Alternate Navigation Plan Using Terrestrial Beacons

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Abstract

Electronic Navigation has become a fundamental part of the maritime community, which accounts for 90% of the world's trade. However, the United States' reliance upon the Global Positioning System (GPS) for navigation can be exploited accidentally or intentionally [2]. This project proposes integrating DGPS ranges to augment eLORAN. Previous studies on DPGS field strength conducted by a team at USCGA EE section and mathematical models developed by Nicholas DeMinco established the basis for the signal power experiments [5, 10]. These experiments did not found the DGPS signal to be above the noise floor range. Using the Minimum Shift Keying nature of DGPS, the project developed two separate algorithms, phase difference and ordered phase pairs, to convert the measured phase into a range from the beacon. Because system relies on accurate timing at the DGPS beacons, the project was unable to test the algorithms on a receiver but the two required phase discrimination of .01μradians or 1 mradian were calculated. With further testing done on phase discrimination capabilities, this system could be used to dramatically decrease the Geometric Dilution of Position for users of eLORAN and provide mariners with a navigation system that uses all available signals for safe navigation.

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Introduction

Electronic Navigation has become the primary method of navigation for the maritime community, which accounts for 90% of the world's trade [1]. In particular, the United States relies upon the Global Positioning System (GPS) for commercial shipping, the US Navy, and the US Coast Guard. Unfortunately, the nature of GPS allows it to be exploited accidentally or intentionally at very low cost [2]. This came to light during the GPS blackout event in California which shut down Coast Guard operations for the several hours, allowing several high interest vessels to arrive unescorted into a major US port [3]. Research conducted by USCGA Electrical and Computer Engineering Section (ECES) has shown that re-creating a GPS blackout event is technologically simple, inexpensive, and very difficult to anticipate. [3] Therefore, the USCGA ECES is sponsoring research into alternative electronic navigation methods that are less vulnerable to the same type of jamming as GPS according to the business case in Appendix A. In particular, USCGA ECES desires to design a terrestrial navigation scheme that uses eLORAN receivers already in place coupled with DGPS beacon ranges that will provide GPS equivalent accuracy with regard to position.

Before describing DGPS ranging, this paper discusses the previous electronic navigation schemes whose algorithms were considered in the implementation of DGPS ranging. This includes an overview of the past OMEGA system, the original LORAN system, the current eLORAN system and the current GPS and DGPS systems. The paper describes how GPS solves the problem of achieving accurate timing and why it is vulnerable to jamming. It then outlines

the history of the DGPS ranging project and the experimental requirements that have yet to be addressed.

With a basic understanding of the electronic navigation field and the role of DGPS in mind, the paper then outlines the specific objectives that this project team sought to accomplish in the 2007-2008 academic year. These objectives include the data gathering and mathematical proof of concept sections of the project as outlined in the project management plan in Appendix B. The data gathering section discusses the need to discover both the field strength skywave interference properties and the required phase resolution of the receivers as a function of distance, time, and weather. The mathematical proof of concept involves the development of the algorithms to convert the received phase into a range from the DGPS beacon.

Like the objectives of the project, the system design includes the test plan for the analysis of skywave interference on DGPS beacon transmissions and the mathematical algorithms for converting phase measurements to range. The results of the skywave interference experiment will set an error limit on the software that will eliminate skywave multipath error. This clarification of signal coverage zones and phase resolution is the basis for the software algorithm that makes use of the DGPS signal to achieve ranges. It is possible that similar algorithms could be applied to utilize many signals for Lines of Position (LOPs) based on a quasi Time of Arrival (TOA) method.

According to the article entitled "Beacon/Loran Integrated Navigation Concept: A Proposal for an Integrated 100/300 kHz Ranging System", there are several possibilities for accomplishing the signal processing from terrestrial beacons in the same way that GPS performs TOA analysis [4]. There is currently a project team involving the USCGA ECE Section developing the

software techniques for correlating of the signals and integrating eLORAN, Differential GPS (DGPS) beacons, and other signals of opportunity, such as satellite television and radio, into a single solution. In the case of DGPS signals however, there is a unique solution due to the minimum shift keying (MSK) nature of the signal.

This system's design was tested and the results for the field strength study and the two mathematical models of phase differential and ordered pairs were analyzed for their adherence to the requirements. It was found that the DGPS beacon signal strength is sufficient out past 150 km of the transmitter. The testing of phase resolution was unable to occur because of a combination of time, equipment, and facility constraints but the mathematical models proved that the accuracy of the range solution depends on the phase discrimination of the receiver or the modulation index at the transmitter which can both be adjusted.

Background

OMEGA and eLORAN

Electronic Navigation has a short (less than 75 years) but varied history that includes OMEGA, eLORAN, GPS, and DGPS. OMEGA was the first global electronic navigation system and was based on Time Difference of Arrival (TDOA) [6]. Because this system depended on skywaves for propagation combined with poorly estimated ionosphere models, OMEGA's accuracy was poor, on the order of 2-4 km [1]. In addition, OMEGA required the user to input the vessel's estimated longitudinal position into a "lane" because the decoding of the signal relied on the phase of the received periodic signal which cannot exceed 2π since a receiver cannot tell the difference between $2\pi - n$ and $2\pi k - n$ where k is an integer number of wavelengths and n is the phase of the signal [6]. Despite all these setbacks, everyone was sure that OMEGA would be the navigation method of choice for the 21st century. However, OMEGA was discontinued in 1997 because GPS had become the standard method of navigation and eLORAN proved itself a more accurate back-up than OMEGA [6].

The figure below displays the hyperbolic lines of position and the lane ambiguity that occur when any electronic navigation system measures phase as a means of determining position. OMEGA was fortunate enough to have a wavelength of ~ 30km which allowed the user to generally select the correct position if they had an estimated position. The projects ranging method reverted back to using OMEGA's method of converting phase because it was not the lane ambiguity that caused the error in OMEGA but the improper skywave modeling and

dependence on modeling. The DGPS ranging method plans to use only groundwave to avoid the errors learned in OMEGA.

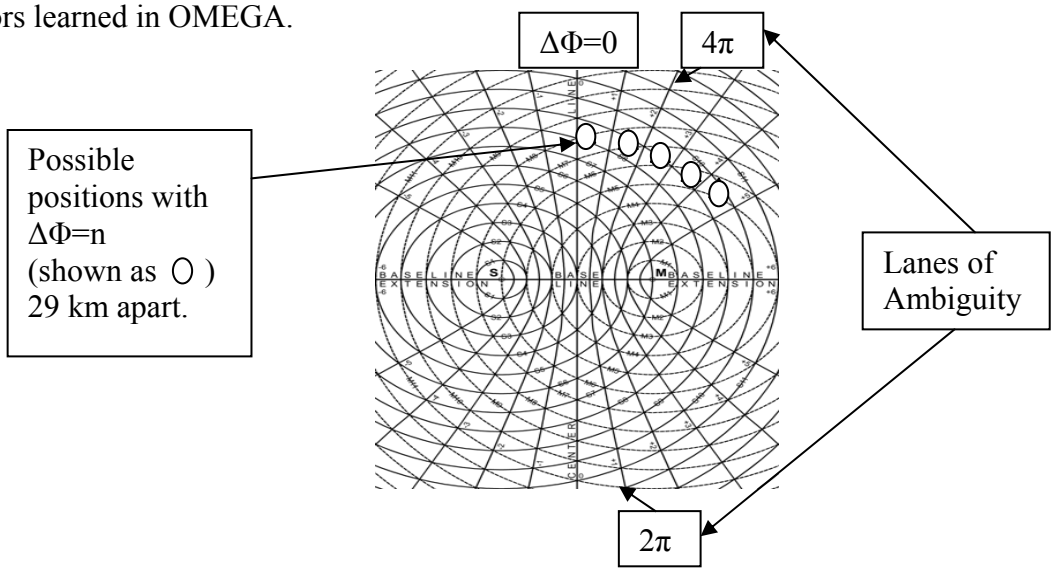


Figure 1: Hyperbolic lines of position and lane ambiguity [14].

Early LORAN systems also used TDOA lines that resulted in extremely poor accuracy and high Geometric Dilution of Precision (GDOP). GDOP is error introduced much like taking two visual lines of bearing from two objects within a small angle of each other. The figure below displays how the lines intersect at more point and therefore the ambiguity of position increases when the two objects are close together and decreases when they are spread apart.

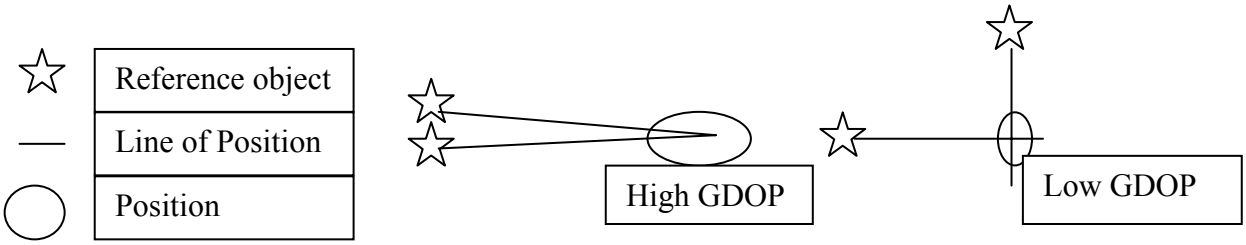


Figure 2: Comparing GDOP error to visual fixes

Modernization of the LORAN system has produced the current eLORAN system, which functions as an adequate back-up to GPS and DGPS systems [6]. However, there is still notable geometric distortion for eLORAN users, especially in Southern Florida and Southern California.

Although eLORAN has an official accuracy much less than GPS on the order of .25 NM it actually attains accuracies close to 10m with differential corrections [6, 11]. At present, Congress is revising the Federal Radionavigation Plan (FRP) which will publish the increased accuracy for eLORAN and establish it as the official back-up electronic navigation system for the US [11]. At the projects conception, the Coast Guard planed for eLORAN to operate for 2 more years [8]. Initially the project assumed that this would be the case and will continue with the support of the new FRP.

GPS and DGPS

The most widely used form of electronic navigation today is the GPS Time of Arrival (TOA) system. GPS requires the signals from 3 or more satellites to solve for position and time. This method eliminates the need for an accurate clock at the receiver if all the satellite clocks are synchronized [6]. The GPS satellites require expensive cesium oscillators, $40K apiece, but the simultaneous equation solution allows the receivers to be relatively inexpensive. The problems with GPS are that it has a short wavelength and low power of transmission. The short wavelength, 5 meters for the L1 band, allows jammers to be built with concealable antennas and the low transmission power allows a jamming signal to easily confuse the receiver.

For years the US government deliberately induced error in the timing signal, called selective availability, into GPS signals to protect accurate positioning as a military asset [6]. President Clinton ordered the military to suspend the use of selective availability but reserved the right to reinstitute it in a time of crisis [6]. Recently, President Bush passed a law that continues the trend by ordering the next generation of satellites to not include selective availability [9]. These decisions have increased the civilian GPS stated accuracy for coastal ship navigation to 2-

5 m [6]. To increase the accuracy of a fix further, an addition to the GPS system was created known as DGPS.

DGPS is a system of land-based transmission beacons with overlapping coverage areas for the coastal US. DGPS beacons increase GPS accuracy to 1-3 m by transmitting the corrections for each satellite that it calculates. These corrections are generated by comparing its known position to its GPS computed position [6]. DGPS sites also send error messages to all available receivers if satellites have passed a threshold of inaccuracy and are no longer viable as sources of information. The DGPS correction signal itself has a wavelength much longer than GPS and, because the beacons are terrestrial, transmits at a much higher power. These two properties are complementary to the two vulnerabilities of GPS which is why DGPS was chosen for the new navigation system. Table 1 below outlines the physical properties of the GPS and DGPS signal as well as reminding that DGPS currently provides meaningless data apart from GPS.

Table 1: Comparison of GPS and DGPS

	GPS	DGPS
Frequency	1.575mHz	300kHz
Wavelength	19 cm	1 km
Signal Strength	50 W	1000 W
Purpose:	Primary Navigation	Corrections only

Source for Project

A navigation method similar to the one proposed in this paper was developed in 1995 by CAPT Hartnett and CAPT Peterson, instructors in the US Coast Guard Academy Electrical Engineering Section, to replace OMEGA for the Navy's nuclear powered cruise under the polar

ice caps. The theory of minimum shift keying (MSK) recovery of phase and timing along with developed systems for signals of opportunity was applied to the problem and, although the specific results are classified, it was a success. [4] For future work, the authors proposed using 2 phase-locked loops, a feed-forward method, or a digital rendition combined with integer second transmissions from the DGPS site to determine the TOA from a DGPS station [4]. This paper's premise is what inspired the USCGA ECE section to research the current system involving TOA ranges from DGPS, eLORAN, and other signals of opportunity [4].

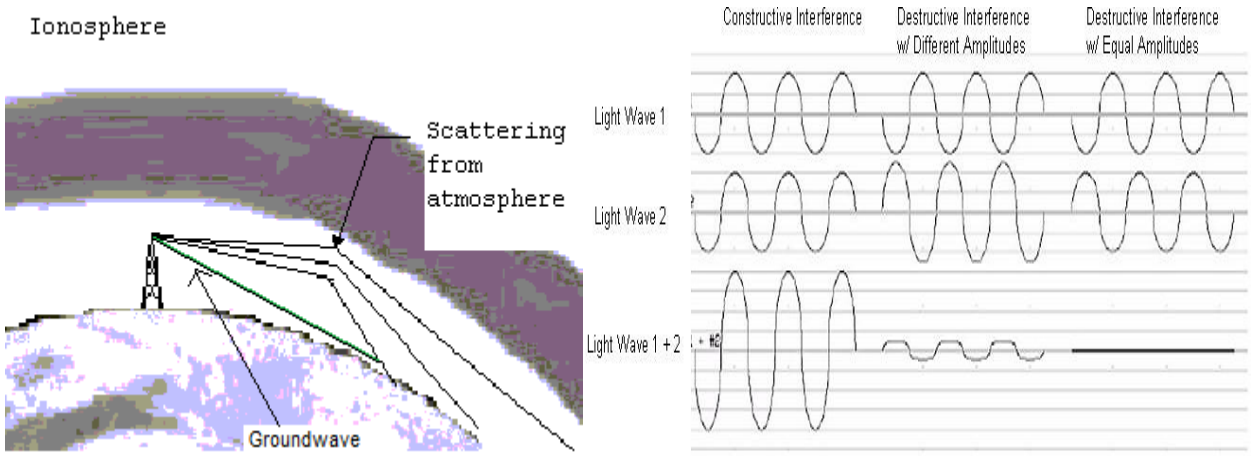
Propagation Range and Zones of Coverage

For implementation of the alternate navigation system, the propagation of the DGPS beacon signal must be verified by experimental data. DGPS beacons transmit in the Medium Frequency (MF) band from 280-325 kHz [6]. While higher frequencies such as GPS propagate primarily by skywave, Medium and Low frequencies propagate mostly by groundwave but may receive interference from the skywave at night [5]. Because the MF band relies mostly on groundwave propagation, its signal range is decreased when absorbed by earth but is increased over seawater. This is because seawater has effectively less "drag" on the signal and this project sought to quantify this effect if possible but it was not a requirement.

