

# **An Investigation of Tracking of Marine Mammals**

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# **Abstract**

Animal tracking devices are frequently used for wildlife studies. Yrless International (PTY) Ltd specialises in the development of such tracking systems. In an effort to expand their service related to market needs, a marine mammal tracking system must be developed. This dissertation forms part of an initial investigation into such a system. The three main aspects that are addressed are acquiring the animal's location, relaying that information to a server for easy access and interpreting the data. After this a conceptual design of the system is proposed.

GPS is chosen as tracking method, mainly because similar tracking devices are already in use in current tracking products, has been used in previous studies and they delivered promising results during the preliminary study. Tests are done to optimise the GPS receiver in a marine mammal environment and to keep the GPS in a "warm start" mode to decrease location acquisition time. Geolocation calculations, which use sunrise and sunset times for estimating location, are considered as an alternative or complementary method to assist GPS.

For relaying information GSM and RF protocols are investigated. An implementation of RF protocol is developed with consideration of practical implementation on marine mammals and optimising power consumption.

A conceptual design is developed from requirements of the final product. The operation of the marine mammal tracking system is similar to current tracking units.

The knowledge gained from this study and system development serves as important stepping-stones towards providing researchers with a small, efficient and low cost tracking device for marine mammals.

# Opsomming

Wild-opsporingsstelsels word gereeld gebruik vir navorsingsstudies van diere. Yrless International (PTY) Ltd spesialiseer in die ontwikkeling van sulke opsporingsstelsels. Om hierdie diens te vergroot in oorleg met mark aanvraag, bestaan die behoefte om 'n marine soogdier opsporingsstelsel te ontwikkel. Hierdie studie vorm deel van die aanvanklike ondersoek na so 'n stelsel. Die drie hoof aspekte wat gedek word is die metode waarop die dier se posisie verkry word, die aanstuur van die data na 'n bediener vir maklike toegang en die interpretasie van die data. Daarna word 'n konseptuele ontwerp voorgestel.

GPS word gebruik as opsporings metode, hoofsaaklik omdat dit reeds gebruik word in huidige opsporingsstelsels, dit tans gebruik word in ander studies en aangesien GPS belowende resultate gelewer het tydens 'n aanvanklike studie. Toetse word gedoen om die GPS te optimiseer vir die omgewing van 'n marine soogdier en om die GPS in 'n "warm start" vlak te hou om die tyd wat dit neem om posisie uit te werk te verminder. Geoposisie berekeninge, wat gebruik maak van sons -opkoms en ondergang tye om posisie uit te werk, word oorweeg as alternatiewe metode om GPS te ondersteun.

Om informasie aan te stuur word GSM en RF protokol te ondersoek. Die implementering van 'n RF protokol word ontwikkel na aanleiding van die praktiese implementasie op die marine soogdier en die optimisering van kragverbruik.

'n Konsep ontwerp word ontwikkel gebaseer op die vereistes van die finale produk. Die werking van die marine soogdier opsporingsstelsel is soortgelyk aan die huidige opsporingsstelsel.

Die kennis wat opgedoen is tydens hierdie studie en die stelsel ontwikkeling dien as noodsaaklike boustene om 'n klein, effektiewe en lae koste opsporingsstelsel vir marine soogdiere aan navorsers te verskaf.

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# List of Acronyms

2D fix	Two dimensional GPS fix that is based on the information of 3 satellites which does not include altitude. 2D fixes are less accurate than 3D fixes.
3D fix	Three dimensional GPS fix that is based on at least 4 satellites and includes altitude. 3D fixes are accurate to within 10 meters.
AMU	Amplitude measurement unit , the minimum signal strength the receiver must use in calculations.
Auto mode	The GPS receiver first attempts a 2D fix and then a 3D fix.
BOM	Bill of Material, a list of components and parts for describing a product.
DOP	Dilution of Precision, an indicator of the quality of the geometry of the satellite constellation. Low DOP values indicate a good geometry and therefore high accuracy, while values higher than 6 are suspect.
EEPROM	Electrically Erasable Programmable Read-Only Memory is a non-volatile storage chip used to store small amounts of configuration data.
ESM	Enhanced sensitivity mode, mode in which GPS use longer time to acquire satellites.
GPS	Global Positioning System, satellite-based radio-navigation and time transfer system developed by the United States Department of Defense.
GSM	Global System for Mobile Communications.
GSV	GPS Satellite Vehicles; see SV.
HLR	Home location register, database of service provider that contain information about the type of contract.
ICO	see MEO.
IMEI	International Mobile Equipment Identity, unique identifier of GSM modem that is used to detect stolen phones.
MEO	Medium Earth Orbit, sometimes called Intermediate Circular Orbit (ICO), is the region of space around the Earth between low Earth orbit and geostationary orbit.
NASA	National Aeronautics and Space Administration, as the American governments sponsored space organisation.
NMEA	National Marine Electronics Association.

NORAD	North American Aerospace Defense Command, is an American and Canadian aerospace warning and control center.
PDI	Pre-detection integration, the time that is used to search for any signals in the frequency range. This is increased in ESM mode.
RF	Radio Frequency refers to that portion of the electromagnetic spectrum in which electromagnetic waves can be generated by alternating current fed to an antenna.
SNR	Signal to noise ratio.
SSM	Standard sensitivity mode, the normal mode in which the GPS operates.
SV	Satellite Vehicles, GPS satellite that orbits the earth at an altitude of 20200km.
TLE	Two line elements data format.
TTFF	Time to first fix, the time that the GPS requires to obtain a fix from GPS satellites.
VHF	Frequency range of 30–300 MHz.
VLR	Visitors location register, database that contains all GSM modems that are connected to an cellular station.

# Chapter 1 Introduction

Many research studies on wild animals have been conducted with the use of tracking systems (Van Dyk, 2003). The level of interest in wildlife tracking is also reflected by the number of companies that specialise in this field. Location data is central to the understanding, amongst others, of migration patterns and breeding and foraging habits. Such research studies rely on accurate and integrated data to make valid assumptions and discoveries.

Tracking of marine mammals poses an additional set of challenges, which include expensive technological devices and harsh environments. Research results are often severely limited due to incomplete data or inefficient tracking instruments. Funding for wildlife research is usually obtained as donations from corporate companies or from research institutions, which often have a limited budget. The general requirement for wildlife tracking is hence for a relatively low cost device that can provide accurate and complete tracking information. For the tracking of marine mammals, the need is even more challenging: As discussed at the Annual Aquatic Research Conference (Spedicate & Guisepe, 2003), researchers studying marine mammals requires a small, lightweight, inexpensive tracking unit that delivers accurate data in a marine environment, i.e. also when the animal is out at sea.

## 1.1 Background

There is a wide need for an accurate, effective and affordable solution to track marine mammals. This will enable researchers to better understand the behaviour of many species that are currently difficult, expensive and even impossible to track. The animals targeted for tracking have a habit of returning to the same location each year, and surfaces regularly to breath. Some of these species include seals, whales, dolphins and sea turtles.

Yrless International is a company that specialises in wild animal tracking, using GPS/GSM devices. In an effort to expand this service, this dissertation investigates how the technology used for tracking land animals can be adapted to be used for the marine tracking environment.

The specific problems that need to be solved are:

- how location data should be acquired by a GPS device attached to a marine mammal that may be at sea for extended periods of time, and that only surfaces for brief periods of time,
- the transmission of location and other data that has been collected at regular intervals so that researchers will have easy access to the migration patterns of these animals, and
- the transformation of the data packets into understandable information.

These problems are discussed in more detail in the next section.

For this study Yrless International has been working closely with Martin Haupt, a researcher associated with the Zoology Department at the University of Pretoria and founder of Africa Wildlife Tracking (AWT), a company that specialises in animal collaring. AWT already uses some of the Yrless products in their collars for land animals. As part of this cooperation Haupt has shared much of his expertise regarding animal tracking with Yrless and his company will be involved in the packaging and deployment of the research units for marine mammals.

## **1.2 Issues to be addressed**

The two main technical challenges of the tracking system is the acquisition of location data, and transmitting the data to researchers. These are discussed next, as well as the system design that is also covered in this dissertation.

### **1.2.1 Location data**

According to Haupt, location data is central to most studies and is often used in combination with other data provided by sensors. These sensors include temperature (Metcalf & Arnold, 1997), heart rate (Almáida et al 2002a), motion-sensing (Beaumont et al 2003), velocity (Williams et al 2000), light levels for use in geolocation calculations (Almeida et al 2002b), conductivity (Lee 2002), depth and pressure (Laidre et al 2003). The implementation of these sensors is not discussed in this survey.

Current techniques used by researchers in the marine environment include satellite pop-up tags, low frequency RF, hydrophones, GPS navigational systems and geolocation calculations. These

techniques are briefly discussed in the literature survey. Based on a survey of this field, GPS and geolocation calculations were chosen for further investigation.

GPS is not used in underwater conditions as GPS receivers require Line of Sight (LoS) to establish communications with satellites. While at sea, marine mammals surface regularly to breathe, and location must be obtained during this time. It is shown that when reasonably accurate ephemeris and time information are provided, the initial GPS position fix can be shortened (Rashid & Poh Poh, 1991).

The applicability of geolocation calculations is demonstrated in the literature survey. Geolocation calculations is a technique whereby sunrise and sunset times are used to determine longitude and latitude. By determining the local noon from these times, the longitude can be calculated. The day length is used to calculate latitude. The challenge is to determine the exact times of sunrises and sunsets.

## **1.2.2 Communication**

GSM is frequently used as communication protocol in machine to machine (M2M) systems, and is currently used in tracking systems provided by YRless International. The reliability, ease of use and availability of GSM coverage makes it a popular choice. YRless International wanted to investigate whether this communication network can be applied for use in a marine mammal environment.

GSM frequencies do not penetrate seawater, and GSM coverage is limited to only a few kilometres at sea. The use of cell extenders can however improve the GSM covered area by up to 20km, especially with the line of sight that can be achieved in open seas.

The favored communication range for major marine tracking companies are in the LF (Low Frequency) range (LOTEK 2005), (WILDLIFE COMPUTERS, 2005). Acoustic transmitters and receivers using hydrophones are normally utilized in marine habitats, where the conductivity of the salt water hinders the transmission of radio signals.

This study will explore whether the GSM protocol is a suitable communication protocol for the application. The performance of the GSM protocol is compared with RF communication from basic RF module transceivers, usually in the VHF range.

### **1.2.3 System design**

The scope of this study is to design a system for use on seals at Marion Island. Testing of the design will be limited to testing within simulated environments and will not include the actual collaring of seals. The time limit of the study and high costs include involved will prevent the inclusion of results from actual collaring expeditions.

The design is based on the current operation of animal tracking units, and knowledge about particular habits of the seals that are relevant to the tracking concept. The expertise of researchers, including Martin Haupt for African Wildlife Tracking (AWT), is used to determine the design specifications.

A crucial specification for the final design is power consumption. Batteries cannot be changed during the lifetime of the unit, as the unit may be unreachable for up to a year. This would also imply that hardware modules should be kept in a low power sleep mode for as long as possible between position fixes.

A software routine is proposed that will enable the GPS en RF modules to function optimally with careful consideration to power consumption. The use of a level switch is proposed to activate the GPS when the animal surfaces.

The system design includes the development of a stationary transceiver device that forms part of the base station. The purpose of this device is to scan continuously for nearby tracking devices. If a tracking unit responds, a data download is initiated. Power consumption considerations for the stationary transceiver are not that strict, as batteries can be changed at regular intervals.

The data received by the stationary transceiver must be converted to meaningful information before it is returned to the client. This process includes the interpretation of GPS data, which are in NMEA data format.

## **1.3 Research methodology**

The following research steps described below have been taken to address the issues listed in section 1.2 in order to solve the problems identified in this study.

### 1.3.1 Location data

A method to use GPS in an ocean environment is developed. The problem of the short time that the GPS receiver is allowed to acquire satellites is addressed as follows:

- GPS parameters are preset to the typically expected environment of the marine mammal.
- parameters that assist the GPS to obtain faster fixes are provided.
- the location of GPS satellites is used to calculate a possible location.
- a hardware level switch is used to initialise the GPS receiver only when the animal is close to the surface.

The GPS parameters that are preset include:

- Type of fix, which influence the number of satellites that the GPS needs to calculate location.
- Signal to noise ratio (SNR), which influence whether signals from weak satellites should be used.
- Elevation mask, which sets a threshold for the elevated level above the horizon that the satellites must be before they are used in calculations.
- Dynamics code, an expected motion of the GPS receiver, which tells the GPS how to reacquire satellites if they are temporarily lost.
- Sensitivity mode, which are preset parameters that influence satellite acquisition.

The algorithms used in Geolocation calculations are discussed in Chapter 2, and the problems facing this technique are highlighted. Two different sunrise times are measured with a light meter and graphically interpreted.

### 1.3.2 Communication

The limitations of GSM are evaluated against the background of the probable behaviour of marine mammals. These limitations include a long start-up and network acquisition time, limited network coverage and the short time spans that the unit is at surface level to be able to send data packets.

A suitable RF module is investigated as alternative means of communication. The advantages and limitations of an RF module are compared to the advantages and limitations of GSM. The RF protocol is implemented and practically evaluated under simulated conditions.

### **1.3.3 System design**

To test the system design, the behaviour of the seals must be imitated to evaluate the effect on the GPS receiver and RF module.

Accurate power consumption data from animal collars is used to predict the battery life of the units. These calculations were applied to all major hardware components and software processes. This included the time a GPS receiver can be switched on, with adequate power available to allow for safe data transfer.

The stationary server was designed and implemented, as this device is versatile and used for other products. The power consumption specifications were calculated and a battery device recommended. A RF module and particular frequency range was proposed for both the tracking device and stationary server.

To demonstrate the final analysis of the GPS data, actual data was processed.

## **1.4 Summary**

The dissertation relies heavily on the performance of GPS in an ocean environment. If a GPS is assisted with time and location information, a GPS fix can be obtained in smaller amount of time (Rashid & Poh Poh, 1991) than what is otherwise possible.

Some marine mammals spend a large amount of time on land, where GPS fixes are quite possible. The challenge is however to also obtain GPS location when the animals are out at sea. Seals are the perfect “guinea pigs”, since they are robust creatures, researchers have relative easy access to them, and they regularly spend large amounts of time above water to breath. This allows adequate time to for the GPS receiver to obtain GPS satellites and possibly a GPS fix. Optimising the GPS receiver will increase this possibility.

For transmitting data, RF communication is compared with GSM based techniques that are currently used in other animal tracking devices. It is shown that the application of GSM to track marine animals is limited to those species swimming close to the shore or frequently staying on land. The method and time that a GSM modem needs to register on the network and send data will be considered, and compared to conventional RF techniques.

If the system design concept and download sequence is adequate, it can be used as a platform for other devices, which include various sensors. The communication protocol is therefore not restricted to a marine mammal tracking system.

## **1.5 Dissertation overview**

The next chapter is the literature survey and provides a more in-depth look at various location data techniques and communication protocols. A feasibility study is performed in Chapter 3 to determine if a GPS is suitable for collecting location data when fitted to a seal. From the research done in Chapter 3, a system design will be implemented in Chapter 4, which includes the communication protocol selected from the research in Chapter 2. Chapter 5 will evaluate the degree of success achieved. Chapter 6 will summarise the work conducted for this dissertation, discuss the viability of the system and make recommendations about future improvements.

# Chapter 2 Literature Survey

This chapter is divided into two parts. The first section discusses positioning techniques that are currently being used, including a description of GPS operation, and considers Geolocation as tracking method. The second section compares GSM with RF communication in an ocean environment.

## 2.1 Location techniques

Here follows a list of location techniques that are currently used. This section ends with an in depth look at the GPS location system.

### 2.1.1 Low frequency RF

The tracking method of choice for most freshwater research is radio telemetry, which operates in the VHF (Very High Frequency) band. Techniques are based on signal strength or presence and absence data of receivers. Telemetry systems designed for operation in higher VHF ranges give better overall performance. Higher VHF frequencies are more efficient and less susceptible to noise than systems operating at low frequencies.

Low cost automatic receivers are commonly deployed to study habitat utilization, by using presence and absence data within the range of each receiver (Lacroix & Voegeli, 2000). Telemetric techniques have been employed for studying behavioural ecology (migration, home-range, habitat utilization, activity and movement) of marine and freshwater animals in different habitats (Bégout & Lagardère, 1994). The usefulness of tracking and habitat use data in telemetric studies depends on the accuracy and precision of tagged fish location estimates. Biased location estimates are often the result of the presence of physical obstacles (e.g. Submerged vegetation, bottom topography) and of the oceanographic condition (e.g. water flow, thermocline, turbidity) (Voegeli & Pincock, 1990a). Telemetry studies are usually preceded by accuracy and precision assessments of the terrain.

Transmitters are small and in some cases implanted. Sizes can be 11 to 28mm in length with a diameter of 2.1 to 3.5mm and weight of 1.5g to 3.2 g. The conductivity of salt water hinders the

transmission of radio signals, limiting the range to approximately 500 meters, and coaxial and yagi antennas are sometimes used (Reine 2005).

### **2.1.2 Pop-up tags**

Satellite pop-up tags retrieve various data from sensors while it is on the marine animal. The tags are designed to drop off and surface somewhere in the ocean after an unspecified time. This time varies between one month and 2 years (Martin et al, 1993). The Argos satellite system uses the Doppler shift of radio transmissions from the tags to estimate location and can provide highly accurate locations (Gunn & Block, 2001a). When the tags surface, the satellites send a signal, which is used to locate the tag. Sometimes a nearby ship is contacted to do the retrieval.

Pop-up tags have been used in studies including tuna fish (Boustany et al, 2002) and sharks (Marcinek et al, 2001). Satellite based communication does have the advantage of combining location data with transmitting data anywhere in the world. Satellite modules are expensive and include a high monthly fee for communication bandwidth.

