Naval Architecture Analysis of the Civil War Ironclad *CSS Virginia*

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ABSTRACT

This thesis presents the results of a naval architecture analysis of the Civil War Ironclad *CSS Virginia*, built by the Confederate States Navy to break the Union Blockade of Hampton Roads, and which engaged the *USS Monitor* on the second day of the Battle of Hampton Roads, March 9th, 1862.

The purpose of the analysis was to examine the ship from a naval architectural standpoint pertaining to hydrostatics, stability, weight and CG, sea keeping, and basic resistance/powering requirements. The goal was to see if the story of the *CSS Virginia*, destroyed on May 11th, 1862 by its own crew to keep it from falling into Union hands, could have ended differently with an attack on Washington, a Northern city, or a run to a friendly Southern port, such as Savannah or Charleston.

Paramarine software was used to build a geometry model based on lines included in a book by Sumner B. Besse for ship modelers. The geometry model provided the basic measures of displacement for the hull form at a draft of 21 ft forward and 22 ft aft which in turn allowed for a weight estimate to be undertaken. The goal of the weight estimate was to obtain, in particular, an estimate for the VCG of the vessel. It also allowed for gyradius calculations based on the resultant weight distribution to be calculated. Historical information coupled with the Paramarine geometry was used for the weight analysis.

Paramarine was used to obtain RAOs for a sea keeping analysis and long term effectiveness ratings regarding MSI and Deck Wetness criterion were obtained based on statistical wave data from NOAA taken from stations in the Chesapeake Bay and in the Atlantic, 64 miles east of Virginia Beach.

A NAVCAD analysis was made for resistance requirements, though any resistance analysis of such an antiquated hull form that is also in its way unique has large uncertainties associated with it.

The results of the analysis shed some light on the *CSS Virginia* and its history.

The hydrostatic analysis leads one to speculate that draft reduction efforts made to allow the *Virginia* to escape Union capture by sailing up the James River were known to be hopeless, but undertaken anyway to save the honor of those involved and shift blame for the loss of the ship elsewhere.

The resistance and powering analysis suggests that an upper speed of 6 knots was probably not outside the *CSS Virginia's* capabilities. Speeds much higher seem unlikely. The only way to know more would be to get better estimates of power provided by the ship's steam engines and do a tow tank test of a ship model. Assuming a speed of 6 knots and based on a coal consumption rate, it was found that range of the CSS Virginia was at best around 614 nautical miles, giving it the distance to attack New York or sail to Charleston or Savannah.

However, the sea keeping analysis shows that the *Virginia* was very much at home on the relatively calm waters of the Chesapeake Bay, but would have run great risks in sailing on the open sea either to attack a Northern city or make a run to the South for safer waters to fight another day. The officers of the *Virginia* felt that the ship was likely to flounder; based on the deck wetness criteria chosen for the sea keeping analysis their professional judgment was correct.

Details of the weight analysis and a full set of RAOs are provided in the Appendices.

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GENERAL AUDIENCE ABSTRACT

This thesis presents an analysis of the Civil War Ironclad *CSS Virginia*, built by the Confederate States Navy to break the Union Blockade of Hampton Roads in Southeastern Virginia, using modern engineering techniques. The *Virginia* famously engaged the Union Ironclad *USS Monitor* on the second day of the Battle of Hampton Roads, March 9th, 1862. The analysis gives critical insight into how they ship may have performed in different scenarios (i.e. on the relatively calm waters of the Chesapeake Bay or the more unpredictable seaways of the eastern Atlantic Ocean).

This thesis begins with a brief overview of the history behind the *CSS Virginia*, including the development of ironclad vessels up to 1862. Ironclad vessels featured wooden hulls that were covered in a layer of iron plating, held together by bolts. Ironclads were developed because the introduction of the exploding shell for naval use posed a significant threat to the wooden hulled warships that had been state of the art for centuries. The shells could penetrate the wooden hulls and explode inside the ship, causing tremendous damage. The iron plating which gave the ironclad its name deflected these exploding shells, allowing an ironclad to survive a naval engagement that a wooden ship of war could not. Ironclads were propelled by steam engines, which also representeded a recent technological development in maritime propulsion.