As the distance from the transmitter is increased and the groundwave attenuates, the skywave eventually dominates, constructively and destructively interfering with the desired DGPS beacon groundwave as shown in figure 3 [5]. In order to have an effective ranging solution, these zones of interference must be quantified.

Figure 3.1 shows the macro principles of skywave bounce off the ionosphere which allow propagation beyond line of sight but also interfere if the angle of return is steep enough. Figure

3.2 shows the sinusoidal summation that occurs at a receiver that is receiving both skywave and groundwave that are out of phase because they have traveled different distances. In the left case, the signals constructively interfere, causing an increase in field strength. In the middle case the signals interfere but one is stronger than the other so some signal still comes through but the user cannot identify if it is skywave or groundwave. In the right case there is a total attenuation of the signal because the skywave and groundwave have equal amplitude. For DGPS it is not necessary for the skywave to cancel out the groundwave completely, it is only necessary to interfere enough as shown in the middle case to put the field strength below the ambient noise floor which will prevent the receiver from locking onto the signal.



Figures 3.1 (left) and 3.2 (right): Skywave and groundwave interference [12-13].

MSK nature of GPS

The reason that a single range can be attained from a DGPS lies in the nature of the signal. DGPS transmits information with a Minimum Shift Keying (MSK) method which is nothing more than an optimized frequency shift keying method where there is a frequency assigned to a binary ‘1’ and another frequency assigned to a binary ‘0’. These frequencies are so

close together, however, that the average of the two presents the center frequency that the receiver locks onto when attempting to demodulate.

Figure 4 below show the averaged lobes of a DGPS MSK signal with the two band pass filters that a receiver would use to determine which bit of information (1 or 0) the transmission is. In the figure, the dotted black line represents the actual MSK signal and the solid lines represent the band pass filter that the receiver applies to the incoming signal, whichever filtering result is higher is the data bit that is demodulated. The instantaneous MSK signal offsets the dotted line to the left and right depending on the data bit that is being transmitted at the particular moment in time.

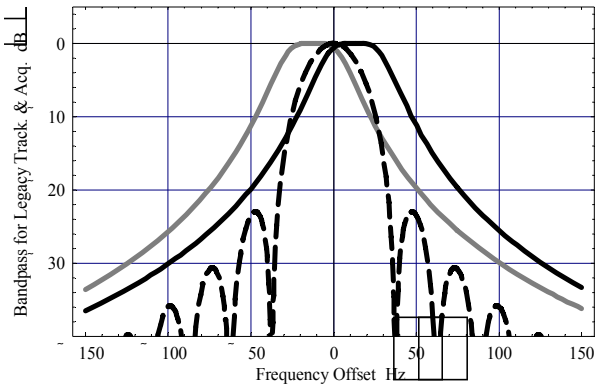


Figure 4: DGPS MSK center frequency searched by two band pass filters [16]

In the time domain, the transmission of MSK 0's and 1's looks like figure 5 below. Figure 5 includes two pure sinusoids with an exaggerated phase difference to display how DGPS MSK bits propagate differently in the time domain. The two phases allows a single DGPS beacon to solve for the range by either translating a unique phase pair or the phase difference.

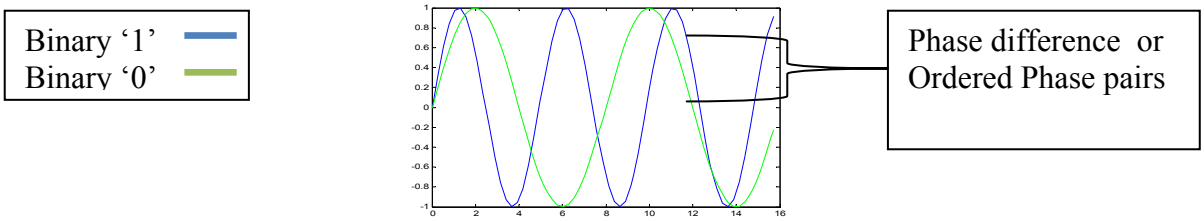


Figure 5: Time Domain MSK binary sinusoids

Objectives

The goal of this project is to design a system for the implementation of DGPS ranging as part of an electronic navigation system as outlined in the project requirements document in Appendix C. The feasibility of the project is based on the study of skywave interference and phase resolution requirements. This will be accomplished by traveling and collecting data on the signal strength and phase variance of the beacon signal as a function of time, distance, and weather. The system design of this project includes utilizing the MSK nature of the DGPS beacon signal and deciding whether to use phase difference or wavelength dependent algorithms to convert the phase of the received signal into ranges. The measure of success for the field strength tests is a range at which our data fell below the noise floor. The measure of success of the algorithms is the required phase discrimination in the receivers.

Timeline

The objectives for the fall semester were to research the applicable fields of electronic navigation, DGPS, antennae theory, and communications theory. By December we had researched the topic, planned out the testing hardware, and begun developing mathematical models for the algorithm. From January to March we dealt with numerous hardware, weather, and availability issues to get the experimental data and finished the MATLAB models. In April

experimental data was collected and analyzed to discover the field strength at various ranges from the transmitter. At the conclusion of this project in May, we had hoped to construct a prototype system to receive a signal from the Moriches DGPS station and give the user a range to the station that is accurate to within 10 meters. However, we were unable to get a receiver for the phase of the signal and were unable to install the cesium oscillator at Moriches to test the method. The timeline is displayed below in Figure 6.

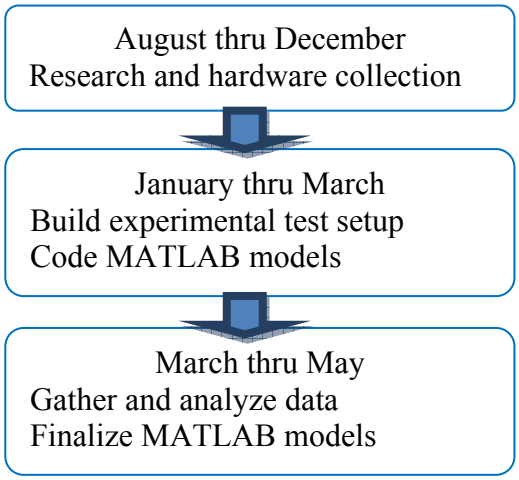


Figure 6: Project Timeline for the Semester

Requirements

The Department of Transportation (DOT), in the 2001 GPS Volpe Vulnerability Assessment, suggested that an alternative electronic navigation system be created to provide more redundancy for the GPS system [2]. Naturally, the DOT requires that the new system be less vulnerable than the system it is replacing (Appendix A). The general maritime community and the public require that it has an accuracy and range similar to current schemes and that it does not interfere with the current GPS system [9]. The Coast Guard requires that it be low cost in development, maintenance, and implementation because of budgetary constraints. The

Academy ECE section took these concerns and dictated the specific requirements for the project and the teams according to Appendix C.

The DGPS signal has a wavelength much longer than GPS and, because the beacons are terrestrial, transmits at a much higher power. These two properties are complementary to the two vulnerabilities of GPS which is why DGPS was chosen as part of the new navigation system.

The sponsor requires accurate ranges within one wavelength of the transmitter, approximately 1500 km, or within the ground wave path, whichever is shorter. The actual range of the transmission will vary depending on the height of the tower and transmission power.

Based on the sponsor's requirements the current system intended to implement the TOA algorithm in software. The current system uses MATLAB because it is already available, understood by all members of the project team, and has sufficient signal processing tools. The choice to use software was made because it is cheaper and easier to produce.

Because the Federal Radionavigation Program (FRP) is currently being rewritten to include eLORAN as the official back-up to GPS for electronic navigation, we can assume that the requirements for our system will change slightly to be used under the new plan. However, this project was designed to meet the old FRP accuracy and availability requirements of 3m 2drms, (95%) accuracy [15]. The propagation and phase data collection as well as the MATLAB simulations will give a detailed list of what hardware precision is required to meet any legal sanctions imposed.

While GPS uses 3 satellites to solve for position and time, finding a range using MSK range only requires a single beacon since there are binary phases to solve for range and time. The GPS method could be applied to terrestrial TOA ranges if three DGPS beacons were within

range but that is for another project to investigate. The current system design focuses on simply getting one range from a single DGPS beacon and integrating it with the existing eLORAN system.

System Alignment and Cost

The proposed navigation system requires accurate time at the transmitter because phase measurements are ineffective without a baseline of time to perform the mathematical conversion. In order to begin developing the DGPS ranging method, we had planned to install a cesium-based oscillator at Moriches in March of 2008. Unfortunately, we were behind on other testing and lacked equipment to actually perform the experiments planned. Cesium based oscillators are $40,000 for each unit but it may be possible to use an eLORAN receiver at the DGPS beacons to establish accurate time for a much lower cost. Some method of accurate timing is unavoidable because testing the phase characteristics of the signal requires consistent timing. It is important to note that by installing accurate timing at the transmitter, the receivers will be able to be produced cheaper. A more detailed support plan for the project can be found in Appendix D.

The reason that accurate timing is required has to do with the way that a receiver measures the phase of a signal. As a signal propagates in a given direction, its phase changes as well. The receiver therefore, must be able to solve for the time that the signal was transmitted in order to compare the binary 1 and binary 0 of the MSK signal because without a reference time the phase difference is useless.

System Design

Our design followed the generic plan presented in the article Beacon/LORAN Integrated Navigation Concept (BLINC) [4]. The design is comprised of DGPS beacon ranges used in conjunction with eLORAN to improve the geometry and present an accurate, reliable, and more secure electronic navigation system. A more thorough discussion is included as Appendix F.

Our specific solution falls into two parts. The first part is research into the mathematical algorithms for converting the information we can receive from the DGPS beacons to ranges and whether that mathematical model is practically feasible. The second part involves the investigation of the physical properties of the beacon's signal in order to determine whether interference renders the algorithm irrelevant. Individual test plans are detailed in Appendix E.

Figure 7 below displays the two different parts of the project. The left part of the diagram was a study of the mathematical algorithms of ordered phase pairs and phase difference. This was conducted in MATLAB and the code is displayed in Appendices H-J. The results of these experiments included the required phase discrimination required for each method. The right part of the diagram outlines the signal propagation experiments conducted with the spectrum master to identify both the field strength and phase ambiguity experienced as varying ranges and conditions.

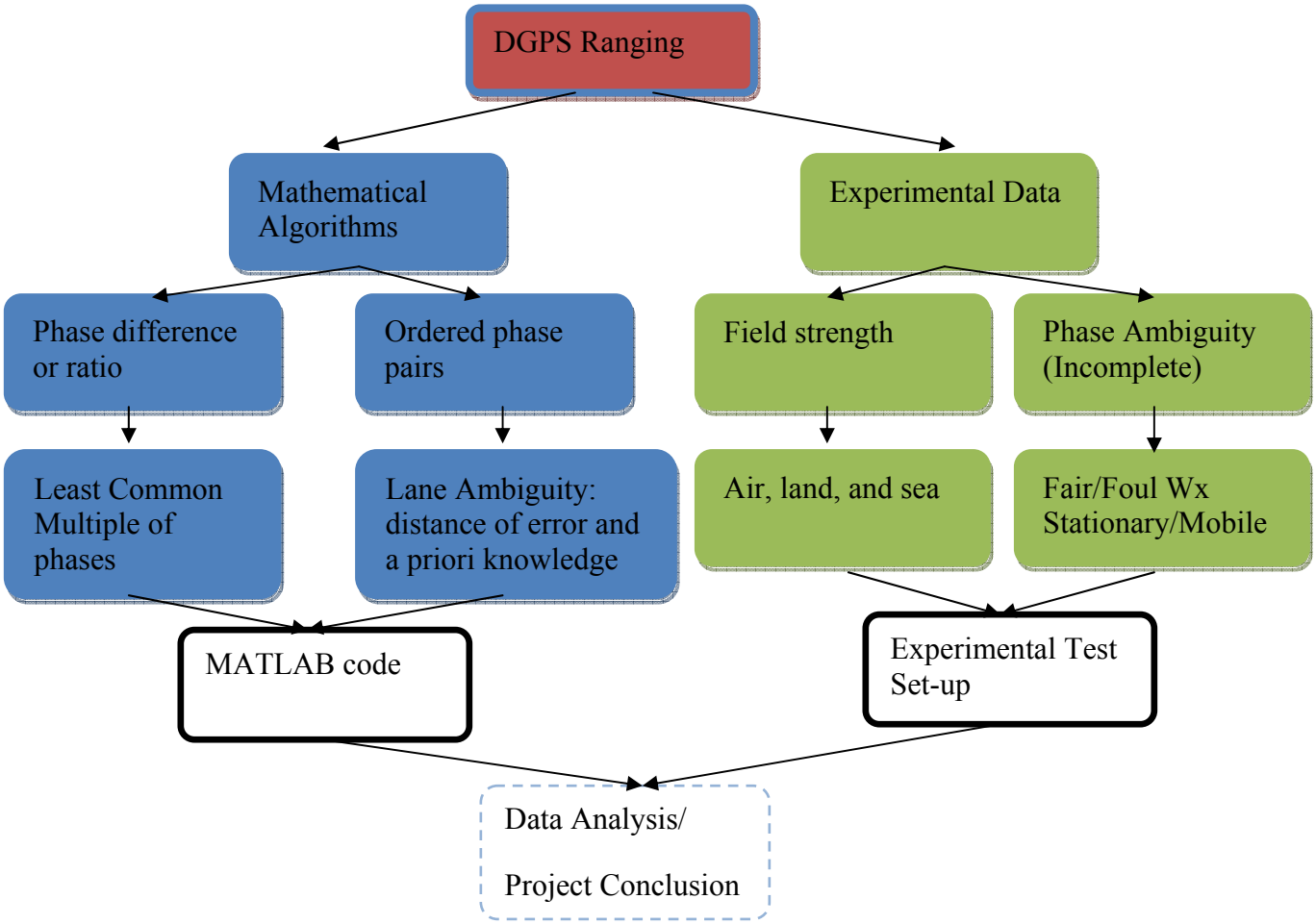


Figure 7: Breakdown of Project Design

Mathematical Algorithms

The Minimum Shift Keying (MSK) properties of the DGPS signal allowed us to calculate the range from a known beacon using the two separate frequencies and phases of the binary '1'

and binary ‘0’. We found that ordered pairs of phases or phase difference of the binary data bits could be converted to a range based on the equation $\lambda = c/f$. However, this requires that the beacons transmitted with extremely accurate time. We investigated exactly how accurate the timing needs to be so we can decide whether to use the timing from an eLORAN receiver or whether a Cesium oscillator is required at each DGPS station. In addition, we also investigated the phase sensitivity that the receiver would require in order to achieve 10m accuracy. Finally, we investigated the range at which the unique nature of the paired phases repeats to determine whether there is a lane ambiguity problem or not.

This lane ambiguity exists, for the ordered pair method, because of the periodic repetition of the binary 0 and 1 phases at certain wavelengths from the transmitter. Figure 8 below shows the MATLAB plot of the binary phase pair method that generated increasing range measurements converted into phi1 and phi2. The red * demonstrates the converted range of USCGA to the Moriches DGPS beacon.