The reliability of the tags depends on the retrieval rate. The retrieval rate of one system deployed 130 tags with a 100% success rate (Ge Demitrio, 2003), while in another survey only 30% of 80 tags were retrieved (Howel & Miller 2003).

### **2.1.3 Hydrophones**

Hydrophones are acoustic transmitters and receivers that are normally utilized in salt water conditions, as the ocean is opaque to electromagnetic waves and transparent to sound (Howel & Miller 2003). A hydrophone is a sound to electricity transducer for use in water or other liquids, similar to a microphone in air. Hydrophones with a detection range of 500 meters are used that usually operate at 40 - 80 kHz (Giacalone et al, 2002).

Location is calculated by creating overlapping regions with hydrophone detection ranges and Omni-directional receivers and pingers to detect in which region they are. From previous studies, it is clear that there is no linear relationship between detection rates and position. This is due to environmental factors like water flow, submerged vegetation, presence of a fish shoal or artificial structures. This often results in a situation where two hydrophones would record different values even if the pinger was located at the same distance from them (Pincock, 1990b). The results of

tests within an artificial reef area the positioning accuracy was found to be 132 +/-54m (Giacalone et al, 2002).

The use of hydrophones is limited to smaller areas like dams, where many detecting hydrophones can be deployed to increase accuracy.

## **2.1.4 GPS**

This section will discuss how a GPS operates and how GPS location fixes are attained. It also looks at the mathematical laws that govern the orbits of GPS satellites, and how the location of satellites can be deduced from almanac information acquired from the satellites.

### **2.1.4.1 GPS operation**

Global Positioning System (GPS) is a satellite-based radio-navigation and time transfer system developed by the United States Department of Defense (Warner & Johnston, 2003). It exists of a constellation of 27 satellites in 6 intermediate circular orbits (ICO), also called medium earth orbits (MEO). At any time of day, between 4 and 10 satellites are visible from any place on earth (Navstar, 1996). Each satellite orbits the earth twice a day at a speed of roughly  $11200\text{km}\cdot\text{h}^{-1}$  at an altitude of approximately 20200 km (Dana, 2002).

GPS satellites have a declination of  $55^\circ$  from the equatorial plane, and a right ascension, or hour angle of  $60^\circ$ . Their position is the same at the sidereal time each day (Callasan et al, 2003). A sidereal day is the time it takes for the Earth to turn 360 degrees in its rotation, which adds to 366.2422 days compared to 365.2422 days of a solar year. A sidereal day has 23 hours, 56 minutes and 4.091 seconds (Weisstein, 1996). GPS satellites will have a displacement of approximately 4 minutes each day.

Each GPS satellites transmit at 1575.42 MHz. A second frequency is used to calculate phase difference to measure the atmospheric effects on the signals and apply precise corrections (Navstar, 1996). GPS signals strengths measured at the surface of the Earth is  $-160\text{dBW}10^{-16}$  Watts, which is equivalent to viewing a 25-Watt light bulb from a distance of 16000km (Warner & Johnston, 2003). Testing at Yrless' showed that in 0.5cm water a receiver can distinguish satellites but won't attain a fix, while in 1cm water no satellites are visible.

A GPS receiver operates by knowing which satellite it should receive and attempts to match a predefined code with one that is sent by that satellite. When a successful match is made the GPS receiver will lock to that signal and can be downloaded from the GPS and the signal strength can be viewed. After this the ephemeris data is downloaded (Lassen, 1999). The ephemeris data from a satellite is valid for 3 to 4 hours (Digglan, 2001).

Each satellite sends its signature every millisecond, which consists of 1023 bits of unique data. The receiver uses the almanac data to estimate the position of the satellite it is interested in and to predict its Doppler shift speed. It then uses its own location and time to attempt to match a copy of the 1023 bit code to exactly match the code from the satellite. If a match is not possible the time and clock frequency are shifted and a match is reattempted (Nato, 1991).

Once the receiver matches the satellite it was seeking it can start decoding satellite information. The data itself is modulated at a 50 Hz rate on top of the signature by using the signature as a carrier. There are 25 frames of data that is divided into 5 subframes of 300 bytes each. A frame is transmitted in 30 seconds, thus each subframe takes 6 seconds to transmit. The first subfield contains health and accuracy data as well as corrections for the satellite clock. The next two subframes contain the ephemeris data. The final 2 frames contain all of the other data, such as almanac data, that is of less importance in obtaining the first fix (Navstar, 1993).

Figure 1 shows the orbits and last position of satellites at 29/9/1998 00:00:00 and 30/9/1998 00:00:00.

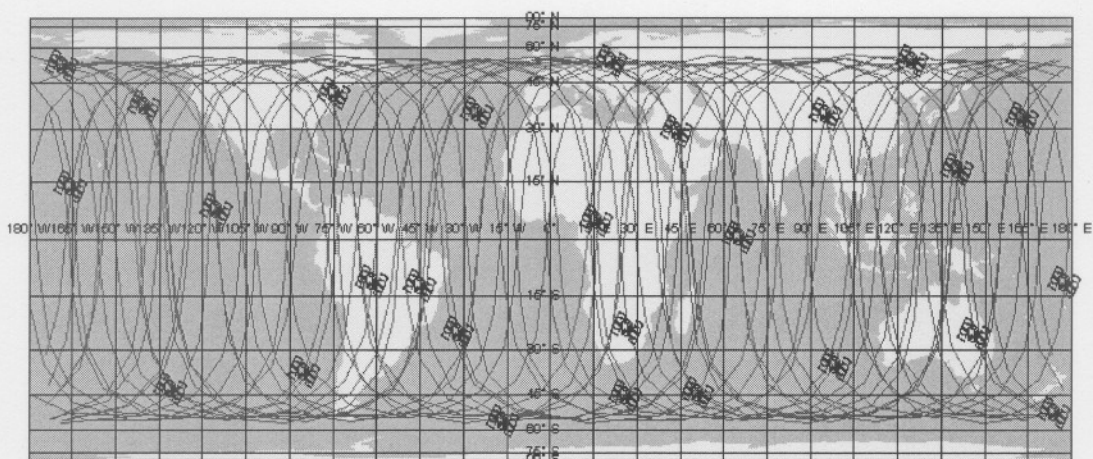


Figure 1: Orbits and last position for GPS satellites for a 24-hour period (Nato, 1991)

Figure 2 below is a simplified representation of the GPS constellation.

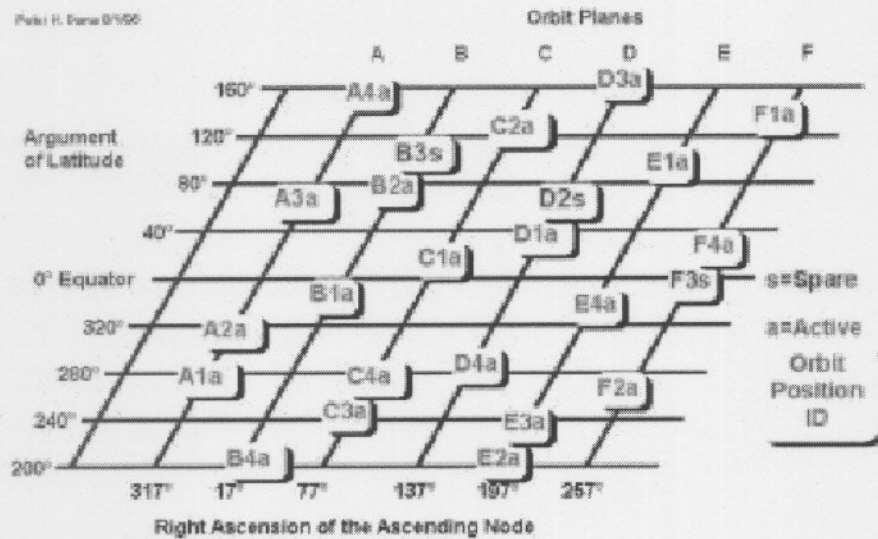


Figure 2: GPS satellites and their orbits (Laidre et al 2003)

Table 1 provides a description of GPS satellites in their orbits (Laidre et al 2003).

Table 1: GPS satellites and their orbits

Orbit Ascension	Satellites
04 hours	5,9,11,23
08 hours	1,3,8,10
12 hours	6,14,16,17
16 hours	4,12,15,21
20 hours	2,7,18,22
00 hours	13,19,20,24

GPS satellites follow a non-geostationary orbit, which means that from the earth's perspective it will seem like they rise and set. As shown in Figure 3, each satellite has a broadcast pattern of  $21.3^\circ$ , which is slightly wider than the angle formed by the earth as seen from the satellite (Gustavsson, 2005). The significance of this is that if the satellite is seen from Earth, the observer will also be 'seen' by the satellite.

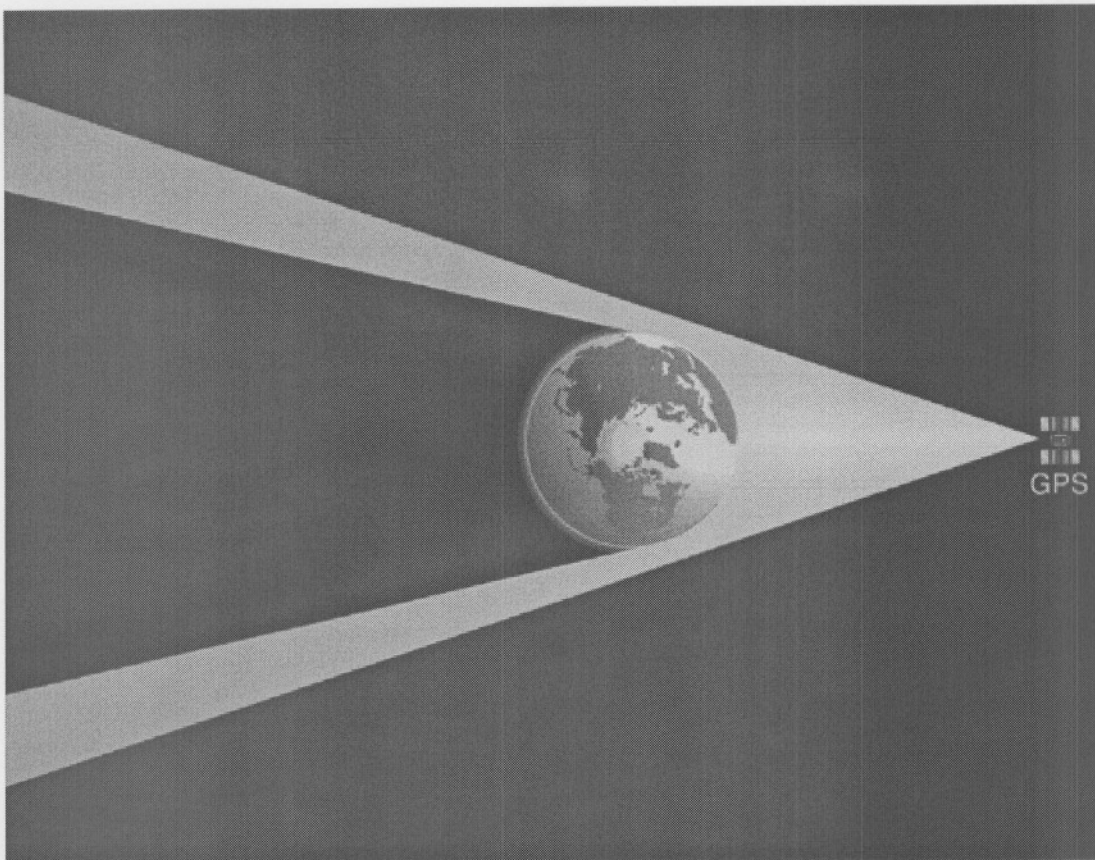


Figure 3: GPS broadcast pattern is slightly wider than the earth (Gustavsson, 2005)

#### 2.1.4.2 Almanac and ephemeris data

A GPS signal contains three different bits of information a

- a pseudorandom code
- ephemeris datum
- almanac datum

The pseudorandom code is an I.D. code that identifies which satellite is transmitting information (Navstar, 1996).

An ephemeris is a set of parameters that provide positions (usually in the Cartesian coordinate system) of objects in the sky at a given moment. Ephemeris data tells the GPS receiver where each GPS satellite should be at any time throughout the day (Weisstein, 1996).

Almanac data is a reduced-precision subset of the ephemeris parameters. It is used by the GPS receiver to compute parameters such as the elevation angle, azimuth angle and the estimated

Doppler effect of the satellites. The system almanac contains information about each of the satellites in the constellation, ionosphere data, and special system messages. Each satellite broadcasts the almanac for all the satellites in the system. Almanac data is constantly transmitted by each satellite, and also contains information about the status of the satellite (healthy or unhealthy), current date and time. A satellite can be temporarily unhealthy if its unsure about its current ephemeris. If a satellite is classified as unhealthy the data it can be unreliable and can cause a GPS receiver to shut down. The almanac allows GPS receivers to use data from the strongest satellite signal to locate other satellites (Lassen, 1999).

Almanac data is periodically updated as satellites deviate from their orbit. These deviations are monitored by 6 ground stations that keep track of the satellite orbits, altitude, location and speed. The ground stations send the orbital data to the master control station (located at Schriever Air Force Base, Colorado) which in turn sends corrected data up to the satellites (Navstar, 1993).

### **2.1.4.3 GPS accuracy**

The main factors affecting GPS accuracy are the placement of satellites, atmospheric delay, internal clock errors and multipath, which are briefly discussed here.

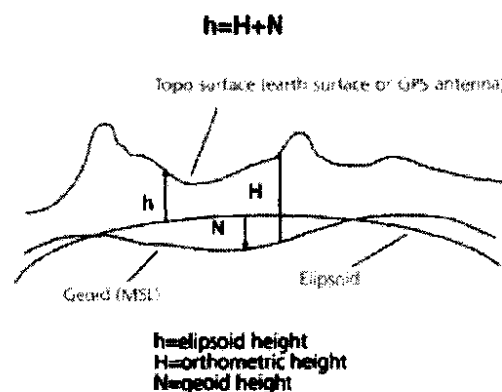
Atmospheric delays are caused when radio waves are slowed significantly as they pass through the Earth's atmosphere, in particular the ionosphere. The ionosphere ranges from an altitude of 50 to 500 km, and exerts a perturbing effect on GPS signals. The transmitted model can only remove about half of the possible 70ns of delay leaving a possible 10 meter error. The troposphere is about 8 - 13 km above ground, and is caused by changes in temperature, pressure, and humidity associated with weather changes. The resulting error can be up to 1 meter (Navstar, 1996).

GPS receivers do not use atomic clocks, which causes internal clock errors. Timing is considerably less precise than the timing of the satellites. GPS receivers do have techniques to synchronise their internal clocks almost exactly to the time of the satellites, though four satellites are required for timing (Warner & Johnston, 2003). This is a reason why 2-D GPS readings using only three available satellites are potentially less accurate than 3-D GPS readings using at least four satellites.

The location of satellites is important for trilateration to be effective. This placement of satellites in the sky is called satellite geometry. Four satellites grouped closely together would result in less accurate location, compared to four satellites that are spaced far from each other. As the satellites spread out overhead trilateration becomes more effective and GPS accuracy improves. The rating system called PDOP (Position Dilution of Precision) is a unitless representation of satellite geometry. Low PDOP ratings represent good satellite geometry whereas high PDOP ratings represent poor satellite geometry (Dana, 2002).

Multipath errors are caused by signals reflecting off objects before they reach the GPS receiver. This increases the distance that the signal travels giving an inaccurate result to the receiver (Axelrad et al, 1996). These objects include buildings and mountains.

Large altitude errors are found on GPS receivers, as the GPS receiver uses an mathematical model to determine altitude. The GPS uses a model of the earth surface, shown in Figure 4 as the orange ellipsoid. The traditional, orthometric height (H) is the height above an imaginary surface called the geoid, which is determined by the earth's gravity and approximated by MSL. The signed difference between the two heights—the difference between the ellipsoid and geoid—is the geoid height (N) (Fraczek, 2003).



**Figure 4: Differences in the earth's surface (Fraczek, 2003)**

#### 2.1.4.4 Trimble GPS information

The current GPS device used by Yrless International is the Lassen LP GPS. This device acquires available GPS satellites and outputs a positional fix after power is applied without any user intervention. When backup power is supplied the unit retains almanac, ephemeris, last position, and time for faster start-ups. User settings, including power parameters and processing options, are stored in non-volatile EEROM (Lassen, 1999).

The satellite data is transmitted in 30-second frames. Each frame contains the clock correction and ephemeris for that specific satellite, and two pages of the 50-page GPS system almanac. The almanac is repeated every 12.5 minutes. The ephemeris is repeated every 30 seconds (Dana, 2002).

Ephemeris data changes hourly, but is valid for up to four hours. The GPS control segment updates the system almanac weekly and the ephemeris hourly through three ground-based control stations. During normal operation, the Lassen LP GPS module updates its ephemeris and almanac as needed (Lassen, 1999).

There are three modes from which a GPS can calculate a fix (Lassen, 1999):

#### ***2.1.4.4.1 Cold start***

A cold start occurs when the GPS is switched on for the first time, and needs to download a complete almanac, which can take up to 15 minutes. In this time position can be calculated within 2 minutes, though tests at YRless International have shown that these first few readings may have large errors.

#### ***2.1.4.4.2 Warm start***

A warm start occurs if the last fix was more than one hour ago, meaning that the ephemeris data is old. The almanac data, initial position and time are stored on the GPS receiver to assist with calculations. Estimated time is less than 45 seconds.

