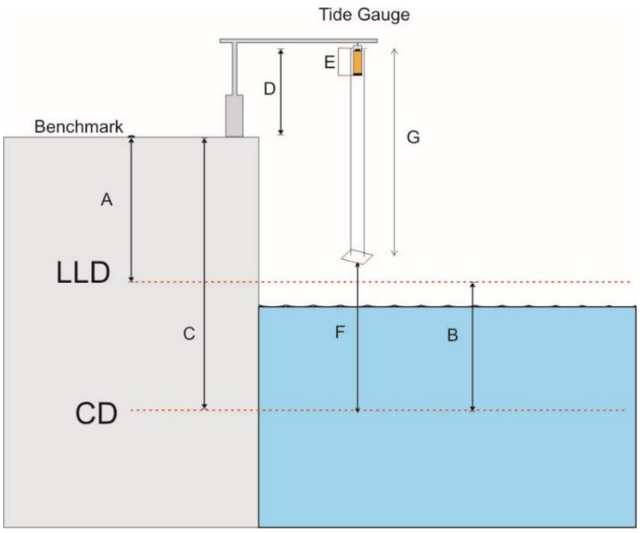

Figure 16 is a graphical representation of an altimeter tide gauge, with calibrating stirrups suspended underneath the transducer, suspended from a davit secured to a harbour wall or quay. A-G are described in the text below (Farre, 2002).

A: Height of a nearby benchmark above Land Levelling Datum (LLD) (from national levelling system).

B: The relationship between LLD and CD / LAT below LLD. (location specific).

C: The height of the benchmark above Chart Datum (CD)/ LAT below LLD.

D: The difference between the local benchmark and the height of the top of the transducer. (Before installation this would be the height of the davit or structure.)

E: The length of the sensor/transducer from its top (where the support plate rests) to its reading face

F: The height of the Transducer reference face above CD

(Before installation this would be the temporary tide gauge zero.)

G: Length of the calibration stirrup [Height of the calibration plate (or simulated tide) above CD]

Before installation Figure 16 can additionally be used to calculate the temporary reference level (F+G) or Z_0 to be input into the data logger, prior to installation, as the values of C + D - E = (F+G) are known.

To confirm the Z_0 on site, as well as calibrate the equipment, a set of calibrating stirrups can be used. The stirrups are made up of 1 m length rods that screw into one another to make up a long rod with an accurately known length (Figure 17). The total length required will depend on the maximum tidal range at a site. The rods can be made up of carbon fibre or thin stainless steel or aluminium tubing. Light material is better to avoid a large weight balancing on top of the transducer, shifting its level position or damaging it. A stainless steel plate can be used as the target that is suspended below the sensor. This has to be at least as large as the expected full beam-width. Calibration should ideally be undertaken at times of spring low tides so as to enable the stirrup to be deployed over a large range of heights.

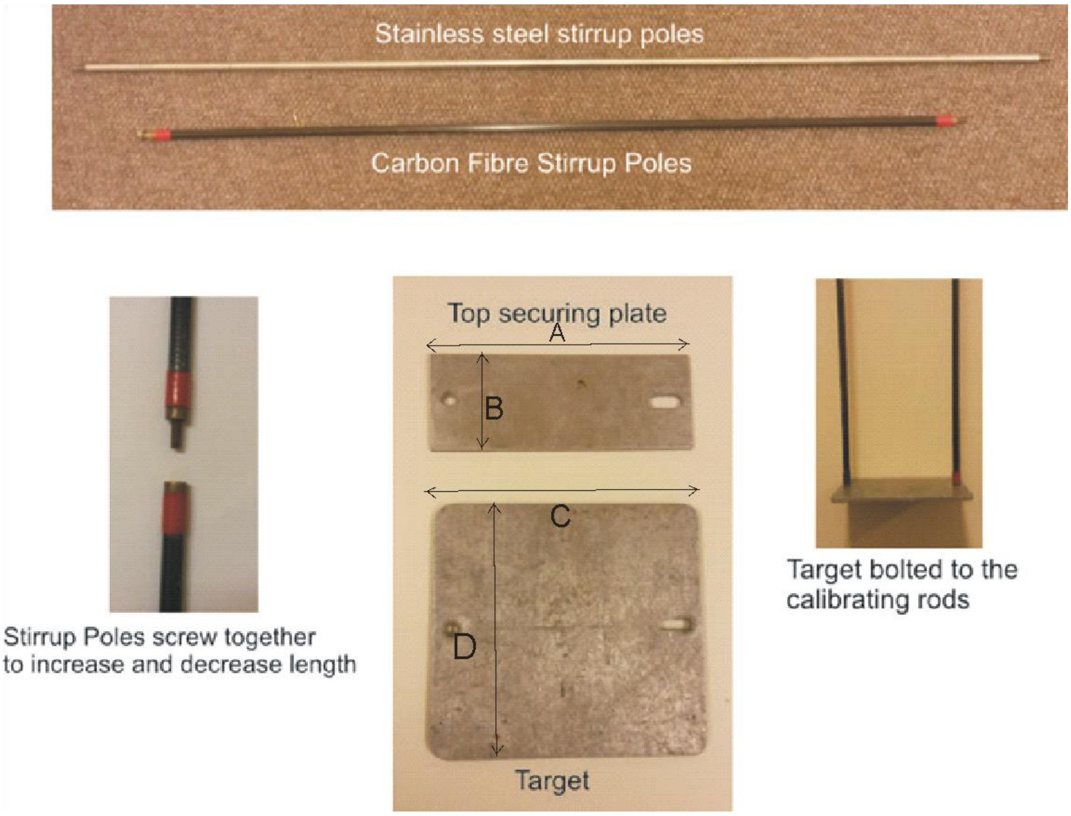

Figure 17 showing detailed images of the SANHO stirrups used for in situ calibration (A = 23cm, B = 8cm, C = 22cm, D = 22cm) (2017).

Using a surveying level (dumpy) and levelling staff (tach staff), “ground height” of the benchmark nearest the tide gauge needs to be obtained. True height of the benchmark above LLD can be obtained from the local land surveying department or NGI. In accordance with international hydrographic survey standards (IHO, 2011) the tripod and dumpy level are placed equidistant between the transducer and the benchmark. The dumpy level and tach staff are then used to obtain the “ground height” of the transducer (Figure 18). Once the "ground heights" are obtained the stirrups are deployed under the sensor at its longest length to simulate spring low tide (Figure 19) and shortest length to simulate spring high tide.

The SANHO recommends that recordings are made for at least 30 minutes. The average of the readings is then determined and compared with F. If the gauge is reading a value less than F, the difference between the average reading and F is to be added to the temporary Z_0 in order to set things up correctly. If the average is greater than F, the difference is subtracted. If they are the same, then the gauge is set up correctly.

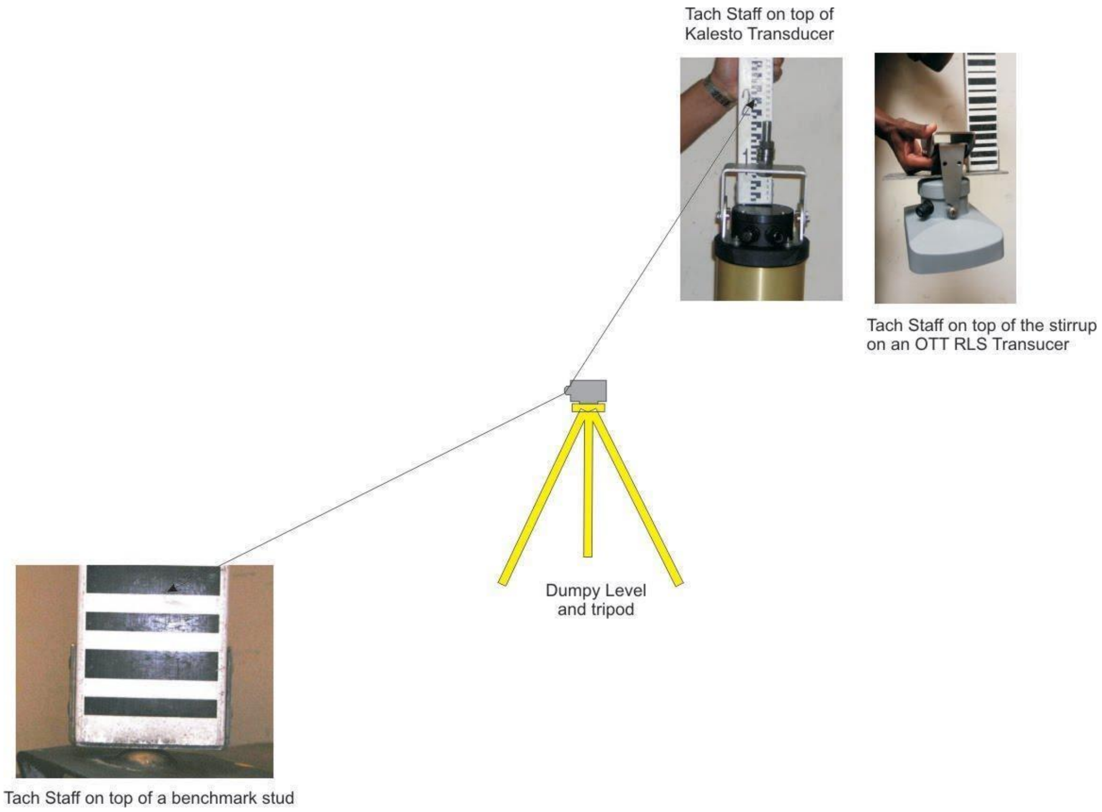

Figure 18 is a Dumpy level and tach staff obtaining "ground heights" of the benchmark and transducer/sensor (Farre, 2017).

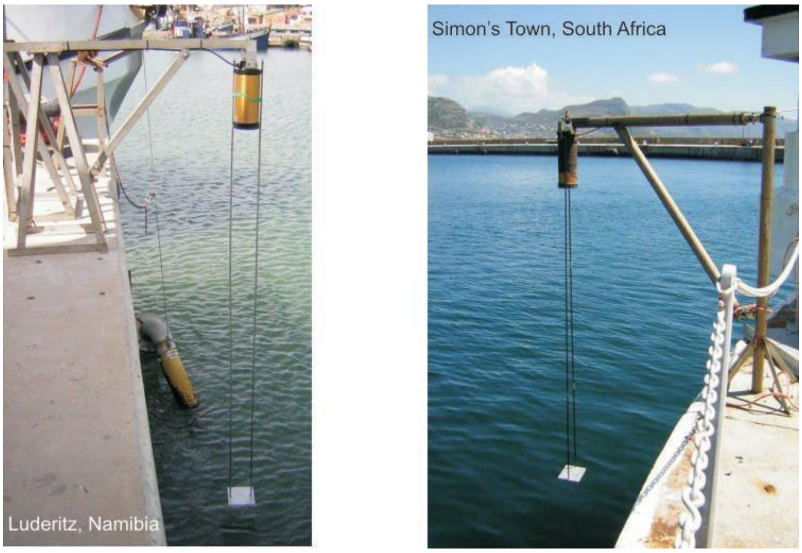

Figure 19 showing calibrating stirrups deployed below the transducer (2017).

In Figure 16, D is now the difference in “ground heights” between the benchmark and the top of the transducer, with G being the length of the rods of the stirrups

Height of Benchmark above MSL	A
Add: Difference between benchmark and top of the transducer	D
Less: length of transducer from the top to the transducer Face	E
Less: thickness of top calibration plate (if used during "ground height" observation)	0.005
Thus the transducer face above LLD is	A+D-E-0.005
Add: the relationship between CD and LLD	B
The height of tide gauge reference face above CD (or Y)	A+D-E-0.005+B

Therefore, the tide gauge should read, at a specific length of stirrups, = Y- (G - E)

However, the above procedure should now be repeated with different lengths of rods to simulate measurements at low and high tides. If the average tide gauge values now correspond with F in both cases, then no further adjustments need be made. All calculations and any changes are noted in the field notes that will be included in the station records.

Minimal long-term sensor drift occurs in equipment. Overtime, mechanical and electrical components, as well as temperature effects, will also contribute to a possible shift in the Z_0 (IOC, 2017). Regular calibration of the Z_0 and equipment, either *in situ* or in a laboratory maintains confidence within the data recorded.

3.3 Alternative methods of calibration or acquiring the Z_0 Value.

The simplest alternative method to calibrate a tide gauge would be to use a tide pole installed next to the tide gauge. An essential part of the tide pole installation, either as a temporary or permanent installation, is the levelling of the tide pole into the national benchmark system and thus the zero of the tide pole is known. Visual observations are then taken and compared with the readings gathered from the tide gauge (IOC, 1985). The disadvantage to this method is that it is extremely labourious and time consuming as measurements should be recorded over all tidal cycles and different times of the year to better refine the reference level (IOC, 1985). There are also no set guidelines on how many readings need to be taken or at what interval in order to obtain the best results. Tide pole reading should always be taken under average meteorological conditions in order to obtain the best results, however error of parallax, human error, and vessel movement within area of installation severely affect the quality of the readings.

An alternative method, to the two methods already mentioned, is the “dribbler gauge” method (IOC, 2016) whereby a pressure sensor is installed in a plastic drainpipe to simulate a stilling well. This method does not require interpretation of the measurements as in the SANHO stirrup method, however it does require funding to purchase a pressure sensor as well as the knowledge and skill to install the drainpipe and pressure sensor. Biological growth in and around the drainpipe can adversely affect the results obtained.

An alternative method for datum determination and control, suggested by the IOC (IOC 1985), is Dipper measurements to a levelled contact point (CP). This method uses an acoustic sensor and should be performed over the entire high to low tide cycle, with repeated repetitions over time. It also requires extremely well trained personnel to carry out this method of calibration (Schöne et al, 2011).

The stirrup method used by the SANHO can be adapted for calibration of any type of sensor in a lab or workshop. The sensor can be set up either in the vertical or horizontal and left to read a target of known distance from the sensor face. Installed sensors can be removed from their locations, returned to their responsible institutions and calibrated. This method is inexpensive to make, cost effective to use and ideal for developing HO’s which often lack the financial resources and expertise required for the alternative methods.

3.4 Problems and possible solutions identified within an operational tide gauge network.

3.4.1 Stainless steel cabinets and bird proofing.

In most ports the lack of secure infrastructure to house the tide gauge electronics has been overcome by the installation of watertight stainless steel cabinets (Figure 20). These cabinets were designed by the Naval Engineering Services (NES) (Thomson, 1990) and built by the Naval Fleet Maintenance Unit (FMU) in Simon's Town. The criteria for the design was that the cabinets had to be watertight, be able to be transported in the back of a double-cab van (bakkie), be light weight enough to be moved by 3-4 persons and easy to mount onto the quay.

After installation of the cabinets it was discovered that, due to the flat top surface, sea birds were nesting on top of the cabinets and fouling the tide gauge and surrounding area, often causing damage to the tide gauges. NES was requested to design a "bird proofing” (Thomson, 1995) that could be placed on top of the already installed cabinets. NES devised an additional component that could be placed on top of the cabinets to discourage birds from even perching on the cabinets, however it does not discourage graffiti by harbour workers (Figure 21).

Figure 20 is a tide gauge electronics cabinet being reinstalled in Saldanha (2018).

Figure 21 is the “bird proofing” on top of the tide gauge cabinets (2018).

3.4.2 Power supply.

A problem that was regularly experienced over the years was that local or national power grid outages in the area of the tide gauge regularly required the logger and 56k modem to be rebooted once the power was restored. It became very important to have a trustworthy local contact that could carry out this hard reboot/ “kick-start”, so as to re-establish communications with the gauge. These power outages often resulted in power surges when the power was restored. Over time these power surges lead to resultant damage within the expensive Power Conversion Units (PCU12) and even to an electrical fire in two of the tide gauge electronics cabinets. It became evident that a stable power supply was required and investigations into alternative methods of supplying power to the tide gauges began. Surge protectors have also been installed at all the mains power points.

With the National Power supplier implementing rolling- blackouts/ load shedding within South Africa the last few years, regular rebooting of the tide gauge systems has been required. The batteries are no longer able to charge sufficiently, requiring regular replacement. In some locations, valuable data is being lost.

In Cape Town Harbour, of which the North Spur is the location of the Cape Town tide gauge, the main quay was leased and the leasing company was given permission by TNPA to demolish the buildings on the quay. Unbeknownst to the leasing company the building that was demolished housed the Cape Town tide gauge telephone and electrical junction boxes. After much negotiation, TNPA committed to resupply power to the tide gauge. Although power was restored to the tide gauge, no data was being received. A maintenance visit was scheduled and after several hours of fault testing, it was discovered that the power to the tide gauge was being supplied from the navigational light on the quay. This is a specifically sequenced flashing navigational light. It was then noted that every time the light flashed on, the tide gauge would power up and when the light flashed off the tide gauge would lose power. The SANHO Technical Warrant Officer at the time redid the wiring so as to maintain a constant flow of power from the light to the tide gauge.

This unfortunate incident produced a positive outcome, resulting in the SANHO doubling its efforts to find an external source to power the tide gauges. In 2013, in conjunction with the CSIR, a solar power system (consisting of a solar panel, regulator and battery) was installed on a trial basis at the Cape Town tide gauge and has yielded excellent results. The SANHO was under the impression that the solar system was a back up to the mains, should the mains power fail. In late 2017 it was discovered that the Cape Town tide gauge had been running purely on solar power for almost 5 years. This confirmed the viability of this option as an alternative to the national power grid. Since then, 10 solar panel power systems (80W solar panel, 12V battery and regulator) have been purchased. Specially designed marine grade steel brackets and davits for the solar panels, that could be easily transported via a double-cab bakkie and easily installed, were designed and delivered to the SANHO in early 2019 (CSIR, HartRAO and SANHO, 2017).

The solar panel bracket was designed to consist of several components that could be combined into an *on-site assembly pack* that would be compact to transport and easy to assemble. In Figure 22, component A and D are the brackets that will affix the solar panel bracket to the davit. In Figure 22, D is shown to be 180º to how it will be installed in reality and its design is such to prevent water collection. Bolts will be fitted to the bracket at C in order to stabilise the panel preventing panel movement. In order to obtain the optimal solar panel angle the rods B can be cut to the desired length. The davit to which the solar panel is affixed is designed to be compact and consists of 2 parts - a base and extension pole (Figure 23, A + B). The extension pole can be adjusted to the required or desired height and is secured with a nut and bolt. Figure 23, C shows the fully extended davit secured with a red rod for illustration purposes.

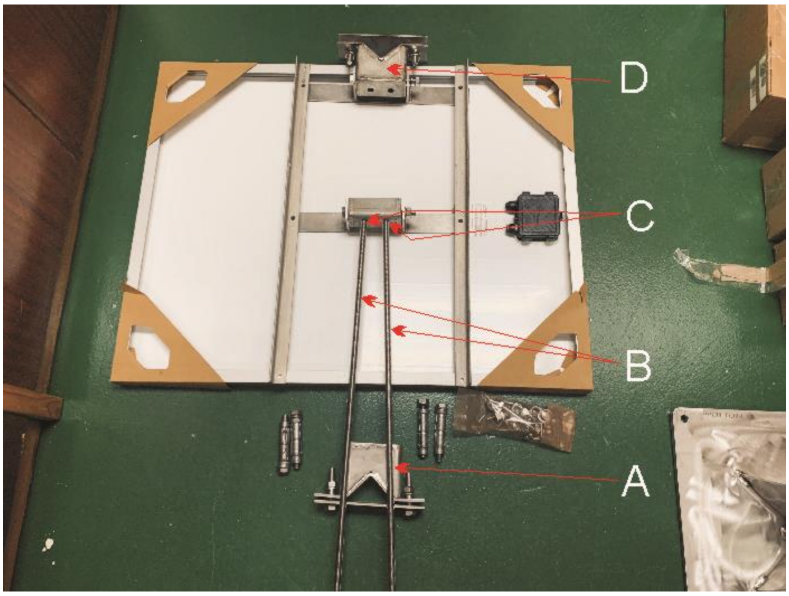

Figure 22 is an example of an 80W Solar panel with bracket components as described in the paragraph above (2019).

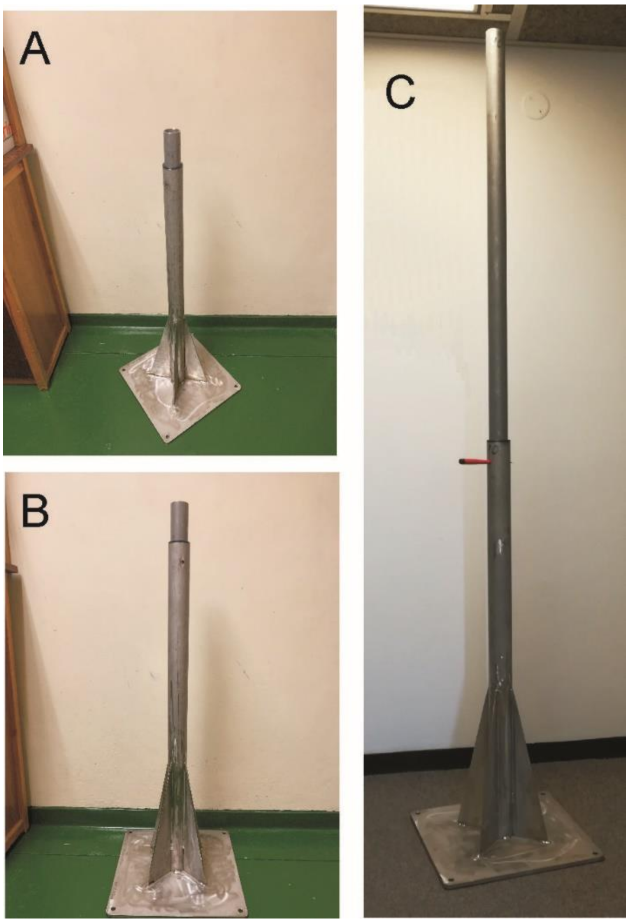

Figure 23 is the solar panel davit as designed by the SANHO as described in the paragraph above (2019).

Over the next 3-5 years the entire South African tide gauge network will be installed with solar power systems, which should alleviate loss of data due to power failures, damaged power lines and power surges damaging equipment.