At the outset of the American Civil War, the Confederate States Navy realized that the only way to break a Union Blockade (made up entirely of wooden vessels) was to construct an ironclad that could defeat the Union Fleet in Hampton Roads. An ironclad, armed with shell guns, would be a severe threat to the Union Fleet, as it could act with virtual impunity unless another ironclad vessel arrived to meet it. On March 8th, 1862, the *CSS Virginia* sailed into Hampton Roads and engaged the Union forces, sinking two ships while suffering very little damage. On March 9th the *USS Monitor,* which had fortuitously arrived on the evening of the 8th, fought the *CSS Virginia* to what most would consider a draw, with neither ship able to significantly damage the other. This engagement is significant in naval history, as it largely is viewed as the final death knell of the wooden hulled warship.

Historical information in the form of model plans and books was used to construct a 3D geometry model of the *CSS Virginia* in a naval architecture (ship design) software suite called Paramarine. The geometry model was used to determine various naval architectural characteristics of the *Virginia* which can be used in various analyses. In parallel, a weight estimate of the *CSS Virginia* was made to determine the overall weight and center of gravity (the location of the overall weight inside the ship). Microsoft Excel was used to estimate the weight, and a variety of sources and methodologies were used to estimate different aspects of the weight. These different aspects include but are not limited to:

- Ship's structure (the hull, decks, iron armor, etc.)
- Armaments and ammunition
- Provisions
- Weight of personnel serving on board and their effects
- Propulsion machinery weights

The weight and center of gravity were input into the Paramarine computer program which, combined with the geometry model, could now analyze various aspects of the *Virginia*. Of particular interest was hydrostatics (i.e. how the ship sits in the water given its weight and center of gravity and how stable it is) and sea keeping characteristics (i.e. how the ship behaves in waves when moving at a certain speed: its seaworthiness). An analysis was also made concerning how much power from the steam engines would be necessary to propel the *Virginia* at different speeds. The *Virginia* was a slow vessel, only able to move between 4 – 6 knots (about 5 – 7 miles per hour). The range (how far the *Virginia* could travel) was also estimated.

The results from these disparate analyses were used to discuss the likelihood of the *Virginia's* story having a different ending. After the battle of Hampton Roads, the *CSS Virginia* continued to play a cat and mouse game with the *USS Monitor* until May 11th, 1862, when Norfolk, VA (where the *Virginia* was based) was taken by Union soldiers as part of the 1862 Peninsula Campaign. The *Virginia's* commander desired to sail up the James River towards Richmond, but the ship sat too deep in the water to get over a sandbar that lay at the entrance to the James. Efforts were made to lighten the ship but these proved futile, and it was decided that the only course of action was to evacuate and destroy the *Virginia*. One notable aspect of the hydrostatic results presented in this thesis is that they suggest that efforts to lighten the ship in a bid to escape James River were known to be hopeless, but were ordered anyway to shift the blame for the loss of the ship away from its commanding officer and onto the ship's pilots.

But were there other options open? Could the *CSS Virginia* set sail for the friendly ports of Charleston or Savannah? Could it have made an attack on New York City or Washington DC? The results of the different naval architecture analyses were used to answer questions like these. It was found that the *CSS Virginia* was very much at home on the relatively calm waters of the Chesapeake Bay, but in all probability would have encountered seas too rough for it to successfully navigate a transit on the open ocean. In making a run to Savannah, Charleston, or New York, the *Virginia* in all likelihood would have sunk.

This thesis presents new insights into the *CSS Virginia* and its performance, and provides a useful springboard upon which future research might be conducted on this unique and historic vessel.

ACKNOWLEDGEMENTS

I would first like to thank my thesis committee: Dr. Alan Brown, Dr. Stefano Brizzolara, and Mr. Sean Keary, for their time and their suggestions, which improved this thesis and the analysis it presents greatly. I would also like to acknowledge my past advisors Dr. Leigh McCue and Dr. Wayne Neu for their support of the initial concept.