Typically, time should be known within 20 seconds of GPS time, position should be known within 100 kilometers, velocity within 25 meters per second, and the satellite almanac should have been collected within the past few weeks. TTFF1 for warm starts is typically in the 2 to 5.5 minute range (Navstar, 1996).

#### ***2.1.4.4.3 Hot start***

A hot start occurs when the last fix was less than one hour and the almanac, position, ephemeris, and time are valid. Estimated time for a fix is less than 20 seconds.

### 2.1.4.5 Kepler elements

The orbit of GPS satellites can be described in terms of Kepler Elements, which are mathematical parameters to describe the motion of orbiting systems. The 6 parameters are described below in Table 2 (Barker & Goldstein, 2001). A graphical representation is shown in Figure 5.

**Table 2: List of Kepler Elements**

Name	Symbol	Description
Semi-major axis	a	Size of the orbit
Eccentricity	e	Shape of the orbit. If the orbit is an exact circle, the value would be 0.
Inclination	i	Orientation of the orbit with respect to the earth's equatorial plane. By convention, inclination is a number between 0 and 180 degrees.
Argument of perigee	$\omega$	Angle between the ascending (the point where the orbiting body passes from the southern to the northern hemisphere) and the periapsis (the point of closest approach to the central body (for example the earth), measured in the body's orbital plane and in its direction of motion.
Right ascension of ascending node	$\Omega$	Location of the ascending and descending orbit locations with respect to the earth's equatorial plane. range 0 to 360 degrees
Mean anomaly	V	The position of the satellite within the orbit with respect to perigee.

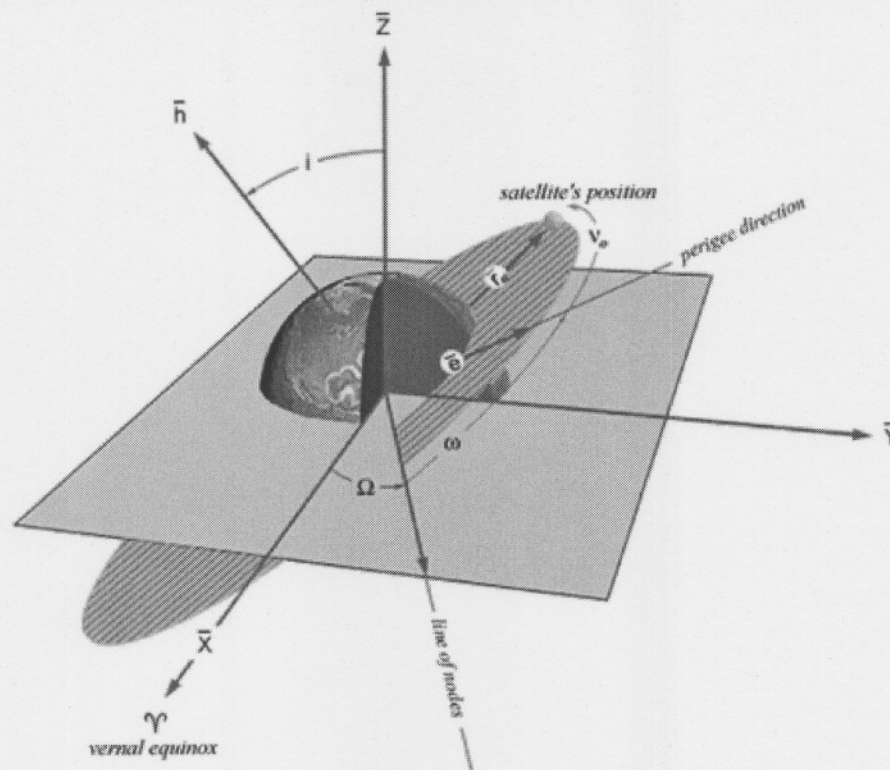


Figure 5: Graphical representation of Kepler elements

#### 2.1.4.6 GPS data

Three data formats are important in GPS operation: NMEA, Two Line Elements (TLE) and Yuma standard. Each of these is discussed below.

##### 2.1.4.6.1 Decode NMEA sentences

Many GPS receivers output data in NMEA-0183 (National Marine Electronics Association) format (DePriest, 2000).

An NMEA sentence contains an address field, data field, and checksum. Each sentence takes a fix amount of input fields which must exist and no empty fields are allowed. The sentence is terminated with the standard CR/LF sequence.

The message format is as follows:

$\$ \langle \text{Address} \rangle, \langle \text{Data} \rangle * \langle \text{Checksum} \rangle \langle \text{CR} \rangle \langle \text{LF} \rangle$

To view the current satellites in motion, the message format would look like this:

\$GPGSV,a,b,c,d1,e1,f1,g1,d2,e2,f2,g2,d3,e3,f3,g3,d4,e4,f4,g4,\*zz

The message parameters are explained in Table 3:

**Table 3: NMEA message format**

GSV	Satellites in view
a	Number of sentences for full data
b	Sentence 1 of 2
c	Number of satellites in view
d	Satellite PRN number
e	Elevation in degrees
f	Azimuth in degrees
g	SNR
*zz	the checksum data, beginning with a *

#### 2.1.4.6.2 Two line elements

Keplerian element parameters can be encoded as text in a number of formats. The most common is the NASA/NORAD Two-Line Elements (TLE) format. (Kelso, 2000a)

The format for TLE is as follows:

```

AAAAAAAAAAAA
1 NNNNNC NNNNNAAA NNNNN.NNNNNNNN +.NNNNNNNN +NNNNN-N +NNNNN-N
N NNNNN
2 NNNNN NNN.NNNN NNN.NNNN NNNNNNNN NNN.NNNN NNN.NNNN
NN.NNNNNNNNNNNNNNN

```

The first line has 11 characters, although 12 and 24 characters are sometimes allowed.

The format for the second line is shown in Table 4.

**Table 4: Second line TLE format**

Column	Description
1	Line number of element data
03-07	Satellite number
08	Classification
10-11	International designator containing the last two digits of launch year

Column	Description
12-14	International designator containing the launch number of the year
15-17	International designator containing the piece of launch
19-20	Epoch year, last two digits of year
21-32	Epoch, day of the year and fractional portion of the day
34-43	First time derivative of the mean motion
45-52	Second time derivative of mean motion
54-61	Second time derivative of mean motion
63	Ephemeris type
65-68	Element number
69	Checksum

The format for the third line is shown in Table 5.

**Table 5: Third line of TLE format**

Column	Description
1	Line number of element data
03-07	Satellite number
09-16	Inclination in degrees
18-15	Right ascension of the ascending node in degrees
27-33	Eccentricity
35-42	Argument of perigee in degrees
44-51	Mean anomaly in degrees
53-63	Mean motion in revolutions per day
64-68	Revolution number at epoch
69	Checksum

#### **2.1.4.6.3 Yuma message format**

The Yuma message format is a simple line description of valid parameters. The name and interpretation of these values are shown in Table 6 (Kelso, 2000b).

**Table 6: Description of Yuma paramters**

Line	Name	Description
1	ID	Sattelite identification number
2	Health	Status of satellite. An unhealthy satellite's data is unreliable and can not be used
3	Eccentricity	This shows the amount of the orbit deviation from circular orbit. It is the distance between the foci divided by the length of the semi-major axis
4	Time of applicability	A timestamp to show the number of seconds in the orbit when the almanac was generated
5	Orbital Inclination	The angle to which the SV orbit meets the equator
6	Rate of Right Ascension	The rate at which the angle of right ascension is changed.
7	Square Root of Semi-Major Axis	This is a measurement from the center of the satellite orbit to the apogee or perigee
8	Right Ascension at Time of Almanac	Geographic Longitude of the Asending Node of the Orbit Plane at the Weekly Epoch
9	Argument of Perigee	The angle along the orbital path as measured from the ascending node to the point of perigee
10	Mean Anomaly	The arc angle of the longitude of ascending node
11	Af(0)	SV clock bias in seconds
12	Af(1)	SV clock drift in seconds per seconds
13	Week	GPS week (0000-1024), every 7 days since 22 Aug 1999

### 2.1.5 Geolocation calculations

For a secondary method of location, the prospect of using sunrise and sunset times for location calculations are discussed.

Many wildlife tracking companies such as Wildlife Computers (LOTEK, 2005) and Lotek Fish and Wildlife Monitoring (WILDLIFE COMPUTERS, 2005) has location products which use light level indicators and geolocation calculations. From the recorded light level curves, software calculates the daily longitude and latitude. Longitude accuracy can be as good as  $\pm 0.5^\circ$ . Latitude accuracy depends upon both the latitude and time of the year. Best accuracies of  $\pm 1^\circ$  are

achieved at high latitudes near the solstices, and worst accuracies,  $\pm 10^\circ$ , occur near the equator near the equinoxes.

As mentioned in the previous section, a GPS must be supplied with location information with a possible error of 100km. Estimates of latitude and longitude can be done with light intensity measurements and the apparent time of dawn and dusk, as indicated by the exponential change in light levels recorded over these periods.

Longitude is calculated by using sunrise and sunset levels to determining the local noon, while latitude is calculated by using the day length. The most important aspect of geolocation calculations is the precise prediction of sunrise and sunset.

A sunrise and sunset are divided in stages depending on the azimuth angle of the sun in relation to the observer. Sunrise or sunset is defined to occur when the geometric zenith distance of center of the Sun is  $90.8333^\circ$  (Ekstrom, 2002). Twilight is the time before sunrise and again after sunset during which there is natural light provided by the upper atmosphere, which does receive direct sunlight and reflects part of it toward the Earth's surface.

Twilight is divided in three stages: Civil, Nautical and Astronomical (Nielson, 2005).

- Civil twilight occurs when the center of the sun is geometrically  $6^\circ$  below the horizon. In this time objects can clearly be defined.
- Nautical twilight occurs when the center of the sun is geometrically  $12^\circ$  below the horizon.
- Astronomical twilight occurs when the center of the sun is geometrically  $18^\circ$  below the horizon.

The best time to record light changes is during civil twilight (Hill, 2002). During this time, light levels changes fastest, so the time of event of the light level measurement can be determined most accurately. The shape of the light curve for a zenith angle of  $87^\circ$ - $95^\circ$  ( $+3 - -5$  sun elevation angle) has a firm shape, which is less significantly influenced by cloud cover or atmospheric refraction (Ekstrom, 2003). Elevation angle ( $a$ ) is related to the zenith angle  $z = 90^\circ - a$ .

A simplified radiative transfer model predicts that for sufficiently strong light scattering attributed to atmospheric dust, the sunrise-sunset transient should have a particular rigid shape against solar elevation angle for angles in  $-5^\circ < a < +3^\circ$  (Nielson, 2005). In this angle range surface irradiance is dominated by light that has been singly scattered in the stratosphere. For

higher angles, light coming directly from the sun begins to contribute significantly, while for lower angles, multiply scattered light (ducted over the horizon) will contribute.

Recent developments in geolocation have improved estimation by using sea surface temperature maps (Gunn & Block, 2001a), or by comparing maximum deep dives or bottom depths to regional bathymetric maps (Gunn & Block, 2001b).

### **2.1.5.1 Techniques**

Although geolocation techniques operate on the same principle, different techniques have different methods to determine sunrise and sunset times. Geolocation is normally done in the following four steps: (Ekstrom, 2003)

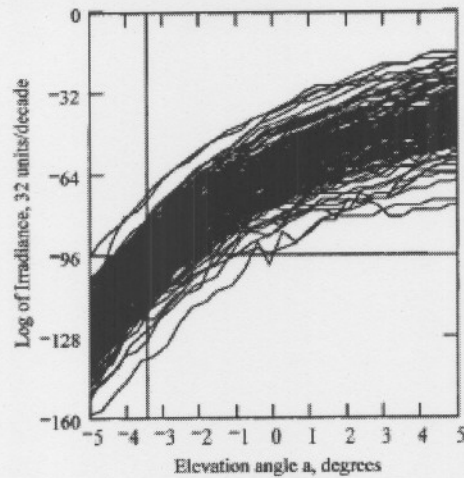
- Model a sequence of simultaneous light measurements.
- Deduce the sequence of surface solar irradiances in each day
- Determine the times of sunrise and sunset
- Calculate possible longitude and latitude values

Three of these most common techniques are listed below.

#### ***2.1.5.1.1 Fixed reference light level method***

The time when inferred surface irradiance is determined when the value matches a predetermined threshold. This threshold value is chosen when the sun is at a particular solar elevation angle.

This method is not very popular, since there is no unique relationship between elevation angle and irradiance, as shown in Figure 6. During a particular sunrise, the irradiance value can cross the threshold value more than one time. It can be seen that the lines do not lie on top of each other, although they do have a similar shape (Musyl et al, 2001). The average curve is steepest by the time the irradiance has fallen a factor of 1000 from its noon value. A steep curve is desirable since it translates a given error in irradiance or threshold position into a relatively small error in angle. The intensity threshold is chosen with respect to some reference intensity. The sun elevation angle corresponding to that threshold is about  $\alpha = -3.5^\circ$  (Ekstrom, 2003).



**Figure 6: Normalized light vs. elevation angles for 80 days between  $-5^{\circ}$  to  $5^{\circ}$  (Ekstrom, 2003).**

#### ***2.1.5.1.2 Dawn and dusk summary method***

This method matches dawn and dusk curves symmetrically to find a midnight time. This avoids errors caused by spurious readings at a standard reference light level (Musyl et al, 2001). The time of midnight is translated to longitude by multiplying the time by 15, and factoring in the equation of time. A value of 15 is used since the effective range of the light sensor from bright sunshine to a level 10 decades less bright is 150 readings lower.

Latitude is calculated by using a threshold latitude, which is taken at a specified day at a known location during which light curves were clean. The zenith angle of the sun is calculated at specific times of day for a given location from standard astronomical equations (Ekstrom, 2003). This translation from light level to zenith angle can then be applied to the rest of the data set, so that for each day there is a plot of zenith angle against time. Latitude is determined by finding the latitude that best matches those zenith angles at the measured times.

This method can calculate latitude throughout the year including the equinoxes, although in equatorial waters the error in the latitude estimate at the equinoxes becomes large (Musyl, 2001).

#### ***2.1.5.1.3 Variable reference light level method***

This method uses a reference light level for each day by using a mark of 70% of that day's average mid-day light level for a threshold (Ekstrom, 2003). The light versus time data for each day is taken from a two hour period around sunrise and sunset was fitted with a 4th order

polynomial using least squares. Initial estimates of the times of dawn and dusk were taken to be the times at which the fitted curve equalled the reference light level. The estimated times of dawn and dusk were then refined by repeating the above procedure but this time fitting a 4th order polynomial to data that extended just 15 min before and after the times of dawn and dusk determined in the first step. A zenith angle of  $94^\circ$  is assumed to correspond to the derived reference light level (Welch & Eveson, 1999).

Techniques such as this that require light level readings throughout the day generally have a higher power consumption.

### **2.1.5.2 Possible errors**

A number of factors can decrease the accuracy of geolocation calculations. Light bends when it encounters thermal or pressure gradients and does not pass through the earth's atmosphere in straight lines. For this reason, it is generally considered impossible to measure the time of dawn or dusk to an accuracy of greater than 2 minutes, even while observing the sun rather than measuring ambient light levels (Hill, 2002).

#### ***2.1.5.2.1 Equinoxes***

The equinox refers to the moment when the sun passes over the equator. On the equinoxes the Sun rises true east (parallel to lines of latitude) and sets at true west, which causes day length to be equal to night length anywhere on Earth. Since Latitude is determined by the variation of day length, small variations in day length will be cause difficulty in estimating position. Any small error in assessing day length will cause a large error in the latitude determination. This does not affect the calculation of longitude (Hill, 2002).

#### ***2.1.5.2.2 Animal behaviour***

If an animal dives for periods between dawn and dusk periods, those values must be ignored. An interpolation technique around the times of dawn or dusk is usually used to filter unwanted readings. Extended dives at dawn or dusk will make sunset and sunrise determinations unreliable or impossible (DeLong et al, 1992).

Another behavioural problem would be found when an animal travels a long distance over latitude during the course of one day.

#### **2.1.5.2.3 Clock drift**

The onboard timer is crucial to all calculations and even slight inaccuracies will have a massive influence. Latitude readings will not be influenced as such as these calculations are dependent on day length, but longitude readings will drift according to the clock.

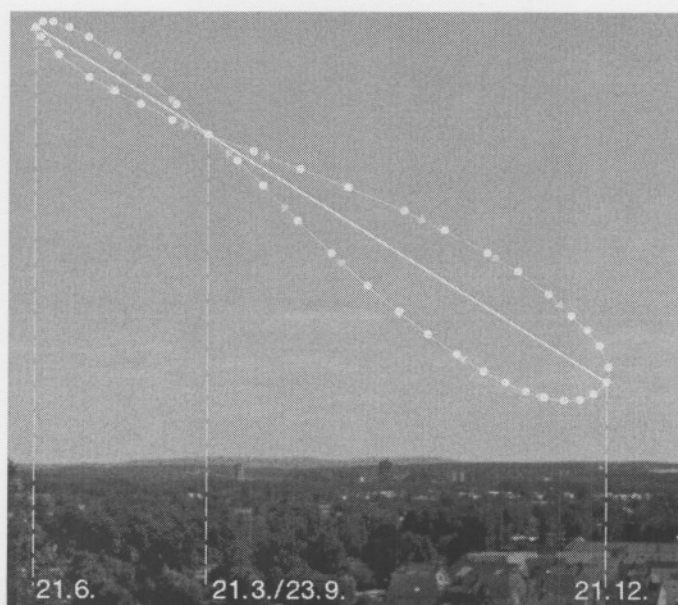
#### **2.1.5.2.4 Cloud cover**

Cloud cover can create discrepancies in the light measurements of sunrises and sunsets. This can cause incorrect assumption of day length, which would influence latitude calculations (Musyl, 2001).