3.4.3 Harsh Coastal Environments.

Due to the extreme corrosive nature of the climate and environment around the South African coastline, all davits/ structures have been built out of marine grade stainless steel in order to maintain the longevity of these structures. Aluminium, even painted or bonded, does not last in the South African coastal environment, the tiniest chip in the coating leads to destructive corrosion within 6 months. This became evident when the satellite antennas in Durban and Simon's Town began to disintegrate. A small chip in the bonded coating of the OTT Kalesto Radar transducer in Durban led to the transducers crumbling and the housing exploding (Figure 24).

Figure 24 highlights Durban's transducer showing corrosion damage (2013).

The SANHO is currently in the process of upgrading the older OTT Kalesto Radar to the OTT RLS radar transducers. These transducers are housed in heavy duty, UV protected plastic. The harshness of the South African sun causes this plastic to become brittle over time. The OTT Kalesto and OTT RLS transducers have been wrapped in Denso Tape (synthetic fibre fabric tape impregnated with a neutral petroleum and inert siliceous fillers) to protect their housings and increase their waterproofing (Figure 25).

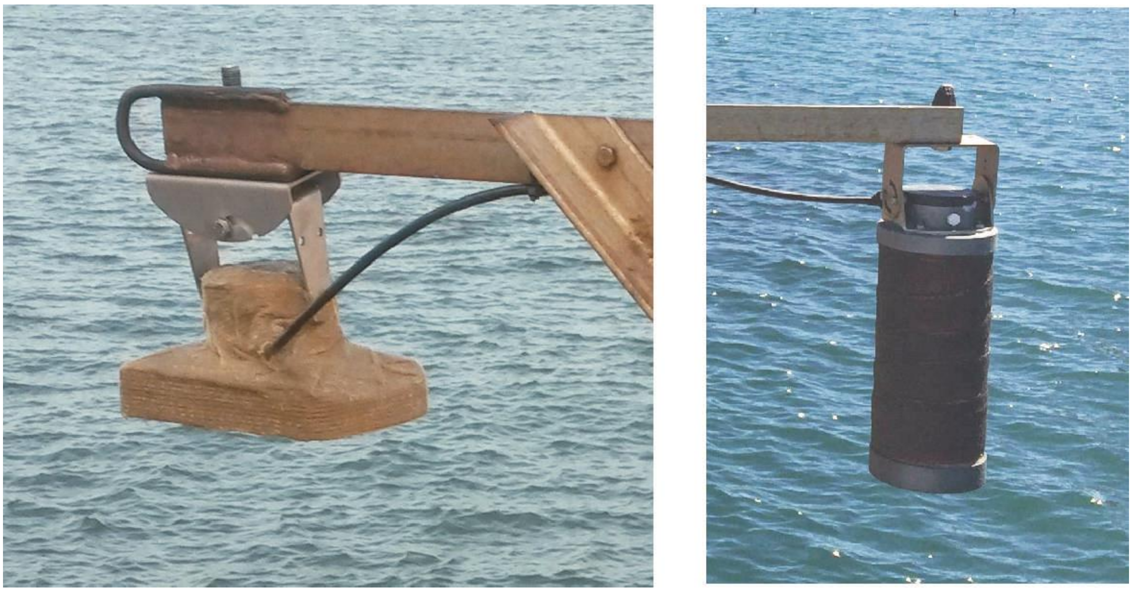

Figure 25 are examples of 2 types of transducers coated in Denso Tape (http://www.denso.co.za/burried/petrolatum.php) (2017).

3.4.4 Extreme Temperatures.

In September 2015 the SANHO STI and Technical Tidal Assistant (TTA) conducted a capacity building workshop in Abu Dhabi, United Arab Emirates. As part of the technical visit, the STI and TTA were shown 2 of the tide gauges installed in Abu Dhabi and assisted with troubleshooting various issues that were experienced.

A common complaint from the attendees of the workshop was that the tide gauges regularly would just stop and then start working. In the controlled classroom environment, this was difficult to try and find a solution for, however once out in the field it was more evident as to what the problem was and to find the solution.

Figure 26 is the inside of the electronics box, Abu Dhabi as described below (2015).

Figure 26 is the inside of the electronics box of one of the tide gauges in Abu Dhabi, mounted on the edge of the quay in the direct sunlight. The extremely high temperatures reached in Abu Dhabi during the day was causing the electronics to overheat and subsequently switch off until cool enough to restart. The large amounts of black electrical cable inside the box, as well as the electronics themselves, give off what is perceived to be insignificant heat signatures, however combined with the outside temperature this becomes significant. The lack of ventilation also contributed to the overheating of the equipment.

It was recommended, by the SANHO, that the electronics box be housed in the shade and the large amounts of excess cabling be removed. Feedback received by the SANHO in 2017 indicated that the recommendations made had been implemented and the overheating problem had now been solved. As most tide gauges are designed and developed in Europe, although the specifications may indicate that it will work up to a specified high temperature, in reality this is not the case. The equipment is tested in a controlled environment over a limited period of time which is not what happens in reality.

The above are just some of the examples of problems, and the possible solutions that the SANHO has developed in order to overcome various installation obstacles. Each environment is unique in the problems that will or can be experienced in developing a tide gauge network and “out of the box” thinking may be required to enable a successful installation and maintain gathering of accurate information.

3.5 Ideal versus reality.

In the ideal scenario the tide gauge network around the South Africa coastline would have tide gauges located every 200-300 km apart. Thus giving the best coverage and data on local tide conditions, improving the quality of available data and predictions. In reality this is not often possible.

At present the South Africa tide gauge network has 2 large gaps, with a possible third gap, that should be closed. They are as follows:

1. West Coast: The stretch of coastline between Saldanha and Port Nolloth.
2. East Coast: The stretch of coastline between East London and Durban, and
3. South Coast: The stretch of coastline between Simon's Town and Mossel Bay.

For the West Coast, the ideal would be to have tide gauge stations at Doringbaai/ Strandfontein and also at Hondeklipbaai. These possible new tide gauge locations on the West Coast would give a better tidal overview of this large stretch of coastline. After extensive investigation it was evident, due to complete lack of required infrastructure in those areas, that they would be unsuitable to place a tide gauge at any of the aforementioned locations. Lamberts Bay (LB) was thought to be a possible alternate location with the availability of power and an established small harbour. After communications with the LB Harbour Master and site visit, the site was found to be unsuitable. There was no available power that could be utilised. At the time, power would have had to be installed by the local municipality and only a pre-paid electricity metre would be installed (pers coms). Due to budgetary constraints and long procurement processes, this would not be a viable option for the SANHO. With the introduction of the solar power systems, this need for a power source has been eliminated however other obstacles remain.

As mentioned previously security of the equipment, and subsequently the data, is paramount to maintaining a sustainable tide gauge network. Theft of or damage to the physical tide gauge can become extremely costly on already strained or limited budgets. Often long procurement processes, limited budgets or manpower shortages/ unavailability will result in extensive loss of valuable data. Should access be gained to the actual data logger, either physically or by hackers, the integrity of the data diminishes, if not identified and corrected early this can even damage the integrity of the organisation.

Similarly, lack of infrastructure and security have inhibited the SANHO from placing additional tide gauges on the East Coast. The secondary port of Hermanus closes the South Coast gap with tide prediction being produced annually for this location.

3.6 CASE STUDY 2: Do the Current Tide Gauge Locations Sufficiently Cover the South Africa Coastline?

This case study was carried out by the author in their position of as the SANHO Superintendent Tidal Information. The aim of this case study is to determine if the current SANHO tide gauge network produces an adequate coverage of the South African coastline versus an ideal[4] tide gauge network and if there is a need for additional tide gauges to improve the current network. An extensive analysis of the recorded and predicted high tide (HT) and low tide (LT) times at both spring tide and neap tide was carried out. This analysis alone would be sufficient for the recreational/ leisure market, however for the broader maritime community the tidal heights would also need to be analysed.

3.6.1 Methodology.

a. Tide Timing.

To carry out a viable comparison, the South African coastline was "split" (Figure 27). Two major ports were selected and the remaining ports analysed in comparison to one of these two major ports. The two major ports that were selected were Durban and Cape Town. Where tide gauges were not installed, tide pole readings were used. Tide pole readings were gathered during various hydrographic survey operations, carried out by the SAS PROTEA (PRO), during the 19 years under analysis.

Port Nolloth, Saldanha Bay, Simon’s Town, Hermanus and Struisbaai were analysed in relation to Cape Town. Mossel Bay, Knysna, Port Elizabeth, East London, Port St John, Richards Bay and Kosi Bay were analysed in relation to Durban. The annual average times of HT and LT for both spring tide and neap tide for the ports were subtracted from the relevant major port over a nodal cycle of 18.6 years rounded up to 19 years and then averaged. An average of the time differences per port per spring/ neap tide was calculated. The tide times for Struisbaai, Port St

[4] In this case study the words “ideal tide gauge network” is a South African tide gauge network that contains additional tide gauges in the areas where large gaps currently exist within the current South African tide gauge network.

John and Kosi Bay were obtained from the SANHO historical survey reports, however no tide height information was available.

Figure 27 showing a cropped section of SANHO navigational chart SAN 27 (with permission SANHO) showing the ports where tide gauges are installed. The red line indicates how the coastline was "split". (Farre, 2019).

b. Tide Heights.

A similar process was applied for the analysis of the heights of the tide where all values are given in metres above Chart Datum (CD) (Table 2 and Table 3). The annual mean heights of HT and LT, for both spring tide and neap tide, for the ports were subtracted from the relevant major port over a nodal cycle of 18.6 years (rounded up to 19 years) and then averaged. The difference between each port's HT and LT or range over the springs/ neaps was then calculated. This analysis was only done for the major ports that SANHO collects data for as the accuracy of the height for the tide pole readings at additional locations could not be verified. In accordance with international standards and IHO recommendations, CD is Lowest Astronomical Tide (LAT) for South Africa (IHO, 2010).

3.6.2 Results

a. Tide Timing.

Table 2 shows the time differences between Cape Town and the various ports as per the coastline "split". The times of HT and LT for both spring tide and neap tide for various ports were compared to that of the same times for Cape Town. The results of the analysis showed that for Port Nolloth, Saldanha Bay, Simon's Town, Hermanus and Struisbaai, analysed in relation to Cape Town, that at Port Nolloth the average tide at both springs high and low, as well as neaps low were about 5 minutes behind Cape Town, with neap high tide taking place at the same time as that of Cape Town. The only time difference between Saldanha, Cape Town and Simon's Town was that neap high tide occurred 5 minutes after the other stations. Both spring and neap low tides occurred 5 minutes after Cape Town and the highs occurred at the same time. Struisbaai showed the largest time difference occurring 10 min before Cape Town at spring high and 5 min before at spring low, while neap high occurred at the same time with neap low 5 min after Cape Town.

Table 2: The time differences between the "standard" port of Cape Town and additional ports on the South West and West Coasts of South Africa in minutes.

PORT	SPRING			NEAP		
	HT	**LT**	**Average time Δ**	**HT**	**LT**	**Average time Δ**
Port Nolloth	-5	-5	-2.5	0	-5	-2.5
Saldanha	0	0	0	-5	0	-2.5
CAPE TOWN	0	0		0	0	
Simon's Town	0	0	0	0	0	0
Hermanus	0	-5	-2.5	0	-5	-2.5
Struisbaai	+10	+5	+7.5	0	-5	-2.5

The results of the analysis for the stretch of coastline from Mossel Bay to Kosi Bay, all in relation to Durban yielded interesting results (Table 3). When looking at the spring tides Durban, Port St John, East London and Port Elizabeth all experienced both spring high and low at the same time, while Kosi Bay, Richards Bay and Knysna only experienced spring low at the same time as the aforementioned locations. Kosi Bay and Richards Bay experienced spring high 5 min before Durban and Knysna 10 min before. Mossel Bay experienced spring high 5 min after and spring low 10 min after Durban.

The majority of the times for the neap tides yielded vastly different results to those at springs. Only Kosi Bay and Richards Bay experienced both neap high and low at the same time as Durban. Further down the East Coast to the South East Coast the times of neaps, both high and low, occur increasingly before Durban. The timing of neap highs increase from 10 min, and 5 min for neap low, before Durban from Port St John to 20 min before (and 10 min for neap lows) for East London, Port Elizabeth and Mossel Bay. Knysna, where the tide readings are taken inside the lagoon, experiences neap high 35 min before and neap low 20 min before Durban.

Table 3: The time differences between the "standard" port of Durban and additional ports on the South and East Coasts of South Africa in minutes.

PORT	SPRING			NEAP		
	HT	LT	Average time Δ	HT	LT	Average time Δ
Kosi Bay	+5	0	+2.5	0	0	0
Richards Bay	+5	0	+2.5	0	0	0
DURBAN	0	0		0	0	
Port St Johns	0	0	0	+10	+5	+7.5
East London	0	0	0	+20	+10	+15
Port Elizabeth	0	0	0	+20	+10	+15
Knysna	+10	0	+5	+35	+20	+27.5
Mossel Bay	-5	-10	-7.5	+20	+10	+15

b. <u>Tide Heights.</u>

Mossel Bay was shifted to be included in the analysis of the data in relation to Cape Town (Table 4) as the results from the time difference analysis placed doubt as to if Mossel Bay was analysed in relation to the incorrect major port. The results from both tables show that Mossel Bay's results were originally analysed within the correct group of ports, in relation to Durban, as seen by the over 0.36 m spring high, 0.20 m neap high and 0.18 m neap low difference with Cape Town.

Table 4: The height differences and the differences in Mean Seal Level (MSL) between the "standard" port of Cape Town and additional ports on the South West and West Coasts of South Africa in metres above Chart Datum, where negative values are heights below the heights for Cape Town.

PORT	LAT	SPRING			NEAP			Δ MSL
		HT	LT	Δ HT and LT	HT	LT	Δ HT and LT	
Port Nolloth	0	0.17	0.03	0.14	0.14	0.08	0.06	0.11
Saldanha	0	0.01	-0.01	0.02	0.01	0.00	0.01	0.01
Cape Town	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Simon’s Town	0	0.05	-0.01	0.06	0.03	0.03	0.00	0.02
Hermanus	0	0.04	0.01	0.03	0.03	0.05	-0.02	0.04
Mossel Bay	0	0.36	0.01	0.35	0.20	0.18	0.02	0.19

Table 4 shows the height differences between Cape Town and the various ports as per the coastline "split". The heights of both spring and neap high and low tides for various ports were compared to that of the same heights for Cape Town. The results of the analysis highlighted that Port Nolloth showed a significant jump in height difference of 0.17 m at spring high and 0.14 m at neap high. The difference between Cape Town and Port Nolloth during spring low was 0.03 m and neap low 0.08 m. Saldanha, Simon’s Town and Hermanus showed between 0.01 m - 0.05 m difference in spring and neap heights, with only Saldanha and Simon’s Town showing a -0.01 m height difference at spring lows. The analysis of the mean sea level (MSL) showed that Mossel Bay was an outlier and should not have been included in the Cape Town analysis group as the MSL difference between Cape Town and Mossel Bay was 0.19 m. Between Saldanha, Simon’s Town and Hermanus there was a MSL difference from Cape Town of between 0.01 m - 0.04 m. The MSL height difference between Cape Town and Port Nolloth was 0.11 m

The results of the analysis for the stretch of coastline from Mossel Bay to Kosi Bay, all in relation to Durban again yielded interesting results (Table 5). The spring lows for these ports were the same for Port Elizabeth, 0.02 m for East London and 0.01 m for Knysna. It is perhaps important to note that East London is South Africa’s only river port with the tide gauge located near the harbour entrance and the Knysna tide gauge is located on Thessens Island in the Knysna lagoon. Mossel Bay experiences spring tides between 0.05 m and 0.09 m difference to Durban. The neap tides in this series show a similar trend to the spring tides with only Richards Bay (0.12 m high and 0.10 m low) and Mossel Bay (0.10 m high and 0.09 m low) having higher tides than Durban. East London, Port Elizabeth and Knysna all have lower neap highs and neap lows than Durban with East London being the lowest with a high tide of 0.11 m and a low tide of 0.09 m lower than Durban. The MSL values show a similar trend in this analysis.

Table 5: The height differences and the differences in Mean Seal Level (MSL) between the "standard" port of Durban and additional ports on the South and East Coasts of South Africa in metres above Chart Datum, where negative values are heights below the heights for Durban.

PORT	LAT	SPRING			NEAP			Δ MSL
		HT	LT	Δ HT and LT	HT	LT	Δ HT and LT	
Richards Bay	0	0.10	0.06	0.04	0.12	0.10	0.02	0.09
DURBAN	**0**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
East London	0	-0.19	0.02	-0.21	-0.11	-0.09	-0.02	-0.09
Port Elizabeth	0	-0.15	0.00	-0.15	-0.07	-0.08	0.01	-0.07
Knysna	0	-0.10	0.01	-0.11	-0.04	-0.05	0.01	-0.05
Mossel Bay	0	0.09	0.05	0.04	0.10	0.01	0.09	0.06

3.6.3 Assumptions

From the analysis of all the data, summarised in the above tables, as well as fair charts ("…*the final, carefully made plot of a hydrographic survey…"* (IHO, 1994:84)) (Figure 32) and survey reports viewed, it was surmised and confirmed by Rautenbach, Barnes & de Vos (2019) that the width of the continental shelf and gradient of the continental slope plays a significant role in the timing and heights of the tides between locations (Figure 10).

It is postulated that the minimal time and height changes from Port Nolloth to Struisbaai can be attributed to the width and gentler angle of the continental shelf, whereas the large and varied results in Table 5 and Table 3 from Kosi Bay to Port Elizabeth can be attributed to the narrow width and steep angle of the continental slope from Kosi Bay to Port St Johns. From East London to Knysna the slope angle decreases marginally and the continental shelf widens. This postulation is supported by work done by Cram (1979) who proved that Redfield's hypothesis from 1958 that the tidal range increases with an increasing width of the continental shelf (Redfield, 1958). The areas that were researched showed a linear relationship between the tidal range and the width of the continental shelf that varied from area to area (Cram, 1979).

Knysna can be viewed as an anomaly, the data collected for all other locations was gathered in harbours along the coastline, whereas Knysna's data was gathered within the lagoon. This possibly explains why the results do not fit into the trends seen for the analysis of the time and height differences in the Durban series.

3.6.4 Conclusion.

As can be seen from the results of the analysis (Table 2 and Table 3) there is an approximate 30 min time difference between the timing of the tides between the west and south west coast and the south east and east coast. It was postulated that this was attributed to the thickening of the continental shelf into the Agulhas Bank and that the tides in these areas are essentially a standing wave. This was validated by the model created by Rautenbach, Barnes & de Vos (2019). Additionally from Figure 5 the amphidromic point, resulting from larger-scale tidal dynamics, positioned to the south west of South Africa may have a large influence on the timing difference.

From all the data analysed, in terms of tidal height and times it is evident that the current SANHO tide gauge network is not ideal. Ideally a minimum of 2 additional tide gauges should be installed – one between the ports of Saldanha and Port Nolloth and one between Durban and East London. However, Case Study 2 shows that, although the current SANHO tide gauge network may not be ideal, it is providing adequate coverage of the tides around the coastline. Inclusion of the 2 additional tide gauges may not be practical due to various constraints as discussed previously.

Upon completion of implementing a functioning tide gauge network, as described in this chapter, data collection can commence. The recorded data collected needs to be analysed and quality control checks performed. The data can then be used in the creation of tidal predictions for the mariner and distributed, as requested, to the scientific community.

Chapter 4 - Analysis of collected data and Tide Predictions.

The analysis and prediction process of the tide data gathered from the tide gauges is an important process, specifically ensuring that it complies with international standards and compares with other international HO's. This is the precursor to how tides are used to increase maritime safety around the South African coastline.

Although historically the SANHO was responsible for the tide gauges in Namibia they are now under the control of the Namibian Ports Authority (NAMPORT) and will not be included or discussed as part of the SANHO tide gauge network. The SANHO calculates and produces the Namibian tide tables for publication within the South African Tide Tables, from the data recorded by NAMPORT and supplied to the SANHO. After collection of the actual observed recordings from each tide gauge, it is necessary to carry out quality control validations on the data. The SANHO carries out a basic quality control bi-weekly by visual inspection of a graphical representation of the recorded data overlaid with the predicted data for the same period. This process allows for minor errors to be corrected or equipment faults to be identified early and repaired.

This chapter will focus on the methods employed in order to carry out the validation, analysis and processing of a full year's worth of tidal observations, focusing on the software used by the SANHO. Case study 3 evaluates the process used in the SANHO software whereby missing observed tide heights within a data set are replaced with predicted tide heights and the validity of this process. Case study 4 highlights the importance of international cooperation in validating and accessing the accuracy of the SANHO's in-house tide prediction software in line with international standards. Finally this chapter will look at the distribution of the tide predictions created by the SANHO in accordance with IHO standards and South African Law.

4.1 Analysis of Recorded Data.

All established Hydrographic Offices (HO) use their own in-house software. Newer HO's are using more commercially available software to process their tide data. Most of the established HO's in-house software uses the Harmonic analysis method (originally written in Fortran programming language now being converted into Python). The SANHO Tidal Office software consists of various main menus, each with their own processes, the most important being the Analysis, Predictions and Utilities menus (more details are found in Appendix F).

The analysis portion of *Tidal Office* must be completed first before preceding to create the predictions. The current year's data is used to predict the tides for each port for 2 years in advance. For example 2018 raw data is analysed and then the 2020 predictions are created. The analysis portion of the software, once all the port information has been input, allows for any significant calibration factors to be applied. The original input data before the reference level adjustment was made is then corrected by the calibration factor.

The raw 1 or 3 minute data, dependent on the sample rate, collected from the tide gauges is converted into hourly data. An average, using the 9 minutes' worth of readings before the hour, the hour reading and the 9 minutes' worth of readings after the hour, is calculated to create the hourly values. All the original raw data is stored and backed-up on the SANHO tidal archives database. The raw calculated hourly data is then pulled into the *Tidal Office* system and analysed for deviations. The deviations are then calculated using a Lagrange polynomial fit with 4 points being used to calculate the centre point (Abrahams et al, 2006). The deviations are marked and individually investigated. "Bad" data is then assessed before being removed. "Bad" or anomalous data can be due to faults in the tide gauge or, in the recent case of Port Elizabeth, a vessel anchored under the tide gauge.

