PROTECTION OF AUTHOR’S COPYRIGHT

This copy has been supplied by the Library of the University of Otago on the understanding that the following conditions will be observed:

1. To comply with s56 of the Copyright Act 1994 [NZ], this thesis copy must only be used for the purposes of research or private study.

2. The author's permission must be obtained before any material in the thesis is reproduced, unless such reproduction falls within the fair dealing guidelines of the Copyright Act 1994. Due acknowledgement must be made to the author in any citation.

3. No further copies may be made without the permission of the Librarian of the University of Otago.
UNIVERSITY OF OTAGO LIBRARY

Declaration concerning thesis

Author's full name and year of birth:
(for cataloguing purposes)

Title: Mr Bradley Scarf

Degree: Bachelor of Surveying (hons)

Department: Surveying

I agree that this thesis may be consulted for research and study purposes and that reasonable quotation may be made from it, provided that proper acknowledgement of its use is made.

I consent to this thesis being copied in part or in whole for

i) a library

ii) an individual

at the discretion of the Librarian of the University of Otago.

Signature: 

Date: 8-11-99

Note: This is the standard Library declaration form used by the University of Otago for all theses.

The conditions set out on the form may only be altered in exceptional circumstances, and with the permission of Senate.

The form is designed to protect the work of the candidate, by requiring proper acknowledgement of any quotations from it. At the same time the declaration preserves the University's philosophy that the purpose of research is to seek the truth and to extend the frontiers of knowledge and that the results of such research which have been written up in thesis form should be available to others for scrutiny.

The normal protection of copyright law applies to theses.

(This form has the approval of the Librarian)
HYDROGRAPHY AND PHOTOMETRY: TOOLS FOR ARTIFICIAL SURFING REEF STUDIES?

By Brad Scarfe

Honours dissertation submitted as a partial requirement for a Bachelor of Surveying Degree.

NOVEMBER 1999
ABSTRACT

Constructing hard rock structures traditionally has controlled coastal erosion but they have negative visual appeal. Much research over recent years has gone into developing artificial surfing reefs as an aesthetically pleasing form of coastal protection with additional recreational benefits. This paper has consolidated previous research on the important wave parameters for recreational surfing in the context of artificial surfing reef studies. The important parameters are breaker type, breaking wave height, offshore seabed gradient, wave peel angle, wave peel rate and wave plunge distance. In addition, wave height transformation during breaking is introduced as an important consideration for reef design. Bathymetry is identified as the largest influence on these parameters.

Numerical modelling has been used to design reefs by researchers. Models must be validated with empirical observations to ensure the reefs form surf as designed. New RTK GPS hydrographic and zoom-in video photogrammetric systems are presented as tools to validate these models. The RTK GPS hydrographic system consists of two Trimble MS750 receivers capable of low latency 20Hz observations, a depth sounder and HYDROpro software. Tests show that the MS750 receivers are consistent with manufacturers claims that they are capable of providing single axis heave compensation. An RTK GPS tidal correction is also manually calculated. The photogrammetric system is made up of two off-the-shelf video cameras that are capable of measuring peel angle, peel rate and wave height changes during breaking. Initial tests show that this system can measure 3D wave coordinates with sub meter accuracy. Further testing is required to improve accuracy.
ACKNOWLEDGEMENTS

This project was possible because of the help of many people who I would like to thank. My supervisor Albert Chong who always had an open door when I needed a hand. He provided encouragement when tough problems arose and always went out of his way to help me. His photogrammetry and GPS knowledge was invaluable. Peter Knight was very kind to organise the loan of the GPS receivers from Trimble Navigation and help to clarify the goals I had for testing the equipment. I am grateful to Steve Taylor, Chris Pearson and Alister Neaves who were also very helpful and willing to lend their time during the busy week that I had the receivers. Mark Gibbs of the Marine Science Department enable me to put my research in perspective from time to time with an alternative view for what my project was trying to achieve. Also to Bill Dixon for not acting bored when driving the boat. Abby Smith, also of the Marine Science Department, generously gave me advice although unfortunately my problem had a change in focus and I was unable to undertake the geological experiments that I hoped to do with her. I would like to thank Ben Knight for laughing at me when I told him my original research idea and along with Andrew Gowans, helped to create this exciting dissertation topic.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td></td>
<td>1-3</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td></td>
<td>1-4</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td></td>
<td>1-5</td>
</tr>
<tr>
<td>1.1</td>
<td>RESEARCH BACKGROUND</td>
<td>1-5</td>
</tr>
<tr>
<td>1.2</td>
<td>RESEARCH PROBLEM</td>
<td>1-7</td>
</tr>
<tr>
<td>1.3</td>
<td>HYPOTHESIS</td>
<td>1-8</td>
</tr>
<tr>
<td>1.4</td>
<td>RESEARCH FOCUS</td>
<td>1-8</td>
</tr>
<tr>
<td>1.5</td>
<td>CONTENT SUMMARY</td>
<td>1-9</td>
</tr>
<tr>
<td>ARTIFICIAL SURFING REEF DESIGN</td>
<td></td>
<td>2-10</td>
</tr>
<tr>
<td>2.1</td>
<td>INTRODUCTION</td>
<td>2-10</td>
</tr>
<tr>
<td>2.2</td>
<td>COASTAL DEVELOPMENT PROBLEM</td>
<td>2-10</td>
</tr>
<tr>
<td>2.3</td>
<td>ARTIFICAL SURFING REEFS</td>
<td>2-15</td>
</tr>
<tr>
<td>2.4</td>
<td>DISCUSSION</td>
<td>2-28</td>
</tr>
<tr>
<td>RTK HYDROGRAPHY</td>
<td></td>
<td>3-31</td>
</tr>
<tr>
<td>3.1</td>
<td>INTRODUCTION</td>
<td>3-31</td>
</tr>
<tr>
<td>3.2</td>
<td>HEAVE COMPENSATION</td>
<td>3-31</td>
</tr>
<tr>
<td>3.3</td>
<td>DESCRIPTION OF RTK HYDROGRAPHIC SYSTEM</td>
<td>3-33</td>
</tr>
<tr>
<td>3.4</td>
<td>TESTING METHODOLOGY</td>
<td>3-43</td>
</tr>
<tr>
<td>3.5</td>
<td>RESULTS</td>
<td>3-51</td>
</tr>
<tr>
<td>3.6</td>
<td>DISCUSSION</td>
<td>3-66</td>
</tr>
<tr>
<td>VIDEO PHOTOGRAMMETRY</td>
<td></td>
<td>4-68</td>
</tr>
<tr>
<td>4.1</td>
<td>INTRODUCTION</td>
<td>4-68</td>
</tr>
<tr>
<td>4.2</td>
<td>THE ZOOM-IN-VIDEO-PHOTOGRAMMETRIC SYSTEM</td>
<td>4-68</td>
</tr>
<tr>
<td>4.3</td>
<td>CAMCORDER INTERIOR ORIENTATION</td>
<td>4-72</td>
</tr>
<tr>
<td>4.4</td>
<td>RESULTS</td>
<td>4-77</td>
</tr>
<tr>
<td>4.5</td>
<td>DISCUSSION</td>
<td>4-80</td>
</tr>
</tbody>
</table>
SUMMARY AND CONCLUSIONS..............................................................................................5-82

5.1 INTRODUCTION...........................................................................................................5-82

5.2 DISCUSSION OF HYPOTHESIS..................................................................................5-82

5.3 ARTIFICIAL SURFING REEFS..................................................................................5-82

REFERENCES.....................................................................................................................6-86
LIST OF FIGURES

Figure 2-1. Long Beach, New Jersey after a large storm. March 7-8, 1962 (Bascom, 1980). 2-11
Figure 2-2. Dolos armour units weighing forty-two tons each (Bascom, 1980). 2-13
Figure 2-3. Tomahawk Beach - Headland and Point Break. 2-19
Figure 2-4. Allen's Beach River Break. 2-19
Figure 2-5. Reef Break. 2-20
Figure 2-6. Wave breaking over a ledge. 2-20
Figure 2-7. Spilling Breaker (Kampion, 1989). 2-22
Figure 2-8. Plunging Breaker (Kampion, 1989). 2-22
Figure 2-9. Surging Breaker (Kampion, 1989). 2-23
Figure 2-10. Measurement of wave peel angle defined by two break point locations. 2-25
Figure 2-11. Peel angle in relation to bathymetry. 2-26
Figure 2-12. Wave plunge distance (Mead et. al. 1998a). 2-28
Figure 2-13. The portable system used to measure bathymetry of surfing reefs (Mead et. al., 1998a). 2-29
Figure 2-14. Measurement of peel angle by path of white water. 2-30
Figure 3-1. Trimble MS750 RTK GPS Receiver. 3-34
Figure 3-2. Factors contributing to RTK Latency (Trimble, 1999). 3-35
Figure 3-3. Phase errors caused by data-link delay (Trimble, 1999). 3-39
Figure 3-4. Trimble’s Configuration Toolbox. 3-39
Figure 3-5. Comparison between derived RTK tide and observed tide. 3-42
Figure 3-6. Difference between derived RTK tide and observed tide. 3-42
Figure 3-7. Comparison between RTK (MS750) derived heave and observed heave (TMS DMS-10) over 3 minutes. 3-43
Figure 3-8. Parameters for calculating seabed height before and during the passing of a wave. 3-47
Figure 3-9. GPS antenna location. 3-48
Figure 3-10. Transducer location below auxiliary motor. 3-48
Figure 3-11. MS750, echo sounder and computer location. 3-49
Figure 3-12. TRIMTALK Setup Interface. 3-49
Figure 3-13. Theoretical graph of soundings resulting from using RTK GPS. 3-51
Figure 3-14. Average latency of land based observations for different receiver settings. 3-52
Figure 3-15. Difference between latency values of CMR Plus and CMR 5Hz modes. 3-53
Figure 3-16. Average accuracy of OUSD observations for different receiver configurations. 3-54
Figure 3-17. Difference between accuracy capabilities of CMR Plus and CMR 5Hz modes. 3-55
Figure 3-18. Accuracy, standard deviation of accuracy, standard deviation of altitude and deviation from true altitude. 3-55
Figure 3-19. Results of spectral analysis on 20Hz height data. 3-56
Figure 3-20. Average latency of boat data for different receiver configurations. 3-57
Figure 3-21. Difference between land and boat tests for latency. 3-57
LIST OF FIGURES

Table 3-1. MS750 Receiver Configurations. ............................................................. 3-36
Table 3-2. Standard deviations of bottom profiles. .................................................... 3-62
Table 4-1. Interior orientation and lens stability test results. ....................................... 4-79
CHAPTER 1 INTRODUCTION

1.1 RESEARCH BACKGROUND

Coastal protection is a complex issue and all the alternative protection methods must be explored and their effects accurately predicted. Coastal protection, in this context, is both the protection of human development from the natural coastal environment and the protection of the coastal environment from human activity. Because of this definition, coastal communities are not the only party that must have their interests considered.

Most popular methods of coastal protection are anthropocentric. When property and buildings have been at risk in the past human interests have been put first. This philosophy is changing as human values and environmental legislation worldwide become more holistic.

Many poorly conceived coastal protection projects are undertaken because residents demand quick solutions to save their investments. However, with the advent of the Resource Management Act 1991 and similar effects based legislation abroad, the trial and error days of coastal planning are hopefully over. The effects of coastal protection activities now must be based on years of monitoring the local and regional wave climate, sediment movements and beach morphology.

There are three options for coastal communities to deal with changing coastlines. The first and most obvious way is to accept that the coastal area is dynamic and hard to control and only develop areas with sound geological foundations (not sandy areas). The second way to mitigate the effects of erosion is to retreat away from the coast allowing natural processes to
occur freely without regard for existing development. This option is unpopular for obvious reasons and very costly but has occurred in even some very affluent areas of the world. The third and most common method is through human intervention to stop the erosion. There are many ways that humans can protect the coastline, some are better than others, but no matter what is done major impacts on sand movements and ecology in the affected region can be expected.

The current solutions for coastal problems, although philosophies are changing, tend to mitigate effects of the sea rather than to discover the reason for the erosion. This is because current methods for coastal protection have developed from ad hoc origins. For centuries when waves have eroded beaches, the solution was to reduce the energy of the waves, strengthen the beach with a seawall or slow the transport of sand. Modern practice begins by investigating why the beach is eroding. The questions that need to be asked are: is erosion the result of changing human activities and, over what period of time has the erosion taken place?

It is unlikely that coastal areas will stop developing, so low impact coastal protection methods must be created. Although it is inevitable that any coastal protection activity is going to impact on the local and possibly regional environment, there are means that have less impact than others. One such activity is to design a breakwater, or artificial reef, that reduces the power of incoming waves and changes the flow of sand in a desired way.

An artificial reef is a structure that protects a shore area, harbour, or anchorage from wave action (Bascom, 1980). Using such a reef for coastal protection is not a new idea and has been around for centuries, but it is only recently with numerical modelling technology that the effects of the artificial reef can be accurately predicted.

Numerical modelling put simply analyses the combined effect of variables on other variables. Modelling is used in many disciplines to predict events based on arrays of formulas that make up the model. Some examples are predicting population and weather changes.

Researchers (Hutt, 1997; Mead et. al, 1997, 1998) have taken the use of artificial reefs a step further than solely shore protection, designing the reefs to produce perfect waves for recreational surfing. These are termed artificial surfing reefs. More than just protecting a beach from erosion, an artificial surfing reef mimics conditions that occur naturally around the world at world class surfing breaks.
The construction of artificial surfing reefs involves a number of disciplines. Surveyors trained in measurement science have skills that may be particularly useful in the study of artificial surfing reefs. Research into the measurement problems related to the surf-zone can widen the skills base of the surveying profession and enable better surfing reefs to be designed more efficiently. Some of the skills that surveyors can apply to artificial reef studies are hydrography, photogrammetry, engineering, resource management, project management and GIS.

1.2 RESEARCH PROBLEM

Various wave parameters are used to design artificial surfing reefs, these parameters are a function of bathymetry. Wave parameters have been modelled numerically to aid the reef design process (Mead et al., 1998a). To ensure that the parameters are modelled correctly and their relationship to bathymetry is clear, models have been validated as part of the existing research (Hutt, 1997). This validation has taken place using existing hydrographic and aerial photographic surveying techniques. It is critical that accurate information is used for validation since if a reef that fails to meet the design characteristics, there is potential for negative environmental effects.

The surf-zone presents a harsh environment for the hydrographic surveyor because of the presence of often-sizeable waves that make depth measurements uncertain and tricky. The problem is being able to correct a single beam echo sounder for the effect of the boat moving up and down in waves. Five-direction heave compensators can remove the effect swell but they are very expensive. New GPS technology can potentially replace the need for expensive accelerometer type heave compensation devices.

The surf-zone is the area between the outer most breaking wave and shore (IHO, 1994). Waves are different from swells. A wave is an individual sinusoidal curve that breaks upon entering shallow water. Swells exhibit a more regular form and flatter crests than individual waves that break at a beach and are defined as a series of waves that have travelled from the area where they were generated (IHO, 1994). Swells are generally non-breaking waves that become breakers when they enter shallow water.

As waves break there are various parameters such wave type, peel angle, peel rate and wave height that change. These different stages in the wave breaking cycle are called sections.
Precise measurement of these variables together with bathymetry must be possible to design reefs that break in sections. The three wave types are discussed in section 2.3.3.

Wave peel angle is a critical reef design parameter and is defined as the angle between the breaking point of a wave at two different moments in time and the direction of wave motion (Hutt, 1997). Aerial photography has been used to measure wave peel angle (Walker, 1974; Hutt, 1997) however this method is only capable of taking a snapshot in time of sets of waves. What is required is a photogrammetric video system that can track individual waves over time.

Peel rate is another critical design parameter. It is the speed at which a wave breaks when it enters shallow water and dictates the ability of surfer who can surf a particular break (Walker, 1974). This is predicted using an equation based on standard wave principles (Silvester, 1975 and Dally, 1990). A video photogrammetric system is required to check the accuracy of this equation for use in numerical models. Accuracy is defined as the degree of conformance between the estimated or measured position and its true position (Denys, 1998).

Changes in wave height occur as waves break due to irregular bathymetry at surf-breaks. Video photogrammetry can be used to measure this change in wave height.