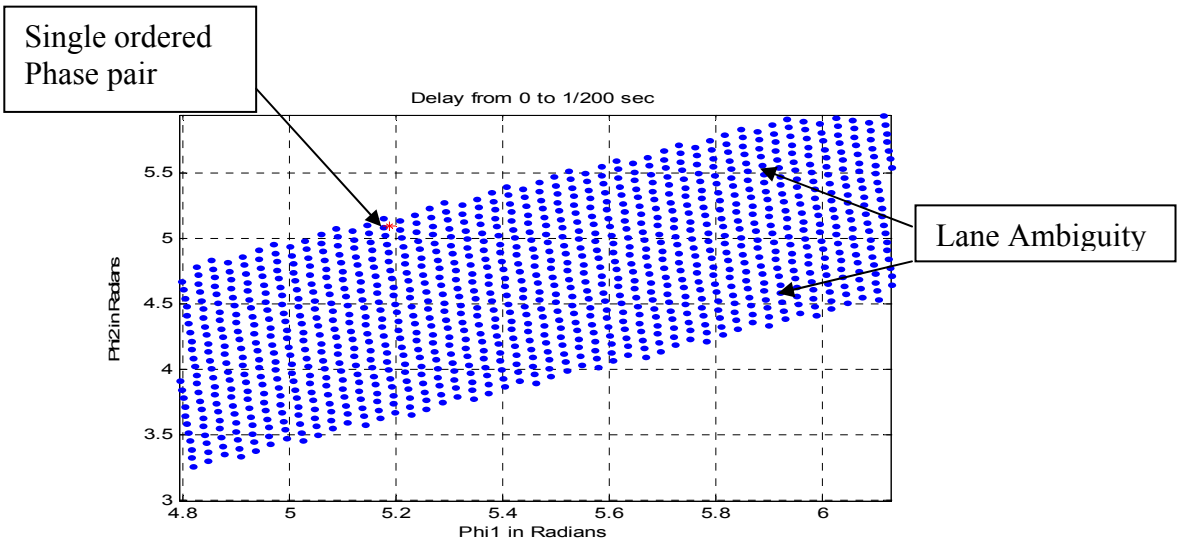


Figure 8: Model showing lane ambiguity of ordered pairs (Appendix J)

If there is a lane ambiguity we must use the relationship $\lambda = c/f$(wavelength = speed of light/frequency) to calculate the fraction of a wavelength the receiver is from the beacon. If it is possible to relate the phases to each other by differential then we will be able to find a deterministic equation that relates the range to phase relationships. This discussion is more of a design choice than a requirement because we have working MATLAB representations of both methods.

The ordered pair method requires more signal processing on the receiver end but less accuracy on the phase measurements because a small error in phase would generate an error large enough to be discarded by the program. The differential method is easier to design a receiver for because there is no lane ambiguity but it requires a much higher precision of phase measurements, on the order of .1mradians. This accuracy is considered attainable according to the work done by CAPT Hartnett on the Archerfish project outlined in BLINC and the extremely narrow band of the MSK signal but the exact proof is classified [4]. It may also be possible to modify the MSK signal at the Beacons to increase the modulation index to allow easier discrimination of phase without affecting the legacy users.

Skywave Experiment

Part of the project team is experimenting to quantify the interference of skywave on field strength and phase corruption to determine the feasibility of the system. This test plan begins with getting a DGPS receiver and antenna assembly that receives the DGPS beacons at Sandy Hook New Jersey, Moriches New York, and Acushnet Massachusetts. Using various software programs, the experiment will take E-field signal strength measurements paired with GPS positions at varying radial distances from the transmitters.

The second part of the project involves analyzing the physical properties of the signal propagation to determine the maximum effective range. A study conducted in 2000 by DeMinco suggests that in the MF band the sky wave interference is not a factor until 150km from the transmitter [5]. If this hypothesis is supported by the data we gather, further funding and resources may be assigned to this project, opening up new possibilities and applications.

The geographic test plan we designed to collect the skywave data is shown below in figure 9 below. Figure 9.1 demonstrates the area of operations that we focused on, with 50 km rings expanding outward from the Moriches DGPS beacon. We choose Moriches because it was a local beacon that we could pick up in lab and it was close enough to visit and install equipment if the project progressed far enough. In the event that plane and boat tests were not able to be conducted, figure 9.2 shows an alternate land route that was considered because it covered the ranges of interest for our project but this particular test path was never executed.

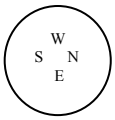


Figure 9.1 (left): 50km ranges from transmitter 9.2 (right) Land test route

In particular, the system that we used to measure the skywave involved the assembly of a testing setup, supplying power to the testing setup, and developing code to analyze the results. The skywave testing required the following equipment: an antenna capable of receiving GPS & DGPS signals, a computer program to record the GPS position data, and an ANRITSU spectrum analyzer that could record the strength of the signal for the three closest DGPS stations: Sandy Hook, Moriches, and Acushnet. We found that we were able to automate both the GPS and the spectrum analyzer to record the data which we later correlated with the time of the MSK measurement. We assumed that the time inaccuracy due to the quartz oscillators in the computer and the spectrum analyzer were negligible because we were looking on the scale of NM so a difference of even 10 seconds would not interfere with this portion of the project. Supplying power to the GPS receiver and the spectrum analyzer was easily accomplished since they operate on 12V DC and there were batteries and cigarette lighter converters in lab for them. Because we were unable to construct or find a converter for the laptop, its battery life was our limiting factor on recording measurements. The setup is shown below:

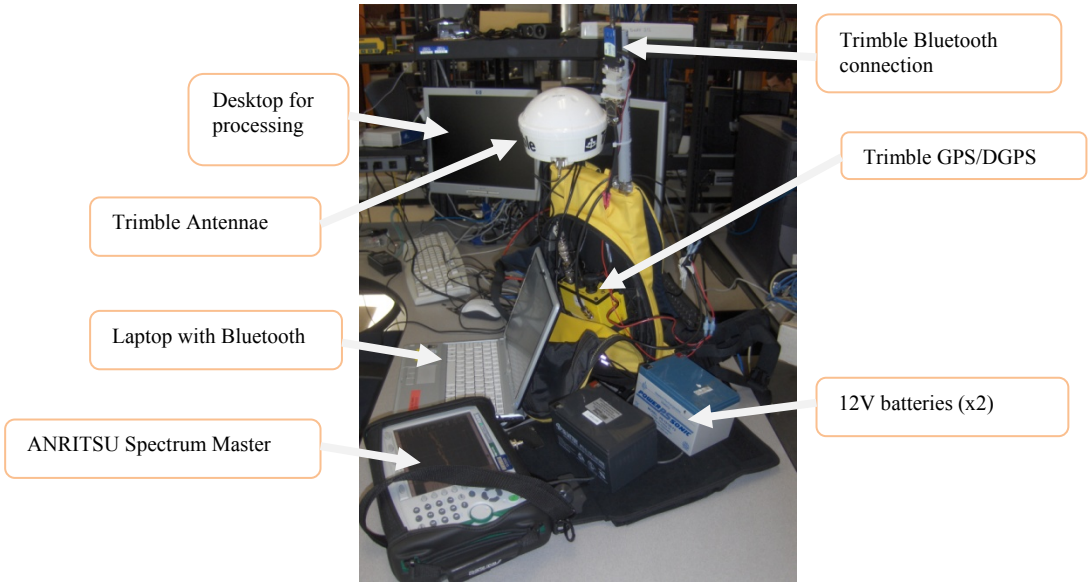


Figure 10: ANRITSU/GPS experimental set-up

Finally we had to match the field strength measurements with the distance they were taken from their respective stations. To do this we used MATLAB to create two vectors: one which contained the spectrum analyzer data which was then updated with the ranges that corresponded to the measurements. This was done by comparing the timestamps of the spectrum analyzer and GPS data. Finally we plotted the results to display the field strength as a function of distance from the transmitter. The figure below outlines the data extraction algorithm:

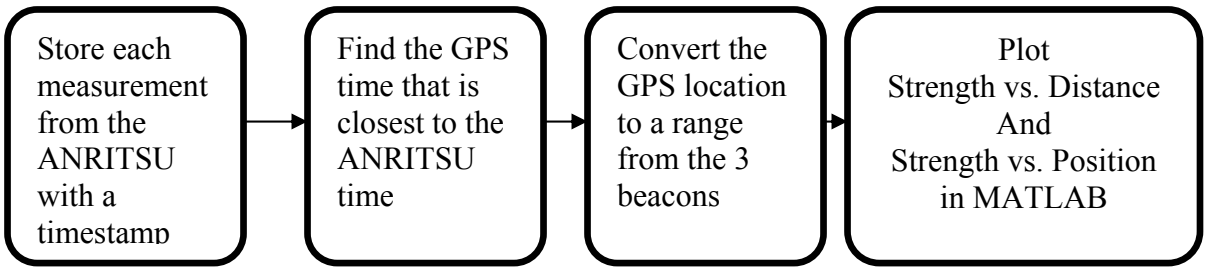


Figure 11: Flow chart of data extraction code (Appendix G)0

There is still additional work to be done on this portion of the project. To be a complete investigation we must record the data during day and night, fair and foul weather, and over ground and sea. This is may not be required for the project to be accepted but will eventually be required to inform consumers of the maximum expected ranges.

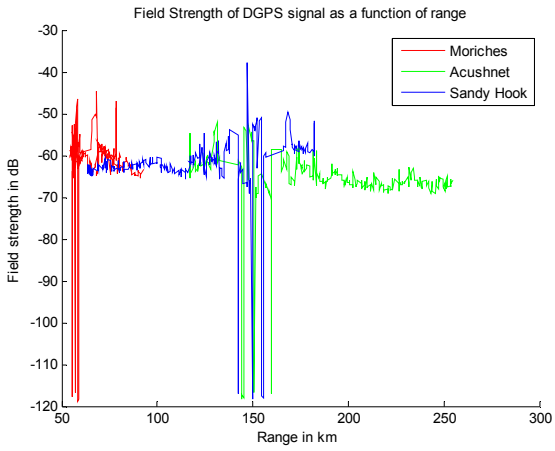
Eventually, future projects could construct a receiver that integrates DGPS signals and eLORAN. This would improve the geometry of the fixes, providing an accurate, reliable, and terrestrial navigation system that can support CG operations. All that is required for this receiver is the algorithm, some form of accurate, GPS independent timing at the DGPS beacon stations, and a receiver sensitive enough to discriminate between the two phases.

Results

The goal of this project is to design a system for the implementation of DGPS ranging as part of an electronic navigation system. This system should take be able to present the user with one range from a DGPS beacon based on the MSK phase information received. This project must mathematically calculate the phase discrimination required for its solution to achieve the desired accuracy of 3m. The project must also establish the distance and conditions that skywave interference begins. All further considerations such as accurate timing at the transmitter, reliability, and prototype construction were established as possible extensions of this project but were not part of the requirements.

Field Experiments: Skywave and phase

The skywave interference experiment was unable to locate a particular range that skywave interference washed out the DGPS signal below the noise floor which was required by the sponsor. The current results prove that the setup and data extraction code functions properly but we are currently troubleshooting why the ANRITSU recorded the measurements at the noise floor as shown in figure 12.1 below. It is apparent that it is the noise floor because it does not obey the fundamental laws of propagation theory which state that the signal strength should get weaker farther away from the transmitter. Figure 12.1 shows this does not occur and some signal strengths actually increase which cannot consistently happen if the correct data was being recorded. Figure 12.2 shows that the drop in field strength at ~150 km was actually due to some interference at the LAT/LONG of the receiver at that point, not skywave interference.



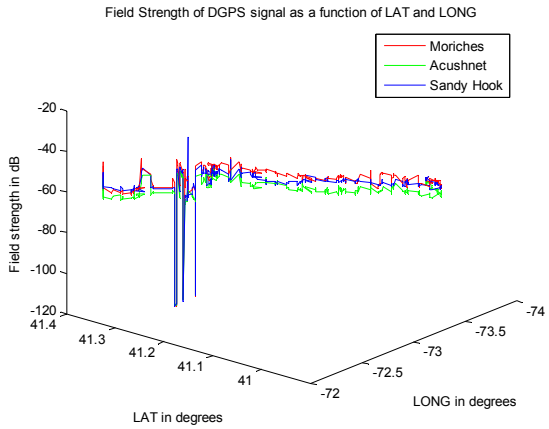


Figure 12.1 (left) Strength v. Range 12.2 (right) Strength v. LAT/LONG

First Test: Car with Bluetooth and Cigarette lighter power

The source of the problem was the wireless BLUETOOTH transmitter that was installed to transmit the GPS position to the computer overpowered the receiver antennae that since it was only 12 inches away. This problem was corrected by running a basic COMM cable from the GPS receiver to the laptop instead of wireless and the system was tested more accurately in CAPT Hartnett's plane. However, the plane test had problems with power supplies and required a re-writing of the software extraction code because it stored the data in a different manner. The results from the plane test were still not sufficient for the project's proof but solved the original problem.

Figure 13 shows the second test run in the same manner as the first test run: field strength vs. range and field strength vs. LAT/LONG. This test was conducted with individual battery power instead of using the cigarette lighter from a car and used COMM port 1 instead of a Bluetooth connection. CAPT Hartnett, who performed the experiment, recorded that the DGPS receiver which we used to plot position had trouble acquiring a beacon when in the plane hangar but was able to acquire a signal out in the open. Unfortunately the experiment was cut short

before enough data could be collected because the DGPS receiver discharged its power supply before the test was completed. It is highly recommended that future tests be conducted with better power sources.

It can be seen from figure 13 below that the experiment correctly recorded a decreasing phase with an increase in range from the transmitter that behaves as predicted. The current mathematical models predict that the signal would monotonically decrease until a certain point at which skywave interference began. One of the project's goals was to find that point but it is apparent that at some particular location, the battery that supplied power to the antennae failed and the subsequent measurements were erroneously recorded. This figure does show the monotonically decreasing nature of the signal and confirms that the BLUETOOTH was the source of the interference in the first experiment. With adequate power this experiment may have met the project's requirements.