Prior to 2010, each possible deviation identified was hand graphed and the deviations analysed in conjunction with the raw data. Anomalous data was them removed or replaced with the hand graphed values. This introduced human error and interpretation into the data sets and was an extremely time consuming process. In 2010 a script was created that allows the user to fit a 3rd order polynomial curve through a set of 4 values by entering the times and then requesting the correct value for an entered time to be added to the *Tidal Office* as a utility (Abrahams et al, 2010). Deviations, upon inspection and comparison with the raw data graphs, can be graphed mathematically and the end user can, if necessary, insert/edit the calculated value in the observed hourlies file. Once the deviations and anomalies have been removed from the data, any required calibrations are then applied to the observed heights file.

The mean tidal level for each day is calculated using a 25 point mean. The monthly and yearly means are then calculated and checked. These means are only calculated for the data that was collected, for example if a month only has 20 days' worth of hourly observations the mean will only be calculated for those values (Appendix G). The missing heights within the datasets are then calculated and these predictions are inserted into the data set under analysis. The value of this method is discussed in Case Study 3.

4.2 CASE STUDY 3: Investigation into the accuracy of the tidal data where missing data is replaced by predicted data.

This case study was carried out by the author in their position as the SANHO Superintendent Tidal Information. The SANHO Tidal Office system is based on the principle that every year of data, for each port, is analysed to extract the 51 tidal constituents used for South Africa in order to produce the tidal predictions for following years. This analysis works on the assumption that a complete set of 8 760 hourly values per port is available. The software calculates the predicted missing hourly heights for each of the ports and inserts the values in order to provide a complete set of data for that port.

The validity of this method needs to be assessed. It could be assumed that the insertion of the missing heights with predicted height could possibly distort the entire tidal data set and, as a result, the extracted tidal constituents. In order to either verify the results or show them to be inaccurate, an investigation was carried out to determine the validity of this practice.

4.2.1 Method.

Using a complete years' worth of data, an interval of missing data was located and the end points of the interval identified, being the last recorded value and the first recorded values on either side of the missing data interval. The predicted values were then inserted into the interval required based on the predictions for this year using previous data.

The missing values within the interval were calculated. The first and last missing data points were calculated using the least squares method over 11 points. This was done irrespective of the amount of data missing. The difference between the calculated values and the predicted values was determined.

Where no missing data intervals for a port were found, a copy of the file was created and data removed to create missing data intervals. This was done as a secondary check on the accuracy of this method. The calculated values were compared with the actual observed values that had been removed.

4.2.2 Assumptions.

If the difference between the calculated value and the predicted value was less than (or more) than 5% of the predicted value, it was assumed that the predicted value must lie reasonably close to what the actual value would have been on the tidal curve. The predicted values were then adjusted to the calculated values across the interval.

4.2.3 Results.

Of all the missing data intervals, less than 4% of the predictions needed to be adjusted to be more in line with the calculated values, or actual recorded values where full dataset were available. Of the remaining 96% of the data analysed, in no instance did the predicted values and calculated values differ by more than 5% and thus no need for adjustment was required.

4.2.4 Conclusion

Where an interval of missing data was found to exist, the first and last missing data point was calculated by applying the Least Squares Method to the existing data on either end of the interval. These calculated values were then compared to the predicted values which had been inserted into the interval. It was found that in most cases the difference between the calculated value and the predicted value was less than 5% of the predicted value and it could therefore be assumed that the predicted value lay reasonably close to what the actuals would have been.

In the few cases where the difference between the calculated value and the predicted value was found to be greater than 5% of the predicted value, the predicted values were adjusted across the interval but these adjustments were never significantly high. From Case Study 3 it can be assumed that where the missing tidal data is replaced by predicted values, the degree of accuracy is acceptable. In cases where extremely large gaps exist within the raw data the data is not used and the tidal predictions for the following years are created from historical data.

The *Tidal Office* software is used to calculate the annual extremes, and the constituents per port are then calculated for the year under analysis. The vectoral means of the tidal constituents for each port for the year being processed, as well as all the years available within each port's historical record is calculated, and then averaged to produce the final constituents to be used in the tidal prediction process. The resulting report is then checked and compared for accuracy with the IHO TWCWG constituent database (IHO, 2019). The report also shows the results of combining the sets of constituents, per port, by the method of weighted vectoral means, analysis of variation in mean amplitudes, analysis of variations in local lags and a summary of results for the principal harmonic constituents for M2, S2, K2, O1 and K1. The information per port is then used to calculate and display Indian Spring Low Water (M2+S2+K1+O1), Mean Spring Low Water (M2+S2) and Lowest Possible Low Water (1.2*(M2+S2+K2)) in metres above chart datum.

Finally the residuals are calculated and a histogram visualisation of percentages of occurrences for each port is created for verification and analysis.

4.3 Calculation of the Tide Predictions.

Upon completion of the analysis of the annual data per port, the prediction portion of the software is used to create the various outputs required to create the annual publication the South African Tide Tables (SAN HO-2), the website formats and various predicted tide outputs as required by various clients. Over the years additional scripts have been written (using the original Fortran programming language) to create additional outputs such as to annually calculate the Mean Low Water Springs (MLWS), Mean Low Water Neaps (MLWN), Mean High Water Neaps (MHWN) and Mean High Water Springs (MHWS) values, as well as to annually confirm the calculations of HAT and LAT (Abrahams et al, 2017).

The SAN HO-2 is created and printed by the Naval Publications Unit (NPU) in Simon's Town and is done 2 years in advance to facilitate international and national distribution. As the SANHO software has been created to produce various, specific prediction outputs, various products are then created through desktop publishing processes. For example the format displayed on the SANHO website and the formats used by various SANHO clients.

Most commercially available programs do not have the versatility and quantity of outputs that in-house software does and the analysis and prediction software are 2 individual software packages. The software annual licences for each package can be quite costly. The Analysis software only extracts the tide constituents for the data sets and can often only handle a data set of 1 year at a time. More expensive software is available for longer time series data sets, however even these are not often able to handle more than 20 years of data. The commercial prediction software only creates one standard output, this being the internationally accepted format (IHO, 2010) for tide predictions as published in any tide tables (Appendix H).

The use of specially designed in-house software is that the applications are endless and specialised to the needs of each HO. Additionally the software can be used for specialised projects as well. For example, the SANHO was approached by a member of the Simon’s Town Historical Society who was doing a talk on a naval battle that took place in 1795 in False Bay. In order to portray the battle more accurately, it was queried if it was possible to obtain the tides for that period. The in-house software was used to back predict the tides successfully. The Historical Society was given the approximate times of the high and low tides and advised that as the weather conditions were not known, the actual sea levels could not be estimated. Feedback received from the speaker indicated that the information supplied aided in a very successful talk, which was yet further proof of the versatility of in-house developed software over commercial applications.

4.4 Standard of the SANHO In-house Software.

As discussed above, all established HO’s use their own in-house software, however the software is not standardised or validated. Developing nations HO's, who do not have the programming specialists or funding to create in house software are encouraged by the IHO to use their bi-lateral agreements with IHO Member States to gain assistance with the development of their own software over commercially available products. Case study 4 assesses the SANHO and 2 additional HO’s in-house tide prediction software to determine if the standards and accuracies are in line with those required by the IHO.

4.5 CASE STUDY 4: The comparison of in-house software at international HO’s.

4.5.1 Introduction.

This case study was carried out by the author in their position of as the SANHO Superintendent Tidal Information. In 2011 the IHO Tidal committee, now the Tides, Water Level and Currents Working Group (TWCWG), embarked on a project to establish the accuracy of these in-house softwares. The participating countries (South Africa, United States of America’s (USA) National Oceanic and Atmospheric Administration (NOAA) and the United Kingdom Hydrographic Office (UKHO)) shared data sets and carried out the analysis and prediction of the participating countries datasets using their software and their country specific constituents.

4.5.2 Method.

The project required the participating countries to compare the harmonic analysis and predictions generated from analysis of the same data set using their own in-house software. One of the data sets was for the USA (NOAA) tide station in Boston for 2010. The USA (NOAA) performed the harmonic analysis using their 120 constituents. The UKHO performed the harmonic analysis using their 86 constituents. South Africa performed the harmonic analysis using their 51 constituents.

The SANHO received a set of actual and predicted tide data for Boston from the USA (NOAA). The SANHO software uses actual data accurate to 1 cm for analysis and predictions are done to 1 cm accuracy. The data was extracted from the supplied file, rounded to 1cm accuracy and reformatted to the standard input format used by SANHO. The Harmonic analysis was carried out on the resultant file, using the 51 constituents used by South Africa, using vectoral mean calculations. The calculated constituent values were then used to do the predictions for Boston for 2010. The file was then reformatted and residuals calculated. The results were analysed and compared with the predictions supplied by each participating country with their datasets.

4.5.3 Results.

The resultant report produced included the predicted values that were received from the USA (NOAA) and the predicted values that were calculated by the SANHO, with a final average difference of 0.005 m. The USA (NOAA) calculated an average residual of 0.002 m.

The differences could be attributed to any or all of the following reasons.

a. The rounding off of the actual values to the nearest cm that was required by the SANHO Analysis and Prediction Program.

b. The tidal constituents calculated by the SANHO program only had one year of data to calculate the tidal constituents from.

c. The SANHO Tidal Office software can only work with the 51 constituents that South Africa use for the analysis of their tides. Thus the predicted tides created for Boston was calculated using only 51 tidal constituents instead of the 120 constituents calculated and used by the USA (NOAA).

The UKHO carried out a similar process on the Boston data set as South Africa, using their in-house software, using 86 constituents and the results were consolidated (Figure 28).

The UKHO, the USA (NOAA) and South Africa each calculated the Harmonic constituents from the Boston data. Of the common constituents, only 2 (µ2 and L2) calculated by the UKHO had a significant variation in their phases from those calculated by the USA (NOAA) and South Africa. The results of the Boston Data set comparison (Table 6 and Figure 28) between the USA (NOAA) and the UKHO, and the USA (NOAA) and South Africa predictions showed very similar results and all are within accepted IHO standards. The IHO's *Manual on Hydrography* (Publication *C-13*, Chapter 3) details the acceptable error budgets for consideration when working with tides and water levels information. The accepted error budget for measured tides allows for "…*0,10m at the 95% confidence level"* (IHO, 2011) where the confidence level is defined as "*The probability that the true value of a measurement will lie within the specified uncertainty from the measured value*…" (IHO, 2008)[5]. This error budget is subsequently applied to the predicted tides as well.

Table 6 Showing the Q-C Statistics between the USA (NOAA), the UKHO and South Africa for the analysis of the Boston data set using differing in house software and different number of harmonic constituents in metres (Gill, Farre & Jones, 2012).

Q-C Statistics	USA (NOAA)-UK comparison	USA (NOAA) - SANHO Comparison
Average Difference	0.005	0.005
Standard deviation	0.038	0.032
Maximum Difference	0.131	0.103
Minimum Difference	-0.121	-0.083

[5] The SANHO attempts to record data in accordance with the 1cm accuracy as per GLOSS standards and archives data to be made available for use by researchers

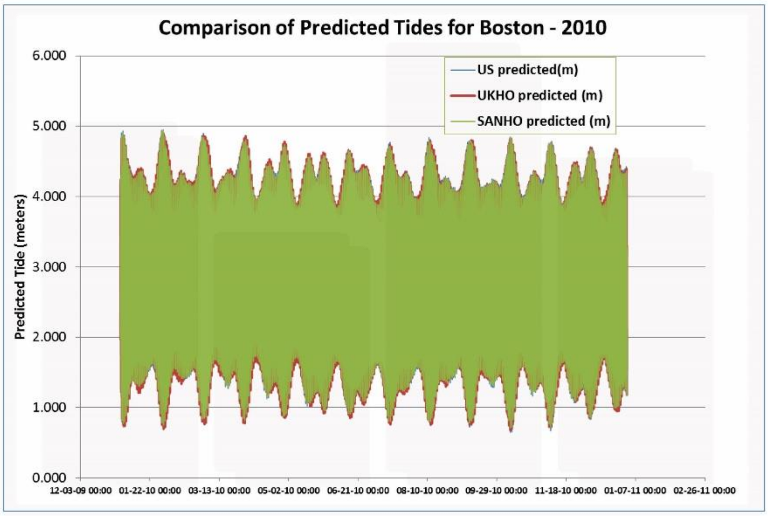

Figure 28 highlighting the closeness of the comparison of predicted tide for the Boston Data set using USA (NOAA), UKHO and South Africa in-house analysis and prediction software (Gill, Farre & Jones, 2012).

The analysis of only one data set from one country was not sufficient to show that each nation's in-house software was comparable. Thus in addition, South Africa supplied a 1 year data set for Port Nolloth for 2010 along with the calculated 51 constituents to the USA (NOAA), the UKHO was unable to partake in this investigation. The USA (NOAA) and South Africa carried out the predictions using their own software, with the calculated values for the common constituents supplied by South Africa and compared the results with those from the USA (NOAA) (Table 7 and Figure 29). South Africa's results were more accurate as they used the correct constituents, as extracted via harmonic analysis, from the data under analysis for the area under investigation. The comparison of the raw data and the predicted data, under normal atmospheric conditions re-enforced South Africa's accuracy of the predictions.

Table 7 showing the Q-C Statistics between the USA (NOAA) and South Africa for the analysis of the Port Nolloth data set using differing in house software and different number of harmonic constituents in metres (Gill, Farre & Jones, 2012).

Q-C Statistics	USA (NOAA)-SANHO Comparison
Average Difference	0.091
Standard deviation	0.009
Maximum Difference	0.118
Minimum Difference	0.064

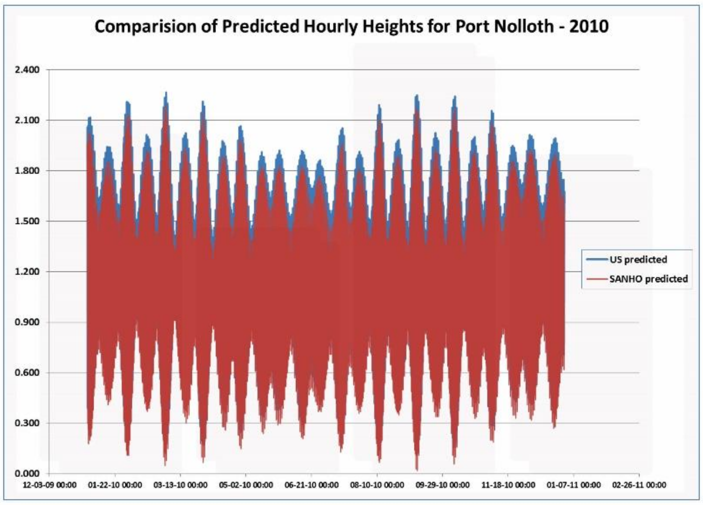

Figure 29 compares the predicted tide for the Port Nolloth data set using the USA (NOAA) and South Africa in-house analysis and prediction software (Gill, Farre & Jones, 2012).

4.5.4 Conclusion.

The results achieved from the analysis and prediction of the Boston tides by the South Africa and the UKHO yielded very similar results. The average difference between the USA (NOAA) and the UKHO results was 0.005 m with a maximum difference of 0.130 m and a minimum difference of 0.121 m. The average difference between the USA (NOAA) and South Africa results was also 0.005 m, however the maximum difference of 0.103 m and a minimum difference of 0.083 m indicated that South Africa's in house software yielded results more in line with the IHO accepted standards than the UKHO's in-house software.

The analysis of the results the Port Nolloth data set comparison between the USA (NOAA) and South Africa predictions showed an average difference of 0.091 m, this is still less than the IHO's accepted error budget of 0.100 m, a maximum difference of 0.118 m and a minimum difference of 0.064 m, were also still within accepted IHO norms. It was surmised that the differences were possibly due to the increased number of constituents required by the USA (NOAA) software, greater/ more advanced computing power used or even a difference in the number of rounding digits in use.

Case Study 4 shows that although the above exercises were valuable, the number of participating countries was considered to be too small. In 2017 this project was revived by the TWCWG and the current software comparisons are now being carried out by over 10 participating countries. This project is a standing action item for the TWCWG and is reported on every 2 years with additional datasets being included for comparison.

4.6 Supply of Tide Predictions.

Upon completion of the creation of the analysis of the data, the calculation of the predictions, the creation of the SAN-HO2 and various tide products, distribution of predicted tide products and actual data can commence.

As the SANHO Tide Tables (TT) are a national publication, each copy has a unique ISBN number and copies must be supplied to the South African National Libraries. Additionally the Harbour Masters and Port Engineers of all the major ports in South Africa, as well as all relevant military vessels and units are issued with complimentary copies of the TT (more details are found in Appendix I).

Tide predictions are extremely important in producing additional navigational products. The mariner and the military, specifically Navies, rely heavily on the use of tide and navigational information for safe passage and military operations.

Chapter 5 – The Value of Tides in the Maritime Environment.

Given the details of developing a national tide gauge network, this chapter will focus on the value of accurately measured tides and subsequently the resultant predictions and hence the need for such networks. The main focus will be on maritime safety, how tides are invaluable together with accurate bathymetric depth readings for navigational chart production. The importance of tides in shallow water navigation and clearances will be discussed with an emphasis on submarine and mine warfare shallow water operations.

5.1 Nautical/ Navigational Charts (Chart).

A nautical chart[6] is a legal, living document considering the safety application thereof in terms of SOLAS. The monthly and annual Notices to Mariners (NTM), distributed by the relevant Hydrographic Offices state the charts with their associated numbers, along with the relevant coordinates, where hazards to navigation need to be added to or corrected on the chart in the mariner's possession. These "corrections" can relate to a variety of hazards for example the installation of a permanent buoy, undersea cables, a new wreck or a wreck that has moved, changes in depths due to sediment movement, dredging or dumping. Temporary NTM's, such as a "no-go" area due to survey operations, temporary buoys or well drilling, do not have to be added to the chart.[7]

Before a new edition or new nautical chart (paper or electronic nautical chart) can be created a hydrographic survey of the area needs to be undertaken. The main purpose of a hydrographic survey is to collect and collate the necessary information for the creation of a navigational chart and associated navigational publications, with an emphasis on any features that could affect the safety of navigation (IHO, 2011). The National Hydrographer establishes

[6] A navigational or nautical chart is a graphic representation of the ocean for a specified area "*…that shows the nature and form of the coast, the depths of the water and general character and configuration of the sea bottom, locations of dangers to navigation, the rise and fall of the tides, locations of man-made aids to navigation, and the characteristics of the Earth's magnetism*" (IHO, 2011:68).Dependent on the scale of the chart, which additionally is limited by its physical size, the detail displayed on the chart will vary. Due to the nature of the environment being charted or mapped, with the majority of the features and hazards submerged by water, the level of accuracy required is far greater than that required for terrestrial maps.

[7] In accordance with IHO standards, Temporary Notices (TN) are for maritime operations lasting less than 6 months therefore they are issued as temporary notices to mariners. Often the mariner will pencil this into their charts however for an HO to do this will be extremely costly and time consuming (especially for smaller HOs with limited resources) to keep having to produce new editions for paper charts with TNs. Additionally to correct already printed stock and then remove the TN will make the chart extremely messy and cluttered. TN's are applied to Electronic Navigational Charts (ENCs) and removed once the TN is cancelled.

the area in need of surveying, a Hydrographic Instruction (HI) is submitted to the Survey department for action. The HI will have a specific order or category, stating the area to be surveyed and outlining the exact requirements of the data needed to be collected. In accordance with the *IHO Standards for Hydrographic Surveys Special Publication No 44* (S-44) there are 4 orders of survey, each with its own requirements and acceptable error budgets (IHO, 2008).

Upon execution of the HI, a Hydrographic Survey Vessel (HSV) fitted with either a single-beam echo sounder (SBES) or a multi-beam echo sounder (MBES) (Figure 30), will carry out bathymetric sounding data collection by sail tracks or lines up and down the specified coordinated area of survey (Figure 31). Should the area or portions of the area to be surveyed be too shallow for adequate under-keel clearances of the HSV, smaller motor boats (Survey Launches) fitted with hydrographic survey equipment will be launched for data collection. Most modern HSV's and Survey Launches are fitted with MBES which allows for high density bathymetric (water depth) data to be collected. During a hydrographic survey georeferenced data of the shoreline including any features that may be of interest to the mariner, water depths of the area, sea floor composition, tide stream and current data as well as the physical properties of the water column are collected and processed.

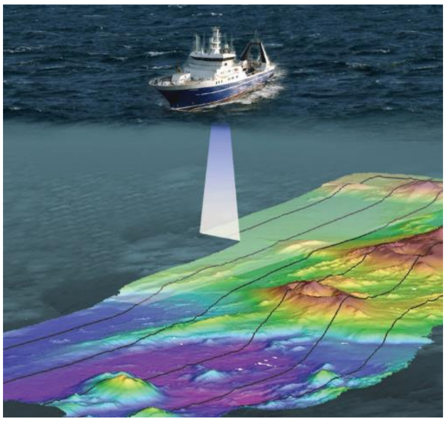

Figure 30 is a Hydrographic Survey vessel, fitted with a MBES, sailing lines collecting bathymetric information. (https://niwa.co.nz/our-science/oceans/bathymetry/further-information)

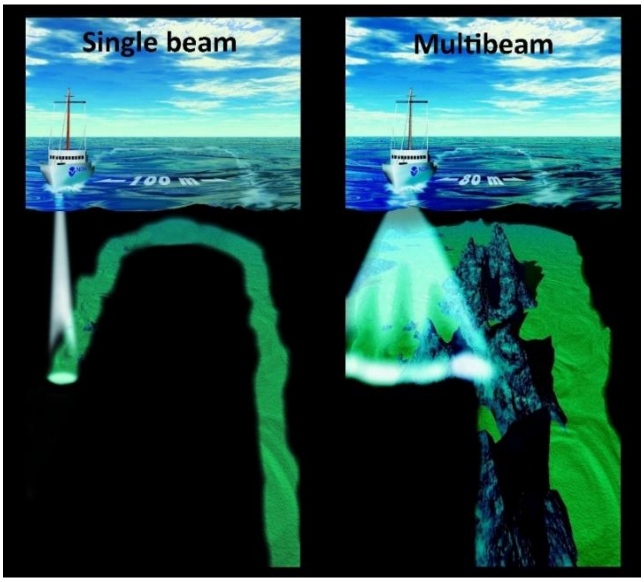

Figure 31 is a Hydrographic Survey vessel collecting bathymetric soundings in lines using SBES and a MBES (Abadie, Marty and Viala, 2017).

