Hybrid Renewable Energy Systems for a Dynamically Positioned Buoy

by

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Hybrid Renewable Energy Systems for a Dynamically Positioned Buoy

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Abstract

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Robert Sean Pagliari

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To ease the burdens associated with deep ocean buoy moorings, a relatively recent technological development known as Dynamic Positioning (DP) could be employed. This method, which is being used on some oil drilling ships and semi-submersible platforms, provides pinpoint positioning for precision drilling and other operations with the use of multiple, multi-axis, thrusters below the waterline of a vessel to counter the effects of winds and ocean currents. This eliminates the need for anchoring in deep oceans, but depending on the characteristics of the vessel and environmental conditions, power requirements for DP tend to be quite substantial and costly.

A theoretical design of a hybrid wind and solar energy system on an ocean surface buoy is made for the purpose of powering a low cost, simple, dynamic positioning system. This system was implemented on a dynamically positioned buoy (DPB) intended for sea keeping using renewable energy sources.
Some prototypes of autonomous surface vehicles have experimented with renewable energies as a source of supplemental power, but these vehicles are typically designed as transient surface vehicles with station keeping capability as a secondary function.

A combination of design requirements set forth by 2004 Defense Advanced Research Projects Agency (DARPA) solicitation number BAA04-33 and 2008 solicitation number DARPASN08-45 are used as a basis for DPB design parameters. The aims of the DPB design thesis are to develop and test a low cost, dynamic positioning system that will continuously maintain a 250 m watch radius and to present a theoretical hybrid renewable energy system to power it, thereby improving on the station keeping buoy (SKB) energy balance problem.

Global Positioning System (GPS) technology, combined with an 8-bit embedded microcontroller and circuitry provide sufficient autonomous control signals to independent thrusters below the waterline. These correct for position offsets caused by sea and air currents in the open ocean.

The results of the system in a 2.5 m s\(^{-1}\) wind validated the feasibility of mounting a horizontal axis wind turbine on a buoy without a necessary counter balancing device. A hybrid wind and solar renewable energy system was designed using [54]. The 100% power load of about 1280 total watts proved too substantial to warrant the practicality of this renewable energy system in three out of four simulations. One optimization, however, was able to produce an annual capacity
shortage of less than 1% using an assumed duty cycle of 10% at one location. Due to pool size restrictions and ineffective tuning parameters the tested dynamic positioning system was unsuccessful in validating the capability of continuously maintaining a 250 m watch circle.
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List of Keywords

Android™
Air Mass Coefficient
Differential Global Positioning System
Dynamic Positioning
Dynamically Positioned Buoy
Embedded Systems
Global Positioning System
Kalman Filter
Ocean Buoy
Ocean Energy
Peripheral Interface Controller
Persistent Ocean Surveillance
Renewable Energy
Smart Phone
Station Keeping Buoy
Solar Energy
Wave Energy
Wind Energy
Wind Turbine
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<th>Description</th>
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<tbody>
<tr>
<td>AGM</td>
<td>Absorbed Glass Mat</td>
</tr>
<tr>
<td>ALDOS</td>
<td>Aluminum-dissolved Oxygen</td>
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ASV</td>
<td>Autonomous Surface Vehicle</td>
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<tr>
<td>ATON</td>
<td>Aids to Navigation</td>
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<tr>
<td>BRG</td>
<td>Bearing</td>
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<tr>
<td>CMOS</td>
<td>Complementary metal-oxide-semiconductor</td>
</tr>
<tr>
<td>COG</td>
<td>Course over Ground</td>
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<tr>
<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
</tr>
<tr>
<td>DD</td>
<td>Decimal Degrees</td>
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<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DMS</td>
<td>Degrees Minutes Seconds</td>
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<tr>
<td>DOE</td>
<td>Department of Energy</td>
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<tr>
<td>DP</td>
<td>Dynamic Positioning</td>
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<td>DPB</td>
<td>Dynamically Positioned Buoy</td>
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<tr>
<td>DPS</td>
<td>Dynamic Positioning System</td>
</tr>
<tr>
<td>ECEF</td>
<td>Earth Centered Earth Fixed</td>
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<tr>
<td>FLIP</td>
<td>Floating Instrument Platform</td>
</tr>
<tr>
<td>GE</td>
<td>Google Earth</td>
</tr>
<tr>
<td>FPSO</td>
<td>Floating Production Storage and Offloading</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Instrumentation System</td>
</tr>
<tr>
<td>GMT</td>
<td>Greenwich Mean Time</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>HDG</td>
<td>Heading</td>
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<tr>
<td>IMCA</td>
<td>International Marine Contractors Association</td>
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<tr>
<td>LORAN</td>
<td>Location Radio Aids to Navigation</td>
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<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
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<tr>
<td>NAD83</td>
<td>North American Datum 1983</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>NMEA</td>
<td>National Marine Electronics Association</td>
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<tr>
<td>NDBC</td>
<td>National Data Buoy Center</td>
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<tr>
<td>NREL</td>
<td>Nationals Renewable Energy Laboratory</td>
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<tr>
<td>OPT</td>
<td>Ocean Power Technologies</td>
</tr>
<tr>
<td>OTEC</td>
<td>Ocean Thermal Energy Conversion</td>
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<tr>
<td>PIC</td>
<td>Peripheral Interface Controller</td>
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<tr>
<td>PID</td>
<td>Proportional Integral Differential</td>
</tr>
<tr>
<td>POS</td>
<td>Persistent Ocean Surveillance</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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</table>
RACON: Radio and Beacon
RF: Radio Frequency
RTCC: Real-time Clock/Calendar
SBIR: Small Business Innovation Research
SKB: Station Keeping Buoy
SWAPS©: Salt Water Activated System
TCP/IP: Transmission Control Protocol/Internet Protocol
USART: Universal Synchronous Asynchronous Receive Transmit
WAN: Wide Area Network
WGS84: World Geodetic System 1984
WLAN: Wireless Local Area Network
Preface

The ocean depths around the world range from 10 m on the continental shorelines to over 11,000 m at the bottom of the deepest ocean trench, the average depth being 3000 m once past the continental shelf. These deep oceans serve as vast separations of continents and are essentially uninhabitable by humans. Throughout history man has overcome these barriers, from the beginnings of Egyptian trade routes to the circumnavigation of the globe, with sea going vessels powered first by man and sail, later by coal and steam, then petroleum and even nuclear power.

The inspirations for a dynamically positioned buoy (DPB) have been many. The first seeds were planted at the age of 14 when I experienced my first wind surfing thrill ride. Feeling the power of the wind in the palm of my hands, moving me gracefully along the white capped chop of the Halifax River, and the subsequent catapult which threw me meters away from my rig when I lost control, had gained my respect for the awesome power of the wind.

Further interest in power systems stemmed from my work as a nuclear power plant operator aboard the naval warship USS Harry S. Truman. Inspiration stemmed, also, from the work by Marshall T. Savage entitled *The Millennial Project Colonizing the Galaxy in Eight Easy Steps*. In this pseudo-science fiction novel Savage presents the idea of a floating colony anchored at sea; “*Aquarius [61]*.” He holds that, as with many civilizations throughout history, the primary building block for independence is energy.

Using an Ocean Thermal Energy Converter (OTEC), as described by Savage, is a way to harvest energy from a thermal gradient that exists in the top layer of the sea. Wind, waves, currents and photo interaction are some other known sources of energy at sea. It is important to understand, however, that all of these energies are derived from the sun. Modern accepted terminologies used to categorize this power are, renewable or green energies. While these are actually misnomers, they all allude to the general fact that they will exist as long as the sun heats the earth.

The most advantageous aspect of using renewable energy for a dynamically positioned buoy is that, by deriving power locally, it has the potential to run as long as environmental conditions allow, without anchoring or refueling.
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1. Introduction

1.1 Motivation

Ocean buoys began to appear as navigational aids in the 13\textsuperscript{th} century to mark channels throughout Spain and other Northern European inlets [1]. While this maintains the primary purpose for moored buoys, other modern uses include oceanographic, meteorological, seismic monitoring, and many other specialized tasks which require a persistent presence at a marked location in the sea. Today, several meteorological and oceanographic buoys exist throughout the oceans of the world, most notably as part of a global oceanic and atmospheric monitoring network maintained by the National Oceanic and Atmospheric Administration’s (NOAA) National Data Buoy Center (NDBC) [2]. The costs and complications of mooring such buoys, however, significantly increase with water depth. Alleviating these factors would prove invaluable for long term sea keeping endeavors.

A first DARPA solicitation used as a basis for designing a DPB using local renewable energy sources for power was announced on July 30, 2004 entitled \textit{Persistent Ocean Surveillance (POS)}. It calls for, “Station-keeping and energy harvesting technologies using local environmental effects capable of maintaining less than a 250 m watch radius for 90\% of the time and a 2,500 m watch radius for 100\% of the time over a four week period in currents as high as 1.0 m s\textsuperscript{-1}; and
 prototype (tactical sized) ocean sensing buoy with continuous RF communications [3].” A second was announced on July 31, 2008 entitled STATION KEEPING BUOY ENERGY HARVESTING/HARNESSING. It further identified, “Two primary challenges for small station keeping buoys (SKBs) that require novel technologies and concepts [4].” They are, “Maintaining a positive energy balance and operating for long periods of time on the open ocean [4].” While these grants have already been awarded, the solicitations do present a likely beginning point for further development.

A buoy that can maintain a fixed position without a mooring system offers advantages of remote instrumentation in the deep oceans, where buoy tenders spend long voyages to maintain. The applications are numerous including remote instrumentation and sensing, ocean aids to navigation, remote emergency beacons, telecommunication relay stations, or even a non-space based maritime positioning system. With readily available computer technology it is feasible to build and operate such a buoy on a low level budget and at a relatively high level of precision.

1.2 A Dynamically Positioned Buoy

Using real-time wind and solar energy the DPB can collect, convert, and redistribute power to two thrusters mounted below the waterline and to six, 12 volt 55 amp-hour absorbed glass mat (AGM) deep cycle batteries for energy storage.
The control system uses a Microchip developed PIC18f27J13 onboard microcontroller to process GPS and magnetometer data from a LOCOSYS LS20126 module. This chip also controls the set of two trolling motors, used for buoy positioning via differential drive. The LS20126 also provides 3-axis accelerometer, real time position, speed and heading data that could be used for dead reckoning input to an inertial navigation system. This type of system was not developed for the DPB. Instead, raw accelerometer data is wirelessly transmitted via a Roving Networks RN-XV, 802.11b/g standard, device with a tested range of up to 305 m. All raw data from the LS20126 module broadcasted through the RN-XV chip was received and viewed in two ways. First, using LOCOSYS developed software GPSFox Utility via virtual serial port emulator [44][43]. A second software package was developed for real time data viewing and wireless remote control of DPB using an Android smart phone. See Appendix A for software package screenshots. Due to time and cost constraints the renewable energy system and components are presented as a theoretical design based on electrical load characteristics found during field tests of the DPB apparatus.

By integrating solar and wind renewable energy systems the feasibility of a direct motor-generator interaction and energy storage combination, to counteract the drift effects of current, wind and waves, is considered. This would allow a buoy to remain in a fixed location at sea without the use of a mooring system.
2. Background

2.1 Buoy Designs

A system of moored buoys throughout the worlds’ inland and coastal waterways, known as the Marine Aids to Navigation (ATON) system, exists today [9]. These buoy designs vary slightly among different countries and applications, but, with the exception of a few outliers like special purpose discus and scow types, ATON buoys are generally one of three design types. The steel can or conical buoy, the unlighted or lighted beacon buoy, and the spar or ice type buoy are each designed to be advantageous in different environments. Can and conical buoys simply float on the ocean surface and are moored to the ocean floor using heavy chain and rope. Unlighted and lighted offshore buoys are the most common within the ATON system. The top beacon light is usually raised up by a support structure that rests on a large floating can buoy ranging from 2.5 – 3.0 m in diameter. Some of these are also affixed with sound capability, limited to a 400 m range, and Radio and Beacon (RACON) systems to signal their presence to nearby vessels. The large surface area and low center of gravity keeps them upright. A spar buoy is distinguished by a hollow, long and slender, cylindrical body that extends primarily below the water line. This low cross section and large mass design effectively reduces the overall influence that surface waves have on the spar buoy. “The
Finnish have made extensive use of spar buoys with taut mooring in ice environments. These buoys have the added benefit of providing a negligible watch circle since they are essentially a variation of the articulated beacon [9]. Figure 1 shows lighted, spar, and can type buoys.

Other buoy designs exist for scientific purposes. Drift buoys and underwater acoustic buoys are some of these. NOAA’s National Data Buoy Center (NDBC) deploys and maintains scientific instrumentation buoys throughout the world. These continually monitor and record meteorological and oceanographic in-situ data in real time. The data is freely accessible through their website www.ndbc.noaa.gov [2]. Figure 2 shows NDBC’s collection of scientific buoys.
**Figure 1** from [9] a) lighted buoy b) spar buoy c) can buoy
Figure 2 from [2] NDBC Moored Buoy Program offshore meteorological and oceanographic buoy collection
2.1.1 Buoy Moorings

Deep water moored ocean buoys exist in waters as deep as 5800 m in the Pacific Ocean. Drawbacks to consider when anchoring this deep are the added weight, material, expense, potential breaks in the mooring line like in Figure 4, shark bites, etc. Other environmental considerations like damage to sea floor environments and corals must also be taken into account.

Buoys that traditionally mark a fixed position in the ocean, for navigation or scientific purposes, are moored to the sea floor with train wheels or iron sinker weights and tethered with a rope and chain. Deployment may require large rolls of mooring lines. Some deeper ocean buoys rely on “A combination of chain, nylon, and buoyant polypropylene materials designed for many years of service [2].” Typical buoy mooring systems are shown in Figure 3. One common occurrence among moored buoys is extensive damage from collision with ships. Another is marine growth. Yet another issue with moored buoys is the maintenance involved. They require a dedicated buoy tender that is designed to handle the weight of steel buoys and mooring chains. Some successful experimentation with light weight glass or fiber reinforced plastics has been done, but most fail after a short time and are, therefore, not cost effective [9]. Also, depending on the mooring configuration and buoy design, a large watch circle is required. Because of tide changes and catenary requirements this radius, which the chain provides the buoy to roam, reduces the accuracy of marking buoys. While much of the expense
involved with deep water mooring systems is from the materials themselves, a large expense is from the data collection and environmental analysis required before a mooring is even established offshore. These include parameters such as 100 year wind and squall statistics, and wave pattern history. Buoy and mooring systems must be designed to withstand loads in the most extreme conditions. “Modern mooring designs typically utilize groups of mooring lines to provide redundancy in the event of a line failure. Spread moored systems typically have mooring lines in groups at each of the four quadrants of the [Floating Production Storage and Offloading] FPSO while turret moored vessels utilize three groups of mooring legs [10].”
Figure 3 from [12] surface buoy mooring configurations a) chain slack mooring b) chain slack mooring with added chain and wire rope c) chain and elastic mooring d) chain and elastic mooring with added lines to reduce watch circle e) taut surface trimoor system f) submerged buoy and a rigid buoyant tether line g) single point mooring for a shallow water spar buoy
Mooring forces that must be considered in any design include environmental extremes, both severe and calm weather, for pre-tensioning and fatigue, termination points, and twisting. In addition to design challenges, installation challenges including installation damage, lost lines, and tensioning accuracy are also a concern [10].

**Figure 4** from [12] a potential for loss of buoy exists during the deployment as the anchor is allowed to twist and kink the mooring line
2.2 Oil Rigs

The oil and gas industry has driven much of the deep ocean mooring technology with the use of semi-submersible and spar type ocean platforms, which provide stability for offshore drilling. Large pontoons are flooded and submerged to a predetermined depth, while hollow cylindrical stanchions raise the platform above the surface waves. This design provides for a minimal cross-section exposed to the surface currents and gravity waves thereby reducing their influence on the rig. They also use tension leg moorings to help minimize the sway, surge, and heave of the platform.

2.3 Dynamic Positioning

As opposed to anchoring, DP is an alternate method of station keeping at sea. By definition of the International Marine Contractors Association (IMCA), dynamic positioning is, “The use of systems which automatically control a vessel's position and heading exclusively by means of active thrust to remain at a fixed location, for precision maneuvering, tracking and for other specialist positioning abilities [15].”

Driven mostly by the needs of the oil and gas exploration industry in the early 1960s, an analogue form of DP was pioneered by Howard Shatto aboard the vessel “Eureka” in 1961 [15]. Modern forms of DP have propagated across several
seafaring industries from passenger cruise lines, for added stability and comfort, to oceanographic research platforms. Commercial systems use a combination of differential GPS, real time kinematics or inertial navigation systems, local environmental sensing, and multi-directional thrusters to consistently locate vessels within 1 m of accuracy.

Advantages include the elimination of costly anchor handling systems and materials involved in deep sea operations as well as the preservation of seabed environmental systems like coral reefs or manmade systems such as pipelines and ship wrecks. DPS can achieve high levels of positional accuracy at sea, whereas anchored vessels must maintain a watch radius to accommodate tethering systems. Regardless of the type of vessel, the three key components of any DP system are the reference, control, and propulsion systems.

The reference system comprises any components or sensors that provide information for DP such as position, heading, environmental conditions, etc. Positioning reference systems determine where the vessel is in reference to where it is supposed to be in the world, usually by employing advanced GPS, which is discussed in the following section. The geospatial reference is fed to the control system along with other common reference information such as vessel heading, wind speed, and vessel motion or acceleration. User input is another required value used to establish the desired set points for any automated system.
Automated computer systems are the primary means of control for any modern DPS. Control algorithms include anything from advanced computer modeling and filtering techniques to proportional integral differential (PID) control or neural networks. As references and set points are fed into the control system, control signals are generated and sent to the propulsion and steering systems to maneuver the vessel into the desired position and keep it there in opposition of environmental forces.

Power and propulsion systems on ships are comprised of main engines, rudders, and bow and azimuth thrusters, while on stationary platforms several directional thrusters are used to correct position differences. Power is usually provided by diesel-electric generators. Depending on the characteristics of the vessel and environmental conditions, power requirements for DP tend to be quite substantial and costly. This, along with the added manpower requirements of operating and maintain a DP system, makes up the two most restrictive disadvantages of DP over other methods of station keeping at sea. Both of which could be overcome, by using integrated renewable energy systems and a fully automated control system.

2.4 Navigation, GPS, and DGPS

The task of navigating and locating something on the earth’s surface has been a part of life ever since humans roamed the earth throughout history. Using
landmarks was a known and obvious way to do this, but when it came to wide open spaces like the ocean, navigators were only equipped with instincts and other crude processes such as dead reckoning. Dead reckoning is a technique of periodically plotting distance and direction traveled on a nautical chart to keep track of location. “A better method arose around 1100 CE, when the Chinese created the first magnetized needle compass [16].” Until the invention of the sextant in the 1731, sailors who ventured out of sight of landmarks could only estimate latitudes based on key celestial markers like the sun or the North Star. They also relied on natural indicators such as currents and bird migratory patterns. Tracking longitudinal positions was never possible until the mid-1700s when John Harrison invented the first precision chronometer. Three key contributions that further advanced the accuracy of modern global positioning were the global adoption of Greenwich Mean Time (GMT) in the late 1800s, the propagation of aviation, and the invention of radar in the early 1900s [16].