### **2.1.5.3 Equation of time**

The use of geolocation calculations requires knowledge of the equation of time and general solar equations.

The equation of time is a mathematical relationship to describe the difference between clock time and true solar time. It results from the combined effect of the  $23.45^\circ$  axial inclination of the Earth, and the eccentricity in the earth's orbit around the sun. This is shown in Figure 7.



**Figure 7: The path of the sun during the year, called an analemma (Jacobs, 1990)**

Apparent solar time, also called true or real solar time, is the time indicated by the sun on a sundial, while mean solar time is the average as indicated by the clocks. The equation of time is the difference between apparent solar time and mean solar time.

The approximate equation of time due to the earth elliptical rotation (Waugh, 1973)

$$\lambda = 0.985653(N - 2) \quad (1)$$

$$v = \lambda + 1.915169 \sin \lambda \quad (2)$$

expressed as  $\lambda$  and  $v$  where  $N$  is the number of the day of the year.

Time difference:

$$3.98892(\lambda - v) \quad (3)$$

Approximate equation of time due to the earth tilt

$$\varepsilon = 0.985653(N - 80) \quad (4)$$

If  $\varepsilon \geq 270$ , subtract 360 from  $\varepsilon$

$$\varepsilon = 0.985653(N - 80) \quad (5)$$

If  $\varepsilon \geq 90$ , subtract 180 from  $\varepsilon$

Time Difference:  $3.98892(\varepsilon - \beta)$

$$\beta = \tan^{-1}(0.917408 \tan \varepsilon) \quad (6)$$

Combined effect

Time Difference:

$$3.98892[(\varepsilon - \beta) + (\lambda - v)] \quad (7)$$

This effect of these equations is seen in Figure 8:

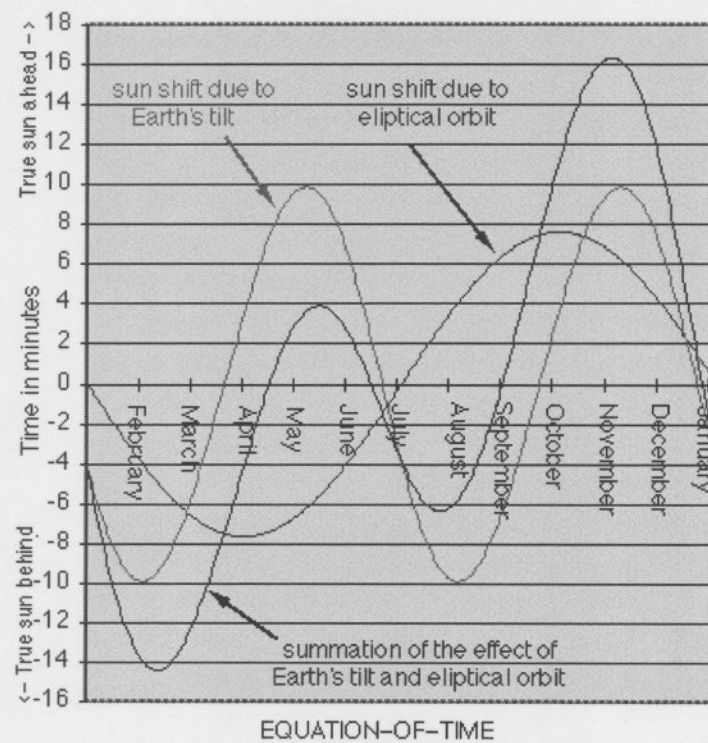


Figure 8: Equation of time (Waugh, 1973)

#### 2.1.5.4 General solar position calculations

Here follows some important solar calculations (Waugh, 1973):

The fractional year ( $\gamma$ ) is calculated, in radians.

$$\gamma = \frac{2\pi}{365} * (\text{day\_of\_year} - 1 + \frac{\text{hour} - 12}{24}) \quad (8)$$

From  $\gamma$  the equation of time (in minutes) and the solar declination angle (in Radians) can be estimated:

$$\begin{aligned} Eq\_Time = & 229.18 * (0.00075 + 0.001868 \cos \gamma - 0.032077 \sin \gamma \\ & - 0.014615 \cos 2\gamma - 0.040849 \sin 2\gamma) \end{aligned} \quad (9)$$

$$\begin{aligned} decl = & 0.006918 - 0.399912 \cos \gamma + 0.070257 \sin \gamma - 0.006758 \cos 2\gamma \\ & + 0.000907 \sin 2\gamma - 0.002697 \cos 3\gamma + 0.000148 \sin 3\gamma \end{aligned} \quad (10)$$

From (1) and (2), the true solar time can be calculated:

$$time\_offset = Eq\_time - 4 * longitude + 60 * timezone \quad (11)$$

where Eq\_time is in minutes, longitude is in degrees, time zone is in hours from UTC.

The True Solar Time *tst* is

$$tst = hr * 60 + mn + \frac{sc}{60} + time\_offset \quad (12)$$

where *hr* is the hour (0 - 23), *mn* is the minute (0 - 60), *sc* is the second (0 - 60).

The solar hour angle, in degrees, is:

$$ha = tst * 180 \quad (13)$$

The solar zenith angle ( $\phi$ ) can then be found from the following equation:

$$\cos \phi = \sin(lat) \sin(decl) + \cos(lat) \cos(decl) \cos(ha) \quad (14)$$

The solar azimuth ( $\theta$ , clockwise from north) is:

$$\cos(180 - \theta) = -\frac{\sin(lat) \cos \phi - \sin(decl)}{\cos(lat) \sin \phi} \quad (15)$$

For the special case of sunrise or sunset, the zenith is set to  $90.833^\circ$  (the approximate correction for atmospheric refraction at sunrise and sunset), and the hour angle becomes:

$$ha = \pm \arccos \left[ \frac{\cos(90.833)}{\cos(lat) \cos(decl)} - \tan(lat) \tan(decl) \right] \quad (16)$$

where the positive number corresponds to sunrise, negative to sunset.

Then the UTC time of sunrise (or sunset) in minutes is:

$$sunrise = 720 + 4(longitude - ha) - Eq\_time \quad (17)$$

where longitude and hour angle are in degrees and the equation of time is in minutes.

Solar noon for a given location is found from the longitude (in degrees) and the equation of time (in minutes):

$$\text{solar\_noon} = 720 + 4 * \text{longitude} - \text{Eq\_time} \quad (18)$$

## 2.2 Communication

The next section deals with communication between the marine mammal tracking device collared to the mammal and a base station used to collect this data. Firstly GSM operation is described, and the reasons why this protocol is not viable is highlighted. Thereafter RF communication in general is discussed and compared with GSM protocol.

### 2.2.1 GSM

Once location data and other sensor information are collected, data should be easily accessible. GSM is the preferred protocol of data communication on dry land, since the established network has wide coverage, is easy to connect to and relatively affordable. GSM as an option in marine mammal environment faces several obstacles. GSM's high frequency low power signals cannot penetrate the water. Secondly, marine mammals are usually found far away from shore, where there is no GSM coverage. This would mean that the marine mammal tracking device would be limited to a small isolated number of marine mammal colonies that are found in areas with GSM coverage.

Another obstacle is that GSM requires an initial time to register on the network. This is shown in Figure 9, which shows the initialisation sequence of the GSM Modem.

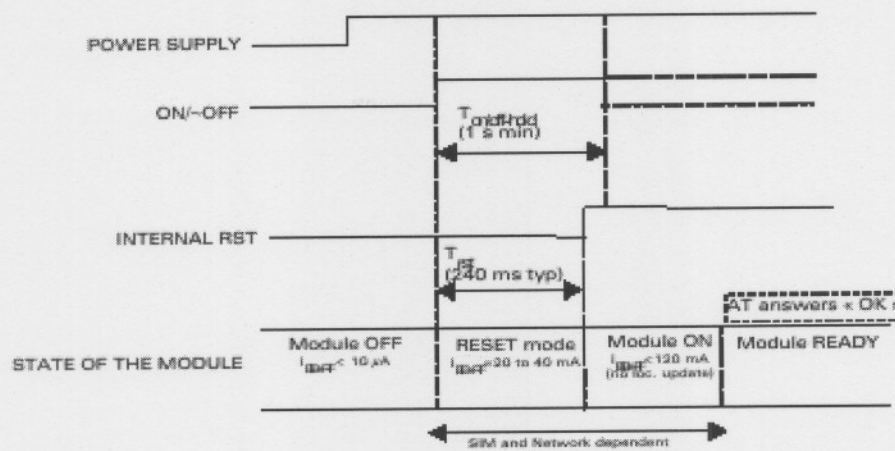


Figure 9: Initialisation sequence of the GSM Modem (WAVECOM, 2001)

The network dependent time shown in Figure 9 may consume from less than ten seconds to nearly a minute depending upon a number of factors including SIM card settings, service provider, received signal strength and quality, and whether or not the modem is roaming on a foreign network. The following section will describe what happens when a GSM modem is initialised and attempts to connect with the network:

When a modem is switched on it will start searching for the base channel frequency that was stored in the SIM when the modem was switched off. This will avoid a long scanning process if the modem is located in the same cell as when it was switched off.

Data about the phone's identity and what services it can access are stored in a SIM record in the Home Location Register (HLR). The HLR is a database maintained by the phone company for all of its subscribers, answering network queries about the contract type and location on the mobile phone network. Each geographic area also has a database called the Visitors Location Register (VLR) which contains details of all the local mobiles. Whenever a phone attaches, or visits, a new area, the Visitors Location Register must contact the Home Location Register (Rahnema, 1993).

The VLR will tell the HLR where the phone is connected to the network and request a copy of the SIM record (which includes, for example, what services the phone is allowed to access). The current cellular location of the phone is entered into the VLR record and will be used during a process called paging when the GSM network wishes to locate the mobile phones.

Two security checks are also done during this time. SIM identity verifications are done by the service provider, which consults the Authentication Center of the home phone company. Then the International Mobile Equipment Identity (IMEI) number are checked against the global Equipment Identity Register to locate stolen phones

Every phone contains a unique identifier (different from the phone number, which is associated at the HLR with the removable SIM card), called the International Mobile Equipment Identity (IMEI). When a phone contacts the network, its IMEI is supposed to be checked against the global Equipment Identity Register to locate stolen phones and facilitate monitoring (Rahnema, 1993).

A power off time graph is shown in Figure 10. If the modem moved to a new location or was not properly de-registered from the network, the next start up time will be comparatively longer.

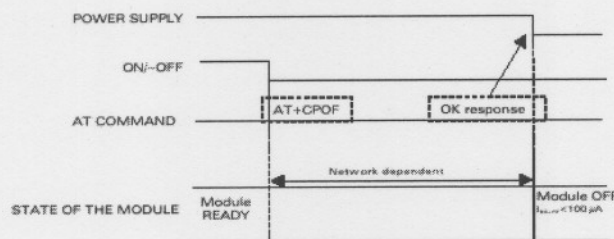


Figure 10: De-initialisation sequence of the GSM Modem (WAVECOM, 2001)

## 2.2.2 RF

Low frequencies experience less attenuation and can be received deeper into seawater (US Navy, 2001). The US navy uses ELF (Extremely Low Frequency) frequencies to communicate with submerged submarines. The disadvantage is low baudrate, high power consumption and long antennas. As mentioned, the favoured communication range for major marine tracking companies is in the LF (Low Frequency) range (LOTEK 2005), (WILDLIFE COMPUTERS 2005).

RF communication chips usually have a simple data send and receive interface, as most of the security, encoding, error checking and other functions are already on the device. Such a device is the Aerocomm RF transceiver that operates at 869.5 – 869.65 MHz. With a sensitivity of -103 dBm a range of 15 km LoS can be achieved (Aerocomm, 2005).

transceiver can be either a server or a client. The servers transmits a beacon every 1.2 seconds which the client recognize, and send an acknowledge signal whereby the link is established. The transceivers can handle many to many download structures without any need for user

Table 7 shows a comparison between RF and GSM protocols. From Table 7 it can be seen that the ease of use of RF is similar to that of GSM as well as most of the specifications, with the advantage of a faster time to establish communication. RF devices have higher power consumption specifications.

**Table 7: Comparison between RF and GSM protocols**

Description	RF	GSM
Easy to use	Yes	Yes
Monthly connection fee and communication cost	No	Yes
Cost	R700	R700
Range	15 km LoS	Areas with cellular coverage
Power Consumption	250 mW	100 mW
Size	49 x 42 x 5 mm	26 x 26 x 6 mm
Temperature	-40°C – 80°C	-40°C – 85°C
Connection time	2 sec	10 sec – 1 minute

## 2.3 Summary

Many different types of location techniques were discussed, with emphasis on two viable techniques, the use of GPS and geolocation calculations. The primary limitation of GPS techniques for marine mammals was shown to be the time taken to obtain a fix, as marine mammals do not always surface for long periods of time. It was shown that these techniques can be used in combination to minimize the time required to obtain a GPS fix.

The second section discussed the viability of GSM and RF protocols, and a table highlighted the main differences and similarities. It was shown that GSM is limited by the time taken to connect to the GSM network, as well as the fact that GSM networks only cover very limited parts of the ocean. RF communication has therefore been selected as preferred technique for this application.

Using the information studied in this chapter, the dissertation will proceed to show how these techniques can be used in the marine mammal environment.

# Chapter 3 Feasibility Study

In this chapter a feasibility study is done to determine how a GPS receiver will perform in an oceanic environment and whether geolocation calculations are a viable option. The first part of the chapter shows methods to increase GPS performance. The second part discusses the implementation of geolocation calculations. Based on these results conclusions will be made about which location system should be used.

## 3.1 GPS location

The performance of the GPS module, which forms part of a tracking unit, in terms of time required to obtain a fix can be improved by optimising GPS parameters. These include the initial parameters of the GPS, and parameters sent to the GPS before each start-up.

The next section discusses the results of a preliminary study that forms part of the technology studies that were conducted as part of this dissertation. Thereafter the available initial parameters and the results of setting changes are discussed, as well as the available start-up values and its influence on the GPS receiver.

### 3.1.1 Preliminary study

The goal of the preliminary study was to see how effective a GPS would be in an oceanic environment. This coincided with a routine trip by researchers to Marion Island. Two GPS loggers were collared to seals and both GPS's were configured to standard settings and set to attempt a GPS reading every 2 hours. Each attempt would last one hour. These configurations meant that the power source of the GPS would only last for a few days.

None of the GPS loggers could obtain a fix during the time they were collared to the seal. The GPS receiver did however manage to lock onto SVs. GPS fixes were obtained while the seals rested on land.

### 3.1.2 GPS initialisation parameters

The GPS have certain set-up parameters than can increase the performance of the receiver in a given geographical environment. If the receiver is moved out of that geographical environment, the performance will decrease (Lassen, 1999). Each set-up parameter and the effect of different settings will be discussed in this section.

#### 3.1.2.1 Type of fix

A GPS fix can either have a 3 dimensional (3-D) or 2 dimensional (2-D) fix, depending on the amount and quality of satellites available. The GPS receiver can be programmed to choose the appropriate position fix for 2-D, 3-D or “Auto” mode:

- In the default “AUTO” mode, the receiver first attempts a 3-D fix while the PDOP value is below both the DOP mask and the DOP switch. If this fails, the receiver attempts a 2-D fix with a DOP less than the DOP mask. Once the receiver has a fix, continuous fixes follows even when there is frequent obscuration. This mode is preferable for most land or air applications, where altitude changes occur frequently and there is occasional obscuration. During auto mode, changes in the PDOP value are done when a switch is made between 3D to 2D.
- In 3-D mode, 4 satellites are necessary with a PDOP value below the DOP mask. This option is used when a high accuracy is required, even when the receiver is obstructed to an extent.
- In 2-D mode, the altitude is either ignored or must be supplied by the user, and three satellites are adequate for a fix. While the 2-D fix will be faster, the drawback is a less accurate fix. The discrepancies result from the fact that in a 2-D fix the GPS assumes that the earth is a perfect ellipse [see section 2.1.4.3].

It is safe to assume that seal’s altitude is at sea level, since the typical tidal range in the open ocean is insignificant.

Table 8 shows the accuracy and TTFF of the different modes.

**Table 8: Difference between 2-D and 3-D fixes**

Mode	TTFF (s)	Accuracy error (m)
3-D	90	6
2-D	31	38

The error in the case of the 2-D fix is much higher than for the 3-D fix, and is also subject to more fluctuations. The error in accuracy can fluctuate from less than 5 meters to 1.5km. Errors larger than 1.5 km were never observed.

Altitude readings in general have large discrepancies. Table 9 shows five consecutive readings of a unit in 2-D mode from the same position, and corresponding altitude readings, each an hour apart. These results were typical for all results, and variations of 30 meters were observed.

**Table 9: Altitude errors in readings**

Time of Fix	Altitude (m)
6:00 PM	1352
7:00 PM	1322
8:00 PM	1341
9:00 PM	1333
10:00 PM	1345

It can be seen from Table 8 that different types of fixes reduce the TTFF, but at the cost of accuracy.

Though a faster TTFF is found in 2D mode, the following tests from section 3.1.2.2 – 3.1.2.5 is done with 3D fixes. There are two reasons:

- for purpose of other devices requiring more accuracy, it is necessary to include tests for 3D readings
- results from 2D or 3D readings would differ in relation to each other depending on other factors.

### 3.1.2.2 SNR mask

The signal to noise ratio (SNR) is a measure of the relation of the power levels of the communication signal and noise on a data line, measured in decibels (dB). Low SNR values

occur when signals are distorted due to reflections in the atmosphere (mainly ionosphere and troposphere) or human made obstacles like buildings. The receiver can track signals with a SNR as low as 0. A SNR value of 3 or higher will decrease the impact of distorted signals.