During the sailing of the survey lines, the bathymetric sounding data is influenced by the pitch, roll and heave of the survey vessels, subsequently needing to be post-processed to exclude these factors. Additionally in waters less than 200 m in depth (IHO, 2008), as the tide correction becomes marginal for depths more than 200 m, the soundings recorded include the rise and fall of the HSV with the rising and falling tide respectively. These depth soundings need to be reduced for tides in order to obtain accurate depths. As per the IHO dictionary "*reduction of soundings* [is] *the correction of the observed depths, for the height of tide above or below the plane of reference at the time of sounding. Usually the term reduction of soundings does not cover corrections other than those due to tide…*" (IHO, 1994).

Upon completion of the hydrographic survey, the reduced soundings are used to create a graphical representation of the survey called a Fair Chart ("…*the final, carefully made plot of a hydrographic survey….the fair chart is plotted from corrected data and represents the official permanent record of that particular survey. Also called fair sheet…"* (IHO, 1994)) (Figure 32). The softcopy of the reduced bathymetric soundings, the Fair Chart and a report of survey containing details of the survey process and additional data collected is submitted to the National Hydrographic Office to be used in the creation of a new navigational chart or updating of existing charts.

During post-processing of the bathymetric data, sounding reductions are carried out using predicted tides. This indicates that the collection of accurate tides and subsequent production of accurate tide predictions is the first step in producing accurate navigational charts. This is particularly evident where under-keel (and masthead) clearance in the approaches to harbours become a critical factor for cargo ships entering and leaving port.

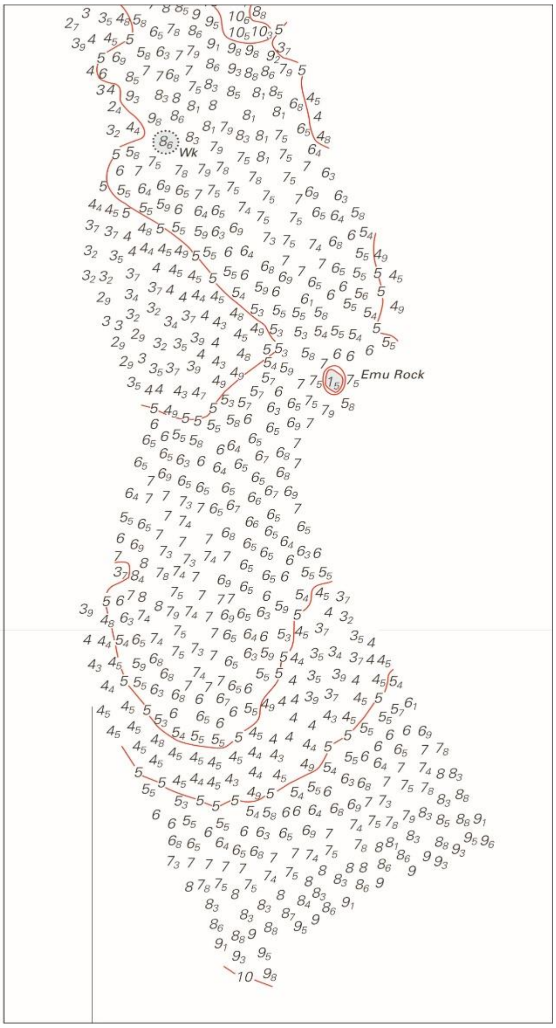

Figure 32 is a cropped portion of fair chart FC 255 – HI 064(S) Knysna Lagoon (Appendix J) showing the post-processed water depths, in metres and decimetres, recorded along the survey tracks.(with permission SANHO) (Farre, 2020).

5.2 Tides in Shallow Water Navigation and Overhead Clearances.

“The primary purpose of nautical [/navigational] *charts is to provide the information required to enable the mariner to plan and execute safe navigation. In constructing charts and selecting content it is therefore important to understand the mariner’s need for appropriate, relevant, accurate and unambiguous information*” (IHO, 2018:43).

Safety is critical, especially during shallow water and overhead clearances navigation. As per the IHO Technical Resolution A2.5 reference 3/1919 as amended 10/2017, paragraphs 6 and 7 (IHO, 2020:61) the datum on all navigational charts, Chart Datum (CD) is recommended to be Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT) be adopted as the datum for vertical clearances (IHO, 1994:59). CD is the datum to which the soundings on all large scale navigational charts are reduced (SANHO, 2020).

In accordance with the IHO's publication S-4, *Regulations of the IHO for International (INT) charts and Chart Specifications of the IHO*, the colour blue must be used to indicate and consequently emphasize areas of shallow water on a chart. An additional darker tint of blue may be used to show a distinction between shallow water and shallower water (Figure 33). Blue may also be used in intricate waters for the depth contours (IHO, 2018:63). All depths and heights are indicated in metres (m) or decimetres (dm) (IHO, 2018:59).

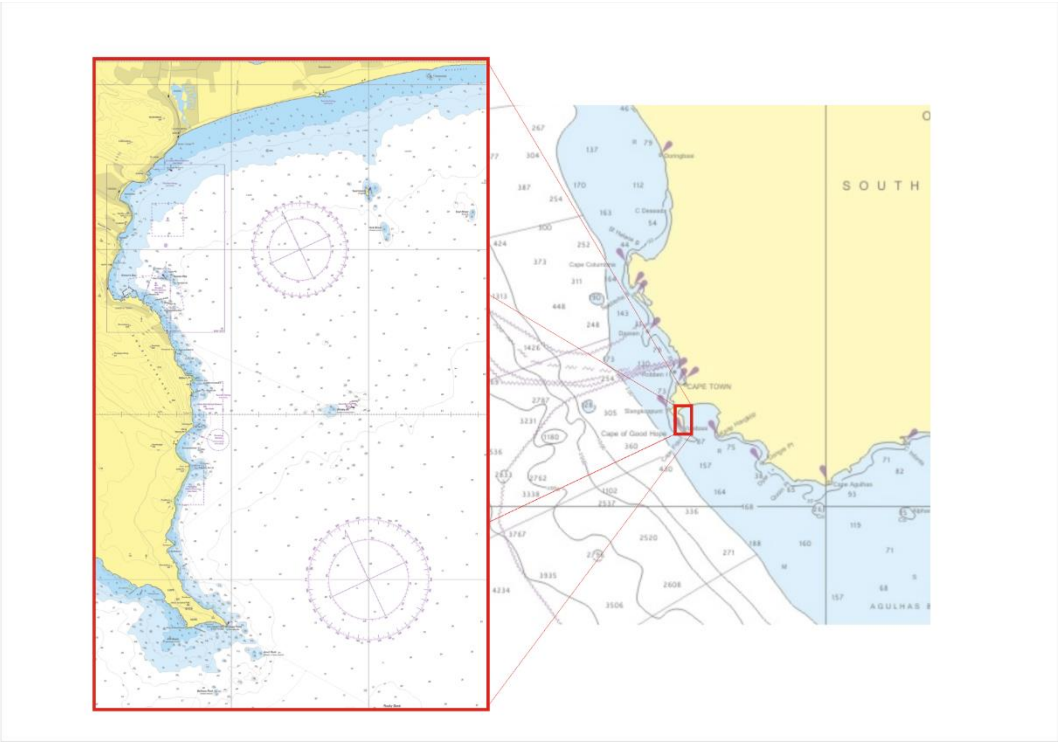

Figure 33 is a portion of SAN 1 with a portion of SAN 1016 (with permission SANHO) used in the enlargement to show shallow and shallower waters depths in 2 shades of blue as per IHO specifications (Farre, RE, 2020).

For the Mariner it is important to know that all depths indicated on a chart, still having to have the height of tide added for the actual depth of water at any given time, depending on the height of tide information provided for a particular city/town along the coast, at the said time on a given day.

In Salvage Operations it is vitally important to know when a grounded ship ran aground and what the state of tide was when the grounding took place. When the Salvage tug begins attempts to pull the stricken vessel off a sandbank or place of grounding, the timing of recovery is dependent on when the tide is at its maximum i.e. probably during a Spring High Tide. Prior to this, if required, ballast water, fuel and fresh water can be pumped off to reduce the vessel displacement, to assist in lightening the vessel for easier extraction from where it is grounded.

The navigator of a surface vessel/ship is required to pay particular attention to the depth soundings, on a navigational chart, for areas where reefs, rocks and shallows constitue a possible danger and plan accordingly. Shallow waters are of particular importance when nearing land with the intention of entering a harbour. In order for the navigator to establish a safe route in shallow water he/she is required to ensure that there is sufficient water under the vessel at all time to avoid running aground. This is known as the under keel clearance, which is calculated by adding the height of the tide at the time of passage, to the charted depth and subtracting the ship's draught (Figure 34). The ship's draught is affected by the additional displacement as a result of the weight of the cargo and the amount of fuel on board. The heavier the vessel, the greater the displacement draught resulting in a smaller under-keel clearance.

Scientific or Hydrographic vessels, with hull mounted sensors, will calculate their under-keel clearances using their navigational draught as opposed to their displacement draught. Under-keel clearances have become of extreme importance to the merchant maritime community. Exact knowledge of the minimum amount of water that a vessel can sail in before departure will determine the weight of the cargo that a vessel can carry, additional cargo weight can have greater economic reward for the cargo carrying company. The port authorities of any commercial port require knowledge of the draught of any large commercial vessel preparing to enter port, so as to ensure the vessel will not exceed the depth of water in the port which would result in the vessel going aground while entering. Port Pilots who manoeuvre these large vessels into a port, also need to be advised on the ships draught, as underwater clearance affects the vessel's manoeuvrability, whilst bringing the vessel alongside. Knowledge of the tides, by the Port Pilot, ensures vessel safety for under-keel clearance and the best anchorage points within the harbour.

The Captain of any ship proceeding into any port or anchorage will require the navigator to provide the height of the tide when going alongside any quay within a harbour. Of primary importance is to ensure the vessel has the required underwater keel clearance and secondly, to determine that the quay height will be sufficient in relation to the vessel's deck height. Additionally, while the vessel is alongside, the rise and fall of the tide will affect the berthing hawser safety and control. The vessel's duty personnel are made aware of the tidal range and rise and fall of the tide in order to maintain adequate control of hawser/ mooring ropes while the vessel is alongside (pers comm: Capt (Ret) P. Louwrens). During the design and building of a vessel's gangplank or companionway, the tidal range and quay heights are carefully considered in order to ensure the gangplank is the correct length. In the case of vessels originating from areas with minimal or a small tidal ranges, gangplanks may not reach the quay when visiting a port with larger tidal highs and lows, resulting in a safety hazard to personnel.

In some areas of the world, bridges or overhead cables span above navigable areas such as fjords, channels, rivers or inside harbours. In these areas, the tide becomes of greater importance than just for the calculation of under-keel clearances, masthead clearances also need to be considered. The masthead clearance is calculated as the distance between the top of the mast of any ship/vessel and a bridge at a specific time, so enabling the vessel to sail safely under the bridge or any other number of overhead obstructions (IHO, 1994). The height of the ship from the waterline to the top of the mast (Figure 34, HM) is known by the navigator, it is vessel class specific[8]. The height HM needs to be adjusted to take into account the additional displacement as a result of the weight of the cargo and the amount of fuel on board.

The IHO chart specifications and technical resolutions recommend that where vertical clearance requirements for overhead obstructions are indicated on a navigational chart, the height of the clearance is to be given in relation to the Highest Astronomical Tide (HAT) or a datum similar to HAT. All vertical clearances, under 10 m, must be rounded down to the nearest whole metre in order to indicate the predicted minimum safe clearance thus erring on the side

[8] In accordance with the Safety of Life at Sea (SOLAS) Convention all vessels/ships will be classified, by a recognised classification organisation such as the International Maritime Organisation (IMO). This classification is based on the design, construction and maintained in compliance with the structural, mechanical, electrical and safety requirements of a specific vessel class (IMO, 2020)

of safety and giving room for increased actual water levels due to meteorological effects (IHO, 2018). The height of HAT in relation to CD will be published in the notes of the chart, the relevant National Tide Tables, along with the predicted height of the tides in relation to CD.

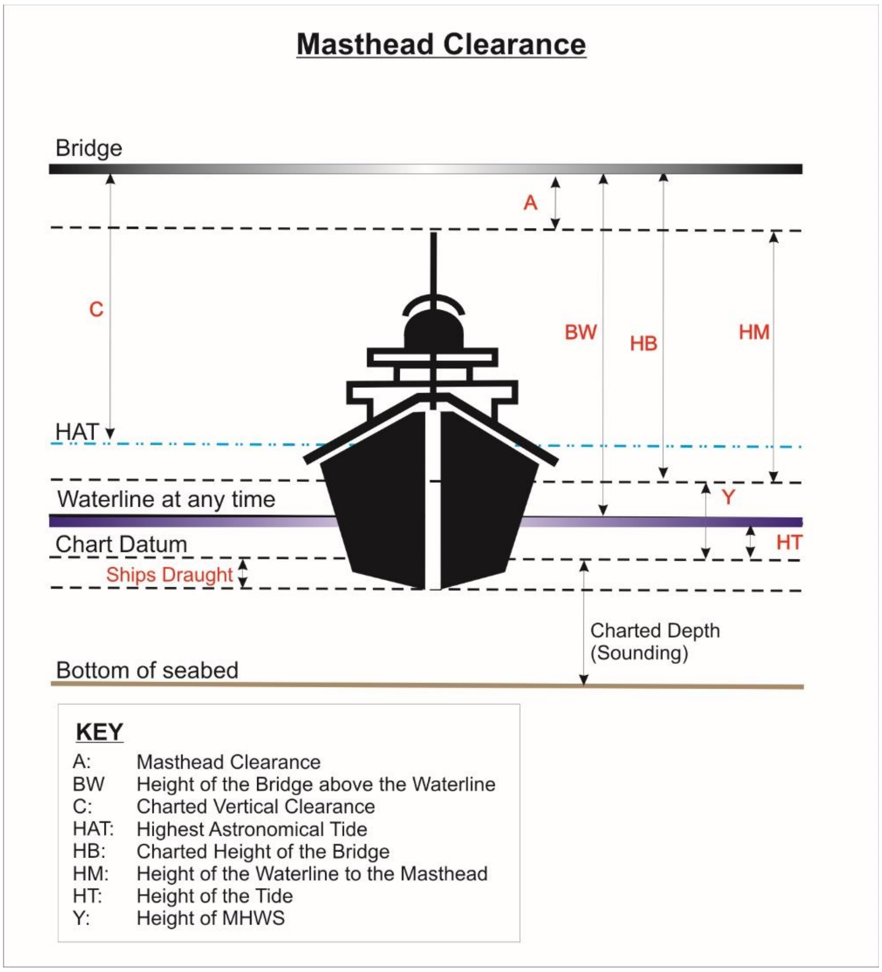

Figure 34 is a graphical representation of the information required for masthead clearance and under keel clearances in shallow water navigation. Adapted from diagram Masthead Clearances (SAN, 2011) and IHO publication S4 (IHO, 2018:192) (Farre, 2020).

From Figure 34, the masthead clearance (A) is calculated by subtracting the height calculated for the vessel from the waterline to the top of the masthead (HM) from the height of the overhead obstruction (BW). BW is the charted height of the bridge plus the height of HAT above CD (Y), less the height of the tide at a specific time (HT). Should the masthead clearance be a negative value, the vessel will not sail successfully under the overhead obstruction, in order to process safely, a suitable height of tide needs to be calculated and the closest corresponding time to that tide height established, with the aid of the Tide Tables, for safe passage (SAN, 2011).

The use of tides in both under-keel and masthead clearances for shallow water navigation, used separately or in conjunction, is extremely important. The resultant financial implications of damage to vessels and infrastructure from not taking the tides correctly into account could be exorbitant.

"May there always be a hand of water under your keel"

Unknown (Lagan, 2006)

5.3 Tides in Warfare.

In warfare the tides also play an important part of naval operations for the Combat Officer and operational planning. It is important to know the height of the tide for amphibious operations for the landing of troops and equipment, depending on the coastal bottom topography and bathymetry while taking into account the specific military requirements at the landing zone. The phase of the tide is also important in amphibious landings as a boat anchored just off the beach can be pushed up on to the beach during an incoming tide. Poorly planned operations can lead to an anchored boat being stranded ashore as the tide goes out further than expected. Special Force boat and diving operations/exercises also require accurate height of tide information. During planning of these operations the level of bottom topography detail required is often not available or the area of operation has not been surveyed. Divers will carry out beach surveys from behind the breakwater to the high water mark, typically during bad weather at high tide, to identify the most suitable route to bring a boat into the intertidal region without grounding it. Divers will brief the boat coxswains of identify rocks, sandbanks, gullies, currents and any additional underwater feature that could impact the mission and the safety of the personnel.

During submarine navigation under-keel and masthead clearances calculations are the same as surface vessels when the submarine is running on the surface. However when navigating shallow waters, specifically during shallow water operations, the under- keel clearance calculations are vital for the submerged submarine.

5.4 Submarine Shallow Water Operations.

Although some submarine shallow water operations took place in the First World War, it wasn't until the Second World War that they began to be used extensively (Stern, 1979). Probably the most challenging tasks in terms of skills, risk and environmental challenges for a submarine crew are Special Operations. It invariably involves dived navigation in shallow waters close inshore, and is directed against an opposing force's maritime and economic infrastructure and resources. Whilst a component of submarine warfare, it is not primarily directed against shipping. The major navies have submarines dedicated to Special Operations missions (Kaplan, 2002). Smaller navies, like the SAN, do not have this luxury. It is forced to switch its submarines between roles and missions as required by operational requirements.

'Shallow Water Operations' are any submarine missions that deliberately take the dived submarine into navigable waters of 50 m or less (Figure 35). During shallow water operations the submarine is operated at the limits of its operational safety envelope. It demands the highest levels of professionalism and skill from the crew, as there is no scope for error (pers comm, Captain M.J. Farre, former South African Navy Submarine Officer (1984 – 2006), Officer Commanding of the submarine SAS ASSEGAAI (2001-2003) and Senior Officer Submarines (SOSM) (2003-2006)).

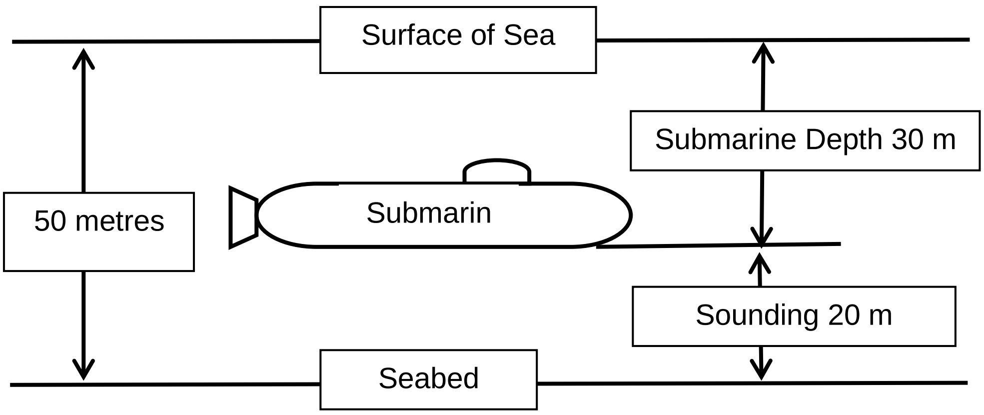

Figure 35 is a submarine in a 'Shallow Water Operations' scenario (pers comm: Farre MJ, 2020).

These shallow water, close-inshore dived operations may be conducted by day or night, depending on the operational requirements and desired results. Shallow water operations are rated high-risk missions, as the submarine is vulnerable to visual detection by aircraft and helicopter crews flying overhead, and if detected, severely restricted in its ability to escape and/or evade hostile forces. Apart from the operational considerations, local navigational data, under-keel clearances and tidal information are crucial for mission success. The following submarine missions are deemed Shallow Water Operations (pers comm: Farre, MJ, 2020).

5.4.1 Port (or Inshore/Beach) Reconnaissance. Port Reconnaissance missions (Port Recce) demand of the submarine to clandestinely navigate dived close inshore to observe and record details and activities ashore. Depending on the coastal slope and depth of water the dived submarine may navigate as close as 50-100 metres from the shoreline. For a medium size diesel-electric submarine of about 60 metres in length, depth under the keel may be as little as 10 metres.

5.4.2 Electronic Surveillance. Electronic Intelligence Surveillance missions (ELINT) to detect electronic transmissions from military and civilian radar stations, military and civilian communication transmissions and associated facilities. It may be a stand-alone mission, but could be combined with either the Port Reconnaissance, Acoustic Surveillance and/or Photo/Video Reconnaissance mission.

5.4.3 Acoustic Surveillance. Acoustic Surveillance missions demand of the submarine to navigate dived close inshore to shipping routes and port entrances. Sustained surveillance may require the submarine to come to rest at the seafloor while systems required for manoeuvring are shut down to avoid radiation of sound or bottom for the duration.

5.4.4 Photo/Video Reconnaissance. The Photo Reconnaissance mission (PHOTOKEN) demand of the submarine navigate dived close inshore so as to place the submarine within the optimum optical focal distance for the periscope camera and/or video camera to the subject(s) to be photographed ashore. Unless time is a factor, photo reconnaissance missions are planned well in advance for both tidal requirements and the desired [sun] light needs to match.

5.4.5 Mine Laying. Mine laying missions demand of the submarine to enter the inshore waters dived so as to enter the navigation channel(s) and approaches to the harbour entrance of the opposing force, so as to lay the mines.

5.4.6 Raiding. Raiding missions demand of the submarine to launch and recover saboteurs in the enemy coastal waters. There are two type of raiding missions: the launch and recovery of either raiding forces, or reconnaissance teams and their inflatable boats and/or canoes, or the launch and recovery of attack divers exiting and entering the dived submarine through the torpedo tubes. (pers comm: Farre, MJ).