1.3 HYPOTHESIS

State-of-the-art hydrographic and photogrammetric techniques can improve currently used methods for measuring bathymetry and wave parameters in the surf-zone. The first result of this improvement will be better validation of numerical models used to design reefs.

1.4 RESEARCH FOCUS

This research assumes no previous knowledge of artificial surfing reefs as a form of coastal protection. It investigates important wave parameters for recreational surfing. Hydrographic and photogrammetric techniques are introduced that can be used for artificial surfing reef studies. The need for artificial surfing reefs is presented to give a background for this research but the pros and cons of this type of coastal protection are not covered in-depth. Numerical modelling for reef design is limited to the modelling of wave parameters that define wave
quality for surfing. Modelling of refraction, wave shoaling and sediment movements are not discussed.

1.5 CONTENT SUMMARY

CHAPTER 2 introduces artificial surfing reefs and important wave parameters for recreational surfing. It begins by introducing the problem of developing land near the coast and the inadequacies of the current forms of protection from coastal erosion. Artificial surfing reefs are then presented as an environmentally sound solution for coastal protection. The difficulties, because of the complexity of the coastal environment system, of designing reefs to produce perfect surfing waves are discussed.

CHAPTER 3 presents the results of testing a new hydrographic system using Trimble Navigation's MS750 Real-Time-Kinematic (RTK) GPS receiver and HYDROpro software to chart bathymetry without heave compensation. Heave compensation corrects for errors induced in echo soundings by waves. It can potentially chart bathymetry with decimetre accuracy.

CHAPTER 4 describes the development and accuracy capabilities of a zoom-in photogrammetric system that can measure wave peel angle, peel rate and wave height transformations during breaking. The system consists of two calibrated off-the-self video cameras setup in elevated positions at the beach. Waves can be monitored with this system continuously to find out relationships of bathymetry with wave peel angles, peel rate and wave height variations.

CHAPTER 5 discusses further possibilities for research. This includes planning future research using the newly developed hydrographic and photogrammetric techniques. The possibility of using multiple RTK GPS receivers for better heave compensation is discussed. Also, the development of automated processing of video images using a simple contrast threshold is suggested. The use of GIS to manage the bathymetric and photogrammetric data is explained.
CHAPTER 2

ARTIFICIAL SURFING REEF DESIGN

2.1 INTRODUCTION

The main focus of this chapter is to give background information on the need to develop new hydrographic and photogrammetric techniques for artificial reef studies. This chapter begins by introducing the problem of land development near the coast and the inadequacies of current forms of protection from coastal erosion.

Artificial surfing reefs are an attempt to provide environmentally sound solution for coastal protection (Hutt, 1997). However designing reefs to produce perfect surfing waves is difficult because of the complexity of the coastal environment system. Numerical models simplify the design process by assuming the environment is made up of a discrete number of interrelated parameters. It is imperative that the equations that make up these models are reliable. The complexity of various wave parameters in reef design demonstrates the importance of developing new hydrographic and photogrammetric techniques.

2.2 COASTAL DEVELOPMENT PROBLEM

The problem with developing towns and cities near coastal zones is that beaches are dynamic and constantly changing, often threatening property. The erosion of soft shore coastlines often escapes human attention until permanent reference marks such as houses are constructed (Jacobson, 1997). By this time it is often too late as can be seen in Figure 2-1. It is not always obvious that erosion will be a problem and buildings in seemingly safe areas can become
threatened because erosion can happen over years, decades and even centuries as the sea encroaches on land. In many locations around the world the sea is eroding beaches to meet towns, such as parts of the eastern United States where shorelines are retreating by as much as 30 feet per year (Smith, 1997b). Developments have occurred in coastal areas without knowledge of the local geology and before the wide use of planning controls.

Figure 2-1. Long Beach, New Jersey after a large storm. March 7-8, 1962 (Bascom, 1980).

There are two types of erosion. Coastal erosion is the wearing away of a beach due to the effects of waves; land erosion caused by weathering from rain and other water sources is another type of erosion. This research is concerned with coastal erosion. Soft shore coastlines in this context are beaches consisting of a dune system with offshore sand bars.
Three options for dealing with coastal erosion are:

- To accept that the coastal area is dynamic and hard to control and only develop areas with sound geological foundations. i.e. not low-lying sandy areas.
- To retreat away from the coast allowing natural processes to occur freely and allowing the existing human to be destroyed.
- To take action and attempt to control the erosion.

The first option is unpopular because people want to live near the beach and modern engineering enables buildings to be constructed almost anywhere. The second option is also unpopular because people's homes are lost and expensive as property is swept into the sea. This second option despite the cost has happened in many places around the world where erosion has been deemed uncontrollable. The third response has traditionally been most common since the lifestyles of coastal communities can be retained and the cost of a coastal protection initiative is low when compared to the value of property protected.

There is a need for better methods for controlling erosion. When erosion becomes a threat to property the traditional response has been to build hard rock structures (Bascom, 1980). In this context hard rock structures are man-made construction such as groynes, seawalls, breakwaters and dikes. However, the negative impacts of these structures, such as possible increased beach scour and lowering of visual and recreational amenity values, indicate that better coastal protection solutions need to be found (Jacobson, 1997, Mead et. al., 1998). Often environmentalists and regulatory authorities consider these negative impacts to outweigh benefits; there are several cases in New Zealand where residents have been denied permission to protect their land from coastal erosion (Mead et. al., 1998).

Hard rock structures that protrude out of the sea lower the visual amenity values of a beach. Seawalls such as Dunedin's Saint Clair beach or groynes like that at the entrance of the Otago harbour stamp an obvious human footprint on previously natural settings. Figure 2-2 is an example of two adjacent groynes in Humboldt Bay, California, that are not pleasing to the eye.
A holistic view needs to be taken for coastal protection initiatives. However many *ad hoc* projects take place as emergency measures to protect property. Changing world legislation is making it more difficult for any construction to occur in the coastal zone without first ensuring that adverse environment effects will be mitigated. In New Zealand, the Resource Management Act 1991 requires an intensive assessment of environmental effects report to be produced to demonstrate how negative effects of an activity will be dealt with. If these effects are not justified then the regional council, who hold an environmental standpoint, will not grant consent.

### 2.2.1 ARTIFICIAL SURFING REEFS

Artificial surfing reefs have developed as an attempt to provide environmentally sound solutions to coastal erosion problems, while creating additional recreational benefits (Hutt, 1997). They incorporate multipurpose uses – coastal protection, habitat for marine organisms (Kakimoto and Tsumura, 1994; Kanenaka, 1994), recreational and professional surfing.
breaks, diving, navigation and swimming safety – to preserve and enhance both environmental and amenity values (Mead et. al., 1997; Mead et. al., 1998).

Submerged artificial reefs mimic naturally occurring reefs that protect many tropical islands from ocean waves. By moving coastal protection structures offshore the negative visual impacts of seawalls and groynes are removed. These submerged reefs are becoming popular in Australia, USA and Japan. (Mead et. al., 1998a). It is possible to incorporate artificial surfing reef design into coastal engineering construction works with minimal changes to construction design (Hutt, et. al., 1997)

Morahan (1971), Pratte (1987), Dally (1990) and Smith (1997a) have commented on the social and economic benefits of surfing. Dally (1990) remarked that surfing has been overlooked during beach development projects sometimes with negative effects on surfing wave quality. As sediment patterns change, so do the locations of the offshore sandbars and the quality of surf. Sometimes changes in sandbar locations can improve surf quality, but it is most likely that a surf spot will be negatively affected.

Artificial surfing reefs combine the use of submerged artificial reefs with an appreciation that recreation values, particularly surfing, are important to the social and economic needs of coastal communities. They are fully submerged so they cannot be seen from the shore apart from a dark outline of the reef in calm conditions (Mead et. al., 1998). The waves produced by the artificial surfing reef may be considered aesthetically pleasing (Mead et. al., 1998) and therefore improve the beaches visual amenity values.

Artificial surfing reefs can be designed from many materials. Suggestions have been to use tyres, old ships, old cars, building rubble and even used oil-rigs but using these materials is contrary to the environmental enhancement objectives that the reefs are meant to promote (Mead et. al, 1998b). The most environmentally friendly material is geotextile-sandbags because they have a finite life and can be removed if necessary (Smith, 1997b; Mead et. al., 1998b). Four cubic yard tetrahedron-shaped sandbags arranged in talus piles provide a soft gravity stabilised structure with high strength (Jenkins and Skelly, 1994). Drop tests have shown these sandbags to withstand impact from as high as 55 feet without bursting and are estimated to last at least ten years in the water (Jenkins and Skelly, 1994). Other researchers (Mead et. al., 1998b) are using larger 15mx2mx2m bags weighing several tonnes each to withstand the impacts of large waves.
2.2.2 COASTAL RESPONSE TO OFFSHORE REEFS

Offshore reefs cause the formation of a tombolo along a shoreline (Black et al., 1997). A tombolo is a bar of sand connecting an island, or this case a reef, with another island or the mainland (Chambers, 1993). Andrews (1997) has studied the shoreline response of natural offshore reefs and islands on beach shape using aerial photography of diverse range of beaches in New Zealand and Australia. This research has enabled the size of waves (including length, offshore amplitude and shape) to be predicted (Black et al., 1997).

2.3 ARTIFICIAL SURFING REEFS

Designing artificial surfing reefs to produce perfect surfing waves is difficult because of the complexity of the coastal environment. The reef must produce ridable surfing waves, breaking to a predetermined degree of difficulty for a maximum number of days in a year. Numerical models simplify the design process by assuming the environment is made up of a discrete number of interrelated parameters.

Defining what constitutes a perfect surfing wave is subjective and depends on the ability of the surfer and their style of surfing. There are however a few characteristics that are common to all good surfing waves. They are:

- The wave must be large enough to float and propel the surfer and surfboard.
- The wave must break by peeling cleanly either to the left or to the right rather as one long wave.
- The wave must peel at a rate that is equal to or slower than the maximum attainable board speed of a surfer.

2.3.1 NUMERICAL MODELLING

Researchers have been designing artificial surfing reefs by using numerical modelling (Hutt, 1997; Mead et al., 1998a, 1998c), scaled wave tank experiments (Button, M, 1991; Jenkins and Skelly, 1994; Mead et al., 1998c) and empirical data collected from world-class surfing breaks (Hutt, 1997; Mead et al., 1998a, 1998c). The most accurate and efficient method is to use numerical modelling, as entire surf breaks cannot be scaled without compromising reality (Mead et al., 1998c). Results of wave tank experiments have differed greatly from
empirically collected data (Anderson, 1997). To test a couple of hundred reef designs, as took place for a reef being built in the Gold Coast of Australia, would not be possible with wave tanks.

Numerical models represent a simplification of reality in order to enable complex systems to be dealt with (Hardisty et. al., 1995). They are commonly used in the environmental sciences to simulate the evolution of the environment (IGBP, 1992) but they can be used also to predict the behaviour of waves passing over a submerged reef. They work by using a series of differential equations (Beck et. al., 1993) based on empirical observations and theoretical principles.

**2.3.1.1 THE COMPLEXITY OF ENVIRONMENTAL SYSTEMS**

When an artificial surfing reef is introduced into the surf-zone environment, wave formation is dramatically affected. There are also effects on sediment movements and ecology but this research is concerned only with the effects on wave formation. Understanding how a reef fits in with an existing environmental system is crucial to design a reef using numerical modelling. However, there are fundamental problems with perfectly understanding an environmental system that reduce the reliability of numerical modelling.

There are many definitions of what constitutes a system. In this case a simple definition provided by Hardisty, Taylor and Metcalfe (1993) will be used. They view a system as a box that contains a set of interrelated parts. There are many inputs and outputs within the box that are dependent on the box boundaries and the openness of the system.

In an environmental context, a system can be viewed at many levels and the extent of the boundaries affects the complexity of the system. On one level, a surf break can be viewed as a system made up of water and sand. The inputs to the system that may effect how the surf break performs are sediments, swell, wind and the tide. The outputs from the system are surfable waves and dissipated wave energy. The systems parameters are interrelated since where the sediments are deposited is dictated by the flow of water and depending on where the sediments are deposited, the water will flow differently. It can be seen that this is a highly simplified system and many other parameters, inputs and output make up the surf break system. To view a system on a different level, all the beaches in a region can be viewed as a system made up of many interdependent ecological, geographical, geological and meteorological parameters. Inputs and outputs are infinite. Examples of inputs are the sun,
winds, and nutrients in the dunes. Examples of outputs are plant life, animal and fish life and the movements of sediments.

The fundamental problems with numerical modelling stem from assuming that the environmental systems are made up of a discrete number of parameters whose relationship to each other is clearly defined. Because of this, the accuracy of model predictions is only as good as data used to validate the model.

2.3.1.2 STEPS IN CREATING A MODEL

The systems approach for modelling environmental systems involves breaking down a complex environmental situation into a discrete system of interconnected parameters, inputs and output (Hardisty et al. 1993). This approach ascertains that in order to understand the functioning of the environment it is not necessary to know how the whole of nature and all its parts interact (Hardisty et al. 1993). The problem with this approach is that it assumes the real world can be divided into discrete parameters and that the relationship between the parameters can be quantified.

The systems approach to modelling involves analysis of an environmental system's parameters and boundaries (Hardisty et al. 1993). Huggett (1980) identified 5 distinct stages in creating a model. Huggett's stages in model creation are:

- Problem identification stage: This involves defining what problem exists. For artificial surfing reefs one problem might be what is the maximum size a wave will become before it breaks?

- The lexical stage: This involves choosing the systems parameters and estimating the value or state of the variables and defining the systems boundaries. The variables are subject to four types of change. They can fluctuate around a fixed state, progressively change in value, move between extremes over time and change randomly.

- The parsing stage: This involves defining the relationship between the variables either, verbally, mathematically or physically. Numerical modelling is concerned with mathematical relationships. Mathematical relationships are either deterministic, as in differential and difference equations, or stochastic, where the relationship is defined by probability.
• Modelling stage: This involves the model construction and running of the model.

• The analysis stage: This is where the reliability of the model is validated or rejected. Analysis is undertaken by comparing the results of the model with known empirical data. If there is poor correlation, then the model must be redesigned.

Numerical models have been made to predict the effects of constructing an artificial reef on sediment movements and wave-breaking characteristics (Hutt, 1997; Black et al., 1997). This has involved much analysis of surfing characteristics and sediment movement patterns. Black and others (1997) defined: wave climate (swell); local beach bathymetry; offshore seabed gradients; length of ride; wave peel angle and wave plunge distance as inseparable components that need to be considered when designing a reef. Other factors to consider are breaking wave height, wave peel rate and wave height transformation during breaking.

2.3.2 TYPES OF SURF BREAKS

Five types of geomorphic categories have been identified for surf breaks (Mead et al., 1998a; Black, 1997). Artificial surfing reefs are most like reef breaks.

• Headland or Point Break: When waves enter shallow water they slow down and bunch up since their speed is depth-determined1 (Brown et al., 1989; Mead et al., 1998d). When waves approach a headland or a point this effect causes them to refract or bend around the point. The amount of refraction depends on the wave period, which is the time it takes for two consecutive waves to pass the same point (Mead et al., 1998d). Point breaks produce clean waves in comparison to other types of breaks because the rough, short period waves are filtered out. Figure 2-3 is a map of Tomahawk Beach on the Dunedin Peninsula. Lawyers Head refracts waves to form a point break. Examples of point breaks are Allens Beach, Murdering Bay (Dunedin), Malibu (California), and Kirra (Australia).

---

1 \( c = \sqrt{gd} \) defines wave speed; where \( c \) is the wave speed (ms\(^{-1}\)), \( g \) is gravity (ms\(^{-2}\)) and \( d \) is the water depth (m) (Brown et al., 1989).
• **Beach Break:** A beach break has peaks of breaking surf that shift with sediment movements. Because the sediment moves around randomly with wave action they do not provide as consistently good waves as point breaks therefore most of the high profile surf breaks in the world are not these types of break. Figure 2-4 shows the Tomahawk beach break. Other well-known Dunedin beach breaks include Saint Clair, Saint Kilda, Aramoana and Blackhead.