I would also like to thank Newport News Shipbuilding (NNS) and managers AJ Bierbauer, Alan Titcomb, and David Cash for their support and also for allowing the use of NNS licensed software (in particular Paramarine) to accomplish the analysis presented herein. I would also particularly like to thank my NNS colleagues Davy Hansch and Scott Opdyke, who provided timely advice and pointed me in the right direction on a number of occasions.

I also thank historian John Quarstein for providing some very insightful historical information, not only in his book Sink Before Surrender but also in person. In the same vein, I also offer a thank you to the Mariner's Museum and the Mariner's Museum Library, which has an incredible wealth of materials not only on the *CSS Virginia* and *USS Monitor* but also on naval architecture in general.

Finally, I would be remiss if I did not remark the Union and Confederate Sailors who fought so gallantly in a theatre now dominated by the Monitor-Merrimack bridge tunnel, traversed by commuters in their cars, sipping their coffee and listening to the radio on the way to work, peaceably passing over hallowed waters without batting an eyelash.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

This report presents a naval architecture analysis of the ironclad *CSS Virginia.* The scope of the analysis includes a weight assessment, hydrostatics, and sea keeping. Resistance and basic powering requirements are considered briefly but due to numerous considerations lack the same fidelity and detail as other aspects of the analysis.

The weight assessment was made using Excel software, and the naval architecture analysis was facilitated with Paramarine. A NAVCAD analysis based on hull geometry parameters from Paramarine geometry models was accomplished to speak to the resistance characteristics of the vessel. An EHP curve based on the analysis is presented.

The sea keeping analysis presented includes RAOs, RMS motions at zero knot roll resonance wave frequency, and long term measures of effectiveness for conditions in the Chesapeake Bay and in the Atlantic Ocean off the coast of Virginia Beach. The information from the various analyses is used to assess the chances of the *CSS Virginia* carrying out different missions, including an attack on Washington DC or a retreat to a safe harbor such as Charleston, SC.

To lend the analysis context, a brief history of the development of ironclads and of the *CSS Virginia's* service life is presented in Section 2 of this report. Various aspects of the ship (armaments, engines, etc.) are also discussed before diving into the analysis process in Section 3. Section 4 details results of the various analyses and ties them together to ask a simple question: Could the story of the *CSS Virginia* have had a second act, or even a different ending?

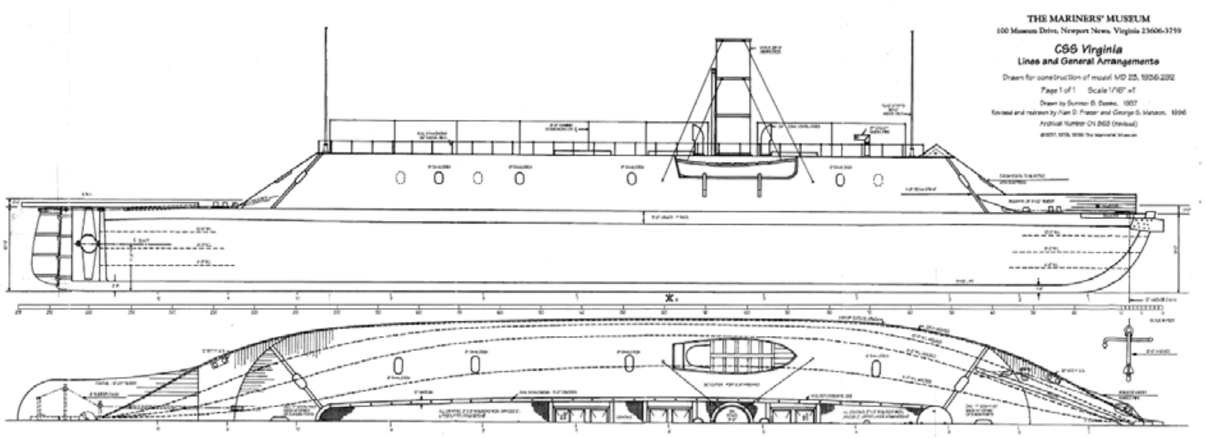

Figure 1: Profile and Plan Views of the *CSS Virginia*, From Besse's <u>C.S. Ironclad *Virginia* and U.S. Ironclad *Monitor*</u>