Shallow water submarine operations are navigationally demanding. A range of meteorological and environmental factors such as sunrise/set, moon rise/set, and the meridian passage of the sun, wind, currents, tides and eddies, waves, internal waves, tidal current, set and drift must be considered. The submarine would for the most part face challenging navigational circumstances, with limited options once the mission had commenced to either amend, or adjust the navigation (pers comm: Farre, MJ).

Mission planning may start months in advance, or in extra-ordinary circumstances, hours before the start of the mission itself. A navigational plan for the mission will be created from pre-calculated soundings based on the planned submarine depth, charted depths indicated on a navigational chart and the predicted tides as published in the relevant national tide tables for the planned date and time of the mission. Reefs, rocks and shallow areas that constitue a possible danger to the dived submarine, will be prominently highlighted in red (pers comm: Farre, MJ).

For a diesel-electric (conventional) submarine it is advantaguous to start the approach towards the mission area following low tide, closing the mission area on the rising tide, to enter the mission area an hour prior to high tide, complete the mission, and to withdraw as the tide turns. In this manner tidal flow can be exploited to the advantage of the submarine. Approaching the mission area on a rising tide very often translate into a flow towards the land, the depth of water subsequently increases by the minute. From the submarine perspective “every centimetre helps”. Whilst the submarine is in the mission area the depth of water will thus be at its maximum, and for the duration of the slack phase, the tidal effect will be negligible. This factor contributes towards more accurate navigation, and gives a vital few extra centimetres under the keel (pers comm: Farre, MJ).

If the mission has gone according to plan and schedule, the withdrawal phase should commence shortly after slack water, allowing the submarine to now exploit the offshore tidal flow as she clears the danger area. For Shallow Water Operations both operational and mission success is dependent on accurate environmental information. From the SA Navy submariner's perspective on shallow water operations, Africa generally has mild tidal streams with the tidal changes normally being the dominant factor in operational planning and execution. Inshore tidal changes have an impact on the close-inshore dived navigation of the submarine, and could result in the loss of the submarine and its crew, or the abandoning the mission (pers comm: Farre, MJ).

Captain M.J. Farre states that there are a number of tide related factors that the astute submarine commander could exploit to their advantage an increased discretion ratio[9] as a result of exploiting tidal flows to save on battery power consumption, reducing the amount of snorkelling required to charge the main battery and exploiting the increase in water depth due to the inflow of the tide to reduce the visibility of the dived submarine (pers comm).

Mine warfare and mine clearance operations also require the Maritime Operational planner to know the height of the tide at various times for a given target or mine clearance area.

5.5 Mine Warfare.

Mine warfare (details in Appendix K) provides, in particular smaller navies with limited resources, greater flexibility to concentrate its forces towards defending military and economically high value areas. The defensive minefield gives the opposing forces three possible choices: commit and risk naval forces to undertake a time-consuming minesweeping effort, accept the casualties that will result if the minefield is challenged, or focus forces in the same waters where the enemy's largest concentration of naval forces (and fire power) are present.

Naval mines are influenced in a number of ways by tides and tidal streams (see Appendix K), and both features must be considered in the planning and design of a minefield. Neglect to do so could either compromise the minefield, or render it impotent.

[9] Submarine Discretion Ratio is defined as the ratio as to amount of time that the officer commanding of a dived submarine at periscope depth deliberately exposed the periscope(s), and hoistable sensor masts (Electronic Support Measures mast, Communications mast, Navigation Radar mast) to achieve operational and navigation objectives and the risk of visual and/or electronic detection by opposing forces, versus the time engaged in a specific operation.

The first line in the use of tides within maritime safety is the use of accurate tide predictions for the accurate reduction of bathymetric soundings to be used in the production of accurate navigational charts. The production of the national tide tables are a carriage requirement[10] that are used, in conjunction with nautical charts, in shallow water navigation and for mast head clearances. Without this information the safety of lives and livelihoods are put at great risk. Knowledge of how tides work, specifically in relation to the phases of the moon are of great value to military shallow water operations, the oil and gas industries and the mariner.

[10] Carriage Requirements is what is required to be carried on board a vessel, at all times, in accordance with the SOLAS Convention Chapter V. This is enforced by the International Maritime Organisations (IMO) and in South African waters by the South African Maritime Safety Agency (SAMSA) (IMO, 2021)

<u>Chapter 6</u> – Additional Value of Tidal Information.

As has been established in the previous chapter, the use of tide information is of great importance to the mariner, specifically for shallow water navigation and military operations. The accuracy of both the collected raw data as well as the predicted data has been discussed as well. This chapter will highlight the additional value of the tide information collected from the South African tide gauge network and the predictions. The dissemination of information pertaining to any extreme events via navigational warnings. The collaborations and capacity building initiatives fostered by the SANHO as well as the value that can be obtained from the validated collected data by both the national and international communities will be discussed.

6.1 Navigational Warnings.

South Africa is the Navigational Area (NAVAREA) VII Coordinator making the SANHO responsible for the dissemination of all maritime safety information[11] (MSI) for South Africa, Namibia and the NAVAREA VII region (Figure 36) in the form of navigational warnings. MSI information is disseminated to all vessels irrespective of class or size on all voyages (IMO, 2019) in the form of either Coastal Navigation Warnings or NAVAREA VII Warnings (Appendix L). The harbour authorities are responsible for the safety of all vessels within harbours.

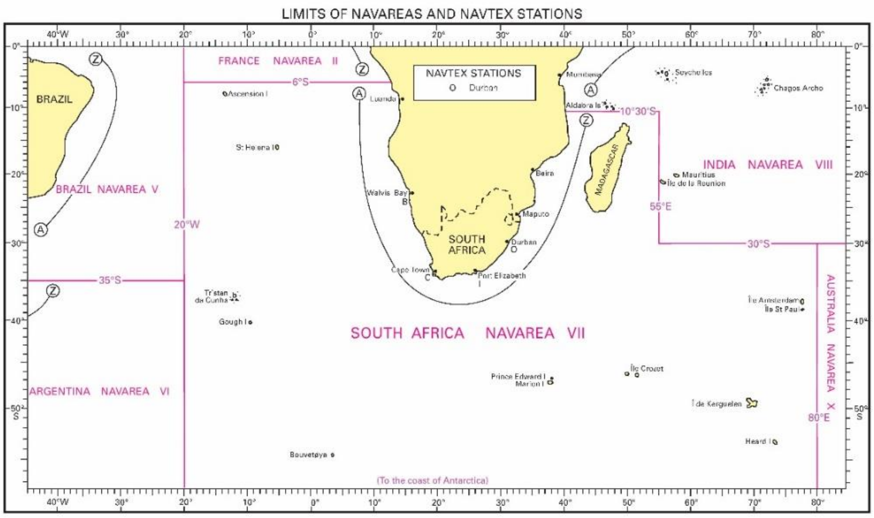

Figure 36 shows the limits of the navigational safety area NAVAREA VII of which South Africa is the Coordinator and the location of NAVTEX Stations (with permission SANHO, 2019).

[11] MSI is defined as "*Navigational and meteorological warnings, meteorological forecasts, distress alerts and other urgent safety related messages broadcast to ships"* (IHO, 1994:144). A navigational warning is defined as "*A broadcast message containing urgent information relevant to safe navigation*" (IHO, 1994:157).

Cape Town Radio, via Telkom Radio Services, is the official Global Maritime Distress and Safety System (GMDSS) service provider and transmits all MSI on behalf of the SANHO. The SANHO provides Cape Town Radio with all navigational warnings and SAWS provides them with daily marine weather forecasts to be disseminated to the maritime community, this information is transmitted to vessels in 3 ways: SafetyNET, NAVTEX and Radio Telephony (pers comm: SANHO, 2019).

a. SafetyNET provides MSI via satellite and covers the entire NAVAREA VII area. The information is received by the vessel's GMDSS receiver and displayed in the form of a printout.

b. NAVTEX has a coverage of 200 nautical miles from the coastline seaward and is transmitted via shore based broadcast station. The information is received by the vessel's GMDSS receiver and displayed in the form of a printout.

c. Radio Telephony is the transmission of a combined navigation~~al~~ warnings and weather report via voices broadcasts. Cape Town Radio broadcasts a single voice broadcast at 1015 and 1815 UTC daily via specific HF and VHF radio channels.

On 26 September 2020 a 6.2 magnitude earthquake took place approximately 1922km South East of Cape Town in the South Western Indian Ocean[12]. Analysis of the data received from the SAN tide gauge network showed increased sea levels. These increased sea levels resulted in the promulgation of a navigational warning.

"*COASTAL NAVWARNING 477 OF 2020*
1. WEST, SOUTH AND EAST COAST
2. ABNORMAL SEA LEVEL CONDITIONS MAY BE EXPECTED ALONG RSA COAST LINE
DUE TO SEISMIC ACTIVITIES ON 26 SEP 20. OFFSHORE SOUTH AFRICA
3. MARINERS ADVISED TO EXERCISE CAUTION
4. CANCEL THIS MESSAGE 272000 UTC SEP 20" (SAN, 2020).

All MSI messages are promulgated with Immediate Priority. The average time elapsed between receipt of the request for promulgation of a navigational warning message by the SANHO and promulgation of the message by Cape Town Radio is 30 minutes (SANHO, 2019).

[12] https://www.volcanodiscovery.com/earthquakes/5924123/2020-09-26/17h10/magnitude6-South-of-Africa.html, 09/11/2020

All NAVAREA VII and coastal navigational warnings are published in full and as a summary on the SANHO's website http://www.sanho.co.za/.

6.2 Extreme sea level events.

Extreme sea levels can be estimated directly from the measurements made by the tide gauge network. When made available in real time, these measurements are a valuable input into warnings of extreme sea levels disseminated by both international and national authorities. Two such examples are now given: the international Indian Ocean Tsunami Warning and Mitigating Service and the national Storm Surge Warnings Service for South Africa.

6.2.1 Indian Ocean Tsunami Warning Monitoring Service (IOTWMC).

The Sumatra Tsunami of December 26, 2004 was a worldwide event that made the maritime safety and academic communities more greatly aware of the need for an early warning system, specifically in the Indian Ocean which at the time had no such system.

In the week 18-24 December 2004, upon the routine inspection of the weekly tide gauge graphics which were produced from the downloaded data from the SAN tide gauge network, the Superintendent of Tidal Information (STI) noted that all 12 tide gauge graphics showed some form of an anomaly. The anomaly appeared to be a "reverberation" or increased "jagged" look to the normally smoother graphs. This type of "jagged" look could normally be attributed to strong winds, however strong winds on one side of the coastline would not explain the increased "jagged" look in all the graphics.

Inspection and analysis of all the recorded data and resultant graphics from the 2 weeks before the Tsunami event up until the first week of January 2005 was carried out by the STI with, at the time UCT's head of oceanography, Professor Frank Shillington and UCT's former head of oceanography Professor Geoff Brundrit. Figure 37 show the signal within the collected tide data once the tide signals had been removed. The presence of the increased "jagged" look of the graphics prior to the tsunami event was attributed to the tide gauges registering the tectonic plate movement that later would result in the submarine slump and subsequent tsunami event.

During the analysis of the data for the tsunami itself, an additional point of interest was noted. The amplitude and frequency of the tide records at Richards Bay (on the East Coast) and Port

Elizabeth (on the South-East Coast) were markedly different. This was presumed to be due to the shape and hydrodynamic interaction of the continental shelf (Merrifield *et al*, 2005). This is entirely plausible as Case Study 2, Chapter 3 uses a similar assumption.

As a result of the 2004 Sumatra Tsunami, the IOC donated 3 satellite transmitters to be installed at the Simon's Town, Port Elizabeth and Durban tide gauges making them part of the Indian Ocean Tsunami Early Warning system.

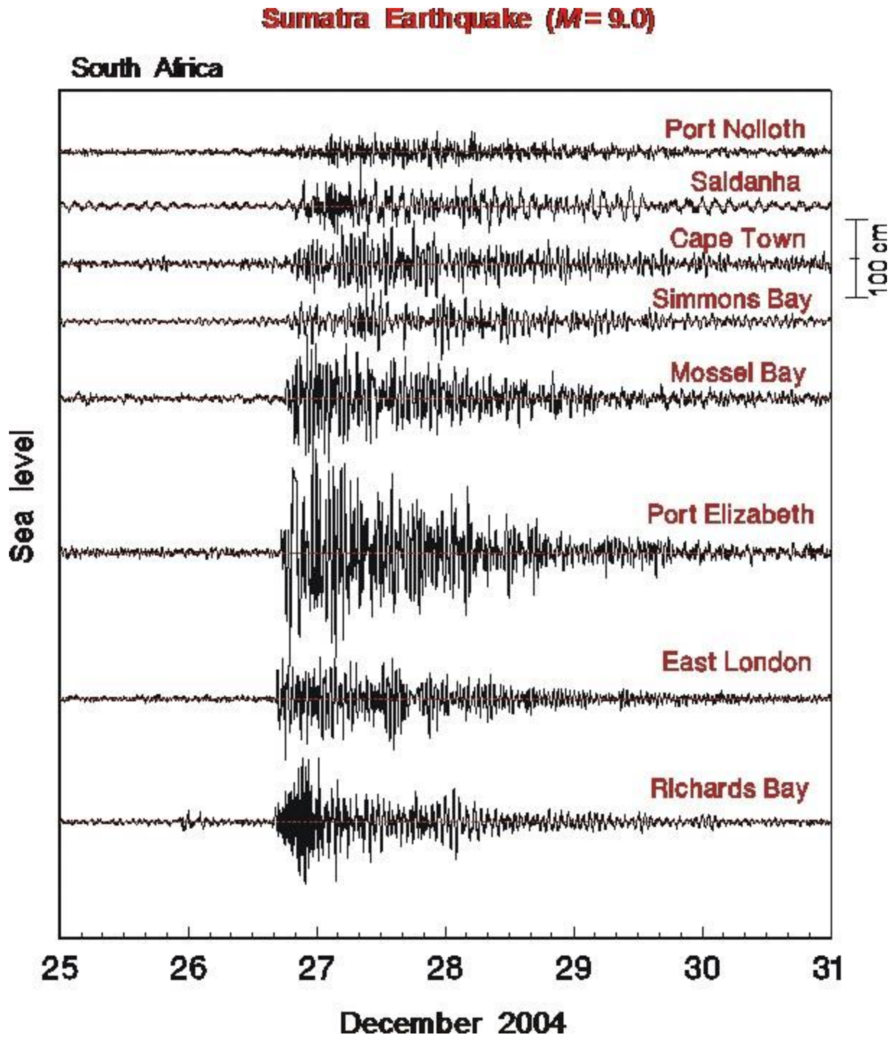

Figure 37 showing the time series, with tidal contributions removed from South African tide gauges before and after the 2004 Sumatra tsunami (Merrifield *et al*, 2005).

The IOC-UNESCO also enlisted international cooperation and the Indian Ocean Tsunami Warning and Mitigating System (IOTWMS) was outlined and implemented. By the end of 2006, funding had been obtained and developing nations around the boundaries of the Indian Ocean were supplied with tide gauges, satellite transmitters with GPS units (for accurate timing) and support to install them correctly. Those developing nations with existing tide gauge networks, of which South Africa was one, were donated satellite transmitters with GPS units in order to rapidly stream strategic tide gauge data to the IOTWMS. Although the IOTWMS primarily makes use of seismic information to detect possible tsunamis, the tide gauge data is used for confirmation of a possible tsunami event. The SANHO installed these transmitters and began transmitting data for Simon's Town, Port Elizabeth and Durban from late 2007.

Tsunami warnings for the Indian Ocean are issued internationally by the United States of America's National Oceanic and Atmospheric Administration (NOAA) and the Japanese Meteorological Agency (JMA). Other regional centres, for example India, also issue warnings for their particular regions. These warnings are disseminated via the international meteorological data-communication network, called the Global Telecommunications System (GTS) to all countries. The GTS is used due to its reliability and the 24/7 operation of meteorological services world-wide. The SAWS is the conduit for reception of tsunami bulletins from the international tsunami warning centres as disseminated over the GTS, and for the dissemination of these original bulletins to the mandated authority. Within-country dissemination of these warnings is then the responsibility of the mandated institution of each country (IOC, 2016).

The National Disaster Management Centre (NDMC) is the responsible authority for issuing tsunami warnings in South Africa. This implies, among others, that the NDMC have to decide (using external advice from other relevant institutions in the tsunami early warning system) if and when a warning must be issued, and what the alert level should be (advisory, watch, or warning). NDMC is also the point of contact for the media. NDMC has to ensure that the final alerts applicable to South Africa are disseminated to provincial and local disaster management centres, the SANHO for coastal navigational warnings, SAWS, the Council for Geoscience (CGS) and the media.

In September 2016 the first Indian Ocean tsunami preparedness simulated exercise was undertaken with participation by 24 countries including South Africa. The exercise consisted of 2 "earthquakes", one with a magnitude of 9.2 south of Indonesia and the other with a magnitude of 9 in the Makran Trench south of Iran and Pakistan some 24 hours later, resulting in evacuation drills of over 50 000 participants in 10 countries (UNESCO, 2016). The exercise was extremely successful with a second larger successful exercise having taken place in 2018.

However in recent times, problems have arisen in South Africa with the reliability of different parts of the equipment. Data from the South African tide gauge network was successfully transmitted, via the Meteosat satellite operated by EUMETSAT, to the IOTWMS until late 2017. After that date, the GPS units began to fail. The inability for the satellite transmitters to obtain a GPS time meant that the data could not be transmitted. New GPS units were obtained and set for installation by end 2018. However at this point the satellite transmitters had begun to fail as well. Due to their age no further firmware updates or technical support from the manufacturers was available. The replacement satellite transmitter units are extremely expensive and at present not approved for sale within South Africa by the Independent Communications Authority of South Africa (ICASA) in accordance with the ICASA Act No. 13 of 2000 (South Africa, 2000). Enquiries with the South African Suppliers indicated that there is no immediate plan to have these units ICASA approved.

At the time of writing, various options to resume sending data to the IOTWMS are being investigated by the SANHO in conjunction with the CSIR and Flanders Marine Institute. Note should be taken that the IOC *Manual on Sea-level Measurements and Interpretation, Volume V: Radar Gauges* (2016) explores these various options.

6.2.2 Storm Surge[13] Warnings.

A meteorological extreme sea level event can be expected when a significant pressure gradient occurs at the same time as an astronomical spring tide i.e. equinoxial spring tide. Should this event occur in conjunction with a forecasted offshore significant wave height in excess of 3 m, a storm surge greater than 0.5 m can be expected. If the storm surge value of 0.5 m is added to the actual spring tide height and exceeds the average tidal level by 1.3 m a storm surge warning should be promulgated (Stander *et* al, 2012). A storm surge is typically associated with the passage of a well-developed or deep cold front/ deep low pressure system, or a slow moving tropical low pressure system (below 1004hPa) close to the coast (Stander *et al,* 2012).

[13] A storm surge is "*a rise above normal water level on the open coast due only to the action of wind stress on the water surface. Storm surge resulting from a hurricane* [due to atmospheric pressure change] *or other intense storm also includes the rise in level due to atmospheric pressure reduction as well as that due to wind stress. A storm surge is more severe when it occurs in conjunction with a high tide*" (IHO, 1994).

SAWS is the nationally mandated sole authority to disseminate storm surge warnings (SAWS Act No. 8 of 2001, South Africa, 2001:13) The SAWS does not have any tide gauges and thus uses their own in-house developed forecast model. The forecast model relies on accurate, official tide gauge data to calibrate and validate the model during creation and periodically check calibrate the performance of the models (pers comm: Mr M. de Vos).

In mid-2018, the SAWS began working on creating a storm surge model for South Africa (http://marine.weathersa.co.za/Forecasts_Surge.html). As actual water level heights, including tide heights, are affected by atmospheric pressure cells which differ from the average, a low pressure cell would result in an increase in all tide heights in that specific area, conversely a high pressure cell would depress the sea surface. Taking into account the bathymetry within the specific area (shallowing effect), the range of the tides in relation to the phase of the moon and the direction of the wind speeds experienced (either onshore or offshore), a tide model would first need to be created to feed into the storm surge model.

In December 2018, the SANHO was approached by the SAWS to assist them with validating their model against official long term harmonic constituents. The SAWS tidal model is periodically validated using actual recorded tide levels, for specific periods where storms had occurred. This was completed and the model produces results with a *"…amplitude accuracy* [of] *on average, 6 cm around the coastline with a less than 3 minute timing inaccuracy"* (SAWS, 2019). The tidally validated model feeds into the SAWS Storm Surge Model which forms part of the South African Multi-Hazard Warning System (Stander *et al*, 2012).

Various hydrodynamic models have been developed with varying results, although none prior to Rautenbach, Barnes & de Vos having an ability to give a complete holistic overview of the characteristics of the South African tides (Rautenbach, Barnes & de Vos, 2019). During the development of the South African Weather Services (SAWS) storm surge model, Rautenbach, Barnes & de Vos developed a tide model to aid in the accurate prediction of the storm surge heights. The SAWS tide model outputs were compared to an additional model (TPXO8 which is a global model) as well as data supplied by the SANHO (Rautenbach, Barnes & de Vos, 2019).

Once the SAWS identifies the need to issue a storm surge warning, the SANHO is notified (as the NAVAREA VII Coordinator) for promulgation to the maritime community in the form of a navigational warning. The National Disaster Management Centre is notified of the threat for dissemination to their Provincial and then Local Municipal Disaster Management centres. These centres will then alert the relevant role players such as the National Sea Rescue Institute (NSRI), the South African Police Services (SAPS) and health and emergency services. SAWS will additionally issue the warning on all media related weather broadcasts.

6.3 SANHO Collaborations in support of tide gauge networks.

The SANHO is actively involved in various national collaborations with the SAWS, Council for Scientific and Industrial Research (CSIR) and the Hartebeeshoek Radio Astronomical Observatory (HartRAO), as well as various government department projects. Internationally, as an active member of the IHO and the IOC the SANHO is actively involved in their various working groups and initiatives. The SANHO representing South Africa, as the former chair and now vice chair of the IHO's Southern Africa and Islands Hydrographic Commission (SAIHC) is involved in capacity building, technical visits and assistance for its member states. As a member of SADC, South Africa and subsequently the SAN and SANHO are involved in capacity building and supporting the SADC nations. Several of these collaborations will be discussed in this section.