Using radio beacon signals at known locations, airplanes and boats no longer needed to rely on celestial bodies which were traditionally useless in adverse cloud conditions. In the 1960s a well-known network of radio beacon towers was known as Location Radio Aids to Navigation (LORAN). This system became obsolete with the introduction of GPS and was discontinued in the US in 2010.

The well-known satellite Global Positioning System (GPS) of today was originally developed by the US Department of Defense. This constellation of 24,
geosynchronous, satellites was commissioned and launched in 1978 by the USAF [17]. To determine any location on earth, the process of trilateration uses distance measurements between the positioned object and at least four different satellites in orbit. Using radio waves, pseudo random code, and atomic clocks for timing accuracy, a GPS receiver can locate itself anywhere on earth within 10 m accuracy. The reason for this limitation is because unpredictable disruptions of the signals occur within the earth’s atmosphere which distorts the distance measurements.

To overcome this, Differential GPS (DGPS) ground stations, in the vicinity of the roving GPS receiver, calculate the timing errors in the atmosphere and transmit this correction factor to GPS units via radio transmissions. More recently, using wide area networks (WAN) has allowed multiple reference stations to collaborate data providing an even better timing correction for more accurate positioning.

2.5 Renewable Energy

To examine the feasibility of renewable energy as a source for the DPB project it is important to understand the potential sources and what they can provide. When dealing with electricity, units of energy are measured in watt hours (Wh) and power in watts (W).
2.5.1 Wind Power

“The earliest mention of windmills in actual use is from India about 2400 years ago [11].” The first ones used to generate electricity, wind turbines, were designed in the late 1800s [8]. Generally, wind is developed by temperature gradients in the earth’s atmosphere. Effects from surface topography, temperature effects on density, rotation of the earth, time of day, time of year, and location on earth are some of the causes of variability and diminished wind speeds. The amount of energy in a strong wind is primarily derived from the speed and the mass of the moving air. The primary advantage of using wind power in offshore environments is that unobstructed airflow over large areas allows wind speed to accumulate. Air density is also fairly constant and highest, 1.225 kg/m$^3$ at 15°C, at sea level [8].

Wind turbines convert linear air motion to rotational kinetic energy. The spinning shaft of the turbine is coupled to a generator to produce electric power. All wind turbines have essentially three main components, a tower, a nacelle, and the rotors.

The tower is simply the mast on top of which the turbine assembly is mounted. The nacelle is the body which houses the sensitive components of the wind machine such as the electric generator, gearing, slip rings, etc. to protect them from environmental elements.

The rotors are arguably the most important part of a wind turbine. They are the mechanisms coupled to the electric generator’s shaft which react to the linear
air motion causing it to rotate. The entire power capacity of a wind turbine can be traced back to the rotors. The characteristics of the rotor blades are so instrumental in determining the usefulness of the wind turbine that Gipe makes the general classification of wind turbines based on the diameter of their rotor blades. Small includes anything under 10 m in diameter, medium, 10 m to 60 m, and large or giant-sized for anything over that.

When dealing with wind turbines “A” in equations 2.1, 2.2, and 2.3 refers to the swept area of the rotor blades and is calculated using the geometric formula for the area of a circle.

\[ A = \pi r^2 \]  

(2.1)

Where radius, \( r \), is half of the rotor diameter.

The general formula for wind energy is given by

\[ \text{Wind Energy} = \frac{1}{2} \rho AtV^3 \]  

(2.2)

Where \( V \) is velocity and mass is broken down into area and density, \( \rho \). Because the air is moving, the time component, \( t \), must also be included for completeness. Wind power being an instantaneous measure, the time component is divided out giving

\[ \text{Wind Power} = \frac{1}{2} \rho AV^3 \]  

(2.3)

Power is simply measured in Watts (W). Equation 2.3 shows that the cubed velocity, or wind speed, component has the most influence on the total amount available power in a wind stream.
One interesting concept in wind turbine development, shown in Figure 5, arose from experiments with vertical axis wind turbines or Darrieus, after the French inventor D.G.M. Darrieus, in the early 1900s [8]. These turbines have the primary advantage of translating wind velocity into rotation from any wind attack angle, whereas the more conventional horizontal axis type require a forward facing direction.

![Figure 5](image)

**Figure 5** From [8] horizontal axis wind turbine (left) and Darrieus type vertical axis wind turbine (right)

2.5.2 Solar Power

“At present the Sun radiates energy at the rate of $3.9 \times 10^{26}$ W. At the top of earth’s atmosphere an average power of 1353 W m$^{-2}$ is passing through a plane perpendicular to the direction of the Sun [11].” Only a fraction of that energy actually makes it to the surface. The primary determination of this fraction is the distance the sunlight has to travel based on the angle of the incoming solar radiation. This distance is characterized by a standard representing the radiation on
earth’s surface known as the air mass coefficient. The highest amount of solar irradiance is achieved when the sun is directly overhead near the equator, correlating to a zenith angle of 0° and one standard air mass (AM1). The standard used to measure solar energy system performance is set forth by the American Society for Testing and Materials (ASTM). “ASTM G173 - 03(2008) Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface” sets this standard to AM1.5, which correlates to a zenith angle of 48.19° and an irradiance of 1000 W m² [64]. Other factors which affect solar insolation include environmental conditions such as cloud cover, rain, etc. Some systems convert this energy to electric power using direct heat, usually by concentrating the radiation on one central area with mirrors, and some form of heat engine such as a steam turbine or sterling engine. Another, more common, way is by using solar cells. Solar cells convert the power contained within the radiation to DC voltage using a combination of specially p and n doped semi-conductive materials, photo-interactions, and conductive metal contacts as depicted in Figure 6 [31].
Today’s solar panels are typically classified into mono-crystalline, polycrystalline, or thin-film amorphous silicon, based mainly on their manufactured process and physical characteristics. “To make mono-crystalline silicon, we have to grow large cylindrical ingots with the Czochralski process [33].” The outcome is highly purified silicon that translates into high energy density per square meter, but also high cost. They characteristically have an, “Even coloring and uniform look [33].” For polycrystalline silicon, “Raw silicon is melted and poured into a square mold, which when cooled can be cut into perfectly square wafers [33].” They are, therefore square in shape, but have a non-uniform look. Thin-film amorphous silicon solar cells use only a small amount of silicon material making them

![Figure 6 from [31] p and n doped semi-conductor cross-section](image)
significantly cheaper and easier to manufacture. “Depending on the technology, thin-film module prototypes have reached efficiencies between 7–13% and production modules operate at about 9% [33].”

Power rating of solar panels is a balance between overall efficiency and density, the main difference being the amount of area the panels require to produce their nominal output. As of December 12, 2011, according to [32], the most efficient modules commercially available, based on power density, are between 15.24% - 16.00% using polycrystalline silicon modules.

2.5.3 Energy Storage

“In 1859, the French physicist Gaston Planté invented the first rechargeable battery. It was based on lead acid, a system that is still used today [41].” Variations of the lead acid battery are typically used with hybrid energy systems as a means of consistently meeting load requirements. The benefits of lead acid, versus other popular battery chemistries such as nickel-metal-hydride and lithium-ion, are the comparatively low cost of manufacturing, simplicity of charging, wide range of operating temperatures, and consistent, reliable discharge characteristics.

Another consideration for a battery storage system aboard DPB is the wide range of rolling and pitching motions associated with offshore environments. In flooded lead acid battery, the electrolyte solution is allowed to slosh around causing spillage and harmful gas build up. They also require a small amount of
maintenance which is undesirable for DPB. An alternative is the use of sealed lead acid batteries, which use either an impregnated gel or an absorbed glass mat (AGM) electrolyte in a completely sealed container. They require no maintenance and are not susceptible to spillage [41].

A third, important consideration for hybrid energy system battery storage is the amount of cycling it will undergo. When it comes to lead acid batteries there are two different types, starter and deep cycle. The starter battery is designed to provide high output for short periods of time while the deep cycle battery can handle longer and deeper discharges due to thicker lead plating. For DPB a deep cycle type AGM battery is preferred [41].

2.6 Similar Systems

A few U.S. patents, having similar motives to DPB, have been awarded. SKB using SONAR reflector or active transponder anchored to the sea floor: US Patent 3,369,516 was awarded to inventor Roger J. Pierce on February 20, 1968 entitled, “STABLE OCEANIC STATION”. The propulsion proposed is a, “Tangential jet [23]” using atomic power. SKB using GPS: US Patent 5,577,942 was awarded to inventor Gregory J. Juselis on November 26, 1996 entitled, “STATION KEEPING BUOY SYSTEM”. The propulsion proposed is a, “Bi-directional vector thrust system [21]” using batteries. A self-orientating water drift compensation method using passive hydrofoil device: US Patent 2009/0095208 A1
was awarded to Cardoza et al. on April 16, 2009 entitled, “WATER DRIFT COMPENSATION METHOD AND DEVICE [22]” also using batteries. Unmanned ocean vehicle using winged sail covered with photovoltaic cells: US Patent 7,789,723 was awarded to Dane et al. on September 7, 2010 entitled, “UNMANNED OCEAN VEHICLE [24]” using hybrid wind and solar power.

There are several maritime vehicles out there that are not buoys. The main distinctions of DPB are a combination of the intended purpose and the hybrid power system. DPB is not an autonomous surface vehicle designed to transit long distances in the ocean. Instead, it is intended to be optimized for station keeping, with an emphasis on the use of renewable energy systems to help maintain position.

Some general applications for DPB could include remote location aids to navigation, surveillance, and sea-air interface communication systems. The following section examines some recent developments in both ASV’s and mobile buoys.

The most similar systems to DPB were developed, and at least partially funded, in response to the [3] and [4] calling for sea power and surveillance. SeaLandAire Technologies, Inc. owns two projects, Persistent Ocean Surveillance – Station Keeping Buoy (POS-SKB) and Gatekeeper, which have successfully demonstrated the abilities of station keeping and energy harvesting. “SeaLandAire’s hardware successfully maintained station in adverse marine environments for over 120 hours, averaging less than 3 meters deviation from the
designated station keeping point [26].” Another SKB system with the same name, Gatekeeper, was developed by Falmouth Scientific Inc. in 2008. This system uses a proprietary Salt Water Activated Power System (SWAPS) by Mil3, Inc. to generate 200 watts using a combination of reactive metal and hydrogen fuel cells [27]. A third noteworthy system was developed by the Johns Hopkins University Applied Physics Laboratory in 2006. It uses a combination of sail and auxiliary thruster for positioning. “The SKB was successful in station keeping within the 250-m watch radius 90% of the time and within a 1000-m watch radius 100% of the time [25].”

Spar buoy designs provide another kind of station keeping advantage, but are a hydro dynamical disadvantaged when transiting. A scaled spar platform with dynamic positioning capability was considered in [14]. Although unrelated to renewable energy systems, this adapted Floating Instrument Platform (FLIP) demonstrates a scaled dynamic positioning system requiring 12 thrusters for six degrees of motion to position and stabilize a spar buoy platform.

One other noteworthy system, developed outside the realm of DARPA or SBIR funding, is Florida Institute of Technology’s Autonomous Mobile Buoy, a thesis by Adam S. Outlaw in 2007 and shown in Figure 7. It was designed for waypoint tracking and station keeping using an automated anchor and 30 m tether, limiting its effectiveness to littoral seas. A renewable energy element was added using solar panels to recharge the system while anchored [13] [62].
Unlike these systems, DPB is not designed for mobility. This allows for focus to be concentrated on power balancing between available environmental sources and the load requirements involved with dynamic positioning. Table 1 below is a summarized, non-inclusive, listing of some ASVs along with their primary function and propulsion power systems.
<table>
<thead>
<tr>
<th>Project Name</th>
<th>Description</th>
<th>Buoy Type</th>
<th>Primary Station Keeping</th>
<th>Primary Power</th>
<th>Secondary Power</th>
<th>Year</th>
<th>Person/Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gatekeeper</td>
<td>A semi renewable energy station keeping buoy designed in response to the 04 DARPA solicitation.</td>
<td>Hydrodynamic spar buoy</td>
<td>DP</td>
<td>200W Salt Water Activated Power System (SWAPS)</td>
<td>60W solar panel</td>
<td>2009</td>
<td>Falmouth Scientific, Inc.</td>
</tr>
<tr>
<td>POS-SKB</td>
<td>A solar powered station keeping buoy in response to the 04 DARPA solicitation</td>
<td>ASV</td>
<td>DP</td>
<td>Solar</td>
<td></td>
<td></td>
<td>SeaLandAire</td>
</tr>
<tr>
<td>Autonomous Mobile Buoy</td>
<td>An autonomous surface vessel designed to transit to a predetermined waypoint and automatically moor for solar charging.</td>
<td>ASV/Nomad</td>
<td>Automated mooring</td>
<td>3-50Ah 12V Gel batteries</td>
<td>2 solar panels</td>
<td>2007</td>
<td>Adam Outlaw</td>
</tr>
<tr>
<td>Rotary Craft</td>
<td>A non traditional wind driven vessel.</td>
<td>NA</td>
<td>NA</td>
<td>Wind</td>
<td>NA</td>
<td></td>
<td>Peter Worsley</td>
</tr>
</tbody>
</table>

### RENEWABLE

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Description</th>
<th>Buoy Type</th>
<th>Primary Station Keeping</th>
<th>Primary Power</th>
<th>Secondary Power</th>
<th>Year</th>
<th>Person/Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station Keeping Buoy system</td>
<td>USPATENT5577942. A station keeping buoy using DGPS and a bidirectional thruster.</td>
<td>Spar</td>
<td>DGPS/DP</td>
<td>Batteries</td>
<td>NA</td>
<td>1996</td>
<td>George J. Juselis</td>
</tr>
<tr>
<td>RDSP</td>
<td>Rapidly deployable stable platform of 1/10 scale which uses a 12 thruster configuration along the submerged length of a spar for dynamic positioning and stabilization.</td>
<td>Spar</td>
<td>DGPS/DP</td>
<td>6-105Ah 12V SeaVolt batteries</td>
<td>NA</td>
<td>2009</td>
<td>Sean Marikle</td>
</tr>
<tr>
<td>BASIL</td>
<td>A semi-autonomous multifunctional surface vessel with station keeping capability.</td>
<td>ASV</td>
<td>DGPS/DP</td>
<td>Diesel</td>
<td>NA</td>
<td>2003</td>
<td>French company ACSA</td>
</tr>
<tr>
<td>OASIS</td>
<td></td>
<td>ASV/Nomad</td>
<td>DP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCOUT</td>
<td>A multifunctional autonomous surface vessel with station keeping capability.</td>
<td>Kayak</td>
<td>MOOS Software Suite/Station keeping</td>
<td>AGM batteries 100Ah</td>
<td></td>
<td></td>
<td>CoastalObs</td>
</tr>
<tr>
<td>Navy ADS</td>
<td>A surveillance buoy with an intelligent mooring system.</td>
<td>Discus</td>
<td>Intelligent mooring</td>
<td>13HP diesel electric generator</td>
<td>Lithium Ion batteries</td>
<td>2007</td>
<td>Navy</td>
</tr>
</tbody>
</table>

### Non-RENEWABLE

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Description</th>
<th>Buoy Type</th>
<th>Primary Station Keeping</th>
<th>Primary Power</th>
<th>Secondary Power</th>
<th>Year</th>
<th>Person/Company</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ASV</td>
<td>DP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOOS Software Suite/Station keeping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>AGM batteries 100Ah</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Additional ASVs and other similar systems
3. Development and Construction

3.1 Design Considerations

The DPB concept for this project was derived from a previously proposed rotary electric wind craft “Windmill Ship” design and analysis. As work progressed on the original project it was determined too broad of scope and focus was shifted to low cost dynamic positioning and integrated power systems. For theoretical design purposes of a DPB, however, it is helpful to examine a well proven physical paradigm presented by Professor B.L. Blackford of Dalhousie University in [18].

It has been established that a surface vessel can travel into an oncoming wind by directly driving a propeller below the surface with a wind turbine above the surface as shown in Figure 8 from [18].

![Figure 8](image)

**Figure 8** from [18] a simple diagram depicting a rotary craft analysis where A1 is the swept area of a wind turbine, A2 is the swept area of a propeller, ρ₁ is the density of air, ρ₂ is the density of water, W is wind speed and V is the resulting water velocity from the propeller.
The key principles that allow for this are both the ratios between the surface area of the turbine and the propeller, $A_1/A_2$, and the differences in density of air and water, $\rho_1/\rho_2$. The maximum theoretical speed is given as twice the wind speed [18]. Recent work has been done by Peter Worsley of the rotary wind craft organization in the UK [30] and shown in Figure 9.

![Figure 9 from [30] Peter Worsley’s rotary craft](image)

In general, prototypes of rotary wind vessels usually transfer power mechanically from the wind rotor to the propeller. This helps to minimize losses that would otherwise occur from energy conversion. This does, however, introduce the complexity of a required power train for speed control as well as precludes the possibility of energy storage. Autonomous steering would also be more
burdensome for a mechanical system and would require, at minimum an electromechanical system in order to interface with the DP control circuit.

An all-electric system does present higher losses involved with energy conversion, but makes automated energy storage, speed control, and steering quite manageable with the DPB control system interface.

3.1.1 Pre-existing Buoy Project

The yellow surface buoy was previously conceived and commissioned by Dr. Stephen Wood, at Florida Institute of Technology, in 2009 and remains readily available. The initial design intent was to provide a low cost solution for an offshore moored buoy. Figure 10 a) is a rendering of the initial design from Pro-Engineer and b) shows the final prototype constructed in 2007.

Using an iterative design process, several configurations were considered to accommodate a hybrid renewable energy system and thrust capability aboard the original yellow buoy. These considerations were size restrictions, structural integrity, buoyancy, and stability.

