GRWS (GNSS-R Rogue Wave Surveyor): Using GNSS-R to Observe the Surface of the Ocean and Survey for Rogue Waves

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Abstract:

Rogue waves are one of many unknown phenomena in the ocean. The GRWS has intentions of contributing wave behavioral data towards this unknown concept. Aboard the ThinSat platform are instruments and computers capable of creating near real-time maps of the ocean's surface using reflected Doppler wave signals received by GRWS. These reflected signals will be received by an on-board receiver to be processed and create a delay-Doppler map of the GPS signals. The current budget for the GRWS is $141.79, including GRWS components and equipment for construction. After successful test flights, GRWS will be outfitted for a low earth orbit launch and provide a map of small sections of the ocean's surface that the satellite happens to be over while powered on. This proof of concept project will attempt to provide small, low-cost and replaceable satellites as additional resources to observe real-time oceanic topology. Extensive networks of ThinSats and CubeSats can cover huge amounts of ocean surface compared to a single larger, more expensive satellite.

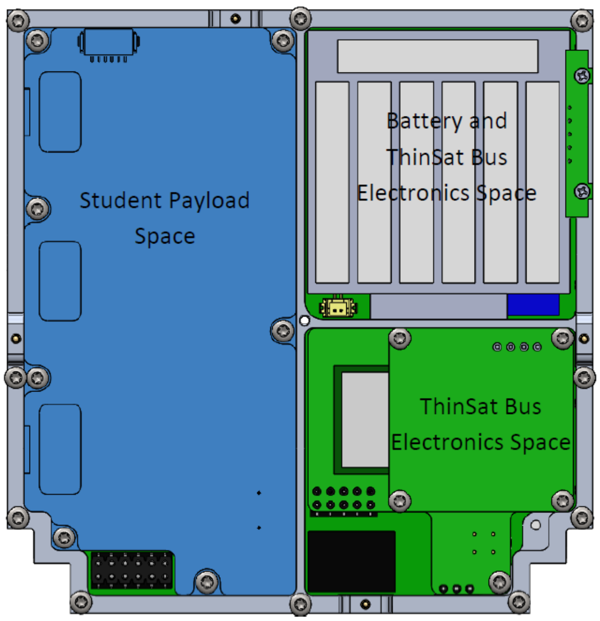

Figure 1

Introduction:

Throughout history, sailors would tell tales of abnormally large waves amidst a calm sea, with no visible cause. As the offshore industry has grown, documented instances of these “monster waves” have popped up, as well as the destruction they cause. Cases of ships whose hulls are ripped open and offshore oil platforms becoming considerably damaged have forced the recognition of these sailor’s tales as a very real problem that must be addressed. The average height of the highest one-third of waves in a region is called the significant wave height. Rogue waves are at least twice the height of the significant wave height, typically greater than sixty feet in height.

Current wave models for rogue waves do not accurately predict the observed frequency of rogue waves. The reason for this discrepancy is still largely debated. This is part of the basis for this ThinSat’s research purpose, named the GNSS-R Rogue Wave Surveyor (GRWS). The ThinSat framework, of which GRWS is built on, is a picosatellite about the size of a slice of bread. The ThinSat program for which this is all possible, was developed and introduced by Virginia Space in partnership with Northrop Grumman Innovation Systems and NASA Wallops Flight Facility as a doorway for middle school through university students to enter the space industry, allowing us the ability to develop satellite hardware and test sensor components in a short-term mission with approximately five days of orbit life. Through a series of low and high altitude balloon testing, upon completion and success, GRWS will then be launched with our GRWS payload into Low Earth Orbit from MARS at NASA Wallops (vaspace.org). GRWS will need to determine its attitude in low earth orbit (LEO) before it can properly read any data received by the onboard antenna. This ThinSat is designed to retrieve visual data for attitude determination via a camera. To achieve this, GRWS will utilize an arduino mounted camera as a horizon sensor to gather visual data on GRWS’s attitude in LEO.

However, to definitively detect rogue waves, the height of the waves of the ocean surface can be calculated. The sensors on board GRWS will map the altitude of a point in a region. To generate a Doppler map, a radar system must be used. To utilize a radar, there needs to be a signal to be reflected and received. However, utilizing a passive radar system (a radar system without an emitter) can compensate for this constraint. The passive radar system would only have a receiver, relying on the signals emitted from GNSS satellites. With the received data, the ThinSat will be able to produce a delay-Doppler map thus geographically locating rogue waves.