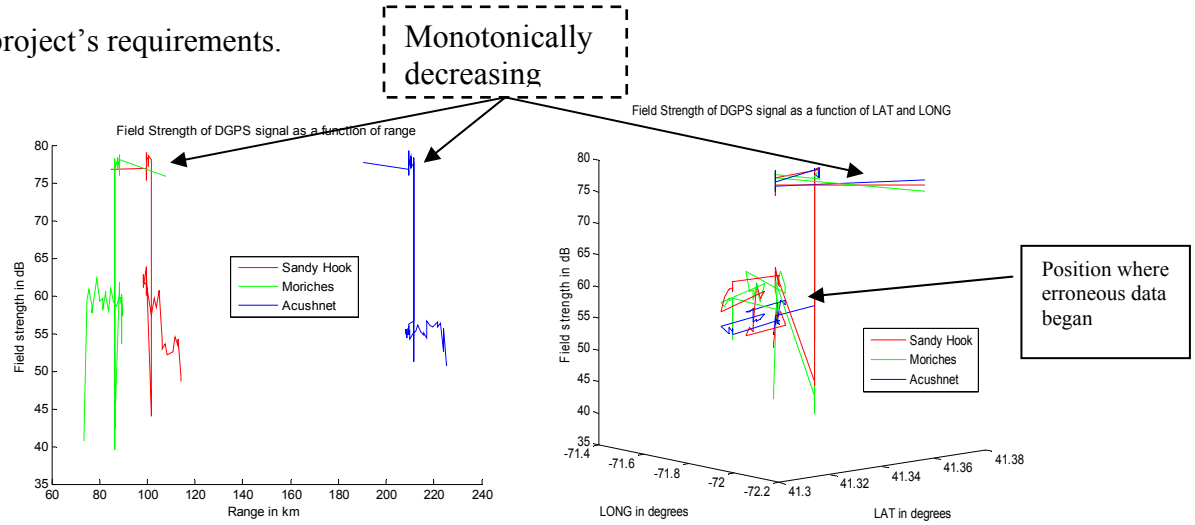


Figure 13.1 (left) Strength v. Range 13.2 (right) Strength v. LAT/LONG

Second Test: Airplane with COMM port and separate battery power

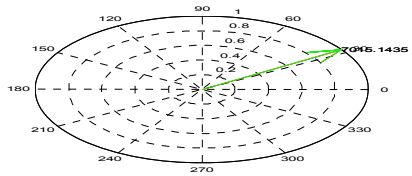
Because of the aforementioned reasons the data we collected does not satisfy the sponsor's requirements for field strength measurements. Furthermore, the phase requirement was

discovered and added to requirements in January and unfortunately the ANRITSU does not record phase measurements. However, the test plan worked to the extent that all of the different components communicated to each other and further testing with a COMM line instead of wireless BLUETOOTH solved the problem. Unfortunately, the period for this projects testing has passed but these two tests show the project was on the right track.

Software Algorithms

We investigated two separate ranging algorithms: Phase difference and ordered pairs. We discovered that the phase difference algorithm requires a phase discrimination of .01μradians but has a lane ambiguity of 1.046e+015 meters, which is best expressed more in astronomical terms and is not an issue for terrestrial navigation. This code is shown in Appendix I. The ordered pair method phase discrimination was not discovered but it has a lane ambiguity of 1 km. However, when used in conjunction with eLORAN, the navigation system should be able to eliminate duplicate ranges with 1km lane ambiguity and the current estimate of phase discrimination required for the ordered pair method is on the order of 1 mradian. Therefore, we concluded that the ordered pair method would be the most practical and cost efficient system since discriminating phases at that precision requires expensive instruments and is easier to confuse.

Figure 14 below shows the problems with the phase difference method. This plot was generated by the MATLAB code in Appendix H plots both the phases on a Cartesian coordinate system. As you can see, there is only one apparent phase in green although the second phase is plotted in blue beneath it. Naturally, the receiver can calculate better than the human eye but the accuracies computed are printed below and are not practically feasible in a receiver.



Accuracy (in meters) is: 3 Accuracy (in radians) is: 1e-008

Figure 14: Illustration of required discrimination for Phase difference method (Appendix H)

Conclusion

Prior to designing a new electronic navigation system, we described the legacy electronic navigation systems including OMEGA, ELORAN, GPS, and DGPS [6]. The vulnerabilities of the current GPS navigation system and the world's dependence on sea trade and the current work to revise the FRP to include eLORAN as a backup navigation system gave this project impetus [1, 11]. The USCGA ECE Section sponsored research into a less vulnerable navigation system using DGPS to augment eLORAN using the theory developed in the article BLINC [4].

This project developed an electronic navigation system that is less susceptible to accidental or intentional jamming or spoofing. The DGPS signal has a wavelength much longer than GPS and transmits at a much higher power. These two properties are complementary to the two vulnerabilities of GPS which is why DGPS was chosen as part of the new navigation system.

The goal of the project was twofold: develop algorithms for converting phase measurements of DGPS signal to ranges and determining the effect of skywave on the signal. In particular, we investigated the two different algorithms of phase difference and ordered pairs which had phase discriminations of .1μradians and .1mradians respectively. The range at which skywave interference began was not determined due to experimental error. Furthermore, equipment limitations prevented determination the skywave's effect on phase. We were also unable to account for all the variables of time, distance, and weather independently due to time constraints.

This project accomplished several other important tasks. We assembled a hardware setup and procedures that will allow the Academy ECE section to take measurements of any signal within the range of the ANRITSU. In addition, the MATLAB code developed will allow future

work to be extracted and displayed. Most importantly though, our project introduced the concept of DGPS ranging to numerous staff officers of the USCG and our results proved the feasibility of our test plan but were unable to clarify the range of skywave interference or the accuracy of the system.

The decision to revise the FRP and include eLORAN as the official back-up to GPS makes this project even more applicable to safe navigation in the US. This project could enhance eLORAN in such a way that our commercial and military vessels could operate in a GPS jamming event or recognize when they are being spoofed. There is still much work to be done for the actual design of the DGPS ranging receiver. However, this project has begun to classify the physical properties of the DGPS signal and established the algorithms that will someday create a more robust electronic navigation system. That navigation system will allow the prudent mariner to use all available means for safe navigation.

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Appendices

A. Business Case

B. Project Management Plan

C. Requirements

D. Support Plan

E. Test Plan

F. Design Specifications

G. Field Strength MATLAB Code

H. Visual Phase Chaser (Phase difference discrimination) MATLAB Code

I. Phase difference lane ambiguity MATLAB Code

J. Ordered Pair Calculations MATLAB Code

APPENDIX A: Business Case

Signals of Opportunity (SOO):
DGPS and LORAN Time of Arrival Enhanced Navigation
1/c Hatch and 1/c Dolton
Under the Advisement of LT Rothberg and CAPT Hartnett

The United States requires a back-up in the event of GPS navigation failure or denial. A Congressional study in 1999 reported that the current GPS system, which is the primary means of navigation on all US shipping, it susceptible to low-cost, low-technology interference. To enhance the resilience and accuracy of navigation we propose using DGPS and LORAN transmissions for lines of position (LOP).

There have been occurrences where the CG was prevented from escorting ships into port in CA due to GPS denial. Concurrent work done on GPS jamming and spoofing by 1/c Ellsworth indicates that it is very easy to deprive the US of its primary means of navigation. Knowing full well that 90% of the worlds' commerce travels by sea, the safety and security of the US economy requires a back-up to GPS.

This requirement for a back-up system to GPS was one of the many factors that retained the LORAN projects funding. LORAN itself does not provide the accuracies that the public has come to expect and depend on but it is being preserved as better than complete blackout of navigation. In addition, the particular geometries of current LORAN stations leave ambiguous holes in the navigation picture in southern Florida and California which are two of the busiest seafaring communities in the US. However, the DGPS transmitters in these two regions complement the nearby LORAN stations geometrically that will allow better fixes. In total, this project seeks to alter LORAN form a time difference of arrival (TDOA) to a time of arrival

system (TOA) system used in GPS and integrate DGPS transmissions wherever possible for better geometric solutions.

In accordance with the expectations of Congress, the American public, the maritime community, and the Coast Guard, our project sponsor, the USCGA EE department, has laid some general requirements and constraints on the project. The first is that nothing the new system does should interfere with the functionality of the current DGPS units. The second is that it has low development cost and no maintenance cost or additional responsibilities so that the CG would not have to petition Congress for new funding or an amendment to their duties. The third requirement is that it produces safe fixes in shoal water areas and functions out to a reasonable distance from shore. This requirement has not been fully articulated yet but will become refined as the project progresses and experimental data is gathered.

Cost/Benefit Analysis

Solving the issue of inaccurate timing for DGPS stations would cost approximately $40,000 apiece for atomic clocks but these clocks already exist at LORAN stations and this investigation will also seek to incorporate these exiting clocks. The worst case purchase of all the clocks would be a single purchase and it may be possible to split the cost with DoT because they are interested in DGPS for land navigation as well.

The development of the TOA algorithm incorporating LORAN, DGPS, and signals of opportunity will involve minimal experimental costs. It is currently being developed at USCGA with no funding and the final portion of the project could be assigned to C2CEN for the final refinement before selling it to the commercial community. Once the commercial community begins building the units, the CG will have to purchase them and there is no estimate on the cost

of units at this time. However, the cost will likely be only as expensive as replacing the current GPS units we have installed and the new units could be installed in accordance with the cutter's life cycles.

The benefits of the system have already been stated but will be mentioned further. The system would provide an independent source for checking a vessel's position in the event of GPS interference. This means that CG cutters will be able to operate in a more hostile environment and execute their missions of homeland security in the face of certain forms of electronic warfare. The costs of implementing this system may be significant but the price for a navigation blackout would be astronomically higher including thousands of tons of delayed shipping, forfeited perishable cargoes like food, and even shipwrecks with lost lives.

APPENDIX B: Project Management Plan

1. INTRODUCTION

This project encompasses the possible implementation of a nation-wide alternate navigation system. Our particular phase of this project is to simply investigate the technological possibilities of a single DGPS ranging prototype including a real world model and experimental data.

1.1 Project Description

DGPS stations transmit medium frequency (MF) signals which are received by DGPS enabled receivers to increase the system's accuracy. It may be possible to use these signals to produce ranges to the DGPS station. If this were possible, DGPS stations could give both DGPS corrections and ranges, which in the case of a GPS jamming event would provide an alternative means of electronic navigation.

Sponsored by C2CEN, this project was finalized on September 6, 2007. Officially known as DGPS Ranging, the project will actually solve several radio navigation problems, the end result providing an arc of position or fix using DGPS stations.

1.2 Project Background

Electronic navigation has taken many names over the years. It has progressed from the OMEGA system to ELORAN and currently to GPS. All electronic navigation systems rely on extremely accurate clocks to measure the time delay in signal pulses from a known source which are converted into distance ranges to obtain a position fix.

The DGPS system is currently only an augmentation to the GPS system which transmits range corrections. However, if GPS were jammed DGPS would be providing a correction to a non-existent service. Therefore, obtaining alternate information through DGPS, independent of a satellite link, could increase the integrity of a vessel's navigation system. Implementing DGPS ranging could help lessen this vulnerability to jamming. Even if all that could be obtained from a DGPS signal is an arc of position, that is a significant gain compared to a complete loss of the system. In conjunction with other systems such as ELORAN or other possible signals a DGPS LOP would merely be a part of the fix picture.

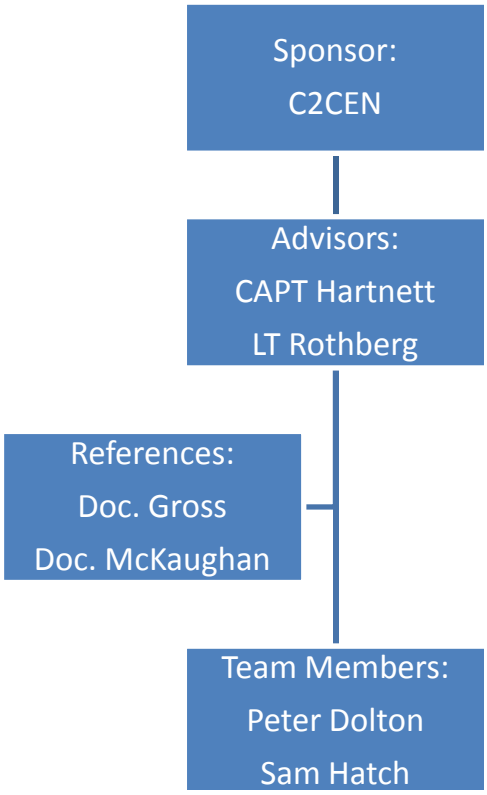
1.3 References

N/A.

2. ROLES AND RESPONSIBILITIES

This project is fairly unique in that, as of yet, there are no deliverables. The primary goal is to find out if the idea is even possible. That being said, the organization is a little different to meet the challenges of such a project.

Team members will work together to perform intermediate research and testing, using references and advisors as a sounding board for ideas. The advisors review the work of the team members, and help to improve and perfect it before continuing to forward findings to C2CEN. The following diagram illustrates how work is done in the project.

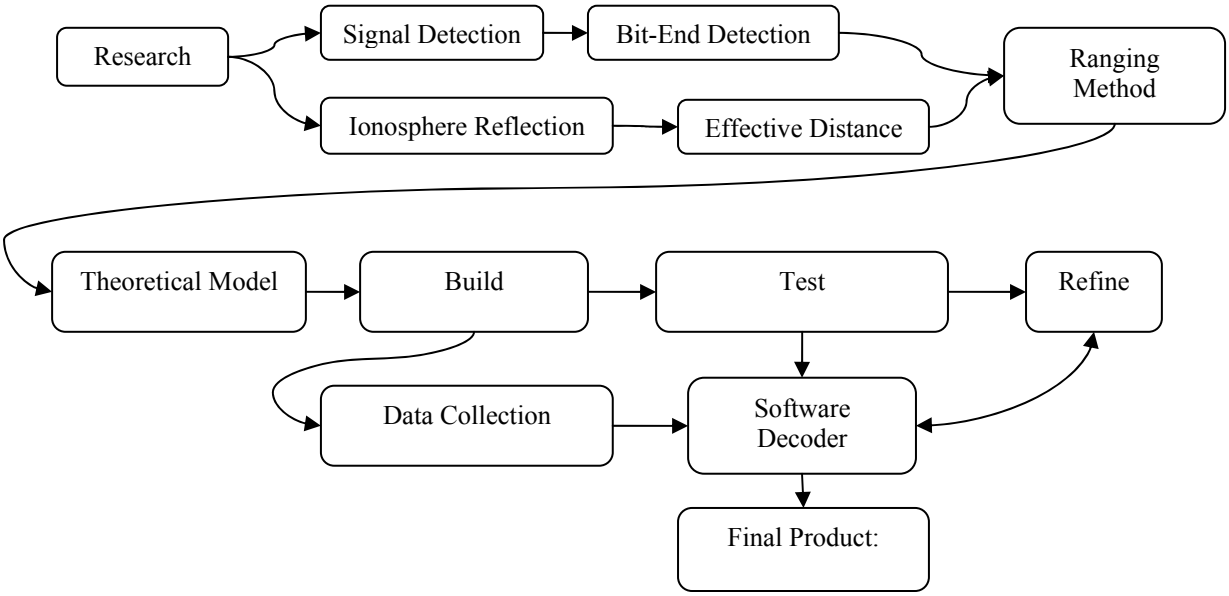


3. PROJECT DESCRIPTION, SCHEDULE, AND RESOURCES

3.1 Project Work Breakdown Structure (WBS)

Initially the project will be primarily research where the team members will be looking into two primary problems: the effective range of the ranging method due to sky-wave interference, and the method to use for the ranging. Parallel processes will be completed by team members

concurrently, and processes in series will be worked on together.



3.2 Resource Estimates

N/A.

3.3 Schedule

This section presents the project schedule. Provide a list that states the date when each major task or deliverable will be completed. Some items are included below.

- Oct 26: Ionosphere Reflection Determined
- Nov TBD : Bit-End Dection Method Complete
- Nov 7: Effective Sky-Wave Distance Determined
- Nov 27 : Draft Fall Paper due to Project Advisor.
- Dec TBD: Fall Presentation
- Dec 10 : Fall Paper/Project Notebooks due.
- Spring 2008: Theoretical Ranging Model Development
- Spring 2008: Averaging Autocorrelation along diagonal developed
- Spring 2008: Field trip to DGPS station to test cesium clock
- Spring 2008: Development or Purchase of software DGPS LOP detector

3.4 Communication Plan

N/A.

