# Wave Monitoring using Wireless Sensor Nodes



Research for



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# Abstract

This thesis describes our research on wave monitoring using wireless sensor nodes. A wireless sensor node is equipped with a 3D accelerometer and built into a canister inside a buoy. A specialized algorithm is developed to calculate wave height based on the approximated vertical acceleration caused by waves. The results from this algorithm are analysed using experiments within a controlled environment. Additionally, experience is gained with deployment of a prototype Wireless Sensor Network setup in the marine environment.

# Samenvatting

Dit document beschrijft onderzoek naar het meten van golven met behulp van draadloze sensor nodes. Een draadloze sensor node is uitgerust met een 3D versnellingsmeter en wordt ingebouwd in een behuizing en bevestigd in een boei. Een gespecialiseerd algoritme is ontwikkeld waarmee de golfhoogte wordt berekend aan de hand van een benadering van de verticale versnelling die veroorzaakt word door golven. De resultaten van dit algoritme worden geanalyseerd met behulp van experimenten in een gecontroleerde omgeving. Bovendien wordt er ervaring opgedaan met het uitzetten van een prototype draadloos sensornetwerk op de oceaan.

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# 1 Introduction

The goal of this master's research project is to develop a system that can be used to monitor wave characteristics with high spatial resolution. Pioneering work with wireless sensor nodes is done to perform the measurements used to determine these wave characteristics. The demand for such a system, based on wireless sensor nodes originates from the needs of marine scientists at AIMS, the Australian Institute of Marine Science. These scientist need detailed information on the delicate ecosystem they observe and protect, the Great Barrier Reef (GBR), Australia. As waves are an important physical force on the reef, measuring this force will help understand the complex dynamics of the reef. Section 1.1 elaborates on why wireless sensor nodes are used and what problems arise when using these for wave monitoring.

Development of this wave measurement system involves defining hardware and software requirements, minimizing power consumption and establishing communication links between measuring devices and on-shore computers. During development, the specific application domain has to be taken into account to optimize sensor selection, measuring schedules and processing algorithms. Therefore extensive knowledge of this application domain is needed.

The wave characteristics are measured using a digital accelerometer added to the sensor node inside a buoy. With practical experiments, the most suitable configuration is determined. These experiments are conducted in a controlled as well as a real world environment, using lab experiments and a prototype setup in the ocean.

# 1.1 Wave Monitoring

The main problem discussed in this thesis is *how to monitor waves (measure wave characteristics) with wireless sensor nodes.* This section presents the bigger picture of research problems that arise with wave monitoring using wireless sensor nodes. Section 1.2 presents the challenges we focus on in our research.

Scientists (mainly marine biologists and marine physicists) are interested in high spatial resolution wave data from various marine areas in the world. Wireless sensor nodes are designed for high spatial resolution sensing, hence we investigate how they can be used. As a wireless sensor node has limited processing capabilities, memory and power supply, we need to devise an algorithm that allows us to calculate wave characteristics within these constraining properties. Keeping the amount of sensors on an individual node as low as possible allows us to remain within these constraints, but does require us to research *how to determine wave characteristics sufficiently accurately with the least amount of sensors possible*.

Current wireless sensor nodes, however, are not designed to be used in the marine environment as their standard radio link for example uses frequencies that attenuate tremendously at sea [1]. This requires one to determine *how to meet the specific requirements that arise when measuring with digital equipment within a marine environment.* 

Areas of interest are often very remote locations, hence maintenance is very costly. This requires one to take into account *the problem of minimisation of power consumption* to prevent frequent battery replacement.

Also when operating in the marine environment one needs to assess how to protect the digital equipment from the destructive forces within the particular environment.

As mentioned before the node's frequencies attenuate tremendously over sea, therefore we are also concerned with *how to setup sufficiently connective radio links between nodes, the gateway and a base station*.

While touching on all of the problems described, we focus on:

How to determine wave characteristics sufficiently accurately with the least amount of sensors possible.

# 1.2 Research Challenges

The research problems described in the previous section pose the following challenges:

#### Limited processing capabilities and memory

Wireless sensor nodes have limited processing capabilities and memory as individual nodes are designed to perform relatively simple tasks like periodically measuring temperature and communicating this measurement. This means that we need to keep the data processing algorithm simple, since we aim for the used algorithm to be implemented on a node.

#### Low power consumption

While for the prototype setup low power consumption is not an important issue, as the site is not very remote, the eventual very remote setup on the reef requires the wireless sensor node to consume little power. Maintenance on a remote location is very costly and therefore battery life needs to be as long as possible. This has been taken into account during the development of the system discussed in this thesis.

#### Choosing a sensor

Finding the most suitable motion sensor is a challenge by itself, because various sensor properties determine the accuracy, influence the power consumption and limit the range of detectable waves for the system. Often there is a trade-off between sensor properties as well, which makes sensor selection a complex issue.

#### Data transfer

Although important issues with data transfer like setting up connections, multi hop communication etc. have been covered by the wireless sensor node's operating system [2], practical challenges in this regard remain. Power consumption of radio communication is very significant and therefore data reduction and careful scheduling is important. Also the before mentioned signal attenuation requires us to determine optimal communication distances and to think of a different way of communication from the onsite gateway node to shore, even for the prototype setup location.

# **1.3 Solution Overview**

Our solution is to use only a single 3D accelerometer as our motion sensor and to use an algorithm that does not require complex mathematic operations to estimate wave height.

# 1.3.1 The Algorithm

We can estimate wave height with only a single 3D accelerometer because we take sensor orientation out of the equation and then approximate the acceleration we are interested in. Taking the sensor orientation out of the equation is done by calculating the acceleration magnitude from the accelerometer readings on individual axes (see Figure 1.1).



Figure 1.1 Acceleration magnitude independent of accelerometer orientation

To approximate the vertical acceleration we are interested in, corresponding with wave height, the normally distorting influence of gravity on the accelerometer is turned into something useful. As section 4.3 explains further and Figure 1.2 depicts; because vertical acceleration is parallel to gravity, the acceleration magnitude is fully affected by the acceleration we are interested in, while accelerations perpendicular to gravity hardly influence the acceleration magnitude (for accelerations relatively small compared to 1 g).



Figure 1.2 Approximated acceleration vs. the vertical component of  $a_0$ 

# 1.3.2 The chosen sensor

Using only one accelerometer and an algorithm with not too many mathematical operations provide a solution to the first two challenges listed in the previous section. Sensor selection is also important for these two challenges. Therefore an ultra low power accelerometer has been selected. It has its own ring buffer, which allows us to retrieve multiple samples on a

regular interval instead of each one separately. Also, it returns values in milli g, saving processing resources, which would otherwise have been used for conversion into milli g.

# 1.3.3 Communication

The data transfer challenge needs more work. The communication from the onsite gateway node back to land has been realised, but the communication between nodes has to be improved. For the prototype setup, the communication back to land has been realised by developing a custom radio link. This link consists of a solar powered device on site that acts as a relaying station and radio device on shore which is connected to a computer. For the communication between nodes better antennae have been added to the canisters that house them. Future work can be to equip the nodes with radios that operate in a lower frequency band, as signals in these frequency bands suffer less attenuation, according to experts at AIMS.

# 1.4 Expected Results

While the calculated wave height is based on an approximated vertical acceleration, we expect the values to be fairly accurate and consistent. The relatively small influence of horizontal accelerations will lead to over approximation of the vertical acceleration and thus to overestimated wave heights. This thesis presents the extent of the overestimation, enabling future research to correct the results for this. The experiments with our system resulting in these wave heights are within a controlled environment. In addition to that, we expect to gain much practical experience within the marine environment by developing and deploying a prototype wireless sensor network setup.

# 1.5 Structure of this Thesis

This thesis employs a top down approach for describing our system. In section 2 we provide background information to the project our system is designed for and we elaborate on the technologies used and wave and movement theory. Following this Background section is a State of the Art section, listing and elaborating on current solutions. The subsequent sections describe the approach we used for our system, the results, and finally the conclusions, discussion and recommendations on our wave monitoring system. In these last sections we will differentiate between a controlled environment and the real world, with our main focus on the experiments within the controlled environment.

# 2 Background

Several parties in Australia as well as the Netherlands collaborate in the Great Barrier Reef project on Wireless Sensor Networks at the Australian Institute of Marine Science. This project is called ReefGrid and this chapter describes it in more detail, informs the reader about Wireless Sensor Networks and then elaborates on Wave Theory and Measuring Movement.

# 2.1 ReefGrid Project: Sensor Networks on the Great Barrier Reef

The Australian Institute of Marine Science (AIMS) is a tropical marine science research institute which investigates topics from broad-scale ecology to microbiology. AIMS is committed to the protection and sustainable use of Australia's marine resources. Its research programs support the management of tropical marine environments around the world, with a primary focus on the Great Barrier Reef World Heritage Area.

Understanding the processes that impact reefs requires high quality data at a range of spatial scales. Autonomous smart sensor based systems provide a way to obtain this data from the scale of oceans to the scale of individual corals [3]. The ReefGrid project was started to harness the potential of these systems.

The goals of the ReefGrid project are:

- to help understand the physical and biological dynamics of the reef
- to allow scientists to evaluate the effects of climate change, tourism, fishing, and pollutants with a more comprehensive dataset than currently available [4]
- to provide real time data so researchers can check conditions in real time and thus rapidly respond to events

The ReefGrid project also aims to find an alternative to current oceanographic instruments, as their price and the (visual) impact of mass deployment of these large instruments prohibits creating a tight grid.