The trade-off is between acquiring more satellites even with distorted signals, or fewer satellites with clear and more useful signals.

Table 10 shows SNR values with fix times, all with 3D fixes.

**Table 10: GPS location fixes with different SNR mask values**

SNR	TTF (s)	Accuracy error (m)	Satellites ignored (per 10 readings)
0	90	6	0
1	89	4	0
2	93	3	0
3	93	4	0.1
4	90	0	0.2
5	93	9	0.4

Table 10 shows that the impact of higher SNR values is not significant. The likely reason is that the SNR values of four or more satellites are usually above the SNR threshold.

### 3.1.2.3 Elevation mask

The elevation mask refers to angle in relation to the horizon where the receiver must use satellites. A low elevation mask means that more satellites can be acquired by the GPS receiver, which will increase the DOP value. The quality of signals from satellites near the horizon is worse as these signals are subject to greater tropospheric and ionospheric distortion. In addition, low elevation satellites can contribute to frequent constellation switches, since the signals from these satellites are more easily obscured by buildings and terrain. Constellation switches can cause noticeable jumps in the position output. By ignoring satellites at lower angles the inaccurate signals do not influence calculations. An angle of less than 5° is not recommended, while a 10° angle can already have a significant impact on TTF and accuracy (Lassen, 1999).

When seals are on land, an adequate TTFF is allowed even though the GPS receiver may be obstructed in various ways. When seals surface the GPS receiver should be able to view satellites from all angles as there are no obstructions such as buildings, mountains et. The drawback is that since the signals from these satellites are not that accurate, calculating iterations would increase.

Table 11 shows test results of how the GPS receiver performed with different elevation mask angles. The GPS receiver was placed in an area with no nearby obstructions.

**Table 11: GPS location fixes with different elevation mask values**

Elevation mask	TTFF (s)	Accuracy error (m)	Satellites ignored (per 10 readings)
0°	91	9	0
1°	89	1	0
2°	92	8	0
3°	95	7	0
4°	87	1	0
5°	93	1	0
6°	96	0	0.1
7°	93	1	0
8°	86	8	0.1
9°	98	1	0.1
10°	92	1	0.1

Table 11 indicates how ignoring satellites that are close to the horizon would decrease the amount of satellites the receiver can obtain. The impact of the elevation mask does not have a significant impact on the TTFF and accuracy.

A probable reason is that four or more satellites are usually available for acquisition above the elevation mask. Figure 11 shows the availability of satellites over an 18 hour period. Four satellites are available 92% of the time.

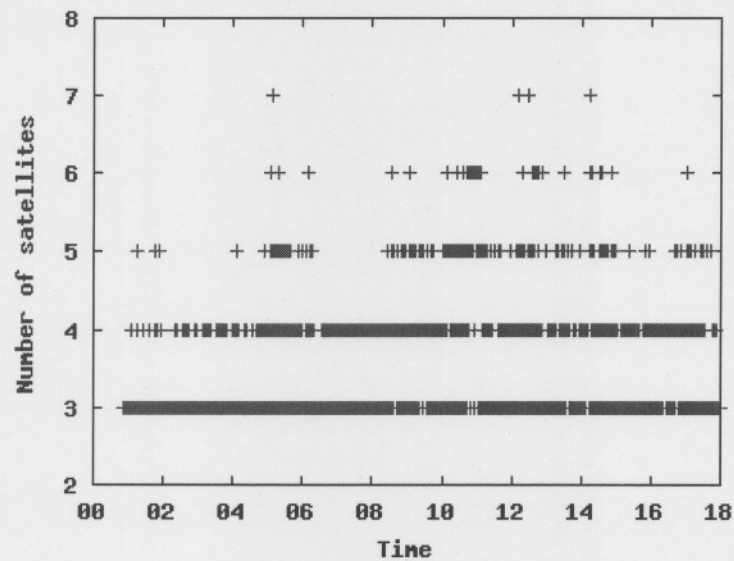


Figure 11: Number of satellites present during an 18 hour period

### 3.1.2.4 Dynamics code

Dynamics Code influences the re-acquisition routing algorithms of the receiver. By knowing the probable speed and altitude changes of the receiver, the GPS can optimised its algorithms to re-acquire satellites if they are temporarily obstructed. If the motion of the receiver is always the same, the dynamics code can be set accordingly to increase performance. The different modes are as follow:

- Land mode – the receiver can be fast moving, similar to a vehicle.
- Sea mode – the receiver is moving either slowly or is stationary.
- Air mode – the receiver can have high variations in speed and altitude.

Seals can only travel up to  $24\text{km}\cdot\text{h}^{-1}$  in water and  $8\text{km}\cdot\text{h}^{-1}$  on land for short periods (SANAP, 2006). These speeds are slow in terms of GPS receivers, and “Sea” mode should have the best results for a stationary receiver. This is verified in Table 12, which shows the TTFF for three GPS receivers each programmed with a different dynamic code. The receivers were placed next to each other and switched on simultaneously. Since the dynamics code concerns re-acquisition times, the receivers were obstructed frequently in the same manner. The experiment was repeated while the GPS receivers were moving at  $80\text{km}\cdot\text{h}^{-1}$ .

**Table 12: Results of different dynamic code settings**

Dynamics Code	TTF (s)	Accuracy error (m)	Speed (km.h <sup>-1</sup> )
Sea	85	6	0
Land	89	5	0
Air	83	6	0
Sea	136	---	80
Land	111	---	80
Air	119	---	80

Table 12 shows that there is not a significant difference in TTF and accuracy of stationary GPS receivers. When the GPS receiver is fast moving, the receiver with the “Sea” mode configuration struggled significantly to obtain a fix. This is because the GPS receiver’s satellite acquisition algorithms are not optimised for fast motion.

### 3.1.2.5 Sensitivity mode

The IQ GPS receiver has two sensitivity modes, the standard sensitivity mode (SSM) and the enhanced sensitivity mode (ESM). The two modes use different pre-detection integration (PDI) and amplitude measurement unit (AMU) settings.

PDI refers to the time that is used to search for any signals in the frequency range. A longer PDI value means that the receiver can detect lower level signals since the search on one frequency is longer. The drawback is that satellite acquisition time is longer.

AMU refers to the minimum signal strength the receiver must use in calculations. If the received signal level is below the AMU mask, the signal will be ignored.

In SSM the AMU mask is set to 2 and the PDI value is 1ms. During ESM the AMU mask is 1.2, and the PDI value switches to 5ms after one complete frequency search.

Table 13 shows how the sensitivity mode affects the GPS receiver.

**Table 13: GPS location fixes with different sensitivity modes**

Environment	Sensitivity mode	TTFF (s)	Accuracy error (m)
Heavily obstructed (70%)	SSM	---	---
Heavily obstructed (70%)	ESM	176	7
Partially obstructed (30%)	SSM	112	4
Partially obstructed (30%)	ESM	125	2
No obstruction	SSM	92	2
No obstruction	ESM	119	2

In ESM the lower AMU mask and longer PDI value will increase the likelihood of a fix in heavily obstructed environments. The more extensive search periods increases the TTFF. ESM mode is therefore a better option in obstructed areas where a fix is crucial.

In a seal's likely environment while at sea, there will be few obstructions. Therefore, the advantages of ESM are insignificant, while the TTFF will most likely be longer. SSM gives the best performance under normal signal conditions, in terms of accuracy and fix times.

### 3.1.3 Refresh GPS

The GPS can receive parameters to obtain faster fixes. This includes current time, current positions and current almanac.

#### 3.1.3.1 Time

Date and time is supplied to the GPS from an external real time clock (RTC). Due to inaccuracies of the RTC, the clock drifts by approximately 1 second per day. This phenomenon can also be seen in other products from YRless International PTY Ltd. The RTC is set to the correct time once it is obtained from the GPS receiver.

Table 14 shows how the TTFF is influenced by the availability of time values.

**Table 14: Influence of time input to GPS**

Time value	TTFF (s)	Accuracy (m)
Accurate Time	49	7
Time – 1 hour	48	6
Time – 2 hours	55	7
Time – 3 hours	73	7
Time – 4 hours	79	7
Time – 5 hours	108	9
Time – 6 hours	107	7
No time value	86	7

Table 14 indicates that time values of less than three hours have a positive influence of the TTFF. Accuracy is not influenced when wrong time values are supplied to GPS receiver. This means that the drift on the RTC is not critical.

### 3.1.3.2 Location

The GPS receiver can have location input of longitude and latitude values. These values are loaded into the GPS receiver by sending a 0x27 packet. Table 15 shows the impact on the TTFF with supplied location data.

**Table 15: Influence of location input to GPS**

Situation	TTFF (s)	Accuracy (m)
Correct location	24	3
Error 100km	32	4
Error 200km	32	0
Error 300km	60	4
Error 400km	76	1
No Location	93	1

Table 15 shows that accurate location data increases the TTFF. Less accurate data up to 300km still has a positive influence on TTFF.

### 3.1.3.3 Almanac

Each region has its own almanac data, which are valid for 300 days. Accurate almanac data decreases TTFF when the almanac is accurate for up to 400km. Beyond that the supplied almanac has a negative effect on the GPS. This implies that if a GPS receiver is covering a distance of greater than 400km, the almanac would not be a reliable method for reducing TTFF.

Due to practical reasons, the impact of wrong Almanac data has not been measured. Wrong or damaged almanac data may seriously harm the GPS receiver. For this application almanac data is not included as a possible input option to increase TTFF. Another reason is that seals travel more than 400km, which means that it is not viable to use almanac data.

## 3.2 Geolocation data

To evaluate the viability of geolocation as a location technique, two consecutive sunrises were measured with a light meter. Figure 12 and Figure 13 shows two separate sunrise measurements. In Figure 12, the Lux measurement are shown as it increased, and in Figure 13 the difference in light during each minute is shown. The time of sunrise was predicted for 6:53 am. Appendix B contains the exact values. In Figure 12 the 16<sup>th</sup> July had a thick cloud cover, while the 17<sup>th</sup> July was a clear morning.

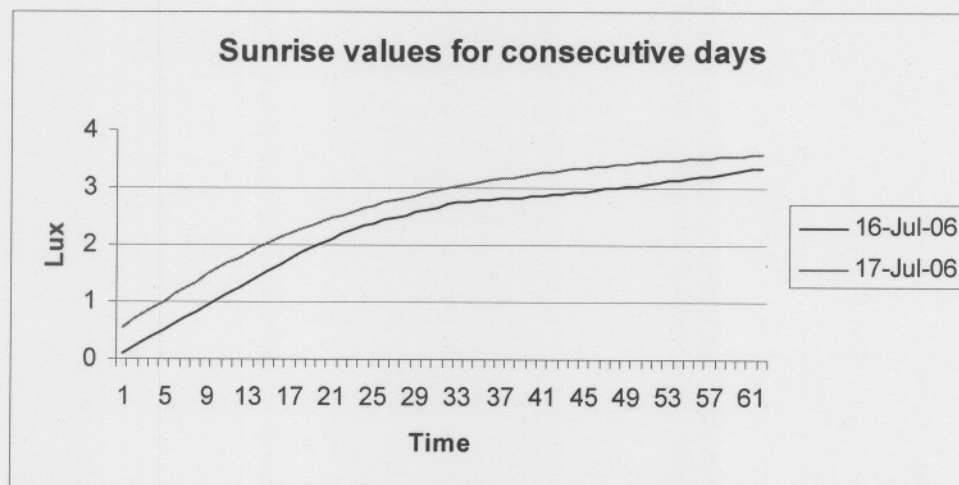


Figure 12: Sunrise values for consecutive days

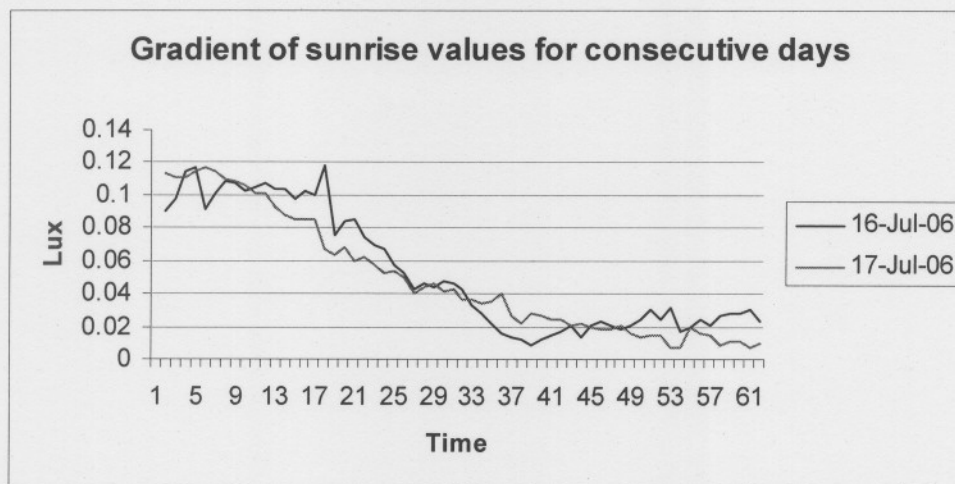


Figure 13: Gradient of sunrise values for consecutive days

The light measurements yielded results similar to the expected theoretical results. However due to the limitations on the scope of the dissertation this method has been abandoned. Several practical reasons contributed to this decision:

- More research and development time will be needed for effective geolocations calculations than are currently available for this dissertation.
- The accuracy of geolocation data is not comparable to GPS readings. More time and effort is therefore spent on achieving accurate GPS readings.

Extra hardware components required will increase the size and cost of the mobile embedded device.

### 3.3 Summary

The feasibility study showed that the GPS receiver is able to detect satellites while the seal is at sea. It is also shown that by optimising the GPS initial parameters, faster TTFF can be achieved. By sacrificing accuracy, 2-D fixes can further increase TTFF.

The GPS receiver TTFF can be increased significantly by optimising initialisation parameters. The initial parameters and the final setting are shown in Table 16.

Parameter	Setting
Type of Fix	2D
SNR Mask	Default
Elevation Mask	5 (Default)
Sensitivity Mode	Off

Geolocation data were collected with a light level meter. The graphical interpretations of two sunrise times during extremely different weather conditions were remarkably similar. However, due to practical limitations of this dissertation the method is abandoned. It is noted that geolocation calculations can be used to assist GPS, as accurate location data reduces GPS TTFF.

# Chapter 4 Conceptual Design

In this chapter the positioning and communication requirements of the marine mammal tracking system are discussed. A conceptual design is proposed with emphasis on the operation, power consumption and cost of the system. Data flow diagrams are supplied for clarity.

## 4.1 Requirements

For the purpose of this thesis the requirements for the marine mammal tracking system are based on the behaviour of seals - in particular the seals of Robin Island. The specifications and operation of existing GPS / GSM and GPS / UHF units are used as design platform for this project. The requirements for positioning and communication will be discussed next in more detail.

### 4.1.1 Location data

Seals make biannual round trips lasting up to 8 months out at sea, sometimes covering up to 7000 km. During this time they visit the packed-ice region of the Antarctic continent or other continents and islands adjoining the southern ocean (SANAP, 2006). Marine mammal researchers want to know where the seals travel and how long they spend on land. While the seals are on land positioning can be done very accurately by means of a GPS fix.

For most parts of their journey the seals are in the water and surface only briefly to breathe. Here the GPS must obtain and store the GPS Satellite Vehicles (GSV) in view, as there is not adequate time for a location fix. This statement is based on the preliminary study done in section 3.1.1 in which the collared GPS were able to acquire GPS satellites but unable to attain fixes while at sea. By analysing the data of where the detected satellites were, the location of the seal can be estimated. This is adequate for behavioural research.

Seals can sleep on land or in the water. When they sleep in water they often assume a posture where their entire bodies remain submerged with just their heads exposed to breathe. If the unit is attached correctly it is possible that GPS fixes can be obtained during this time.

## 4.1.2 Communication

Seals generally return to their place of birth to breed and moult on average about two times per year for a period of between 30 and 40 days (SANAP, 2006). Commencing of this period can be detected when the level switch indicates that the seal has been out of the water for an extended period of time. The transceiver can then be switched on at various times in order to attempt to establish a data link.

While the seal is at its colony base (in this case Marion Island) such a data link should be easy to establish. Therefore it is not necessary for an extensive search of the beacon if it is not detected initially. If the data link could not be established, the unit will attempt to communicate at a later stage.

A stationary RF transceiver needs to be set up at the seal colony on Marion Island. This transceiver should send continuous beacons. When a unit responds to a beacon the stationary transceiver will initialise the download sequence. The data could be stored on a MMC card on the stationary RF transceiver, which can be collect and replaced by the researchers.