• **River Entrance Bar:** River mouths form good surf breaks since sediment builds up as sandbars where the water flows out to sea. Figure 2-4 shows Allen's Beach in Dunedin where water from Hooper's Inlet (to the left) form a sand bar.

• **Reef Breaks:** Most of the worlds best breaks are reef breaks. They work the same as the previously mentioned sandbar breaks to produce surf, but are made of immovable coral or rock so provide more consistent waves. Well-known reef breaks are Raglan (New Zealand), Pipeline (Hawaii) and Padang Padang (Indonesia). Figure 2-5 shows a reef
break. Notice how the wave has broken along a distinct curve to right of the picture due to the effect of the reef

![Figure 2-5. Reef Break.](image)

- **Ledge Breaks**: Ledge breaks are by far the most difficult surfing waves to ride. They are often made up of step rock ledges that instantly stop the movement of waves so that they become powerful plunging breakers. Figure 2-6 shows a wave breaking over a ledge, note the amount of water that is surging forward. The Wedge (California) and Shark Island (Australia) are two ledge breaks.

![Figure 2-6. Wave breaking over a ledge.](image)

### 2.3.3 WAVE BREAKING PARAMETERS

There are many interrelated wave parameters that must be understood to use numerical modelling for reef design. They have complex interrelationships that can be defined mathematically with either deterministic or stochastic equations. A large database of
empirical and theoretical knowledge about how waves change when passing over submerged reefs must be established to create these equations. One group of researchers have collected data by studying bathymetry and wave parameters of 33 world-class surfing breaks in New Zealand, Australia, Bali, Hawaii, California, Brazil and Mexico (Mead et. al., 1997, 1998a).

Decades of research have simplified the wave environment into various interrelated parameters. Walker (1974a, 1974b) undertook the initial work on the important wave parameters for recreational surfing. He defined many of the terms used to break down the complex environmental system of a surf break into a closed system of finite parameters with known interrelationships. In more recent times Dally (1990), Sayce (1997) and Hutt (1997) have done research into wave breaking parameters. The research has enabled numerical modelling to be used test many artificial surfing reef shapes in a small amount of time.

2.3.3.1 BREAKER TYPE

How a wave breaks depends on how much energy is being released during breaking. The types of waves produced are classed as spilling, plunging and surging (Kampion, 1989; Mead et. al., 1998e). Not all waves can be classified exactly into these categories. They are classed according to the amount energy that is released during breaking with spilling releasing the least energy and surging releasing the most.

When waves enter shallow water there is a limit to how high waves will grow before the top of the wave collapses to release energy producing white-caped waves. Generally speaking, the ratio of wave height to wavelength is approximately 1:7 before a wave breaks (Kampion, 1989).

SPILLING BREAKER

Spilling breakers are characterised by foam and turbulence at the wave crest (Brown et. al., 1989) as depicted in Figure 2-7. They are produced by gradually sloping seabeds. The angle of the crest of the wave is less than 120° and the release of energy is relatively slow (Kampion, 1989). Spilling waves are the least powerful wave and therefore easier to surf than the other types of waves.

For a list of these surf breaks see APENDIX ONE.
Figure 2-7. Spilling Breaker (Kampion, 1989).

**PLUNGING BREAKER**
Figure 2-8 shows an example of a plunging breaker. They form over relatively steep seabeds where energy must be released quickly. Plunging breakers occur because the rapid advancement of water over a shallow bottom causes a sudden deficit of water ahead of the wave (Kampion, 1989). They are difficult to surf, but most prized by surfers (Kampion, 1989).

Figure 2-8. Plunging Breaker (Kampion, 1989).

**SURGING BREAKER**
Figure 2-9 is an example of a surging breaker. These breakers are found where waves from relatively deep water approach steep beach profiles quickly (Kampion, 1989). The wave peaks up as if to plunge but then the base of wave surges forward and the whole wave collapses (Mead *et. al.*, 1998e). These waves are not ideal for surfing.
2.3.3.2 **Bathymetry**

Bathymetry is the main influence on how waves break. Numerical models work on relationships estimated relationships between the wave parameters, as defined below, and bathymetry.

2.3.3.3 **Breaking Wave Height**

The breaking wave size is the height of the wave when it begins to break. The size of breaking waves dictates the ability required for a surfer to ride a particular wave. The breaking wave height differs from the size of a swell that reaches a beach because swells bunch up and change size when they enter shallow water. The best swells for surfing have a constant height and arrive at regular intervals (Anderson, 1996).

2.3.3.4 **Offshore Seabed Gradient**

The offshore seabed gradient along with the wave height dictates what type of wave forms. When the gradient is steep, waves increase in size quickly since the same amount of energy must pass through a small volume of water that was passing through a larger volume of water resulting in plunging waves. Shallow gradients slowly dissipate wave energy resulting spilling waves.

The effect of seabed gradient can be viewed from a macro and a micro level. At a macro level, the gradient of the continental shelf surrounding a coastline impacts the size of waves reaching a beach. Hawaii and Dunedin both have steep continental shelves making large waves frequently found. Of more interest for artificial surfing reef studies is looking at the
seabed gradient at a macro level. It is possible to change the seabed gradient of existing reefs and sandbars so that they produce larger waves than would be naturally possible.

University of Western Australia researchers have built an artificial surfing reef at Cable Station, near Perth. The reef has a seabed gradient of 1:20, which was determined through wave tank experiments (Anderson, 1996). This gradient however is likely to be too shallow and the reef only produces surf on very large swell. Mead (Anderson, 1997) surveyed the seabed gradients of 33 of the world’s top surfing reefs and found that the gradient should be as high as 1:7.

2.3.3.5 SURFABLE WAVE

A surfable wave has been defined as a wave on which a surfer can maintain an average board speed that is as fast or faster than the rate at which a wave breaks, i.e. the peel rate (Walker, 1974 and Dally, 1989, 1990). Peel rate is a relationship between peel angle and wave period. A wave's peel angle is determined by the wave break point location.

When the break point overtakes a surfer a wave is said to have closed-out. A surfable wave in the most basic sense is defined by the relationship between the peel rate and maximum attainable board speed inferred by the Irribarren number (Dally, 1990; Hutt, 1997). The Irribarren number is a classification system that has developed to categorise types of breakers (Galvin, 1968; Battjes; 1974; Dally, 1990; Hutt, 1997).

Break point location is the position where a wave collapses and turns into whitewash. It follows the depth contours of a beach (Hutt, 1997) and changes with different sized waves since different sized waves break at different depths. Break point location is influenced by swell size, tide and wind, which can delay breaking when offshore winds are present or hasten breaking when onshore winds are present. Offshore winds as their name suggests come from the shore and blow opposite to the direction of wave travel. Onshore winds are generated at sea and blow in the same direction as the path of the wave.

Surfers refer to waves as 'lefthanders' and 'righthanders' depending on the direction a wave peels when it breaks (Hutt, 1997). The ability for a wave to be surfed is dependent on the surfer's skill. The wave characteristics that define the difficulty of a wave to be surfed are the wave height, wave peel angle and wave peel rate.
2.3.3.6 WAVE PEEL ANGLE

Walker (1974) originally defined peel angle and consequently subsequent researchers have adopted his definition (Silvester, 1975; Dally, 1990; Hutt, 1997; Mead et al., 1998f). Figure 2-10 shows how peel angle, $\alpha$, is the angle between a the direction of wave travel and a line scribed by joining the break point of a wave at $t=1$ and $t=2$ (Hutt, 1997).

![Diagram of wave peel angle](image)

**Figure 2-10.** Measurement of wave peel angle defined by two break point locations.

Large peel angles form slowly breaking waves which for a given skill level are easier to surf than waves with small peel angles (Mead, et al., 1998f). Waves with small peel angles are more likely to form plunging breakers that are desired by surfers.

Peel angle is solely influenced by the break point location of a wave so when designing an artificial surfing reef the peel angle will change for different swells and tides. It has been found that surf break quality is highly sensitive to peel angles changes (Hutt, 1997).

Couriel (in Anderson, 1996) estimated a peel angle of 30 degrees as optimum. Walker (Anderson, 1996) has shown that at 30° a beginner could handle a 1.5m wave, an intermediate surfer a 3.5 m and an advanced surfer 7.0m wave. Hutt (1997) determined Walkers classification scheme to be too simple, mainly classifying difficulty according to wave height. He developed a new classification scheme that gives more weight to the effect of peel angle. Hutt classifies all waves with peel angles of 30° or less to be expert waves. It has been shown that good surfing reefs have a range of peel angles between 30 and 60° (Jackson et al., 1997).

Figure 2-11 shows the relationship between peel angel and bathymetry for Queens in Hawaii (Walker, 1974).
2.3.3.7 WAVE PEEL RATE

In order to surf on a wave, the speed of the board must be greater than speed that the wave breaks, termed peel rate (Mead and Black, 1997). The peel angle and the wave speed determine the peel rate and are determined by the Equation 2-1.

\[
V_{bp} = \frac{c}{\sin(\alpha_b)}
\]

where \( V_{bp} \) is the peel rate, \( c \) is the wave speed and \( \alpha_b \) is the wave peel angle (Silvester, 1975; Dally, 1990).
2.3.3.8 WAVE SECTIONS

As waves break the peel angle, peel rate, wave height and wave type change. These stages in the wave cycle are called sections. The reason different sections form is predominantly due to changes in bathymetry. Generally shallower water will create more plunging waves and deeper water will create more spilling waves.

2.3.3.9 WAVE HEIGHT TRANSFORMATION DURING BREAKING

Different wave sections have different wave heights. Bathymetry is the main influence on the wave height of a section but wind also affects wave height.

2.3.3.10 WAVE PLUNGE DISTANCE

Sayce (1997) has worked on quantifying wave plunge distance. Plunge distance is defined by the ratio of width to height inside the breaking wave. The ratio is zero for spilling waves and increases the more a wave plunges, or increases in hollowness. Seabed gradient is the most important parameter effecting wave plunge distance (Sayce, 1997). Figure 2-12 shows how wave plunge distance is measured by the semi-axis major and minor of and ellipse on the inside of a plunging wave.

Figure 2-12. Wave plunge distance (Mead et. al. 1998a).
2.4 DISCUSSION

The desire of people to live near the coast has historically caused problems as dynamic coastlines erode. The popular methods for coastal protection such as groynes, seawall and breakwaters are inadequate because of their negative impacts, particularly visual aesthetics. Artificial surfing reefs have many positive recreational and ecological effects that warrant them as an environmentally sound solution to coastal protection. However, they do impact natural process when constructed so the design must be careful and correct first time.

Using unrealistic numerical models for designing reefs has the potential for reefs to create waves that act differently to their design. Precise methods for mapping bathymetry and measuring peel angle, peel rate and wave height transformations will enable models to be calibrated precisely. Because of difficulties with surf-zone mapping, our understanding of near-shore hydraulics and sediment transport processes is based primarily upon theories and laboratory experiments rather than extensive field information (Birkemeier et al., 1978).

One method being used to chart reef bathymetry is a portable hydrographic system towed behind an inflatable kayak (Mead et al., 1997; Robinson, 1998; Mead et al., 1998a). The system consists of an echosounder and roving GPS receiver controlled by a Tattletale microprocessor (Figure 2-13) with a land based GPS reference-station. A single axis heave compensator is used to reduce errors induced by wave motion (Black et al., 1997). The limitations of this type of heave compensator are discussed in section 3.2. The GPS units are Trimble Geo-explorers capable of horizontal single point positioning of 10 to 100 meters. The accuracy is reduced to 5 meters when the roving data is post-processed with the base station data although 10m errors are common. Claims made estimate the vertical accuracy of this system are ±0.30m (Hutt, 1997) although this is considered to be conservative.
A more robust system is the Coastal Research Amphibious Buggy (CRAB), which consists of a 10.6m high, motorised tripod with reflector prisms that can be tracked with a total station (Birkemeier et. al., 1978). This system is capable of precise surveys of the bathymetry in the surf-zone in to a depth of 9m. However this system is not very portable, particularly for overseas travel. It is designed for use on sandy bottom sea floors and would not be suitable for some of the reef surveys undertaken as part of artificial surfing reef research.

Previous studies of wave peel angle have involved aerial photography (Walker, 1974; Hutt, 1997). These studies have involved investigating the path of white-water left by breaking waves in relation to the bathymetry of a surf-break as seen in Figure 2-14. The problems with using aerial photography are listed below.

- Using still photographs assumes waves follow the path of the previous wave. However, peel angle needs to be tracked over time because break point location, therefore peel angle, can vary even over minutes (Hutt, 1997). A video based system is required that averages wave peel angle over time (Hutt, 1997).
- Angles are not measured from changes in break point location.
- The cost and weather dependability of aerial photography means that it is not suitable for long term and intensive monitoring of the peel angle.
- Waves changes over short lengths (<10m) cannot be measured.
- Peel rate cannot be accurately measured with standard aerial photographic or video methods.

A video photogrammetry system can determine peel angle to a much more precise level than previously possible. It potentially will enable information about peel angle and peel rate changes over short sections (<10m) of wave breaking to be studied. Hutt (1997) measured peel angle every 50m based on aerial photography mosaics, which only enabled general assumptions about wave behaviour to be made.

It is important that waves can be monitored in all weather conditions, as good quality waves often occur during low-pressure systems. Aerial photography is largely dependent on good weather.

Figure 2-2. Measurement of peel angle by path of white water.
CHAPTER 3  
RTK HYDROGRAPHY

3.1  INTRODUCTION

The ability of RTK GPS to replace existing heave compensation equipment in hydrography
has been restricted by the position update rate of receivers. Until recently a 1Hz update rate
was the norm for RTK GPS receivers. Trimble’s new MS750 receiver has an update rate of
20Hz. A hydrographic system using this 20Hz receiver has been tested. It has applications in
artificial surfing reef design to chart the bathymetric characteristics of world-class surfing
breaks and the bathymetric profiles at beaches where new reefs are to be constructed.

Land based tests on the MS750 receiver enabled the receiver setup procedures to be practised
and latency and positional accuracy capabilities to be investigated. The receiver was then
setup on a 5.8m Naiad vessel with an echosounder and data was recorded in waves. The raw
data in HYDROpro is analysed to test accuracy and latency capabilities. Matlab 5.0 is used to
manually calculate a RTK derived tide correction. Baker’s (1999) experiment on using the
MS750 for heave compensation is supported by testing.

3.2  HEAVE COMPENSATION

A depth sounding measures the depth of water beneath the transducer. Soundings must be
then reduced for the level of the tide, which is constantly changing and is traditionally
measured by a local tide gauge. They are also contaminated by the effect of waves that cause
the echosounder to take measurements from the crest or trough of the wave (heave errors) and
that are not truly vertical (*pitch and roll errors*). The crest of a wave is the highest point on a wave and the trough is the lowest (Brown, 1989). The effect of these errors can be corrected for by the use of heave compensation.

Heave compensation is required to correct for errors induced by waves in soundings through *heave, pitch and roll*. Heave, strictly speaking means, to lift up or to raise, (Chambers, 1993) but in the context of hydrography it is defined as the oscillatory rise and fall of a vessel due to the entire hull being lifted by wave action (IHO, 1994). Pitch is the oscillation of a ship about the transverse axis due to the bow or stern being raised or lowered on passing through successive crests and troughs of waves (IHO, 1994). Roll is the side-to-side motion of a vessel induced by waves. Although heave compensation by definition only removes vertical errors, compensators that remove pitch and roll also are given the same name.

Heave can be measured to correct soundings in five directions. They are:

1. Vertical
2. Pitch up
3. Pitch down
4. Roll left
5. Roll right

The simplest heave compensator is a single axis accelerometer that measures vertical heave only. These are suitable for vessels over 30 meters long, in well formed swell, at a constant speed, on straight run lines and not surfing the waves (Tyson pers. comm., 1999). Straight run lines must be used because when the vessel turns, a centrifugal effect is created in the heave compensator, generating errors in the heave measurements (Tyson pers. comm., 1999). Surfing waves can confuse a single axis accelerometer. They assume that waves are sinusoidal so when a vessel accelerates, or surfs, down a wave, the vessel motion does not conform to the motion that was expected (Tyson pers. comm., 1999). This effect of surfing can be reduced to an extent by applying a *box filter* (Tyson pers. comm., 1999). A *box filter* smoothes data based on a specified bandwidth.