Impact Statement:

Rogue waves are large and unexpected phenomena which can cause substantial damage to vessels at sea. Waves reaching the height of 60 feet and greater are a threat to all ships, including large vessels such as ocean liners out at sea. In oceanography, rogue waves are defined as waves that are twice the size of the significant wave height in the area. The unpredictability of rogue waves is a major factor in their threat and damaging capabilities. The international shipping industry is responsible for transporting nearly 90% of the world’s trade (Shipping and World Trade Shipping Facts). The rarity of rogue waves can be considered fortunate, but it does not change the wave’s lethality once one appears. There have only been a handful of encounters since the twentieth century, yet the encounters are deadly to ships and crew alike. There is not much source material when it comes to rogue waves, as they are an uncommon phenomenon. With GRWS we hope the data can contribute to a better understanding of these waves, specifically how and when they might occur. This retrieval of data can lead to the development of tracking and alert systems for ocean vessels, which would provide greater warning response times for vessels at sea, potentially saving lives.

Project Description:

The main goal of the GRWS project is to be able to use small scale satellites to detect rogue waves. The project will be a proof of concept to determine if a global network of small satellites (e.g., CubeSats and ThinSats) will have the precision and capabilities required to detect rogue waves. The ThinSat will accomplish the task of detecting rogue waves by utilizing a form of passive radar known as Global Navigation Satellite System Reflectometry (GNSS-R). The GRWS will use an arducam with a custom image processing algorithm as a horizon sensor. This will give the GRWS the ability to determine its attitude in low Earth orbit.

While most radar systems have an emitter, which sends a signal to be reflected and then received by a receiver, GNSS-R relies on the signals of Global Navigation Satellite Systems, meaning that GNSS-R systems have only a receiver and no emitter. The lack of an emitter greatly reduces the ThinSat's power consumption. Power consumption is a valuable resource considering that the satellite is 500mW for 10 minutes out of every hour. The system is not intended to provide precise measurements of smaller waves, however the rogue waves of greater magnitude may be detectable. It should be noted that the receiver does not demand an exact orientation with the Earth, so long as it is facing the Earth. However, the attitude of the spacecraft must be recognized in order for the data to be properly calculated. The adjustment of data is due to different attitudes which will result with the signals reaching with the receiver at different angles. By utilizing a custom algorithm, which requires the nadir vector of the spacecraft, the satellite will be able to compensate with the adjustment in data processing. The nadir is the direction pointing directly downward for a specific location as well as orthogonal to a horizontal flat surface. In the context of a satellite, the nadir vector is the vector pointing to the center of the Earth. A horizon sensor produces two solutions and is therefore classified as a vital component to GRWS. The solutions provided are two vectors that are either pointing in the direction of the Earth, the nadir vector, or pointing in the opposite direction.

Methods/Data Collection

GNSS

The Global Navigation Satellite System (GNSS) is the broad term used for the constellations of all the global satellite systems in orbit. GNSS satellites are in geosynchronous orbit. This means that the satellites revolve around the Earth at the same rate that it spins. Thus, each satellite is only viewing one part of the Earth at all times. These satellites constantly transmit signals towards Earth that allow any GNSS enabled device to know its position. The most well-known GNSS system is the Global Positioning System (GPS) used in the United States.

Devices equipped with GNSS receivers can triangulate their position with multiple signals from different satellites. At least four satellites are needed to give a location, and the more satellite signals that a GNSS receiver can pick up, the more accurate the position will be. Triangulating a device's position works by first knowing the coordinates of each satellite. Then those satellites send out an electromagnetic signal in all directions, traveling at the speed of light.

The signals that travel directly to a GNSS receiver can be picked up, and used to calculate an approximate distance, *x*, the receiver is from the satellite. This is possible because knowing the coordinates of the satellite, the time the signal leaves the satellite, the speed the signal travels, and the time the signal is received can determine the receiver's distance from a satellite.

However, because signals that leave a satellite go in all directions, there is a sphere of radius, r, that could be the position of the GNSS receiver. Each satellite has its own sphere with its own r value. This is the reason 4 satellites are required to locate a GNSS receiver's location. Having 4 satellites allows us to calculate for the x, y, z, and t components of the GNSS receiver. With each additional satellite signal after the first, the number of possible locations that the receiver could be drastically decreased, until there is only one. The satellites still have an error margin in the location, so having more satellites decreases the error margin of the receiver's location.