It was suggested by Dr. Stephen Wood that adding an extended length of pipe below the surface could help to mitigate drift by acting as a type of drag anchor as well as provide increased stability. Based on these considerations, a final design rendering, shown in Figure 11 a), was made using [46]. Figure 11 b) shows the final construction of DPB and Table 2 is a listing of final DPB specifications.
Figure 10 a) a yellow buoy rendering from Pro-Engineer and b) final yellow buoy construction

Figure 11 a) rendering of DPB from [54] b) final DPB apparatus photo courtesy of Dr. Stephen Wood
### Table 2 DPB final specifications

<table>
<thead>
<tr>
<th>Overall Dimensions</th>
<th>DPB Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length: 1.45 m</td>
<td><strong>Length</strong>: 1.45 m</td>
</tr>
<tr>
<td>Width: 1.6 m</td>
<td><strong>Width</strong>: 1.6 m</td>
</tr>
<tr>
<td>Height: 1.89 m</td>
<td><strong>Height</strong>: 1.89 m</td>
</tr>
<tr>
<td>Cross-section in air: 2.86 sq m</td>
<td><strong>Cross-section in air</strong>: 2.86 sq m</td>
</tr>
<tr>
<td>Cross-section in water: 0.4 sq m</td>
<td><strong>Cross-section in water</strong>: 0.4 sq m</td>
</tr>
<tr>
<td>Frame Weight: 37 kg</td>
<td><strong>Frame Weight</strong>: 37 kg</td>
</tr>
<tr>
<td>Buoyant Ring Weight: 73 kg</td>
<td><strong>Buoyant Ring Weight</strong>: 73 kg</td>
</tr>
<tr>
<td>Dry Weight w/o Addons: 215 kg</td>
<td><strong>Dry Weight w/o Addons</strong>: 215 kg</td>
</tr>
<tr>
<td>Draft: 0.79 m</td>
<td><strong>Draft</strong>: 0.79 m</td>
</tr>
<tr>
<td>Freeboard w/o Addons: 1.1 m</td>
<td><strong>Freeboard w/o Addons</strong>: 1.1 m</td>
</tr>
<tr>
<td>Displacement:</td>
<td><strong>Displacement</strong>:</td>
</tr>
<tr>
<td>Max speed: 0.7 m/s</td>
<td><strong>Max speed</strong>: 0.7 m/s</td>
</tr>
<tr>
<td>Max thrust: 129 N</td>
<td><strong>Max thrust</strong>: 129 N</td>
</tr>
<tr>
<td>Voltage: 12 V DC</td>
<td><strong>Voltage</strong>: 12 V DC</td>
</tr>
<tr>
<td>Peak current: 107 A</td>
<td><strong>Peak current</strong>: 107 A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Add-on Components</th>
<th><strong>Add-on Components</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery: SeaVolt AGM Deep Cycle x2 79 Ah @ 20 Hrs 525 CCA 735 MCA weight: 24 kg ea. dimensions: 27.6 cm x 17.1 cm x 25 cm</td>
<td><strong>Battery</strong>: SeaVolt AGM Deep Cycle x2 79 Ah @ 20 Hrs 525 CCA 735 MCA weight: 24 kg ea. dimensions: 27.6 cm x 17.1 cm x 25 cm</td>
</tr>
<tr>
<td>Motor: Unknown make/model x2 600 W thrust: 129 N weight: 10.4 kg ea. dimensions: L 25.4 cm x 10.2 cm OD</td>
<td><strong>Motor</strong>: Unknown make/model x2 600 W thrust: 129 N weight: 10.4 kg ea. dimensions: L 25.4 cm x 10.2 cm OD</td>
</tr>
<tr>
<td>Add-ons: Battery box Fiberglass x2 weight: 10.4 kg ea. dimensions: 50.8 cm x 33 cm x 30.5 cm</td>
<td><strong>Add-ons</strong>: Battery box Fiberglass x2 weight: 10.4 kg ea. dimensions: 50.8 cm x 33 cm x 30.5 cm</td>
</tr>
<tr>
<td>Wind turbine: Custom x1 weight: 14.5 kg rotor: x6 0.6 m swept area: 1.3 sq m</td>
<td><strong>Wind turbine</strong>: Custom x1 weight: 14.5 kg rotor: x6 0.6 m swept area: 1.3 sq m</td>
</tr>
<tr>
<td>Wind turbine support: Electrical conduit weight: 9.1 kg dimensions: 305 cm x 3.8 cm ID</td>
<td><strong>Wind turbine support</strong>: Electrical conduit weight: 9.1 kg dimensions: 305 cm x 3.8 cm ID</td>
</tr>
<tr>
<td>Selected Solar Panel: Sanyo Electric 225 W mono-crystalline Hybrid x2 weight: 16 kg ea. dimensions: 158 cm x 80 cm x 4.6 cm</td>
<td><strong>Selected Solar Panel</strong>: Sanyo Electric 225 W mono-crystalline Hybrid x2 weight: 16 kg ea. dimensions: 158 cm x 80 cm x 4.6 cm</td>
</tr>
<tr>
<td>ET Solar 95 W mono-crystalline x2 weight: 8.2 kg ea. dimensions: 120 cm x 54.5 cm x 3.5 cm</td>
<td><strong>ET Solar 95 W mono-crystalline x2 weight</strong>: 8.2 kg ea. dimensions: 120 cm x 54.5 cm x 3.5 cm</td>
</tr>
</tbody>
</table>
3.2 DPB Build

The original buoy was not designed for mobile operation and, therefore, had no corrective capability. Onboard power requirements of the original design were also limited to minimal instrumentation loads in the 1 to 5 watt range as opposed to DPB thruster loads in the kilowatt range.

Waterproof battery housings were designed and built for DPB using coarse fiberglass and West Marine epoxy system in order for DPB to accommodate two 72-Ah deep-cycle AGM batteries. Each housing was wood reinforced with two 2 X 4’s on the bottom forward floor to support the batteries and one 2 X 6 on the aft bulkhead for the trolling motor addition as shown in Figure 12.

Figure 12 reinforced waterproof battery housing and motor mount
To transfer the force from the motors to the DPB body and support the weight of the propulsion system, two aluminum channels were welded to the frame shown in Figure 13 a). Housings were mounted with 15.875 mm stainless steel through bolts and metal bar stock. Figure 13 b) is a view of DPB with the motors mounted to the housings which are in turn mounted to the frame.

![Figure 13 a) aluminum channels transfer thrust to DPB frame and support the weight of the housings and b) bottom mounted trolling motors photos courtesy of Dr. Stephen Wood](image)

3.3 Instrumentation and Control

The primary instrument designated for the DPB apparatus is the stand-alone GPS receiver module. “LOCOSYS LS20126 GPS smart antenna module is a high sensitivity, low power, SMD type, 20 channels with built-in magnetic sensor, 3-
axis acceleration sensor L1 GPS receiver and 10 mm patch antenna designed for portable applications [5].” It was selected as a low cost unit with compatible interfacing to the selected microcontroller via USART, low 3.3 volt CMOS levels, and a wide range of operating voltage characteristics. It was selected over the popular Lassen™ iQ GPS receiver module from Trimble which only has a 12-channel receiver with no built-in magnetic or acceleration sensing. The Trimble unit also requires an external antenna and connector cable unlike the stand-alone capability of the LS20126. Both output position solutions at 1Hz in standard National Marine Electroinics Association (NMEA) format, have similar start-up times, and similar electrical characteristics. The PIC18F27J13 microcontroller was selected due to its compatible voltage levels, onboard storage capacity, multiple interface peripherals, and personal preference.

3.3.1 GPS Receiver Module

The LS20126 module contains a 20-channel GPS receiver with onboard antenna for latitude and longitude positioning solutions, a magnetometer for direction and heading, and an accelerometer for attitude sensing and dead reckoning capability intended for future development. Three-axis attitude data may also be used for orientation and wave data measurement. Serial output from the module is communicated at 1Hz on the TX pin following the NMEA developed standard protocol for maritime electronic systems (NMEA 0183).
For GPS, this standard set includes $GPGGA, for Global Positioning System Fixed Data, $GPGLL Geographic Position – Latitude / Longitude, $GPGSA, GNSS DOP and Active Satellites, $GPGSV, GNSS Satellites in View, $GPRMC, Recommended Minimum Specific GNSS Data, and $GPVTG, Course Over Ground and Ground Speed. Aside from the standard GPS output strings, the unit output includes proprietary strings which carry the magnetic sensor and accelerometer data. They are $PLSR,245,1, calibration and acceleration report, $PLSR,245,2, attitude, and $PLSR,245,7, 3D GPS speed output (ECEF coordinate) [5]. Table 3 describes the LS20126 minimum recommended output string,

$GPRMC,053740.000,A,2503.6319,N,12136.0099,E,2.69,79.65,100106,,,A*53.

Picking out information for the microcontroller to use is a process called parsing which will be covered further in the software and application section 3.4.
Table 3 from [5] RMC data format

<table>
<thead>
<tr>
<th>Name</th>
<th>Example</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message ID</td>
<td>$GPRMC</td>
<td></td>
<td>RMC protocol header</td>
</tr>
<tr>
<td>UTC Time</td>
<td>053740.000</td>
<td>hhmmss.sss</td>
<td></td>
</tr>
<tr>
<td>Status</td>
<td>A</td>
<td></td>
<td>A=data valid or V=data not valid</td>
</tr>
<tr>
<td>Latitude</td>
<td>2503.6319</td>
<td>ddmm.mmmm</td>
<td></td>
</tr>
<tr>
<td>N/S Indicator</td>
<td>N</td>
<td>N=north or S=south</td>
<td></td>
</tr>
<tr>
<td>Longitude</td>
<td>12136.0099</td>
<td>dddmm.mmmm</td>
<td></td>
</tr>
<tr>
<td>E/W Indicator</td>
<td>E</td>
<td>E=east or W=west</td>
<td></td>
</tr>
<tr>
<td>Speed over ground</td>
<td>2.69</td>
<td>knots</td>
<td>True</td>
</tr>
<tr>
<td>Course over ground</td>
<td>79.65</td>
<td>degrees</td>
<td>At low speed or in state of rest, the GPS heading is not valid. LS20126 will derive the heading information based on magnetic sensor in such circumstance.</td>
</tr>
<tr>
<td>Date</td>
<td>100106</td>
<td>ddmmyy</td>
<td></td>
</tr>
<tr>
<td>Magnetic variation</td>
<td></td>
<td>degrees</td>
<td></td>
</tr>
<tr>
<td>Variation sense</td>
<td></td>
<td>E=east or W=west (Not shown)</td>
<td></td>
</tr>
<tr>
<td>Mode</td>
<td>A</td>
<td>A=autonomous, D=DGPS, E=DR</td>
<td></td>
</tr>
<tr>
<td>Checksum</td>
<td>*53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;CR&gt; &lt;LF&gt;</td>
<td></td>
<td></td>
<td>End of message termination</td>
</tr>
</tbody>
</table>

The module outputs latitude and longitude coordinates in the format
\[ddmm.mmmm \text{ N/S} \text{ and } dddmm.mmmm \text{ E/W}\] once every second. The four decimal places represent a resolution of +/- 5 m according to [5] and tested in section 5.2.3. This nominal accuracy is a 2DRMS rating, meaning the position is expected to be within 5 m for 95% of the time [65]. When performing discrete calculations with these coordinates, it is sometimes desirable to convert to decimal degrees (DD) or degrees minutes seconds (DMS) format. The formulas for converting from the given format to DD and DMS are:
Where \( dd \) is degrees, \( mm \) is the integer part of the minutes given by \( mm.mmmm \), and \( .mmmm \) is the remaining fractional part of the given minutes. See Appendix B for the corresponding “get_position” function showing the implementation of all coordinate conversions coded in PIC C18.

In practice, because modern day GPS systems use trilateration, a range-range process requiring precise timing to calculate position, and because radio signal interactions with the troposphere and ionosphere causes slight variations in this timing, raw GPS coordinate data tends to be noisy, hence a +/-5 m accuracy. Another factor when considering a floating platform in the ocean is the environmental effects of wind, waves and current. Kalman filtering is a method commonly used to account for all of the system noise involved with DPS. It is an iterative algorithm, based on Riccati gain equations, system modeling, and process noise that attempts to calculate an accurate position, or system state. Three basic steps performed during each iteration of the Kalman filter are, a real-time measurement is taken, a correction is applied to a previously estimated state prediction based on that measurement, and a new estimated state is projected forward to the next iteration.

It is noteworthy that for a typical DPS an extended Kalman filter is usually implemented to account for the slightly non-linear nature of offshore positioning.
caused by wind, current, and waves. The DPB designed for this thesis is not equipped to implement such filtering due to limited program memory, processing power, and lack of environmental sensors. Instead, DPB uses a 0th order, linear Kalman filter, based on [19], applied to the LS20126 module output in a simple attempt to clean up noisy data. See section 5.2.4 for results of an applied filter. See Appendix B for the corresponding “kalman_filter” function showing the implementation of the filtering algorithm coded in PIC C18.

A valuable, open source, computer software package developed by Google, Inc. was developed and released in 2005. Google Earth allows analysis of GPS data based on the WGS 84 Datum [45]. Some precision and accuracy testing of Google Earth projections in conjunction with the LS20126 module used on DPB was done using National Geodetic Society benchmarks and differential GPS systems.

### 3.3.2 Waypoint Tracking and Positioning

A waypoint generally refers to a set of coordinates referencing a particular location on the earth. In relation to DPB, this waypoint is considered to be the marked position where the buoy is deployed. It is intended to be set manually by the user at the time of deployment, and remain unchanged for the lifetime of that deployment. To better understand waypoint tracking and positioning it is important to realize the differences between courses over ground (COG), heading (HDG), and bearing (BRG). An insightful distinction is given in [20]. “Stand at the Helm and
sight down the bow of your vessel. Look at what your Magnetic Compass reads. This is the Vessels Heading. Your GPS takes several fixes per second and plots them on a digital chart. The direction of the track created by this succession of fixes is your Course over the Ground. Note: Depending on the vessel’s drift created by wind and current, your vessel’s heading may be several degrees different. Do not confuse the two. The direction from your vessel to the waypoint as referenced on the Compass is your Bearing to the Waypoint [20].”

By applying a pseudo Cartesian coordinate system to a longitudinal versus latitudinal grid, and by knowing a vessel’s current position and heading, a bearing to any given waypoint can be calculated using basic trigonometric formulas. In Figure 14, the buoy heading is given arbitrarily as 15° and the mark is at some waypoint away from the center of the buoy’s current position. The difference in longitude and latitude between the waypoint coordinates and the current positional coordinates gives a dimensional length to two legs of a hypothetical right triangle.

\[ yLON = LONmk - LON \]  \hspace{1cm} (3.3)
\[ xLAT = LATmk - LAT \]  \hspace{1cm} (3.4)

Where \( LONmk \) and \( LATmk \) are given waypoint coordinates, and \( LON \) and \( LAT \) are current vessel coordinates.

The angle, \( \theta \), is now calculated using the formula:

\[ \theta = \arctan \left( \frac{yLON}{xLAT} \right) \]  \hspace{1cm} (3.5)
Where $\theta$ is some angle between two imaginary major axes, a North to South representing x and West to East representing y.

**Figure 14** A pseudo Cartesian coordinate system applied to a longitudinal verses latitudinal grid used to calculate bearing via basic trigonometric functions.
It is important to note that coordinate positions should be in positive and negative decimal format so that if the waypoint position is not in the same global proximity, which might occur at locations on or near the equator and meridians, the tracking algorithm still holds true in most locations on earth. Special cases arise in the Pacific Ocean across the 180° meridian and in the Arctic Oceans across the poles where, for obvious reasons, the simple tracking algorithm breaks down. While these special cases would be important to incorporate into global tracking algorithms meant for transects on the order of kilometers, they are not considered for DPB which is only designed to correct for small offsets in position on the order of tens of meters.

Again, using the pseudo Cartesian coordinate system, the marked location must be sorted into one of the four imaginary quadrants based on the values of yLON and xLAT. This information can then be used to determine the bearing to the waypoint in relation to the current position by adding \( \theta \) to the axis referencing that quadrant. For instance, if yLON and xLAT are both negative, the waypoint is in Quadrant I and the angle theta is exactly the bearing in which the buoy heading needs to match; therefore the bearing is \( \theta + 0^\circ \). If the waypoint is in QII, yLON is negative and xLAT is positive and the bearing becomes \( \theta + 90^\circ \), and so on. Table 4 provides a full listing of the sorting equations and exceptions that occur when the waypoint lies directly on an axis.
Table 4 sorting equations and exceptions used for waypoint tracking algorithm

<table>
<thead>
<tr>
<th>yLON</th>
<th>xLAT</th>
<th>Corresponding Quadrant</th>
<th>Bearing Calculation Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>-</td>
<td>QI</td>
<td>$\theta + 0^\circ$</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>QII</td>
<td>$\theta + 90^\circ$</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>QIII</td>
<td>$\theta + 180^\circ$</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>QIV</td>
<td>$\theta + 270^\circ$</td>
</tr>
<tr>
<td>0</td>
<td>+</td>
<td>N/A</td>
<td>$BRG = 180^\circ$</td>
</tr>
<tr>
<td>0</td>
<td>-</td>
<td>N/A</td>
<td>$BRG = 360^\circ$</td>
</tr>
<tr>
<td>+</td>
<td>0</td>
<td>N/A</td>
<td>$BRG = 270^\circ$</td>
</tr>
<tr>
<td>-</td>
<td>0</td>
<td>N/A</td>
<td>$BRG = 90^\circ$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>At waypoint</td>
</tr>
</tbody>
</table>

Once this waypoint bearing is established the buoy determines a turning direction based on the bearing value being greater or less than $180^\circ$ and activates the turn until the heading matches the bearing to the mark. Once they are matched, both thrusters engage to move the buoy forward towards the waypoint. See Appendix B for the corresponding “get_bearing” and “track” functions coded in PICC18.

Another important distinction to be made here is the difference between magnetic north and true north. Magnetic instrumentation, such as compass or magnetometer, can sense earth’s magnetic poles. This measurement is location dependent. True north, or grid north, takes into account geographical position to correct for this variation. The $GPRMC$ string obtained after a valid first fix contains a value for magnetic variation which the LS20126 module uses to calculate corrected heading.
3.3.3 PIC 18F Series Microcontroller

The integrated circuit controller selected to process, filter, and differentiate position and control signals was the Microchip developed PIC18F27J13, embedded, 8-bit microcontroller running at 20MHz clock frequency via an external timing crystal. It was originally selected for its low (3.3 V) operating voltage, wide range of operating frequency, hardware real-time clock/calendar (RTCC), and wide variety of peripherals which are shown in Table 5 from [6]. Other microcontrollers considered were the PIC18F4520, 4585, 2553, and 32KA301. Table 6 below is a direct comparison of these units.

| Table 5 from [6] DEVICE FEATURES FOR THE PIC18F2XJ13 (28-PIN DEVICES) |
|----------------------------------|------------------|------------------|
| **Features**                     | **PIC18F26J13**   | **PIC18F27J13**   |
| Operating Frequency              | DC – 48 MHz       | DC – 48 MHz       |
| Program Memory (Kbytes)          | 64               | 128              |
| Program Memory (Instructions)    | 32,768           | 65,536           |
| Data Memory (Kbytes)             | 3.8              | 3.8              |
| Interrupt Sources                | 30               |                  |
| I/O Ports                        | Ports A, B, C    |                  |
| Timers                           | 8                |                  |
| Enhanced Capture/Compare/PWM Modules | 3 ECCP and 7 CCP |                  |
| Serial Communications            | MSSP (2), Enhanced USART (2) |                  |
| Parallel Communications (PMP/PSP) | No               |                  |
| 10/12-Bit Analog-to-Digital Module | 10 Input Channels |                  |
| Resets (and Delays)              | POR, BOR, RESET Instruction, Stack Full, Stack Underflow, MCLR, WDT (PWRT, OST) |
| Instruction Set                  | 75 Instructions, 83 with Extended Instruction Set Enabled |
| Packages                         | 28-Pin QFN, SOIC, SSOP and SFPDIP (300 mil) |
Table 6 a comparison of microcontroller selection criteria

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Sink/Source Current</th>
<th>Program Memory</th>
<th>SRam</th>
<th>EEPROM</th>
<th>EUSART</th>
<th>RTCC</th>
<th>ADC</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIC18F4585</td>
<td>4.2-5.5v 25mA</td>
<td>48k bytes</td>
<td>3328 bytes</td>
<td>1024 bytes</td>
<td>1</td>
<td>0</td>
<td>10-bit/11ch</td>
</tr>
<tr>
<td>PIC18F4520</td>
<td>4.2-5.5v 25mA</td>
<td>32k bytes</td>
<td>1536 bytes</td>
<td>256 bytes</td>
<td>1</td>
<td>0</td>
<td>10-bit/13ch</td>
</tr>
<tr>
<td>PIC18F27j13</td>
<td>2.0-3.6v 25mA</td>
<td>128k bytes</td>
<td>3760 bytes</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>12-bit/10ch</td>
</tr>
<tr>
<td>PIC18F2553 *USB 2.0 compatible</td>
<td>4.2-5.5v 25mA</td>
<td>32k bytes</td>
<td>2048 bytes</td>
<td>256 bytes</td>
<td>1</td>
<td>0</td>
<td>12-bit/10ch</td>
</tr>
<tr>
<td>PIC24F32ka301</td>
<td>1.8-3.6v 25mA</td>
<td>32k bytes</td>
<td>2k bytes</td>
<td>512k bytes</td>
<td>2-UART</td>
<td>1</td>
<td>12-bit/12ch</td>
</tr>
</tbody>
</table>

3.3.4 Circuit Configuration

DPB is separated into two electrically isolated circuits to accomplish dynamic positioning, hybrid energy integration, and motor control. The control and relay circuits are linked via two EL817C PS2501-1 photo-couplers. Figure 15 shows the control circuit designed using [55]. The final circuit was exported to a printed circuit board layout, shown in Figure 16, and specifications submitted to an online fabrication company, www.batchpcb.com, for printing.