The most complex heave compensators are five-axis compensators and correct for heave, pitch up and down and left and right roll. These heave compensators can be used when vessel surf waves, perform rapid turns, have non-linear horizontal motion and non-sinusoidal vertical
motion (Tyson pers. comm., 1999). This type of compensation is required in the most extreme of hydrographic situations.

The two extreme cases that require five-axis heave compensation are when using a multi-beam echosounder that sends out wide swaths of beams to measure large areas of bathymetry at rates of up to 200Hz and when surveying in the surf-zone. When surveying in the surf-zone is complex for the following reasons:

- A small vessel is required to dart in and out of the breaker zone between sets of waves.
- Straight run-lines are impossible, as the vessel must perform rapid turns often to gather soundings between sets.
- Non-linear horizontal and non-sinusoidal vertical motion is amplified in the surf-zone because the shallow water causes the waves to be steeper.
- The shallow water increases the frequency of waves as they bunch up while entering shallow water.

### 3.3 DESCRIPTION OF RTK HYDROGRAPHIC SYSTEM

Two low-latency, high update MS750 receivers were loaned to the Department of Surveying of the University of Otago for one week from Trimble Navigation New Zealand. A hydrographic system using the receivers was developed and tested on a small (5.8m) research vessel belonging to the Marine Science Department, the Nautilus, to chart bathymetry in the surf-zone. The system uses RTK GPS for single-axis heave compensation without the errors caused by the momentum of traditional single-axis compensators. The system consists of an echosounder, capable of measuring to 0.10m, a roving and a reference MS750 GPS receiver and a laptop computer running HYDROpro software.

The more components that make up a hydrographic, or any other equipment intensive system, the more potential problems can arise. The MS750 RTK GPS when used with HYDROpro software potentially can replace the need for a tide gauge and a heave compensator.

The associated problems of momentum affecting single axis accelerators when a vessel turns sharply and surfs waves do not exist with GPS. RTK GPS gives the actual position of the
antenna at a specific time and errors are not generated by momentum or rapid acceleration due to surfing.

**3.3.1 Trimble’s MS750 RTK GPS Receiver**

Many advances in recent years have been made to receiver technology, antenna design, and RTK algorithms (Baker, 1999). Early generations of RTK systems could only produce update rates of 1 Hz (Baker, 1999). The update rate of a GPS receiver refers to how often a GPS position can be calculated. This rate is normally quoted in hertz. For example, a 5 Hz receiver can calculate 5 positions a second. Receivers with a 1 Hz rate can determine and correct for long period waves and tides (Baker, 1999). Trimble’s MS750 (Figure 3-1) is a new generation of RTK receiver that can determine long period waves and tidal corrections more efficiently along with high frequency waves (heave) when used with Trimble’s HYDROpro Navigation software (Baker, 1999).

![Figure 3-1. Trimble MS750 RTK GPS Receiver.](image)

The MS750 receiver can measure centimetre-level accurate positions using RTK/OTF (Real-Time Kinematic/On-the-Fly) initialisation is based on L1 carrier phase observations and C/A (Coarse/Acquisition) code measurements (Trimble, 1999). The L1 carrier phase observation is the measured number of complete and part 19-centimeter sinusoidal wavelengths broadcast from each satellite. Initialisation is the process where a receiver resolves ambiguities. Ambiguity resolution is the process where the number of whole carrier phase wavelengths between a satellite and a GPS receiver is determined (Denys, 1998). RTK is a method for calculating GPS positions in real-time relative to a reference receiver setup over a known mark (Trimble, 1992, 1998). This reference receiver resolves the integer ambiguity in the L1
carrier phase and broadcasts the solution so the roving receiver can quickly solve its integer ambiguity. The most robust RTK initialisation method, which is used for all Trimble RTK systems (Baker, 1999), is OTF ambiguity resolution, which enables solutions to be calculated while the receiver is in motion (Denys, 1998; Trimble, 1998). This C/A code is a 293-meter mathematical algorithm in the form of a binary sequence (Denys, 1998) modulated onto the L1 carrier phase to enable ambiguity resolution.

Latency has been one of the most important considerations when using RTK for hydrography (Baker, 1999). It defined as the lag in time between when a position is valid and when a position is displayed or logged (Trimble, 1998). For heave compensation latency must be negligible since shallow water waves pass by in fractions of a second. Figure 3-2 shows the factors contributing to latency in a RTK solution. The accumulation of the following parameters will cause a latency of between 0.5 and 2 seconds (Trimble, 1999).

- Reference receiver observation collection time
- Reference data formatting
- Data transmission
- Synchronisation of reference and rover data
- Position Calculation
- Solution display/output

![Figure 3-2. Factors contributing to RTK Latency (Trimble, 1999).](image)

To determine and therefore correct for latency, an auxiliary 1 Pulse per Second (1PPS) timing strobe and associated time tag has been used in the past (Baker, 1999). This time tag enabled Trimble’s HYDRO software to match GPS positions to soundings correctly. The MS750 performs the same routine, presumably with an internal timing tag of some kind.
Talbot (in Baker, 1999) rated the performance of an RTK system according to the following parameters:

- Cost
- Size/weight/ergonomics
- Operating range
- Initialisation time and solution reliability
- Solution latency and update rate

Operating range refers to the maximum distance between a roving and reference receiver. As the range increases the satellite and atmospheric errors become different for the two receivers, reducing the reliability in a solution (Baker, 1999; Denys, 1998). GPS manufacturers typically quote a maximum operating range of 10-15km (Baker, 1999).

Initialisation time and solution reliability are determined by the algorithm the receiver uses to determine resolve ambiguities and filter noisy observations (Baker, 1999).

### 3.3.1.1 RECEIVER CONFIGURATIONS

The MS750 has twelve configurations that are relevant for this project. They are based on two possible settings on the reference station and six on the roving receiver as shown in Table 3-1. The reference receiver can be set to broadcast carrier phase measurements using the CMR Plus or CMR 5Hz options. The six roving receiver modes offer different update rates for synchronised and low latency modes.

**Table 3-1. MS750 Receiver Configurations.**

<table>
<thead>
<tr>
<th>Reference Station Receiver Setting</th>
<th>Roving Receiver Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMR PLUS</td>
<td>1Hz Synchronised</td>
</tr>
<tr>
<td></td>
<td>5Hz Synchronised</td>
</tr>
<tr>
<td></td>
<td>1Hz Low Latency</td>
</tr>
<tr>
<td></td>
<td>5Hz Low Latency</td>
</tr>
<tr>
<td></td>
<td>10Hz Low Latency</td>
</tr>
<tr>
<td></td>
<td>20Hz Low Latency</td>
</tr>
<tr>
<td>CMR 5Hz</td>
<td>1Hz Synchronised</td>
</tr>
<tr>
<td></td>
<td>5Hz Synchronised</td>
</tr>
<tr>
<td></td>
<td>1Hz Low Latency</td>
</tr>
<tr>
<td></td>
<td>5Hz Low Latency</td>
</tr>
<tr>
<td></td>
<td>10Hz Low Latency</td>
</tr>
<tr>
<td></td>
<td>20Hz Low Latency</td>
</tr>
</tbody>
</table>
Trimble Navigation developed the Compact Measurement Record (CMR) for broadcasting of phase measurements between the reference and roving receiver (Talbot, 1996). The Radio Technical Commission for Maritime Services (RTCM) have created an international standard (RTCM/RTK) for RTK outputs (RTCM, 1998) although industry acceptance of this standard has been limited mainly because a radio data link with a baud rate of 4800 is required (Trimble, 1999). Trimble has still uses the CMR output because a baud rate of only 2400 is required and also the RTCM/RTK format cannot be compressed to output at 5Hz.

A base station is set to output CMR when using 4000 and 4600 series roving receivers. The CMR Plus mode is a newer format and is used when the MS750 is in synchronized 1Hz or low latency modes. CMR Plus is broadcasted by the MS750 at a 1Hz rate and is incompatible with 4000 and 4600 series receivers. The CMR 5Hz is unique to the MS750 receiver. It is a highly compressed version of the 1Hz CMR message that is repeated at a 5Hz rate. It is for use with synchronized 5Hz or low latency modes (Trimble, 1998; Trimble, 1999). The CMR package at this compressed rate is less than 9600 bits for nine satellites (Trimble, 1999).

**SYNCHRONISED RTK MODES**

The synchronised roving receiver modes are the most accurate and widely used method of gaining a GPS position. The receiver can be set to 1Hz or 5Hz update rates.

For the 1Hz mode, the base station receiver broadcasts its carrier-phase measurements once per second (1 Hz) enabling the roving receiver to calculate positions at a rate of 1 Hz. Trimble claims the latency of the 1Hz mode to be typically 0.5 seconds for a 4800-baud rate radio data-link and can be reduce with 9600-baud rate radios (Trimble, 1999). However, data-link noise is increased as the baud rate is increased.

The 5Hz mode has similar latency and precision values to the 1Hz mode but with a higher update rate. Applications such as vehicle, ship and plane guidance, photogrammetry and aircraft landing system calibration require data updates faster than 1 Hz. Trimble ascertains that using the CMR 5Hz base station setting is ‘critical to the operation of the fast update synchronised RTK scheme’ (Trimble, 1999). They also suggest that at least a 9600-baud rate data link is required for satisfactory results.
LOW LATENCY RTK MODES

MS750 receiver has low latency modes where centimetre-level positioning can be obtained at 1, 5, 10 and 20Hz update rates and 20 millisecond latency with only a slight degradation in accuracy (Trimble, 1999; Baker, 1999).

The transmitting of reference station phase measurements is the major cause of latency (Figure 3-2). The MS750 is capable of such low latency because phase measurements observed at a fixed reference receiver generally exhibit a smooth trend (Trimble, 1999). The roving receiver can then predict the phase measurement of the reference station a few seconds ahead of time (Baker, 1999). Accuracy is reduced by 3-5 centimetres in low latency mode (Baker, 1999) because of errors in predicting phase measurements. The difference between when a phase measurement is observed and when the rover receives it is called the projection time. Cycle slips, unmodelled satellite orbit variations, selective availability, short-term receiver and satellite clock instabilities and atmospheric delay cause variations to this trend (Trimble, 1999).

Figure 3-3 shows an empirically derived model for reference receiver projection phase errors as a function of the projection time. A one second delay will cause approximately 0.004m phase projection error for the L1 carrier phase with a 0.19m wavelength. The reliability of the position is reduced by 0.012m over a normal RTK solution when combined with a PDOP of 3.0. However for hydrographic work this is negligible as the echo sounder error budget is usually at least 0.10m.

![Figure 3-3. Phase errors caused by data-link delay (Trimble, 1999).](image-url)
TRIMBLE'S CONFIGURATION TOOLBOX

Trimble's Configuration Toolbox (Figure 3-4) is a Windows based application that can be used to configure Trimble GPS receivers remotely. Any setting on the receiver can be changed using the Toolbox. Many different receiver configurations can be stored on a computer and then uploaded to the receiver. The configuration settings are stored in an application file (*.cfg) (Trimble, 1998).

Two applications files always present in the receiver are Default and Current. They represent the default factory receiver settings and current receiver configurations (Trimble, 1998). By having multiple configuration files, different users can share receivers without spending time reconfiguring the receiver manually. The number of total files that can be stored on a receiver is dependent on the model of receiver (Trimble, 1998). The MS750 can store ten files i.e. the default and current files as well as eight others.

The toolbox can configure the antenna details and height, coordinate system, elevation and PDOP mask, rover receiver mode and update rate, rover serial output type (GGK, GGK Sync, GGA, GST, etc.) and baud rate, reference receiver output (CMR Plus, CMR 5Hz, RTCM, NMEA etc.) and coordinates and restrictions on individual satellites. For a more information on the Configuration Toolbox see APPENDIX TWO.
3.3.2 TRIMBLE'S HYDROPRO NAVIGATION SOFTWARE

A software package that can make use of the MS750 receiver's features is needed for hydrographic work. Trimble's HYDRO package has been superseded by a new version called HYDROpro to utilise the new features of the MS750. HYDROpro is a real-time data acquisition and guidance package specifically designed for the hydrographic and marine survey market (Baker, 1999). It can manage inputs from a wide range of sensors; accurately time stamping and logging data into a Microsoft Access database.

Baker (1999) states that the most critical part of real-time data acquisition software is to accurately time stamp each individual record, regardless of the input frequency. When used with the MS750 receiver, HYDROpro uses various time mechanisms to determine and correct for latency (Baker, 1999). For other RTK receivers, latency can be calculated from the 1PPS or NMEA ZDA³ timing tag. If latency is not such a critical issue, for example when determining tides with a 1Hz update rate, a constant latency value given by the GPS manufacturer can be entered.

HYDROpro can be used to configure the MS750 receiver remotely. No extra cables are required so this is a far simpler method of changing receiver settings than by the configuration toolbox or receiver faceplate. Configuration is done by the same serial link that downloads data from the receiver to the PC. This ability to remotely configure the receiver means that the Configuration Toolbox is only required to initially setup the reference station receiver.

3.3.2.1 RTK TIDE CORRECTION

HYDROpro calculates RTK tides using Equation 3-1 (Baker, 1999):

Equation 3-1. Tide Correction = GPS Height - Antenna Height - Datum Separation

³ NMEA - stands for National Maritime and Electronics Association. It is a standard ASCII output giving position, velocity, heading, or other information is required. NMEA ZDA outputs UTC time, day, month, year and local offset from GMT
Instantaneous GPS heights cannot be used for tide determination because they contain noise induced by heave, pitch and roll. HYDROpro uses two filters on raw GPS heights to remove noise (Baker, 1999). The first filter simply removes any heights that are not based on a *fixed integer solution*. A fixed integer solution is a GPS solution after the roving receiver has initialised. The second filter is an averaging function that smoothes noise over a user-defined sample period.

The datum separation a survey site is the height difference between WGS84 and zero value of the local tide datum (Baker, 1999). The separation can be found using conventional survey techniques. The WGS84 and local tide datum’s are generally not parallel so will change for different part of a survey site. For the range of a RTK system (10-15km), this change is not usually more than a few centimetres (Baker, 1999).

Baker (1999) investigated the difference between a RTK tide and a tide measured with a tide gauge. Figure 3-5 shows a two-hour period of tidal observations. The RTK tide was derived using a filter period of sixty seconds. It was not stated what the update rate of positions was or what type of receiver was used. It is assumed that it was the MS750 set to low latency 20Hz mode because this will give the most number of positions in a minute. However, accuracy would be reduced by 3-5-centimetres so it is possible that the 5hz synchronised mode was selected.

![Figure 3-5. Comparison between derived RTK tide and observed tide.](image)
Figure 3-6 shows the difference between the derived RTK tide value and observed tide value. The average difference between the two tide profiles is 0.03m accountable to the accuracy of the GPS height, vessel motion and accuracy of the datum separation entered into HYDROpro.

![Graph](image)

**Figure 3-6.** Difference between derived RTK tide and observed tide.

### 3.3.2.2 HIGH FREQUENCY WAVE COMPENSATION

Earlier RTK systems with 1Hz output rates and two second latency were not capable of measuring high frequency waves. Walker (in Baker, 1999) showed that these earlier systems are capable of correcting for low frequency waves with a period greater than 5 seconds. High frequency waves with periods greater than 5 seconds still required the use of a heave compensator.

Heave compensators such as the TSS DMS-10 output heave, pitch and roll corrections at 50Hz. The largest effect of vessel motion is however in vertical heave. Since the MS750 can generate 20Hz positions there now is an opportunity to compare heave data measured with both types of instruments. Baker (1999) compared three minutes of heave data measured with both methods as can be seen in Figure 3-7. The RTK data still contains the effects of pitch and roll that could have been removed using an inexpensive pitch and roll device such as the AGI MD900-TW (Baker, 1999). The wave period is about 2 seconds with amplitude of ±0.30m. Figure 3-7 makes analysis of the results difficult. It would have been better to have a graph
showing the differences between the two methods as Baker did for tide analysis. The RTK heave was generally within ±0.05m (Baker, 1999).

![Comparison between RTK (MS750) derived heave and observed heave (TMS DMS-10) over 3 minutes.](image)

**Figure 3-7.** Comparison between RTK (MS750) derived heave and observed heave (TMS DMS-10) over 3 minutes.

### 3.4 TESTING METHODOLOGY

Testing was done on land first then as a complete hydrographic system on a research vessel.