Important physical forces on the reef come from waves and currents. These forces drive the flow of nutrient-rich waters on the reef, which is crucial for the health of the coral reefs. As there is a lot of variation in depth and seafloor structure on reefs, which influences waves and currents, these forces can vary significantly in locations only meters apart. Therefore scientists need high spatial resolution measurements of these forces to investigate the smaller scale effects (e.g. effects on individual corals or parts of a reef).

# 2.2 Wireless Sensor Networks

The specific system used in ReefGrid is a Wireless Sensor Network (WSN). Wireless Sensor Networks are tiny computers that communicate with each other through wireless communication. These tiny computers (nodes) can monitor their environment with a variety of sensors that can be added to a node. A report on Sensor Networks from the U.S. National Science Foundation [5] reads:

In the 1980s, the PC revolution put computing at our fingertips.

In the 1990s, the Internet revolution connected us to an information web that spans the planet.

And now the next revolution is connecting the Internet back to the physical world we live in - in effect, giving that world its first electronic nervous system.

Call it the Sensor Revolution: an outpouring of devices that monitor our surroundings in ways we could barely imagine a few years ago. Some of it is already here. The rest is coming soon.

To differentiate between sensing devices and network entities this thesis distinguishes sensors and nodes, where the sensing devices are called "sensors" and network entities are called "nodes". Nodes can be equipped with various sensors. Nodes are continuously becoming smaller and smarter and wireless technologies allow them to be deployed without cables [4]. Wireless sensor nodes are low cost compared to current oceanographic instruments which makes it inexpensive to replace a node if necessary.

As the WSN used for ReefGrid needs to monitor different aspects, different sensors are connected to the nodes. Besides sensors that measure movement (accelerometers), temperature sensors are connected as well. Though temperature measurement does not have the main focus in this thesis, it will be mentioned where relevant.

The diagram in Figure 2.1 shows the Wireless Sensor Network setup for the ReefGrid deployment on Davies reef. The prototype setup, which is discussed in this thesis, is equivalent to the setup in Figure 2.1, but instead is deployed in Nelly Bay with a pole instead of a weather station holding the gateway node and long range transmitter.



Figure 2.1 Schematic overview of Wireless Sensor Network setup

This setup has a two dimensional grid of buoys on the sea surface equipped with sensors that measure movement. That potentially allows for construction of a three-dimensional image of the wave pattern from combined measurements. In this three-dimensional image wave direction is expressed in the two dimensions along the sea surface and wave height will account for the third dimension.

Temperature sensors are installed in the tubes between each buoy and its anchoring. This allows for a three-dimensional image of water temperatures. Measurements from the sensors are processed by the node and transmitted, possibly via other nodes, to a gateway node. Intermediate nodes can reduce the data they forward by combining various measurements. This type of data reduction is called data aggregation. There are various levels of data aggregation from simple to complex: from for example algorithms based on just combining two messages into one, to algorithms based on correlation between measurements [6]. The

gateway node is connected to the long range radio equipment on a weather station. This long range radio equipment forwards the aggregated data from the WSN to shore, where it can be interpreted and used for monitoring.

# 2.2.1 Wireless Sensor Node

At the University of Twente, research in the field of Wireless Sensor Networks is conducted by the Pervasive Systems group. People from this group founded the company Ambient Systems to make Wireless Senor Networks commercially available [7] [8].

In close collaboration with researchers at the University of Twente, researchers and engineers at Ambient created the " $\mu$ Node v2.0" (in this document from now on referred to as " $\mu$ Node" - pronounced as: "micro node"), see Figure 2.2. The  $\mu$ Node is the wireless sensor node used in the initial deployment for ReefGrid.



Figure 2.2 µNode

The remainder of this section outlines the relevant features of the  $\mu$ Node for its use within ReefGrid.

#### Power consumption

The  $\mu$ Node is powered by batteries and, as these nodes eventually are to be left out on the reef for months, low power consumption is crucial. Extending battery life as far as achievable is crucial, since the nearly 200 km trip to the reef is very costly due to running costs of the used ship, fuel prices, planning, and health and safety regulations.

The  $\mu$ Node requires a power supply that has a supply voltage of around 3 Volts. Power consumption of the  $\mu$ Node depends on the application, but is typically 0.5 mA when active and only 2  $\mu$ A on standby. The  $\mu$ Node is therefore classified as Ultra Low Power, but this is without any sensors attached and not taking into account power consumption of radio communication. Radio communication takes a peak current of 12.5 mA when receiving, approximately 15 mA when sending and 2.5  $\mu$ A on standby [9]. Therefore it is crucial to communicate no more than required and hence have the node process sensor readings as much as possible to reduce the amount of data to be transmitted.

#### Processing limitations

The  $\mu$ Node houses a Texas Instruments MSP430 microcontroller, operating at a clock speed of 4.6 MHz [9]. This speed allows for some complex calculations, but seems nearly insignificant compared to the processing power of current Personal Computers. The purpose of a  $\mu$ Node, however, is totally different from a PC.  $\mu$ Nodes support a limited set of functions to communicate with each other and with peripherals (like sensors and actuators), where PCs have to support many more interfaces and ways to communicate. The  $\mu$ Node operating system (AmbientRT) is therefore very lightweight, especially when compared to some operating systems with graphical user interfaces that run on Personal Computers. The  $\mu$ Node has a very good power safe mode, used when inactive. Therefore, to minimise power consumption, the amount of time that the  $\mu$ Node is active should be kept as low as possible, hence processing algorithms have to be optimized in a way that they use the MSP430s processing power to its full potential, but do not require more of it than it can handle.

#### Memory limitations

The microcontroller on the  $\mu$ Node has 48 KB of Flash Memory and 10 KB of RAM. To keep processing as fast as possible only RAM should be used during computations. This restricts processing algorithm further as the maximum amount of memory used at any time cannot be more than 10KB minus the amount in use by the operating system. However, flash memory can be used to store the results from the processing algorithm, until these are transmitted.

#### Communications

The  $\mu$ Node is equipped with a radio transceiver that can be configured to use a frequency within the range of 844.8-947 MHz. This range envelops the ISM (Industrial, Scientific and Medical) frequencies in Australia (918-926 MHz [10]). On land the  $\mu$ Node has a transmission range of over 200 meters [9]. For frequencies around 900 MHz signal attenuation above the ocean is high and is to be expected to limit range significantly [1]. The attenuation is due to signal absorption by wave formations and conductive properties of the ocean surface.

 $\mu$ Nodes are available with and without serial port connection. A serial port on a  $\mu$ Node allows that node to be used as a gateway node, which can be connected to a PC or long range radio equipment for example.

With Wireless Sensor Networks one should assume communication packets frequently do not arrive. Since for ReefGrid completeness of the dataset is important, the communication of results should be as reliable as possible. AmbientRT assures a certain level of fault-tolerance and makes sure the network is self healing [9]. However, the high level protocol used to communicate measurements needs to have a mechanism that allows for identification of missing measurements.

# 2.2.2 Prototype Setup

The prototype setup in the ocean (see section 4.5) allows us to gain experience with deployment of a WSN within the harsh marine environment. It presents various challenges, which are discussed in this thesis. After dealing with some software challenges, the main issues concern radio communication and the housing for the electronics. The canisters created to house the sensor nodes weakened the radio signal and the default radio's frequency attenuates tremendously over the ocean. This was solved by modifying the canister, fitting it with a high gain antenna. The issue with the housing of the electronics is that the current tube, holding the temperature sensors and serving as mooring, withstands the forces of the ocean for weeks instead of months. This issue is hard to solve and unfortunately resulted in the prototype setup to be taken out of the ocean before all planned experiments were completed. Further elaboration on findings from the prototype setup can be found in section 5.3.

While engineers at AIMS work on new housing and mooring, we continue with controlled environment experiments. Hence, besides other aspects of the development of our wave measurement system, these experiments have the main focus in this thesis.

# 2.3 Wave Theory

This section describes wave theory relevant to the project described in this thesis. First we will look at various types of waves to be considered and then we will discuss the physics involved with these. Finally two methods of measuring waves are discussed.

Waves are disturbances of a fluid medium through which energy is moved. Ocean waves travel on the interface between oceans and the atmosphere. Waves are caused by friction between wind and the water surface, gravitational attraction, earthquakes or volcanic eruptions. As will be elaborated on later, we focus on waves caused by wind.



Figure 2.3 depicts the different properties of a basic wave.



As illustrated in this figure, wave length ( $\lambda$ ) is the distance between two crests. The time it takes the wave to travel this distance is called wave period. Wave height is the vertical distance between the crest and trough.

In oceanography different wave types and classes are distinguished [11]. The wave types are listed in Table 2.1 and the wave classes are compared in Table 2.2.