The instrumentation and control circuit includes the most sensitive components of the system including the GPS receiver module, microcontroller, and wireless communication module. The TX pin of the receiver module is shared with the wireless module and the microcontroller RX pins. The raw data is, therefore, processed and transmitted simultaneously. After processing, detailed in the section 3.4, the output signals are pre-amplified using transistors and sent to the photo-
couplers. These, essentially, light activated transistors allow grounding of the designated 80 A relay which provides a separate source of power to the associated thruster.

The integration of the control and power relay systems is physically accomplished using a four way flat connector. This connector type is typically used for integration of vehicle and trailer lighting systems. It was selected based on its simplicity, safety, and the power and signal transmission needs of DPB. Figure 17 shows the power relay circuit.

![Figure 15 DPB embedded control circuit](image)
Figure 16 DPB printed circuit board

Figure 17 DPB power relay circuit
3.3.5 Android™ Smart Phone

The Android smart phone is a multi-purpose, hand held, device that is in widespread use among consumers. It allows users to stay connected to the internet as well as stay in contact over cellular frequency. The Android OS uses a Linux kernel to run modular applications on the device that range anywhere from interactive calendars to gaming.

Its popularity can be partly attributed to the open source paradigm in which it follows. This allows any user the ability to design and market his or her, content-rich, applications using any combination of pre-installed hardware peripherals and services. Typical peripherals, at a minimum, include cellular module, Wifi and Bluetooth wireless modules, GPS receiver, cameras, accelerometer, and storage. The shocnet application, discussed in section 3.4.2, makes use of the Wifi and storage peripherals for communication with and remote control of DPB.

3.4 Software and Application

Two primary software packages were developed for DPB. Embedded systems code, DPBfinal.c, was written with [47] and [48] and mobile wireless communication and control application, shocnet, was written with DPB using [49].
3.4.1 Embedded Systems and Pseudo Dynamic Positioning

The DPB communication and control functions saved in flash ROM on the microcontroller interact with the LS20126 and RN-XV modules as well as the trolling motor relays, to drive DPB in both manual and auto modes of operation.

The default mode of operation for DPB on start up is manual. After initialization, the main() function calls manual_control() which listens for a signal input from the RN-XV module on port B. Corresponding output signals are then distributed from port C to activate either the port, starboard, or both motors for steering, and to set DPB into auto tracking mode. For local control the user push button switch signals are sent directly to the relays, bypassing the controller entirely.

When activated, auto mode calls the get_position() function storing the current latitude and longitude coordinates, the setpoint, to memory. Get_position is a function which communicates with the GPS module via RS-232 USART, at a rate of 9600 baud, using 8 data bits, 1 stop bit, and no parity to acquire raw NMEA strings. It is also a parsing algorithm used to assign latitude, longitude, and heading values to integer variables whenever there is a valid position fix. When a fix is invalid a sub function, get_heading(), is called which returns only magnetometer heading. Filtering is also applied each iteration via a subfunction filter() within the get_position() function. The filtered outputs are in integer format to accommodate simple bitwise operator comparisons.
A noteworthy problem when capturing string arrays using the 8-bit PIC chips is that the memory is pre-banked by default into 256 byte allocations, therefore, limiting the number of characters that can be read into a single array before spilling over into another bank. This is solved by combining two banks in the linker script to increase the bank size as suggested in [29].

In auto, once the setpoint is determined, the track() function carries out the bulk of the positioning and control operations of DPB. The sub function get_bearing() determines waypoint bearing using the method described in the previous section and a simple differential control signal activates the appropriate motor relay or relays to drive DPB back towards the set point. Figure 18 below is a flow chart illustrating the code sequence of DPB. See Appendix B and C for the source code listing DPBuoyFinal.c containing all functions, and 18f27j13_lrgarry.lkr containing the linker script.
3.4.2 Remote Control and Logging Application for Android™

The shocnet application was developed as a result of field testing DPB apparatus in February 2012. It was decided that a wireless system for remote operation and testing would be more practical than the locally tethered control box. Since 802.11 WiFi communication was already established for relaying data from the LS20126 module and because the Android smart phone has a built in TCP/IP protocol stack for use over wifi, the shocnet application uses TCP/IP over WLAN. Another immediate advantage of using this type of network is internet compatibility which could provide remote, multi-user, access from any internet access.
connected device regardless of the proximity of the user to DPB. Other applications associated with shocnet are [49], [51], [56], and [57] shown in Figure 19.

![Android home screen containing all applications associated with DPB and shocnet](image)

**Figure 19** Android home screen containing all applications associated with DPB and *shocnet*

A combination of shocnet application, shown in Figure 20, and [51] allow the user to connect and disconnect to the RN-XV module onboard DPB to view
raw GPS data, steer remotely, start and stop data logging, and activate or deactivate
the setpoint. A WLAN may be set up locally using either the android smart phone
or the RN-XV module as an infrastructure network access point. The current
configuration uses the smart phone as an access point for an infrastructure network,
dually named shocnet. The RN-XV module is pre-configured to automatically find
and connect to shocnet on startup. Once wirelessly connected, the shocnet
application allows the user to input the IP address and port of DPB to establish a bi-
directional data transfer stream. For this project DPB uses a static ip address of
192.168.3.100 on port 2000.

The auto/manual button is used to establish the positional setpoint. The
current position of DPB, shown in the first two latitude and longitude text boxes,
may be converted between $ddmm.mmmm$, $dd^\circ mm^\prime ss^\prime\prime$, and decimal degree
formats using the format button. The setpoint position is displayed in the
subsequent two text boxes maintaining the formatting in which it is set. Heading
and speed are given in the last two text boxes to help the user determine DPBs
general orientation. Pressing the log button creates a text file log of raw data in the
/sdcard/dpblog directory on the Android device, using the naming convention
mmdhhmmss.txt where month, day, hour, minute, and second are represented. In
the manual mode of operation, port and starboard buttons at the bottom of the
application are used to steer DPB left, right, or straight ahead. Figure 21 shows
shocnet connected to shocnet in automatic mode and displaying the data stream
from DPB. See Appendix D for the source code listing *MainActivity.java* containing all methods.

![Figure 20](image)

**Figure 20** *shocnet* application connected to DPB and bi-directional data stream
4. Hybrid Renewable Energy System

To analyze the effectiveness of a renewable energy system it is important to consider the available resources. Since the DPB operational environment is offshore these resources include primarily wind and solar. As mentioned earlier the unobstructed surface of the ocean is conducive to high wind velocities. Solar is also a great resource during daylight hours, particularly at low latitudes, precluding cloud cover. The power requirements of DPB are another important consideration that is dependent on environmental effects. Characteristics such as duty cycle and drag are highly affected by the total wind and surface current forces imparted on DPB. The overall design of the hybrid renewable energy system must account for the capabilities and the maximum loading associated with DPB. Battery storage is also a required inclusion in the hybrid system to allow for power stability between periods of resource shortages.

4.1 Resources

4.1.1 Wind Resources

Variable wind resources around the globe are mainly created by temperature differentials and earth’s rotation. They follow a general circulation pattern based on these factors. Low latitude winds between 0° and 30° are easterly, mid latitude
Winds between 30° and 60° are westerly, and high latitude winds between 60° and 90° are easterly [37]. Figure 21 is a representation of these average wind velocities from [35]. Based on the relationship between these velocities and power given in equation 2.3, Figure 22 plots the total power available per square meter of surface area. One important thing to note is the Betz limit associated with extracting wind energy. This limit is 59.3% due to the fact that a wind turbine can never achieve 100% efficiency as the resulting wind velocity downstream would be zero [38].

**Figure 21** from [35] average world wind speeds
4.1.2 Solar Resources

When considering solar energy, as with wind, the total availability is looked at. As mentioned in section 2.5.2, the average instantaneous solar irradiance on earth is roughly $1.0 \text{ kW m}^{-2}$, but is limited to daylight hours and affected by seasonal variations. To account for this, it is necessary to include a factor of time in total hours per day. Figure 23 below is a solar irradiance map of the world for the months of April and January accounting for the total kilowatt hours per square meter per day \cite{34}. 

*Figure 22* the available wind power per square meter of surface area
Figure 23 from [34] average world solar irradiance

The conversion efficiency of this power is limited by the panels themselves. Table 7 is a summary of the most common panels on the market as of May 2012 from [32] which suggests that the most efficient solar panel available can convert about 0.2 kW m\(^{-2}\).
Table 7 from [32] common 220W solar panels on the market as of May 19, 2012

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>ID</th>
<th>STC</th>
<th>Density</th>
<th>Eff.</th>
<th>Tier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanyo Electric</td>
<td>HIT-N220A01</td>
<td>220</td>
<td>15.23</td>
<td>17.64%</td>
<td>1</td>
</tr>
<tr>
<td>SunPower</td>
<td>SPR-220-WHT-U</td>
<td>220</td>
<td>14.95</td>
<td>17.68%</td>
<td>1</td>
</tr>
<tr>
<td>Kyocera Solar</td>
<td>KD220GX-LFBS</td>
<td>220</td>
<td>12.95</td>
<td>15.40%</td>
<td>2</td>
</tr>
<tr>
<td>Suntech Power</td>
<td>PLUTO220-Udm</td>
<td>220</td>
<td>12.7</td>
<td>14.97%</td>
<td>3</td>
</tr>
<tr>
<td>Schuco USA</td>
<td>SPV 220 SMAU-1</td>
<td>220</td>
<td>12.52</td>
<td>15.02%</td>
<td>2</td>
</tr>
<tr>
<td>Canadian Solar</td>
<td>CS6P-220PE</td>
<td>220</td>
<td>11.83</td>
<td>14.20%</td>
<td>3</td>
</tr>
<tr>
<td>Evergreen Solar</td>
<td>ES-E-220-fc3</td>
<td>220</td>
<td>11.61</td>
<td>13.99%</td>
<td>4</td>
</tr>
<tr>
<td>Sharp</td>
<td>ND-220UCJ</td>
<td>220</td>
<td>11.47</td>
<td>13.99%</td>
<td>4</td>
</tr>
<tr>
<td>Phono Solar</td>
<td>PS220P-20/U</td>
<td>220</td>
<td>11.39</td>
<td>13.52%</td>
<td>4</td>
</tr>
<tr>
<td>ET Solar Industry</td>
<td>ET-P660220</td>
<td>220</td>
<td>11.32</td>
<td>13.52%</td>
<td>4</td>
</tr>
<tr>
<td>Siliken Modules</td>
<td>SLK60P6L SLV/ WHT 220Wp</td>
<td>220</td>
<td>11.27</td>
<td>13.55%</td>
<td>4</td>
</tr>
<tr>
<td>Yingli Green Energy</td>
<td>YL220P-29b</td>
<td>220</td>
<td>11.22</td>
<td>13.46%</td>
<td>4</td>
</tr>
<tr>
<td>Trina Solar</td>
<td>TSM-220PA05</td>
<td>220</td>
<td>11.21</td>
<td>13.44%</td>
<td>4</td>
</tr>
<tr>
<td>Mitsubishi Electric</td>
<td>PV-UJ220GA6</td>
<td>220</td>
<td>11.2</td>
<td>13.35%</td>
<td>4</td>
</tr>
<tr>
<td>BP Solar</td>
<td>BP3220Q</td>
<td>220</td>
<td>11.04</td>
<td>13.20%</td>
<td>4</td>
</tr>
<tr>
<td>Schott Solar</td>
<td>Perform Poly 220</td>
<td>220</td>
<td>11.02</td>
<td>13.15%</td>
<td>4</td>
</tr>
<tr>
<td>REC Solar</td>
<td>REC220PE</td>
<td>220</td>
<td>10.99</td>
<td>13.33%</td>
<td>4</td>
</tr>
<tr>
<td>Solyndra</td>
<td>SL-200-220</td>
<td>220</td>
<td>7.57</td>
<td>8.81%</td>
<td>5</td>
</tr>
</tbody>
</table>
4.2 Loads

4.2.1 Primary Electrical Load

The primary electrical load of DPB comes from the motors associated with positional correction. System load data was gathered from field and tank tests detailed in section 5.1. These instantaneous power values, however, only account for one operational environment during one instance. While this may be integrated over a period of time to account for full loading, a load duty cycle that represents a total expected annual run-time is used for determining the true requirements of DPB. This duty cycle is affected by unpredictable environmental variability throughout different locations and time. A way to account for this would involve a long term field trial of DPB under various environmental conditions and locations. Instead, simulations use an assumed value of 10%.

Curcio, et al. presents a detailed analysis of the ASC SCOUT, an autonomous surface vehicle with station keeping capability, which suggests using a 10% propulsive duty cycle for station keeping [28]. At 100% loading, DPB requirements would correlate to approximately 30 kWh per day. At this high value, the likelihood of a renewable energy system is improbable. A 10% duty cycle gives a more practical 3.1 kWh per day value.
4.2.2 Control System Electrical Load

The major control system loads for DPB are from the GPS module, PIC18 series microcontroller, and wireless module. A listing of control system loads is given in Table 8 below.

Table 8 Instrumentation and control system loads

<table>
<thead>
<tr>
<th>Unit Specifications</th>
<th>Peak Power</th>
<th>Steady State</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS20126 Module</td>
<td>587 mW</td>
<td>102 mW</td>
</tr>
<tr>
<td>PIC18F27J13 Microcontroller</td>
<td>64 mW</td>
<td>33 mW</td>
</tr>
<tr>
<td>RN-XV Wireless Module</td>
<td>594 mW</td>
<td>123 mW</td>
</tr>
<tr>
<td>Total Loads from Data sheets</td>
<td>1.2 W</td>
<td>0.25 W</td>
</tr>
<tr>
<td>Actual Measured Loads</td>
<td>3.4 W</td>
<td>2.9 W</td>
</tr>
</tbody>
</table>

It was concluded these maximum power requirements for the DPB instrumentation and control system are negligible when compared to the power requirements of the propulsion system and considering the nominal power capacity of the hybrid energy system.

4.3 Hybrid Energy System Design

4.3.1 Hybrid Optimization Model for Electric Renewables (HOMER)

Hybrid Optimization Model for Electric Renewables (HOMER) is the power systems modeling and analysis tool that was used for renewable energy system design simulations on DPB. It was selected because the software’s legacy
version is freely distributed and offers both standalone as well as grid tied system modeling capabilities.

HOMER was developed by the National Renewable Energy Lab (NREL) in the 1990’s as an internal modeling program used to, “Understand the design trade-offs between different systems configurations [36].” The software allows analysis of several hybrid energy system configurations based on inputs of environmental resource data and renewable energy components. Results from the simulations made at four different locations around the world suggest that the hybrid energy system could be feasible, pending advancements in energy storage technology.

Inputs to [54] include the solar and wind resources imported from [2] and [63], along with the selected renewable energy system components. These were entered manually and based on performance characteristics of available solar panels and wind turbines. Considerations for the renewable energy system components were size restrictions, based on space available on the buoy, weight, and total power requirements of DPB.

Two sets of solar panels were included in the analysis. One set was the Sanyo Electric 225 W mono crystalline/amorphous silicon hybrid panel (HIT-N225A01) from Solarsystems USA online at www.solarsystemsUSA.net. These cost $606.38 and weigh 16 kg each. They have a power density of 209.1 W m\(^{-2}\) or 17.8% module efficiency. The panel dimensions are 158 cm X 80 cm X 4.6 cm. Another set was the ET Solar 95 Watt mono crystalline panels (ET-M53695, 95/36)
which are $184.89 from solarsystemsusa.com. They have 14.47% module efficiency and weigh 8.2 kg. Dimensions are 120 cm X 54.5 cm X 3.5 cm. These dimensions allow for the inclusion of two panels each on DPB as shown in Figure 24. The combined weight of the solar panels is 48 kg which DPB can support [39].

For DPB wind energy, the Air Breeze Marine 12 V DC Wind Generator from Southwest Windpower, online at http://store.windenergy.com, was selected. This generator is a 0.4 kW nominally rated, 12 V DC, brushless permanent magnet type, with a 1.07 m$^2$ swept area, 3.1 m s$^{-1}$ startup speed, and total weight of 6 kg [40]. The size and weight restrictions of DPB allow for the potential inclusion of two wind turbines mounted above the solar panels as illustrated in Figure 25. Figure 26 is a plotted power curve exported from [54].
Figure 25 a potential placement of two wind turbines

Figure 26 power curve for SW Air Breeze wind turbine exported from [54].
Batteries selected for DPB hybrid energy system analysis were the Vision 6FM55TD, 12 V DC, 51 Ah, online at www.wholesalebatteriesdirect.com, cost $142.95. They weigh 18.5 kg each with dimensions 23 cm X 13.8 cm X 21.3 cm allow for the inclusion of six on DPB. The total 102 kg can be supported by DPB [42].

Based on the aforementioned restrictions and selected components, the hybrid energy system configuration inputs to [54] are given in Table 9 below. This, “search space” lets HOMER consider several of these components and optimize the configuration based on the total load and allowable capacity shortage.

**Table 9** search space from [54]

<table>
<thead>
<tr>
<th>PV Array (kW)</th>
<th>AIR (Quantity)</th>
<th>6FM55D (Quantity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.095</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.190</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>0.225</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.320</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.415</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.450</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.545</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.640</td>
<td></td>
</tr>
</tbody>
</table>

DPB load data is primarily determined using the propulsive duty cycle which depends heavily on wind and current speeds at the DPB set point location. Due to the variability of these conditions, hybrid system designs are based on the assumed value of 10% percent as shown in Figure 27.
For HOMER simulations, 2011 wind and solar resource data was gathered at four buoy sites given by [2] and [63]. Stations 41009 (LLNR 840), off the coast of Cape Canaveral, 41044 in the Caribbean Sea, 46035 (LLNR 1198) in the Bearing Sea, and 51004 (LLNR 28005) in Hawaii were used. Averaged monthly wind and solar resources from station 51004, located at latitude 17° 31' 31" N and longitude 152° 22' 55" W, are shown in Figures 28 and 29 respectively imported into [54].

*Figure 27* load inputs to [54] based on a 10% propulsive duty cycle
Figure 28 averaged monthly sustained wind data imported into [54] from [2] taken at station 51004

Figure 29 averaged monthly solar irradiance imported into [54] from [34] taken at station 51004
4.3.2 Simulation Results

Interpretation of the results from HOMER requires the identification of load shedding conditions and capacity shortage. Load shedding occurs when the energy demand exceeds generated power placing energy storage in a discharge state. Capacity shortage is the fraction of load shedding that exceeds the total capacity of the hybrid system. This fraction is used as the ultimate determination of whether or not the hybrid renewable energy system will work for DPB [54].