#### 3.4.1 LAND BASED TESTS

**3.4.1.1 OBJECTIVES**

Preliminary tests were performed using the MS750 receivers on land before they were setup on the vessel. These tests were carried out to achieve the following two objectives.

1. To have the MS750 receivers working in RTK mode before they were setup on the vessel.

2. To setup HYDROpro to remotely configure the MS750 roving receiver and log RTK GPS data.

3. To setup HYDROpro to log RTK GPS data to test claims made by Trimble (1999a) and Baker (1999) about latency and accuracy capabilities of the receivers.
3.4.1.2 RECEIVER SETUP

Two MS750 receivers were setup using a spliced connection to the Otago University Surveying Department's base station antenna, OUSD. Using a single antenna was not considered to affect the results. One receiver was setup as a base station and the other as a rover. Since the primary objective of the land-based tests was to get the receivers working with HYDROpro, there were no radio links between the receivers. Instead a null modem cable was used to simulate the effect of two radios.

The two receivers were setup in all 12 possible configurations. The reference station was configured with Trimble’s Configuration Toolbox, and HYDROpro configured the roving receiver.

3.4.1.3 METHODOLOGY

Data was logged into HYDROpro for 80 seconds using all twelve possible receiver settings. This generated a large amount of data especially when using the 20Hz mode because 80 seconds of data produces 1600 position fixes with associated time, accuracy, error ellipse information, PDOP and HDOP. To ensure the data logged was reliable, redundant observations were made. At least five sets of data were logged for each receiver setting giving a total of sixty sets of data. The data was logged over 3.5 hours, further increasing the reliability of data by allowing satellite geometry and atmospheric conditions to change.

3.4.1.4 DATA ANALYSIS

A copy of the list of tables created by HYDROpro in Access is included in APPENDIX THREE. The important tables for analysing latency and accuracy capabilities of the MS750 are DecodedGPSPostion, DecodedGPSErrorEllipse and DecodedGPSStatus, which are also shown in APPENDIX THREE.

The columns of relevant data were copied from the Access database into Microsoft Excel for analysis. The analysis involved firstly separating out the sixty sets of data. This was done according to the GPS time tag, which is in seconds of the GPS year, noted after logging each set. Twelve workbooks were opened in Excel, one for each receiver configuration. From here the averages and standard deviations for latency, accuracy and altitude (height) were found for each set. The results were copied through to a summary workbook for further analysis.
To check for gross errors firstly all of the standard deviations were looked at. Secondly, graphs were generated for random sets of data to ensure they exhibited the predicted trends.

**ACCURACY COMPUTATIONS**

In the DecodedGPSPostion table there is an accuracy prediction for position. It is not known how this accuracy value is calculated because horizontal and vertical accuracy are not separated. It could be calculated based on the GSOF output of the MS750. GSOF stands for General Serial Output Format and outputs binary data about receiver position, time, velocity data, DOP values etc. The accuracy value could be based on the PDOP, HDOP or error ellipse values from this output. The DecodedGPSErrorEllipse table gives horizontal error ellipse information so possible the accuracy values in the DecodedGPSPostion table could be vertical accuracies.

**LATENCY MEASUREMENTS**

A latency figure is recorded for each position in the DecodedGPSPostion table.

### 3.4.2 BOAT TESTING

#### 3.4.2.1 OBJECTIVES

1. To provide initial research for the Surveying Department in hydrography using high update, low latency RTK GPS systems.

2. To support the land based tests of latency and accuracy capabilities of the MS750 receiver.

3. To manually determine an RTK tide.

4. To field test the claims (Baker, 1999) that the MS750 can correct for heave.

#### 3.4.2.2 RTK HYDROGRAPHY PRINCIPLE

For a specific epoch the WGS84 height of the echo sounder transducer \((H_{TR})\) can be determined by taking the antenna height \((H_A)\) away from the GPS height \((H_{GPS})\). When the depth of sounding \((D_S)\) from the same epoch is subtracted from this transducer height, the
result is a sebed height \((RL_{SEABED})\) is WGS84 coordinates (Figure 3-8). This relationship is shown by the Equation 3-2.

\[
\text{Equation 3-2. } RL_{SEABED} = H_{GPS} - H_A - D_s
\]

Theoretically, \(RL_{SEABED}\) and \(H_A\) remain constant when a boat floats over a stationary position in waves. This means that when a vessel rises due to being on the crest of wave, so must the value of \(H_{GPS}\), hence \(D_s\) increases to keep the equation balanced. When a vessel is in the trough of a wave the opposite is true.

This principle is the basis for the testing methodology chosen. Many environmental factors when the vessel is in the water, such as uncorrected pitch and roll errors will most likely contaminate the results but whether or not definitive result are obtained or not, the specific objectives will still be achieved.

Figure 3-8. Parameters for calculating sebed height before and during the passing of a wave.

### 3.4.2.3 METHODOLOGY

- A small (5.8m) vessel setup with a complete RTK hydrographic system on board was positioned behind the breakers at the Otago Harbour side of Aramoana Beach.

- The boat was to float in a stationary position held by two anchors. However, only one anchor was used and the boat slowly drifted. This was not a major problem.
A 5m-prism pole was lowered into the water to ground truth soundings. A total station was setup on the Aramoana Mole to observe change in heights between the total station and the prism.

Data was logged in all twelve-receiver configurations as the vessel was moved around by wave action.

**VESSEL SETUP**

The 5.8m long Marine Science research vessel, the Nauplius, was used for testing. A GPS antenna mounted close to and above the echo sounder transducer (1.03m high and 0.13m offset) to minimise the effects of pitch and roll. The location of the GPS antenna in relation to the transducer can be seen in Figure 3-9 and Figure 3-10.

Figure 3-11 shows the boat cockpit where the all the hydrographic equipment was situated. A wooden bracket provides a stand for the laptop, echo sounder and a 14” monitor for run-line navigation (not pictured). The MS750 receiver is located on the dash above the helm. The space the front of the boat was used to store three 12-volt truck batteries. These provided a 12V DC-240V AC power supply for the computer and a 24-volt power supply for the echosounder. Additional equipment not shown was the Trimtalk radio and aerial.

*Figure 3-9. GPS antenna location.*
HYDROPRO SETUP

HYDROpro was setup in the same way as for the land based tests, expect tide averaging turned on (sampling rate 60 seconds) and echo sounder data was being logged.
GPS SYSTEM

TRIMTALK radios were used as a radio link between the reference and roving receiver. It was hoped that Beech radio could have been used because of their ability to transmit further but they were incompatible with the MS750 receivers. The TRIMTALK radios were not user friendly because they had to be configured by a computer with TRIMTALK setup installed (Figure 3-12).

![TRIMTALK Setup Interface](image)

Figure 3-12. TRIMTALK Setup Interface.

The TRIMTALK radios are meant to have a non-volatile memory so that the radios configuration can be stored even when the radio is powered down (Trimble, 1992b). This did not happen with the radio used and they had to be reconfigured every time they powered down. The reference station receiver had to be configured at the Surveying Department and then the power maintained until the testing was completed.

A reference station receiver was setup over a survey mark with known elevation in WGS84 coordinates on the Aramoana Mole at the entrance to the Otago harbour. This receiver was initially setup in CMR 5Hz mode. Tests were repeated again with the receiver in CMR Plus mode.

ECHO SOUNDER SETUP

The analogue echo sounder was setup with a Raytheon digitiser that converted the analogue depths to digital. A data converter takes the signal from the digitiser and converts it to a modem serial output acceptable to HYDROpro. The echo sounder was calibrated with a sounding plate in shallow water (<5m).
3.4.2.4 DATA ANALYSIS

When a vessel floats over a non-changing seabed bottom in waves Equation 3-2 is true. If the GPS heights ($H_{GPS}$) are plotted with depth of soundings ($D_S$) against time, the resulting seabed height ($RL_{SEABED}$) should be a flat horizontal line with an offset determined by the antenna height ($H_A$). Figure 3-13 shows this theoretical graph. The $RL_{SEABED}$ will be not be a flat because of errors induced by pitch, roll and the accuracy capabilities of the receiver. In small waves (<1m) these error would be in the order of 0.10-0.20. A 20° roll (extreme) setup close to the receiver will reduce accuracy by approximately 0.07m. Low latency GPS is capable of accuracies of 3-5cm.

![Figure 3-13. Theoretical graph of soundings resulting from using heave compensation.](image-url)
3.5 RESULTS

3.5.1 LAND TESTS

The receivers were setup with the degree of difficulty expected when learning to use new GPS equipment. It was a process of deduction to find out what components of the system were causing problems. For example, when the two receivers did not communicate a standard serial cable was replaced with a null modem cable.

HYDROpro was setup successfully to remotely configure the MS750 receiver and log RTK GPS data. The Access database was opened and it could be seen that the GPS positions and associated data was being logged at the various different user selected rates. The DecodedGPSPostion table in APPENDIX THREE shows that data is being logged at a 20Hz rate.

Data was successfully logged using all twelve-receiver configurations giving results that backed up claims made by Trimble regarding latency and accuracy capabilities.

3.5.1.1 LATENCY

Latency is largely caused by a slow data-link (because of limitations of radios). Because a null modem cable connected the two receivers, latency figures obtained during these tests were only used to draw conclusions about general characteristics of each receiver setting. These conclusions however were not backed up by the data obtained during the boat tests, effectively rendering the result unreliable. The results presented are still important because they show a possible method of analysing RTK GPS data for hydrographic purposes.

The results showed there is no substantial difference between latency values obtained using CMR Plus or CMR 5Hz reference receiver modes. Also the update rate does not seem to affect the latency of GPS positions using the MS750 receiver.

Figure 3-14 shows the average latency values for the twelve different receiver settings, six using a CMR Plus reference receiver output mode and six using a CMR 5Hz reference receiver output mode. 1HzS is an abbreviation for when the rover was set to synchronised mode with a 1Hz update rate. 1HzLL is an abbreviation for when the rover was set to low latency mode with a 1Hz update rate. It is based on 5-6, 80 seconds sets of data for each
receiver configuration that all exhibited similar trends. Figure A-, APPENDIX FOUR shows a graph of all the sets.

![Graph showing latency and standard deviation for different receiver settings.]

**Figure 3-14.** Average latency of land based observations for different receiver settings.

On first observation what seems to stand out is that the low latency modes give negative latency. This is peculiar because the definition of latency is 'the lag time between when a position is valid and when a position is displayed or logged' (Trimble, 1998). A possible reason for negative latency is that the roving receiver predicts the phase measurements of the reference receiver before they are actually observed. When dealing with such small latencies it is not important whether they are negative or positive.

The second feature of this graph is that very similar results have been obtained with the two different reference station output modes. Figure 3-15 shows no substantial difference between latency values for the two modes. The difference for synchronised modes is considered negligible since the difference ranges from 20-50 milliseconds and the quoted latency values are 0.5 seconds (Trimble, 1999a). In the low latency modes the differences ranges from 3-8 milliseconds, which is also negligible.
The third observation that can be made from Figure 3-14 is that the latency values differ from those quoted by Trimble (1999a). The two synchronised modes are stated to have the same latency of around 0.5 seconds, which is larger than the observed latencies probably because a null modem cable was used instead of radios. The 1Hz mode clearly has a greater latency value than the 5Hz mode. The low latency modes surprisingly have a longer latency (0.04-0.07 seconds) than ascertained by Trimble (0.02 seconds). The final observation is that the low latency mode exhibit consistent behaviour regardless of the update rate.

3.5.1.2 ACCURACY

Because accuracy values outputted by HYDROpro into the DecodedGPSPosition table are not separated into horizontal and vertical accuracies they cannot be compared directly to the manufacturers specifications. It was not considered necessary to investigate in-depth the 5900 horizontal error ellipses generated during the testing because obtaining accurate horizontal positions is not a problem when using RTK for hydrographic tasks.

Similar assumptions can be made by these accuracy tests that were made about latency regarding reference receiver mode and update rate. There is no substantial difference between accuracy capabilities obtained using CMR Plus or CMR 5Hz reference receiver modes and the update rate does not seem to affect the precision of GPS positions.

For each receiver setting, the accuracy value from DecodedGPSPosition table was averaged and then plotted as seen in Figure 3-16. There is no difference in accuracy between the synchronized and low latency modes (~0.5cm). This is surprising because Baker (1999) states...
that a 3-5cm accuracy degradation is traded low latency results may differ due to the use of a null modem cable as a data-link. The standard deviations of the accuracies are smaller when the accuracy increases as would be expected. Figure 3-17 shows that there is no difference between using CMR Plus and CMR 5Hz modes.

**Figure 3-16.** Average accuracy of OUSD observations for different receiver configurations.

**Figure 3-17.** Difference between accuracy capabilities of CMR Plus and CMR 5Hz modes.
Figure 3-18 shows the relationship between accuracy, standard deviation of accuracy, standard deviation of altitude and deviation from true altitude. Unsurprisingly there is a clear relationship between the accuracy and the standard deviation of the accuracy. However the relationship between the two accuracy plots and the standard deviation of the altitude suggests that the accuracy value given the DecodedGPSPosition table could be a height accuracy figure. The forth graph shows the difference between the average observed altitude and the true altitude showing all modes measured the height correctly to 0.01m.

The MS750 seems to have a systematic instrument error. When a series of position data is plotted a sinusoidal wave can be seen to pass through the data. The results of spectral analysis on this data are shown in Figure 3-19. It can be seen that a 1 cycle per second (CPS) wave is present in the data. This is interesting because the 20Hz positions are calculated based on 1Hz reference station phase measurements. This error makes up approximately 0.01m of the overall error budget for this receiver mode.
3.5.2 BOAT TESTS

The hydrographic system was successfully setup on the research vessel. GPS data at various update rates, RTK tide data and echo soundings were logged into HYDROpro. Unfortunately no good data was logged in synchronised rover mode and it was hard to identify data recorded using the CMR Plus reference receiver mode so only low latency data based on CMR 5Hz output has been analysed. Initial problems with configuring the radio forced a second day of testing to be undertaken as the first day did not yield any data. Unfortunately the wave conditions were not as large as hoped (0.5-0.7m).

3.5.2.1 LATENCY

Latency results obtained for the low latency setting were smaller than found with the land based tests and closer to the specifications of the manufacturer (Figure 3-20). The results were smaller most likely because the receiver became confused with the fast data link of the null modem and calculated incorrect values. Because the latency of the low latency settings were closer to the manufacturers specifications it is probable that results of synchronised mode testing would be too. Land based tests of synchronised show a smaller than expected latency which would be increased when a radio data link is used to the 0.5 second specification.

Figure 3-19. Results of spectral analysis on 20Hz height data.
Figure 3-20. Average latency of boat data for different receiver configurations.

Figure 3-21. Difference between land and boat tests for latency.

Figure 3-21 show that there is a 40-50 millisecond difference between the land and boat tests. It is concluded that the land based tests with a null modem cable is not as a reliable method for testing latency as required. The comments made in section 3.5.1.1 about latency being consistent for both CMR Plus and CMR 5Hz modes cannot be proven without tests using a radio link.
3.5.2.2 ACCURACY

Figure 3-22 shows the accuracy results for low latency modes. It is clear that the faster update rates (20Hz and 10Hz) compromise accuracy by a few centimetres. The 5Hz rate seems the optimum for accuracy possibly because of the 5Hz output of the reference receiver. There are very different patterns displayed between the land and boat tests further enforcing the poor reliability of using a null modem as a data connection for testing. Figure 3-23 shows a 10-20mm difference between land and boat tests.

![Figure 3-22. Average accuracy of boat data for different receiver configurations.](image)

![Figure 3-23. Difference between land and boat tests for accuracy.](image)
3.5.2.3 **TIDAL DATA**

RTK tide data was collected for twenty-five minutes at a rate of 1Hz, which HYDROpro filtered to remove noise caused by wave as explained in 3.3.2.1. Presented here are the results of manual filtering using a box filter in MATLAB 5.0.

Figure 3-24 shows graphically how raw RTK GPS data is filtered in MATLAB. The y-axis shows the tide level in WGS84 datum, the x-axis shows the time in GPS seconds and the z-axis is the filtering rate. It can be seen at filtering width zero that the data is noisy and contains many unwanted spikes. As the filter width approaches the length of the data set (1565 observations), the resulting data set approximates a straight line.