Wave type	Depth
Deep water waves	$\geq 1/2$ wavelength
Intermediate waves	$\frac{1}{20}$ wavelength - $\frac{1}{2}$ wavelength
Shallow water waves	$\leq 1/_{20}$ wavelength

 Table 2.1 Different wave classes

Wave class	Period	Wavelength	Cause	Wave type	
Capillary	< 0.1 s	< 2 cm	Local winds	Deep to shallow	
Chop	1-10 s	1-10 m	Local winds	Deep to shallow	
Swell	10-30 s	Up to hundreds of m	Distant storms	Deep to shallow	
Seiche	10 min-10 hrs	Up to hundreds of km	Wind, tsunamis, tidal resonance	Shallow or intermediate	
Tsunami	10-60 min	Up to hundreds of km	Earthquakes or volcanic eruptions under or near the ocean	Shallow or intermediate	
Tide	12.4-24.8 hr	Thousands of km	Gravitational attraction of sun and moon	Shallow	

 Table 2.2 Different types of wave

For this project we focus on capillary waves, chop and swell. Seiche (pronounced approximately as "Saysh") is a standing wave in an enclosed or partially enclosed body of water. As Nelly Bay is not enclosed, for the deployment there, seiches are not to be expected. However, in future locations (inside atolls for example) they might be relevant. Wave height of Seiches is very low and their wave period very long, therefore detecting the contribution of seiches to waves will prove to be quite a challenge. Tsunamis could be detected, but do not have particular focus, as there are dedicated detection and warning systems in place for tsunamis. The system is designed for monitoring smaller scale events. For this reason tide is not required to be detected, though it is important to be considered, for the design of mooring for example.

The waves we see are deformations of the water surface, due to moving water particles. When sea depth is at least half the wave length, the movement of these particles will not be influenced by the sea floor and, if other influences are minimal, they will move in close to perfect circular orbit, as illustrated in Figure 2.4 (modified from [12]).



Figure 2.4 Wave propagation direction and the orbital movement of water particles

Figure 2.4 illustrates the movement of water particles related to the deformation of the surface. The wave propagation direction is equal to the direction of the wind causing the wave, and results in orbital movement of water particles.

To determine wave characteristics, two important measuring principles are distinguished. One measures the orbital movement of water particles and one measures the ocean surface level in a fixed position. In an ideal situation a buoy placed on the ocean surface follows the same path as surface water particles, hence buoys allow for measurement of the orbital movement of water particles. The ocean surface level in a fixed position can for example be measured by pressure sensors placed under water, or by a so called wavestaff. More on various wave measurement instruments can be found in section 3. Figure 2.5 illustrates the two measuring principles.



Figure 2.5 Buoy (orbit) measurement compared to wavestaff (fixed point) measurement

The figures used thus far show simplifications of sea surface waves. In reality various waves together determine the movement of water particles and thus the trajectory detected by a wave measurement buoy. The surface level detected by a wavestaff also depends on the accumulation of all waves present.

Buoys follow the orbital movement of water particles (as much as possible) and measure their trajectory and thus the waves. Wavestaffs detect the water level in a single location over time and measure waves that way. See Figure 2.6 for a comparison of the two principles. This figure is from [13], with a slight alteration of the text in it. The left hand diagram shows the orbital motion of water particles. A buoy would ideally move in the same way as the particles at the water's surface, depicted in the top row of the diagram. Fixed observers would see what is shown in the right hand diagram. Which would be the wave contour at different moments in time, around the average water surface level (heave = 0).



Figure 2.6 Orbital motion of water particles compared to wave contour

# 2.4 Measuring Movement

Measuring movement can be done with a device called an Inertial Measurement Unit (IMU). An IMU can sense changes in its yaw, pitch and roll as well as its acceleration in all directions (degrees of freedom, see Figure 2.7) using a combination of accelerometers and gyroscopes. An accelerometer senses forces applied to it and translates this to acceleration relative to gravity, thus the output of an accelerometer corresponds to a certain amount of (milli)g. A gyroscope senses change in its orientation, i.e. change in its yaw, pitch and roll.



Figure 2.7 Degrees of Freedom

Mechanical (analogue) gyroscopes like the ones found on aircraft and ships use gyroscopic forces on a spinning disc to detect changes in rotation. Rather than having the spinning disk, MEMS (Micro-Electro-Mechanical Systems) and Piëzo gyroscopes have a vibrating component. For these gyroscopes the phenomenon of Coriolis force is used to detect changes in rotational angular velocity in oscillating bodies. This allows for a faster response and can be produced using Piëzo electronics. In particular for MEMS gyroscopes only very small vibrations on a very small body are needed, which allows for production of small, lightweight, low cost gyroscopes [14].

Since current digital IMUs, accelerometers and gyroscopes are accurate and very energy efficient, we will use these rather than their analogue peers. A further evaluation of motion sensors can be found in section 4.1.

As we use a buoy to determine wave characteristics, we are concerned with the orbital movement of water particles to determine wave characteristics, as discussed in section 2.3. The path of movement of a water particle in a deep water wave ideally follows a perfect circle. Figure 2.8 depicts the relation between this tracked circle and wave height.



Figure 2.8 Relation between buoy orbit and wave height

The number of times a certain point on the buoy orbit is passed equals the number of waves that passed the buoy. As Figure 2.8 shows, in order to determine the wave height, we need to know the vertical distance covered by the in one orbit. The average vertical distance covered per orbit can be determined by calculating the total distance covered during a certain time period and dividing that by the number of waves that passed during that period. However, the commonly used measure of the height for ocean waves is significant wave height (H<sub>S</sub>). H<sub>S</sub> is the average height of the waves which comprise the highest one-third of waves in a given sample period [15]. Thus, to be able to calculate H<sub>S</sub> we need to know the wave height of each single wave instead of an average. The height of a single wave is defined as the vertical distance between a crest and trough, hence we need to detect crests and troughs. In section 4.3, we elaborate on how we achieved this.

# 3 State of the Art

This section describes devices currently used to determine wave characteristics. The devices discussed here were also evaluated in the WADIC project: a comprehensive field evaluation of directional wave instrumentation [16]. The article about this project [16] can be referred to for a more detailed description and comparison of devices. Note, however, that the authors were making an incorrect comparison [13] [17], as they conclude that the measurement buoys tend to underestimate the spectral energy. They draw this conclusion by comparing the buoys with a fixed observer (wavestaff), but the difference is caused by the fact that in principle wavestaffs and buoys measure different phenomena, as discussed in section 2.3.

# 3.1 Waverider Buoy

The (directional) Waverider buoy is used all over the world to measure wave height and direction. The Waverider buoy is produced by the Dutch company Datawell. After the devastating floods of 1953 in the southern coastal area of the Netherlands, monitoring waves became important for the Dutch government, hence Datawell was founded in 1961 [18]. After a good six years of research and development the first Waverider buoy was taken into production. The design of this buoy formed a solid foundation as the new and improved models of today are still based on it. Especially the stabilisation platform serving as an artificial horizon (see Figure 3.1), combined with tailor-made acceleration sensors has proven to be very successful [19]. Just recently Datawell started the production of buoys that measure wave characteristics in a different way: using GPS, in addition to the buoys with motion sensors [20].

Typical Waverider buoys (Figure 3.1) measure wave height with a precision of 1 cm from -20 to 20 meters at wave periods of 1.6 - 30 seconds. The accuracy of measurements by this buoy is very high (gain error < 1%). The directional Waverider buoy measures direction with a precision of  $1.5^{\circ}$ , with a heading error < 2°. These specifications are according to company specifications for the Directional Waverider MkIII [21]. This is quite an improvement compared to the first directional Datawell buoy Wavec, introduced in 1983 [18], which had a mean heading error of 4° [16].



Figure 3.1 Stabilisation platform



Figure 3.2 Waverider [47]

The MkIII can be supplied in hull with a diameter of 70 cm, offering easier handling and sufficient space to hold batteries for 1 year of continuous operation, or the MkIII can be supplied in a 90 cm hull for 3 years of continuous operation. The measurements are communicated from the buoy via Satellite, GSM or HF radio. The cost of a Waverider buoy with sensors is around 60.000 euro [22].



Figure 3.3 GPS Waverider [20]

At the turn of the 21st century, GPS was significantly improved for civilian applications and the Selective Availability, deliberate degradation of GPS accuracy for non-US military GPS receivers, was discontinued, which allows all users to receive a non-degraded signal globally [23]. This inspired Datawell to develop the directional Waverider that uses GPS instead of sensors to calculate wave characteristics. First independent sea trials were started in July 2002 [19], concluding: "The new GPS system performed excellently in the field, producing virtually identical results to the tried and tested accelerometer sensors...". The conclusion from [19] continues: "...The GPS system also has certain disadvantages. The performance of the new GPS buoy may be compromised in high sea states when reception of the GPS signal can be interrupted".

# 3.2 Fixed Point Measurement Devices

As discussed in section 2.3 fixed point measurement devices are an alternative to wave measurement using a buoy. The most common are the wavestaff and pressure sensor, which are presented in this section.

#### 3.2.1 Wavestaff

The Wavestaff (Figure 3.4, reconstructed from [24]) is a device that measures wave height from a fixed structure. A staff (or wire) hangs from a fixed structure above water down into the water. Measurement technologies used are usually resistance or capacitance based. Depending on which technology is used, the position of the water level along the staff (or wire) determines the resistance or capacity of it. The measured resistance or capacity is translated to distance, from which the height of the water level can be concluded. Measuring this over time will allow for calculation of wave height, frequency and energy spectrum.



Figure 3.4 Wavestaff



Figure 3.5 Marine Fouling

An advantage of the Wavestaff is that measuring the correct water level is not very complicated, compared to the complex dynamics of measuring the movement of an accelerometer buoy correctly. This results in a low cost device.

A disadvantage is that in order to use a Wavestaff, a fixed structure needs to be placed on the location where the measurements are to be taken. This is often not feasible or desirable. Creating many of these structures on the reef for example would impact the ecosystem too much.