Simulation results from station 51004 are presented in Figure 30 which revealed the most promising solutions. They indicated that the optimum wind and solar hybrid energy system configuration for DPB, if located in the southeastern Hawaiian Islands, could sustain load requirements with less than a 1% annual capacity shortage. Results from station 46035 had the highest capacity shortage of 38%.

Stations 41009 and 41044 simulations suggest that seasonal variability of renewable energy resources such as light winds during the summer months may be a leading contributor to the capacity shortage at these Florida and Caribbean sites. Battery storage capacity was identified as the most considerable restriction for the hybrid energy systems in these cases. In order to cover these shortages the battery storage capacity would have to include approximately 1,700 Ah or 31 batteries.
Figure 30 HOMER simulation results for DPB at station 51004 based on a 10% propulsive duty cycle

4.3.3 Systems Integration

When integrating renewable energy systems the most important consideration is the type of current and voltage range produced by each system. Wind turbines generate AC and solar panels generate DC. To combine the two it is most convenient to convert all systems to DC using a rectifier. Due to variability inherent in renewable energy systems, efficiency and charge can be lost during periods of fluctuating output. A maximum power point tracker (MPPT) and charge controller circuit can help mitigate, but not eliminate, these losses. They provide...
sensing of the voltage differences and voltage conversion to accommodate the most
efficient charging cycle for the energy storage system. They also provide reverse
current protection using diodes during periods of solar outages. Figure 31 is a
diagram of the inputs and configuration considered with [54]. Figure 32 shows an
overall DPB electrical layout including a hybrid renewable energy system
integrated with the instrumentation and control systems.

![Figure 31 hybrid system configuration input to [54]](image-url)
Figure 32 DPBs electrical configuration layout
5. Testing

Testing of the DPB apparatus and associated hardware was done in four stages. Tank testing in the FIT wave tank was performed to determine thruster output. Stability, loading, and performance field testing was performed at the Eau Gallie causeway boat ramp. LS20126 module precision and accuracy field testing was performed at various locations around New London, Connecticut and off the coast of Aberdeen, Scotland. Pseudo dynamic positioning system testing was performed using a small model test platform in a pool.

5.1 Tank Test

DPB thruster testing was performed on April 3, 2012 in the FIT wave tank. Testing apparatus included one DPB thrust package with manual control circuit, the wave tank itself, a mechanical strain gauge with 15 kg capacity, and an 800 A, clamp-on DC ammeter. The objectives were to determine capability and current load of the DPB’s 12 volt trolling motors in a controlled environment for hybrid energy system design.

To discover the peak and steady state amounts of thrust force, in newton, that the selected trolling motors can deliver, a trolling motor mounted to one of the battery boxes designed for the buoy was floated in the wave tank. A strain gage was then attached to the apparatus on one end and held fixed on the other as
depicted in Figure 33 below. The motor was engaged and the force measured for both peak and running conditions.

**Figure 33** Thrust test apparatus in the FIT wave tank facility with a fixed strain gauge to measure output force

The current load test of the thrusters was designed to discover the peak and steady state power requirements for DPB. It is important to note that motor speed control was not used as field testing indicated acceptable maneuvering response without it. See section 5.2.1 below. Instead, the tested states were simply on and off. Peak and running current loads were measured using the clamp-on ammeter around the cable connected to the motor’s positive lead as shown in Figure 34. Combined test results are given in Table 11.
**Figure 34** DC ammeter clamped to the positive lead of the motor

**Table 10** Measured and calculated characteristics of the DPB propulsion system

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Peak</th>
<th>Steady State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>129 N</td>
<td>124.6 N</td>
</tr>
<tr>
<td>Load</td>
<td>53.3 A</td>
<td>51 A</td>
</tr>
<tr>
<td>Power</td>
<td>639.6 Watts</td>
<td>612 Watts</td>
</tr>
<tr>
<td>Max. DPB Design requirement</td>
<td>1279.2 Watts</td>
<td>1224 Watts</td>
</tr>
</tbody>
</table>
5.2 Field Tests

5.2.1 Dynamic Load, Stability, and Performance

The majority of DPB field testing was performed on February 2, 2012 at the Eau Gallie causeway boat ramp. Selected test equipment included the DPB apparatus, the designed wireless instrumentation and control package, Figure 39 at the end of this section, a laptop computer, a Kestrel 4000 digital anemometer for wind speed and direction, Aanderaa inductive current meter for surface current velocities, Magellan Triton 1500 handheld GPS for positional reference, and a Boston Whaler support skiff.

The objectives were to observe the overall functionality, handling of the DPB apparatus and to discover its power requirements. Observed parameters were difficulty of deployment, the ability to float level in the water with a wind turbine mounted 3 m above the waterline, acceleration dampening capability without a motor speed controller, forward movement and turning capability. Measured parameters included maximum and steady state speed and power while maneuvering in both static and dynamic environments.

DPB was transported via a small, flatbed, trailer to the Eau Gallie causeway and deployed by backing it into boat ramp. A static environment was verified within the confines of the boat ramp using the Aanderaa current meter reading of 0.07 m s\(^{-1}\) and no obvious wind. Ease of deployment was observed by the ability of two people being able to push the unit off of the trailer shown in Figure 35.
The buoy was immediately observed successfully floating level in the water. DPB was driven manually to the end of the dock using a simple push button switch and relay circuit to activate the thrusters. Sufficient acceleration dampening was observed. Maneuverability observations were made by driving DPB manually while sitting on top of it shown in Figure 36. Forward, left, and right turning maneuvers were observed to be successful and practical.

Once basic handling had been successfully and safely demonstrated, the wind turbine was mounted 3 m above the waterline. The analog ammeter was introduced in series to the circuit via quick release electrical connectors and the buoy was again driven through a series left, right and forward maneuvers. The results of the power and speed tests in a static environment are given in Table 12 at the end of this section. For dynamic environment testing, DPB was followed closely with the support vessel and driven from the bow as shown in Figure 37. Load testing was repeated while heading forward into the oncoming current and headwind.

A wireless connection was established and maintained throughout the Eau Gallie causeway field test and all NMEA raw data broadcast from DBP was logged using [44] on the shore based laptop computer. This data, along with ammeter data, was used to measure maximum speed capability and power requirements. Due to necessary wiring reconfigurations made to accommodate the dynamic environment testing, ammeter data was unable to be recorded.
Figure 35 DBP deployment observation image courtesy of Dr. Stephen Wood

Figure 36 Eau Gallie causeway static environment field test and control scheme image courtesy of Dr. Stephen Wood
Figure 37 Eau Gallie causeway dynamic environment field test apparatus and control scheme image courtesy of Dr. Stephen Wood

The data analysis software used for the Eau Gallie causeway field tests were [44], [45], [50], and [53]. Figure 38 is a graphic representation from [45] of the dynamic field test depicting the full path of DPB over the entire 35 minutes of testing and applicable environmental condition overlays.
Figure 38 Eau Gallie dynamic environment field test site with environmental condition overlays
**Table 11** Static and dynamic environmental conditions

<table>
<thead>
<tr>
<th>String</th>
<th>UTC</th>
<th>Valid LAT</th>
<th>LON</th>
<th>SOG</th>
<th>COG</th>
<th>Date</th>
<th>Variation</th>
<th>Chksum</th>
<th>Data Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGPRMC</td>
<td>173210 A</td>
<td>2808.1438 N</td>
<td>8036.3585 W</td>
<td>0.29</td>
<td>97</td>
<td>20212</td>
<td>6.2 W D*10</td>
<td>5:32:10 - 5:32:53</td>
<td></td>
</tr>
<tr>
<td>AVG</td>
<td>0.35</td>
<td>135.56</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 12** Current data

**Boat Ramp (28° 8' 8.45" N, 80° 36' 21.13" W)**

<table>
<thead>
<tr>
<th>MANEUVER</th>
<th>Peak (Amps)</th>
<th>Running (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCKWISE ROTATION</td>
<td>47-49+</td>
<td>45-47</td>
</tr>
<tr>
<td>COUNTER CLOCKWISE ROTATION</td>
<td>47-49+</td>
<td>45-47</td>
</tr>
<tr>
<td>FORWARD (each motor)</td>
<td>*47-49+</td>
<td>*35-42</td>
</tr>
<tr>
<td>TOTAL FORWARD (dual motors)</td>
<td>94-98</td>
<td>70-84</td>
</tr>
<tr>
<td>SOG: (m/s) COG: (deg)</td>
<td>0.19 avg</td>
<td>134°</td>
</tr>
</tbody>
</table>

* Note: Value must be doubled to account for both motors

**Test Area (28° 8' 7.51" N, 80° 3 6' 20.95" W)**

<table>
<thead>
<tr>
<th>MANEUVER</th>
<th>MEASURED AMPERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCKWISE ROTATION</td>
<td>No Data</td>
</tr>
<tr>
<td>COUNTER CLOCKWISE ROTATION</td>
<td>No Data</td>
</tr>
<tr>
<td>FORWARD</td>
<td>No Data</td>
</tr>
<tr>
<td>SOG: (m/s) COG: (deg)</td>
<td>0.61 avg</td>
</tr>
</tbody>
</table>

**Table 13** Static and dynamic test environment velocity data

Eau Gallie causway field test velocity data

80
The trolling motors ran at 12 volts and between 35 to 50 amps each (0.42 - 0.6 kW) which means that the combined peak output of all renewable energy systems needs to be 1.2 kW. This is in agreement with the test tank data. The control circuit was rebuilt with 80 A relays vice the 40 A ones to accommodate the higher than expected electric currents observed during the field test.

In light of this relatively high power requirement, some observations were made which may help to reduce it. The currents were not very fast moving in our test area, and it appeared that the buoy was slightly overpowered. Potentially,
smaller or more efficient motors could be used to minimize the power requirements and still hold the buoy on station. Additional power requirements could be met by adding an additional wind turbine.

5.2.2 Form Drag Analysis from Dynamic Field Test

For completeness the drag force for DPB is calculated using an assumed drag coefficient, values obtained from the DPB tank and field tests, and cross sections shown in Figures 41 and 42. Based on this result, the form drag curves are extrapolated using the drag equation 5.1 and are given in Figure 40.

Assumptions include steady, irrotational, and incompressible flow for water. Due to low average air velocities below 2.5 m s\(^{-1}\) resulting in Mach numbers less than 0.3, air may also be treated as incompressible as suggested by [58]. Only the x component of apparent velocities, averaged over the given test sample, are used for simplification of force calculations. Wave drag is neglected due to insignificant wave heights observed during testing. All values are converted to metric for consistency. The drag equation, 5.1 below, was taken from [58]. All assumed values were taken from [58] and [60].

\[
\vec{F}_{\text{drag}} = \frac{1}{2} \rho v^2 C_d A
\]  \hspace{1cm} (5.1)

Where \(\vec{F}_{\text{drag}}\) is the drag force on the buoy resulting from the respective fluid, \(\rho\) is density given as 1027 kg m\(^{-3}\) for seawater and 1.16 kg m\(^{-3}\) for air at sea level, \(v\) is the average apparent velocity of 0.77 m s\(^{-1}\) for water current and 2.51 m s\(^{-1}\) for
wind, $C_d$ is the drag coefficient 1.08 for a cubed shape, and $A$ is the cross-section of 2.86 m$^2$ in air and 0.4 m$^2$ in water.

**Figure 40** extrapolated drag curves for DPB
Figure 41 DPB cross-section measurements
Figure 42 wind turbine swept area and mounting cross-section measurements
5.2.3 Accuracy and Precision

Due to the availability of National Geodetic Society (NGS) bench marker locations around New London, CT, two US test sites for Locosys LS20126 embedded GPS receiver module field testing were selected; Ft. Trumbull and Eastern Point Beach. These tests were conducted on April 20 and 21, 2012. A third site off the coast of Aberdeen, Scotland was used for redundancy on May 6, 2012. Besides the GPS module itself, other test equipment included a Samsung Galaxy Prevail smart phone running Android OS V2.2.2: FROYO.EE14 that was rooted to allow WLAN infrastructure setup via [51] at each test site. Smart phone GPS capability with [52] as a benchmark locating device and a secondary coordinate reference. The same laptop computer and software packages from the Eau Gallie field test were used for tracking and logging as well. Veripos and C-NaviGatorII (C-Nav) DGPS instrumentation was provided aboard the seismic survey vessel C-Pacer. Final analysis was done with [53]. The primary objective of the accuracy and precision field testing was to discover the effectiveness of the LS20126 module as the positioning source for DPB.

The site locations were based on NGS benchmark control survey markers shown in Figure 43. These markers are located at thousands of points across the US and have very accurate GPS coordinates. They were found using a combination of [52] and the NGS datasheets available from www.ngs.noaa.gov. An example is
given in Appendix E. It is important to note that only benchmarks with adjusted, not scaled, position values were selected due to their increased accuracy.

![Figure 43 NGS benchmark at Ft. Trumbull](image)

The first benchmark site was Ft Trumbull, PID LX5234, datum North American Datum 1983 (NAD83), coordinates 41° 20’ 37.70649” N, 072° 05’ 37.17539” W. The DPB instrumentation was placed on the benchmark site and 5 minutes of full NMEA raw data was logged at 1Hz frequency. Another 2 minute log was taken at 1.5 m removed from the benchmark and another 2 minutes at 1.5 more meters further removed. The second benchmark site was Eastern Point, PID LX5212, datum NAD 83, coordinates 41° 19’ 09.70436” N, 072° 04’ 30.00195” W. The DPB instrumentation was placed on the benchmark site and 5 minutes of
full NMEA output string data were logged at 1Hz frequency. Another 5 minute log was taken at 7.3 m North by Northeast from the Eastern Point marker. This distance was selected to be greater than the 5 m accuracy of the LS20126 module and based on the practical placement of the unit on a level surface away from the original mark. A third test was conducted onboard the seismic node vessel C-Pacer while outside the harbor in Aberdeen, Scotland, datum World Geodetic System 1984 (WGS 84), coordinates 057° 10’ 39.135” N, 002° 00’ 36.049” W using RTNu corrected DGPS positioning data to ensure sub-meter accuracy. The DPB instrumentation was placed next to the GPS antenna and 5 minutes of data recorded. The unit was then moved to a pre-surveyed point on the vessel at a known distance (11.6 m to port and 0.3 m forward) from the antenna and 5 minutes of data was recorded. All $GPRMC$ strings were parsed for latitude and longitude coordinates then plotted using [53].

The Ft. Trumbull benchmark was located on the top wall of the fort. Luckily there were maintenance personnel on site that allowed access to the benchmark for this test. Three positions within 3 m of each other were logged. Unfortunately the log files were not taken separately so there was no way to tell which position is which. Figure 44 shows all plotted coordinates from the Ft. Trumbull field test.
The Eastern Point Beach benchmark was the most easily accessible. It was embedded into a large rock outcrop near the water in a public park. The benchmark is shown as the diamond shaped mark in the lower left corner of Figure 45.

Lessons learned from the Ft. Trumbull test were the use of separate log files for each position measurement. The plus shaped plots show position measurements when the DPB instrumentation placed directly on the benchmark. Northing and easting coordinates applied to the measurements during post analysis indicated that the maximum outlier positions from the benchmark are within in a 15 m radius, an
acceptable range for the DPB design parameters. The last position was taken at a point 7.3 m NNE from the benchmark with positions plotted as crosses. The distance was chosen based on the +5 m nominal accuracy of the unit as mentioned in section 3.3.1. Results indicate a distinguishable positional difference.

![Eastern Point Beach](image)

**Figure 45** Eastern Point Beach field test results

The Aberdeen pilot station field test was conducted while on board R/V C-Pacer seismic node vessel while on DP. The ship’s dynamic positioning system is precise enough to hold the vessel at a fixed position with sub-meter accuracy.
Due to the inhibitive locations of the Veripos and C-Nav antennae on the vessel, the first data set was taken at a position within 0.5 m of the Veripos antenna. The C-Nav antenna was located 2.28 m away. The second data set was taken at a known position 11.6 m port of the Veripos antenna. Results shown in Figure 46 are consistent with both of the previous tests conducted in the US.

**Figure 46** Veripos and C-Nav relative positions with LS20126 module plot overlays

The inconsistency between benchmark data points based on the NAD83 and the Locosys LS20126 module data based on WGS84 was considered, however, the third test using the Veripos DGPS system revealed consistent accuracy results from
the embedded module. Test results from all three stations indicated that the GPS position data resolution was good enough to meet the DPB design requirements of a 250 m watch radius.

5.2.4 Small Model Performance

To determine the effectiveness of the dynamic positioning system, a small model apparatus, shown in Figure 47, was built to have similar differential steering characteristics of the full sized test apparatus. The DPB instrumentation and control package was installed on this model for testing. This apparatus as well as the Samsung Galaxy Prevail smart phone with shocnet application, for remote steering and setpoint activation capability, and a laptop computer with MPLAB, for connection and adjustment of the DPB tuning variables, were used for the small model test on September 8, 2012. Tests were conducted at Cypress Head community pool, Port Orange, FL.

![Figure 47 DPB small model with differential steering](image)

*Figure 47 DPB small model with differential steering*
The objectives were to observe the maneuvering and controllability of the model, test the station keeping capability of the DPB instrumentation and control system, test the effectiveness of the zeroth order Kalman filter, and to test the effectiveness of adjusting the tuning variables Q, R, associated with the filter, and posfudge, brgfudge, turntimeCW, turntimeCCW, ahdttime, associated with the allowable corrective ranges and duty cycles.

The first test was simply an observation of the maneuverability and operation of the small craft by placing it the pool and connecting to it with shocnet. The craft was then driven, remotely, through a series of left, right, and ahead full maneuvers.

Once maneuverability was observed, the vessel was driven to a location near the center of the pool. The set point then activated remotely and the craft observed. The desired outcome was that the craft would remain stationary.

For positional correction, the tuning variables Q, process noise covariance, and R, measurement noise covariance, are associated with the Kalman filter, and refer to the certainties of the process model and measurements respectively. A high value for R and low value for Q will not give too much weight to the measurements and depend more heavily on the model while a low value for R and a high value for Q will follow more closely to the measurements and give less dependency to the model [19].
Based on results from stationary position and accuracy field testing, the uncertainty of the LS20126 module measurements, R, should be a low value. This is indicative of the fact that it was able to consistently deliver a +/- 5 m accuracy while stationary. The model should have a high amount of uncertainty, the Q value, due to the lack of environmental inputs. Figure 48 illustrates the effects of setting initial values for R and Q to 0.36 and $1 \times 10^{-4}$ respectively applied to a five minute sample of raw GPS data obtained from the LS20126 module at an arbitrary location. The initial tuning variables for position and bearing allowance were set to 4, and the duty cycle variables set to 12. Parameters were adjusted based on the results of observed behavior.
Figure 48 application of the zeroth order Kalman filter with initial values of 0.36 for R and $1 \times 10^{-4}$ for Q
Observations of the initial maneuvering test revealed a left favored motion during ahead full maneuvers. Ahead and CCW timing adjustment variables were lowered to reduce the thruster on cycle those maneuvers. Figure 49 is satellite view of the initial positioning test of DPB from [45]. Results indicate that the initially applied filtering parameters were ineffective. Subsequent tests over a range of tuning values yielded similar, disappointing, results.