In 2001, the Tide Gauge Benchmark Monitoring Project (TIGA) was initiated with the purpose of processing and analysing Global Navigation Satellite System (GNSS) data from or near tide gauges from all over the world. The use of GNSS data is important in sea level research as it shows the position of the associated tide gauges in a 3-dimensional space (UNESCO, 2020). The SANHO is collaborating with the Hartebeeshoek Radio Astronomical Observatory (HartRAO) and their research into earth tides. HartRAO has installed a GNSS sensor at Simon's Town and Richards Bay tide gauge, with the remaining stations to be included over the next few years. The IHO TWCWG has also recommended that where possible GNSS sensors should be placed at strategically located tide gauges (Wyatt, 2019). A review of the TWCWG technical resolutions proposes that the relevant technical resolutions be amended to include GNSS information (Farre et al, 2020). HartRAO has installed and maintains a tide gauge on Marion Island on behalf of the German Research Centre for Geoscience (GFZ) which feeds into the IOTWMS. They have also installed a GNSS sensor at the tide gauge in order to monitor the stability of radar altimetry measurements. This data is used in the study of local and regional sea level changes and contributes to the HartRAO sea level monitoring program[14]. It is the intention of HartRAO, over the next 5 years, to extend this project to all of South Africa's tide gauges in order to expand their research (pers coms: Dr R. Botha). An additional benefit of the GNSS is, as well as measuring land movements, it can function as a tide gauge itself, thereby providing complimentary data to the main tide gauge (Larson, Ray & Williams, 2017).

6.3.1 SANHO Cooperation with CSIR.

The CSIR supplies and supports the TNPA with an Integrated Port Management/Operations System (IPOS). One of the components of this system supplies Port Control with a graphical display of 10 min predicted tides as supplied by the SANHO. The IPOS system is used by port control and the Harbour Pilots with the relevant information to bring vessels safely in and out of the harbours.

6.3.2 Department of Environment, Forestry and Fisheries - Operation Phakisa.

Operation Phakisa - The Ocean Economy, is a South African government project that was implemented in July 2014 with the main objectives being to improve economic growth and increase job creation (DEA, 2020). The word "phakisa" is a Sesotho word meaning "hurry – up". Ops Phakisa is a results-driven national initiative designed to rapidly implement solutions to critical development issues (DPME, 2020). Ops Phakisa has various initiatives, of which the SAN and the SANHO are stakeholders in the *Marine Protection Services and Ocean Governance - Initiative 6: "National Ocean and Coastal Information System (OCIMS) and Extending Earth Observation Capability"* (DEA, 2020). OCIMS is a collaboration of various stakeholders, led by the Department of Environmental Affairs (DEA) and the Council for Scientific and Industrial Research (CSIR), under the authority of the Department of Science and Innovation in 2015.

Over the last 5 years the OCIMS project has created various tools that are designed to aid in the governance of the South African waters and coasts, and subsequently South Africa's blue economy. The Marine Spatial Planning, Coastal Flood Hazard model, Marine Domain Awareness, Fisheries and Aquaculture, Water Quality, Sea State and Marine Predators tools have been developed and are available on the OCIMS website (https://ocims-dev.dhcp.meraka.csir.co.za/) with additional tools being developed in accordance with

[14] https://www.gfz-potsdam.de/en/section/global-geomonitoring-and-gravity-field/topics/geodetic-hazard-monitoring/gnss-controlled-tide-gauges-for-tsunami-warning-and-sea-level-research/

stakeholder requirements. The SANHO consults, collaborates and supplies tidal information, as well as bathymetric data, for use within the OCIMS models.

Although the SANHO's main requirement for the collection of accurate tide data is to produce accurate navigational products (charts and tide tables) to fulfil its mandate for safety of life at sea the collection of accurate tides can have many additional uses. The Operation Phakisa model that was created for the NSRI uses tide information, bathymetry and currents to track the possible search areas for sea rescue operations. Not only is the data relevant to scientists for the study of possible sea level rise but also for use in early warning systems.

6.3.3 SANHO Co-Operations with Sea-Level Research Centres.

The Global Sea Level Observing System (GLOSS) is an international programme under the auspices of the IOC and its objective is the "*establishment of high quality global and regional sea level networks for application to climate, oceanographic and coastal sea level research*" (UNESCO, 2020:1). As a part of the SANHO's involvement with the IOC, South Africa disseminates tide/sea level readings directly to sea level research centres (Figure 38).

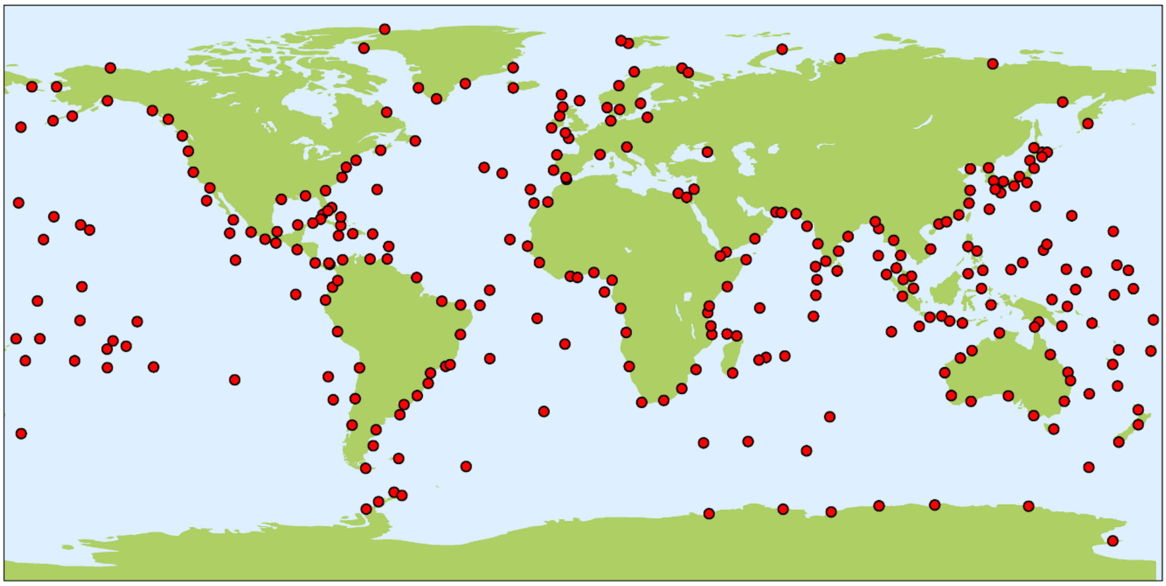

Figure 38 where each red dot indicates a tide gauge in the GLOSS Global Core Network (GCN2019) (UNESCO, 2020).

The tide data recorded for GLOSS stations, denoted in Appendix D are sent to the University of Hawaii's Joint Archives for Sea Levels (JASL) in two formats.

a. Fast Data (FD) consist of any tide records that are received by the JASL within 1-2 months of the data being recorded (UNESCO, 2020). This data is raw un-validated data directly from the relevant tide gauges and can have a sample rate of anywhere from 1 minute to 15 minutes. At the SANHO, the raw 1 or 3 minute data collected from the tide gauge is graphed and the predictions overlaid on to the graph. This is done bi-weekly and visually inspected for anomalies or deviations. The SANHO sends FD as near real time, emailed bi-weekly with the raw data text files attached and notations on any visible anomalies.

b. Research Quality (RD) data which is validated hourly data. RD is sent annually once the hourly data for the year has been analysed and validated. The hourly data sent by the SANHO is quality controlled data with anomalous data removed and deviations corrected where necessary. This process is done in the *Tidal Office* in-house software as described in Chapter 4 – Analysis of Recorded Data.

The Permanent Service for Mean Sea Level (PSMSL), in the United Kingdom, has access to the JASL's GLOSS data supplied by the SANHO and use that data to calculate their own monthly and annual means. Should the month have less than 15 days' worth of data, the monthly mean is not calculated for that month (PSMSL, 2019). As the PSMSL's focus is on the means of the data recorded, the SANHO annually forwards the PSMSL the monthly and annual means for each of the GLOSS Stations as calculated in the in-house software *Tidal Office* (Appendix G).

The SANHO, as the National Tide Archives and owners of the official tide data for South Africa, also supplies tide data upon request to researchers both nationally and internationally.

6.4 International Capacity Building.

The SANHO, as the only established long standing HO in the SADC region, is an active participant of the IHO Capacity Building[15] initiative. The SANHO's co-operations includes capacity building initiatives and assistance with tide gauge installations within the Southern African Development Community (SADC) region. In 2005 South Africa assisted members of the Mozambique Hydrographic Office (IHAHINA) with the installation of 2 radar tide gauges at Pemba and Inhambane at the IOC's request. These members were given onsite training on the full installation process as well as basic tide gauge maintenance and calibrations. The Namibian Ports Authority (NAMPORT) had a member spend 6 months working in the SANHO Tidal Department where they underwent training in tides and tide equipment installation, maintenance and calibration. In 2008, the SANHO assisted NAMPORT with the installation of 2 radar tide gauges in Walvis Bay and Lüderitz.

In 2012, the Hydrographer of the SAN tasked the author in their position of as the SANHO Superintendent Tidal Information (STI) to create and develop an introduction to tides workshop with the emphasis on installation of equipment, maintenance and various technical aspects. The workshop is aimed at developing countries to increase their tidal capabilities which are essential for hydrographic survey and the production of accurate charts. The STI presented the workshop, in February 2015, to various SAIHC member states as well as SADC member states. Delegates from Angola, Comoros, Kenya, Malawi, Mauritius, Mozambique and Tanzania attended the workshop which was well received and promoted co-operation between the members present.

In September 2015, the SANHO was invited to present the Tidal and Water Levels Technical Workshop to the member states of the Regional Organization for the Protection of the Marine Environment (ROPME) Sea Area Hydrographic Commission (RSAHC) as part of the IHO Capacity Building Committee work program and South Africa's contribution to create hydrographic awareness and improve safety of navigation at sea. Delegates from Bahrain, Iran, Iraq, Oman, Pakistan, Saudi Arabia and the United Arab Emirates attended and feedback received was positive and proved the value of the workshop.

[15] "*the process by which the Organization assesses and assists in sustainable development and improvement of the States, to meet the objectives of the IHO and the obligations and recommendations related to hydrography, charting and maritime safety described in SOLAS Chapter V, UNCLOS and other international instruments*" (IHO, 2019) (https://iho.int/en/capacity-building-and-technical-cooperation:31/10/2019)

The workshop has subsequently been turned into an introductory technical training course and has been accepted by the IHO TWCWG as an approved capacity building training course. This course has been presented by the Australian Hydrographic Service to members of the South West Pacific Hydrographic Commission in 2017. It has been translated into French and Spanish with the Portuguese translation set for completion in 2021.

Chapter 7 – Conclusion.

The current South African tide gauge network was investigated in order to ascertain the key elements in designing and realisation of the tide gauge network. Within the design phase, case study 1 (Chapter 2) showed the importance of carrying out a theoretical investigation into the proposed installation sites (i.e. harbour plans, nautical charts, historical port files, local land surveying records) followed up by a site visit before any installations were carried out. This should not only take into account local infrastructure but also wider oceanic and meteorological effects that will have an effect on the quality of the data. It is important to install the tide gauge in a location that will produce measured data with the most accurate representation of the ocean tides while being located within the protection of the harbour.

The installation of the tide gauge commences once the desired tide gauge location has been established, the relevant equipment purchased (Chapter 2) and any required davits/structures have been constructed. Budgetary constraints and the realisation of the network, while taking into account the selection of the most practical, affordable equipment to be used, the procurement processes and time frames over suitable period (i.e. 3 or 5 year budget cycles) are important.

During the installation of the tide gauge the reference level that the data will be recorded in relation to is calculated. This reference level is often referred to as the sensor offset (Z_0). The SANHO has set all their tide gauges to record the tides in relation to Chart Datum (CD). The SANHO uses the very simple, easily constructed stirrup or calibrating rods method as discussed in Chapter 3's *Use of a Stirrup to obtain the Z_0*. This method is easily transportable and quick to assemble without any specialised skills or equipment required. This method is also be used to check the Z_0 of the sensor during routine maintenance onsite visits, thus validating the accuracy of the tide data being collected.

Throughout the current lifespan of the SAN tide gauge network various issues have arisen resulting in “outside the box” thinking in order to maintain the sustainability of the network as well as the equipment. Chapter 3 highlights a few of the various problems that have been experienced and the solutions that the SANHO have devised to combat them.

Case Study 2 (Chapter 3) looks at the SANHO tide gauge network and investigates if the current locations of the tide gauges provide adequate coverage of the coastline. However, looking only at the timing differences between locations did not give an adequate picture of the tide gauge networks coverage. The average spring/neap high and low tide times and heights (where available) were compared, the height differences were investigated as well. From Port Nolloth, around the coastline, to Struisbaai there is a maximum time difference of +10 minutes at spring HT and a minimum of -5 minutes at neap LT. For the ports analysed in relation to Cape Town, only Port Nolloth showed a significant jump in height difference of 0.17 m at spring high and 0.14 m at neap high. Saldanha, Simon's Town and Hermanus showed no greater than a 0.05 m difference in heights, with only Saldanha and Simon's Town showing a -0.01 m height difference at spring lows. The analysis from the stretch of coastline from Kosi Bay to Mossel Bay yielded vastly different results. Between Durban, Kosi Bay and Richards Bay the only time difference was at spring HT of +5 minutes. From Durban to Port Elizabeth there was no time difference at springs, a maximum time difference of +20 minutes at HT and +20 minutes at LT was found at neaps. The time differences between Durban and Mossel Bay shows a time difference of a maximum of -10 minutes at spring LT, with a maximum +20 minutes at HT was found at neaps. The section of the coastline from Richards Bay to Mossel Bay showed markedly different results in height differences to the section from Port Nolloth to Hermanus. The evidence indicated that the average spring and neaps highs and lows for East London, Port Elizabeth and Knysna are lower than that of Durban while Richards Bay and Mossel Bay are higher. It was postulated that the width and slope of the continental shelf around the South African coastline plays a significant role in the height of the tides and the amphidrome south west of South Africa contributed to the timing differences experienced around South Africa.

The South African Navy Hydrographic Office (SANHO) has been the responsible authority for the production of maritime safety information and products since 1954 in accordance with the international standards as set out by the International Hydrographic Organization (IHO) and International Maritime Organisation's (IMO) Chapter V of the International Safety of Life at Sea (SOLAS) Convention. One of the key requirements to be carried out by the SANHO was the initialisation of a National Tide Gauge network, the subsequent maintaining of that network and the collection of accurate tide data. On 26 May 2020, the President of South Africa signed the Hydrographic Bill making it the Hydrographic Act No 35 of 2019 which now gives the SANHO an official presidential mandate as the South African National Hydrographic Office, SA Navy (SAN).

The main aim of this thesis was to investigate and explain what the key technical elements are in the design and realisation of a national tide gauge network around the South African coast and the value of the data collected. Upon the implementation of a sustainable tide gauge network and successful collection of high quality, accurate data this thesis goes on to investigate how the tide gauge network (and subsequently collected data) can be used to increase maritime safety around the coastline and the additional possible benefits that may ensue from the data. This will become increasingly important in buttressing new national governance and economic development initiatives in the coastal ocean, such as Operation Phakisa. The thesis recognizes the value of international exchange and cooperation with organisations such as the IHO and IMO, both now and into the future. The thesis ends with recommendations for future developments.

7.1 What are the key technical elements in the design and realisation of a national tide gauge network around the South African coastline?

After the SAN took over the tide gauge operations from the old SA Railways and Harbours (Now Department of Transport) they began installing newer equipment with their first gauge being installed in 1957. Due to the sanctions against South Africa during the apartheid era, the SANHO had to have newer gauges designed in the country. The SANHO additionally had to devise their own methods of check calibrating the information received, the details of which are given in Chapter 3. It wasn’t until 2002 that an opportunity and funding became available whereby imported tide gauges could be tested and purchased in order to replace the less effective “home grown” tide gauges. The SANHO was one of the first countries in the world to use the radar type tide gauges. The success and proven accuracy of these tide gauges (Appendix B) has resulted in the radar altimeter type gauges now being the most widely used tide gauge internationally.

The key technical elements start with the selection of the best available location in which to measure the best quality data. Local benchmarks need to be identified and accurate heights obtained. Local infrastructure needs to be considered, such as access to power and communication options for data collection, while considering the safety of the equipment and subsequently the collected data. The specific type of equipment selected needs to meet the operational and budgetary requirements.

Chapter 4 explains how the SANHO in-house software uses the recorded tide data in order to extract the harmonic constituents for each of the ports and year under analysis. Periodically there are “gaps” or “missing data” within the datasets either due to power failures or equipment malfunctions/ damage. The method of replacing missing data intervals within the recorded was investigated in Case Study 3 which proves that the method of inserting missing data with predicted data is a valid method for calculating harmonic constituents with an acceptable degree of accuracy.

In 2011 a study was conducted by the IHO Tides, Water Level and Current Working Group (TWCWG) which is explained in Case Study 4, Chapter 4. Data sets for 1 port for 1 complete years’ worth of data was exchanged between the United States of America, the United Kingdom and South Africa. Each country ran the data sets through their own software. The Boston data set was analysed by South Africa and the United Kingdom and then compared with the United States of America’s results, the results showed that South Africa’s in-house software produced better results than that of the United Kingdom’s. The United States of America ran South Africa’s dataset for Port Nolloth and their software produced similar results to the South African Boston dataset. These results are all within the IHO’s accepted standards whereby the accepted error budget for measured tides allows for “…*0.10m at the 95% confidence level”* (IHO, 2011). Case Study 4 validates the accuracy of the SANHO’s in-house software with international standards.

7.2 How can the tide gauge network be used to increase maritime safety around the coastline and what are the additional benefits that may ensue from the data?

As with all National Hydrographic Offices the main purpose is safety of lives at sea and thus the production of navigational safety products such as nautical/navigational charts, electronic navigational charts (ENC’s), tide tables, Notices to Marines (NTMs) and various other navigational publications. These products are required to conform to minimum international standards as set out by the IHO and IMO. The starting point to designing any tide gauge network is clarifying the main outcomes required of the collected data. In the case of the SANHO, there are two main purposes of the collected data from the tide gauge network. The first is to produce the annual publication the *South African Tide Tables (SAN HO-2)* so that vessels sailing through South African waters are in compliance with carriage requirements. The second is to produce accurate tide predictions to be used in the reduction of bathymetric soundings (Chapter 5) in order to create accurate nautical charts for use by the mariner for safe navigation at sea.

The water depths, as obtained by a hydrographic Survey vessel (HSV) during a hydrographic survey are reduced to remove the tide at the specific time the depth was recorded. Chapter 5 shows how this is done in order to remove the rise and fall of the vessel, due to the rise and fall of the tide, to give accurate depth or bathymetric soundings. This information is then used to create accurate navigational charts.

Chapter 5 further goes on to explain how during shallow water navigation or overhead clearances the tides are used to calculate the optimal time to transverse over shallow areas or under bridges without damaging the vessel, infrastructure or risking the lives of those on-board. The use of accurately predicted tides (Tide Tables) and navigational charts is of significant importance. A vessel running aground would result in costly delays in getting cargo from one location to the next, including the cost of damage to the vessel. In many cases the tides and depths are used to calculate the exact maximum amount of cargo that can be transported by a vessel. The more cargo, the lower the vessel sits in the water and more important under-keel clearances become. The more cargo a vessel can carry creates greater financial reward for the company/owners of the vessel. Incorrectly calculated masthead clearances can result in costly damage to the vessel in question as well as the bridges infrastructure.

Tides also play an important role in naval operations. Shallow water submarine operations take place in waters of 50 m or less. Port (or Inshore/Beach) Reconnaissance, Electronic Surveillance, Acoustic Surveillance, Photo/Video Reconnaissance, Mine Laying and Raiding are all classified as shallow water submarine operations as described in Chapter 5 and are all strongly affected by tides.

Currently, the SAWS is legally mandated to promulgate all severe weather warnings including possible storm surges. In 2019 the SAWS completed a storm surge model, for the South African coastline with the aid of the SANHO’s tide gauge records explained in Chapter 1 and Chapter 6. SAWS will notify the SANHO should significant surges, either positive or negative, be required to be promulgated to the maritime community.

Chapter 6 discusses Operation Phakisa and OCIMS (National Ocean and Coastal Information System) in which the SA Navy and the SANHO are stakeholders. OCIMS has many various projects and is aimed at not only other government departments but the scientific community, search and rescue organisations and the general public. OCIMS makes use of the tide information collected by the South African tide gauge network and SANHO bathymetric information, with permission of the South African National Hydrographer, in their Coastal Flood Hazard and Marine Awareness Domain models.

The tide data collected from the South African tide gauge Network has additional value to the above. Chapter 6 outlines how Global Navigation Satellite System (GNSS) stations aid in more accurate local and regional sea level change research by positioning the tide gauge benchmark in a 3-dimensional space. The IHO's TWCWG is in the process of updating their technical resolutions with GNSS data to be included in all metadata where available. The Hartebeeshoek Radio Astronomical Observatory (HartRAO), in collaboration with the SANHO, has 2 GNSS stations already installed as 2 of their tide gauges with plans to install GNSS stations at the remaining 8 tide gauge stations over the new few years.

After the 2004 Sumatra Tsunami, the data collected from the South African tide gauge network, once analysed, showed how the tectonic plate vibrations were being picked up by the South African tide gauges before the submarine slump that precipitated that actual event took place (Chapter 6, Figure 37). The South African tide gauge network was then linked to the Indian Ocean Tsunami Warning Monitoring Service (IOTWMC) via the Durban, Port Elizabeth and Simon's Town tide gauge stations.

Knowledge of tides, how they work and how to create and execute an operational tide gauge network is being used in capacity building projects in order to expand the world's tide gauge network. The expansion of correctly installed tide gauges, linked to geodetic systems, producing accurate tide data aids the scientific communities in understanding sea-level rise while linking these values to land tide and land subsistence/ rebound data thus producing more accurate sea level rise information. The South African tide gauge network contributes raw sea-level data to the GLOSS, JASL and UHSLC in the form of either fast data or research quality data. Monthly and annual means are supplied to the PSMSL (Chapter 6).