The measured capacity or resistance of the wavestaff, and therefore each wave measurement, is also influenced significantly by fouling of the device. The severity of fouling depends on the location of deployment. The rich waters of the Pacific Ocean near the equator tend to rapidly and seriously foul nearly anything left submerged in it. Fouling in this sense means that algae and other marine life will start growing on the submerged equipment, see for example Figure 3.5, which shows fouling on a buoy and its mooring at sea surface level after only about a month.

### 3.2.2 Pressure Sensors

Pressure sensors basically measure according to the same principle as wavestaffs. Pressure sensors are mounted at a fixed position underwater, and they measure the height of the water column that passes above them. As wave crests pass by, the height of the water column increases; when troughs approach, the water column height falls. By deducting the depth of the sensor from the water column heights, a record of sea surface elevations can be generated. Though easily deployed on a reef, pressure sensors risk becoming less accurate due to marine fouling as well.

# 3.3 Conclusions on Current Solutions

The fixed measurement devices have the advantage over buoys that calculating wave characteristics is more straightforward. The best fixed measurement device for the reef would be the pressure sensor as this could be placed on a patch of sand, between corals, as the mooring of a buoy is. Building structures for wavestaffs would have a more severe impact on the reef. Buoys, however, can give more detailed information on wave direction and the frequency spectrum of waves.

# 4 Approach

This section describes how we measure waves with our sensor node. First we examine various sensors and then we discuss how wave height is calculated from the sensor readings. After that we describe the various experiments done to evaluate the system.

# 4.1 Sensor

The Inertial Measurement Units (IMUs) and accelerometers introduced in section 2.4 are evaluated below. As mentioned in that section, current digital motion sensing devices are accurate and very energy efficient, hence we will use these rather than their analogue peers. Another, rather obvious, advantage is that measurements from digital devices do not need to be converted from the analogue to the digital domain before further processing by the node. Also, from reading through the sensor documentation we can conclude that most digital sensors are coarsely factory calibrated, which saves us some of the issues that can occur with non-calibrated sensors (see next section).

### 4.1.1 Sensor Evaluation

The following features are examined while evaluating the sensors.

#### Degree of Freedom

While comparing IMUs we only considered to use devices with a Degree of Freedom (DoF) of 6, which means they can measure movement along all three orthogonal axis in threedimensional space (x, y and z) and rotation around those axes (pitch, roll and yaw). See Figure 2.7. For the accelerometers we compared 3-axis devices, which can measure acceleration along the three dimension axes (but no rotation). We need this full measurement spectrum to be able to track the circular movement of the buoy in all possible directions, as discussed in section 2.3.

#### Maximum swing

Very important for measuring wave characteristics is the minimum and maximum acceleration the device can detect. In device specifications these minimum and maximum values are usually noted as maximum swing, which is the maximum positive and negative g-force the device can measure (a maximum swing of 3 means the device can measure forces between -3 and 3 g). A device will always measure 1 g distributed over its axes, which is caused by gravitational force.

#### Communication protocol

We require the sensor to have a digital interface and we prefer the use of the  $I^2C$  or SPI communication protocol instead of digital Pulse Width Modulation. Whether the sensor uses  $I^2C$  or SPI is not of much interest for this work. Choosing  $I^2C$  has the slight advantage that the basis for a software accelerometer driver and experience with this driver is readily available at the Pervasive Systems research group from the early stages of the development of our wave measurement system.

#### Power consumption

As with the wireless sensor node, power consumption is of great importance for choosing the most suitable sensor. Device specifications describe what current a device uses at a certain voltage. With the IMUs the voltage range varies, see Table 4.1, where with the accelerometers it is 2.5 volts (allowing up to 3.6 volts) for all devices, see Table 4.2.

#### Price

As the nodes equipped with sensors need to be inexpensive to allow for large scale deployment, the price of sensors needs to be low as well. For the development stage of the WSN the total cost of one node with movement sensor was set to be around 100 euro. As the price of a  $\mu$ Node for us is approximately 60 euro, we have around 40 euro for the sensor. All considered accelerometers are available for less than 40 euro, but the prices of IMUs are considerably higher and vary significantly.

#### Form factor

Existing buoys used at AIMS hold a custom made watertight canister which does not have much space for anything besides the  $\mu$ Node and its batteries. Therefore the sensor's form factor is important as we want to refrain from requiring production of new canisters, if possible.

#### Calibration

All digital sensors evaluated are coarsely factory calibrated. Calibration of analogue accelerometers can be complicated as output signals may depend on supply voltage for example. Such issues with calibration are minimized by using factory calibrated sensors.

#### 4.1.2 Sensor Evaluation Results

An overview of the sensors we evaluated can be found in Table 4.1 and Table 4.2. At the time of the Sensor Evaluation we have not found suitable accelerometers from two of the major manufacturers, i.e. Analog Devices and Freescale. This is because only recently they started releasing digital 3-axis accelerometers.

The price and power consumption of IMUs do not meet the requirements, because they are both too high. Power consumption is too high because IMUs use multiple sensor and often utilize a general purpose CPU for inertial measurement calculations. Hence a different solution needs to be found. This leads to the decision to use one 3D accelerometer as the sensor for our wave measuring sensor node. This way the power consumption can be reduced to a bare minimum and cost is within budget. The feasibility of measuring wave characteristics with a single 3D accelerometer is introduced as a research problem by this decision, but it can be combined with the research problem of feasibility in general.

As mentioned, existing buoys used at AIMS hold a custom made watertight canister which does not have much space for anything besides the  $\mu$ Node and its batteries. The addition of only such a small device as a single accelerometer just fits, which is another important advantage, as development and production of new buoys and canisters would be costly both in time and money. Even the smallest off-the-shelf IMU would be too big to add inside current canisters.

The accelerometer selected is the VTI SCA3000-E02. The configurable narrowband bandwidth of 11 Hz is exactly right for wave measurements. Its power consumption of 200 uA @ 2.5 V is very low in comparison to others and the  $I^2C$  communication protocol is convenient, as explained earlier. A maximum swing of 2 g instead of 3 g would be better but the devices that support a maximum swing of 2 g consume at least twice the amount of power and only support higher bandwidths.

# 4.1.3 Connecting the Sensor to the µNode

We have purchased the VTI SCA3000-E02 sensor mounted on a printed circuit board (PCB), allowing for fast prototyping. This PCB is inserted into an adapter board we have made specifically to connect the sensor PCB to the  $\mu$ Node (see Figure 4.1).



Figure 4.1 Sensor connected to µNode

The schematic of the adapter board can be found in Appendix A and more information on how to connect to and retrieve data from the sensor can be found in [25] [26].

Brand	Product	DoF	Max. Swing (+ and - g)	Communication Protocol	Voltage (V)	Current (mA)	Approx. Price (€)	Remarks
Archangel Systems	IM^3 [27]	6	10	SPI	5	200		
Xsens	MTi [28]	6	5		7.2	50	retail: 1750	includes magnetometer and temperature sensor, operating voltage: 4,5-15 V, OEM available
Motion Node [29]		6	6				750	includes magnetometer
Microstrain	3DM-GX1 [30]	6	5		9.6	65	1100	includes magnetometer and temperature sensor, operating voltage: 5,2-12 V
MEMSense	nlmu [31]	6	5	I <sup>2</sup> C	7.2	113	2100	includes magnetometer and temperature sensor, operating voltage: 5,4-9 V
Spark Fun	IMU 6 DoF	6			5	500	240	Created "for Fun". Tilt readings instead of x-, y- and z- acceleration.
Cloud Cap Technology	Crista Sensor Head [32]	6	10	SPI	6.5	30		operating voltage: 5,5-8 V

Table 4.1 IMUs

	Product	#	Max. Swing		Bandwidth	Communication			
Brand	number	axes	(+ and - g)	Sensitivity	(Hz)	Protocol	Voltage (V)	Current (uA)	Remarks
ST	LIS3LV02DQ [33]	3	2 or 6	1024 LSb/g	40 - 640	SPI / I2C	2.5	600	Configurable max. swing
VTI	SCA3000-D01 [34]	3	2	1333 count/g	45	SPI	2.5	480	Includes temperature sensor and output buffer
VTI	SCA3000-E01 [35]	3	3	1000 count/g	9 or 35	SPI	2.5	120	Includes output buffer Configurable Bandwidth
VTI	SCA3000-D02 [36]	3	2	1333 count/g	45	12C	2.5	650	Includes temperature sensor and output buffer
VTI	SCA3000-E02 [26]	3	3	1000 count/g	11 or 40	12C	2.5	200	Includes output buffer Configurable Bandwidth

Table 4.2 Accelerometers

# 4.2 Important Sensor Characteristics

This section elaborates on the two most important characteristics of accelerometers that have to be taken into account.

### 4.2.1 Gravity

Accelerometers measure the forces applied to them. One of the forces applied to everything is gravity, which on earth is significant. This force is read by the accelerometer as 1 g, distributed over its axes, in a manner depending on its orientation. An accelerometer is unable to give us readings without gravity, as it is only possible to determine and compensate for the vector of gravity if the accelerometer is kept stationary. This means we have to take into account that the reading from each accelerometer axis is the acceleration we are interested in plus some, probably hard to predict, component of gravity. Figure 4.2 shows the very significant shift of measured acceleration from the accelerometer's z-axis ( $a_z$ ) to its x-axis ( $a_x$ ), when the accelerometer is slightly tilted and the same gravity vector is applied.



Figure 4.2 Gravity distributed amongst accelerometer axes

Section 4.3 discusses how the algorithm we have created deals with the influence of gravity.