Figure 49 from [45] a satellite image of small model test with the recorded path superimposed

It was concluded that either the tuning parameters were ineffective as fixed values and DPB would benefit from real-time, self-tuning, capability, or that the
relatively small dimensions of the pool were too restrictive for conclusive results of the test. One key observation was that the influence of wind speed and direction strongly dictated the positional offsets. This resulted in extreme changes of DPB heading. The addition of an anemometer input to the system should greatly increase the positional correction capability of DPB.
6. Conclusion and Further Development

The DPB system demonstrated the ability to mount a self-feathering, horizontal axis wind turbine at a height of 3 m from the water line while maintaining upright stability during maneuvering in wind speeds up to 2.5 m s\(^{-1}\). The originally conceived vertical axis wind turbine centered within the body of the buoy, a radical concept which would alleviate wind attack angle concerns, was discarded due to a lack of availability and size restrictions that would be imposed.

Among several other design considerations, such as structure, cost, availability, and existing buoy designs, power requirements turned out to be extremely prohibitive towards the practical use of a wind and solar hybrid renewable energy system. While the optimal design configurations of a hybrid solar and wind renewable energy system using a 10% propulsive duty cycle input to [54] were able to attain a minimum capacity shortage of less than 1% at one Hawaiian Islands location, all other simulated locations had results greater than 15%. A lack battery storage capacity was also determined to contribute considerably to this shortage. The addition of surface wave energy to the hybrid system was considered, but after reviewing the results from [59] and an exhaustive internet search for off the shelf linear generators it was concluded that a surface wave energy generator system would be impractical at this time.
Using electric propulsion was concluded to be less effective than a direct mechanical drive train due to the poor efficiencies associated with renewable energy systems. An electric propulsion system also has a restrictive total output which is independent of wind power, whereas a mechanical drive train would provide an output that is simply proportional to and limited only by the wind speed. An ideal, electro-mechanical, propulsion system would take advantage of heavy wind or high solar irradiance conditions as well as provide back-up power and propulsion during periods of low wind and poor insolation. A low cost dynamic positioning system was deemed feasible, but overall limited with respect to the selected microcontroller, lack of environmental sensing, precision positioning module, and variable speed control.

6.1 A Better DPB Design

A better station keeping design, which has a propensity for station keeping, should present the least amount of drift from position when affected by ocean and wind currents, therefore, requiring the least amount of power input for corrections. A similar buoy with rudder type steering and an electromechanical drive train could be developed to use very little electrical power. Integration of inertial navigation and dead reckoning would also provide reliability during periods of GPS blackout. Also, Blackford acknowledges that the omni-directional nature of a vertical-axis windmill should give a practical advantage in the application of rotary wind craft
To that end, and considering a spar buoy design, a likely optimization is given in Figure 50. The spar buoy would be the ideal candidate for station keeping at sea due to its reduced cross sectional area and hydro dynamic advantage.

**Figure 50** a more ideal design for renewable energy station keeping
6.2 Further Development

The sea anchor, or drag anchor, is another type of stationary positioning that can be deployed from vessels floating on the surface. While anything submerged in the water and tethered to a surface vessel can provide drag, most modern drag anchors are shaped like upside down parachutes. They cannot hold a vessel completely stationary, but a drag anchor could help mitigate the effects of wind drift. Modern life boats use them to keep from drifting too far from the distress position during search and rescue operations. An automated water drag system addition, which could sense surface currents and determine a beneficial adjustment angle, could provide extra drag as a counter force to wind currents in some cases.

The most highly recommended addition to the control system is an anemometer for wind speed and direction data. A power sensor measurement, motor speed control, accelerometer feedback, and current sensing are also valuable inputs for the incorporation of a full blown DPS using a true extended Kalman filter.

Solar tracking would provide increased performance of the renewable energy system and could be accomplished by adjusting the mounting angle of the panels along with heading correction based on photo sensing.
References

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Appendix A (Third Party Software Packages)

Figure 51 from [44] LS20126 module monitoring software including accelerometer output

Figure 52 from [43] used to redirect and split TCP/IP port connections to virtual serial port
Figure 53 from [50] terminal software used for serial and TCP/IP communication

Figure 54 from [47] used for development of control software using PICC18 compiler
Figure 55 from [51] wireless tether application used to establish a mobile WLAN
Figure 56 from [49] used for mobile application development
Figure 57 from [54] used for hybrid energy configuration analysis
Appendix B (PIC C-18 Control Code)

C:\Projects\PICProjects\DPBuoy\DPBuoyKalman.c

// This code rendition of DPBuoy is further developed than DPBuoy_GPS_27j12PCB.c as is was developed for the PCB board. The pins have been remapped for the pc board. The get_bearing is completed and the control "track" function attempts to use the filter to get positions. THE LCD FUNCTIONS AND DISPLAY MESSAGES ARE REMOVED*/

#include <p18f27j13.h>
#include <xlcd.h>
#include <delays.h>
#include <stdio.h>
#include <usart.h>
#include <adc.h>
#include <string.h>
#include <stdlib.h>
#include <math.h>

// this section sets up a large character array by combining 3 banks of 256 bytes. Be sure to use "18f27j13lrgarry.lkr" files.
#pragma udata directive
#pragma udata LRGARRY // section LRGARRY
char GPS_string[512];
#pragma udata // return to default section
char *capture = &GPS_string[0]; //Use a pointer to access the values in the large array
#define pi 3.14159265359
#define posfudge 150 // positional offset allowance
#define brgfudge 10 // bearing offset allowance
#define turntimeCW 12 // how long the thrusters stay on for turning
#define turntimeCCW 4 // how long the thrusters stay on for turning
#define ahdttime 12 // how long the thrusters stay on for ahead full corrections
#define R 0.36 // (R - measurement noise covariance) represents the uncertainty in the measurement
#define Q 0.0001 // (Q - Process noise covariance) represents the uncertainty in the process model

// A tight filter: large R and small Q will not give too much weight to the measurements
// A relaxed filter: small R and large Q will follow more closely to the measurements

// Function Prototypes.............................................
int get_heading(void);
void get_bearing(void);
void get_position(void);
void kalman_filter(void);
void track(void);
void move_far(void);
void manual_control(void);

//Global Variables..............................................
char PLSR_parse[]="PLSR,245,1",GPRMC_parse[]="GPRMC",delim1[]="$",delim2[]=",";PLSR_parsed[80],GPRMC_parsed[80];
char NSmk="X",NSind,EWmk="X",EWind;
void main()
{
    memset(GPS_string, NULL, 512);
    TRISCbits.TRISC3 = 0; // This is for the GPS status light
    TRISCbits.TRISC1 = 0; // This is for the Calibration status light
    TRISCbits.TRISC2 = 0; // These are for the set point button and indicator light
    TRISCbits.TRISC4 = 0; TRISCbits.TRISC5 = 0; // set up the thruster control pins
    ANCON1 = 0b11111111; ANCON1 = 0b00001111; // sets port B pins as digital not the same as ADCON1
    TRISB = 0b11111110; // B ports are inputs except RB0
    LATCbits.LATC1 = 1; LATCbits.LATC2 = 1; LATCbits.LATC3 = 1; // turn on indicator lights
    // test for signal to relays. this should turn on both motors
    LATCbits.LATC4 = 1; LATCbits.LATC5 = 1; for (cnt = 0; cnt < 5; cnt++) { Delay1KTCYx(100); LATCbits.LATC4 = 0; LATCbits.LATC5 = 0; }
    LATCbits.LATC7 = 0; LATCbits.LATC7 = 1; // This loop is to stall the GPS transmission long enough for the wifi to connect to the saved network by activating USART output pin
    for (cnt = 0; cnt <= 20; cnt++) { Delay10KTCYx(100); }
    LATCbits.LATC1 = 0; LATCbits.LATC2 = 0; LATCbits.LATC3 = 0; LATCbits.LATC7 = 0; // turn all indicator lights off
    TRISCbits.TRISC6 = 0; TRISCbits.TRISC7 = 1; // set up USART1 pins
    while(1){
        LATCbits.LATC4 = 0; LATCbits.LATC5 = 0; // Ensure motors are off
        get_position();
        while (PORTBbits.RB1 == 1 && on == 0){ // the unit defaults to manual control until the set point is activated
            LATCbits.LATC2 = 1; // manual control indicator light
            manual_control();
        }
        if (PORTBbits.RB1 == 0 && on == 0 && signal == 1){ // when the setpoint is set and the signal is invalid
            LATCbits.LATC4 = 0; LATCbits.LATC5 = 0; // turn off both thrusters
            for (cnt = 0; cnt < 15; cnt++) { LATCbits.LATC2 = 2; Delay10KTCYx(20); LATCbits.LATC2 = 1; Delay10KTCYx(20); }
            LATmkf = LATf; LATmkf = LATf; NSmk = NSind; // mark the latitude and longitudes at this point
            LONmkf = LONi; LONmkf = LONf; EWind = EWind;
        }
        else if (PORTBbits.RB1 == 0 && on == 0 && signal == 0){ // when the setpoint is set and the signal is invalid
            LATCbits.LATC4 = 0; LATCbits.LATC5 = 0; // turn off both thrusters
            for (cnt = 0; cnt < 15; cnt++) { LATCbits.LATC2 = 2; Delay10KTCYx(20); LATCbits.LATC2 = 1; Delay10KTCYx(20); }
            LATmkf = LATf; LATmkf = LATf; NSmk = NSind; // mark the latitude and longitudes at this point
            LONmkf = LONi; LONmkf = LONf; EWind = EWind;
        }
    }
}
printf("Can't track, no valid signal");
Nop();
}
}
// End of main

void get_position(void){
  long UTCi;
  int UTCf;
  int SOGi,SOGf,COGi,COGf,DATE,vlength,nmhldr;
  float flthldr;
  char *gps,*name,*UTC,*valid,*mode,*plchldr;
  memset(GPS_string, NULL, 512);
  TRISCbits.TRISC3=0;  //This is for the GPS status light
  Open1USART(USART_TX_INT_OFF & USART_RX_INT_ON & USART_ASYNCH_MODE &
  USART_EIGHT_BIT & USART_CONT_RX & USART_BRGH_HIGH,129);
  while(!DataRdy1USART());
  for(cnt=0;cnt<=511;cnt++){
    while(!DataRdy1USART());
    capture[cnt]=Read1USART();
  }
cnt = 0;
  sprintf(GPRMC_parsed,"%s",strtokstrstr(capture,GPRMC_parse),delim1));
  vlength = strlen(GPRMC_parsed);

  // Get the sub-parsed Data Strings
  name = strtok(GPRMC_parsed,dlim2);
  UTCi = atol(strtok(NULL,delim2));UTCf = atoi(strtok(NULL,delim2));
  valid = strtok(NULL,delim2);
  if (*valid == 'V'){
    signal = 0;
    LAt1=0;LATf=0;LONi=0;LONf=0;'NSind = 'X';'EWind = 'X';
    HDG = get_heading();
    LATCbits.LATC3 = 1;Delay1KTCYx(75);LATCbits.LATC3 = 0;
    on = 0;  //break from while loop in tracking function
    inicounter = 0;  //this indicates that new apriori data is required for the kalman filter
    printf("Signal=%d HDG: %d inicounter: %d
",signal,HDG,inicounter);
  }
  else if (*valid == 'A' && vlength>=50){
    signal = 1;

    //latitude, longitude CONVERSION to decimal
    /* nmhldr =
      atol(strtok(NULL,delim2));flthldr=atof(strtok(NULL,delim2))/10000;
      LATi = nmhldr/100; LATf =
      (int)((fmod(nmhldr,100)/60)+(flthldr/60))*10000;
      NSind = strtok(NULL,delim2);
      nmhldr =
      atol(strtok(NULL,delim2));flthldr=atof(strtok(NULL,delim2))/10000;
      LONi = nmhldr/100; LONf =
      (int)((fmod(nmhldr,100)/60)+(flthldr/60))*10000;
      EWind = strtok(NULL,delim2);*/

    //latitude, longitude NO CONVERSION to decimal
    LATi = atoi(strtok(NULL,delim2));LATf = atoi(strtok(NULL,delim2));
    NSind = strtok(NULL,delim2);
    LONi = atoi(strtok(NULL,delim2));LONf = atoi(strtok(NULL,delim2));
}
```c
EWind = strtok(NULL, delim2); /*

//degmin sec Lati:###dm Latf:##sec format
LAT1 = atoi(strtok(NULL, delim2)); LATf = .06 *
(atoi(strtok(NULL, delim2)));
NSind = strtok(NULL, delim2);
LON1 = atoi(strtok(NULL, delim2)); LONf = .06 *
(atoi(strtok(NULL, delim2)));
EWind = strtok(NULL, delim2);
SOGi = atoi(strtok(NULL, delim2)); SOGf = atoi(strtok(NULL, delim2));
COGi = atoi(strtok(NULL, delim2)); COGf = atoi(strtok(NULL, delim2));
DATE = atoi(strtok(NULL, delim2));
plchldr = strtok(NULL, delim2); plchldr = strtok(NULL, delim2);
mode = strtok(NULL, delim2);
LATCbits.LATC3 = 1; //GPS status LED is on
HDG = COG;

if (inicounter == 0) {Xk1=LATf; Xk2=LONf; inicounter++;}
else {inicounter = 1;}
//this stops the inicounter from counting
//until signal is lost in which case the
//inicounter will be zero
printf("\n\rLATf: %d LONf: %d Signal:%d inicounter:%d\n\r", LATf, LONf, signal, inicounter);
kalman_filter();

else {LATCbits.LATC3 = 1; Delay10KTCYx(75); LATCbits.LATC3 = 0;}
}

void kalman_filter(void)
{
float Pkminus1,Kk1,Zk1; //Covariance, updated covariance, Prediction, Kalman
error, measured state Latitude
float Pkminus2,Kk2,Zk2; //Covariance, updated covariance, Prediction, Kalman
error, measured state Longitude
Open1USART(USART_TX_INT_OFF & USART_RX_INT_ON & USART_ASYNCH_MODE &
USART_EIGHT_BIT & USART_CONT_RX & USART_BRGH_HIGH,129);

//filter latitude
Zk1 = LATf; //get the current measurement
Pkminus1 = (Pk1+Q);
Kk1 = Pkminus1/(Pkminus1+R);
Xk1 = Xk1 + (Kk1*(Zk1-Xk1));
Pk1 = (1-Kk1)*Pkminus1;

//filter longitude
Zk2 = LONf;
Pkminus2 = (Pk2+Q);
Kk2 = Pkminus2/(Pkminus2+R);
Xk2 = Xk2 + (Kk2*(Zk2-Xk2));
Pk2 = (1-Kk2)*Pkminus2;
LATf = (int)(Xk1*10);
LONf = (int)(Xk2*10);
printf("Filtered Lat:%d Filtered Lon:%d\n\r", LATf, LONf);
}

int get_heading (void)
{char *name;
int ident, dir, field, accX, accY, accZ, tptrC, tptrF, mtmd, cal, autocal;
memset(GPS_string, NULL, 512);
```
Open1USART(USART_TX_INT_OFF & USART_RX_INT_ON & USART_ASYNCH_MODE & USART_EIGHT_BIT & USART_CONT_RX & USART_BRGH_HIGH, 129);
while(!DataRdy1USART());
for(cnt=0;cnt<=511;cnt++){
while(!DataRdy1USART());
capture(cnt) = Read1USART();
cnt = 0;
sprintf(PLSR_parsed,"%s",strtok(strstr(capture, PLSR_parse), delim1));
  if (strlen(PLSR_parsed) >= 10){
    name = strtok(PLSR_parsed, delim2);
    ident = atoi(strtok(NULL, delim2));ident = atoi(strtok(NULL, delim2));
    dir = atoi(strtok(NULL, delim2));
    autocal = atoi(strtok(NULL, delim2));
    field = atoi(strtok(NULL, delim2));
    accX = atoi(strtok(NULL, delim2));accY = atoi(strtok(NULL, delim2));accZ =
    atoi(strtok(NULL, delim2));
    tptrC = atoi(strtok(NULL, delim2));tptrF = tptrC*9/5+32;
    mtd = atoi(strtok(NULL, delim2));
    cal = atoi(strtok(NULL, delim2));
  } // Print values to buffers if the string is identified as PLSR, 245, 1 vice 245, 2
  or 245, 7
  if (autocal == 0) {
    LATCbits.LATC1 = 1; Delay1KTCYx(75); LATCbits.LATC1 = 0;
  } else if (autocal > 0 && autocal < 7) {
    LATCbits.LATC1 = 1; Delay1KTCYx(75); LATCbits.LATC1 = 0;
  } else if (autocal == 7) {
    LATCbits.LATC1 = 1;
  } else { Nop(); }
  return dir;
} else { Nop(); }

void get_bearing(void){
  int xLATf, yLATf, yLONf, offset, add;
  xLATi = LATmki - LATi;xLATf = LATmf - LATf; //discover x distance from
  yLONi = LONmkf - LONi;yLONf = LONmkf - LONf; //discover y distance from
  setpoint
  printf("xLATf: %d yLATf: %d\n", xLATf, yLATf);
  if (xLATi != 0 || yLONi != 0) move_far();
  else if (xLATf >= posfudge && yLATf >= 0) { BRG = 180; return; } //N
  else if (xLATf >= posfudge && yLATf >= posfudge) { add =
    180; xLATf = fabs(xLATf); yLATf = fabs(yLATf); } //SW Q3
  else if (xLATf == 0 && yLATf >= posfudge) { BRG = 270; return; } //E
  else if (xLATf <= -posfudge && yLATf >= 0) { BRG = 360; return; } //S
  else if (xLATf <= -posfudge && yLATf <= -posfudge) { add =
    0; xLATf = fabs(xLATf); yLATf = fabs(yLATf); } //NE Q1
  else if (xLATf == 0 && yLATf <= -posfudge) { BRG = 90; return; } //W
  else if (xLATf >= posfudge && yLATf <= -posfudge) { add =
    90; xLATf = fabs(xLATf); yLATf = fabs(yLATf); } //SE Q2
  else { Nop(); return; } //NA
  offset = (atan2(yLATf, xLATf)) * (180/pi); //calculate offset to degrees
  BRG = add-offset;
  printf("BRG: %d OFFSET: %d add: %d\n", BRG, offset, add);
}

void track(void){

120
while (on = 1) {
    if(PORTBbits.RBl == 1 & & on == 1) { // if the button has already been pressed (on = 1) and it gets pressed again, set on to off (on == 0)
        LATmki = 0; LATmkf = 0; LONmki = 0; LONmkf = 0; NSmk = 'X'; EWmk = 'X'; HDGmk = 0;
        for (cnt = 0; cnt < 5; cnt++) {
            LATCbits.LATC2 = 0; Delay10KTCYx(100); LATCbits.LATC2 = 1;
        }
        LATCbits.LATC2 = 0; // unmark setpiont routine
        on = 0; Close1USART();
        break;
    } else {
        get_position();
        if (signal == 0) { break; }
        get_bearing();
    }