7.3 Recommendations for future developments.

It is acknowledged that although the earlier work on the tide gauge network is recognized both nationally and internationally, its outcomes and all its benefits are in a "mature state". Over time more and more maintenance to the current systems will be needed. In order to keep up with advances in technology it is recommended that newer models or types of tide gauges be investigated in order to maintain the sustainability of the South African tide gauge network well into the future. This will ensure that full advantage of new technologies are investigated which may lead to new opportunities to sustain the South African tide gauge network. The SANHO has, at the time of writing this thesis been approached, and approved, to trial a compact single component locally produced tide gauge unit. Testing commenced on 17 September 2020, for a minimum of 12 months, with promising results already being noted.

It is also recommended that better outreach education on how tides work and the effects of tides could be established to enable better coastal planning and greater general safety of the general public to limit damage to property and even drowning’s.

With the rapid technological advances within navigation the priorities of Hydrographic Offices worldwide are beginning to shift from the traditional paper products to digital products. Several HO’s now have tide applications (i.e. the United Kingdom Hydrographic Office’s *EasyTide* and the Australian Hydrographic Office’s *AusTides*) available for purchase that are replacing the traditional tide tables. At present the TWCWG are working on developing the specifications for the implementation and use of tides (astronomical, modelled or real time) within the Electronic Chart Display and Information System (ECDIS) as used as an alternative to paper nautical charts and publications. ECDIS is the future of navigation and it is envisioned that in the next twenty years the paper nautical/navigational charts and publications will most likely only be used as a backup or failsafe. It is recommended that the SANHO invest time and effort into advancing their capabilities within this area. The SANHO is currently investigating the development of a tide application as well as how to implement astronomical predicted tides within the ECDIS systems.

7.4 Conclusion.

Although the current South African tide gauge Network may not be ideal, the methods used to ensure the correct technical aspects were considered and the best possible locations are sound. The coverage produces results that are used for the safety lives at sea and comply with international standards in accordance with the IHO, IMO and SOLAS requirements. South Africa has carried out a competent design and realisation of the network. Budgetary constraints will require excellent planning for sustainability into the future with an emphasis on the advances in technology needing to be taken into account.

The information provided by the South African tide gauge network not only complies with international standards, but produces high quality data and navigational products. These products are used by all mariners, be they military or civilian, with special emphasis on the use of the tides within shallow water navigation. The tide data collected from the South African tide gauge network is proven to have vast additional value to not only the maritime community, but the scientific community as well.

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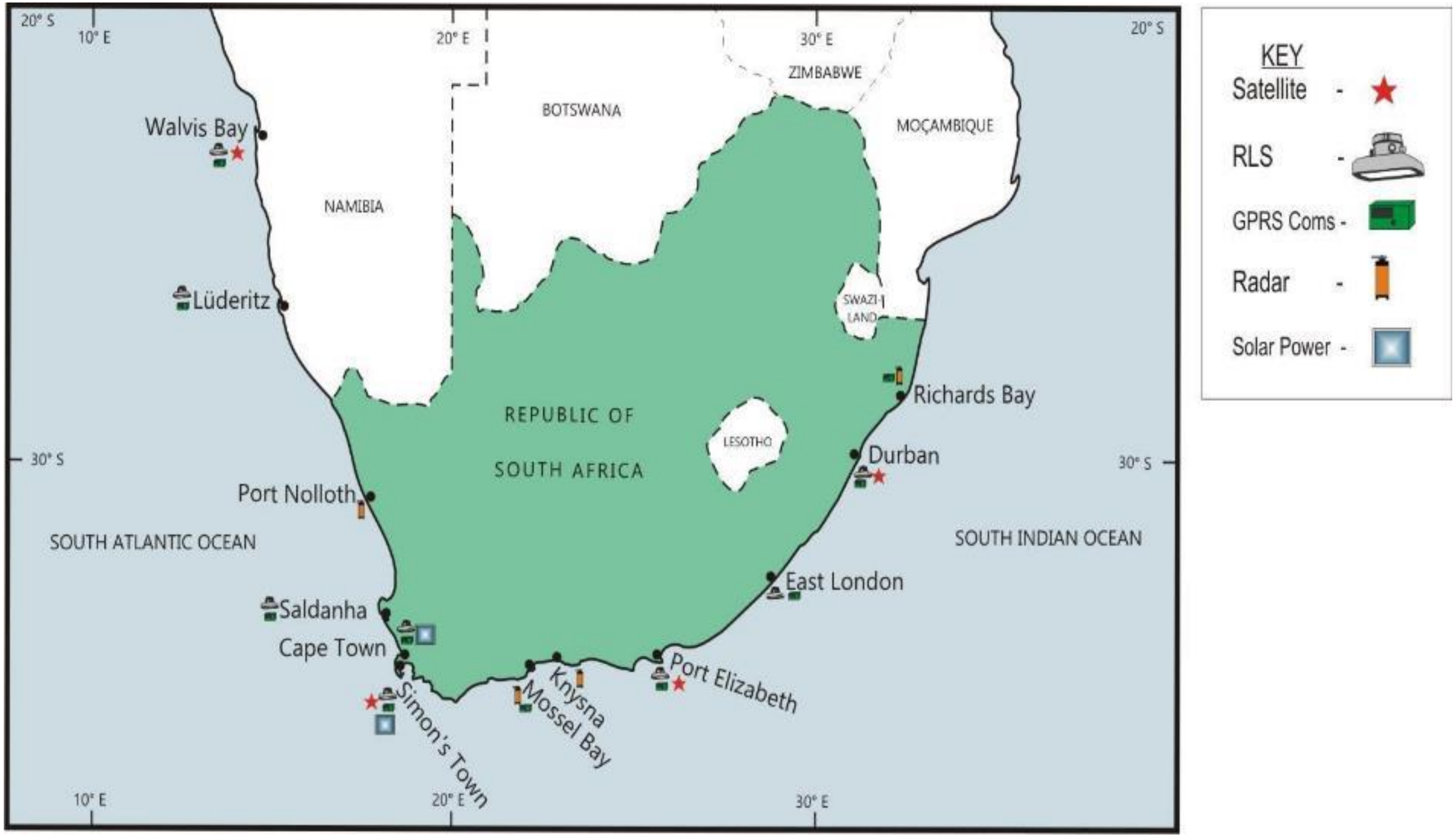
Figure 39 is the positions and equipment of the South African and Namibian Tide Gauges (Farre, 2017).



At the beginning of 2002 an OTT “Kalesto” radar-actuated gauge and an OTT “Thalidemes” high quality shaft encoder with a heavier float and counterweight were placed under trial in Simon’s Town as possible replacements for the acoustic gauges in use. Both performed with a much higher degree of accuracy and stability than had been encountered previously. The results of the calibration tests for the Kalesto (Table 8) indicated that, in general:

- 81% of the readings were within 2 mm of the above-stated mean
- 93% of the readings were within 3 mm of this mean
- 97% of the readings were within 5 mm of this mean.

Table 8: Analysis of “Kalesto” Readings (3 Min Means)

<table>
<tr><th>VALUE
mm</th><th>No</th><th>Sub-Totals</th><th>%</th><td rowspan="21">In general:
a. 81% of readings were within 2mm of the mean
b. 93% of readings were within 3mm of the mean
c. 97% of readings were within 5mm of the mean</td></tr>
<tr><td>2506</td><td>1</td><td rowspan="7">47</td><td rowspan="7">=3.3%</td></tr>
<tr><td>2505</td><td>4</td></tr>
<tr><td>2504</td><td>3</td></tr>
<tr><td>2503</td><td>6</td></tr>
<tr><td>2502</td><td>10</td></tr>
<tr><td>2501</td><td>11</td></tr>
<tr><td>2500</td><td>12</td></tr>
<tr><td>2499</td><td>50</td><td>=3.4%</td><td rowspan="7">92.8%</td></tr>
<tr><td>2498</td><td rowspan="5">1164</td><td rowspan="5">=80.7%</td></tr>
<tr><td>2497</td></tr>
<tr><td>2496</td></tr>
<tr><td>2495</td></tr>
<tr><td>2494</td></tr>
<tr><td>2493</td><td>126</td><td>=8.7%</td></tr>
<tr><td>2492</td><td>34</td><td rowspan="6">56</td><td rowspan="6">=3.9%</td></tr>
<tr><td>2491</td><td>9</td></tr>
<tr><td>2490</td><td>7</td></tr>
<tr><td>2489</td><td>3</td></tr>
<tr><td>2488</td><td>2</td></tr>
<tr><td>2487</td><td>1</td></tr>
<tr><td></td><td>1143</td><td></td><td>= 100%</td><td></td></tr>
</table>

Additional information on the Hydrographic Act.

The Department of Transport (DOT) ratified the SOLAS agreement on behalf of the RSA Government, thus making the DOT responsible for the maritime safety of RSA. Leading up to the Simon's Town Agreement of 1957, the DOT handed over the responsibility of hydrographic services in terms of SOLAS to the Department of Defence (DOD), South African Navy (SAN). This was done via Ministerial Memorandum of 1954. The Ministerial Memorandum of 1954 made the SANHO responsible for the production of all navigational safety charts (a map of the sea floor) and publications, as well as the dissemination of all navigational warnings (DOD, 2019). As a result, the SANHO works closely with the South African Maritime Safety Association (SAMSA) and the South African Weather Service (SAWS). The SANHO Archives was also made a part of the South African National Archives with all tide and hydrographic survey bathymetric data for RSA being stored on its premises.

The 1983 Report of the Committee of Inquiry into a National Maritime Policy for the RSA, generally known as the *Floor Report,* recognized the non-compliance in terms of mandate to the International Convention for the Safety of Life at Sea commonly referred to as (SOLAS (Floor *et* al, 1993). In 2007, RSA underwent a Voluntary IMO Audit (VIMSA) (Hindborg *et al*, 2008). The VIMSA, once again, found that RSA was fully compliant except for Chapter 5 regulation 2.2 which refers to a dually mandated organisation producing navigational charts and publications. The VIMSA recommended that the appointment of the SAN Hydrographer, as the National Hydrographer, within the National Defence Force/SAN, should be in terms of legislation (Kampfer, 2015). This legislation would define the Hydrographer's responsibilities and liabilities in terms of Chapter V of SOLAS. The next IMO voluntary audit was set to take place in 2021, however this has been rescheduled to take place in March 2022 (pers comm). The first iteration of the Hydrographic Bill was prepared in 1995 as a direct result of these recommendations[16]. The Hydrographic Bill, B17B-2018 was approved and signed by the Select Committee on Security and Justice at the SANHO on 03 December 2019

On 26 May 2020, the President of South Africa signed the Hydrographic Bill making it the Hydrographic Act No 35 of 2019 where by the purpose of the act is

> *"To provide for the establishment of the [National] Hydrographic Office, to provide for its objects, functions and the manner in which it is to be managed, to provide for the appointment and powers of the Hydrographer and the staff in the Hydrographic Office, to regulate the submission of hydrographic data, to regulate the manner in*

[16] Admiral (Ret) N.Guy, subsequent amendments by former Capt (SAN) A. Kampfer

which hydrographic survey marks and copyrights may be protected, to provide for the limitation of civil liability, to provide for the manner in which the income of the Hydrographic Office must be dealt with, to provide for co-operation agreements and to provide for matters connected therewith." (RSA, 2020)

The Hydrographic Act describes the functions of SANHO as the following

"…4. *To achieve the objects of this Act, the Hydrographic Office must—*

(a) direct the collection and compilation of hydrographic data;

(b) sell to users the nautical publications and nautical charts necessary for the safety of navigation within the exclusive economic zone and the internal waters of the Republic;

(c) provide services to users in the manner most suitable for the purpose of aiding navigation—

(i) by consulting with all the relevant maritime safety users in order to ensure that hydrographic surveying is carried out in accordance with the requirements of internationally accepted specifications and standards;

(ii) to prepare and issue nautical publications and nautical charts;

(iii) to issue sailing directions, lists of lights, notices to mariners and tide tables where applicable, satisfying the needs of safe navigation; and

(iv) to update the nautical publications and nautical charts;

(d) maintain uniformity of nautical publications and nautical charts, taking into account the resolutions and recommendations of the International Hydrographic Organisation;

(e) coordinate hydrographic activities in order to ensure that hydrographic data, nautical publications and nautical charts are made available on a world-wide scale as timely, reliably and unambiguously as possible;

(f) take the necessary steps to ensure that the navigational warnings relating to safe navigation in NAVAREA VII is communicated promptly to persons navigating in NAVAREA VII; and

(g) represent the Republic at the International Hydrographic Organization and at the International Maritime Organisation on hydrographic matters and participate in regional and international forums." (South Africa, 2018)

Table 9: SANHO tide gauge Network Station information (NAMPORT – Namibian National Ports Authority, HartRAO - Hartebeesthoek Radio Astronomy Observatory)

GLOSS ID	Station Name	Port ID	Latitude	Longitude	Time Zone	Type of Gauge	Responsibility
	Port Nolloth	PN	29° 15' 25.56"S	16° 52' 01.34"E	GMT + 2	OTT Kalesto Radar	SANHO
	Saldanha Bay	SA	33° 01' 25"S	17°57' 37.21"E	GMT + 2	NetDL, RLS Radar	SANHO
	Cape Town	GB	33° 54' 19.22"S	18° 26' 02.18"E	GMT + 2	NetDL, RLS Radar	SANHO
268	Simon's Town	SB	34° 11' 16.92"S	18° 26' 22.04"E	GMT + 2	NetDL, and Kalesto Radar fitted with satellite transmitter	SANHO
	Mossel Bay	MB	34° 10' 46.27"S	22° 08' 49.74"E	GMT + 2	NetDL Radar	SANHO
	Knysna	KN	34° 02' 58.51"S	23° 02' 44.15"E	GMT + 2	Kalesto Radar	SANHO
76	Port Elizabeth	PE	33° 57' 35.19"S	25° 37' 46.12"E	GMT + 2	NetDL, RLS fitted with satellite transmitter	SANHO
	East London	EL	33° 01' 37.79"S	27° 54' 53.20"E	GMT + 2	NetDL, RLS Radar	SANHO
13	Durban	DU	29° 52' 27.18"S	31° 03' 02.8"E	GMT + 2	NetDL, RLS fitted with satellite transmitter	SANHO
	Richards Bay	RB	28° 47' 43.86"S	32° 04' 42.15"E	GMT + 2	NetDL, RLS Radar	SANHO

Table 10: SANHO Tidal Equipment Technical Specifications (Consolidation summary of OTT Hydrometry (Pty) Ltd Product Specification Sheets supplied with products. Created by SANHO)

	Kalesto	**RLS 24 GHz**	**RLS 25.3 GHz**	**NetDL 500**
Measuring Range in metre	1.5 ~ 30 m	0.8 ~ 35 m	0.4 ~ 35m	-
Resolution	1 mm	1 mm	1 mm	-
Accuracy	±10 mm	±10 mm	±10 mm	-
Measuring Time s	20 s	20 s	2 ~ 20 (Default 20 s)	-
Beam Angle	±5°	±12°	±12°	-
Transmission Frequency	24.125 GHz	24 GHz	25.3 GHz	-
Transmission Power in Watts	5 mW	<5 mW	<5 mW	-
Interface	RS 485	SDI-12, 4 -20 mA, RS 485 Using SDI-12 Protocol	SDI-12, 4 -20 mA, RS 485 Using SDI-12 Protocol	**Sensor**: SDI-12, 4 -20 mA, RS 485 Using SDI-12 Protocol, **Comms**: RS-232, USB-A, USB-B, GSM/GPRS/3G & SMA Antenna Connector
Memory	-	-	-	30.8 MB ± 1.1 Million Measured Values
Power Supply Volt Direct Current (V DC)	10.5 ~ 15	9.6 ~28	5.4 ~ 28	9 ~ 28
Current Consumption Ampere (A) at 12 V				
Active	550 mA	< 12 mA	< 15 mA	25 ~ 400 mA
Standby	< 1µA	<0.05 mA	<0.05 mA	0.25 ~ 10 mA
Dimensions	(L) 500 mm x (Diam) 160 mm	(L) 222 mm x (W) 152 mm x (H) 190 mm	(L) 222 mm x (W) 152 mm x (H) 190 mm	(L) 148 mm x (W) 124 mm x (H) 68 mm
Weight	±8 kg	±2.1 kg	±2.1 kg	±0.4 kg
Temperature Range	-40 to +85 °C	-40 to +60 °C	-40 to +60 °C	-40 to +70 °C
Protection Rating	IP 68	IP 67	IP 67	IP 41
Notes: Older versions were distinguished by FCC and EC standards (25 GHz vs 24GHz versions) EC now also 25GHz				

SANHO In-house software.

The SANHO Tide Analysis and Prediction Software was developed in the mid 1950's by INFOPLAN, now the State Information Technology Agency (SITA). It was written in Fortran and compiled with the WATCOM Fortran Compiler and the DISLIN Graphics Utilities and needed no additional software to be loaded before running the software in the previous *MS-DOS* and *Windows 3.11* environments. Each output had its own script that was run via the *MS-DOS* line command interface (INFOPLAN, 1957).

With the rapid evolution of computing technology, *MS-DOS* was no longer compatible with the faster Pentium 1 computer processors that were on the market and it was determined by the STI and SITA representative at the SANHO that the in-house software required an "upgrade" (Farre and Schulz, 2004). In 2005 the individual components of the program were given a GUI (Graphic User Interface) to work in the new Windows 2000 and Windows NT environments, subsequently making it more user friendly (Abrahams et al, 2006). Initially the data calculated from an already processed data set was not yielding satisfactory results and a commercial software package (approved by the IOC) was obtained to assist in establishing the nature of the issue. It was determined that due to the higher rounding capabilities of the new Windows environment, the results were being affected, showing unacceptable inaccuracies (pers comm: Mr U. Schultz). The software errors were corrected and to date the software is working extremely accurately. The software was renamed from *Tide Analysis and Prediction Software* to *Tidal Office*

WTPP041A. MEAN SEA-LEVEL REDUCTIONS - XO TECHNIQUE. PAGE 001

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THE MONTHLY AND YEARLY SEA-LEVEL MEANS FOR SA FOR THE YEAR 2018

MONTH	NO.DAYS	MEAN (CM)
JAN	0	0.000
FEB	7	0.000
MAR	30	96.441
APR	30	95.818
MAY	31	94.646
JUNE	30	91.546
JULY	31	88.781
AUG	31	86.005
SEPT	28	91.133
OCT	31	95.503
NOV	30	91.274
DEC	31	93.390
YEARLY MEAN * 2018	310	92.454 *

RECORD OF YEARLY MEAN LEVELS FOR PORT SA

NOTE: ALL VALUES ARE GIVEN AS ORIGINALLY REPORTED

YEAR	LEVEL(CM)
1973	78.089
1974	77.363
1975	78.114
1976	109.452
1977	104.311
1978	103.542
1979	84.036
1980	105.019
1981	103.583
1982	107.908
1983	102.667
1984	100.223
1985	105.098
1986	107.589
1987	108.556
1988	108.732
1989	110.739
1990	110.203
1991	108.017
1992	109.983
1993	110.863
1994	110.296
1995	110.455
1996	109.653
1997	109.745
2000	114.232
2001	117.918
2002	106.314
2003	106.349

2004	106.316
2005	107.363
2006	107.553
2007	108.237
2008	109.448
2009	110.471
2011	117.843
2014	108.878
2015	108.572
2016	110.559

****

Example of the Tide table display format

DURBAN
2021

TIME ZONE - 2

TIME ZONE - 2

APRIL

DAY	TIME	M	DAY	TIME	M
1	05 56	2.08	16	05 36	1.84
T	12 05	0.27	F	11 48	0.39
	18 14	1.88		17 53	1.75
				23 54	0.46
2	00 15	0.30	17	06 02	1.73
F	06 32	1.89	S	12 15	0.50
	12 40	0.44		18 21	1.64
	18 51	1.71			
3	00 53	0.50	18	00 22	0.59
S	07 11	1.66	$	06 32	1.59
	13 20	0.63		12 46	0.63
	19 35	1.52		18 55	1.51
4	01 39	0.73	19	00 56	0.74
$	08 03	1.43	M	07 10	1.45
	14 14	0.82		13 27	0.78
	20 51	1.33		19 43	1.37
5	03 12	0.94	20	01 50	0.89
M	10 12	1.27	T	08 21	1.31
	16 49	0.94		14 49	0.91
				21 45	1.27
6	00 05	1.33	21	04 42	0.97
T	06 37	0.90	W	11 16	1.29
	12 45	1.34		17 47	0.89
	19 06	0.81			
7	01 26	1.51	22	00 20	1.39
W	07 39	0.73	T	06 40	0.82
	13 44	1.51		12 48	1.44
	19 54	0.64		19 01	0.72
8	02 08	1.68	23	01 16	1.60
T	08 16	0.57	F	07 29	0.63
	14 22	1.66		13 36	1.63
	20 28	0.49		19 44	0.53
9	02 40	1.83	24	01 56	1.82
F	08 46	0.44	S	08 08	0.43
	14 53	1.79		14 15	1.81
	20 57	0.37		20 21	0.34
10	03 09	1.94	25	02 32	2.01
S	09 13	0.34	$	08 44	0.26
	15 21	1.88		14 52	1.95
	21 23	0.28		20 56	0.19
11	03 35	2.01	26	03 08	2.15
$	09 40	0.27	M	09 20	0.14
	15 47	1.93		15 29	2.04
	21 49	0.22		21 31	0.09
12	04 00	2.04	27	03 44	2.23
M	10 06	0.23	T	09 56	0.08
	16 12	1.95		16 06	2.07
	22 14	0.21		22 07	0.05
13	04 24	2.03	28	04 21	2.22
T	10 31	0.23	W	10 33	0.09
	16 37	1.94		16 43	2.05
	22 39	0.22		22 44	0.09
14	04 48	2.00	29	04 59	2.13
W	10 57	0.25	T	11 09	0.16
	17 02	1.90		17 21	1.97
	23 04	0.27		23 22	0.20
15	05 12	1.93	30	05 37	1.98
T	11 22	0.31	F	11 47	0.28
	17 27	1.83		18 01	1.84
	23 29	0.35			