This twenty-five minute data set demonstrates how HYDROpro filters raw tide data but does not attempt to draw any conclusions about the accuracy of the reduced tide. Baker (1999) estimates the RTK tide is within ±0.03m of a tide gauge. In order to test Baker’s claims, a repeat experiment to compare traditional tide gauge measurements and the derived RTK tide over three to four hours as done by Baker (1999) would have to be undertaken. An extension of this test would involve a comparison between HYDROpro’s filtered tide and a tide derived by box filtering in MATLAB.
Figure 3-24. Box filtering of tide data at various filter widths.

Figure 3-25 is a plot of the raw RTK tide data and the filter tide data. The data was filtered with a width of 4/5th the data set length. It would be assumed that over twenty-five minutes that the tidal correction would be a straight line however a flat section is present in the middle of the tide. This is because RTK lock was lost twice while recording this data. Figure 3-26 show the final tide plotted to a more accurate time scale where gaps in the data can be more clearly seen.

A long-wavelength sinusoidal wave can be seen to pass through the data. To determine the exact frequency of the wave, spectral analysis would need to be undertaken. By looking at the graph, it can be seen that the frequency is approximately 600 observations or 10 minutes.
In an ideal situation were no noise contaminates data, as shown in Figure 3-8, logging GPS heights and echo soundings while floating over the same location in waves was expected to show a flat seabed profile when graphed. Table 3-2 shows the standard deviation (σ) of bottom profiles, using data based on CMR 5Hz output, obtained from the boat tests. The results imply that for the waves present during the day of testing, the bottom profile can be determined to 0.20m in 10 and 20Hz low latency modes and with slightly less accuracy in 5Hz mode. This accuracy value is determined based on Table 3-2, the accuracy of the
echosounder (0.10m), ability of RTK GPS to measure heave (±0.05, Baker, 1999) and pitch and roll noise (0.05).

Table 3-2. Standard deviations of bottom profiles.

<table>
<thead>
<tr>
<th>Receiver Mode</th>
<th>( \sigma ) (m) Unfiltered</th>
<th>( \sigma ) (m) Filtered</th>
<th>( \sigma ) (m) EXTREME FILTERING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Hz Low Latency</td>
<td>0.04</td>
<td>0.04</td>
<td>Not Done</td>
</tr>
<tr>
<td>5Hz Low Latency</td>
<td>0.22</td>
<td>0.17</td>
<td>Not Done</td>
</tr>
<tr>
<td>10Hz Low Latency</td>
<td>0.17</td>
<td>0.16</td>
<td>Not Done</td>
</tr>
<tr>
<td>20Hz Low Latency</td>
<td>0.16</td>
<td>0.15</td>
<td>0.07</td>
</tr>
</tbody>
</table>

DATA PROCESSING

The raw data outputted from HYDROpro is not in a format that can be used to find a seabed profile immediately. GPS data is logged at four different frequencies and echo sounder data varies from 6-8 hertz. The GPS and sounding data had to be reduced to a common frequency using Matlab. The information also contained noise caused by pitch and roll of the boat which had to be removed also with Matlab. The programs that were written specifically for this processing were:

- Samplegps.m – this program resamples GPS data to a given frequency (20Hz for this project).
- Depthnew.m – This program resamples sounding data to the same rate as the GPS data.
- Boxfilterraw.m – The program box filters GPS and sounding data and outputs the difference (seabed height file) between the two data sets.
- Boxfilterfinal.m – This program box filters the seabed height file to remove latency errors.
- Meshplot.m – This program box filters seabed height file at all filter widths to help determine the optimum filter rate.

First data was resampled with Samplegps.m (Figure 3-27) and Depthnew.m (Figure 3-28). Boxfilterraw was then used on the new data. A plot of this data can be seen in Figure 3-29. In ideal circumstances the seabed profile (middle graph) should be a flat line. Because the seabed profile data contains noise, it had to be filtered. First the ideal filtering rate had to be decided on so all rates were plotted with meshplot (Figure 3-30). Similar to the tidal data, the y-axis shows the seabed, the x-axis shows the time in GPS seconds and the z-axis is the filtering rate. The unwanted noise (spikes) was filtered out at a narrow width so boxfilterfinal
was set to 1% (100) of the data set length. APPENDIX SIX is attached to show how the data was changed for different filtering widths.

Figure 3-27. Sample of box filtered GPS data.
Figure 3-28. Sample of box filtered sounding data.

Figure 3-29. Filtered GPS data (top), filtered sounding data (bottom) and the difference (middle) for 20Hz low latency mode.
Figure 3-30. Results of box filtering at different sample rates.
Figure 3-31 shows the final seabed profile for the 20Hz data. It still contains noise but the noise only ranges over about 0.20m. The standard deviation of this data as shown in Table 3-2 is 0.15m.

3.6 DISCUSSION

3.6.1 LAND BASED TESTS

The two MS750 receivers were set up to work in RTK mode and the roving receiver could be successfully configured using HYDROpro, achieving objectives one and two of the land based tests. The results of latency and accuracy tests on the receivers gave results that most likely are incorrect because of the use of a null modem cable instead of radios as a data-link leaving objective three unachieved.

The results of latency tests showed latency of synchronised modes (0.05-0.20 seconds) to be less than specified by Trimble (1999a). For low latency modes, latency (~0.05 seconds) was found to be greater than claimed by Trimble. The fact that low latency mode did not display dramatically different results to synchronised mode suggests that the results are unreliable.

The results of accuracy tests showed all modes to give a similar precision (~0.02m). Low latency modes are meant to degrade accuracy by 3-5cm (Baker, 1999) because of the projection time of phase measurements. Because a null modem was used this projection time was small, improving the results.

There was no difference between CMR Plus and CMR5Hz modes for accuracy and latency when using a null modem data-link. This may or may not be true but cannot be proven for
sure with these unreliable results. Figure 3-18 suggests that the accuracy figure given in the DecodedGPSPosition table may be vertical precision.

3.6.2 BOAT TESTS

Objective one was achieved since this research will provide background information that will be useful for directing future areas of research for the Surveying Department. Objective two was not achieved because the results of latency and accuracy tests differed dramatically from the land tests. These were deemed more reliable because they supported claims made by Trimble. However, these results still show that latency, and accuracy are not issues for hydrography with RTK. There was only good data from four of the twelve receiver configurations so conclusions could only be made about the 1, 5, 10 and 20Hz low latency modes when the reference station was broadcasting CMR 5Hz phase measurements. It was not found whether the operation of fast synchronised RTK requires CMR 5Hz output.

A twenty-five minute RTK tidal correction was reduced using Matlab and achieving objective three. However further testing is required to support findings of Baker (1999) using a longer tidal period (3-4 ours) and comparisons with a conventional tide gauge.

Claims made by Baker (1999) about the ability of the MS750 receiver to be used for heave compensation are supported by this research, achieving objective four. Results show that the hydrographic system used in this research can chart bathymetry to and accuracy of 0.20m. Both tests however have only proven the ability for heave to be compensated for in small waves (0.30-0.70m). Further testing is required for larger waves because the effects of pitch and roll will be greater. Also testing is required to determine the MS750’s ability to measure heave of different frequency waves. A possible test is to raise and lower the antenna at various rates and heights to determine the limitations of the receiver.
CHAPTER 4 VIDEO PHOTOGRAMMETRY

4.1 INTRODUCTION

Ideally artificial surfing reefs would be designed so they produce wave sections designed to break differently for different sections to a micro level (<10m). Precise measurement of wave peel angle, peel rate and height change during breaking to design such reefs has not previously been possible. Preliminary testing of a zoom-in-photogrammetric system to perform this task is presented to investigate the feasibility of developing such a system.

Photogrammetry is the science and art of determining the size and shape of objects as a consequence of analysing images recorded on film or electronic media (Fryer, 1996a) without direct measurement (Cooper and Robson, 1996). Video camera calibration tests were undertaken to determine the camera stability, lens distortions and principle distance for any arbitrary zoom.

4.2 THE ZOOM-IN-VIDEO-PHOTOGRAMMETRIC SYSTEM

This system consists of two off-the-shelf video cameras that record waves breaking. Images are captured from the video cameras using a frame-grabber so that the wave-break points and heights can be coordinated with Australis (University of Melbourne) photogrammetric software. The location of break points and wave heights can then plotted in relation to the surf-break bathymetry to determine peel angle, peel rate and changes in wave height. The resulting frames can then be saved as bitmap images and for later analysis.
A frame grabber is typically a printed circuit board that is designed to instantaneously sample the output from a solid state sensor (Shortis and Beyer, 1996b). The solid state sensor used in a video camera is called charge coupled device (CCD). A CCD is a device used in scanners, digital cameras and video cameras to capture images. Just like a negative in a traditional camera, a CDD measure the amount of light entering through a lens. Linear and two dimensional CDDs are available but the later is used for close range photogrammetry (Dowman, 1996).

\section*{4.2.1 PROJECT OBJECTIVE}

To determine whether terrestrial zoom-in video images can replace aerial photography for surf and reef studies to improve the metric accuracy.

\section*{4.2.2 DATA CAPTURE}

The two cameras used were standard Sony Handycams. The Handycams had SVHS capabilities and recorded onto Hi8 tape. They are set up approximately 25m apart to provide adequate stereo overlap. The Handycams are mounted on theodolites (Figure 4-1) so the camera orientation parameters are known, improving the obtainable accuracy of the 3D measurements. In order to measure depth accurately the cameras must be elevated 10-15° above the surf-break. Control targets must be located within the view of the cameras to enable all wave breakpoints to be coordinated in terms of a local datum.
The cameras can then record waves breaking for any combination of tide, swell direction and size and wind conditions. The video cameras must be synchronised by having some object visible to both cameras simultaneously. Ideally, 15-20 minutes of waves would be recorded so that 2-3 good sets of waves can be analysed later. This would be repeated for every hour of the 12-hour tidal cycle. However, this would result in a large amount of data that had to be reduced. After more information is learnt about peel angle, it may be possible to make generalisation based on footage of half the tidal cycle.

4.2.3 DATA REDUCTION

Footage from each camera will be converted into digital video format (.avi\(^4\)) and saved onto a computer using a software package such as Adobe Premier. Footage from each camera must be synchronised and then individual frames captured and saved as bitmap images. The rate of frames that need to be captured has not yet been tested but will be around one per second.

---

\(^4\) .avi is stands for Audio-Video Interleave. This is a computer VIDEO specification by Microsoft Corporation for use on PCs. AVI is one of several motion-oriented file formats for computing and is the one most often associated with PCs and Microsoft Windows (TechSmith, 1999).
The images can then be processed using DVP photogrammetric software to give a coordinates in terms of the local system. This involves digitising the targets, breakpoint location and wave height for all visible waves. A coordinate database of the wave breakpoint location and wave heights for a given set of surf condition will be formed once all the frames are digitised.

4.2.4 DATA ANALYSIS

There are a variety of possible ways that this data could be analysed. This paper presents one possible method.

STEP ONE: OVERVIEW OF WAVES BREAKING

This step will enable a general understanding of how waves break at a particular location and will check that there are no gross errors in data. Firstly, each wave break point will be plotted on an individual bathymetry image. A bathymetry image will be a graphics file of the bathymetry of a surf break. Secondly, for each break point, the wave height at breaking will be tagged on. All images can then be compiled into a digital video format (.avi) so that waves characteristic can be viewed breaking over the bathymetry.

When viewing the video, hopefully waves will be breaking in consistent areas and in sections. There may be one, two or possibly three places where waves break depending on wave height. If the wave break point can be seen to be a function of height, then the data can be separated out according to wave height and break point location.

STEP THREE: PEEL ANGLE MEASUREMENTS

When the data has been separated, paths of the waves will be averaged. This averaged data will be re-plotted against the bathymetry. The various wave sections will be defined by where it can be seen the peel angle changes. Peel angle will then be measured for each section.

STEP FOUR: WAVE HEIGHT VARIATIONS

For each section, wave height may or may not be consistent. We will hope to determine if there is a relationship between section with constant peel angle and wave height.
STEP FIVE: PEEL RATE

Peel rate (m s$^{-1}$) will be defined by the distance travelled (m) over time (s). Waves following the average break point locations will be used to measure peel rate. Because coordinates of the break points are known, m can be defined. Also each break point has a time stamp from the video enabling s to be found.

There is expected to be a relationship between peel angle and peel rate because small peel angles generally break fast while the converse is true for large peel angles. The expected relationship between changes in wave height and peel rate are unknown.

4.3 CAMCORDER INTERIOR ORIENTATION

Interior orientation is the term used to describe the internal geometric configuration of a camera and lens system (Fryer, 1996b). Ideally, light would pass through a lens and form a sharp image on the plane of focus according to the physical laws of optics (Fryer, 1996b). However limitations in the construction of lens cause aberrations, or deviations from the ideal conditions. The interior orientation of a camera must be calibrated to compensate for these aberrations for precise measurement. Fryer (1996b) defined the various camera calibration parameters as principle distance, image offsets, radial distortions, decentring distortions and out-of-phase distortions.

The principle distance (c) is a term used by photogrammetrists describing the focal length of focusable lens cameras. It is the perpendicular distance from the perspective centre of the lens system to the image plane. This is one of the most important camera parameters for photogrammetry. It can be determined after images are taken from the coordinate grid used for control, which is the assumption that makes this zoom in system possible. The principle distance does not need to be determined precisely because the least squares adjustment done by photogrammetric software is used to determine the final value (Fryer, 1996b).

The image offsets ($x_p, y_p$) are the differences in the x and y axis between the PPA and the fiducial origin. The PPA is the direct axial ray that passes through the centre of the lens system. The fiducial origin is the intersection of two imaginary lines drawn between the corners of an image. Adding this offset to image coordinates correctly centres an image.
Radial distortions \((k_1, k_2, k_3)\) are caused by images being radially either closer to or farther from the PPA. This distortion increases towards the edges of an image and is greatest for wide-angle lenses.

Decentring distortions \((p_1, p_2)\) result from misalignment of the lens system causing geometric displacement of images. This misalignment is either the vertical displacement or the rotation of a lens.

Out-of-phase distortions \((b_1, b_2)\) result from the charged-coupled-device (CCD) in a video camera not being completely flat. A CCD is the device used in video cameras to capture images. The Handycam used has only a small CDD so correcting for these distortions will not significantly increase the accuracy of a photogrammetric system.

**PRINCIPLE DISTANCE CURVE**

Video cameras are used commonly for close range photogrammetry and machine vision applications (Shortis, *et al.*, 1996a; McIntosh, 1996; Chong, 1998). The procedures for video cameras are similar to analogue cameras (Fryer, 1996b) however this zoom-in photogrammetric system differs because the principle distance of the camera is unknown. Every time the video camera is turned on the principle distance changes because Handycams are not designed specifically for precision measurements. Also to observe waves from a distance, the video camera must be zoomed in, changing the principle distance.

The interior orientation of the Handycam is calibrated using standard procedures then a new methodology for determining an arbitrary principle distance is presented. This new method assumes that principle distance can be plotted as a non-linear curve (*principle distance curve*) across the focal range. Testing of various different zooms will enable the principle distance to be determined from this curve for any arbitrary zoom.

**4.3.1 METHODOLOGY**

**HANDYCAM INTERIOR ORIENTATION AND LENS STABILITY**

Camera calibration can have several objectives:

- Evaluation of the performance of a lens;
- Evaluation of the stability of a lens;
- Determination of the optical and geometric parameters of a lens;
- Determination of the optical and geometric parameters of a lens-camera system; or
- Determination of the optical and geometric parameters of an imaging data acquisition system (Fryer, 1996b).

These objectives were achieved using the camera calibration wall in the Surveying Departments photogrammetry lab along with Australis digital photogrammetric software. This involved images of the wall taken from four different angles. The images were converted from video footage to bitmap graphic images using a frame-grabber. ASUS Live3800 software in conjunction with an ASUS SGP-V3800/TVR graphics/TV card was used for this task. The tests were repeated three times to provide redundant results. Figure 4-2 shows images taken 3m from the calibration wall form four different angles.