GNSS constellations are designated different regions of frequencies within the electromagnetic spectrum referred to as L bands (Subirana et al. 20). The breakdown of which L bands are assigned to which constellations is shown in the figure below. These signals can be broken up into three components, the carrier, ranging code, and the navigation data. (Subirana et al. 20). The carrier is the sinusoidal waveform the signal has at a given frequency. The ranging code is made up of pseudo-random noise (PRN) codes. They are an arrangement of ones and zeros that tells the receiver the travel time of the wave. Finally, the navigation data reports relevant satellite information including position, velocity, and clock parameters as binary code.

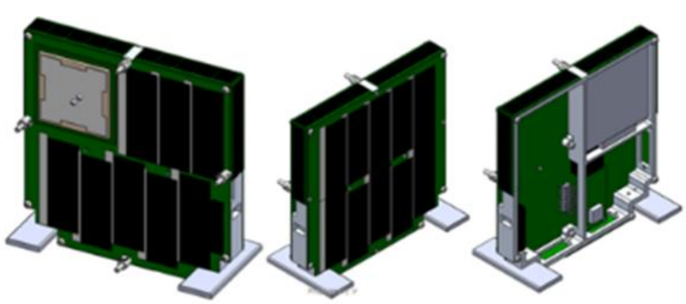

Figure 2

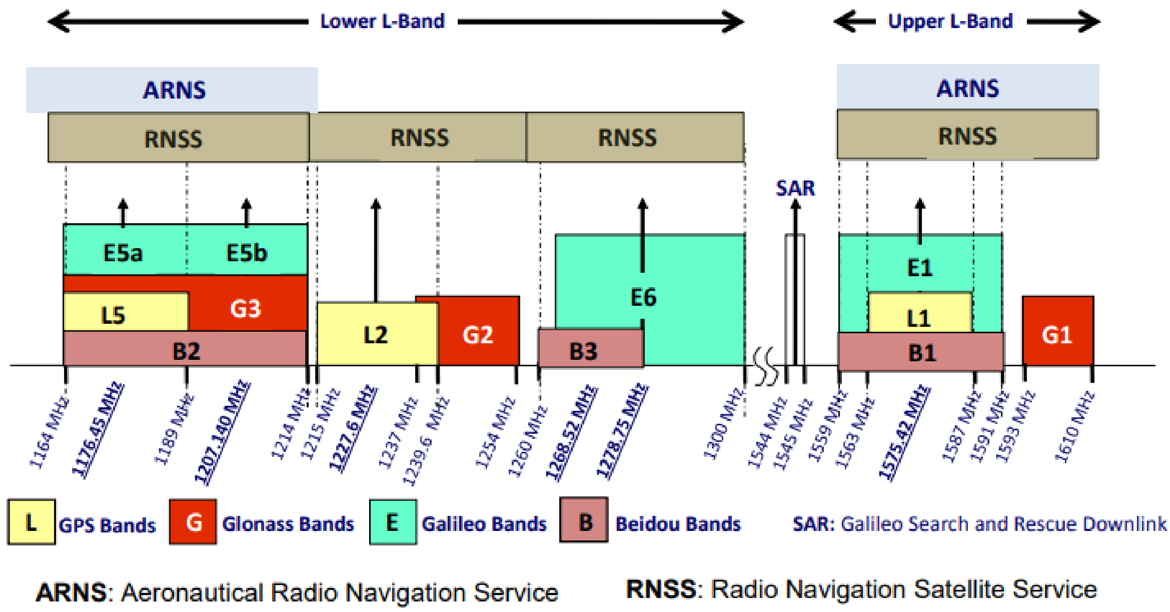

Figure 3

GNSS-R

The primary use of GNSS systems like GPS in travel is to help navigate people to specific locations. Using multiple signals from orbiting satellites to identify where one is and where one would like to go. This technology has led to other uses as well, the electromagnetic waves that are transmitted from satellites travel in all directions. Meaning that many will hit the surface of the Earth and be reflected back into space. The use of these reflected signals to collect data is referred to as Global Navigation Satellite System Reflectometry (GNSS-R).

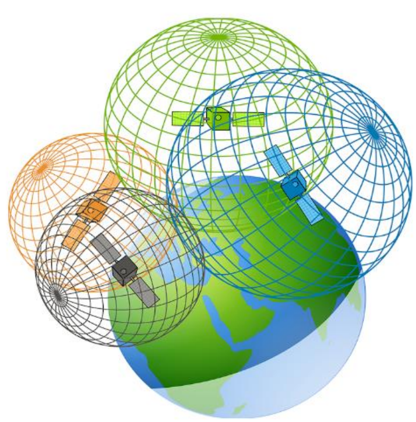

Figure 4

Using reflectometry from dispersing satellite signals, an application of GNSS now includes being able to determine geometric and material properties on the surface of the Earth. This includes research on the sediment on the surface of the Earth, research on the atmosphere, and research determining mean wave height using gravity and wind generated waves (Chen-Zang 11). Leading to the application of this project to research rogue waves.