# 4.2.2 Sensor Calibration

While the accelerometer we use is factory calibrated, the offset and sensitivity calibration error influence our results significantly since we calculate distance from acceleration by double integration. With double integration the errors accumulate.

Therefore we compensate the accelerometer measurements for calibration errors. This is done by applying a least squares calibration algorithm [37] to acceleration data from a stationary accelerometer placed in 6 different orientations. We used orientations where for each accelerometer axis, the axis is kept close to parallel with gravity, its direction once against and once with gravity. The algorithm yields a value for g and the scale factors/offsets to correct each acceleration axis for calibration errors.

# 4.3 Algorithm

Section 2.4 introduced the concept of using the buoy's orbit to measure wave height. What we are actually interested in is the vertical movement of the buoy, which gives us the wave height. To determine this wave height, we need to detect the period of each wave, which gives us the wave frequency. This section elaborates on the algorithm we use to approximate vertical acceleration and detect wave periods, giving us wave height and frequency. More details on the exact implementation of the algorithm can be found at the end of this section.

One way of determining the vertical movement would be to keep the accelerometer horizontal with gimbals<sup>1)</sup> (see Figure 4.3), or similar, and use only z-axis readings.



Figure 4.3 Gimbals

This would work, on the condition that the accelerometer is kept perfectly horizontal at all times, since the slightest tilt of the accelerometer causes gravity to be distributed differently on the axes, resulting in distorted output. Beside the fact that it would be challenging to meet this condition, it is not feasible within the scope of our project to create a buoy which incorporates a device to keep the accelerometer horizontal. Neither is it feasible for us now to create and use an artificial horizon, like with the (non-GPS) Waverider, to compensate 3-axis accelerometer readings for orientation.

A second way to determine the vertical movement is to measure acceleration along all 3 axes and compensate these readings for rotational movement. That would require a (digital) gyroscope in addition to the accelerometer. A big disadvantage is that adding more measurements means adding more errors. Digital gyroscopes cope with significant offset drift, which can be hard to compensate for [38].

A third solution is to use only one accelerometer and turn the nuisance of gravity influencing the accelerometer into something useful, as is explained in this section. Using only one accelerometer instead of more devices keeps complexity low and is less likely to put too much strain on the  $\mu$ Node's processing capacities and power supply, therefore we opt for this solution.

<sup>&</sup>lt;sup>1)</sup> Pivoted supports that allow an object mounted on the innermost gimbal to remain immobile [48]

We take the orientation of the accelerometer to be unknown. I.e. the orientation of the body reference frame within the local inertial reference frame [39] is unknown, see Figure 4.4 for a comparison of these two reference frames. The body reference frame changes with the orientation of the body, in this case the accelerometer. The local inertial reference frame does not change.



Figure 4.4 Inertial reference frame compared to body reference frame

As we are not aware of the accelerometer's orientation, we calculate the acceleration magnitude  $(a_{mag})$  from the measurements on all three axes  $(a_x, a_y \text{ and } a_z)$  [40], defined as

$$a_{mag} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$
(1)

The acceleration magnitude will, in theory, be the same when the same relative force vectors are applied and only accelerometer orientation differs, see Figure 4.5. Acceleration magnitude is depicted as if it has a direction, but that is just to help understand the relation between it and the forces it is caused by. Directional information is lost when measurements are squared.



Figure 4.5 Acceleration magnitude independent of accelerometer orientation

In practice the acceleration magnitude can be slightly different when the same force vectors are applied and only accelerometer orientation differs, because of differing accelerometer axis properties like the cross-axis sensitivity and non-linearity. The expected error is small and we do compensate for calibration errors. The errors are caused by inaccuracy of readings from individual axes, so they are not related to the fact that we use the acceleration magnitude. However, using readings from all three axis for each sample instead of from one axis does introduce two more sources of error (i.e. the other two axes). This small error introduced by using all three axes instead of one is a good trade-off for being able to take accelerometer orientation out of the equation in our algorithm.

If we presume a circular movement perpendicular to a horizontal axis, the forces on an object following a circular orbit will be as depicted in Figure 4.6. Centrifugal force is left out for

clarity of the image, as it is always opposite to the force that causes the orbital movement and, in practice, will only slightly dampen the measurement of this force by an accelerometer. The force that causes the orbital movement will from now on be referred to as  $F_0$ .  $a_0$  is the acceleration caused by  $F_0$ .



Figure 4.6 Forces on an object following a circular orbit

As visualised in Figure 4.6 the difference between the acceleration magnitude and gravity are maximal at the highest and lowest point of the orbit. These points correspond with the crest and trough of a wave, hence we use them to detect the trough and crest.

The vertical distance covered between the trough and crest equals the wave height. This vertical distance is caused by the vertical component of  $a_0$ , from now on referred to as  $a_{0z}$  (not to be confused with  $a_z$ , the accelerometer z-axis measurement). Now this is where gravity proves to be useful. For relatively small accelerations, because of gravity, the acceleration magnitude is hardly affected by acceleration perpendicular to gravity, while it is fully affected by acceleration parallel to gravity (as can be noticed in Figure 4.6). Hence the acceleration magnitude can be used to approximate  $a_{0z}$  by subtracting gravity from it. We define the approximated (vertical) acceleration ( $a_A$ ) as

$$a_A = a_{mag} - g \tag{2}$$

The approximation of  $a_{Oz}$  by  $a_A$  is visualised in Figure 4.7.



Figure 4.7 Approximated acceleration vs. the vertical component of  $a_0$ 

Waves normally yield accelerations less than 200 milli g, which is relatively small compared to gravity (1000 milli g), hence  $a_A$  closely approximates  $a_{Oz}$ . This is shown in Figure 4.8 for a 0.5 Hz wave with accelerations of up to 200 milli g.



Figure 4.8 Acc. magnitude minus gravity compared to the vertical component of  $a_0$ 

The close approximation of  $a_{Oz}$  by  $a_A$  allows us to double integrate  $a_A$  into a distance covered that approximates the actual distance covered. Doing this in between a detected crest and trough gives us the approximate wave height. See Figure 4.9 for a comparison of the actual wave height (*H*) and the approximated wave height ( $H_A$ ), based on the accelerations from Figure 4.8.



Figure 4.9 Wave height (H) compared to approximated wave height ( $H_A$ )

After each measured wave height we reset the wave height calculation to prevent the added error from becoming too significant. This is especially important because of the double integration. Figure 4.10 shows what would happen if we would not perform a reset.



Figure 4.10 Velocity and distance over time, without reset

Also due to the double integration of acceleration into distance, the error in the approximated wave height gets bigger with longer wave periods. This increases the importance of defining the error.

Besides the acceleration magnitude for the accelerometer (as defined in equation (1)), there is a second acceleration magnitude, within the inertial reference frame, instead of the body reference frame. We will call this magnitude the real acceleration magnitude ( $a_{Rmag}$ ) and its components  $a_{Rx}$ ,  $a_{Ry}$  and  $a_{Rz}$  (see Figure 4.11 and equation (3)). For clarity of Figure 4.11, the y-axis is omitted, it is perpendicular to the x- and z-axis in both cases.



Figure 4.11 Acceleration magnitude compared for different reference frames

$$a_{Rmag} = \sqrt{a_{Rx}^2 + a_{Ry}^2 + a_{Rz}^2}$$
(3)

When using a perfect accelerometer (an accelerometer without errors), its acceleration magnitude equals  $a_{Rmag}$  (equation (4)). Until now we have always visualised  $a_0$  with its y-axis component  $(a_{0y})$  equal to zero, to be able to leave it out of the equation, but what if  $a_{0y}$  is not zero?  $a_0$  can be split up into a vertical component (which is  $a_{0z}$ ) and a horizontal component  $(a_{0xy})$  which causes  $a_{0x}$  and  $a_{0y}$ . The horizontal acceleration squared equals  $a_{0x}^2 + a_{0y}^2$  (equation (5)).

$$a_{mag} = a_{Rmag} = \sqrt{a_{Rx}^2 + a_{Ry}^2 + a_{Rz}^2}$$
 (4)

$$a_{0xy}{}^2 = a_{0x}{}^2 + a_{0y}{}^2$$
 (5)

When only gravity and the orbital acceleration are involved  $a_{Rx} = a_{0x}$  and  $a_{Ry} = a_{0y}$ , hence

$$a_{mag} = \sqrt{a_{Rz}^2 + a_{0xy}^2}$$
(6)  
With

$$a_{Rz} = a_{Oz} + g \tag{7}$$

Giving us

$$a_{0z} = \sqrt{a_{mag}^2 - a_{0xy}^2} - g \tag{8}$$

If  $a_{0xy}$  is known, equation (8) can be used to compensate for the error in the approximated vertical acceleration and thus in the approximated wave height. The issue with this is that, as we discussed earlier, the accelerometer readings do not allow us to determine  $a_{0xy}$  right away. However, the size of  $a_0$  can be determined in the crest and trough of the wave, since  $a_0$  is with or against gravity there, so in the crest and trough  $a_0 = a_{mag} - g$ . For a perfect circular orbit we can calculate  $a_{0xy}$  at time *t* with

$$a_{0xy}(t) = |a_0| \cdot -\sin(\frac{2\pi}{T} \cdot t)$$
(9)

Where *T* is the wave period. The time passed between a crest and trough is taken as  $\frac{1}{2}T$ . For  $a_0$  one can choose  $a_0$  in either the crest or trough, or take the average of their modulus.