![Sample images of calibration wall.](image)

**Figure 4-2.** Sample images of calibration wall.

**PRINCIPLE DISTANCE CALIBRATION – FIELD TESTS**

The principle distance curve was determined by taking images of targets over a range of distances (100-300m) The test involved setting up 16, 0.40mx0.60m white ply targets, 5m apart (Figure 4-3). Images were taken at 100, 150, 200, 250, 300m distances from the targets to plot the principle distance graph. Additional images were taken at 225m to check the accuracy of the graph.
COORDINATE ACCURACY

Initial tests on the obtainable accuracies of 3-dimensional coordinates involved the system being setup on a hill overlooking an array of targets on a beach. These tests were unsuccessful and it was realised that a more rigorous and repeatable test site was required. The black targets were too small and blended in with shadows on the beach (Figure 4-4). The targets could not be left in the sand so the tests could not be quickly repeated.

It was decided a valley located on farmland would provide the required elevation (10-15°) for testing. Figure 4-5 show the cameras setup on one side of the valley and target array on the other. The cameras were set up approximately 25m apart and orientated with the theodolites so that the line of sight of each camera was parallel. An RTK topography survey was performed on the site and long-sections were then plotted to find ideal locations for the cameras and targets to simulate an elevation angle of 10-15°. Figure 4-6 shows the Trimble
4000 series reference station and roving receivers beside the survey pillar, which was used as an origin for the survey.

Figure 4-5. Setup of cameras and targets for coordinate accuracy tests.

Figure 4-6. RTK equipment for topography survey.

4.3.1.1 **IMAGE COMPRESSION AND ENHANCEMENT**

All images were compressed using the JPEG algorithm. This type of compression has been widely accepted by for use in photogrammetry because it does not significantly reduce the accuracy obtainable from images (Jaakkila and Orava, 1994; Toth, 1994; Lammi and Sarjakoski, 1995; Robinson *et. al.*, 1995; Fraser and Edmundson, 1996). Images can be compressed to between 10 and 20% of their original size. Various options are available for compression but quality was always chosen over size.
Image enhancement can be used for two different purposes. Firstly, it is used to improve the visual appearance of an image to a human viewer and secondly, to prepare images for measurement tasks (Russ, 1992; Dowman, 1996). For photogrammetric purposes visual appearance is not the most important consideration for image enhancement. No image enhancement was necessary for the processing of images as the automated photogrammetric software easily identified targets.

If image enhancement was performed, the first step would be to perform contrast stretching. This is used because most often the range of colour in an image does not cover the range available (Dowman, 1996). Contrast stretching makes objects clearer but not necessarily more pleasing to look at. The second step would be to apply a filter. A filter may be applied to images to remove noise or enhance edges (Dowman, 1996). Filters should be used with care because they can cause geometric displacement of pixels.

### 4.4 RESULTS

#### 4.4.1 HANDYCAM INTERIOR ORIENTATION AND LENS STABILITY

Table 4-1 shows the interior orientation parameters of the Handycam. The standard deviations are based on the average of the standard deviation values outputted from the three tests. The small standard deviations show that the Handycam is fairly stable between the three tests. The greatest variance appears to be in the image offsets \((x_p, y_p)\). This variance is most likely because the frame grabber used is not of high quality. Variations in the results will be present due to the automatic focusing of the Handycam slightly changing the lens position. The focal length is consistent around 5.6mm when the camera is set to wide angle.
Table 4-1. Interior orientation and lens stability test results.

<table>
<thead>
<tr>
<th></th>
<th>Interior Orientation</th>
<th>Stability Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6290</td>
<td>5.6025</td>
<td>5.5685</td>
</tr>
<tr>
<td>-0.0930</td>
<td>0.892</td>
<td>0.1796</td>
</tr>
<tr>
<td>-0.1062</td>
<td>0.921</td>
<td>0.1263</td>
</tr>
<tr>
<td>0.892</td>
<td>1.078</td>
<td>0.964</td>
</tr>
<tr>
<td>8.6463E-03</td>
<td>7.7683E-03</td>
<td>8.7557E-03</td>
</tr>
<tr>
<td>2.3725E-04</td>
<td>9.5629E-04</td>
<td>3.1190E-04</td>
</tr>
<tr>
<td>-1.5685E-05</td>
<td>-7.9529E-05</td>
<td>-2.3802E-05</td>
</tr>
<tr>
<td>-1.5975E-03</td>
<td>-1.1498E-03</td>
<td>-2.0811E-03</td>
</tr>
<tr>
<td>1.4674E-02</td>
<td>1.6439E-02</td>
<td>1.4969E-02</td>
</tr>
</tbody>
</table>

4.4.2 PRINCIPLE DISTANCE CALIBRATION

DVP photogrammetric software was used to coordinate the targets in relation to the pixels of the image. A spreadsheet was then designed to enable the focal length to be determined for each camera setup. Because the distance from the camera to the targets and the distance between the targets were known, this spreadsheet basically used trigonometry to determine the principle distance.

Figure 4-7 shows the principle distance curve for these tests. It can be seen that the curve drops away after the 225m camera setup. This makes the graph unreliable, as the principle distance must increase. However the reason for this could have been due to the 225m and 250 images being swapped. Figure 4-8 shows the curve if the 225m and 250m values are transposed. It shows a smooth curve that was expected. When interpolating between the 200m and 250m principle distance, a value of 8.4mm is found. This is only 0.4mm off what was actually computed suggesting the images were swapped.
COORDINATE ACCURACY

4.4.3

DVP software was used to test the attainable precision of the photogrammetric system. Results were not as good as hoped and the 3D coordinate precision was less than a meter.
4.5 DISCUSSION

The Handycam interior orientation is stable. This means that the camera is of high enough quality to be used for photogrammetry. The determination of the principle distance curve was done successfully based on the assumption that the 225m and 250m images were swapped. This method has potential for determining principle distance accurately. Further testing is required however. The tests must be repeated again with different methods to prove the reliability of this method. Perhaps recording images at denser intervals will increase the accuracy of the graph. Also testing with a still camera with known capabilities would further backup any findings.

A limitation of this system has been the frame grabber used. The frame grabber has a large influence on the quality of a video photogrammetric system. Images can geometrically altered because of poor synchronisation of signals coming from the video camera to the frame grabber (Shortis and Beyer, 1996b). Unfortunately, accurate synchronisation is often not possible because camera manufacturers do not supply this information or the frame grabber has a fixed sampling resolution (Shortis and Beyer, 1996b). The frame grabber used was a hybrid graphics/frame grabbing card with a fixed sampling resolution. Line jitter also effects image quality by displacing horizontal lines within an image (Shortis and Beyer, 1996b). This is caused by signal or circuit noise, voltage drifts or clock cross-talk (Dähler, 1987 in Shortis and Beyer, 1996b). The other limitation of some cheaper frame grabbers is the buffering of frames during the analogue to digital conversion. This is caused when a card does not have enough memory to convert all frames (~25/second) so captured frames are based on averaging of other frames. Figure 4-9 show a frame captured for this research. It can be seen that the edges of the image are not sharp (line jitter) and the image is noisy. Noise is always present in electrical signal but the effects can be removed by image subtraction (Shortis and Beyer, 1996b).
Figure 4-9. Example of image captured with a low quality frame grabber.

The coordinate accuracy could have been improved to possibly 0.3-0.5m. The camera setup did not have ideal geometry. Although the line of sight was the same for both cameras, they were set up at different heights and the imaginary line joining the two cameras was not perpendicular to the line of sight. The processing did not use the lens distortion values found during the lens stability tests and the principle distance was only estimated.

A use of this system that has not been previously discussed is the location of surfer when they catch waves. Walker (1994a) used resection with theodolites to determine the point on take-off used by most surfers. This would be worthy of further research because when the take of point is known, this can be compared to the wave parameters to discover the type of waves most surfed by different levels of surfers.
CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 INTRODUCTION

This research first discussed the coastal protection problem and introduced artificial surfing reefs as a possible solution. The various wave parameters important for recreational surfing as established by previous researchers are then summarised. The importance of reliable numerical models to design reefs is discussed and new hydrographic and photogrammetric technology is presented to validate these models.

5.2 DISCUSSION OF HYPOTHESIS

This research hypothesised that state-of-the-art hydrographic and photogrammetric techniques can improve currently used methods for measuring bathymetry and wave parameters in the surf-zone. This hypothesis has been accepted.

5.3 ARTIFICIAL SURFING REEFS

The problem with developing towns and cities near coastal zones is that beaches are dynamic and constantly changing. The negative impacts of hard rock structures for coastal protection indicate that better coastal protection solutions need to be found (Jacobson, 1997, Mead et al., 1998). Artificial surfing reefs are an attempt to provide an environmentally sound solution to coastal erosion problems along with creating additional recreational benefits (Hutt, 1997).
Designing artificial surfing reefs to produce perfect surfing waves is difficult because of the complexity of the coastal environment system. Defining what constitutes a perfect surfing wave is subjective and depends on the ability of the surfer and their style of surfing. The characteristics that are common to all good surfing waves are:

- The wave must be large enough to float and propel the surfer and surfboard.
- The wave must break by peeling cleanly either to the left or to the right rather than as one long wave.
- The wave must peel at a rate that equal to or slower than the maximum attainable board speed of a surfer.

The most accurate and efficient method is to use numerical modelling (Mead et. al., 1998c). However numerical models assume that the environmental is made up of a discrete number of parameters whose relationship to each other is clearly defined. The accuracy of model predictions is only as good as data used to validate the model. The new hydrographic and photogrammetric techniques presented in this paper are tool that can enable models to be validated more precisely.

Five types of geomorphic categories have been identified for surf breaks, headland or point, beach, river entrance, reef and ledge (Mead et. al., 1998a; Black, 1997). Artificial surfing reefs are most like reef breaks.

Walker (1974a, 1974b), Dally (1990), Sayce (1997) and Hutt (1997) have defined the wave parameters for recreational surfing.

- Breaker type
- Breaking wave height
- Offshore seabed gradient
- Wave peel angle
- Wave peel rate
- Wave plunge distance

In addition the parameter of wave height transformation during breaking has been introduced. This could not be measured until the new zoom-in photogrammetric system was developed.
5.3.1 RTK HYDROGRAPHY

Trimble's MS750 RTK GPS receiver when used with HYDROpro software can replace the need for a tide gauge and heave compensation. This system has applications for artificial surf reef studies because charting the bathymetry of surf-zones during swell is a crucial task in reef design. Preliminary tests suggest that bottom profiles can be measured to 0.20m of a meter in 0.7m waves. More testing is still required.

This system is capable of single axis heave compensation but without the errors induced by momentum in traditional single axis heave compensators. However to remove the effect of pitch and roll a separate compensation device is still required. Multiple RTK receivers could be used for five-axis heave compensation. This would require the use of at least three receivers and new software to calculate the five-axis corrections. It may be possible for software to calculate this correction and then input it into HYDROpro as if it was data from a heave compensator.

The cost of having three receivers on one vessel and one as a reference station limits the feasibility of RTK for five-axis heave compensation. There are two options that may reduce the cost. First is the use of two RTK receivers on board the hydrographic vessel with a DGPS receiver on land. The MS750 has the option of using a mobile reference receiver so that relative positions can be found between the two receivers. An additional DGPS reference station will enable the absolute position of both RTK receivers to be found. One RTK receiver can be mounted on the bow of the vessel and one on the stern. This method will make three-axis (heave and pitch) heave compensation possible. Roll can be minimised by careful driving of the boat directly into waves. The second option for cheaper RTK heave compensation would be for a new receiver that can take the input from three antennas simultaneously.

5.3.2 VIDEO PHOTOGRAHAMMETRY

The preliminary tests presented prove that a video photogrammetric system is capable of measuring peel angle, peel rate and wave height transformation during breaking. These preliminary tests are subject to more rigorous testing. There is still much more work that needs to be done before this system can be used to monitor waves. These tests only deal only with obtainable accuracies of this video system and the method for processing and analysing the images is still subject to further research.
A photogrammetric system must output image coordinates quickly so that the results can be analysed (Cooper and Robson, 1996). However processing images with the photogrammetric system presented here is likely to be very labour intensive. It will take much time for the wave peel angle, peel rate and height to be measured for an entire tidal cycle. An automated system that recognises and coordinates the break point of a wave will enable peel angle and peel rate to be determined in a much quicker time.

An automated system when used to process photogrammetric images is a complex task, as unstructured bitmap images must be converted to represent a real object (Gruen, 1996). Many advances in recent years have been made in image matching, feature extraction, differential rectification, monoplotting and high accuracy 3D point positioning including sensor and system calibration and modelling (Gruen, 1996). It is now possible for an automated system to be developed to coordinate wave break point. Once the wave break point coordinates have been found, peel angle and peel rate can then be measured. This automated system will be based on a simple contrast threshold with a motion algorithm to track the movement of white water at the wave break point. The contrast threshold will enable the white water to be separated from the unbroken wave while the motion algorithm will aid in the correct identification of the wave break point. To develop an automated system for measuring changes in wave height during breaking would be much more complicated because the algorithm complexity is highly correlated to the image complexity (Gruen, 1996). This paper does not want to trivialise the complexity of crating an automated photographic system. It would be a substantial project that would require the writing of specialist software for the processing.
CHAPTER 6 REFERENCES


Lyons, M., 1992. *Design of an Artificial Surfing Reef*, Bachelor of Engineering, Department of Civil and Environmental Engineering, The University of Western Australia.


Tyson, R. 1999. Email Correspondence, New Zealand Ocean Technology Ltd, 27 September.


APPENDIX 1

WORLD-CLASS SURFING BREAK DATABASE
NEW ZEALAND

Indicators
Manu Bay
Outsides
The Valley
Whale Bay
Whangamata

AUSTRALIA

Angourie
Bells Beach
Bird Rock
Burleigh Heads
Dee Why
Kirra Point
Merimbula
Shark Island
Summer Cloud
Winkipop

INDONESIA

Bingin
Padang Padang
Sanur

CALIFORNIA

El Capitan
Fort Point
Rincon
The Wedge

MEXICO

Zippers

HAWAII

Aa Moana Bowl
Backdoor Pipeline
Off-the-Wall
Rock Piles
Rocky Point
APPENDIX 2

TRIMBLE'S CONFIGURATION TOOLBOX

Extracts from Configuration Toolbox's help program (Trimble, 1998)
OVERVIEW
Configuration Toolbox is a Windows application (FIGURE A-1) that provides tools to configure Trimble GPS receivers. Receiver configuration involves changing the settings that control the operation of the receiver. The configuration settings are stored in an application file (*.cfg).
Configuration Toolbox lets you create and edit application files, transfer them to and from your receiver, and manage application files stored in the receiver. The receiver also stores two special applications files, Defaults and Current, which represent the default and current receiver configurations respectively.
Application files can be stored on both your receiver and computer. Multiple files may be maintained to represent multiple users sharing a device and/or multiple modes of operation. They may also be saved to audit the operating settings of a receiver. The number of total files which can be stored on a receiver may vary. Refer to your receiver manual for limitations on application file storage.

FIGURE A-1. Coordinate Tool Box Interface
Building and Editing an Application File

Application files are viewed and/or modified in the Configuration File dialog (FIGURE A-2). This dialog contains a list of the pages that are currently contained in the application file, shown in the Contents window, and a list of all other pages which could potentially be selected and included in the application file, shown in the Available window. In addition, the configurable settings which correspond to the highlighted page in the Contents window are also listed. At the bottom of this dialog are four buttons: three are operations buttons, and the fourth is the on-line Help button. These boxes and buttons are discussed in detail below.

![Configuration File](image)

FIGURE A-2. Configuration file dialog box

If the application file has been opened from or saved to your computer, the dialog caption includes the application file's full filename.

Contents and Available List Boxes

The receiver settings stored in the application file are grouped into pages. Each page controls one aspect of the receiver's operation. The Contents list box lists the types of pages that have already been selected for the chosen application file type. The Available list box shows all the possible pages which may be added to the application file. Selecting a page from the Contents list box displays the contents of that page in the page area.

The File page is always included in an application file and therefore is always displayed in the Contents box. All other pages must be selected from the Available list and added to the Contents box in order to be applied in the Application file.
Note that if you select a page using the File / New / Any Receiver option which does not apply to your specific receiver, the receiver will ignore the settings contained on that page.