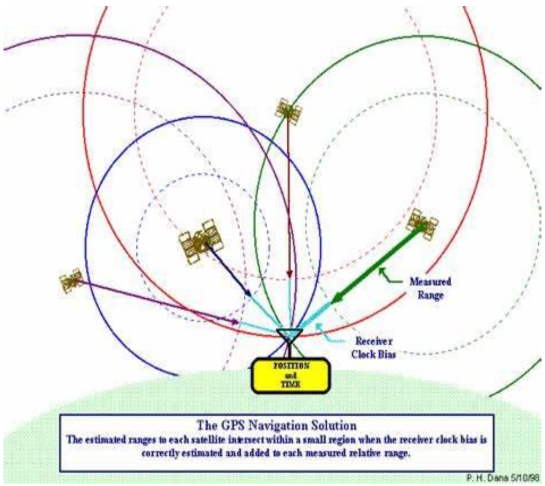

Figure 5

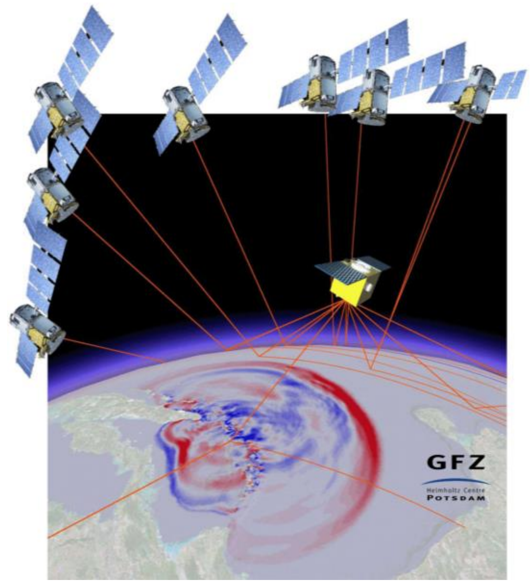

Figure 6

Using GNSS-R to get wave height data requires a direct signal from neighboring satellites and a reflected signal. The reflection point at which a transmitted signal hits the surface of the Earth is reflected and received by another satellite is called the point of specular reflection or the specular point. “This point on the Earth’s surface will satisfy the law of reflection, where the incident and reflected angles are an equal angel θ [to an imaginary line perpendicular to the surface] (Gleason 14).” Around the specular point, there is a varied elliptical area called the glistening zone where power can still be scattered towards the receiver. “At each point in the glistening zone, the path delay and reflection angles are different. This results in a range of different path delays (between the transmitter and receiver) and Doppler frequencies at the receiver (Gleason 15).” Each individual line in the glistening zone has a constant path delay and doppler frequency shift known as iso-range lines and iso-Doppler lines (Gleason 15). Iso-range lines form ellipses around the specular point, and iso-Doppler lines will result in parabolic lines that can be mapped onto the image of the Earth’s surface..

The size of the glistening zone is determined by how much change is happening around the specular point. For example, during a calm day where the sea is still, the specular point would be the only position where the GNSS receiver would receive a reflected signal from an individual satellite. However, during a clear day where there are rough seas, the glistening zone will grow, and the GNSS receiver will receive multiple reflected signals. This occurs due to the number of slopes with angles created by waves that now have the possibility of reflecting a signal off of the surface (Gleason 16).

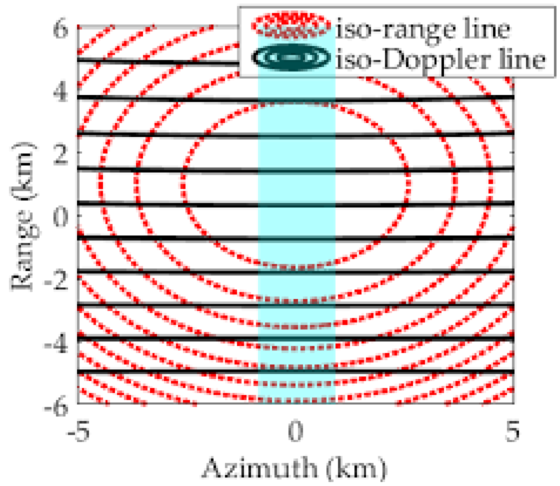

Figure 7

If a Rogue wave appears at the glistening zone there will be less reflected signals received by the GRWS then on a standard choppy day, but more than just 1 reflection. The difference between reflected points on a rogue wave on the top and bottom will be very pronounced. This will be received by the GRWS as a delay waveform. “A delay waveform is the returned power profile as a function of delay only, with the frequency set to a constant value”(Gleason 16). Using this information collected from the reflected signals, we can map the signal power as a function of frequency and delay together to create a delay-Doppler map (Gleason 16).