    // Set up and make comparisons with and pulse the output voltage.
    if (HDG < (BRG - brgfudge) || HDG > (BRG + brgfudge)) { // if heading is not within +/- brgfudge deg and bearing is 0-180deg turn clockwise by activating port thruster
        if (BRG < 180) {
            LATCbits.LATC4 = 1;
            for (cnt = 0; cnt < turntimeCW; cnt++) { Delay1KTCYx(100); LATCbits.LATC4 = 0; }
        } else if (BRG >= 180) { // if heading is not within +/- brgfudge deg and bearing is 180-360 deg turn counter clockwise by activating starboard thruster
            LATCbits.LATC5 = 1;
            for (cnt = 0; cnt < turntimeCCW; cnt++) { Delay1KTCYx(100); LATCbits.LATC5 = 0; }
        } else if (HDG < (BRG - brgfudge) || HDG > (BRG + brgfudge)) { // activate both thrusters to move forward this is a longer thrust move than the directional moves
            for (cnt = 0; cnt < ahdtime; cnt++) { LATCbits.LATC4 = 1; LATCbits.LATC5 = 1; Delay1KTCYx(100); LATCbits.LATC4 = 0; LATCbits.LATC5 = 0; }
        } else { Nop(); }
    }

    void move_far(void) {
        // this function is to be written at a later date
    }

    void manual_control(void) {
        LATCbits.LATC2 = 1;
        Delay10KTCYx(100); // indicator light
        if (PORTBbits.RB3 == 1 & & PORTBbits.RB2 == 0) {
            LATCbits.LATC4 = 1; // turn on port thruster
            LATCbits.LATC5 = 0; // turn off starboard thruster
        }
    }
else if (PORTBbits.RB3 == 0 && PORTBbits.RB2 == 1) {
    LATCbits.LATC5 = 1; // turn on starboard thruster
    LATCbits.LATC4 = 0; // turn off port thruster
}
else if (PORTBbits.RB3 == 1 && PORTBbits.RB2 == 1) {
    LATCbits.LATC4 = 1; LATCbits.LATC5 = 1; // turn on both thrusters
}
else if (PORTBbits.RB3 == 0 && PORTBbits.RB2 == 0) {
    LATCbits.LATC4 = 0; LATCbits.LATC5 = 0; // turn off both thrusters
}
LATCbits.LATC2 = 0; Delay10KTCYx(100); // indicator light flashing
Appendix C (18f27j13_lrgarry.lkr)

```c
#define CODEEND _DEBUGCODESTART - 1
#define CEND CODEEND + _DEBUGCODELEN
#define DATAEND _DEBUGDATASTART - 1
#define DEND DATAEND + _DEBUGDATALEN
libpath:
#define CRUNTIME
#define EXTENDEDMODE
files c018i_e.o
files clib_e.lib
files p18f27j13_e.lib
#else
files c018i.o
files clib.lib
files p18f27j13.lib
#fi
#endif
#define DEBUGCODESTART
codepage name=page start=0x0 end=CODEEND
codepage name=debug start=_DEBUGCODESTART end=_CEND protected
#else
codepage name=page start=0x0 end=0x1FFF7
#fi
codepage name=config start=0x1FFF8 end=0x1FFFF protected
codepage name=devid start=0x3FFFFE end=0x3FFFFF protected
#define EXTENDEDMODE
 databank name=gpre start=0x0 end=0x5F
#else
accessbank name=accessram start=0x0 end=0x5F
#fi
databank name=gpr0 start=0x60 end=0xFF
databank name=lr Garr start=0x100 end=0x2FF protected
databank name=gpr3 start=0x300 end=0x3FF
databank name=gpr4 start=0x400 end=0x4FF
databank name=gpr5 start=0x500 end=0x5FF
databank name=gpr6 start=0x600 end=0x6FF
databank name=gpr7 start=0x700 end=0x7FF
databank name=gpr8 start=0x800 end=0x8FF
databank name=gpr9 start=0x900 end=0x9FF
databank name=gpr10 start=0xA00 end=0xAFF
databank name=gpr11 start=0xB00 end=0xBFF
databank name=gpr12 start=0xC00 end=0xCF F
#endif DEBUGDATAstart
 databank name=gpr13 start=0xD00 end=_DATAEND
 databank name=dbgspr start=_DEBUGDATASTART end=_DEND protected
#else //no debug
 databank name=gpr13 start=0xD00 end=0xFFD
#fi
databank name=gpr14 start=0xE00 end=0xEA F
databank name=sfr14 start=0xEB0 end=0xEF F protected
databank name=sfr15 start=0xF00 end=0xF5F protected
accessbank name=accesssfr start=0xF60 end=0xFFFF protected
#endif CRUNTIME
section name=CONFIG rom=config
section name=LRGARRY ram=lr garr
#endif DEBUGDATASTART
stack size=0x100 ram=gpr12
#else
stack size=0x100 ram=gpr13
#fi
#fi
```
Appendix D (MainActivity.java)

MainActivity.java
package com.dpbuoy.nmea;
import android.app.*;
import android.os.*;
import android.view.*;
import android.view.View.OnClickListener;
import android.widget.*;
import java.net.*;
import java.io.*;
import java.util.*;
public class MainActivity extends Activity {
    public TextView tv1;
    public TextView tv2;
    public TextView tv3;
    public TextView tv4;
    public TextView tv5;
    public TextView cog;
    public TextView sog;
    public ScrollView sv;
    public EditText txt1;
    public EditText txt2;
    public ToggleButton tgl1;
    public ToggleButton tgl2;
    public ToggleButton tgl3;
    public ToggleButton tgl4;
    public Button btn1;
    public Button btn2;
    public boolean isComs=false;
    public boolean noskt=true;
    public boolean isLogging;
    public int change=0;
    public Socket skt=null;
    public Double lat;
    public Double lon;
    public String[] tokens;
    public String latMk;
    public String lonMk;
    public String dpblog;
    Handler nmeaHandler = new Handler(){
        @Override
        public void handleMessage(Message msg){
            Bundle nmeaMsg = msg.getData();
            String nmeaString = (nmeaMsg.getString("nmea Key")+
            tv1.append(nmeaString);
            if(isLogging){
                try{
                    FileWriter fStream = new FileWriter(dpblog, true);
                    BufferedWriter fOut = new BufferedWriter(fStream);
                    // Further code...
                } catch (IOException e) {
                    // Handle exception
                }
            }
        }
    );
}
fOut.write(nmeaMsg.getString("nmea Key") + "\n");
fout.close();
}
} catch (Exception e){
Toast.makeText(getBaseContext(), e.getMessage(), Toast.LENGTH_SHORT).show();
}
}
sv猾猾ScrollTo(0, tv1.getBottom());
tokens = (nmeaMsg.getString("nmea Key")).split(",");
if(tokens[0].equals("$GPRMC") && tokens[2].equals("V")){
tv2.setText(tokens[1]);
tv3.setText(tokens[9]);
sog.setText("NoSig");
cog.setText(tokens[8] + " °");
} else if(tokens[0].equals("$GPRMC") && tokens[2].equals("A")){
double lat = Double.parseDouble(tokens[3]);
int degLat = (int)(lat / 100);
int minLat = (int)(((lat / 100) - degLat) * 100);
double mmmmLat = lat - (degLat * 100 + minLat);
double lon = Double.parseDouble(tokens[5]);
int degLon = (int)(lon / 100);
int minLon = (int)(((lon / 100) - degLon) * 100);
double mmmmLon = lon - (degLon * 100 + minLon);
sog.setText(tokens[7] + " kts");
cog.setText(tokens[8] + " °");
switch (change){
 case 0:
  latMk="" + degLat + "°" + minLat + "'");
  lonMk="" + degLon + "°" + minLon + "'");
  tv2.setText("" + degLat + "°" + minLat + "'");
  tv3.setText("" + degLon + "°" + minLon + "'");
  break;
 case 1:
  latMk="" + lat;
  lonMk="" + lon;
  tv2.setText("" + lat);
  tv3.setText("" + lon);
  break;
 case 2:
  latMk="" + (degLat + ((double)minLat / 60) + (mmmmlat / 60));
  lonMk="" + (degLon + ((double)minLon / 60) + (mmmmLon / 60));
  tv2.setText("" + (degLat + ((double)minLat / 60) + (mmmmlat / 60)));
  tv3.setText("" + (degLon + ((double)minLon / 60) + (mmmmLon / 60)));
  //
  tv2.setText(String.format("%2d.%4d%s", ((degLat) + ((double)minLat / 60)), (mmmmlat / 60), tokens[4]));
}
tv3.setText(String.format("%3d.%4d%s",((degLon)+((double)minLon/60)),(mmmLon/60),tokens[6]));
break;
default:
change=0;
break;
}
}
}

/** Called when the activity is first created. */
@Override
public void onCreate(Bundle savedInstanceState)
{
    super.onCreate(savedInstanceState);
    setContentView(R.layout.main);
tv1 = (TextView) findViewById(R.id.widget70);
tv2 = (TextView) findViewById(R.id.widget71);
tv3 = (TextView) findViewById(R.id.widget72);
tv4 = (TextView) findViewById(R.id.widget75);
tv5 = (TextView) findViewById(R.id.widget76);
cog = (TextView) findViewById(R.id.widget95);
sog = (TextView) findViewById(R.id.widget96);
txt1 = (EditText) findViewById(R.id.widget67);
txt2 = (EditText) findViewById(R.id.widget68);
btn1 = (Button)findViewById(R.id.widget69);
sv = (ScrollView)findViewById(R.id.scvw);
btn1.setOnClickListener(new View.OnClickListener(){
    public void onClick(View view){
        Thread initComs = new Thread(new Runnable(){
            String ip = txt1.getText().toString();
            int port = Integer.valueOf(txt2.getText().toString());
            BufferedReader din = null;
            @Override
            public void run(){
                if(!isComs){
                    try{
                        Bundle nmeaMessage=new Bundle();
                        Message msg1 = new Message();
                        nmeaMessage.putString("nmea Key","CONNECTING TO: "+ip+"":"+port);
                        msg1.setData(nmeaMessage);
                        nmeaHandler.sendMessage(msg1);
                        skt = new Socket(ip,port);
                        noskt=false;
                        isComs=true;
                        din = new BufferedReader(new InputStreamReader(skt.getInputStream()));
                        while(skt.isConnected()){
                            Message msg2 = new Message();
                            nmeaMessage.putString("nmea Key",din.readLine());
                            }catch(Ela
msg2.setData(nmeaMessage);
nmeaHandler.sendMessage(msg2);
}
}
catch(Exception e){
Message msg2 = new Message();
nmeaMessage.putString("nmea Key","A network error has occurred:\n"+e.toString()+"\nPlease ensure the IP address and port are correct and try again\n");
msg2.setData(nmeaMessage);
nmeaHandler.sendMessage(msg2);
isComs=false;
}
} else if(skt.isConnected()){
Message msg = new Message();
Bundle nmeaMessage=new Bundle();
nmeaMessage.putString("nmea Key","\n!!!ALREADY CONNECTED!!!\n"+
"PRESS+HOLD Connect button to DISCONNECT.\n");
msg.setData(nmeaMessage);
nmeaHandler.sendMessage(msg);
}
}
}
initComs.start();
}
}
btn1.setOnLongClickListener(new View.OnLongClickListener(){
public boolean onLongClick(View view){
if(!isComs){
tv1.append("\nNOT CONNECTED\n");
return true;
}else{
try{
skt.close();
tv1.append("\nDISCONNECTED\n");
isComs=false;
}
catch(Exception e){
tv1.append("\nOn skt.close():\n"+e.toString());
}
return true;
}
}
});
btn2 = (Button)findViewById(R.id.widget73);
btn2.setOnClickListener(new View.OnClickListener(){
public void onClick(View view){
change++;
}
});
class Steering {private boolean MARK, PORT, STBD;}

final Steering steeringMode = new Steering();
final ToggleButton togglebutton[] = {
(ToggleButton) findViewById(R.id.widget77),
(ToggleButton) findViewById(R.id.widget78),
(ToggleButton) findViewById(R.id.widget79),
(ToggleButton) findViewById(R.id.widget80)};
togglebutton[0].setOnClickListener(new OnClickListener(){
@Override
public void onClick(View v){
if (((ToggleButton) v).isChecked()){
try {PrintWriter dout = new PrintWriter(new BufferedWriter(new OutputStreamWriter(skt.getOutputStream())),true);
dout.println("$$$\n");
dout.println("set sys output 0\r\n");
dout.println("exit\r\n");
steeringMode.MARK = true;
// if(togglebutton[1].isChecked()){Togglebutton[2].setChecked();}
Toast.makeText(getApplicationContext(),"IN AUTO",Toast.LENGTH_SHORT).show();
tv4.setText(""+latMk);
tv5.setText(""+lonMk);
}
catch(Exception e){
Toast.makeText(getBaseContext(),
e.getMessage(),Toast.LENGTH_SHORT).show();
}
} else{
try {PrintWriter dout = new PrintWriter(new BufferedWriter(new OutputStreamWriter(skt.getOutputStream())),true);
dout.println("$$$\n");
dout.println("set sys output 0x100\r\n");
dout.println("exit\r\n");
steeringMode.MARK = false;
Toast.makeText(getApplicationContext(),"IN MANUAL",Toast.LENGTH_SHORT).show();
}
catch(Exception e){
Toast.makeText(getBaseContext(),
e.getMessage(),Toast.LENGTH_SHORT).show();
}
}
}

}.

togglebutton[1].setOnClickListener(new OnClickListener(){
@Override
public void onClick(View v){
if (((ToggleButton) v).isChecked()){
isLogging = true; File dpblogDirectory = new File(Environment.getExternalStorageDirectory().getPath()+"/dpblog/" );

dpblogDirectory.mkdirs();

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Calendar calLog = Calendar.getInstance();
String logSeq = ""+(1+calLog.get(Calendar.MONTH))+calLog.get(Calendar.DAY_OF_MONTH)+calLog.get(Calendar.HOUR_OF_DAY)+calLog.get(Calendar.MINUTE)+calLog.get(Calendar.SECOND);
dpblog = Environment.getExternalStorageDirectory().getPath()+"/dpblog/"+logSeq+".txt";
Toast.makeText(getApplicationContext(),"logging to file "+dpblog,Toast.LENGTH_LONG).show();
}else{
    isLogging = false;
}
}
togglebutton[2].setOnClickListener(new OnClickListener(){
    @Override
    public void onClick(View v){
        if (((ToggleButton) v).isChecked()){
            steeringMode.PORT = true;
            if(!steeringMode.MARK){
                try{
                    PrintWriter dout = new PrintWriter(new BufferedWriter(new OutputStreamWriter(skt.getOutputStream())),true);
                    dout.println("$$$\r\nset sys output 0x182\r\nexit\r\n");
                    //tv1.append(steeringMode.PORT+" set sys output 0x182");
                    Toast.makeText(getApplicationContext(),"ALL AHEAD!",Toast.LENGTH_SHORT).show();
                }
                catch(Exception e){
                    Toast.makeText(getBaseContext(), "Not connected"+e.getMessage(),Toast.LENGTH_SHORT).show();
                } }else if(steeringMode.PORT && !steeringMode.STBD){
                try{
                    PrintWriter dout = new PrintWriter(new BufferedWriter(new OutputStreamWriter(skt.getOutputStream())),true);
                    dout.println("$$$\r\nset sys output 0x180\r\nexit\r\n");
                    //tv1.append(steeringMode.PORT+" set sys output 0x180");
                    Toast.makeText(getApplicationContext(),"TURNING RIGHT!",Toast.LENGTH_SHORT).show();
                }
                catch(Exception e){
                    Toast.makeText(getBaseContext(), "Not connected"+e.getMessage(),Toast.LENGTH_SHORT).show();
                } }else{
        //
Toast.makeText(getApplicationContext(), "Can't! DPB IS IN AUTO", Toast.LENGTH_SHORT).show();
}

else if (steeringMode.MARK)
Toast.makeText(getApplicationContext(), "Can't! DPB IS IN AUTO", Toast.LENGTH_SHORT).show();
} else{
steeringMode.PORT = false;
try{
PrintWriter dout = new PrintWriter(new BufferedWriter(new OutputStreamWriter(skt.getOutputStream())), true);
dout.println("$$$");
dout.println("set sys output 0x100\r");
dout.println("exit\r");
// tv1.append(steeringMode.PORT+"set sys output 0x100+steeringMode.STBD");
Toast.makeText(getApplicationContext(), "ALL STOP!", Toast.LENGTH_SHORT).show();
} catch (Exception e){
Toast.makeText(getBaseContext(), "Not connected" + e.getMessage(), Toast.LENGTH_SHORT).show();
}
}
}

override
public void onClick(View v){
if (((ToggleButton) v).isChecked()){
steeringMode.STBD = true;
if (!steeringMode.MARK){
if (steeringMode.STBD & steeringMode.PORT) {
try{
PrintWriter dout = new PrintWriter(new BufferedWriter(new OutputStreamWriter(skt.getOutputStream())), true);
dout.println("$$$");
dout.println("set sys output 0x182\r");
dout.println("exit\r");
// tv1.append(steeringMode.PORT+"set sys output 0x182+steeringMode.STBD");
Toast.makeText(getApplicationContext(), "ALL AHEAD!", Toast.LENGTH_SHORT).show();
} catch (Exception e){
Toast.makeText(getBaseContext(), "Not connected" + e.getMessage(), Toast.LENGTH_SHORT).show();
}
} else if (steeringMode.STBD & !steeringMode.PORT){
try{
PrintWriter dout = new PrintWriter(new BufferedWriter(new OutputStreamWriter(skt.getOutputStream())), true);
dout.println("$$$");
dout.println("set sys output 0x182\r");
dout.println("exit\r");
// tv1.append(steeringMode.PORT+"set sys output 0x182+steeringMode.STBD");
Toast.makeText(getApplicationContext(), "ALL AHEAD!", Toast.LENGTH_SHORT).show();
} catch (Exception e){
Toast.makeText(getBaseContext(), "Not connected" + e.getMessage(), Toast.LENGTH_SHORT).show();
}
}
```java
dout.println("$$\$\$\$\$\$");
dout.println("set sys output 0x102\r");
dout.println("exit\r");
// tvl.append(steeringMode.PORT+" set sys output
0x102"+steeringMode.STBD);
Toast.makeText(getApplicationContext(),"TURNING
LEFT",Toast.LENGTH_SHORT).show();
}
catch(Exception e){
    Toast.makeText(getBaseContext(), "Not
connected"+e.getMessage(),Toast.LENGTH_SHORT).show();
}
}
}
else{
    Toast.makeText(getApplicationContext(),"Can’t! DPB IS IN
AUTO",Toast.LENGTH_SHORT).show();
}
else if(steeringMode.MARK){
    Toast.makeText(getApplicationContext(),"Can’t! DPB IS IN
AUTO",Toast.LENGTH_SHORT).show();
} else{
    steeringMode.STBD=false;
    try{
        PrintWriter dout = new PrintWriter(new BufferedWriter
        (new OutputStreamWriter(skt.getOutputStream())),true);
        dout.println("$$\$\$\$\$\$");
dout.println("set sys output 0x100\r");
dout.println("exit\r");
        // tvl.append(steeringMode.PORT+" set sys output
0x100"+steeringMode.STBD);
        Toast.makeText(getApplicationContext(),"ALL
STOP!",Toast.LENGTH_SHORT).show();
    }
catch(Exception e){
        Toast.makeText(getBaseContext(), "Not
connected"+e.getMessage(),Toast.LENGTH_SHORT).show();
    }
    }
});
}
@Override
protected void onDestroy(){
    Toast.makeText(this,"Good bye shocnet",Toast.LENGTH_SHORT).show();
super.onDestroy();
}
@Override
public boolean onCreateOptionsMenu(Menu menu){
    menu.add(0,1,1,"Exit");
    return super.onCreateOptionsMenu(menu);
}
@Override
```
public boolean onOptionsItemSelected(MenuItem item){
    if(item.getItemId()==1){
        if(noskt){finish();}
        else{
            try{
                skt.close();
            }catch(Exception e){
                Toast.makeText(getBaseContext(),"Error closing socket:"+e.getMessage(),Toast.LENGTH_SHORT).show();
            }
            finish();
        }
    }
    return super.onOptionsItemSelected(item);
}
Appendix E (Example NGS Datasheet)