Adding a Page

To add a new page type to an application file, highlight the desired page in the "Available" list box, then click on the Add button. The page will move to the Contents box, and all settings relating to that page will be displayed in the right hand side of the Configuration File dialog box.

Note that most pages may appear in the application file only once, and hence no longer appear in the "Available" list box once they have been added. However some page types, such as Output, may have different instances to control different settings of that type. Such page types remain in the "Available" list box even after one or more instances have been added.

Removing a Page

To remove a page from an application file, highlight the desired page in the Contents box, then click on the Remove button. The page will return to the Available list.

Note that if a page is removed from a file, the page's settings do not change. These are retained in the page's display as long as the Application File dialog is open, so that if you decide to re-include the page, it is not necessary to re-enter the settings.

Page Area

The page area is the right hand section of the Configuration File dialog box. It is used to view and edit the selected page's configuration. Modifications are only stored when the application file is saved on the computer or transmitted to a receiver.

Details of each page, the settings they contain, and how they effect the receiver are discussed in the section Pages.

Default

The Default button resets the contents of the current page to the default settings. The page is then in the same state as it would have been when the page was first created. Some pages, like the Serial page use an index to configure each serial port. Pressing the Default button resets only the page that is currently visible.

Note The Default button does not reset the entire file to defaults.

Pages
An application file (FIGURE A-3) is composed of individual pages. Each page configures a group of related settings and can be included in the application file as required. The File page is an exception and is always included in the application file.

Configuration Toolbox supports the following pages:

- **File Page** – configures the file name, mode and creation details of the application file. Since this data is always associated with the file, the File page is always included in your application file.
- **Alarm Page** – activates or deactivates various alarm conditions in a receiver. The result of an alarm condition being met (i.e. triggering an active alarm) is dependent on the receiver.
- **Antenna Page** – allows users to enter antenna heights, with an associated antenna group, type and measurement method. All heights must be entered in meters.
- **Coordinate System Page** – Trimble applications use geodetic information to convert coordinates between the WGS-84 coordinate system used by GPS and the local coordinate system.
- **Device Page** – is used to configure devices which may be attached to the receiver.
- **General Page** – contains controls commonly used when configuring a receiver. They include GPS solution masks, measurement rates, frequency sources and RTK Mode.
- **Logging Page** – configures how a receiver records GPS position and measurement data for postprocessing.
- **Output Page** – contains settings for each data output message that the receiver may transmit. They are used in conjunction with the Serial page to completely configure a receiver port for output.
- **Reference Page** – contains settings for defining a reference position to be stored in the receiver.
- **Input Page** – is used to configure the reception of RTCM corrections.
- **Serial Page** – configures a receiver's serial ports. Up to four ports can be configured; if the receiver supports fewer than four, records for non-existent ports are ignored.
- **Static Page** – instructs the receiver to start in kinematic or static mode.
- **SV Enable Page** – specifies under what health conditions each of the 32 GPS satellites will be used (SV stands for Space Vehicle).
Select Coordinate System

This dialog lets the user select a Geolib database, select a coordinate system (FIGURE A-4) or site from the Geolib database, and import a Survey Collector file into the Geolib database. A Coordinate System contained in an Application File may, or may not, have originated from the Geolib database. Therefore, the Coordinate System is not displayed automatically in the Select Coordinate System dialog. When a Coordinate System has been selected, the parameters of the given Coordinate System can be viewed (FIGURE A-5).
GSOF Output

General Serial Output Format (GSOF) messages are used to output various kinds of positional information. If the user selects All GSOF Messages Off, then all GSOF messages for the given receiver port are disabled (FIGURE A-6).
RTCM Output

RTCM output correction types can be configured (FIGURE A-7) for RTK and/or Differential GPS (Type 1 or Type 9-3). Note that RTK and DGPS (Type 1) can be output simultaneously, while RTK and DGPS (Type 9-3) cannot.

FIGURE A-7. RTCM Output Message
Figure A-8: List of table from Microsoft Access database
### Figure A-9. DecodedGPSPosition Table

<table>
<thead>
<tr>
<th>ID</th>
<th>DecodedGPSPosition</th>
<th>DecodedGPSError</th>
<th>DecodedGPSStatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.017884405</td>
<td>-0.789859018</td>
<td>2.974419202</td>
</tr>
<tr>
<td>2</td>
<td>2.974419202</td>
<td>-0.789859018</td>
<td>2.974419202</td>
</tr>
</tbody>
</table>

### Figure A-10. DecodedGPSErrorEllipse Table

<table>
<thead>
<tr>
<th>ID</th>
<th>DecodedGPSPosition</th>
<th>DecodedGPSError</th>
<th>DecodedGPSStatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.017884405</td>
<td>-0.789859018</td>
<td>2.974419202</td>
</tr>
<tr>
<td>2</td>
<td>2.974419202</td>
<td>-0.789859018</td>
<td>2.974419202</td>
</tr>
</tbody>
</table>
Figure A-11. Average latency for each set of land based observations using different receiver modes

Figure A-12. Average accuracy for each set of land based observations using different receiver modes
APPENDIX 5
MATLAB PROGRAM FILES
SAMPLEGPS.M

% Program to resample GPS data to a given frequency

function sampgps
format bank
format long

load gps20.txt %load GPS file

gps = sortrows(gps20,1); % sorts row so they are not monotonic

freqfornewrate = 20; % new frequency required in Hz

starttime = gps(1,1);
endtime = gps(end,1);
noofsamples = (endtime-starttime)*freqfornewrate;

newtimegps = (linspace(starttime,endtime,noofsamples)).';

newgpsposn = interp1(gps(:,1),gps(:,2),newtimegps,'linear');
ndata = [newtimegps newgpsposn];
plot(ndata(:,1),ndata(:,2))
save new20hzgpsdata.txt ndata -ascii -double

DEPTHNEW.M

% Resamples depth data to the rate of GPS data

% Loading GPS and Depth files
% Remember to crop data so matrices are the same size
% Have 2 columns depth and time
load new20hzgpsdata.txt
load depth20.txt

% Sorts depth data so it is not monotonic
depth = sortrows(depth20,1);
x=find(diff(depth(:,1))<=0);
depth(x,:) =[];
gpstime = new20hzgpsdata(:,1);

newdepth = interp1(depth(:,1),depth(:,2),gpstime);
ndata = [gpstime newdepth];
plot(ndata(:,1),ndata(:,2))
save new20hzdepthdata.txt ndata -ascii -double
%Program to box filtering GPS and depth data then graph the difference between the data sets

clear

load new20hzdepthdata.txt
load new20hzgpsdata.txt
hold on;

%Box filter depth data
filtereddepth=boxaver(new20hzdepthdata(:,2),5);
plot(new20hzdepthdata(:,1),new20hzdepthdata(:,2),'g') plot(new20hzdepthdata(:,1),filtereddepth,'r')

%Box filter gps data
filteredgps=boxaver(new20hzgpsdata(:,2),21);
plot(new20hzgpsdata(:,1),new20hzgpsdata(:,2),'g') plot(new20hzgpsdata(:,1),filteredgps,'b')

%Graph and file of difference between depth and GPS
depth = filteredgps(:,1)-filtereddepth(:,1);
enddata = [new20hzdepthdata(:,1) depth];
save final20hz.txt enddata -ascii -double
plot(enddata(:,1),enddata(:,2))

%Program to plot mesh graph of all box filter rates

clear
load final20hz.txt;

boxwidth=[];
for i=1:40
filtereddepth(:,i)=boxaver(depth,((i+1)*i)-1);
boxwidth=[boxwidth ((i+1)*i)-1];
end

boxwidth1=boxwidth;
time=new20hzdepthdata(:,1);
mesh(boxwidth1,time,filtereddepth);

%Program box filter seabed profile to correct for latency

clear
load final20hz.txt;

filtereddepth=boxaver(final20hz(:,2),101);
plot(filtereddepth);
axis([0 10000 4.6 6.2]);
APPENDIX 6

BOX FILTERING AT DIFFERENT WIDTHS
Raw data

Box filter width 0.5% (50)

Box filter width 1% (100)
Box filter width 5% (500)

Box filter width 10% (1000)

Box filter width 20% (2000)
APPENDIX 7

PHOTOGRAMMETRY

RESULTS
**TEST ONE**

Bundle Adjustment  
University of Melbourne  
Department of Geomatics  
10 September, 1999  
17:06:21

Project: D:\surf_studies\6a August\48x Austalis Calibration\48x3m\48x3m.apf

Adjustment is Free-Network -- There are no explicit control points ***

Results for Camera 1  
**48x**  
**Lens**

<table>
<thead>
<tr>
<th>Camera Variable</th>
<th>Initial Value</th>
<th>Total Adjustment</th>
<th>Final Value</th>
<th>Latest Adjustment</th>
<th>Initial Accuracy</th>
<th>Final Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>5.5685</td>
<td>0.0000</td>
<td>5.5685</td>
<td></td>
<td>1.0000E+003</td>
<td>4.4744E-002</td>
</tr>
<tr>
<td>XP</td>
<td>0</td>
<td>0.1062</td>
<td>-0.1062</td>
<td>1.0000E+003</td>
<td>1.6699E-001</td>
<td>1.4247E-001</td>
</tr>
<tr>
<td>YP</td>
<td>0</td>
<td>-1.078</td>
<td>1.078</td>
<td></td>
<td>1.0000E+003</td>
<td>1.7589E-003</td>
</tr>
<tr>
<td>K1</td>
<td>0.0000E+000</td>
<td>-8.7557E-003</td>
<td>8.7557E-003</td>
<td></td>
<td>1.0000E+003</td>
<td>2.7424E-004</td>
</tr>
<tr>
<td>K2</td>
<td>0.0000E+000</td>
<td>-3.1190E-004</td>
<td>3.1190E-004</td>
<td></td>
<td>1.0000E+003</td>
<td>1.2949E-005</td>
</tr>
<tr>
<td>K3</td>
<td>0.0000E+000</td>
<td>2.3802E-005</td>
<td>-2.3802E-005</td>
<td></td>
<td>1.0000E+003</td>
<td>1.2852E-003</td>
</tr>
<tr>
<td>P1</td>
<td>0.0000E+000</td>
<td>2.0811E-003</td>
<td>-2.0811E-003</td>
<td></td>
<td>1.0000E+003</td>
<td>4.9539E-016</td>
</tr>
<tr>
<td>P2</td>
<td>0.0000E+000</td>
<td>-1.4969E-002</td>
<td>1.4969E-002</td>
<td></td>
<td>1.0000E-016</td>
<td>4.9539E-016</td>
</tr>
<tr>
<td>B1</td>
<td>0.0000E+000</td>
<td>-2.6868E-028</td>
<td>2.6868E-028</td>
<td></td>
<td>1.0000E-016</td>
<td>4.9539E-016</td>
</tr>
<tr>
<td>B2</td>
<td>0.0000E+000</td>
<td>1.3870E-028</td>
<td>-1.3870E-028</td>
<td></td>
<td>1.0000E-016</td>
<td>4.9539E-016</td>
</tr>
</tbody>
</table>

Maximum Observational Radial Distance Encountered: 3.4 mm

Camera Station Summary

<table>
<thead>
<tr>
<th>Camera Station Summary</th>
<th>X Value</th>
<th>Y Value</th>
<th>Z Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2443.0634</td>
<td>-319.7676</td>
<td>2900.0015</td>
</tr>
<tr>
<td>2</td>
<td>315.8095</td>
<td>-302.9787</td>
<td>2887.5766</td>
</tr>
<tr>
<td>3</td>
<td>298.7968</td>
<td>1881.1351</td>
<td>2855.2203</td>
</tr>
<tr>
<td>4</td>
<td>2338.2448</td>
<td>1921.1353</td>
<td>2915.1868</td>
</tr>
</tbody>
</table>
TEST TWO

Bundle Adjustment
University of Melbourne
Department of Geomatics
17 September, 1999 11:16:34

Project: D:\surf_studies\9a sept-48x3m\48X3c.apf

Standard Adjustment - Preferred control points specified ***

Results for Camera 1 48x Lens

<table>
<thead>
<tr>
<th>Camera Variable</th>
<th>Initial Value</th>
<th>Total Adjustment</th>
<th>Final Value</th>
<th>Latest Adjustment</th>
<th>Initial Accuracy</th>
<th>Final Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>5.6042</td>
<td>0.0017</td>
<td>5.6025</td>
<td></td>
<td>1.0000E+003</td>
<td>2.3932E-002</td>
</tr>
<tr>
<td>XP</td>
<td>-0.1685</td>
<td>0.01108</td>
<td>-0.1796</td>
<td></td>
<td>1.0000E+003</td>
<td>6.8764E-002</td>
</tr>
<tr>
<td>YP</td>
<td>0.9368</td>
<td>0.01552</td>
<td>0.9213</td>
<td></td>
<td>1.0000E+003</td>
<td>6.0410E-002</td>
</tr>
<tr>
<td>K1</td>
<td>8.2879E-003</td>
<td>5.1960E-004</td>
<td>7.7683E-003</td>
<td></td>
<td>1.0000E+003</td>
<td>3.9291E-003</td>
</tr>
<tr>
<td>K2</td>
<td>7.7666E-004</td>
<td>-1.7961E-004</td>
<td>9.5629E-004</td>
<td></td>
<td>1.0000E+003</td>
<td>1.0259E-003</td>
</tr>
<tr>
<td>K3</td>
<td>-6.7988E-005</td>
<td>1.1541E-005</td>
<td>-7.9529E-005</td>
<td></td>
<td>1.0000E+003</td>
<td>7.9660E-005</td>
</tr>
<tr>
<td>P1</td>
<td>-1.4599E-003</td>
<td>-3.1008E-004</td>
<td>-1.1498E-003</td>
<td></td>
<td>1.0000E+003</td>
<td>7.6213E-004</td>
</tr>
<tr>
<td>P2</td>
<td>1.6090E-002</td>
<td>-3.4964E-004</td>
<td>1.6439E-002</td>
<td></td>
<td>1.0000E+003</td>
<td>8.2925E-004</td>
</tr>
</tbody>
</table>

Maximum Observational Radial Distance Encountered: 2.9 mm
TEST THREE

Bundle Adjustment
University of Melbourne
Department of Geomatics
17 September, 1999   12:07:42

Project: D:\surf_studies\9 Sept-48x3m\48x3m.apf

Standard Adjustment - Preferred control points specified ***

Results for Camera 1 48x Lens

<table>
<thead>
<tr>
<th>Camera Variable</th>
<th>Initial Value</th>
<th>Total Adjustment</th>
<th>Final Value</th>
<th>Latest Adjustment</th>
<th>Initial Accuracy</th>
<th>Final Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>5.5087</td>
<td>-0.0203</td>
<td>5.6290</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XP</td>
<td>-0.1519</td>
<td>-0.05886</td>
<td>-0.0996</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YP</td>
<td>0.9747</td>
<td>0.08301</td>
<td>0.8917</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K1</td>
<td>1.0044E-002</td>
<td>1.3982E-003</td>
<td>8.6463E-003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K2</td>
<td>1.5864E-004</td>
<td>-7.8608E-005</td>
<td>2.3725E-004</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K3</td>
<td>-1.9154E-005</td>
<td>-3.4697E-005</td>
<td>-1.5685E-005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>-2.0744E-003</td>
<td>-4.7686E-004</td>
<td>-1.5973E-003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>1.5346E-002</td>
<td>6.7403E-004</td>
<td>1.4674E-002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>3.3143E-027</td>
<td>-1.0508E-027</td>
<td>4.3651E-027</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>-1.4875E-026</td>
<td>-4.8201E-026</td>
<td>-1.4393E-026</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Maximum Observational Radial Distance Encountered: 2.9 mm

Camera Station Summary

<table>
<thead>
<tr>
<th>Camera Station Summary</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1  2426.3454</td>
<td>46.8855</td>
<td>3053.0393</td>
</tr>
<tr>
<td>2  207.9007</td>
<td>42.4635</td>
<td>2950.2995</td>
</tr>
<tr>
<td>3  227.6931</td>
<td>2019.5644</td>
<td>2714.5382</td>
</tr>
<tr>
<td>4  2305.9462</td>
<td>2055.3270</td>
<td>2867.5248</td>
</tr>
</tbody>
</table>