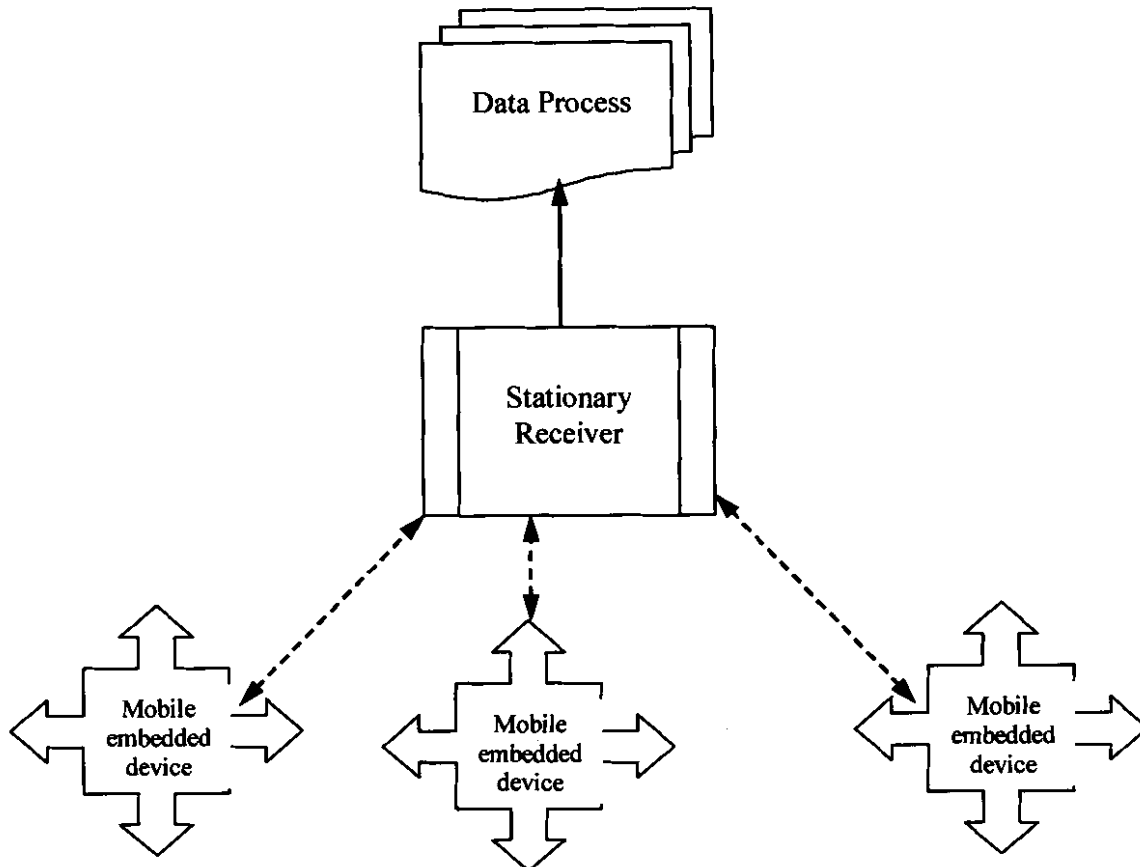
The mortality rate of the seals that is reported to be 3.8% per annum on Marion Island (SANAP, 2006) will have an influence on the performance of the system.

## 4.2 Conceptual Design

The proposed marine mammal tracking system consists of the following three elements:

- Mobile embedded module attached to the seal
- Stationary RF transceiver for uploading the data from the mobile embedded modules.
- Data processing software for converting the data received from mobile embedded modules.

Figure 14 shows a diagram of the proposed concept for the marine mammal tracking system. The mobile embedded module is collared to the seal and stores location data from a GPS receiver. The stationary receiver receives the data once the seal returns to its place of birth to moult and breed. After the data is collected from the stationary receiver, it must be processed for utilization by the researchers.



**Figure 14: Proposed structure diagram of the marine mammal tracking device**

Each of the three elements is discussed separately in sections 4.3, 4.4, 4.5.

### 4.3 Mobile embedded module

The mobile embedded module is collared to the seal. The requirements of the embedded system are discussed next.

#### 4.3.1 Requirements

The embedded device must be able to withstand the harsh elements of the marine mammal environment. This includes high temperature variations and deep dives. These physical requirements are not emphasized in this dissertation, and will be considered during production preparations.

As mentioned, the two main requirements are location fixes and data transfer. The device must be able to show the migration route of the marine mammal. The actual amount of readings is unclear, though a simulation of expected data will be produced in Chapter 5.

Access to the data must be easy for researchers involved. While physical de-collaring of the seal is a possibility to retain data, this technique is intruding and should be avoided if possible. The mobile embedded module must manage power consumption so that the module is able to download the data.

### 4.3.2 Operation

The flow diagram is shown in Figure 15. It is partly based on current GPS / GSM operation, and the unique environment of marine mammal.

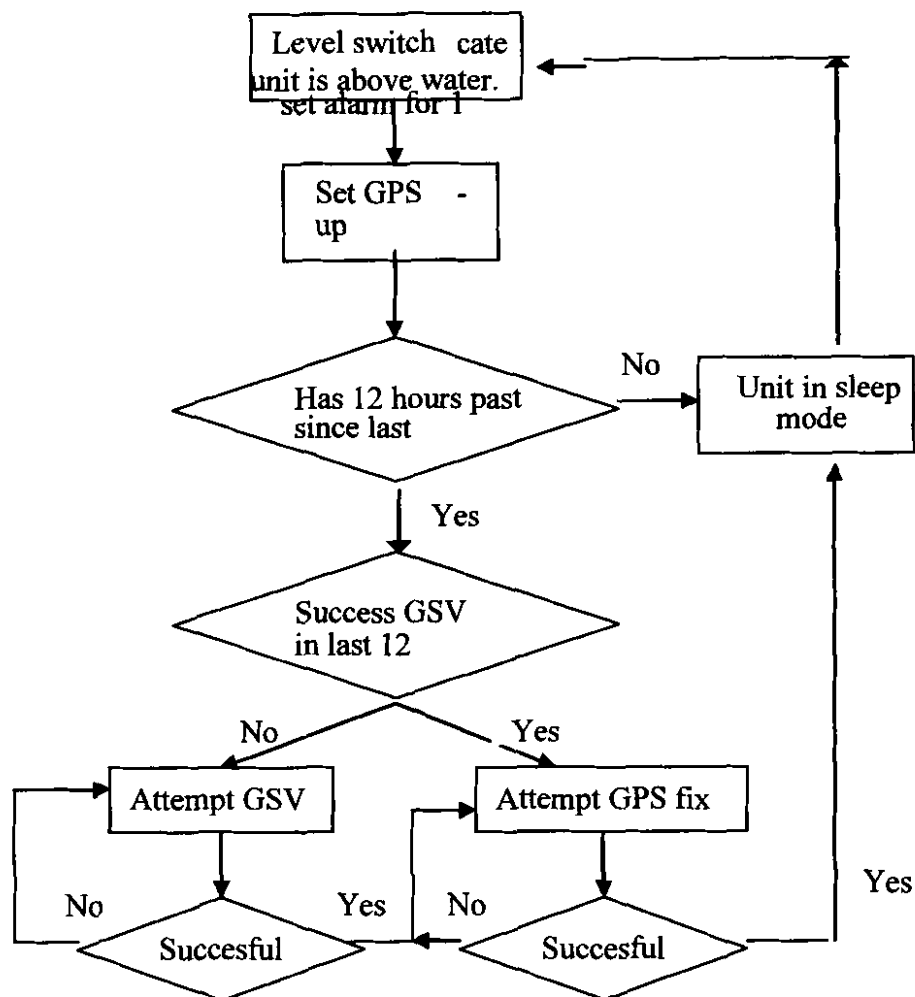


Figure 15: Flow diagram of mobile embedded device

When the level switch detects that the module is above water, the GPS receiver is switched on and start-up values are send to the GPS receiver. The receiver will first attempt to acquire the available SVs. After this the GPS receiver will attempt to obtain a fix for at least 12 hours after a

successful SV detection. This is to ensure that battery life is not wasted on too many readings at a particular time. GPS data as well as time stamps of level switch activity are stored on external memory when the level switch detects that the unit is submerged.

Communication is scheduled to start 1 hour after the unit has been continuously above water. The communication sequence is covered in section 4.3.7

The parameters discussed here are chosen based on seal behaviour but can easily change during initial testing.

Important operational activities are discussed next. These include:

- the detection of the water level for activating the GPS receiver.
- detection of the power level to ensure that enough battery power is available to upload data.
- recording the time at which the unit is above or beneath water.
- recording location data with GPS receiver.
- position storage structures.
- scheduled communication.

### 4.3.3 Detect power level

If the power level drops below a threshold value, future GPS activation must be avoided. This is to reserve adequate battery power to download the data recorded. To determine the correct value of this threshold, the power consumption of the download as well as the rate at which the battery power dissipates near the end of its lifetime must be considered.

Table 17 shows the power consumption and time needed to download readings.

**Table 17: Power consumption needed to download readings**

Readings	Size (KB)	Estimated Download time (s)	Estimated Power Consumption (mAh)
1000	15	96	1.06
2000	30	192	2.13
3000	45	288	3.20

Readings	Size (KB)	Estimated Download time (s)	Estimated Power Consumption (mAh)
4000	60	384	4.27

Figure 16 shows the battery life cycle of the NiCad battery. In this example the unit was obtaining GPS fixes and transmitting data at selected intervals. It can be seen that the battery recovers to an extent when all components are in sleep mode.

Battery life cycle on fixed schedule

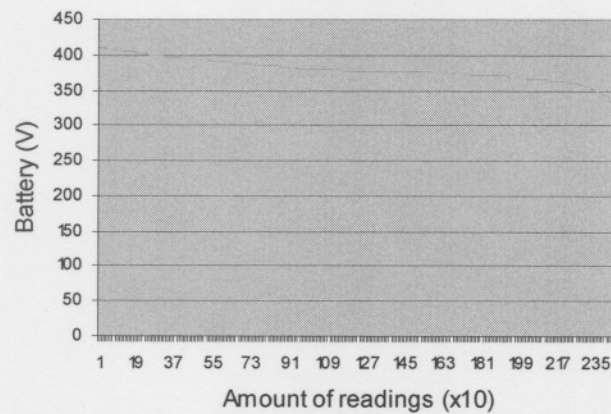


Figure 16: Battery life cycle for NiCad batteries

Table 17 and Figure 16 indicate that when the battery is nearing the end of its life cycle, the power output depreciates dramatically. The download must begin before this happens. In accordance with Figure 15 this dissertation proposes that enough power resources are left to enable the RF module to download 128 KB data, which equals 16000 readings. This will mean that the 4000 readings can be downloaded 4 times before the battery cycle enters a critical state.

To determine the critical stage on Figure 16 at which other activity is stopped to ensure a safe download, a total of 10 000 readings or 80 KB data are used. This is roughly 2 times more data than expected. The estimated power consumption is 10.67 mA and should take about 16 minutes to download. According to Figure 16, battery power falls quickly after 3.5 V. The critical stage 16 minutes above 3.5V is calculated and measured at 3.65 V.

### 4.3.4 Detect water level

A level switch is used to detect when the unit is above water. The detection of this condition will enable the localization process and subsequently the RF module. The detection is done by a simple level switch, which will output a logic high if the device is below the surface, and a logic low if the device is above the water level.

### 4.3.5 GPS

The GPS is switched on when the level switch is triggered. Initialisation commands are sent to the GPS. The GPS receiver will first attempt to detect satellites. On successful detection the GPS receiver will attempt to obtain a fix. When the previous successful fix is more than 24 hours old, the GPS receiver will re-attempt to detect satellites.

#### 4.3.5.1 Satellite detection

Satellite detection is done by sending a "0x47" command to the GPS receiver. The response from the GPS receiver system is less than 2 seconds, after which updates are available every 1 second.

#### 4.3.5.2 Location fix

If the previous GSA satellite command is completed, or recent satellite detection was adequate, an attempt is made by the receiver to obtain a GPS fix. This is done by sending "0x56" command to the GPS receiver.

### 4.3.6 Store position

The information that is stored in the unit consists of:

- time snapshots of each surfaced and submerged time
- GPS satellites
- GPS coordinates

The data is stored on a DT736 external memory chip. Each chip can store 512KB data.

Each of these types of data set starts with a unique signature. The signature defines the interpretation and length of the data set. Table 18, Table 19 and Table 20 show the internal structure of the data sets.

#### 4.3.6.1 Time snapshots

The format of the time stamp when the level switch was triggered is shown in Table 18. The offset is the memory position for the data, shown here in hexadecimal format.

**Table 18: Data structure of time snapshots**

Offset	Description
0x00	Signature
0x01-0x05	Time stamp from RTC

#### 4.3.6.2 GPS satellites

The GPS satellite data is stored according to the format shown in Table 19.

**Table 19: Data structure of GPS SV**

Offset	Description
0x00	Signature
0x01	Number of satellites stored (max 12)
0x02-0x03	Satellite Number
0x04-0x05	Satellite elevation
0x06-0x08	Satellite azimuth
0x09-0x0A	Satellite SNR
0x0B-0x13	Satellite x2
0x14-0x1C	Satellite x3
etc	ect

### 4.3.6.3 GPS coordinates

The GPS position data is stored as shown in Table 20. The compression of the GPS reading is not described in this dissertation. Valid GPS readings consist of a longitude and latitude value, direction, speed, and date and time.

**Table 20: Data structure of GPS reading**

Offset	Description
0x00	Signature
0x01-0x0A	Compressed GPS reading

### 4.3.7 Scheduled communication

The scheduling of data upload depends on various parameters that are chosen based on animal behaviour. Parameters include the time for detection whether the animal is above land, the time span for receiving the stationary beacon and the interval for reattempting communication. These parameters are soft coded so that they can easily be optimised during implementation.

A data flow diagram of the scheduled communication is shown in Figure 17.

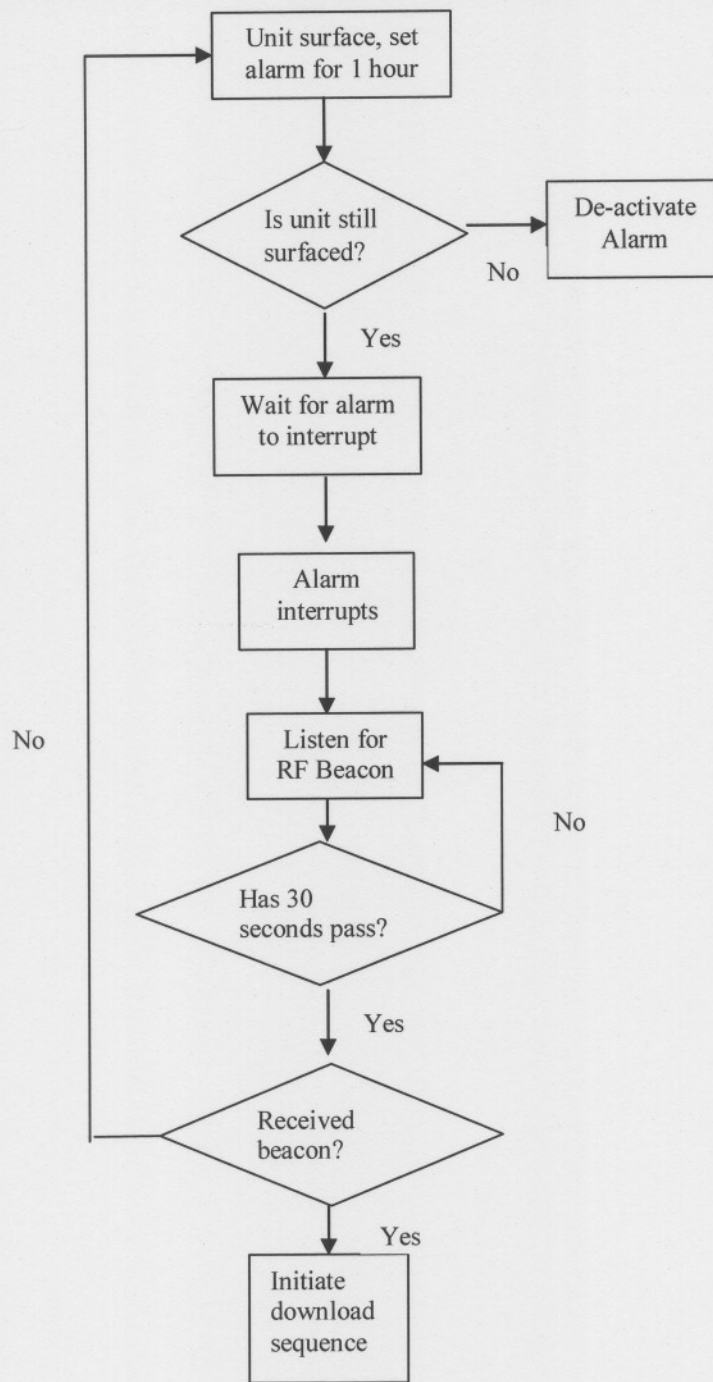


Figure 17: Flow diagram of scheduled communication

#### 4.3.8 BOM – Mobile embedded module

The BOM and cost breakdown for the main components of this module are shown in Table 21:

**Table 21: BOM and cost breakdown of primary components of the mobile embedded module**

Component	Manufacturer	Distributor	Size	Cost (R)
GPS antenna	Trim	GPS Location and Timing		125
RF transceiver	Aerocomm	RF Design	49x42x45	700
18F252	Microchip	Microtronix	19x12x2	35
RF transceiver	Aerocomm	RF Design	49x42x45	700
RTC	Dallas Semiconductor	Microtronix	8x8x1	15
Manufacturing	Microchip	---	---	200
Other components	Microchip	---	---	50
Batteries	Soft Batteries	Uniross Batteries	Height: 24.8 Diameter: 14.65	140

Total cost of the electronic parts of the system is estimated at approximately R 1 965 based on a Rand / Euro exchange rate of R 9,67.

### 4.3.9 Power consumption

The embedded unit is required to last at least 10 months, as this is time the seals are expected to be out at sea. A battery power safety margin must be included in the design to ensure successful data transmission. GPS activities are suspended when battery life drops below a crucial level. This will ensure that a final download is possible.

The power consumption parameters for the three main components are shown in Table 22:

**Table 22: Power consumption of main components during different modes**

Modes	PIC (mA)	GSM (mA)	RF Module (mA)
Full power	10	57	400
Idle	0	0	30
Sleep	0.001	0.008	0.12

**Table 23: Current consumption while the GPS is active**

	PIC (mA)	GSM (mA)	RF Module (mA)
Full Power	10	47	--
Idle Sleep	-- --	-- --	-- 0.12
Total: 0.06712 Ah			

While the unit is searching for a beacon the RF module is in idle mode. During data transmission the module is in full power mode. The power consumption for the RF module is show in Table 24.