MAY

DAY	TIME	M	DAY	TIME	M
1	00 02	0.36	16	05 46	1.69
S	06 17	1.78	$	11 59	0.47
	12 25	0.43		18 11	1.65
	18 44	1.68			
2	00 46	0.56	17	00 12	0.59
$	07 02	1.58	M	06 22	1.59
	13 09	0.61		12 36	0.58
	19 37	1.52		18 51	1.55
3	01 43	0.76	18	00 54	0.71
M	08 02	1.38	T	07 08	1.47
	14 09	0.77		13 23	0.70
	21 04	1.38		19 47	1.45
4	03 30	0.90	19	01 57	0.82
T	09 57	1.27	W	08 19	1.37
	16 10	0.87		14 36	0.80
	23 23	1.39		21 20	1.39
5	05 54	0.86	20	03 49	0.87
W	11 59	1.32	T	10 11	1.34
	18 12	0.80		16 28	0.81
				23 14	1.46
6	00 43	1.51	21	05 40	0.78
T	06 59	0.74	F	11 49	1.43
	13 04	1.44		17 59	0.70
	19 10	0.67			
7	01 29	1.64	22	00 25	1.62
F	07 40	0.61	S	06 44	0.62
	13 46	1.57		12 51	1.57
	19 50	0.55		18 56	0.55
8	02 04	1.75	23	01 15	1.80
S	08 12	0.49	$	07 31	0.45
	14 20	1.68		13 40	1.71
	20 22	0.45		19 42	0.39
9	02 34	1.84	24	01 58	1.96
$	08 42	0.39	M	08 14	0.31
	14 50	1.76		14 23	1.84
	20 51	0.37		20 25	0.26
10	03 02	1.90	25	02 39	2.06
M	09 10	0.32	T	08 55	0.20
	15 18	1.82		15 05	1.92
	21 19	0.32		21 06	0.18
11	03 28	1.94	26	03 21	2.11
T	09 38	0.27	W	09 35	0.15
	15 46	1.85		15 47	1.96
	21 46	0.29		21 48	0.16
12	03 54	1.94	27	04 02	2.08
W	10 05	0.26	T	10 15	0.15
	16 13	1.85		16 29	1.96
	22 13	0.30		22 30	0.19
13	04 20	1.91	28	04 44	2.00
T	10 32	0.27	F	10 56	0.20
	16 40	1.84		17 12	1.91
	22 41	0.34		23 13	0.28
14	04 47	1.86	29	05 27	1.87
F	10 59	0.31	S	11 37	0.30
	17 08	1.80		17 57	1.82
	23 09	0.40		23 58	0.41
15	05 15	1.79	30	06 12	1.72
S	11 28	0.38	$	12 19	0.41
	17 38	1.73		18 44	1.71
	23 39	0.48			
			31	00 47	0.56
			M	06 59	1.57
				13 05	0.54
				19 37	1.59

JUNE

DAY	TIME	M	DAY	TIME	M
1	01 44	0.70	16	00 56	0.63
T	07 55	1.43	W	07 08	1.57
	13 59	0.67		13 19	0.57
	20 45	1.49		19 43	1.59
2	02 59	0.81	17	01 53	0.71
W	09 08	1.34	T	08 05	1.49
	15 12	0.76		14 15	0.65
	22 13	1.44		20 50	1.55
3	04 36	0.84	18	03 07	0.76
T	10 40	1.31	F	09 19	1.43
	16 47	0.79		15 27	0.70
	23 37	1.47		22 11	1.56
4	05 56	0.78	19	04 35	0.74
F	12 01	1.36	S	10 45	1.43
	18 06	0.74		16 51	0.69
				23 29	1.63
5	00 37	1.55	20	05 53	0.66
S	06 51	0.69	$	12 03	1.49
	12 59	1.45		18 07	0.61
	19 02	0.66			
6	01 22	1.63	21	00 34	1.73
$	07 34	0.59	M	06 56	0.54
	13 44	1.54		13 07	1.59
	19 44	0.58		19 08	0.51
7	01 58	1.71	22	01 29	1.83
M	08 10	0.49	T	07 49	0.42
	14 21	1.62		14 02	1.70
	20 20	0.50		20 02	0.40
8	02 31	1.77	23	02 19	1.91
T	08 43	0.41	W	08 37	0.32
	14 54	1.69		14 52	1.80
	20 53	0.45		20 52	0.32
9	03 02	1.81	24	03 07	1.95
W	09 14	0.36	T	09 23	0.26
	15 25	1.74		15 39	1.88
	21 24	0.41		21 39	0.28
10	03 32	1.82	25	03 53	1.95
T	09 45	0.32	F	10 07	0.23
	15 55	1.78		16 24	1.92
	21 55	0.39		22 26	0.28
11	04 02	1.82	26	04 39	1.91
F	10 15	0.32	S	10 49	0.24
	16 26	1.79		17 09	1.91
	22 26	0.40		23 11	0.32
12	04 33	1.80	27	05 23	1.84
S	10 47	0.33	$	11 31	0.28
	16 57	1.79		17 52	1.88
	22 59	0.42		23 55	0.40
13	05 06	1.77	28	06 05	1.75
$	11 19	0.37	M	12 11	0.35
	17 31	1.76		18 34	1.81
	23 33	0.48			
14	05 42	1.71	29	00 38	0.50
M	11 54	0.42	T	06 46	1.65
	18 08	1.71		12 50	0.44
				19 17	1.71
15	00 11	0.55	30	01 23	0.60
T	06 22	1.64	W	07 28	1.55
	12 33	0.49		13 31	0.54
	18 51	1.65		20 03	1.61

46

Distribution of predicted tides

In accordance with the IMO SOLAS Chapter V regulation 19, all vessels at sea must comply with "*carriage requirements for shipborne navigational systems and equipment*" (IMO, 2019) of which Regulation 19.2.1.4 states that the Tide Tables and Tidal Stream Atlases are required publications (IMO, 2019). A carriage requirement is what navigational safety equipment, charts and publications must be on board all ships/boats on all voyages in order to ensure safety of all lives at sea and is strictly regulated by the IMO and each sovereign state's regulating authority. In South Africa, the South African Maritime Safety Association (SAMSA) is responsible for thorough regular inspections, ensuring that all vessels in South Africa waters are in compliance with carriage requirements. As the SANHO is not permitted to sell products directly to clients, SAN-HO2 and other navigational products, are sold via Value Added Retailers (VARs) as approved by the Department of Defence and National Treasury.

In accordance with IHO Technical Resolutions (TR) relating to tide predictions, TR A6.2 (Figure 39), the SANHO supplies advanced copies of the tide predictions to various IHO Member States for inclusion in their tide tables (TT) (specifically United States of America, the United Kingdom, Japan, and India). The British Admiralty (the United Kingdom) still produces a large folio of international publications and charts, with their TT covering over 500 standard ports and over 5 700 secondary ports (UKHO, 2019). They reproduce the South African tides for Cape Town and Durban in their publications Admiralty Tide Tables NP208 (Vol 8) which includes coverage of the West Coast of Africa and NP203 (Vol 3) covering most of the Indian Ocean (Figure 40).

	ADVANCE SUPPLY OF TIDAL PREDICTIONS	**10/1919 as amended**	**75/2006**	**A6.2**
1	It is resolved that advance copies of tidal predictions shall be supplied on request to those Member States who require them for inclusion in their own published tables.			
2	It is strongly recommended that these advance copies be supplied in sufficient time to be in the hands of the publishing authority not later than twelve months before 1 January of the year of predictions.			
3	It is recommended that when tidal constituents or values of harmonic constants are changed from those used for tidal predictions for the previous year, the tidal constituents should also be supplied to the producer nation upon request together with the national tidal predictions.			
4	It is recommended that tidal predictions supplied to other countries be in the form of the times and heights of high and low waters, unless these values are not normally predicted or are requested in another form.			

Figure 40 is an extract from IHO publication M-3, technical resolution A6.2 *Advanced Supply of Tidal Predictions* (IHO, 2016).

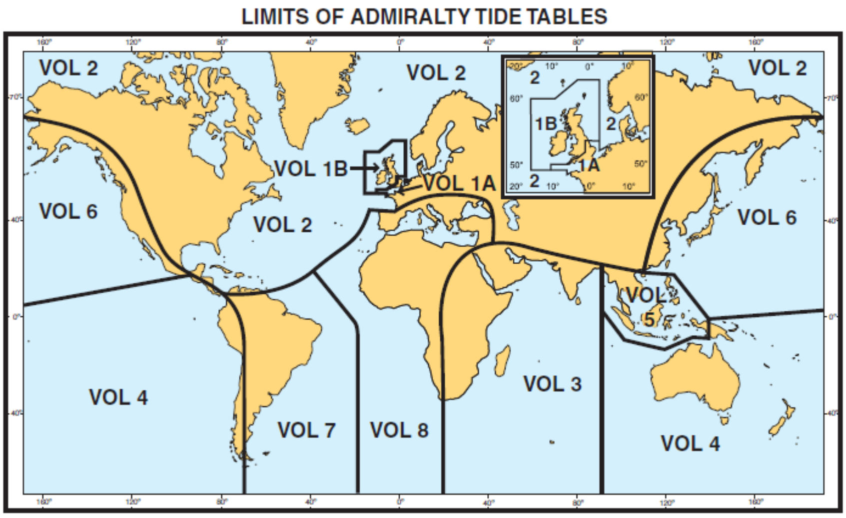
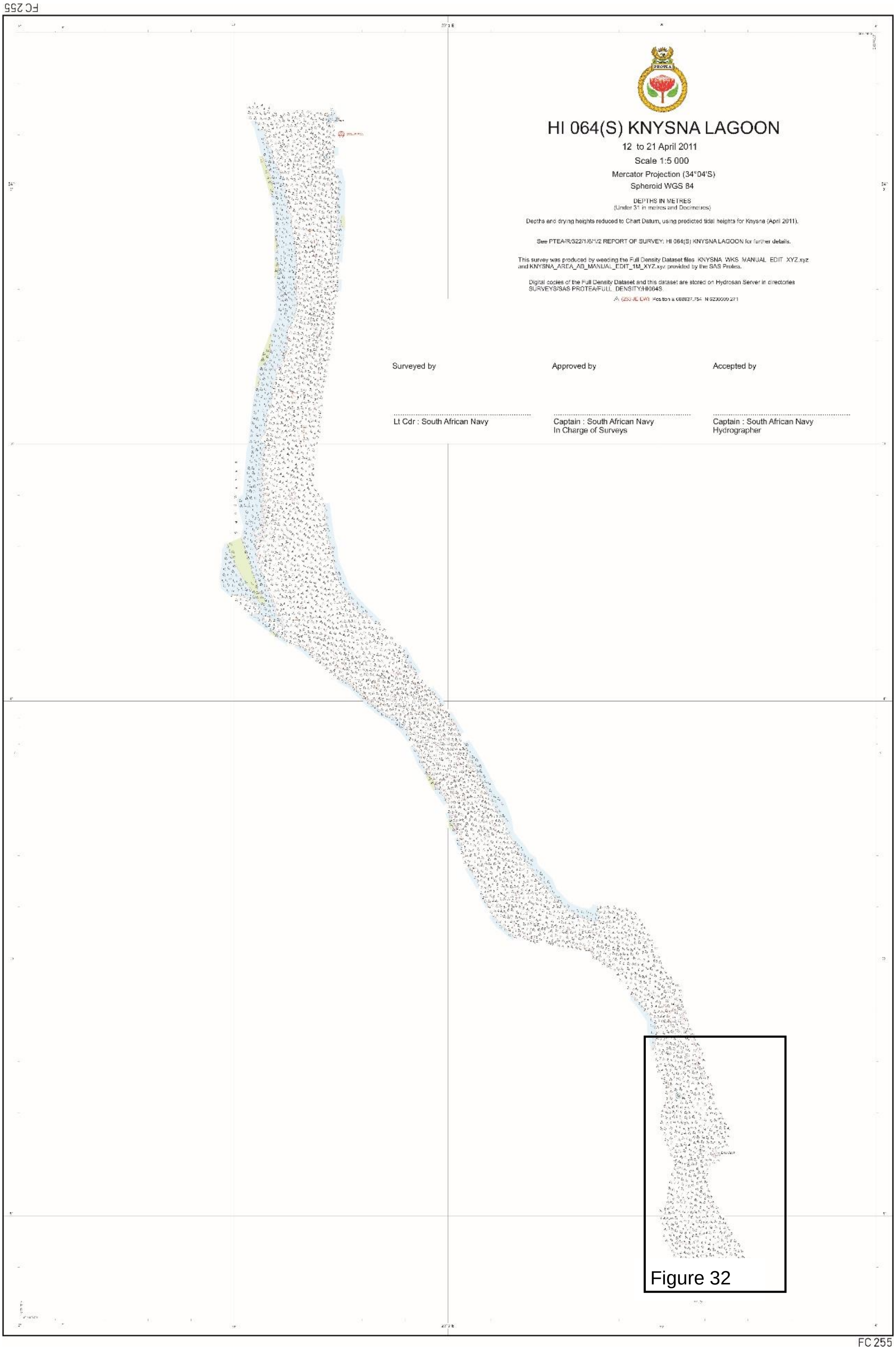


Figure 41 showing the limits of the United Kingdom Hydrographic Office (UKHO) Admiralty Tide Tables (UKHO, 2019).

The SAN-HO2 is just one of the many products produced by the SANHO that are used by the national and international communities. Many of these products or portions of these products are reproduced by various clients, with the written permission of the Hydrographer. As the information supplied is not source data, but a product it becomes subject to the Copyright Act, 1978 (Act No. 98 of 1978 as amended up to the Copyright Amendment Act 2002) (South Africa, 2002) and royalties need to be paid for the use of the information supplied.

With the introduction of the South African Spatial Data Infrastructure (SASDI) Act, 2003 (Act No. 54 of 2003) (South Africa, 2003) and the Policy on Pricing of Spatial Information Products and Services, as made by the Committee for Spatial Information under the section 6 of the Act, came into effect in 2015. The Hydrographic Act No 35 of 2019 makes provision for the SANHO to charge for royalties as well as specialised products as laid out in the SASDI Acts Cost of Fulfilling User Request (COFUR) principle.

Fair Chart FC255 where Figure 32 (pg. 87) was cropped from (with permission SANHO).



Mine Warfare - additional information

Mine warfare is defined as the strategic, operational, and tactical use of mines and mine countermeasures (USA DoD Dictionary, 2020). The naval mine is a self-contained explosive device placed in the water with the sole purpose to damage or destroy ships or submarines. Mine warfare is divided into two subdivisions: the laying of mines to degrade the enemy's capability to wage maritime war and the countering of enemy-laid mines to permit friendly manoeuvre or use of selected sea areas (United States of America, 2020). A defensive minefield is laid by own forces to protect own inshore waters, channels and harbour approaches from incursions by enemy warships. An offensive minefield is laid by own forces in enemy waters to deny the enemy the use of its own inshore waters, channels and harbours (USA DoD Dictionary, 2020).

Following the Second World War many of the minefields in European waters were not cleared. To date it is not uncommon, after a storm at sea, for moored mines from the Second World War to wash ashore, or end in the nets of fisherman. The latest such incident was on 16 December 2017 when a German mine that had probably been part of a former minefield in the Adriatic, washed up on a beach in Dubrovnik, Croatia (Denmark, 2017).

The naval mine is routinely laid in waters less than 50 metres in depth. An explosion in shallow waters differs slightly in characteristics from an explosion in deep waters, having a secondary shock-wave reverberating off the seabed before it is directed upwards. The characteristics of the seabed will influence the reverberated shock wave. A sandy or muddy bottom shall weaken the reverberated shock wave, as much of the energy is absorbed. A rocky bottom will not absorb much energy resulting in the majority of the energy being redirected upwards (NRC, 2000). The target vessel's hull, in this case, is hit by two shock waves from below, the primary explosion and the secondary reverberated shock wave displaced in time by a fraction of a second. This type of explosion causes the most extensive underwater damage to the target vessel's hull (SAN, 2018).

The modern naval mine can be divided into two categories, static and propelled/mobile mines. Static mines include the traditional moored mines, drifting mines, sub-surface drifting mines, and bottom mines. Propelled mines include a diverse range of sophisticated weapons such as homing mines, targeted (aimed) mines, rising mines, and encapsulated torpedoes. Moored and bottom mines are influenced by the tides, whereas drifting mines and propelled mine was largely immune to tides, but not necessarily tidal streams (Benes and Sandel, 2009; NRC, 2001; SAN, 2018).

The bottom mine (or ground mine) comes in two varieties, the deep-water bottom mine aimed exclusively at deep-dived submarines that must navigate past a deep-water choke point, and bottom mines laid in inshore waters. If the bottom mine was deliberately laid in an area with a large tidal range, there is the risk of exposure. Otherwise bottom mines are only marginally influenced by tides (Benes and Sandel, 2009).

The most basic naval static mine is the horn type moored (or contact) mine. It consists of a buoyant explosive chamber anchored to the seabed. The buoyant explosive chamber consist of a watertight buoyant chamber that contain the explosive charge, the trigger, and the trigger and detonating mechanism. This design allows for the mine to be anchored deep enough in shallow water for the target ship to pass directly overhead prior to exploding (Figure 42).

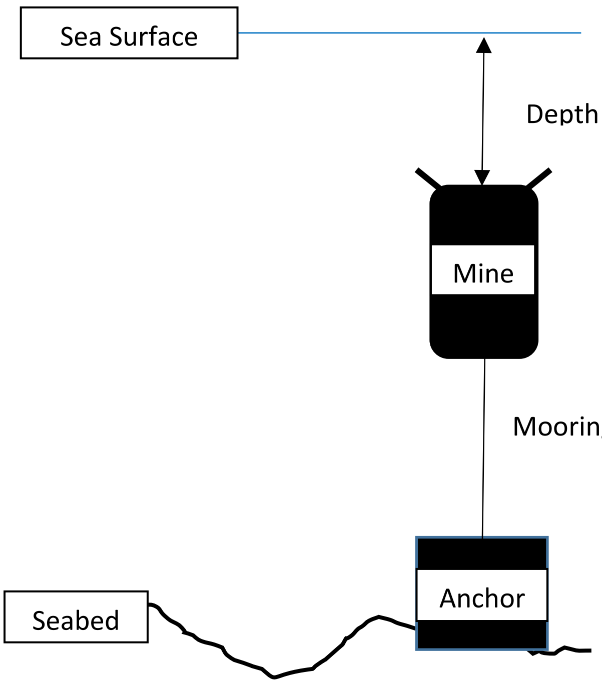


Figure 42 showing how a horn type contact mine can be anchored to the seafloor by means of a mooring line (Farre, RE, 2020).

The moored mine is laid in waters less than 50 metres in depth. Once the mine is laid, the length of the mooring cable (or anchor chain) cannot be adjusted. The distance between the moored mine and the seabed is fixed. Knowledge of the tide characteristics, maximum range, possible meteorological effects on the sea level and tidal stream characteristics will have an impact on depth of water for the mine deployment (SAN, 2018). Changes in tide phases alter the depth at which the mine and/or trigger float below the surface so spring and neap tides must be considered. Both the depth of the horned mine, or the floating trigger is calculated so as to accommodate these changes to ensure contact with the mine’s trigger.

To overcome this drawback the more modern moored mines can be fitted with a hydrostatic pressure sensor to keep the mine at a fixed depth below the surface. As the tides change, the water pressure on the sensor is altered. An increase in pressure would indicate an incoming high tide, and the mine cable would automatically adjust to keep the mine at a fixed depth below the surface. A decrease in pressure would indicate an outgoing tide, and the mine cable would automatically be wound in to keep the mine at a fixed depth below the surface.

During the planning process, the designer of the proposed mine field must consider the average depth of water and calculate the mean tidal level in the area where the fixed moored mine is to be laid, including the extreme tidal changes. If the horned mine, or the remote trigger, floats too shallow it could be exposed during low tide. The position of the minefield would be compromised, and enemy shipping would avoid the area. If the horned mine, or the remote trigger, floats to deep there was the risk that even at low tide shipping will clear the horned mine, or the remote floating trigger rendering the minefield impotent.

An example of an unclassified severe weather and rough seas navigational warning

UNCLAS

PRIORITY 300#81773 Page 1

SENDING COMCEN: 16@300 LOGON OPR: NAVCOMCAPE

SERIAL NUM: 300#81773

MESSAGE HANDLING INSTRUCTIONS:
300/05 T BUNS
300/02 T AFB OVB
300/16 T PORT CAPT CT CT RADIO PORT CAPT PE WB RADIO PORT CAPT WB
PORT CAPT DBN PORT CAPT SAL PORT CAPT RB PORT CAPT ELN

DTG:
P 151530Z

FROM: HYDROSAN

TO: COASTAL NAVWARNING

INFO:

ORIG REF: HYD/074/15 MAY 20

HYDROGRAPHIC OF...
PRIVATE BAG / PRIVA...
18 MAY 2020
TOKAI 7966
HIDROGRAFIEKANT...

=================== START OF MESSAGE ===================

COASTAL NAVWARNING 218 OF 2020
1. SOUTH TO EAST COAST - PORT ALFRED TO EAST LONDON
2. SEVERE WEATHER WARNING - GALE FORCE WINDS OF 35 KNOTS EXPECTED BETWEEN PORT ALFRED AND EAST LONDON.
VERY ROUGH SEAS WITH WAVE HEIGHTS BETWEEN 4 TO 5 METRES EXPECTED BETWEEN CAPE AGHULAS AND EAST LONDON
3. NAVIGATE WITH CAUTION
4. CANCEL THIS MESSAGE 162300 UTC MAY 2020

==================== END OF MESSAGE ====================

DIST: H MSI MTI NCAGS MARO K7 5

ORIG REF: 300#81773 Page 1

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Our ref: FOF/HYD/R/320/13/1

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NAME: R.E. Farre

COMPANY: University of Cape Town

SIGNATURE: RFarre

DATE: 01/06/2020

(T.STOKES)
SOUTH AFRICAN NATIONAL HYDROGRAPHER: CAPTAIN (SA NAVY)

DATE: 01/06/2020

Your Chart, Our Art.
Actively Contributing to South Africa's Development