Project Members:

Sam Hatch _____ Date: __08OCT_____

Peter Dolton _____ Date: __08OCT_____

Project Advisor:

LT Rothberg _____ Date: __08OCT_____

APPENDIX C: Requirements Specification

INTRODUCTION

Background/Project Description: Electronic navigation is vital to commercial trade, homeland security, and military operations of the US since 90% of the worlds commerce is done by sea (2). A 1999 performed by the US government discovered several vulnerabilities in the current GPS navigation system and prompted the extension of LORAN's life cycle (3). The vulnerabilities we are concerned with are the low level of technology required to jam a GPS signal or spoof the signal to give the user false information.

The attack of 9/11 gave a new urgency for contingency plans in case the next attack is to disrupt or misinform US shipping interests that rely on GPS for fixes. However, it is not acceptable to revert back to LORAN because there is an expectation of better accuracy for all shipping. This project investigates one possible solution to this navigation problem called DGPS ranging.

DGPS stations are convenient navigation aids to use because the infrastructure is already in place. An alternate use for these sites makes better use of resources because a DGPS signal becomes useless if the GPS signal is jammed . Currently DGPS sends out range correction equations which approximate the errors of every satellite within the currently visible constellation. There is currently no time synchronization with the DGPS signal; it transmits data and not time of arrival sensitive distance/range measurements. Part of the challenge of using DGPS sites for ranging is utilizing the existing signal for ranging without interfering with its original purpose.

In theory any powerful radio transmission can be used to aid in navigation if some of its characteristics are known. As one of the most developed nations on earth the U.S. has a lot of radio transmissions: satellite TV, radio, cell phones, LORAN, DGPS, etc. All of these could be integrated to form a more accurate navigation picture. DGPS ranging is just the beginning.

Purpose:

The purpose of this project is to increase the integrity of electric navigation, by giving navigators another tool by which to locate their position. Achieve this using existing infrastructure to minimize monetary costs and implement a system that can function concurrently with the current system. Because the infrastructure of DGPS is already in place there will be low overhead costs compared to developing a new navigation system. The current plan is to use DGPS ranging in conjunction with ELORAN so the maintenance for the LORAN stations would require funding.

There will be costs involved with installing the new units on the cutters although it may be possible to make all the changes in software. Solving the issue of inaccurate timing for DGPS stations would cost up to $40,000 apiece for atomic clocks but these clocks already exist at LORAN stations and this investigation will also seek to incorporate these exiting clocks with signal broadcasts.

The costs of implementing this system may be significant but the importance of navigation to US interests in a world where "90% of the world's commerce travels by sea"

cannot be stressed enough. This system proposes to make a redundant system for US military and civilian use that enhances national security.

Assumptions and Constraints:

Given the vulnerability of GPS, our method would compliment LORAN during a GPS "outage." That being said, it should in no way interfere with existing systems, and in some way be more difficult to disrupt than the system it is expected to supplement.

The current infrastructure requires that it merely be a supplement to ELORAN not an independent system.

A summary of the constraints are listed below

- Only Loran towers within 1200km can be used
- Only Beacons within 350 km can be used
- Loran power values are as specified in the Loran handbook (400kW – 1.6MW)
- Beacon power is uniformly 1kW
- Beacons have a 300:1 advantage to Loran (10:1 due to power being continuous not pulsed, 30:1 due to 1kHz noise bandwidth vs: 30kHz).
- Power falls off proportional to $1/d^2$
- Because of the nature of PECE class this project has a time constraint of early May. We prefer to have a working software algorithm in MATLAB by February 15th.

A summary of the assumptions are listed below

- LORAN will be a continued system.
- We will be able to synchronize the DGPS stations with a cesium based clock
- We will be able to detect the bit shift with an accuracy of meters.
- We can create a piece of software that can translate LORAN and DGPS signals into one picture.
- CAPT Hartnett's method for averaging the cross correlations along the diagonal will solve the accuracy issue.
-

Documents Reference:

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Sponsor Needs / Operational Requirements:

The 2001 Vulnerability Assessment performed by the Department of Transportation (DOT) requires that an alternative electronic navigation system is provided and specifically that an alternative to GPS is provided. Naturally the DOT requires that the new system be less vulnerable than the system it is replacing.

The general maritime community and the public require that it has an accuracy and range close to what they are used to. Likewise, the maritime community requires that while GPS is functioning, this new system does not interfere.

The Coast Guard requires that it be low cost and interact with future systems to prevent modification costs.

The solution is only required to give accurate ranges within one wavelength of the transmitter approximately 1500km or within the ground wave path, whichever is shorter. The general goal is a navigation system for coastal approaches only.

REQUIREMENTS TRACEABILITY MATRIX:

Level	Sponsor Need	Engineering Requirement	Justification
1	Alternate Electronic Navigation system	Combination of electromagnetic receiver and processor that converts signals to position	Basic requirement of the project put into engineering terms.
2	Alternative to GPS	Dual purpose	This project scope

		utilization of the DGPS signals to give a range to a given DGPS station as part of a fix picture	must be limited to a single study and our assignment was the feasibility of DGPS not all possible solutions to the electronic navigation problem.
2a	Reasonable level of accuracy	Error comparable to GPS	If the method is to be accepted, it needs to meet public expectations.
2b	Useable a reasonable distance from the nearest DGPS transmitter.	1500km or within the ground wave path, whichever is shorter.	This will be determined by experimental evidence and redesign of the project once we enter the experimental stage.
2c	Low Cost	Uses current infrastructure of DGPS and should be compatible with current charting software	This project will not be involved in this aspect except at the end for predictions. Integrating our method with CG software is beyond the scope of this course. However the fact that we developed it in software well commented should allow future projects to do it. The cheapest way to accomplish something is to use existing infrastructure.

2d	Less vulnerable to jamming or misdirection	Requires significantly more power, technical knowledge, and money to interfere with than GPS	The project was started because GPS is susceptible to jamming. Therefore we must make sure that the new system requires more effort and cost. There may be a secure system but that is not our goal. Our goal is a system that is one step harder to attack.
3	Does not interfere with current electronic navigation	All DGPS transmissions must be unaffected by what we change in the signal.	Until we have a complete replacement for GPS we must keep using it regardless of how vulnerable it is and so this project cannot change the value of the information DGPS transmits.
4	Can interact with future systems	Well documented in standard format and done in software that can be understood	It would be foolish to develop a system that would bottleneck the CG farther down the line. This is polishing of the project however and will be done all along but confirmed at the end.

APPENDIX D: Support Plan

Signals of Opportunity (SOO):
DGPS and LORAN Time of Arrival Enhanced Navigation
1/c Hatch and 1/c Dolton
Under the Advisement of LT Rothberg and CAPT Hartnett

Purpose: The United States requires a back-up in the event of GPS navigation failure or denial. Congressional studies have shown that the current GPS system, which is the primary means of navigation on all US shipping, it susceptible to low cost, low technology jamming. To enhance the resilience and accuracy of navigation we propose using DGPS and LORAN transmissions for lines of position (LOP).

There have been occurrences where the CG was prevented from escorting ships into port in CA due to GPS denial. Concurrent work done on GPS jamming and spoofing by 1/c Ellsworth indicates that it is very easy to deprive the US of its primary means of navigation. Knowing full well that 90% of the worlds' commerce travels by sea, the safety and security of the US economy requires a back-up to GPS.

This requirement for a back-up system to GPS was one of the many factors that retained the LORAN projects funding. LORAN itself does not provide the accuracies that the public has come to expect and depend on but it is being preserved as better than complete blackout of navigation. In addition, the particular geometries of current LORAN stations leave ambiguous holes in the navigation picture in southern Florida and California which are two of the busiest seafaring communities in the US. However, the DGPS transmitters in these two regions complement the nearby LORAN stations geometrically that will allow better fixes. In total, this project seeks to alter LORAN form a time difference of arrival (TDOA) to a time of arrival

system (TOA) system used in GPS and integrate DGPS transmissions wherever possible for better geometric solutions.

Design Solution:

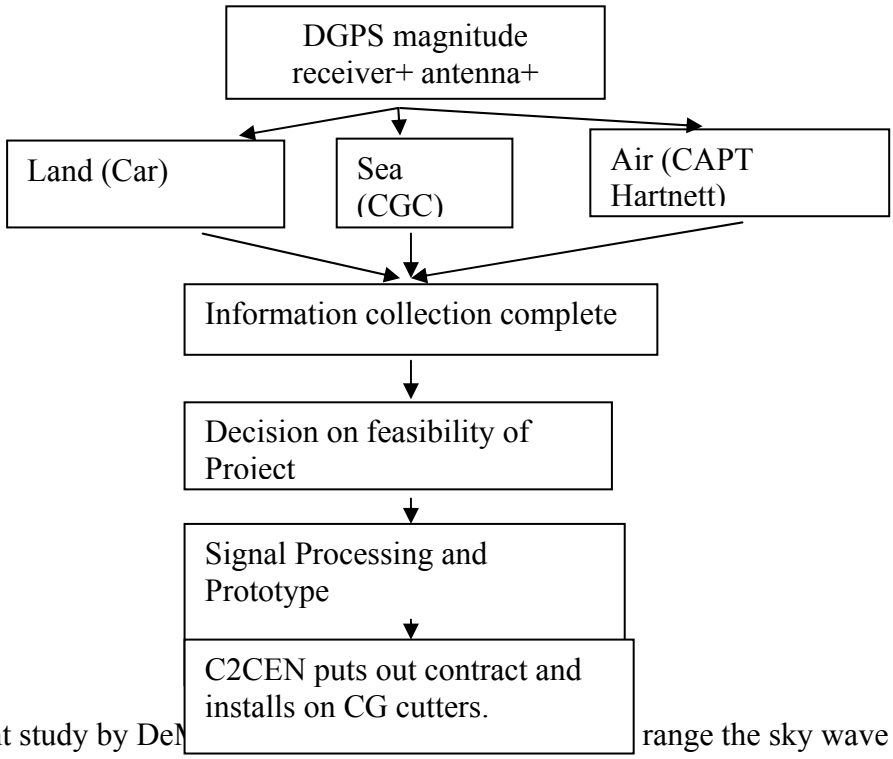
While the specifics of the method are still in development, a generic plan has been developed using the methods described in Beacon/Loran Integrated Navigation Concept (BLINC) [1]. Signals of opportunity used in conjunction with LORAN LOP's will be used to improve the geometry of the fixes providing an accurate and reliable navigation system.

For the final design solution we are currently considering PC-based operations with programs such as MATLAB and are considering offering the algorithm up for contract to the lowest bidder. The final design solution will include the capacity to take GPS, DGPS, LORAN and LORAN fixes and provide the user with positioning information using a weighted evaluation algorithm.

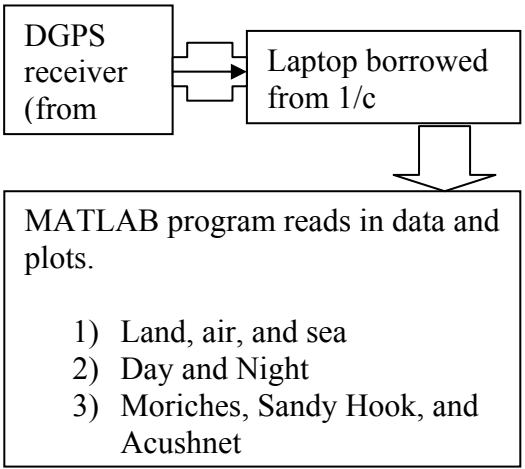
Our team has been working on a test plan for mapping the interference of skywave propagation to determine the feasibility of the system. This test plan begins with getting an IFR DGPS receiver and antenna assembly centered at the frequencies of the local DGPS stations at Sandy Hook, Moriches, and Acushnet. After interfacing the receiver to a laptop we will take magnitude measurements paired with GPS positions to determine the signal strength of DGPS signals at varying radial distances from the transmitters. We will approach the stations from air, set up an automated system and ask a local CG cutter to assist us, and drive from one of the stations in a personal vehicle. After compiling all the data over both day and night cycles we will be able to determine the maximum effective range and possible ways of mitigating the skywave interference. The hardware for this experiment should be ready before December 21st 2007 but the experimentation will continue into 2008 until sufficient data has been collected. The amount

of time spent on this experiment will vary enormously depending on the initial findings because there is insufficient experimental research done on the problem.

The other aspects of the system signal processing and integration are still being considered but the pressing question of skywave interference will determine whether the project should be given any more time or if the physical limitations of the signal will render the project a moot point. The following diagram is a simple timeline of the current model progress plan.



A recent study by DeN range the sky wave interference may not be a factor until around 150km from the base station [2]. If his hypothesis is supported by the data we gather, further funding and resources may be assigned to this project, opening up new possibilities and applications. The system we designed to collect the skywave data is shown below.



Make design decisions and revise

Support Considerations:

Economic: Currently there is no need to fund our project because the prototype can be written in software and the hardware receivers have already been purchased, there is no cost. Should small appropriations be necessary for the project, the USCGA EE department senior design program has allotted the group sufficient funds to deal with any minor equipment procurements. Cesium clocks may have specific restrictions governed by some agency but as they are already in place at LORAN sites we would only have to follow the same regulations. This might be something to look into.

Manufacturability: The design is merely a prototype to prove that LORAN and DGPS TOA navigation is possible and accurate. The receiver prototype that is developed will be implementable through software so that existing units might be upgradeable to a new method. The product would be contracted out and built commercially.

Sustainability and Reliability: Sustainability of the system will be more dependent on how long the legacy and secondary systems it relies on remain operational. Being a back-up system to GPS requires similar availability requirements. Unfortunately, this system cannot achieve the same accuracy as GPS, but will allow operations to continue on a more alert basis. The prototype does not require spare parts because it is beyond the scope of this project to design a maintenance project for the fleet.

Life-Cycle Costs: The life-cycle of our design is paired with the developments in the systems it is dependent on, such as LORAN and DGPS transmitters. The only possible costs from this system would be the upgrading of existing equipment software and training for people to use it. If the prototype is succeeds, C2CEN will take interest and present the idea to commercial companies. Final adoption of the project would involve costs per unit purchased commercially and no more cost than is already used to maintain the DGPS stations.

External Considerations:

Environmental: The design should have no impact on the environment or vis versa. The system uses existing signal radiation, equipment and manpower. Environmental impact is irrelevant. In addition, since there is effectively no new equipment, disposal of equipment can be handled through existing methods. No new ground is being opened either, so the EPA will have no standing to challenge the work.

Health and Safety: The public and users should remain un-impacted by this engineering solution, in respect to health and safety. OSHA should also have no standing

since the system will merely be business as usual for most users. No special training is required to understand the prototype's health and safety impact.

Ethical, Social and Political: No ethical or social considerations were made because it only involves adapting existing transmission waves and existing computers for other uses. However, room must be made for political matters. Funding for navigation systems can be cruel and capricious, so the system must be sold to the stockholders, or die a quick and ultimately useless death at the hands of budget cutters and legislators. For this reason the system is meant to operate as a back-up and supplement for normal GPS navigation.

Works Cited

[1]CAPT Peterson, CAPT Hartnett. "Beacon/Loran Integrated Navigation concept." (n.d.).