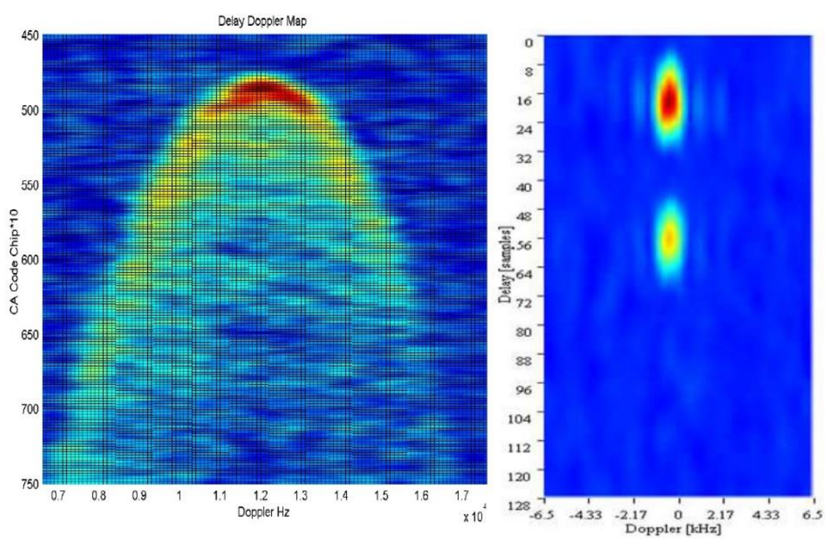

Figure 8

Delay-Doppler maps create a plot of signal reflections to generate an image of what the target should look like using specular reflection of doppler signals reflected off of the surface. As the ocean surface becomes more choppy, the image generated will become less specular, alternatively, the areas of increased specular reflection (greatest local wave heights) will become more pronounced in the imagery and correspond to evidence of rogue waves. The reason a local maximum wave height will increase specular reflection for a particular area is due to the convex nature of the wave shape. The satellites are far enough away that the signals can be considered parallel over the small areas being observed. Once those parallel signals reach the wave's surface, they will diverge in many directions. This will increase the chance of the GRWS to receive signals reflecting off the wave compared to the relatively flat ocean surface surrounding the wave. Using GNSS-R, the GRWS is able to generate a delay-Doppler map of the ocean surface below, giving information about the height of the waves. An example of a delay-Doppler map is shown above from NASA's CYGNSS mission.

Engineering Specifications:

In order to successfully pass inspections, the onboard instruments must be fixed in order to fit in the satellite's small dimensions. The GRWS cannot exceed 4.5'' x 4.5'' x ⅝'', in volume, cannot surpass 280g in mass, or draw more than 100mA from each power switch (3.3V and 5V) for 10 minutes on the hour. The ThinSat holds a set of base requirements that are immalleable. All requirements must be successfully met before there is any successful launching of the ThinSat into low orbit.

The GNSS-R sensor is limited to solely receiving signals, the sensor cannot emit any form of radiation or signals due to equipment restrictions. The sensor instead relies on satellites that contain their own GPS, emitting, and receiving signals to retrieve data to make delay-Doppler maps for the ThinSat.

Some unknown variables that are appropriate in regards to the sensor as well and the on board computer (OBC). Currently, there is an uncertainty that the satellite is allowed and/or capable of receiving data from other positioned satellites that utilize GPS.

Circuitry

Figure (n) (block diagram) is a block diagram that explains how the components interact within the student payload and also with the rest of the ThinSat. It can be seen that all the signals are processed through the W2SG0084i for the processor to do the calculations and perform algorithms to create the delay-Doppler map of the section of the ocean surface below. Images from the arducam are sent to the processor where an image processing algorithm will discern the horizon of the Earth and thus determine the GRWS's attitude. The student payload is connected to the batteries, flight processor, simplex radio inside the rest of the ThinSat via the payload connector. This allows the transmission of power, serial analog and digital data between the payload and the flight processor (*Et-Sat Interface Control Document (ICD)*).