**Table 24: Power consumption while the RF module is on**

	PIC (mA)	GSM (mA)	RF Module (mA)
Full Power	10	--	--
Idle	--	--	30
Sleep	--	0.008	--
Total: 0.032 Ah			

The power consumption while the system is in sleep mode is shown in Table 25. During a 24 hour sleep period the total power consumption will be 0.129 mAh.

**Table 25: Power consumption while the components are in sleep mode**

	PIC (mA)	GSM (mA)	RF Module (mA)
Full Power	--	--	--
Idle	--	--	--
Sleep	0.001	0.008	0.12
Total: 0.129 mAh			

NiCad batteries are used since they are well equipped for high frequency current ripple when the GPS receiver and RF modules are switched on. The normal capacity is 13000Ah. Due to size limitations, only 2 AA batteries can be used. The GPS receiver can be left on continuously for three months on one NiCad battery. Since batteries are not always working to capacity, a safety factor of 80% is used in calculations

## **4.4 Stationary RF transceiver**

The stationary RF transceiver consists of an RF module operating at 875 MHz. The purpose of this device is to enable data transfer between the mobile embedded device and the researchers.

### **4.4.1 Requirements**

The stationary receiver must be able to download data from the seals as they rest in their colonies. This implies that the receiver must distinguish between different mobile embedded devices and download each separately. Data range must be at least 1 km, which can be achieved with the Aerocomm 868 MHz RF transceiver. During initial range testing, beacons were detected from a distance of 7 km (LoS). The device must be easy to set up and move to different locations if necessary.

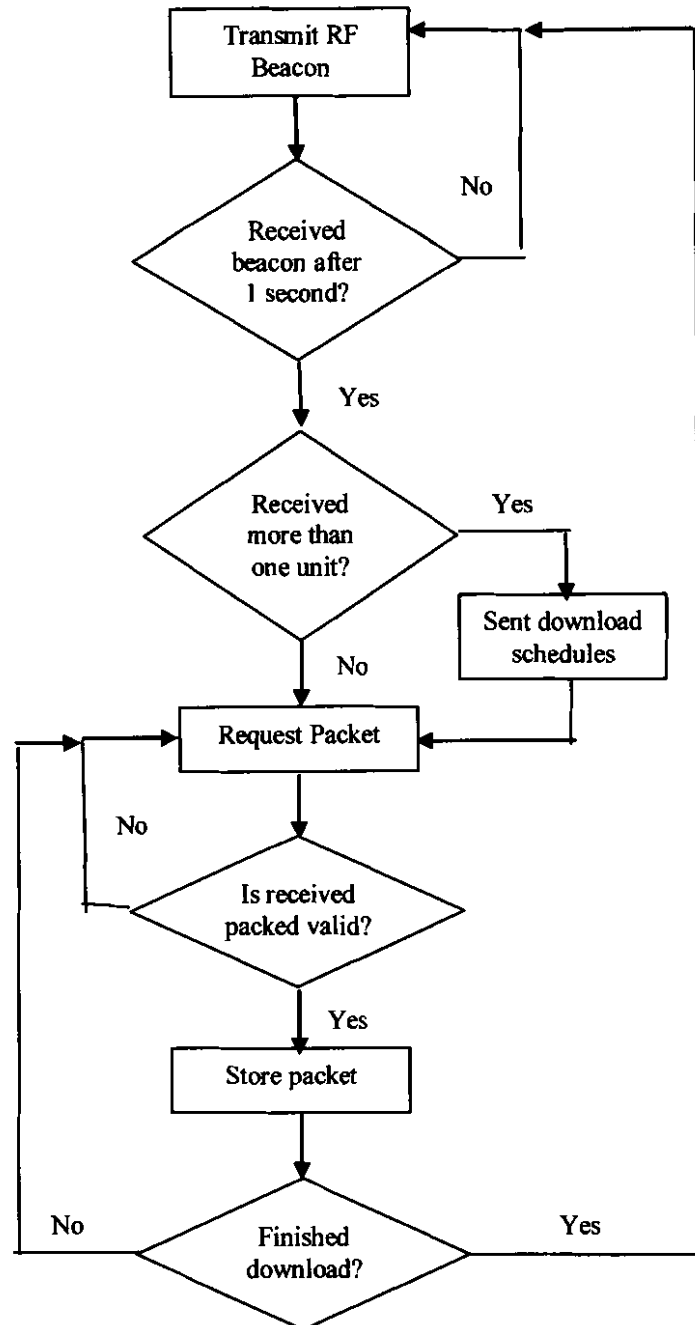
### **4.4.2 Operation**

The remote server must continuously send beacons to search for units. Beacons are data packets that will be recognised by units and that are continuously sent at 1 second intervals. When a unit responds to the beacon, the remote server must initiate downloading. If two or more units respond to the beacon, the remote server must indicate to both units in which sequence downloading will take place. This implies that one unit will go into a wait mode. In wait mode, the unit will be switched on at set intervals to listen if the remote server has finished downloading.

When a connection is established between the server and client, the client sends the amount of data that must be downloaded. This enables the server to keep track of download progress and terminate the connection when download is complete.

During the download sequence, the unit sends data packets of 8 bytes each. This size is recommended in the data sheets (Aerocomm, 2005). The last byte is a CRC value. After each packet is received by the server, a CRC check is done. On successful CRC check an OK response is sent to the unit and the next data packet is transmitted. In case of a CRC failure the server will ask the unit to resend the packet. The unit will keep track where download was successful. If connection fails the server will abort asking for the next data packet and continue sending beacons.

The beacon is a 2 byte value that is sent every second. After the beacon is sent, the server listens for a response. Figure 18 shows a flow diagram of the server.



**Figure 18: Flow diagram for the stationary receiver**

### 4.4.3 Power consumption

To calculate power consumption, Table 24 is used. The power consumption for the stationary receiver is shown in Table 26.

**Table 26: Power consumption of the stationary RF transceiver**

	PIC (mA)	RF Module (mA)
Full Power	10	--
Idle	--	30
Sleep	--	--
Total: 0.032 Ah		
PC for one day: 960 mAh		

#### 4.4.4 BOM – Stationary RF transceiver

The BOM and cost breakdown for the primary components are shown in Table 27.

**Table 27: BOM and cost breakdown of primary components of the stationary RF transceiver**

Component	Manufacturer	Distributor	Size (mm)	Cost (R)
18F252	Microchip	Microtronix	19x12x2	35
RF transceiver	Acrocomm	RF Design	49x42x45	700
RTC	Dallas Semiconductor	Microtronix	8x8x1	15
Memory (MMC card)	Kingston	Bluetek	36.07 x 74.23 x 13.90	140
Manufacturing	Microtronix	---	---	200
Other components	Various	Microtronix	---	50
Batteries (x6)	Saft	Uniross Batteries	Height: 24.8 Diameter: 14.65	140 x 6 = 840

Total cost of the electronic part of the system is estimated at approximately R 1 980 based on a Rand / Euro exchange rate of R 9,67.

## **4.5 Data processing**

After data is downloaded from the mobile unit, the data must be processed. Due to size limitations, this processing is done on a PC. Data processing is necessary for time snapshots, GPS readings and GPS satellite acquisition. These will be discussed here.

### **4.5.1 Time snapshots**

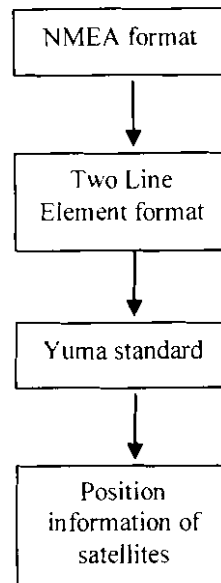
The times at which the level switch was triggered are used to calculate the frequency and time length that the seal surfaced. A list that shows these times is stored in CVS file format, from which researchers can do analysis.

### **4.5.2 GPS readings**

The compressed GPS reading received from the unit is decompressed and presented in a CSV file. The researchers can plot this data in applications such as ARCVIEW, or Yrless Software that uses the Google Earth interface.

### **4.5.3 GPS satellite readings**

The GPS satellite readings from the GPS receiver are in NMEA format [see section 2.1.4.6.1]. Before the satellite location can be plotted on a map, the readings must be converted to TLE format [see section 2.1.4.6.2]. The TLE data is transformed to a standard YUMA format [see section 2.1.4.6.3], from which position can be derived. A flow diagram of the data processing is shown in Figure 19.



**Figure 19: Data processing of satellite detection readings**

## 4.6 Summary

In this chapter, the requirements regarding location data and communication have been outlined. A conceptual design was developed based on these requirements and on the operation of current GPS / GSM and GPS / RF units and on known seal behaviour. The power consumption and BOM for each section of the system was calculated and the method for retrieving location data from the GPS was developed.

The next chapter will describe the performance of the system in simulated conditions.

# Chapter 5 System Performance

This chapter is divided into three parts that each describes how a specific aspect of the system performed during testing. Location data as obtained by altering the set-up parameters of the GPS receiver, and providing initial data at start-up. While the implication of each change was discussed separately in the Chapter 3, the performance resulting from the combined changes is now discussed. Next the performance of the communication protocol is tested. This includes the actual time in which download is completed, system performance when the data link is interrupted and range testing. The last section deals with data processing, and will show the processing of actual GPS readings.

## 5.1 GPS performance

To optimise GPS performance the initial parameters are set and initial data on start-up is re-sent on every separate initialisation. This includes setting the initial parameters as shown in the summary of Chapter 3 in section 3.3, and providing the GPS with a close approximation of the current location time on each start-up. The initial parameters that have a positive influence on the TTFF and which are set to specific values are type of fix, the dynamics code and the sensitivity mode. Other initial parameters are set to default values. The start-up values that are supplied to the GPS receiver include the time and location data.

### 5.1.1 GPS fixes

The primary method of location is GPS fixes. The effect of the combined changes to the initial values during 5 readings is shown in Table 28.

**Table 28: GPS receiver of TTFF with initial parameter settings and setting initial start-up values for 2D readings**

Reading	TTFF (s)	Accuracy error (m)
1	26	4
2	25	15
3	29	115
4	21	11
5	23	12

It should be noted that during testing accuracy errors of up to 1.5km were noticed. Less accurate readings did not have a significant effect on TTFF.

To further analyse the performance of the GPS receiver the likely environment of the seal is simulated. This is achieved by switching the GPS receiver on during short intervals, similar to how the level switch will enable the GPS receiver when the seal surfaces briefly.

Table 29 shows the results of such simulations. In each case the GPS receiver is switched on for a fixed amount of time, which correlates to the possible surface time of the seal. Thereafter the GPS receiver is switched off for a fixed amount of time, which correlates the submerged time of the seal. This sequence was repeated until the GPS receiver acquired a fix.

**Table 29: Simulation results of TTFF of GPS receiver**

Surface time (s) (GPS on)	Submerged time (s) (GPS off)	TTFF (s)	Accuracy error (m)
Always on	0	23	29
2	20	---	---
2	60	---	---
2	120	---	---
5	20	273	19
5	60	498	23
5	120	---	---
10	20	97	18
10	60	340	19
10	120	---	---

A surface time of 2 seconds combined with any length of submerged time do not allow adequate time for the receiver to obtain a fix. During surface times of 5 and 10 seconds a fix was possible after repeated surfacing.

### 5.1.2 Satellite detection

A secondary method of location is achieved by deriving location from the amount and position of satellites. The speed at which satellites are acquired varies. Table 30 shows the average time

necessary for satellite acquisition from 10 readings that were taken days apart. The detection of more than 7 satellites was only possible on 6 occasions.

**Table 30: Number of SV acquired by GPS**

Number of SV	Time (s)
1	9.5
2	13.8
3	21.0
4	29.2
5	33.4
6	41.8
7	49.7
8	56.0
9	68.8
10	88.1
11	109.5
12	143.6

The process of plotting SV location is done in section 5.3. Depending on the number and position of the SVs location can be determined with a certain amount of accuracy. This is done by graphically considering all possible locations from which the GPS receiver could see the SV's.

## 5.2 Communication

The communication link between the mobile embedded device and the stationary RF transceiver is tested. Two important factors are the download range and download time.

The download range is needed to assist the researcher with the placement of the stationary RF transceiver. The download time enables better power consumption calculations.

The RF module used has range specifications of 15 km LoS (Aerocomm, 2005), though a range of only 7 km LoS was achieved during initial testing.

To improve communication range the stationary receiver was elevated to 30 meters above ground level to increase LoS, and the baud rate was set to 4800 bps. Higher baud rates did not significantly influence download time but increased range and percentage of success rate. The mobile embedded device was covered with dental acrylic, a waterproof substance that is currently used for animal collars. This creates a realistic mould for the mobile embedded device, as the molt should have a negative influence on RF signal attenuation. Table 31 shows the range that was achieved, and the success rate of data transfer. Each time the data had to be resent a software counter was set, which was used to determine the data transfer success rate.

**Table 31: Results of range testing**

Range (m)	Success rate (%)
200	96
500	91
1000	84
2000	77
3000	44
4000	35
5000	15
6000	17
7000	14
8000	6

An adequate data transfer rate was achieved at 1 km from the stationary RF transceiver, though this rate fell rapidly after 2 km. The last data transmission was received from a distance of 8023 meters from the stationary RF transceiver.

The download time was tested at a distance of 1000 meters. Conditions similar to those used in range testing were applied. Table 32 shows the results for various amounts of data.

**Table 32: Results of download time testing**

Number of readings	Size (KB)	Actual Download time (s)	Estimated Power Consumption (mAh)
1000	15	115	1.27
2000	30	243	2.7

Number of readings	Size (KB)	Actual Download time (s)	Estimated Power Consumption (mAh)
3000	45	372	4.13
4000	60	518	5.76

A 77% success rate was achieved during the transmission of 4000 readings. Download time is much slower than expected considering the baud rate of 4200bps. The main reason is the acknowledgments that are sent between the server and clients that slow download time.

### 5.3 Data processing

The satellites acquired by the GPS receiver in a single reading are processed as outlined in section 4.5. An example of the data in NMEA format, TLE format and Yuma are shown in Appendix B. The GPS receiver can be viewed on a map as shown in Figure 20. Figure 21 shows the aerial view of the acquired satellites.

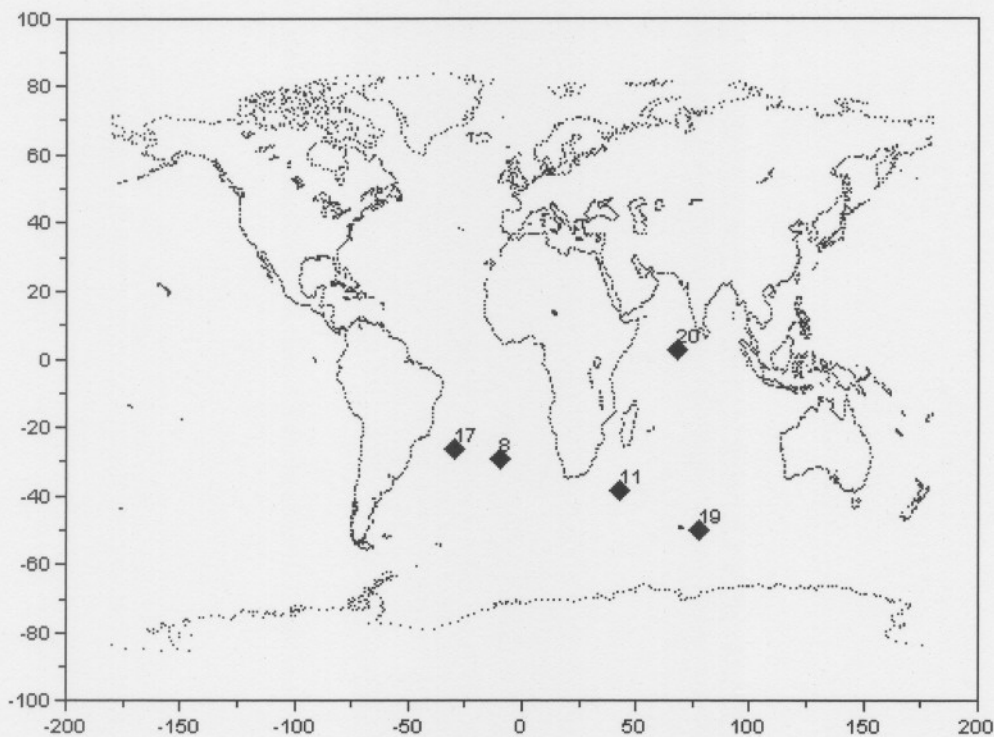
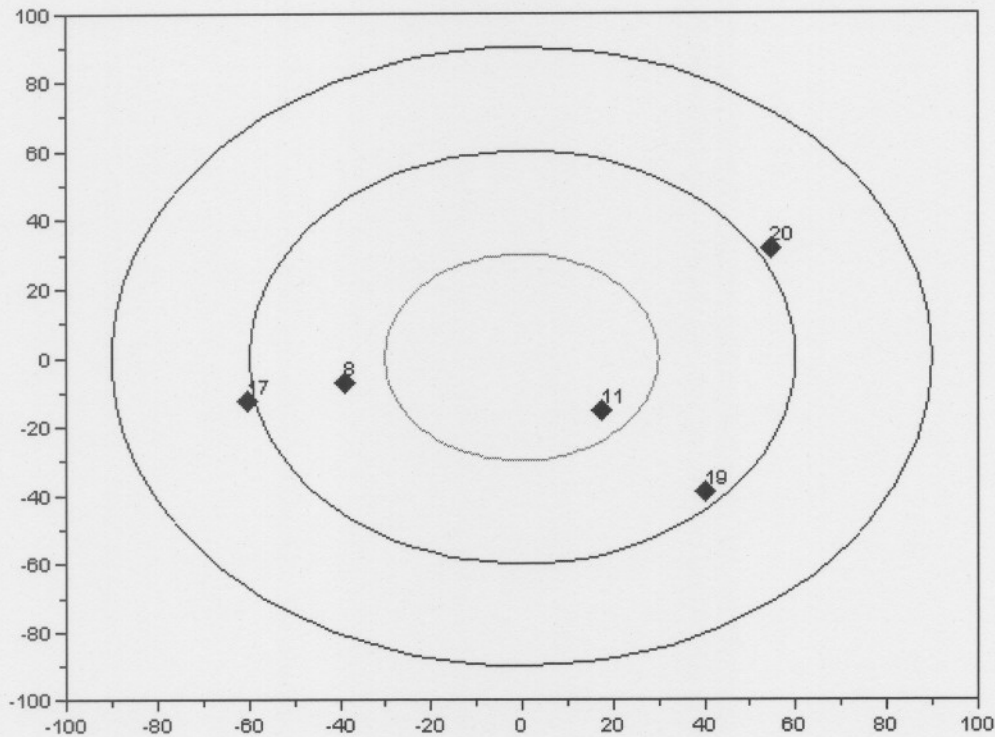