[2] DeMinco, Nicolas. "Propagation Prediction Techniques and Antenna Modeling (150-1705 KHz) for Intellignet Transportation Systems (ITS) Broadcast Applications." IEEE (2000): 9-33.

DGPS Ranging
1/c Hatch & 1/c Dolton
Test Plan
25 March 2008

Synopsis: The following tests are designed to allow our method of using terrestrial DGPS beacons for ranging to be accepted as a viable part of electronic navigation. The four tests discuss the following: establishing theoretical periodicity, gathering data on sky wave interference, verifying a mathematical model of the phase to range conversion, and taking experimental data to determine required equipment specifications.

Personnel: CAPT Hartnett, LT Rothberg, 1/c Hatch, and 1/c Dolton are required for all four of the tests to analyze the results and agree on the validity. To execute the tests the personnel requirements vary.

1. Fast Phase-Chaser and Visual Phase-Chaser M-Files: one person.
2. Vehicle-based data collection: one person qualified to operate vehicle, data collection is autonomous.
3. Phase to range conversion M-File: one person.
4. Experimental Phase discrimination: two people to carry the equipment, data collection is again autonomous.

Procedure:

For experimental data collection the procedure is as follows:

Each test below has its recommended location for testing and no approval is required since the tests are passive.

The entire test plan should be completed by April 10th to allow time for the results to be analyzed.

Equipment Required:

1. *ANRITSU Spectrum Master*
2. *Bluetooth Laptop*
3. *TRIMBLE GPS Backpack*
4. *Computer with MATLAB and .edu access*

Initial Set-up: The system's for testing are in two parts.

1. The setup for the experimental data gathering mentioned above is outlined in the procedures

section. It consists of powering the equipment, initializing it, and automating it. There is no need for any personnel off-site. Weather considerations and time of day are factors in some experiments and must all be met in any order to ensure quality data.

2. The setup for the MATLAB M-Files is even simpler. All that is needed is a computer with MATLAB that has access to the Academy .edu network or a jump drive with the files loaded on it.

Parameter	**Required Value**
Range without skywave interference	150 km
Maximum phase difference noted by equipment	3 mradians

Test # 1 – *Fast Phase-Chaser & Visual Phase-Chaser M-Files*

Objective: Analyze the nature of the DGPS MSK signal to determine if the lane ambiguity of the binary phase pairs will prevent it from being useable at a distance of 150 km from the transmitter.

Requirements: Useable a reasonable distance from the nearest DGPS transmitter (2b). This requirement is based on our predictions of the skywave interference range that would prevent the signal from being received. Currently that range is 150 km. If this test discovers that the lane ambiguity is less than 150 km we will have to develop further software processing techniques to use DGPS MSK beacons.

Test Overview: Explore the theoretical cycle of phases between the zero and one bits in the MSK encoded DGPS signal. Quantifying the lane ambiguity is one limiting factor on the distance from transmitter the signal is useable. The MATLAB simulation will generate phase pairs beginning at the beacon and takes the difference between the two phases as a simulated receiver increases in distance from the beacon. The simulation compares the difference between the two phases and detects when they are equal. At that point they have passed through one 'lane' and the result is converted to distance.

Test Procedure:

1. Build a program that plots the phase of the binary '1' and '0' simultaneously, takes the difference of the phases, and displays both numerically and graphically the difference at any given time.
2. One program named "Fast" will output the position of phase repetitions/matches as the "Store" variable, the wavelength of the repetition cycle as "l_fphase" and the frequency as "fphase." These are the three parts of the difference between the two phases.
3. The other program named "Visual" will show a graphic representing the phases at a specific time/distance from the transmitter reflecting the relationship of the phases.
4. Run the M-File and read the outputs in the command window and observe the figure.
5. Record results.
6. Procedure should take minutes to execute the files. Analyzing the data may take up to 5 minutes.

Results:

Frequency of repetition _____ (frequency)

Distance of repetition from beacon _____ (time)

Distance of repetition from beacon _____ (distance)

Test # 2 – *Vehicle-Based Data Collection*

Objective: Collect data for signal strength and phase for the Moriches, Sandy Hook, and Acushnet and establish a radial distance at which the skywave interferes with the field strength of the signal in such a way that it prevents our method of DGPS ranging from being applied. We know that skywave interference will affect our signal but we don't know how it will affect the phase of the signal or how far from the beacon we can place a receiver that functions.

Requirements: Useable a reasonable distance from the nearest DGPS transmitter (2b). This requirement is based on our predictions of the skywave interference range that would prevent the signal from being received. This test in particular is designed to refine that requirement by taking experimental data.

Test Overview: Fly/Drive/Sail in the New England area to collect signal readings from multiple beacons. Post-process collected data to gain an understanding of signal behavior and gain insights to the distance the skywave begins to interfere with the groundwave. The final analysis of the

Test Procedure:

1. Turn on testing set-up.
    a. Backpack: Connect battery-pack in the DGPS backpack, turn on switch for Bluetooth connection at the top of the pack..
    b. Anritsu Spectrum Master: Turn on unit by pressing the green button, unit will blink and hold with a green light. Recall settings DGPS.
    c. Laptop: Log-on to the laptop. Open shortcut on desktop, DGPS testing. Run the eNavLab1.m file in MATLAB.
2. Fly/Drive/Sail the route required by the method available. Record magnitude, time, weather, and nuances of the certain geographic position.
3. Once done with route, stop MATLAB code running. Extract the required data:
    a. DGPS: Run extraction code.
    b. Anritsu: Use program and script file.
4. Analyze data and agree with project team on likely point of skywave interference.
5. Repeat experiment focusing at previous estimate of skywave interference point until CAPT Hartnett is satisfied with the results.

Results:

Plot of field strength vs. radial distance __

Radial distance from beacon where skywave interference noticeably affects the field strength _____

Test # 3 – *Phase to Range Conversion M-File*

Objective: Test the techniques required to convert phase measurements of a DGPS MSK beacon signal to range in a mathematical model and identify any potential problems with the method.

Requirements: Alternate Electronic Navigation System (1). The projects ideal goal is to prove that DGPS can be used to find a range to a terrestrial beacon. One part of that acceptance that this tests is using the two different MSK phases to calculate a range.

Test Overview: Test a mathematical model for converting both coordinate pair of phase measurements to a range or a range to its possible coordinate pairs. Plot the results and determine if the solution is implementable in software.
Hypothesize what phase accuracy is required.
Hypothesize a method for dealing with measurements that have error.

Test Procedure: Build code to view the problem in both two and three dimensions and solve for a series of phases and ranges in MATLAB. Write approximation functions to deal with possible experimental error and prepare hypotheses for field experiments.

The code can be found in the "PS Senior Design" folder on \\edufp1\Cadet Temp Storage.

This procedure is complete when the Sponsor, CAPT Hartnett, approves of the findings and definitively states the maximum theoretical accuracy of the method, the lane ambiguity, and the required phase discrimination for the method to work. We also require his approval for the method of resolving error.

Results:

Approval of CAPT Hartnett _____

Test # 4 – *Experimental Phase Discrimination*

Objective: Discover how accurately we can discriminate between the two phases of the binary '1' and '0' with our equipment and how they fluctuate with distance, time, and weather.

Requirements: Reasonable level of accuracy (2a). This requirement deals with the actual effectiveness of the DGPS beacon range. As of now we are attempting to achieve 3m accuracy in range with the phase measurements.

Test Overview: Using the same procedure as Vehicle-Based Data Collection but record phase measurements instead of magnitude. Use MATLAB method already developed to convert phase measurements to range and compare with actual range gathered by GPS unit working in tandem.

Test Procedure: Initialize test equipment on the USCGA academy with two personnel carrying the equipment to record during the full battery time of the ANRITSU. This takes place in two phases:

1. Stationary Phase: Let the equipment sit at a fixed range from the transmitter and see how the phase changes as a function of time.
2. Mobile Phase: Move the equipment all over the academy and discover how the phases matche the traveled path ranges recorded by the GPS unit.

If possible, repeat experiment in overcast or rainy conditions and compare to clear conditions.

This experiment does not cover the affect of the receivers speed.

This experiment will be successful if there is a 3m accuracy for range difference in the mobile measurements and if the variation during the stationary phase does not take it outside a 3m range.

Results:

	Stationary/Mobile	Fair Wx/Foul Wx	Day/Night
Phase Resolution Adequate (Yes/No)			
Phase Resolution Phase Required			

DGPS Ranging

1/c Sam Hatch & 1/c Peter Dolton

Design Specification

08 April 08

Purpose:

There have been occurrences where the CG was prevented from escorting ships into port in CA due to GPS denial. Concurrent work done on GPS jamming and spoofing by 1/c Ellsworth indicates that it is very easy to deprive the US of its primary means of navigation. Knowing full well that 90% of the worlds' commerce travels by sea, the safety and security of the US economy requires a back-up to GPS. Therefore, we designed a system that computes a range from a DGPS beacon that can be used in conjunction with the eLORAN system to improve Geometric dilution of precision (GDOP) to an electronic fix. Furthermore we are investigating a method that should be applicable to numerous other signals of opportunity, such as radio and cell phones, because as prudent mariners we are interested in using all means available for safe navigation.

Design Solution:

Our design solution falls into two parts. The first part is research into the mathematical algorithms for converting the information we can receive from the DGPS beacons to ranges and whether that mathematical model is practically feasible. The second part involves the

investigation of the physical properties of the beacon's signal in order to determine whether interference renders the algorithm irrelevant. Figure 1 below displays the two different parts of the project.

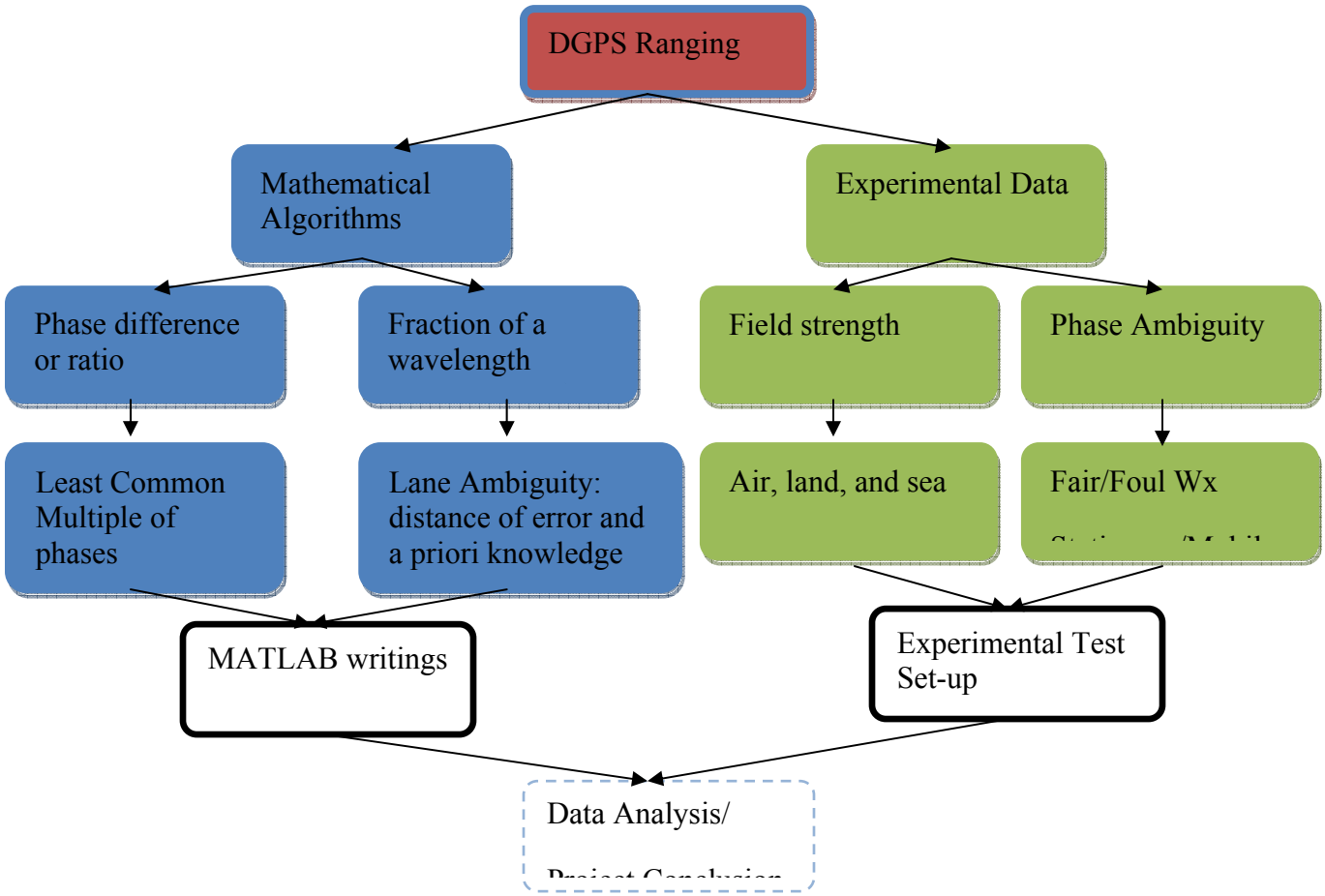


Figure 1: Flowchart of Project Work

Using the methods described in Beacon/Loran Integrated Navigation Concept (BLINC) [1], we tested a method to use DGPS beacons for ranges. The Minimum Shift Keying (MSK) properties of the DGPS signal allowed us to calculate the range from a known beacon using the two separate frequencies and phases of the binary '1' and binary '0'. It was proved that ordered pairs of phases, phase difference, or a ratio of the phases could be converted to a range based on

the fixed position of the DGPS beacons. However, this required the assumption that the beacons transmitted with extremely accurate time. Currently we are investigating exactly how accurate the timing needs to be so we can decide whether to use the timing from an eLORAN receiver or whether a Cesium oscillator is required at each DGPS station. In addition, we are also investigating the phase sensitivity that the receiver would require in order to achieve 10m accuracy. Finally, we are investigating the range at which the unique nature of the paired phases repeats to determine whether there is a lane ambiguity problem or not. This lane ambiguity exists because of the periodic repetition of the binary 0 and 1 phases at certain wavelengths from the transmitter. Figure 2 below illustrates how the unique MSK signal translates into the phases of the binary 1 and 0 resulting in a lane ambiguity represented by the rows of blue dots in figure2.2