### 4.3.1 Algorithm Implementation

Details on how we implemented the described algorithm are presented in this section.

#### Calculating $a_A$ (equation (2))

Calibrating the accelerometer, as described in section 4.2.2, yields the acceleration magnitude value corresponding with g, which for the selected accelerometer is around 1000. We sample the acceleration at a rate of 11 Hz, since we expect no waves with a frequency higher than half of this (Nyquist-Shannon sampling theorem). Each sample gives us the measured acceleration from all three axes ( $a_x$ ,  $a_y$  and  $a_z$ ). For each sample we calculate the acceleration magnitude, then subtract gravity from it and multiply it by the gravity constant, giving us  $a_A$ . We filter the results using a partial implementation of a Kalman filter [41], without a prediction model, which is in essential a weighted running average filter where the weight is determined dynamically and with high responsiveness.

#### Detecting crest and trough

We detect each local maximum and local minimum for  $a_A$  to determine when we are passing a crest or trough. The detection works as explained below.

The previous two  $a_A$  values, that differ more than a certain threshold, are saved in memory. This threshold is used because samples, even after applying our filter, contain some noise that would otherwise lead to the detection of too many peaks. Each new  $a_A$  value (differing more than the threshold from the previous value) is compared with the values in memory and if the oldest value and the new value are both smaller or bigger than the other value in memory, a peak or trough is detected respectively. Independent of whether a crest or trough is detected, the oldest value in memory is replaced by the other value in memory, which in turn is replaced by the new value. If a crest is detected, the  $a_A$  in that crest is saved to support compensation of the error in the approximation of the wave height (see ).

#### Calculating distance covered

In between a crest and trough, we compute the vertical distance covered. After detecting a crest, to keep processing and memory requirements low, each sample is processed immediately into a distance by adding  $a_A$  to speed ( $v_A$ ) and this speed to distance ( $d_A$ ). After detecting a trough the distance is returned as the approximated wave height and the speed and distance are set to zero.

#### Compensating the approximation error

Because of the immediate processing of acceleration data, the individual acceleration measurements are no longer available when the approximated wave height is returned. So instead of correcting each sample's  $a_A$  (shown in equation (9)), we can only correct the approximated wave height. Therefore we also return T (equation (10)) and an estimate of  $a_0$  (the average of  $|a_A|$  in the crest and  $|a_A|$  in the trough).

$$T = 2 \cdot \frac{\text{the amount of samples in between a crest and trough}}{\text{sampling frequency}}$$
(10)

With these, one could correct the returned wave height according to a model of the approximation error (which is subject to further research).

# 4.4 Experiments within a Controlled Environment

To create and test a suitable system, contraptions were needed to simulate waves. To test only vertical movement a sliding cylinder is used. To test slightly more complicated movements we use different Ferris wheels. This section discusses each of them in more detail.



Figure 4.12 Sliding cylinder

# 4.4.1 The Sliding Cylinder

We test the implemented algorithms in the simplest situation first, which means we focus on change in accelerations along only one axis. To be able to measure accelerations caused by movement along one axis, the sliding cylinder contraption is created. With this contraption accelerations along the other axes are minimized.

The sliding cylinder is inside a tube and holds the node with accelerometer. The cylinder is connected to a motor outside the tube and moves up and down with the turning movement of this motor. The motor is from a car windscreen wiper and rotates back and forth over an angle of 80°. See Figure 4.12.

The connection between the cylinder and the wheel consists of three metal rods connected to each other with two joints. One end is fixed to the motor, the other end is solidly connected to the cylinder.

The motor can be run at various speeds, ranging from moving back and forth in 1 to 4 seconds, depending on the voltage of the power supply. The cylinder moves back and forth over a selectable distance of 57, 47 or 37 cm.

# 4.4.2 The Ferris Wheel

The second contraption needs to represent the slightly more complicated wave movement. The movement of buoys on waves resembles a circular motion, as explained in section 2.3. Therefore the node is inserted into a basket hanging from a wheel. See Figure 4.13. On the opposite side of the wheel there is another basket with a weight in it equal to the total weight in the other basket, to improve the balance of the system. Both baskets can turn around their connection on the wheel so the orientation of the accelerometer is only changed by the inevitable swing of the basket.

When the wheel turns, the node makes a circular movement with a selectable radius of 28.5, 23.5 or 18.5 cm, corresponding to a wave height of 57, 47 and 37 cm.





Figure 4.14 Ferris Wheel

Figure 4.15 Datawell Ferris Wheel

In succession to the wheel described in the previous paragraph, a the third contraption was made [42], see Figure 4.14. This contraption is like a Ferris wheel with only two gondolas. Like with the wheel, one side holds the node with accelerometer and the other side houses a counterweight to balance it out.

When the Ferris Wheel turns, the "gondolas" make an circular movement with a radius of 50.5 cm, corresponding to a wave height of 101 cm. This Ferris wheel is driven by a motor that rotates the wheel with a period of up to 5 seconds, depending on the voltage applied to the motor.

### 4.4.3 The Datawell Ferris Wheel

The wheel contraptions discussed above have their equivalent (see Figure 4.15) at Datawell, the company that develops and manufactures the Waverider buoys. Datawell allows us to conduct experiments with their NMI calibrated wheel as well.

This wheel is driven by a motor, with a selectable speed between 2 and 17 rpm. The radius of the wheel is 90 cm, corresponding to a wave height of 1.8 m.

# 4.5 Experiment in a Real World Environment

The fifth experiment conducted for our research is to deploy a prototype setup (as visualised in Figure 2.1) in the real world environment. This experiment allows us to gain experience with installing the system in the harsh marine environment, and to get a preliminary dataset from this environment.

The setup has been deployed in Nelly bay on Magnetic Island, Australia. The locations of the buoys and gateway are shown in Figure 4.16. Three buoys are defective, these buoys are either never placed or taken out of the water, their (planned) coarse location is indicated.



Figure 4.16 Nelly Bay Setup (photo from [43]) on the coast of Magnetic Island (photo from [44])

The particular location is chosen for its close proximity to shore, which allows for relatively easy access to the buoys and gateway, while it is sufficiently distant from the beach, as not to cause visual pollution or attract inquisitive people.

The setup consists of 8 sensor nodes and a gateway node. The prototype setup is deployed for two projects, a project on plankton assemblages and our project. The temperature sensors shown in Figure 2.1 are installed for the project on plankton assemblages (for more information see [45]).

The temperature software application for the  $\mu$ Node is provided by Ambient Systems and adjusted by us to work together with the our wave measuring application. Temperature is measured once every 20 minutes and the readings from the temperature sensors do not require further processing, hence it hardly strains the  $\mu$ Node. The wave measurements, however, strain the  $\mu$ Node much more, as the sample frequency for this is 11 Hz (instead of  $\frac{1}{1200}$  Hz for the temperature application). The wave measuring application is therefore adjusted to put less strain on the  $\mu$ Node and the network in order to guarantee unimpeded results from the temperature application.

The buoys float above coral on various depths of water, at low tide between 1.2 m (the one closest to shore) and 6.2 m. The expected significant wave height is between 30 cm and 1 m.

# 4.5.1 Prototype Setup Implementation

This section discusses the implementation of the prototype setup (see Figure 2.1) which we have deployed in a real world environment.

The sensor buoys used in the prototype setup consist of a customized polystyrene buoy and a purpose built canister containing the  $\mu$ Node. The canister is inserted into the polystyrene buoy and a tube is connected which houses the temperature sensors string. This tube is then fed through and connected to a subsurface buoy, and fixed to a train wheel which serves as an anchor. The subsurface buoy keeps the tube between it and the anchor relatively straight at all times, ensuring temperature measurements from approximately the same height off the ocean floor under normal circumstances.



Figure 4.17 Canister and a µNode



Figure 4.18 Sensor buoy

#### Housing the electronics

The canister housing the  $\mu$ Node, as displayed in Figure 4.17, consist of two halves. The bottom half has a connector for the tube. The top half has an extension for the  $\mu$ Node's antenna and screws onto the bottom half. The connection is kept watertight with an O-ring. The canister, however, significantly restricts the signal from the  $\mu$ Node's radio (see section 5.3.1). Therefore we modify the canister and replace the watertight antenna cover with an external antenna, as shown in Figure 4.18. This antenna also helps compensate for the signal attenuation, however, range is still restricted (see section 5.3.1). The antenna has a weather (and salt water) resistant coating and its connection to the canister is sealed off watertight, with an O-ring.

On the bottom end of the canister the tube is connected which houses the string of temperature sensors and serves as mooring. The tube is basically a hydraulic cable, consisting of a plastic outer and inner layer, with a layer of metal threading in between for reinforcement. This tube is estimated to last over 3 months, but practice proves otherwise (see section 5.3.2).

#### Temperature Sensor Strings

The temperature sensor strings inside the tube consist of a cat 5 networking cable with 7 Dallas temperature sensors, type 18B20, connected to it. The way they are connected is



Figure 4.19 Temperature sensor on temperature string

#### shown in Figure 4.19.

Each string holds 7 temperature sensors in total, spaced 2 meters apart. At one end of the string is a connector, used to connect the string to the  $\mu$ Node, on the other end is a temperature sensor.

#### Long range radio

As can be seen in Figure 4.16 the distance between the shore and the closest buoy is over 400 m. This distance cannot be covered by the radio equipment installed on our sensor buoy, hence a long range radio system needs to be deployed for forwarding the measurements from the buoys back to shore. Close to our site is a pole on which we can install such a radio. However, the radio needs its own power supply but also needs to be limited in size, not to attract any curious passersby.