Figure 20: Satellites seen by GPS receiver located in Potchefstroom



**Figure 21: Top view of the acquired satellites**

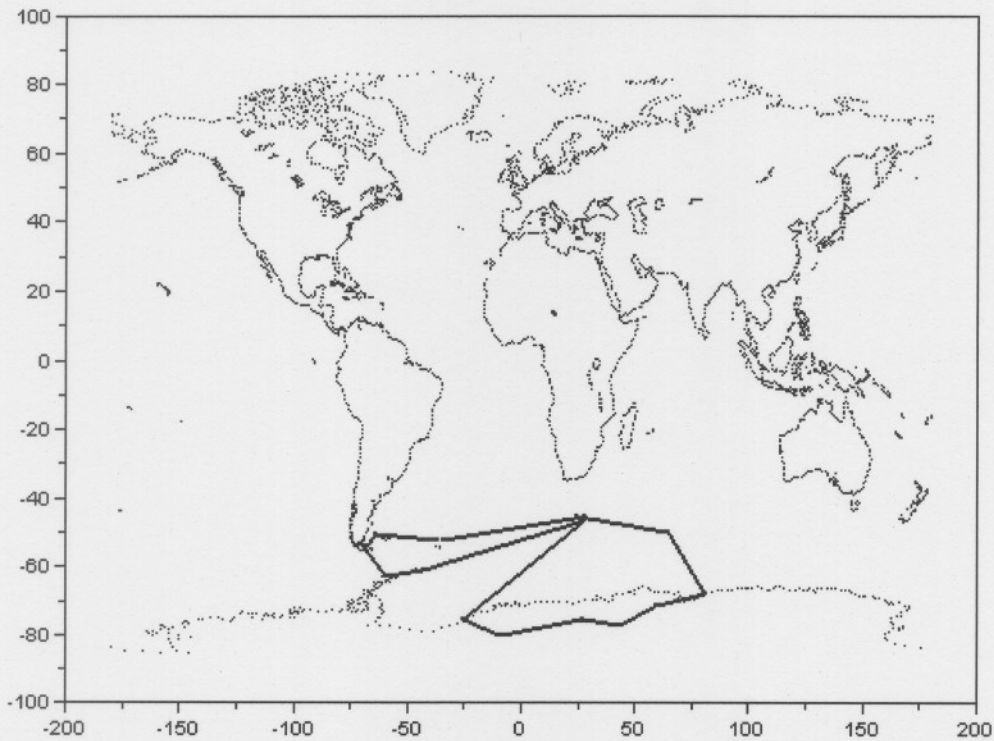
The ellipses are drawn assuming the earth a perfect spherical body and using 6,371,229m as the earth's radius.

The possible location of the GPS receiver can be deduced to within a few 100 km. This error will increase when fewer satellites are acquired.

## 5.4 Simulated results

To simulate the expected outcome of the marine mammal tracking system, the likely migration paths are plotted and the expected data from the system entered. This is the elephant seal's route of Marion Island. These simulations represent a worst case scenario, as more locations fixes are expected while seals are resting at sea. It is shown how data from detected satellites can be used to determine possible location.

The typical migration path of Marion Island elephant seals is shown in Figure 22. It is known that the seals are capable of staying away from Marion Island for up to one year. During this time the seals visit places as far as South America and Antarctica.



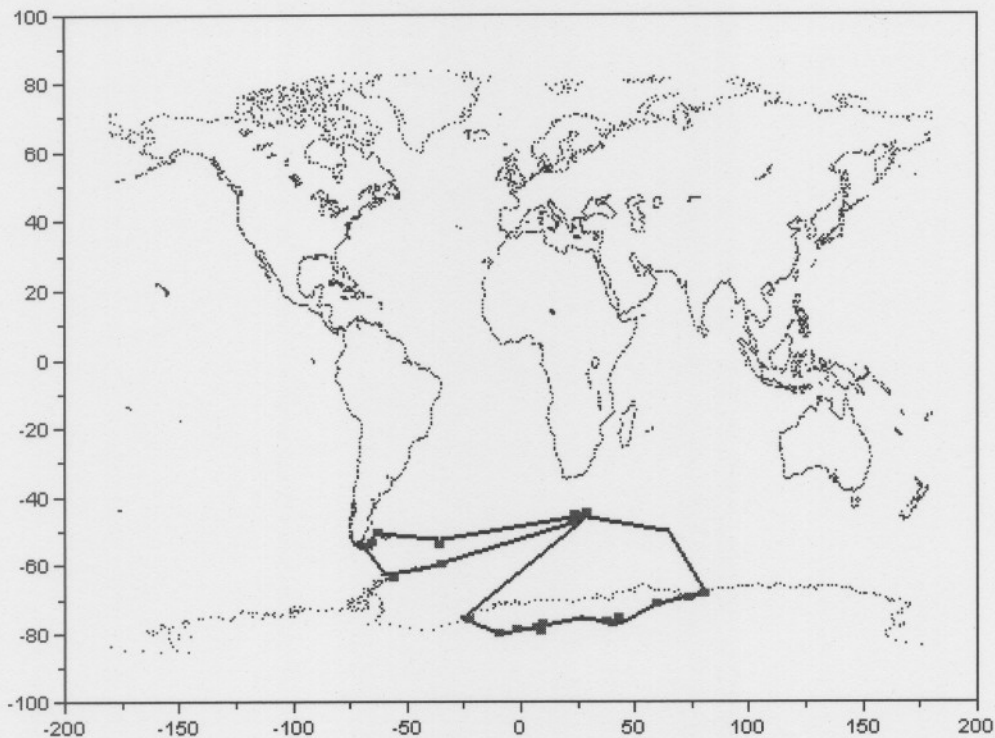
**Figure 22: Two expected migration routes**

In Figure 23, the expected GPS fixes are shown. The following assumptions were made for the probability of these fixes:

- no location fixes are possible while seals are resting at sea, although such fixes would be likely.
- Seals were resting on islands for at least 30 seconds, or a combined time of 30 seconds at which each surface time lasted at least 5 seconds.

These fixes are at locations on land that the seals visit as well as locations on sea. Less location fixes are expected on this route, as the seals do not visit land that often. However, the seals are known to lie on ice floats. More fixes on sea are expected directly after the seals leave land, as the location data entered into the GPS are still accurate.

Although Figure 23 represents a worst case scenario and more location fixes are possible, these fixes are adequate for research purposes. In the past, similar fixes would have been attained at a much higher cost.



**Figure 23: Expected GPS fixes in a worst case scenario**

For the purpose of demonstrating the expected satellite readings, Figure 24 shows the location of GPS satellites that should be seen on this route during one satellite reading while the marine mammal is at sea. X marks the spot of the seal and GPS receiver, and the grey area is the possible location of the seal. This grey area is the intersect of all possible locations, as the ellipses represent possible positions of the GPS receiver when viewing the satellites.

Although the grey area constitutes a large area, the probable location of the seal can be improved by many such readings during consecutive hours and days.

However, there is a problem due to the nature of this route. As seen in Figure 1, GPS satellites do not move over the artic. The further seals move to the South Pole (and similarly the North Pole) the more difficult satellite detection would become.

A discussion of satellite detection results is done in section 6.1.2.2.

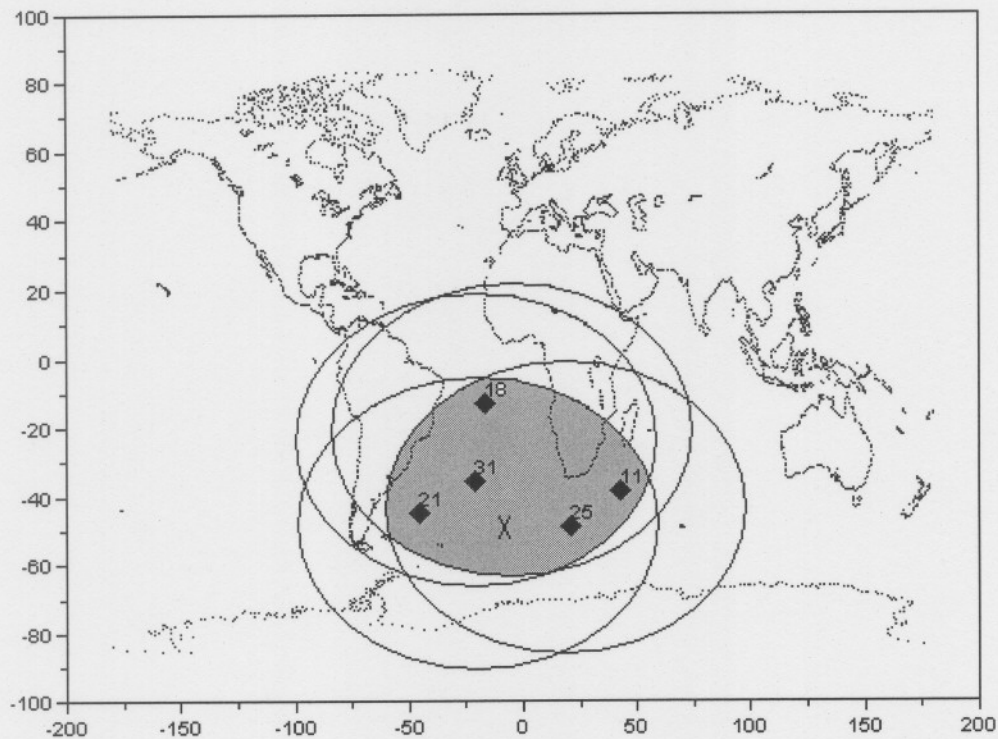


Figure 24: Expected satellite readings

## 5.5 Summary

Three different aspects of the system were analysed in this chapter. The GPS TTFF was minimised by customizing start up parameters and providing the GPS with initial data. Tests were done by simulating the environment of the seal in order to obtain an understanding how a GPS would perform in these conditions.

The communication protocol was thoroughly tested with adequate results. A data transfer success rate of close to 80% was achieved at a range of 1 km.

A satellite view of 7 GPS satellites was achieved in 32 seconds. The processing of this data was demonstrated and plotted with freely available software.

The next chapter will conclude this dissertation by discussing specific important aspects of the study.

# Chapter 6 Conclusions and suggestions

In this chapter final conclusions are drawn and suggestions are made for future work and improvements to the system.

## 6.1 Final conclusions

The results of the study are assessed against the criteria of the original problem statement. The successes achieved, problems encountered and contingency resolutions are discussed in this section under corresponding headings.

### 6.1.1 Conceptual design

The functionality of the prototype tracking unit complied with the target requirements determined for the conceptual design. As the conceptual design is partly based on software routines and hardware interactions that have been used in existing products, no serious flaws were experienced.

### 6.1.2 Location data

The key requirements for the marine mammal tracking system are derived from the general behaviour observed for marine mammals, and include the fact that such mammals

- return to the same location each year and
- surface periodically for periods of over 10 seconds on average.

Mammals that rest on islands are more likely to obtain GPS fixes.

Two methods of location data were researched: geolocation calculations and using a GPS device.

#### 6.1.2.1 Geolocation calculations

Geolocation measurements were taken with a light meter. A graphical representation of the data correlated to expected theoretical results. The method was abandoned due to practical reasons concerning the time limit of this study and the amount of research necessary for effective usage.

An added benefit of geolocation calculations is the combination of this technique with GPS. GPS TTFF improves if accurate simulated location data is supplied [see Table 15]. The accuracy of geolocation calculations can be approximately 100km, which can be used to decrease TTFF.

### **6.1.2.2 GPS**

The success of using GPS in the marine mammal's tracking environment depends on the amount of time that the GPS has available for acquiring relevant location information. This includes the detection of SV's and GPS location as calculated by the GPS receiver. In this project the GPS was optimised by testing the effect of a number of initial parameters relevant to the environment of the GPS. Additional testing involved assisting the GPS with location and time information to increase TTFF.

Results obtained from these tests have proven to be valuable for other applications as well and will be deployed in software on all other and future GPS devices.

A GPS device can detect a satellite's presence in 9.5 seconds on average, though faster and slower acquisitions have been observed. By acquiring multiple satellite positions at various times during the day the accuracy of the calculated probable location of the unit can be significantly improved.

A GPS fix can be attained in 23 seconds on average. Tests have also been done to show GPS performance when the receiver is submerged for various durations. These tests need to be compared with the likely surfacing habits of the marine mammal in question when recommending this tracking system.

Calculating the probable location from satellite detection is not as accurate as expected, and the migration path of the satellite cannot be deduced from satellite detection readings alone. This is because:

- the detection area is extremely large
- satellites do not move over the pole regions.

Methods to improve this location technique are suggested in section 6.2.1.2.

The manner of collaring the mammal is crucial to the performance of the system. The GPS antenna should be placed to allow for maximum exposure to possible LoS when the mammal

surfaces. An example of where this becomes important is with mammals such as seals that keep part of bodies emerged while sleeping in the sea in order to breath. This will obviously differ between species and careful consideration should be taken in this regard.

### **6.1.3 Communication**

Two methods of communication protocol were researched: GSM and RF devices.

In Chapter 2 GSM based tracking was investigated. The method was abandoned mainly for two reasons:

- Marine mammals do not surface for extended continuous periods to allow a GSM device to register on the GSM network since GSM signals do not penetrate water.
- Marine mammals generally do not stay in GSM coverage areas, which imply that the unit cannot be used as a generic device.

The decision to use RF communication is based on:

- Most marine mammals have a habit of returning to a specific place each year or every other year during their lifetime, meaning that the principle of using a stationary RF download station is viable.
- The receiver RF module can be moved if necessary.
- RF range is in excess of 1 km, which covers the width of most marine mammal colonies such as seals, sealions and penguins.
- RF devices are small and cost effective, as it requires no monthly subscription compared to satellite and GSM communication.

The use of the RF protocol delivered adequate results for data transfer from a distance of less than 1 km. The data transfer speed is on average 133 bytes per second. Slower transfer speeds increases the success rate of data transfer.

### **6.1.4 Data processing**

The data processing is done to convert the GPS satellite acquisitions to an understandable GUI interface. This process involves that the NMEA data format is changed to TLE format, which is changed to a standard Yuma almanac format. Many freely available software programs can calculate the location of the satellites.

By viewing the SVs that the unit was able to see, a rough estimation can be made of the possible location of the unit. By taking several such readings at regular intervals the accuracy of this method can be improved as discussed in the previous section. For this purpose it is necessary to know the location of satellites at various times. This information can be downloaded from an active GPS or downloaded from the Internet.

## **6.2 Suggested future work**

Some recommendations for improvements as well as alternative methods for the different design aspects of this project are proposed in this section.

### **6.2.1 Location data**

Other forms of tracking methods such as pop-up tags, Low frequency RF devices and hydrophones are costly, too large or do not cover a large area. In comparison GPS receivers are small and inexpensive and offer world wide coverage. Geolocation calculations could also be considered as a cost effective solution.

#### **6.2.1.1 Geolocation calculations**

The use of geolocation calculations to determine position is an extensive subject worth exploring. It involves the measurement of ambient light and requires a sensitive light meter. Challenges include determining the exact time of sunrises and sunsets especially during dive times and cloudy days. Minimising the cost of a sensitive light meter is also important. Successful geolocation data can be used as primary tracking method, or as a secondary method to assist GPS receivers to increase TTFF.

#### **6.2.1.2 GPS**

GPS advancements are made regularly and it will be worthwhile to attempt similar tests on different GPS modules from other manufacturers. Continued tests should be done to further reduce TTFF.

Two possible methods can be done to increase probable location of satellites:

- increasing the elevation mask can decrease the total area of satellite detection (see section 3.1.2.3). This will however, decrease the possibility of a GPS location fix.
- by decoding satellite information, the possible location of the GPS receiver can be reverse engineered. Further investigation will be done.

These changes will provide a reliable indication of the actual migration path.

## **6.2.2 Communication**

The actual data transfer speed achieved is relatively slow and compares badly to the physical baud rate of 4800 bps of the RF module. This is due to the delay in the acknowledgements that are sent to indicate the status of data transfers.

Both the range and data transfer time can be improved by optimising the placement and length of the RF antenna. Another option is to elevate the stationary receiver to improve LoS. The software routines that manage the data transfer could also be further optimised. A trade-off exists between the data packet length and success rate of data transfer. This relationship requires further exploration.

## **6.2.3 Data processing**

The different phases of data processing are currently performed through the use of different software algorithms. These could easily be merged into one software package. To increase functionality a software algorithm can be included to calculate approximate position based on current and previous readings. For this purpose the available DOP value should be used. Such algorithms can also be implemented on the embedded unit to improve the accuracy of the estimated location data that is supplied to the GPS.

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