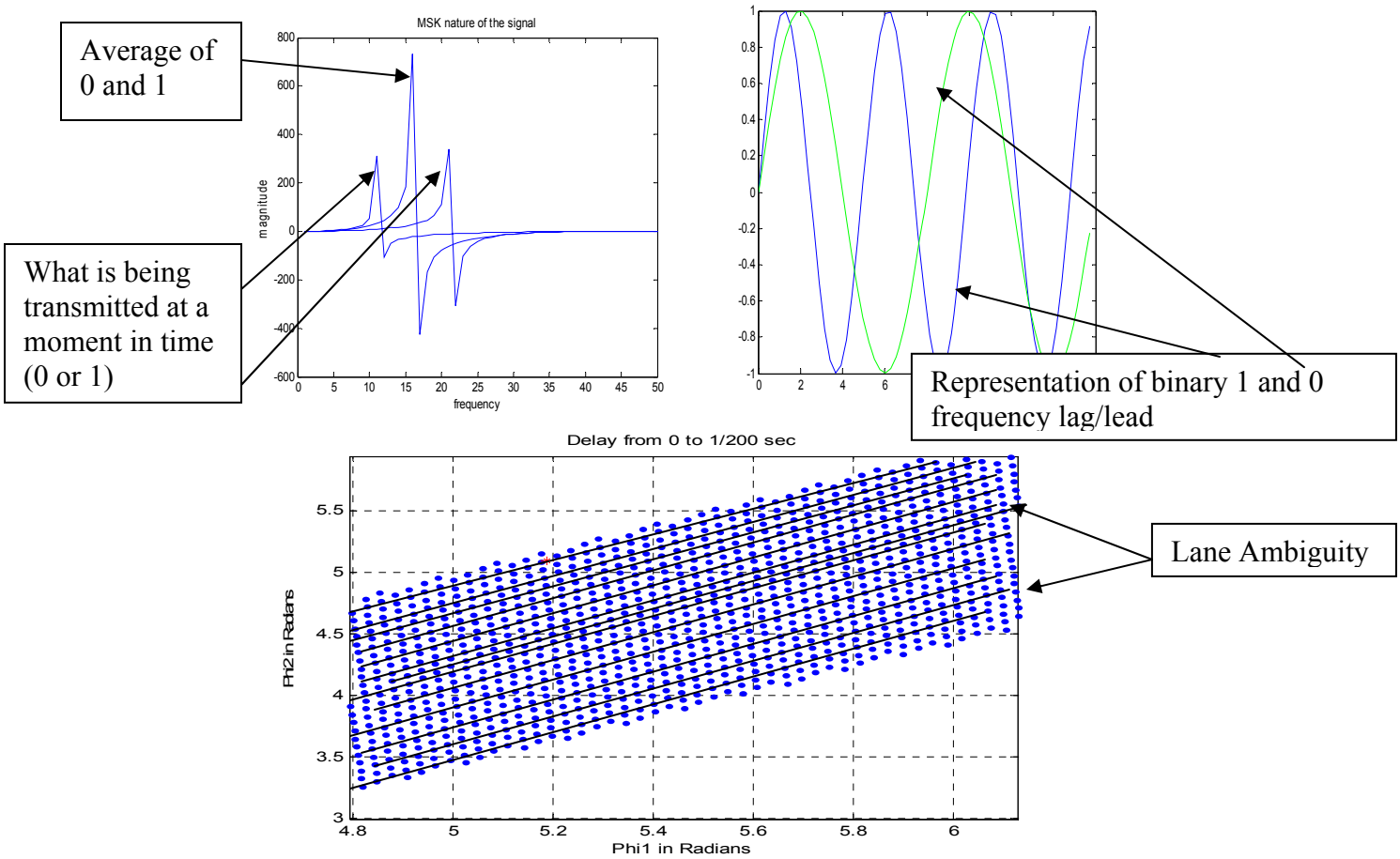


Figure 2.1Figure showing MSK 2.2 Frequencies of binary 1 and 0 2.3 Lane Ambiguity

If there is a lane ambiguity we must use the relationship $\lambda = c/f$(wavelength = speed of light/frequency) to calculate the fraction of a wavelength the receiver is from the beacon. If it is possible to relate the phases to each other by ratio or differential then we will be able to find a deterministic equation that relates the range to phase relationships. This discussion is more of a design choice than a requirement because we have working MATLAB representations of both methods.

The second part of the project involves analyzing the physical properties of the signal propagation to determine the maximum effective range. A study conducted in 2000 by DeMinco suggests that in the MF band the sky wave interference is not a factor until 150km from the transmitter [2]. If this hypothesis is supported by the data we gather, further funding and resources may be assigned to this project, opening up new possibilities and applications. The system we designed to collect the skywave data is shown below in figure 3.

Figure 3: 3.1 Geographic picture of 50km ranges from transmitter 3.2 Land test route

In particular, the system that we used to measure the skywave involved the assembly of a testing setup, supplying power to the testing setup, and developing code to analyze the results. The skywave testing required the following equipment: an antenna capable of receiving GPS & DGPS signals, a computer program to record the GPS position data, and an ANRITSU spectrum analyzer that could record the strength of the signal for the three closest DGPS stations: Sandy Hook, Moriches, and Acushnet. We found that we were able to automate both the GPS and the ANRITSU to record the data which we later correlated with the time of the MSK measurement. We assumed that the time inaccuracy due to the quartz oscillators in the computer and the ANRITSU were negligible because we were looking on the scale of NM so a difference of even 10 seconds would not interfere with this portion of the project. Supplying power to the GPS receiver and the ANRITSU was easily accomplished since they operate on 12V DC and there were batteries and cigarette lighter converters in lab for them. Because we were unable to construct or find a converter for the laptop, its battery life was our limiting factor on recording measurements. The setup is shown below:

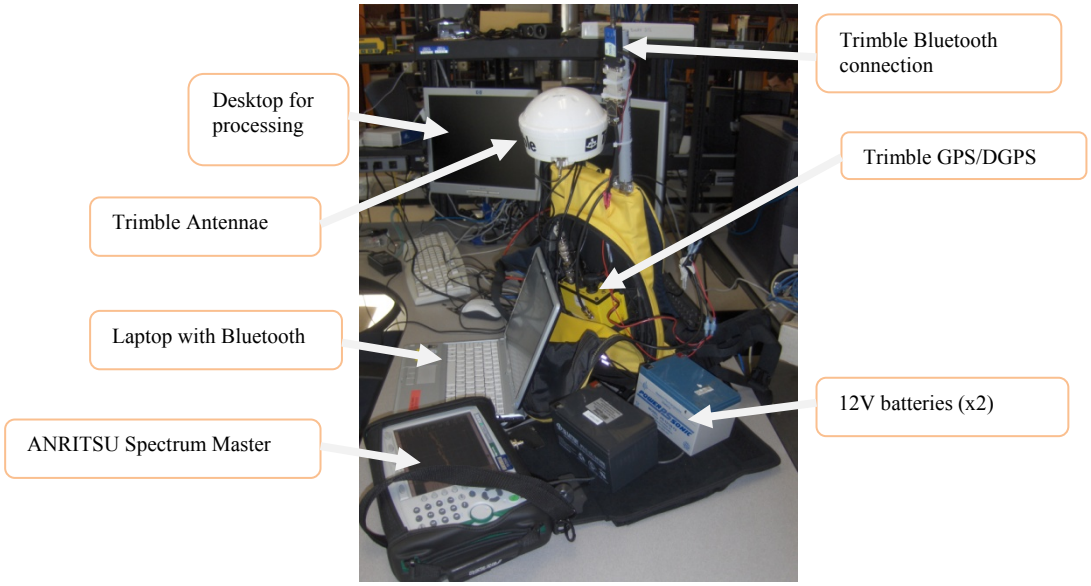


Figure 4: ANRITSU/GPS experimental set-up

Finally we had to match the field strength measurements with the distance they were taken from their respective stations. To do this we used MATLAB to create two vectors: one which contained the ANRITSU data which was then updated with the ranges that corresponded to the measurements. This was done by comparing the timestamps of the ANRITSU and GPS data. Finally we plotted the results to display the field strength as a function of distance from the transmitter. The figure below outlines the data extraction algorithm:

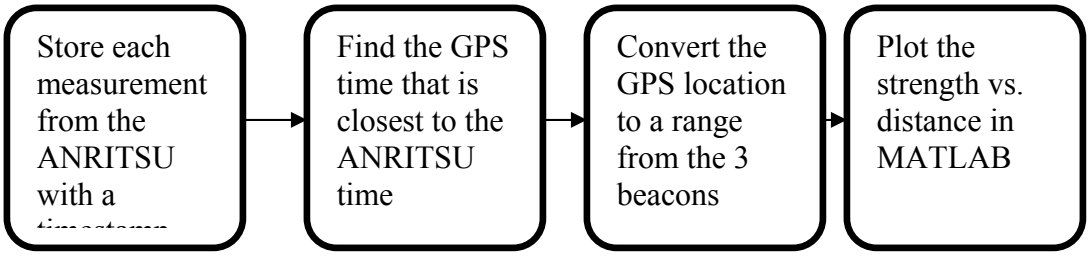


Figure 5: Flow chart of data extraction code

There is still additional work to be done on this portion of the project. To be a complete investigation we must record the data during day and night, fair and foul weather, and over ground and sea. This is may not be required for the project to be accepted but will eventually be required to inform consumers of the maximum expected ranges.

Eventually, the project goal is to construct a receiver that integrates DGPS signals and eLORAN. This will improve the geometry of the fixes, providing an accurate, reliable, and terrestrial navigation system that can support CG operations. All that is required for this receiver is the algorithm, some form of accurate, GPS independent timing at the DGPS beacon stations, and a receiver sensitive enough to discriminate between the two phases.

Design Decisions:

Support Considerations:

Economic: The hardware for the project had already been purchased including the ANRITSU spectrum master, laptop from networks class, and borrowed GPS TRIMBLE backpack so there is no additional funding required at this time. The consideration for accurate timing may require Cesium beam oscillators but we are currently investigating using eLORAN receivers for timing to lessen the cost of installation at the DGPS sites.

Manufacturability: The design is a prototype to prove that LORAN and DGPS TOA navigation is feasible and accurate. The receiver prototype that is developed will be implementable through software so that existing units will be upgradeable to a new method. The actual product would be contracted out and built commercially.

Sustainability and Reliability: Sustainability of the system will be dependent on how long the legacy and secondary systems it relies on remain operational. In March of 2008 the government decided that eLORAN will be continued as an official backup navigation system so the Coast Guard can depend on eLORAN being present for the foreseeable future. The prototype does not require spare parts and it is beyond the scope of this project to design a maintenance project for the fleet. Being a back-up system to GPS requires it to be reliable at all times.

Life-Cycle Costs: The life-cycle of our design is paired with the developments in the systems it is dependent on, such as LORAN and DGPS transmitters. The only possible costs from this system would be the upgrading of existing equipment software and training people to use it. If the prototype is succeeds, C2CEN will take interest and present the idea to

commercial companies. Therefore, final adoption of the project would involve costs per unit purchased commercially at no more cost than is already used to maintain the DGPS stations.

External Considerations:

Environmental: The design should have no impact on the environment. The system uses existing signal radiation, equipment and manpower so there is no more environmental impact. In addition, since there is effectively no new equipment, disposal of equipment can be handled through existing methods. No new civil engineering is required either, so the EPA will have no standing to challenge the work.

Health and Safety: The public and users should remain un-impacted by this engineering solution, in respect to health and safety. OSHA should also have no standing since the system will merely be business as usual for most users. No special training is required to understand the prototype's health and safety impact.

Ethical, Social and Political: There are no ethical or social considerations at this time other than those already associated with electronic navigation and radiation pollution. There is a political discussion about what department of the government should be responsible for maintaining the infrastructure and who is responsible for the reicievers.

Software Considerations:

Privacy: All of the software we have developed will be open source code because the USCG cannot patent anything. In addition, the software developed for the receiver is merely an implementation of previously known techniques so it is not practical to protect it.

Security: There is no need to enable security for the software we have written.

Requirements:

1. Alternative to GPS
    a. Reasonable level of accuracy (>3m): The data for this has not been discovered at this time and verification is beyond the scope of this project. With that being said, our mathematical models in MATLAB theoretically have an accuracy of greater than 3m.
    b. Useable a reasonable distance from the transmitter: This involves two physical properties: the signal strength and the phase interference. We have just received the data to determine maximum signal strength range and the results are forthcoming. The equipment for measuring the phase interference is not available at this time and but we have discovered the mathematical requirement for 3m accuracy converted to phase discrimination. Also, because the DGPS stations are not transmitting with accurate time it is impossible to measure the accuracy of the phase without first obtaining access to the DPGS site.

c. Low Cost: we have satisfied this requirement in our study by using already purchased equipment. We are investigating whether using eLORAN receivers at DPGS stations for accurate timing will provide accurate enough phase measurements to obtain the accuracy.

d. Less vulnerable to jamming or spoofing: this was an inherent property of the DGPS MF terrestrial beacon signal. Its lower frequency increases the size of antennae required for jamming or spoofing. The fact that it is a terrestrial system allows it to have a large power budget that is not easily overpowered.

2. Does not interfere with current infrastructure: The current plan is to simply change when the DGPS beacons transmit which will not interfere with their original function of transmitting corrections to DGPS receivers. If larger phase discrimination is required, the signal might require modification to increase the MSK index. This would require further analysis to determine the effect on legacy users.

3. Can interact with future systems: this aspect of the project requires the prototype to be constructed first for future systems to be theorized. In general, we have provided well documented code and thorough testing procedures that will allow future developers to retrace our work and adapt it to future projects.

Works Cited

[1] B. Peterson and R. Hartnett, "Beacon/ELORAN Integrated Navigation Concept: A Proposal

for an Integrated 100/300 kHz Ranging System," *Unpublished Paper,* Oct. 2007.

[2] Nicholas DeMinco, "Propagation Prediction Techniques and Antenna Modeling (150 to 1705 kHz) for Intelligent Transportation Systems (ITS) Broadcast Applications," *IEEE*, Aug. 2000.