LX5327

*****************************************************************************
****
LX5327  DESIGNATION - BLUFF
LX5327  PID - LX5327
LX5327  STATE/COUNTY- CT/NEW LONDON
LX5327  USGS QUAD - NEW LONDON (1984)
LX5327
LX5327
LX5327                         *CURRENT SURVEY CONTROL
LX5327
LX5327
LX5327* NAD 83(1996) - 41 18 54.94996(N) 072 02 01.62697(W)
LX5327 ADJUSTED
LX5327* NAVD 88 - 13.6 (meters) 45. (feet)
LX5327 VERTCON
LX5327
LX5327  LAPLACE CORR - -0.83 (seconds)
LX5327 DEFLEC99
LX5327  GEOID HEIGHT - -30.64 (meters)
LX5327 GEOID99
LX5327
LX5327  HORZ ORDER - SECOND
LX5327
LX5327.LX5327.The horizontal coordinates were established by classical
LX5327.geodetic methods
LX5327.and adjusted by the National Geodetic Survey in August 1998.
LX5327
LX5327.LX5327.The NAVD 88 height was computed by applying the VERTCON
LX5327.shift value to
LX5327.the NGVD 29 height (displayed under SUPERSEDED SURVEY
LX5327.CONTROL.)
LX5327
LX5327.LX5327.The Laplace correction was computed from DEFLEC99 derived
LX5327 defections.
LX5327
LX5327.LX5327.The geoid height was determined by GEOID99.
LX5327
LX5327
LX5327.Converg.
LX5327;  North  East  Units  Scale
LX5327; SPC CT - 206,170.759  364,770.164  MT  0.99999037
LX5327; +0 28 29.6
LX5327; SPC NY L - 129,399.875  464,627.840  MT  1.00002781
LX5327; +1 17 09.8
LX5327; UTM 18 - 4,578,000.379  748,285.176  MT  1.00035873
LX5327; +1 57 33.5

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LX5327; UTM 19 - 4,578,196.098 246,058.196 MT 1.00039370
-2 00 14.3
LX5327
LX5327: Primary Azimuth Mark
Grid Az
LX5327: SPC CT - NEW LONDON LEDGE LIGHTHOUSE  253
36 58.8
LX5327: SPC NY L - NEW LONDON LEDGE LIGHTHOUSE  252
48 18.6
LX5327: UTM 18 - NEW LONDON LEDGE LIGHTHOUSE  252
07 54.9
LX5327: UTM 19 - NEW LONDON LEDGE LIGHTHOUSE  256
05 42.7
LX5327
LX5327:------------------------------------------------------------
---------
LX5327: PID    Reference Object                     Distance
Geod. Az  |
LX5327|
LX5327| dddmmss.s |        |
LX5327| LX5256 PRENTIS WHITE CHIMNEY                     APPROX. 0.8 KM
0144647.9 |
LX5327| LW3386 MYSTIC ELEV TANK                           APPROX. 6.7 KM
0441734.9 |
LX5327| LW3390 NOANK SPIRE                                APPROX. 4.1 KM
0731322.7 |
LX5327| LX5289 LONG POINT TANK                           APPROX. 2.1 KM
0852736.5 |
LX5327| LW3410 SIMMONS CHIMNEY                            APPROX. 9.6 KM
1053958.8 |
LX5327| LX5281 MANDALAY FLAGPOLE                         APPROX. 2.0 KM
1080849.8 |
LX5327| LW3413 COAST GUARD CUPOLA                         APPROX. 8.3 KM
1152640.8 |
LX5327| LX5282 WESTERNS FLAGPOLE                         APPROX. 2.1 KM
1155932.6 |
LX5327| LX5280 WESTERNS CHIMNEY                           APPROX. 2.1 KM
1161938.6 |
LX5327| LW3423 CLUBHOUSE CHIMNEY                          APPROX. 8.2 KM
1181451.6 |
LX5327| LX5253 MUMFORD POINT                              448.987 METERS
1375411.3 |
LX5327| LX5320 CAMP TABOR BARN CUPOLA                    APPROX. 6.8 KM
1553018.3 |
LX5327| LX5255 FORT WRIGHT SILVER TANK                   APPROX. 6.4 KM
1783118.2 |
LX5327| LX5193 SEAFLOWER REEF LIGHT                      APPROX. 2.1 KM
1784849.9 |
LX5327| LX5367 3501 A PT                                  225.630 METERS
25253 |
LX5327| LX5215 NEW LONDON LEDGE LIGHTHOUSE               APPROX. 3.8 KM
2540528.4 |
LX5327| LX5366 3501 | 219.387 METERS
LX5327| BLUFF RM 1 | 13.736 METERS
LX5327| LX5209 GROTON CG TRNG STA TANK | APPROX. 2.6 KM
LX5327| LX5197 GAYS SILO | APPROX. 2.2 KM
LX5327| LX5205 MAX POLLOCK CO STACK | APPROX. 4.1 KM
LX5327| LX5207 MAX POLLOCK CO ELEV TANK | APPROX. 4.0 KM
LX5327| LX5194 GROTON AIRPORT AIRWAY BCN | APPROX. 2.0 KM
LX5327| BLUFF RM 2 | 16.063 METERS
LX5327| LX5325 BAPTIST CHURCH TOWER | APPROX. 3.5 KM
LX5327| SUPERSEDED SURVEY CONTROL
LX5327| NAD 83(1992) - 41 18 54.94874(N) 072 02 01.62604(W) AD(2)
LX5327| NAD 83(1986) - 41 18 54.94954(N) 072 02 01.63122(W) AD(2)
LX5327| NAD 27 - 41 18 54.59900(N) 072 02 03.36400(W) AD(2)
LX5327| NGVD 29 - 13.9 (m) 46. (f) VERT ANG
LX5327| Superseded values are not recommended for survey control.
LX5327| NGS no longer adjusts projects to the NAD 27 or NGVD 29 datums.
LX5327| See file dsdata.txt to determine how the superseded data were derived.
LX5327| MARKER: DS = TRIANGULATION STATION DISK
LX5327| SETTING: 80 = SET IN A BOULDER
LX5327| STABILITY: C = MAY HOLD, BUT OF TYPE COMMONLY SUBJECT TO SURFACE MOTION
LX5327| HISTORY - Date Condition Recov. By
LX5327| 1934 MONUMENTED CGS
LX5327| 1940 GOOD CGS
LX5327| 1943 GOOD CGS
LX5327| 1954 GOOD CGS
LX5327| 1971 GOOD CTDT
LX5327| 1975 GOOD NGS
LX5327| 1984 POOR USPSQD

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LX5327                          STATION DESCRIPTION
LX5327
LX5327''DESCRIBED BY COAST AND GEODETIC SURVEY 1934 (GCM)
LX5327''THE STATION IS LOCATED ON THE S END OF BLUFF POINT ON THE FIRST
LX5327''LEVEL ABOVE THE BEACH WHICH IS ABOUT 40 FEET LEVEL, AND ABOUT
LX5327''220.0 METERS N OF HIGH WATER LINE. THE POINT IS UNDEVELOPED,
LX5327''THERE BEING ONLY A NUMBER OF SHACKS ALONG THE BEACH. THE
LX5327''STATION IS MARKED BY A STANDARD DISC SET IN THE TOP OF A FLAT
LX5327''BOULDER FLUSH WITH THE GROUND, ON THE GARDNER ESTATE.
LX5327''IS REACHED FROM THE VILLAGE OF POQUONOCK BRIDGE. TURN S ON THE
LX5327''BLUFF POINT ROAD WHERE IT INTERSECTS THE BOSTON POST ROAD AND
LX5327''GO 2.2 MILES TO THE STATION.
LX5327''REFERENCE MARKS NO.1 AND NO.2 ARE STANDARD DISCS SET IN LEDGE
LX5327''SW AND NW OF THE STATION RESPECTIVELY. REFERENCE MARK NO.3 IS
LX5327''ALSO A STANDARD DISC SET IN A LARGE BOULDER IN THE SIDE OF THE
LX5327''HILL, NE OF THE STATION AND ABOUT 200 METERS DISTANT.
LX5327''HEIGHT OF LIGHT ABOVE STATION MARK 25 METERS.
LX5327''STATION RECOVERY (1940)
LX5327
LX5327''RECOVERY NOTE BY COAST AND GEODETIC SURVEY 1940 (PLB)
LX5327''THE STATION AND BOTH REFERENCE MARKS WERE RECOVERED IN GOOD
LX5327''CONDITION.
LX5327''THE STATION IS ABOUT 4.5 MI. SE OF NEW LONDON, AND AT MUMFORD
LX5327''POINT, WHICH IS KNOWN LOCALLY AS BLUFF POINT. IT IS ABOUT 250
LX5327''YDS. N OF THE S TIP OF THE POINT, ABOUT 75 YDS. SE OF A KNOLL
LX5327''WHICH IS SLIGHTLY HIGHER, ABOUT 100 YDS. NW OF THE ONLY SHACK
LX5327''LEFT STANDING ON THE POINT, AND 63 FT. W OF A N-S STONE
LX5327''FENCE. THE MARK IS SET IN A ROCK ABOUT 5 FT. IN DIAMETER WHICH PROJECTS ABOUT 12 IN. ABOVE THE GROUND. THE
LX5327''DISK IS STAMPED BLUFF 1934.
LX5327''REFERENCE MARK 1 IS 45.07 FT. (13.740 M.) W OF THE STATION. THE
LX5327''MARK IS IN A ROCK ABOUT 3 FT. IN DIAMETER WHICH
PROJECTS ABOUT 6 IN. ABOVE THE GROUND. THE DISK IS STAMPED BLUFF NO 1 1934.
REFERENCE MARK 2 IS 52.72 FT. (16.069 M.) N OF THE STATION. THE
MARK IS IN A ROCK ABOUT 5 FT. IN DIAMETER WHICH PROJECTS ABOUT 12 IN. ABOVE THE GROUND. THE DISK IS STAMPED BLUFF NO 2 1934.
'NEW LONDON LEDGE LIGHTHOUSE IS A GOOD AZIMUTH MARK. IT IS ABOUT 2-1/2 MI. W OF THE STATION, ON THE W SIDE OF SOUTHWEST LEDGE, AT THE E SIDE OF THE ENTRANCE TO NEW LONDON HARBOR. THE FINIAL OVER THE LIGHT WAS OBSERVED UPON.
'A 4-FT. STAND AT THIS STATION WILL SEE 4-FT. STANDS AT STATIONS MYSTIC AND NORTH HILL.
STATION RECOVERY (1943)
RECOVERY NOTE BY COAST AND GEODETIC SURVEY 1943 (FN)
STATION WAS RECOVERED AS DESCRIBED, AND THE MARKS WERE FOUND IN GOOD CONDITION. THE SHACK MENTIONED IN THE 1940 DESCRIPTION NO LONGER STANDS. A NEW DESCRIPTION FOLLOWS--
STATION IS LOCATED ABOUT 4.5 MI. SE OF NEW LONDON, ON MUMFORD POINT, WHICH IS KNOWN LOCALLY AS BLUFF POINT. IT IS ABOUT 250 YDS. N OF THE S TIP OF THE POINT, ABOUT 75 YDS. SE OF A KNOLL WHICH IS SLIGHTLY HIGHER, AND ABOUT 63 FT. W OF A N-S STONE FENCE. THE STATION MARK IS STAMPED BLUFF 1934 AND PROJECTS ABOUT 12 IN.
REFERENCE MARK 1 IS W OF THE STATION. IT IS STAMPED BLUFF NO 1 1934 AND PROJECTS ABOUT 6 IN.
REFERENCE MARK 2 IS N OF THE STATION. IT IS STAMPED BLUFF 2 1934 AND PROJECTS ABOUT 12 IN.
TO REACH THE STATION FROM THE TOLL GATE OF THE NEW BRIDGE ACROSS THE THAMES RIVER AT NEW LONDON, GO E ON U.S. HIGHWAY 1 FOR 3.15 MI. TO THE INTERSECTION WITH DEPOT ROAD IN THE VILLAGE OF
POQUONOCK BRIDGE. TURN RIGHT ON DEPOT ROAD, AND GO 0.3 MI. TO THE END OF THE PAVED STREET AND A FORK. TAKE THE RIGHT FORK (GRAVEL ROAD), PASS UNDER A BRIDGE AND GO 0.45 MI. TO A GATE WHICH IS JUST PAST A SINGLE RAILROAD TRACK. GO THROUGH THE GATE AND FOLLOW A WOODS ROAD FOR 0.5 MI. TO A FORK. TAKE THE RIGHT FORK AND GO 0.45 MI. TO A REVERSE Y. CONTINUE FOR 0.55 MI. TO THE TOP OF A KNOLL AND THE STATION.

NOTE--THE R.M. 1 DISTANCE FOR 1943 WAS CAREFULLY CHECKED AND THE 1940 DISTANCE WAS FOUND TO BE IN ERROR AS SHOWN.

STATION RECOVERY (1954)

STATION RECOVERY (1971)

STATION RECOVERY (1975)
LX5327
LX5327''RECOVERY NOTE BY NATIONAL GEODETIC SURVEY 1975 (HRR)
LX5327''THE STATION, REFERENCE MARKS 1 AND 2 WERE RECOVERED IN GOOD
LX5327''CONDITION. THE DISTANCE TO REFERENCE MARK 1 CHECKED THE
1940
LX5327''MEASUREMENT AND THE DISTANCE TO REFERENCE MARK 2 CHECKED THE
LX5327''1943 MEASUREMENT. THE DIRECTION TO BOTH REFERENCE MARKS
LX5327''CHECKED. CONNECTICUT GEODETIC SURVEY MARK 3501 WAS USED AS AN
LX5327''AZIMUTH MARK AT THIS TIME. A COMPLETE NEW DESCRIPTION
FOLLOWS.
LX5327''
LX5327''STATION IS ABOUT 4-1/2 MILES SOUTHEAST OF NEW LONDON, 3
MILES
LX5327''EAST OF OCEAN BEACH, 1/4 MILE WEST OF THE WATERS EDGE ON
BLUFF
LX5327''POINT AND ON PROPERTY OWNED BY THE STATE FOREST AND PARK
SERVICE.
LX5327''
LX5327''TO REACH THE STATION FROM THE JUNCTION OF U.S. HIGHWAY 1
AND
LX5327''DEPOT ROAD AT THE TOWN OFFICES IN GROTON, GO SOUTH ON DEPOT
LX5327''ROAD FOR 0.25 MILE TO THE JUNCTION OF INDUSTRIAL ROAD ON THE
LX5327''LEFT AND GROTON TOWN BEACH ROAD STRAIGHT AHEAD. CONTINUE
LX5327''SOUTHERLY ON GROTON TOWN BEACH ROAD FOR 0.8 MILE TO THE
GROTON
LX5327''TOWN BEACH. CONTINUE ACROSS THE BEACH AND GO SOUTHERLY ON A
LX5327''WOODS ROAD FOR 0.9 MILE TO A FORK. (TO REACH 3501 (CGS)
FROM
LX5327''HERE, TAKE RIGHT FORK AND GO WESTERLY ON MAIN TRAVELED ROAD
LX5327''FOR 0.2 MILE TO A HIGH KNOLL AT THE WATERS EDGE AND THE MARK
LX5327''ON THE KNOLL AS DESCRIBED). TAKE LEFT FORK AND GO
SOUTHWEST
LX5327''ON A DIM TRACK ROAD FOR 0.15 MILE TO A SMALL OPEN AREA AND
LX5327''THE STATION ON THE LEFT AS DESCRIBED.
LX5327''
LX5327''STATION MARK, STAMPED BLUFF 1934, IS A STANDARD DISK
CEMENTED
LX5327''IN A DRILL HOLE IN OUTCROPPING BEDROCK WHICH PROJECTS ABOUT
6
LX5327''INCHES ABOVE THE GROUND SURFACE AND IS ABOUT 3 BY 4 FEET IN
LX5327''SIZE. IT IS 83 FEET EAST OF CENTER OF THE TRACK ROAD, 12
FEET
LX5327''NORTH OF AN 8-INCH APPLE TREE AND 4.5 FEET NORTHEAST OF A
LX5327''METAL WITNESS POST.
LX5327''
LX5327''REFERENCE MARK 1, STAMPED BLUFF NO 1 1934, IS A STANDARD
DISK
LX5327"'CEMENTED IN A DRILL HOLE IN OUTCROPPING BEDROCK WHICH PROJECTS
LX5327"'ABOUT 4 INCHES ABOVE THE GROUND SURFACE AND IS ABOUT 2 BY 3
LX5327"'FEET IN SIZE. IT IS 42 FEET WEST OF THE METAL WITNESS POST
LX5327"'AT THE STATION MARK AND 38 FEET EAST OF CENTER OF THE TRACK
ROAD.

LX5327''REFERENCE MARK 2, STAMPED BLUFF NO 2 1934, IS A STANDARD
LX5327''DISK CEMENTED IN A DRILL HOLE IN OUTCROPPING BEDROCK WHICH
LX5327''PROJECTS ABOUT 10 INCHES ABOVE THE GROUND SURFACE AND IS
LX5327''ABOUT 2 BY 3 FEET IN SIZE. IT IS 55.5 FEET NORTH OF THE
LX5327''METAL WITNESS POST AT THE STATION MARK AND 7.5 FEET NORTH
OF A
LX5327''TWIN TRUNKED APPLE TREE.

LX5327''AZIMUTH MARK, STAMPED 3501, IS A U.S. COAST AND GEODETIC
LX5327''SURVEY AND STATE SURVEY DISK SET IN A 6 BY 6 INCH CONCRETE
LX5327''POST WHICH PROJECTS ABOUT 6 INCHES ABOVE THE GROUND
LX5327''SURFACE. IT IS 30 FEET EAST OF THE WEST EDGE OF A BLUFF
LX5327''AT THE WATERS EDGE, 27 FEET NORTH OF CENTER OF A BOULDER
LX5327''WHICH IS ABOUT 5 BY 7 FEET IN SIZE AND 26 FEET WEST OF
CENTER.

LX5327''OF A TRACK ROAD.

LX5327''HEIGHT OF LIGHT ABOVE STATION MARK 4 FEET.

LX5327''AIRLINE DISTANCE AND DIRECTION FROM NEAREST TOWN
LX5327''3 MILES EAST OF OCEAN BEACH.

LX5327

LX5327

LX5327

LX5327

STATION RECOVERY (1984)

LX5327

LX5327

LX5327

LX5327

LX5327

LX5327

LX5327

LX5327

LX5327

LX5327

LX5327"'RECOVERY NOTE BY US POWER SQUADRON 1984 (BWR)
LX5327"'BLUFF 1934 DAMAGED.

LX5327''RECOVERED AS DESCRIBED - EXCEPT THE 1943 REFERENCE GROTON
COAST

LX5327''GUARD TRAINING STATION, WATER TANK. TANK WAS DEMOLISHED IN
AUGUST

LX5327''1983 WITNESS POST IN AREA OK. R. M. NO. 1 AND R. M. NO. 2
FOUND

LX5327''IN GOOD COND.

LX5327''NOTE--R. M. NO. 3 FOUND IN GOOD CONDITION IN AN AREA GROWN
OVER

LX5327''HEAVY IN BRUSH AND WEEDS. A SEARCH OF OVER TWO HOURS
RECOVERED

LX5327''IT. IT IS THE MOST PROMINENT BOULDER IN THE AREA.