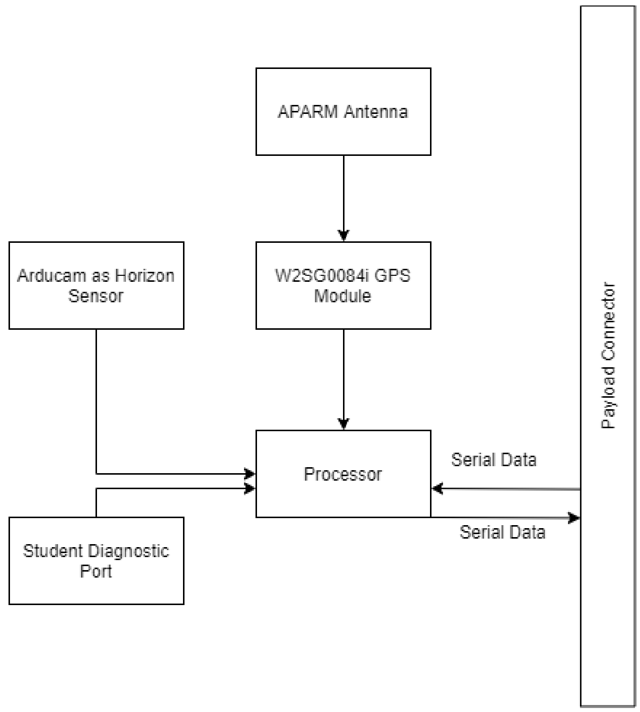

Diagram 1

The programming and algorithm architecture would follow this basic flow diagram (figure below). The payload antenna will detect the GPS signals with data that provides the time the signal received, the frequency of the signal and from which GPS satellite (Citation needed). Later, the GRWS will receive the signal again, but this time the signal has been reflected off the ocean surface. The time difference between the detection of the GPS specific signal is the time delay and due to the reflection, there is a frequency shift in the reflected signal as well. The Arducam will take an image, and a custom image processing algorithm would be able to discern the edge of the Earth providing a way to determine the satellite's attitude. A custom algorithm would be implemented to create the delay-Doppler map from the time delay, frequency shift and attitude.

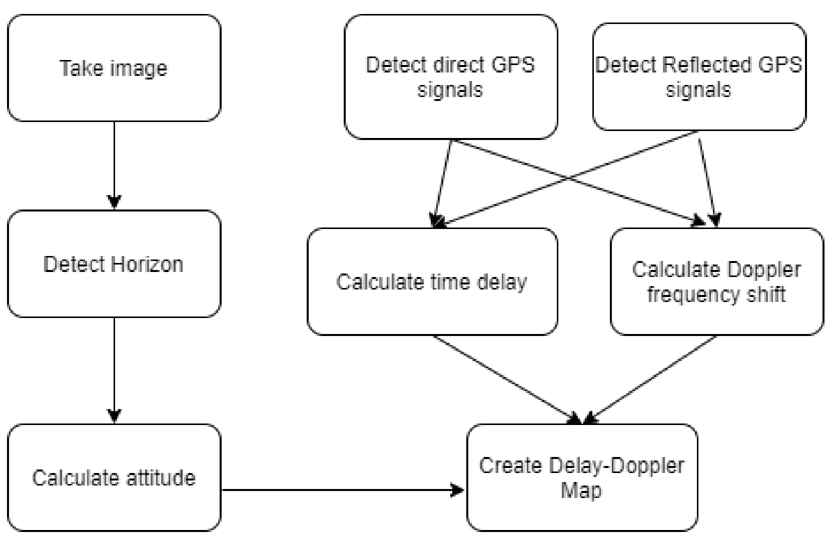

Diagram 2

The GPS module chosen for this project is the W2SG0084i. The W2SG0084i module is specifically chosen for its compact design as well as “ultra-low power consumption” that contains a 3.3V input requirement (GPS Module W2SG0084i Product Datasheet). The W2SG0084i GPS module is a surface mount component which in order to test the GPS in the prototype, a surface mount to breadboard adapter is designed using the open source PCB design software KiCad. Figure 9 (left) is the footprint of the GPS adapter board used by KiCad and is essentially the blueprint used by print computer board (PCB) manufacturers. Figure 10 (right) shows an image of the physical GPS adapter board. This adapter is pivotal in the design process of the satellite as it allows testing and troubleshooting of the GPS module through the use of a breadboard with temporary connections.

In order to maximize on the circuitry per weight and space limit, the project requires the fabrication of a custom PCB. All components and sensors for the payload must fit upon the PCB. Upon the PCB will sit the arduino processor, GPS module, antenna, and the arducam.