Field Strength MATLAB Code

Used to plot GPS position/range vs. ANRITSU spectrum master measurements

Data Collection.M

```
% 1/c Peter Dolton
% 1/c Sam Hatch
% Data collection and plotting program for determining the range that a DGPS
% beacon that he signal is useful.
%
% This is the main program.
% It calls the function search_file to pull the field strength and time
% from a particular ANRITSU .spa file in the directory.
% It must then call the function gps_text_store to pull the GPS LAT and
% LONG from a text file created by Excel.
% Finally the main program will call the function plot_gps_ANRIT_data
% to plot the range vs. signal strength and LAT vs. LONG vs. signal
% strength.

% This is set to the default time that the machine can run on battery: 2
% hours and 41 minutes
% n = (2+41/60)*60*60;

% This is the time that the ANRITSU actually recorded
% There is a lot of wasted time here...
n = 20080328090410-20080328053019 ;

% The time is given in year, month, day, military time, seconds in a .spa
% file.
file_name_time = 20080328053019 ;

% A nX4 matrix that has 4 colums of: Time|Moriches|Sandy Hook|Acushnet
ANRIT_master_vec = [] ;
% This is a 1x3 Matrix that temporarily stores the 3 measurements before
% being incoporated in the ANRIT_master_vec.
data_vec = [] ;

for i=0:1:n

    % ANRITSU is a file identifier or -1 if the file does not exist.
    SPA_file_name = ['EOS' num2str(file_name_time) '.spa'];
    ANRITSU = fopen(SPA_file_name);

    if  ANRITSU ~= -1
        % This stores the information in the vector in the following order:
        % time of measurement followed by three field strength
        % measurements.

        % This conversion is simply so that to watch the values put into
        % ANRIT_master_vec because if the time is to large the values
        % appear as zeros.
```

```
        converted_time = num2str(file_name_time);
        converted_time = converted_time(9:14);
        converted_time = str2num(converted_time);

        data_vec = search_file(ANRITSU);
        ANRIT_master_vec = [ANRIT_master_vec; [converted_time data_vec]];

        fclose(ANRITSU);
    end;

    file_name_time = file_name_time + 1 ;

end;

%User created function
position_vec = gps_text_store();

% User Created function
plot_gps_ANRIT_data(position_vec, ANRIT_master_vec);
```

GPS_Text_store

```
function [position_vec] = gps_text_store()

% 1/c Peter Dolton
% 1/c Sam Hatch
% Function: gps_text_store()
% Parameters: none
% Returns: None
% Description: This funciton opens a file that must be hard-coded in and
%   stores every 15th sample in a data structure by position. It stores
%   every 15th because that is the time between ANRITSU samples.


%There is always going to be one GPS file, the information is embedded in
%it. Now we are using our file created by excel
GPS_file_name_str = 'excel_gps.txt' ;

GPS_file_tag = fopen(GPS_file_name_str);

position_vec = [];

time = 0;

while (time < 6449)
   % This gets the next line of the file
   time = fscanf(GPS_file_tag, '%d5',1);
   LAT = fscanf(GPS_file_tag, '%g11',1);
   LONG = fscanf(GPS_file_tag, '%g11',1);

    if mod(time,15) == 0
```

```
        LAT  = num2str(LAT);
        LAT_deg = str2num(LAT(1:2));
        LAT_min = str2num(LAT(3:4));
        LONG = num2str(LONG);
        LONG_deg = str2num(LONG(1:2));
        LONG_min = str2num(LONG(3:4));

        LAT = LAT_deg + LAT_min/60 ;
        LONG = -1*LONG_deg - LONG_min/60 ;

        % We stored the information as degreesminutes.decimal?
        position = [LAT LONG]  ;

        position_vec = [position_vec; position];
    end
end

fclose(GPS_file_tag);
```

MyRange

```
function S=MyRange(Xmtr,MyLocation)

%Xmtr is the Lat/Lon of the Transmitter
%MyLocation is the Lat/Lon of my location
%
% the return value is S, which is range in meters between
% Xmtr and MyLocation


RE=6378135.0;   % Equatorial radius in meters  WGS-84
RP=6356750.5;   % Polar radius in meters
Min=0.9e-05;

OurPosit=MyLocation;
TransPosit=Xmtr;
%****************************************
Rat=RP/RE;
Pone=atan(Rat*tan((pi/180.0)*TransPosit(1)));
Ptwo=atan(Rat*tan((pi/180.0)*OurPosit(1)));
%C is the difference in longitudes in radians
C=(pi/180.0)*abs((TransPosit(2)-OurPosit(2)));
Cone=abs(C-pi);

if (C<Min)|(Cone<Min),
   if (C<Min),
      disp(['C is less than minimum value']);
      CC=abs(Pone-Ptwo);  %  ********  CHANGED
   end;
   if (Cone<Min),
```

```
      disp(['Cone is less than minimum value']);
      CC=pi-abs(Pone+Ptwo);
   end;
   H=sin(CC);
else
   D=sin((Pone-Ptwo)/2);                        %check
   E=sin((pi-(Pone+Ptwo))/2.0);                 %check
   Aone=atan((D*cos(C/2))/(E*sin(C/2.0)));      %check
   F=cos((Pone-Ptwo)/2.0);                      %check
   G=cos((pi-(Pone+Ptwo))/2.0);                 %check
   Atwo=atan((F*cos(C/2.0))/(G*sin(C/2.0)));    %check
   A=Aone+Atwo;                                 %check
   H=((sin(C))*sin(pi/2.0 - Ptwo))/sin(A);      %check
   CC=asin(H);
end;
I=cos(CC);
J=sin(Pone);
K=sin(Ptwo);
M=(J+K)^2;
N=(J-K)^2;
U=(CC-H)/(1.0+I);
V=(CC+H)/(1.0-I);
%S is range in meters
S=(RE*CC)-(((M*U) + (N*V))*(RE-RP)/4.0);
%disp([sprintf('Arc length = %.1f',S) ' meters']);
StatuteMiles=S*0.6213711922e-03;
NauticalMiles=StatuteMiles*5280/6000;

return;
```

plot_gps_ANRIT_data

```
function [] = plot_gps_ANRIT_data(position_vec, ANRIT_master_vec)

% 1/c Peter Dolton
% 1/c Sam Hatch
% Function: plot_gps_ANRIT_data()
% Inputs/Outputs: None
% Description:    This function is responsible for the construction of the
% range vector that is eventually plotted vs. the field strength
% measurement at any one. It also plots the 3D plot of the field strength
% as it relates to LAT and LONG.
% This function uses the user defined function MyRange to calculate the
% range from [LAT LONG] in degrees. LAT: E(-) W(+) LONG:N(-)S(+)
% The following are the locations of the three DGPS sites:
% Acushnet:     41 44.57N, 070 53.19W
% Moriches:     40 48.3N, 072 45.68W
% Sandy Hook:   40 28.29N, 074 00.71W



range_vec = [];

limit_pos_vec = size(position_vec);
```

```
for index = 1:limit_pos_vec(1)
    range_Acushnet = MyRange([41+44/60 -70-53/60],...
        [position_vec(index,:) ])/1000;
    range_Moriches = MyRange([40+47/60 -72-44/60],...
        [position_vec(index,:) ])/1000;
    range_SandyHook = MyRange([40+28.5/60 -74-0.71/60],...
        [position_vec(index,:) ])/1000;

    % Push the next three ranges on teh vector
    range_vec = [range_vec; range_Acushnet range_Moriches range_SandyHook];
end;
% Now we will plot the range_vec values vs. the ANRIT_master_vec values.

figure(1)
hold on;
plot(range_vec(:,2),-1*ANRIT_master_vec(1:397,2),'r-');
plot(range_vec(:,1),-1*ANRIT_master_vec(1:397,3),'g-');
plot(range_vec(:,3),-1*ANRIT_master_vec(1:397,4),'b-');
legend('Moriches','Acushnet','Sandy Hook')
title('Field Strength of DGPS signal as a function of range')
xlabel('Range in km ')
ylabel('Field strength in dB')
hold off;

figure(2)
hold on;
plot3(position_vec(:,1),position_vec(:,2) ,-1*ANRIT_master_vec(1:397,2),'r-
');
plot3(position_vec(:,1),position_vec(:,2),-1*ANRIT_master_vec(1:397,3),'g-');
plot3(position_vec(:,1),position_vec(:,2),-1*ANRIT_master_vec(1:397,4),'b-');
legend('Moriches','Acushnet','Sandy Hook')
title('Field Strength of DGPS signal as a function of LAT and LONG')
xlabel('LAT in degrees')
ylabel('LONG in degrees')
zlabel('Field strength in dB')
hold off;
```

plot_route

```
function [] = plot_route()

% 1/c Peter Dolton
% 1/c Sam Hatch
% Function: plot_route()
% Description: Extract the GPS data from the file that we created and plot
% it with the mapping software to get independent confirmation that the GPS
% data is good.
% Input: None (user types in the file name on the first line of code)
% Returns: None (plots a figure of the points extracted for visual
% confirmation.
```

```
% input file name manually
GPS_file_name_str = 'G-28-Mar-2008.txt' ;

GPS_file_tag = fopen(GPS_file_name_str);

% Create a new file that will store all the lines read in this program
% BUILT FOR DEBUGGING ONLY
fid = fopen('GPS_lines_read.txt','w');

% Case for GPS recording every second
while feof(GPS_file_tag) == 0

   % This gets one line of the file
   tline = fgetl(GPS_file_tag);

   % Weird file quirk makes every other line show up blank. This removes it
   if length(tline) == 0
        % This gets one line of the file
        tline = fgetl(GPS_file_tag);

        % write the lines to a file

        fprintf(fid,tline);

   end;

%    % Because of the way the file is structured this should extract the time
%    % from the GPS line
%    timestart = 8;
%    searched_time = str2num(tline(timestart:timestart+6))/100;
%
%    % This is where the time should start
%    latlongstart = 19;
%    LAT = str2num(tline(latlongstart, latlongstart+12));
%    LONG = str2num(tline(latlongstart+16:latlongstart+28));
%
%    position = LAT+LONG*j;
%

   %display('There was no time equal to the search time on that line')
end

% plot(real(position), imag(position))

status = fclose(fid);
```

search_file

```
function [data_vec] = search_file(ANRITSU)

% 1/c Peter Dolton
% 1/c Sam Hatch
```

```
% Function: serach_file()
% Parameters: ANRITSU        String that contains the filename of an
%                            ANRITSU text file to be searched.
%
% Description:               Searches the file for the field strength of
%                            Moriches (293k), Sandy Hook (301k), and
%                            Acushnet (306k) and records the field strength
%                            in the order that the ANRITSU records the
%                            markers.

% This is the number of significant figures that the ANRITSU records in its
% field strength measurements.
sigfigs = 8;

% This is the first string that we are searching for. After it is found we
% will change it to the next thing we are searching for.
% I'm operating on the assumption right now that Marker0 is actually
% Marker1
text_searched = 'MKR_REF_MAGNT0';

% This keeps track of which text we are searching for and increments
% number_text = 1           we are searching for Maker1
% number_text = 2           we are searching for Maker2
% number_text = 3           we are searching for Maker3
number_text = 1;

data_vec = [0, 0, 0];

while feof(ANRITSU) == 0

   % Change the string we are searching for
   if number_text == 1
       text_searched = 'MKR_REF_MAGNT0';
   else if number_text == 2
        text_searched = 'MKR_REF_MAGNT1';
       else if number_text == 3
               text_searched = 'MKR_REF_MAGNT2';
           end;
       end;
   end;

   % This gets one line of the file
   tline = fgetl(ANRITSU);

   % Search here for whatever strings I'm looking for and stores the
   % starting index of the searching string.
   start_index = findstr(tline, text_searched);

   % This just checks if there were any matches on that line
   num = length(start_index);

   if num > 0
       % take the field strength and make it a number
```

```
        field_stre = str2num(tline(start_index+16:start_index+16+sigfigs));
        % Push that number on the end of the Data_vec
        data_vec(number_text) = field_stre;

        % Change the string that we are searching for
        number_text = number_text+1 ;
    end
end
% Done in main program
% fclose(ANRITSU);
```

Visual Phase Chaser (Phase difference discrimination)

Code written to discover how accurate this method could be and what the hardware would have to discern in order to get that accuracy. It also displays a visual graphic of the two phases and how they separate over time.

```
clear all;hold off;clf;clc;
%Group Moriches DGPS Transmitter
    Bitrate = 100;
    %Signaling Frequencies
    Cf = 293000;
    f1 = Cf + Bitrate/4;
    f0 = Cf - Bitrate/4;
    %Period @ Signaling Frequencies
    p1 = 1/f1;
    p0 = 1/f0;
%Set Range and Resolution of Samples
Res = 9;
Max = 0.01;
Min = 0;
%Constants and Resulting Resolutions
C=2.99792458e+8; %Speed of Light in Atmo. m/s
disp( ['Accuracy (in meters)is: ' num2str(C*10^(-Res) )] );
disp( ['Accuracy (in radians) is ?: ' num2str(10^(-Res) )]);
%Zero the Variables
Delta1 = 0;
Delta0 = 0;
Dist = 0;
%Calculate Deltas and Distances
h = waitbar(0,'Please wait Calculating:');
for Tau=Min:1*10^-Res:Max,
     %Calculate the Phases of the DGPS Signal
     Phi1= exp(j*f1*Tau);
     Phi0= exp(j*f0*Tau);
     %Calculate Distance from the Transmitter
     Dist = C * Tau; %meters
     strDist = num2str(Dist);
     compass(Phi1,'r');
     text(real(Phi1),imag(Phi1),strDist);
     hold on;
     compass(Phi0,'g');
     text(real(Phi0),imag(Phi0),strDist);
     hold off;
     waitbar(Tau/Max);
end
close(h);
```

Phase difference lane ambiguity

This code demonstrates that the repetition of the phase difference method is extremely large and not an issue to be concerned about.

```
clear all;hold off;clf;clc;
close(figure(1));
%Group Moriches DGPS Transmitter
    Bitrate = 100;
    %Signaling Frequencies
    Cf = 293000;
    f1 = Cf + Bitrate/4;
    f0 = Cf - Bitrate/4;
    %Period @ Signaling Frequencies
    p1 = 1/f1;
    p0 = 1/f0;
%Set Range and Resolution of Samples
Res = 7;
Max = 0.01;
%Constants and Resulting Resolutions
C=2.99792458e+8; %Speed of Light in Atmo. m/s
% disp( ['Accuracy (in meters)is: ' num2str(C*10^(-Res) )] );
% disp( ['Accuracy (in miliradians) is ?: ' num2str(2*pi*10^(-Res) )]);
%Zero the Variables
Delta1 = 0;
Delta0 = 0;
Dist = 0;
Store = zeros(0,0);
%Calculate Deltas and Distances
h = waitbar(0,'Please wait Calculating:');
for Tau=0:1*10^-Res:Max,
     %Calculate the Phases of the DGPS Signal
     Phi1= exp(j*f1*Tau);
     Phi0= exp(j*f0*Tau);
     %Calculate Distance from the Transmitter
     Dist = C * Tau; %meters
     waitbar(Tau/Max);
     %Check for Redundant Phase Matchings across Frequencies
     if ( (Phi1 ~= 0 && Phi0 ~= 0 && Phi1 == Phi0) )
         Cnvrg = [Phi0,Phi0,Dist];
         Store = [Store  Cnvrg ];
     end
end
Store
close(h);
%Mathimatically Predict Repetition-Rate
%l_f1 etc. is the wavelength
l_f1 = round(C / f1 * 10^9);%nanometer
l_f0 = round(C / f0 * 10^9);%nanometer
%l_fphase is the wavelength of the phase repetition
l_fphase = ( lcm(l_f1,l_f0) * 10^(-9) )
fphase = C / l_fphase
```

Ordered Pair Calculations

This MATLAB file was written by CAPT Hartnett. It demonstrates the translation of ranges into ordered pairs.

```
%Group Moriches bit rate
clear all;hold off;clf;clc;
BitRate=100;
% two signaling frequencies for Moriches
f1=293000+BitRate/4;
f2=293000-BitRate/4;
Period1=1/f1;
Period2=1/f2;

Delta1=[];
Delta2=[];
for Tau=0:1e-5:1/1000,
    Delta1=[Delta1 rem(Tau,Period1)];  %in seconds
    Delta2=[Delta2 rem(Tau,Period2)];  %in seconds
end;

plot(Delta1*2*pi*f1,Delta2*2*pi*f2,'.');
grid;
xlabel('Phi1 in Radians');
ylabel('Phi2 in Radians');
title('Delay from 0 to 1/200 sec')

%distance from USCGA to Morches Transmitter in km
dist = (MyRange([40+47/60 -72-44/60],[41+22/60 -72-5/60]))/1000

%now let's look at what combinations of "Delta1 & Delta2" would occur
%within a K km radius of USCGA ...

C=2.99792458e+8;  % approximate speed of light in air, m/s

Transit_Time=(1000*dist)/C;

USCGA_Delta1=rem(Transit_Time,Period1);
USCGA_Delta2=rem(Transit_Time,Period2);
hold on;
plot(USCGA_Delta1*2*pi*f1,USCGA_Delta2*2*pi*f2,'r*');
```