Our purpose build relaying device is displayed in Figure 4.20.



Figure 4.20 Relaying device containing long range radio

The relaying device consists of a gateway  $\mu$ Node connected to a long range radio (Campbell RF411 [46]). The output of the gateway  $\mu$ Node is input for the long range radio and forwarded immediately to its counterpart on shore. Both devices are powered by a 12 volt battery (the  $\mu$ Node through a voltage regulator), which in turn is recharged by a solar panel. More on this device can be found in Appendix B. The box that houses this equipment is fitted with two antennae, one on top for the long range radio and one on the bottom, pointing downwards, for the gateway  $\mu$ Node. The lit of the box is fitted with an O-ring to ensure it is watertight. The hole for the solar panel's power cable and the antenna connections are also sealed off.

The relaying device communicates with its on shore counterpart, consisting of another long range radio (Campbell RF411) connected to a computer, or in our case usually a data logger.

# 5 Results

This section presents results from the various practical experiments conducted to test our wave measurement system and algorithm. Results from individual experiments are presented, followed by a table that provides an overview all the experiments.

The graphs shown display  $a_z - g$  instead of  $a_z$  for the clarity of the figure, as it shows how the variation of  $a_z$  compares to that of the other axes. The wave height is shown after each wave (beginning in the crest), as the system only outputs this every time a crest is detected.

The filtered approximated acceleration is noted as  $a_{AF}$ .

# 5.1 Experiments within a Controlled Environment

The experiments with the sliding cylinder and the first wheel help in developing our hardware/software configuration and algorithm. They lead to the construction of the Ferris wheel on which we conduct further experiments. The results from these experiments are described here.

### 5.1.1 The Ferris Wheel

The self made Ferris Wheel in our lab at the University of Twente allows us to experiment with changing system settings during development, due to the easy access to it. Data from these experiments is presented in this section.

#### Height of 101 cm, inside gondola

When put inside the gondola, the accelerometer follows an orbit with a diameter of 101cm. The motor can be set to a certain speed by supplying it with a certain voltage. When set to 4.5s period, results as displayed in Figure 5.1, are obtained.



Figure 5.1 Ferris Wheel results for 4.5 s period, 101 cm Height

As can be seen in the first graph in Figure 5.1, acceleration in the peaks and troughs is rather noisy. This is caused by friction in the joint connecting the gondolas and the arms of the Ferris wheel. Despite that, the peak detection succeeds, and the average wave height is overestimated at 134 cm. The average approximated wave period is 4.55 s.

#### Height of 75 cm

As the accelerometer orientation should in theory not influence the results of the system (as is explained in section 4.3, it is interesting to see what happens if we fix the accelerometer node to the Ferris Wheel arm instead of in a gondola. Doing so eliminates the direct effects of gondola sway. The indirect effect of vibrations caused by the gondola may still be there, but does not influence the results.

In the real world the situation described is unlikely to occur as the buoy will be restricted in its movement by mooring. The accelerometer node is fixed to the arm 37.5 cm from the rotational point of the Ferris Wheel, hence a wave height of 75 cm is simulated. In this experiment, the Ferris wheel rotates with a period of 3.7 s.





As the accelerometer turns within the pane perpendicular to it z-axis, hardly any acceleration is measured for  $a_z$ , the readings for  $a_x$  and  $a_y$  however, range between -1 and +1 g. At around sample 910 the effect of message loss can be seen. This results in an underestimation in the succeeding wave height approximation. This is due to the fact that in

the experimental stage messages are sent via a gateway node to a pc, which then calculates wave height. Average detected wave height is 83.6 cm and the average detected wave period is 3.79 s.

### 5.1.2 The Datawell Ferris Wheel

The results from the experiments at Datawell are summarised in this section.

The fixed diameter of the Datawell Ferris wheel is 180 cm, hence our system should measure a wave height of 180 cm for each setup. The turning speed of the wheel, and thus the period, is variable. Experiments with 4.5, 5, 12.5 and 20 s periods are discussed in this section.

#### Period of 4.5 seconds

The graphs in Figure 5.3 show the results for the first 600 samples (around one minute) of data for the experiment where each revolution of the Ferris Wheel takes 4.5 seconds.



Figure 5.3 Datawell Ferris Wheel results for 4.5 s period

This figure show that detection of the first wave height equals only about one meter, this is because the wheel is still getting up to the rotational speed corresponding with a 4.5 s period and therefore the detected period is too short. After that the wave height approximation overestimates the height by about 20 cm. The difference in the various wave heights detected is caused by relatively big accelerations on the horizontal inertial axes. This plus gravity on a tilted sensor contributes to the high readings on the accelerometer's y-axis. The effect on the approximated acceleration is shown in the second graph of Figure 5.3. Also, peak detection becomes less accurate, resulting in detecting varying wave periods. Because of the double integration over this period, wave height is impacted noticeably, as can be seen with the last four wave height approximations in the third graph in Figure 5.3.

The detected average wave period is 4.9 s and the average detected wave height is 197 cm

#### Period of 5 seconds

As a fair bit of gondola sway occurred with the 4.5 s setting, the Ferris wheel was configured to rotate with a period of 5 seconds. The amount of sway with this setting was significantly less, resulting in smaller measurements for  $a_v$ , see Figure 5.4.



The detected average wave period is 5.2 s and the average detected wave height is 185 cm. In addition to the 5 s experiment, an experiment with a 6 second period is conducted, confirming the results for the 5 s period, with similar looking graphs for the accelerometer readings and a detected average wave period and height of 6.35 s and 182 cm.

#### Period of 12.5 seconds

To see how the results are with smaller accelerations, we conduct an experiment with more than double the period, i.e. 12.5 s. A part of the results from this experiment is shown in Figure 5.5.



Figure 5.5 Datawell Ferris Wheel results for 12.5 s period

The wave height approximations for this experiment are very consistent, overestimating with little over 20 cm. The odd underestimation, like the second to last approximation shown in graph 3 of Figure 5.5, is responsible for the average detected wave height of 195 cm. The detected average wave period is 12.7 s.

#### Period of 20 seconds

Our final experiment in the controlled environment tests the system's limits by using a 20 s



Figure 5.6 Datawell Ferris Wheel results for 20 s period

period, which yields very low accelerations (between approximately -10 and 10 milli g). Despite pushing the system to its limits, the peak detection still works with these low accelerations and the detected wave heights are consistent. These approximated heights average to 213 cm and the detected average wave period is 20.3 s.

# 5.2 Overview of Results from the Controlled Environment

Table 5.1 summarizes the results from the controlled environment. The table displays actual and approximated average heights and periods for each experiment with the standard deviation for the approximations and the error in the approximation. The standard deviation of the approximated wave height indicates the continuity of the wave height approximation, where the standard deviation of the approximated wave period indicates the accuracy of the peak detection, which affects the approximated wave height.

	Actual		Approxim	ated Heigh	nt	Approximated Period		
	Height Period		Average	Std.dev.	Error	Average	Std.dev.	Error
Experiment	(cm)	(s)	(cm)	(cm)	(%)	(s)	(s)	(%)
Ferris Whl 101	101	4.5	134.05	2.60	32.72	4.55	0.0120	1.11
Ferris Whl 75	75	3.7	83.56	1.03	11.41	3.79	0.0093	2.43
Datawell 4.5	180	4.5	196.89	9.51	9.38	4.88	0.0394	8.44
Datawell 5	180	5	184.83	22.13	2.68	5.23	0.0568	4.60
Datawell 12.5	180	12.5	195.48	0.90	8.60	12.68	0.0072	1.44
Datawell 20	180	20	212.96	6.39	18.31	20.28	0.0324	1.40

#### Table 5.1 Results from the controlled environment

As can be seen in Table 5.1 the predicted overestimation is rather consistent for most experiments. The standard deviation of wave height is high for the 5 s. period experiment at Datawell, presumably because of gondola swing at this speed, resulting in less accurate peak detection and higher overestimation of approximated acceleration. The system performs best during the 12.5 s. period experiment at Datawell.

# 5.3 Experiment within a Real World Environment

The experiment within the real world yields the results discussed in this section. These results are of a different nature than the results from the controlled environment. Instead of numbers and graphs we present mainly experience and issues with deployments in a marine environment, as explained in section 2.2.2.

# 5.3.1 Radio Communication

The canister housing the  $\mu$ Node, as displayed in Figure 4.17, significantly restricts the signal from the  $\mu$ Node's radio, resulting a range of only 5-8 m. when deployed in the ocean. This is measured by navigating a boat equipped with a gateway node connected to a notebook towards a deployed buoy. Only within about 5-8 meters of the buoy signal strength is sufficient to retrieve measurements from the buoy, as soon as one moves out of this range communication is lost.

When the buoy is equipped with an external antenna and deployed on the ocean (>75 m. off shore) range is around 50-70 m. This was measured by placing one buoy in the ocean and taking another buoy away from it. When the distance between the two buoys is beyond the before-mentioned range, communication is lost. While a buoy is kept reasonably upright most of the time by the weight and rigidity of the tube, the orientation of the antenna can change due to waves, which influences communication. Also it is possible that crests are between buoy and thus blocking communication.

The relaying device mentioned in section 4.5.1 is elevated, hence waves will be less likely to block the signal between it and buoys within range. It also helps the long range radio incorporated in the device, allowing its signal to carry thousands of meters, which is sufficient as we need around 800 m.