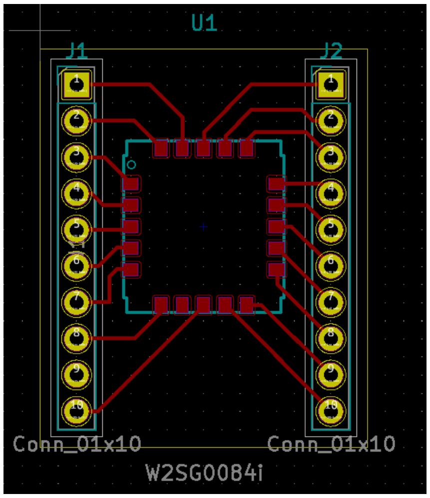

Figure 9

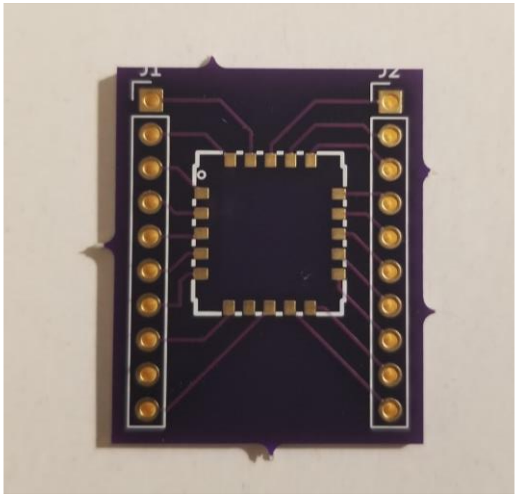

Figure 10

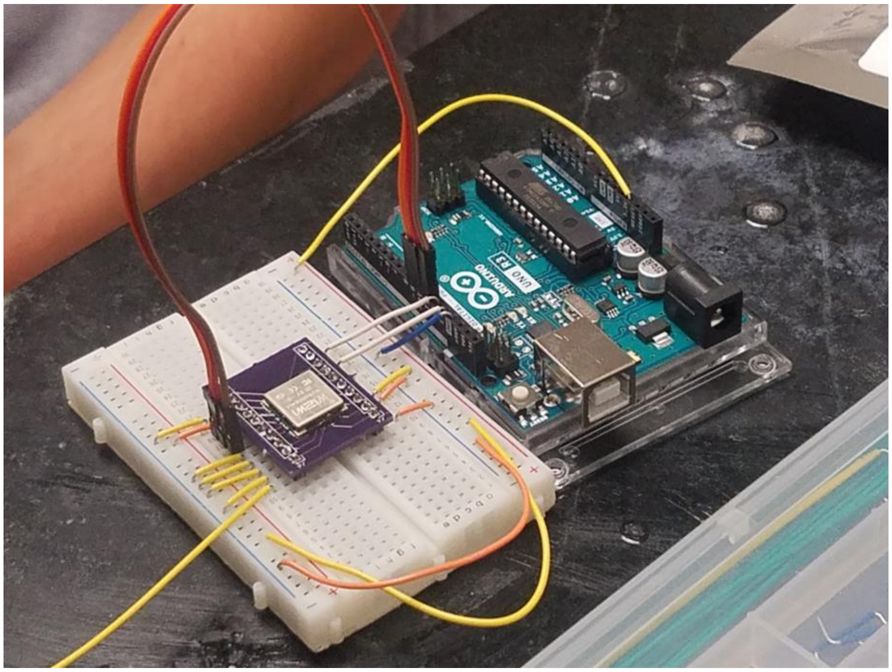

Figure 11

<u>Budget:</u>

Current Price Table:

Object	**Quantity/Bundle**	**Total Price**
GPS Board	3	$17.25
GPS Module	3	$59.97
Pinheaders	10	$ 4.99
Antenna	3	$29.61
Arduino Camera	3	$ 29.97
Leaded Solder Paste	1	$ 0.00
Heat Gun Solder	1	$ 0.00
	Order Total	$141.79

The W2SG0084i module is a robust, reliable, and compact GPS receiver module based on CSR's SiRF Star IV™ architecture. This model is certified for global markets and supports full operation in industrial operating temperature range. Due to the overall benefits that the W2SG0084i model provides, the model has been deemed the best choice for the GRWS GPS board.

Figure 12

The antenna chosen is the APARM2508S-SG3L5. This antenna was specifically chosen for its "dual stacked patch for GPS L1 and L5" feature and compact dimensions (Mouser Electronics). This feature allows the antenna to pick up the signals used by the GPS constellation in the L1 band and the L5 band. The operating frequency of the L1 band is 1575.42 ± 1.023 MHz and the operating frequency of the L5 band is 1176.45 ± 12 MHz. This antenna also supports signals from other GNSS constellations: GLONASS/BEIDOU and GALILEO. The antenna is a passive antenna and thus only has one connection to the GPS module. This lowers the power consumption of the whole satellite.

In order to satisfy the dimensions requirement and power usage of the board, the selection of camera narrowed down to the ArduCam. The MT9D111 ArduCam features a ⅓ inch (4:3) optical format, with a 4.48mm x 3.36mm (5.60mm diagonal active imager size, consisting of 1600H x 1200V active pixels, each being 2.8µm square. With an RGB Bayer pattern color filter array and an electronic rolling shutter to provide crisp images.

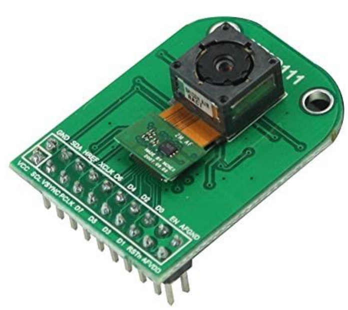

Figure 13

Further features and specifications include:

- ADC Resolution: 10-bit, on-chip
- Supply Voltage
  I/O Digital: 1.7V–3.6V
  Core Digital: 1.7V–1.9V (1.8V nominal)
  Analog: 2.5V–3.1V (2.8V nominal)
- Power Consumption:75mW at 30 fps, 36 MHz, Preview mode
  125mW at 15 fps, (VAA, VAAPIX and VDD only) 36 MHz, Full frame mode

Analysis/Results:

During the start of the construction phase of the GRWS there developed a variance between the initial and final pricing for the satellite. Initially it was believed that the overall pricing would be substantially higher than the current cost, to clarify, the current cost is approximately half of what the initial cost was calculated to be. Comparing the initial and current price table, the most notable difference is the ThinSat Board, where the initial cost was predicted to be $100 while currently the cost stands at $17.25. The difference between the initial and current board stands at an $82.75 discrepancy. The rest of the price comparisons contain the same pattern of the initial price of parts being higher than the current price of the parts on the GRWS.

Initial Price Table:

Object	**Price**
ThinSat Board	$100 for 3
GNSS Receiver	$80 for 4
GNSS Antenna	$20 for 5
Camera	$50 for 2
Other sensors and components	$50
Total Price	~$300

Current Price Table:

Object	**Quantity/Bundle**	**Total Price**
GPS Board	3	$17.25
GPS Module	3	$59.97
Pinheaders	10	$4.99
Antenna	3	$29.61
Arduino Camera	3	$29.97
Leaded Solder Paste	1	$0.00
Heat Gun Solder	1	$0.00
	Order Total	$141.79

Concluding Statement:

The GRWS was designed to be the first implementation of a small budget satellite capable of detecting rogue waves. The intention is to provide proof that a global constellation of these satellites is effective at detecting these waves for small cost and greater detection coverage than a single large rogue wave detector. The use of GNSS-R in the GRWS greatly increases the capabilities of the ThinSat by removing the necessity for an emitter on the ThinSat itself. With a custom PCB, designed to handle on-board calculations, the GRWS would be valuable to implement even with its small scale. If a network of small satellites can be effective in recording rogue wave activity, then students across the globe will be able to contribute to the development of the rogue wave model. This group of satellites can provide a lot of knowledge and safety for vessels at sea and those living in coastal areas, thus helping secure the lives of thousands of people. Like hurricanes and tsunamis before, natural disasters can happen all over the world. An important first step is to identify them and study them to find a cause and solution for such problems. As Albert Einstein said, “if I had an hour to solve a problem I’d spend 55 minutes thinking about the problem and five minutes thinking about solutions.” If nothing is done to take care of these waves millions of dollars of damage will still be inflicted on offshore infrastructure and sea vessels.

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Additional Resources

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<u>Figures we did not make</u>

Figure 3:

Subirana, J. Sanz, et al. *GNSS Data Processing*. ESA Communications, 2013. gssc.esa.int/navipedia/GNSS_Book/ESA_GNSS-Book_TM-23_Vol_I.pdf

Figure 4:

GIS Geography. *Trilateration vs Triangulation- How GPS Receivers Work* gisgeography.com/trilateration-triangulation-gps/

Figure 5:

"Multilateration Orbit Determination Concept - ASEN5050.Kemble." *Google Sites*, sites.google.com/site/asen5050kemble/multilateration-orbit-determination-concept

Figure 6:

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Figure 7:

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Figure 8:

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