### 5.3.2 Housing of Electronics

#### Buoy

The housing of the electronics inside the buoy initially withstands the forces of the ocean, but after 3 to 5 weeks of slight but continuous twisting and pulling, the tube reveals its weak spot. This weak spot is at the clamp that secures the canister inside the buoy (as visible in Figure 4.18, just under the buoy, on the tube). At this point the metal layer becomes exposed to the salt water, which causes this layer to corrode rapidly. Then the inner layer of plastic will puncture, allowing water into the tube and up into the canister, destroying all electronic equipment inside, see Figure 5.7 and Figure 5.8. The highest financial loss, however, is the tubes, therefore no new buoys with undamaged tubes of the current type are deployed.



Figure 5.7 Damaged µNode

After becoming aware of the issue with the tube, we have fitted a buoy with a  $\mu$ Node equipped with an accelerometer but no temperature sensor string, and we have sealed off the canister's opening to the tube. We have connected this buoy to an already damaged tube, which in this case only serves as mooring, and we have deployed it. However, within weeks after deployment, water also manages to seep into this canister and destroy more equipment. To be able to deploy new accelerometer buoys (without temperature string), new canisters need to be produced without the opening for the sensor string, as we do not want to risk leakage again. Before buoys with temperature strings will be deployed, an alternative for the current type of tube needs to be found.

#### **Relaying Device**

The relaying device has been deployed for 3 months and withstands the forces above the ocean during this time period. The electronics inside are not harmed and the solar panel provides sufficient current to recharge the battery. The device is elevated high enough so it is not directly in contact with the ocean. The threats to it are mainly rain combined with wind and birds that possibly find it a good place to rest and defecate.

# 5.3.3 Other Experience Gained

#### Maintenance

While the location of the prototype setup is close to shore, it does not mean we can go out to it for maintenance at any given time. The boats at our disposal are relatively small and are very unstable on slightly rough seas, which makes pulling up the surface buoy for maintenance too much of a risk. In our experience the conditions can be too rough for periods of up to multiple weeks, preventing repairs or instalment of new equipment.

#### Temperature Sensor Strings

Many times the temperature strings have shown defects. The defects usually occur after or during deployment, when friction inside the tube snaps one of the wires (see Figure 5.8). Therefore a more robust way of fixing the temperature sensor to the cable has been devised (see Figure 5.9). A temperature string has been repaired using this method as the top two sensors were disconnected. The other sensors have not been changed and before deployment all 7 sensors work. During deployment however, the sensor string must have been damaged, since only measurements from the top two sensors have been received during the period the buoy has been deployed.



Figure 5.8 Damaged temperature string



Figure 5.9 New temperature sensor connection

#### **Buoy Size**

Since we need to keep visual pollution minimal, a relatively small surface buoy is used (25 cm diameter). This can be a problem as this size buoy may go under water in rougher conditions, causing the buoy not to follow the wave correctly. A solution to that is to use bigger buoys, like the subsurface buoy we used, which has a diameter of 50 cm.

#### Sensor Data

Sensor data has been retrieved from the prototype setup. Besides some other, smaller periods, a week of data has been logged from one buoy equipped with temperature sensors and another buoy equipped with an accelerometer. While useful to confirm that the system is working, the data cannot be used to draw noteworthy conclusions from regarding waves. The accelerometer buoy concerned is configured to send only z-axis data, since it is primarily meant to confirm the working of the system. Unfortunately this is not enough for our wave height algorithm to give good results. A buoy has been prepared and configured to return measurements from all accelerometer axes, but after noticing the problems with the sealed off opening in the canister (see section 5.3.2), the decision was made not to deploy the buoy. Appendix C contains a selection from the preliminary sensor data, both from temperature sensors as well as from the accelerometer.

# 6 Conclusions, Discussion and Recommendations

This thesis describes work in the field of wave monitoring using wireless sensor nodes. Specifically we combine a wireless sensor node with an accelerometer to measure wave characteristics, we deploy an initial prototype WSN setup in the real world environment and we further develop the system using laboratory experiments.

The goal of measuring wave characteristics with a wireless sensor node is to gain high spatial resolution, real-time wave data from a certain area. The main goal from the real world environment is to gain experience with actual deployment in a harsh environment and confirming whether the system works by collecting preliminary data from various sensors. Equipping the wireless sensor node with only a single accelerometer requires us to develop an algorithm. The algorithm needs to approximate wave height accurately and has to be suitable to implement on the wireless sensor node, which has limited memory, processing capabilities and available power. Choosing the most suitable accelerometer is also essential.

The wave measurement system is developed using the first Ferris wheel, described in section 4.4.2. After that the prototype setup in the real world environment is deployed. Finally the algorithm calculating the wave height is further developed and verified by conducting several experiments in a controlled environment.

The prototype WSN setup deployed in the real world environment consists of several nodes with proven temperature measurement technology (on land, that is). A node with an accelerometer is added to be able to record initial accelerometer readings from waves. This deployment results mainly in assessment of issues with deployments in a marine environment. First of all the standard µNode radio proves not to be suitable for the marine environment. Replacement by a low frequency radio should be considered. Secondly the marine environment is known to be harsh to electronics, due to the destructive forces caused by wind, currents, salt water and various forms of life (like humans) that inhabit the marine environment. In this environment the question is not if the protection of the equipment will be broken, but when. Our current experimental housing is anticipated to withstand these forces for 6 months or more. Unfortunately, in practice, they last about one month as the constant movement of the tube holding the temperature string causes its protective outer layer to crack, allowing the sea water to reach the metal layer of the tube, which corrodes very rapidly. Then water reaches the electronics inside the tube and thrusts upwards into the canister, causing the sensor node to fail. Further development of the housing for the electronics is essential. During the period of deployment we have logged several measurements confirming that the system is working, but as discussed in section 5.3.3, the data cannot be used to draw noteworthy conclusions from regarding waves.

After the experiments in the real world environment, the processing algorithm has been further developed. The algorithm's strength is in the simplicity of the way it approximates vertical accelerations. The algorithm uses gravity, which normally only complicates the use of accelerometers, to its advantage. To be specific, the gravitational force is always measured by the accelerometer. This force is parallel to the force we are interested in, i.e. the forces that cause vertical acceleration of the buoy that houses our sensor node. By calculating the magnitude of all forces applied to the accelerometer, accelerometer orientation is taken out of the equation and the influence of forces perpendicular to gravity is minimised. The algorithm does require a well calibrated accelerometer and works best when accelerations are relatively small (<200 milli g). This approach allows for the use of only one 3-axis accelerometer, which helps to keep the financial cost of the system low.

The results from the experiments in a controlled environment show that the system works well with different wave heights and periods. A very satisfying result is that even with the highest waves and longest periods (180 cm and 20 s respectively) the system is still able to return fairly consistent wave heights, despite the relatively low accelerations that occur with such waves. The experiments in a controlled environment, however, also show us that the system consistently over-approximates the vertical acceleration corresponding with wave height. This is due to the influence the accelerations perpendicular to gravity have on the vertical acceleration calculated from the acceleration magnitude, as expected. This influence always results in an approximated acceleration larger than the actual acceleration. However, the system could be extended to correct for the over-approximation, as discussed in section 4.3.

Since the approximated acceleration is integrated twice into distance over one wave period of time, the over-approximation accumulates. This is why the double integration is done over a period of time which is as brief as sensible, which is one wave period. Determining this period as accurately as possible is crucial. A slight error in this period results in a very significant error in the approximated wave height, where a relatively big error in approximated acceleration only results in a slight error in the approximated wave height. The period starts in a crest and ends in the next crest, where the next period starts. This way, if a peak detection is slightly off, resulting in an error in the wave period, this will be compensated for in the next period.

This research has delivered a solution on how to measure wave characteristics with wireless sensor nodes. A method has been found that uses a minimum of sensors (a single accelerometer) and produces wave measurements from a surface buoy instead of from single point measurements (as discussed in section 3.3). Our method returns consistent and fairly accurate wave measurements and part of the error can be compensated for, as discussed in this thesis. With the prototype setup in a real world environment we have learned (the hard way) what specific requirements rise when measuring with digital equipment within a marine environment, in particular with regards to radio communication and the housing of electronics. Minimizing power consumption has been taken into account from the start, for example in the choice of our accelerometer, but actual power consumption tests and optimisations are subject to further research.

The following topics are subject to further research, listed in descending order of priority:

- Creating sufficiently robust housing for the electronics
- Extending the range of the radio used on the buoys
- Generating more results from the real world environment
- Correcting for the error caused by the overestimation of vertical acceleration
- Working further towards full algorithm implementation on the µNode
- Analysing and optimising power consumption

# Appendix A SCA3000 PCB adaptor board

- Analogue Ground 1 XReset, active low 2 Interrupt Output 3 Digital Ground 4
  - Digital Supply 5
  - Digital Ground 6 Digital Ground 7

Digital I/O Supply 8



- 15 Analogue Ground
  14 Analogue Supply
  13 Do not use (CSB)
  12 I<sup>2</sup>C Data (SDA)
  11 Do not use (MOSI)
  10 I<sup>2</sup>C Clock (SCL)
  9 Not Connected
- Connected to µNode: - Digital & Analogue Ground - I2C Data (SDA) - I2C Clock (SCL)



# Appendix B Relaying device

Internals



#### Voltage regulator board

Top view:



Bottom view:



# Appendix C Selection from preliminary sensor data

Selection of temperature data (from [45]):



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