Basic Ship Characteristics	
Length over all	278 feet
Beam	51 feet, 2 inches
Displacement 3/8/1862	Approx. 3870 LT
Drafts 3/8/1862	21 feet fwd, 22 feet aft
Armament	4 Brooke Rifles, 6 Dahlgren IXs
Personnel	320 – 350
Top speed	About 6 knots
Range	Estimated 614 nautical miles

2 CONSTRUCTION, SHIP CHARACTERISTICS, AND SERVICE LIFE[1]

A thorough retelling of the *CSS Virginia's*[2] history is beyond the scope of this thesis; anyone interested in more information is welcome to peruse the wealth of material already written about the ship and the engagement between the *CSS Virginia* and the *USS Monitor*, known as the Battle of Hampton Roads. However, some history will lend the analysis context, especially as the ultimate goal of the analysis was to see if, from a con-ops perspective, the *CSS Virginia* could accomplish other missions such as attack a northern city or a run to a friendly southern port after the fall of Norfolk to Union forces in 1862. Particular attention is paid here to the evolution of ironclad vessels, the decision to convert the *USS Merrimack* into the *CSS Virginia*, the construction process, and ship characteristics.

2.1 The Evolution Towards Ironclad Vessels

The Battle of Hampton Roads represents an important step in the evolution of war ships, a knee in the curve as naval technology moved from the Napoleonic Era Ship of the Line to the Dreadnaught Class Battleships of the early 20th Century.

The technological evolution leading to the first battle between ironclads really begins years before, with the development of the shell gun for naval use. Shell guns were cannons that fired an exploding shell rather than solid shot. By the early 19th century, wooden sailing vessels with thick hulls were reasonably well protected against solid shot even when fired at close range. In 1822, French Brigadier General Henri-Joseph Paixhans published *Nouvelle Force Maritime et Artillerie*, which advocated the use of standard caliber shell guns. Paixhans tested his theories by conducting a demonstration; an 80-pounder shell gun was fired at an old French Ship of the Line, *Le Pacificateur*, at Brest. The solid wooden hull was no match for exploding shells and was demolished after only 16 shots.

The power of the new shell guns was demonstrated with devastating effect during the Crimean War. At the Battle of Sinope, which started the war in 1853, a Russian squadron of nine warships armed with shell guns destroyed a Turkish squadron of thirteen ships in two hours. In 1854 a squadron of wooden British and French ships attacked Russian fortifications around Sebastopol. The Russians were armed with shell guns and inflicted severe damage on the allied squadron while suffering relatively minor damage themselves.

It was obvious that wooden hulls were no match against shell guns, and the next step towards the Battle of Hampton Roads was taken when the French deployed armored floating batteries against Russian defenses along the Dnieper River at the Battle of Kinburn in 1855. These floating batteries were unpropelled ironclad vessels that were towed in place for the attack. Their slanted iron shielding deflected the Russian shells, enabling the French cannon protected within to pour fire into the Russian fortifications with relative impunity. A technological answer to the shell gun had been found.

The Battle of Kinburn made a great impression on military observers, and the race was on to build the first true Ironclads[3], which combined the then modern technologies of iron armor, steam propulsion, and shell gun armaments. The French were the first, launching *La Glorie* in 1859. The British followed soon after, launching the *HMS Warrior* in 1860.

2.2 The Civil War and the Confederate Need for an Ironclad Vessel

The main goal of the United States Navy during the Civil War was to blockade Confederate ports. This would stifle commerce with the rest of the world, hampering the Confederate economy. It would also keep any sympathetic European nations from supplying the Confederacy, a major concern especially early in the war. The goal of the nascent Confederate Navy, aside from commerce raiding, was to find a way to break the Union blockade.

CSA Secretary of the Navy Stephen Mallory understood all this. Before the Civil War he was a U.S. Senator from Florida and had served as the chairman of the Committee on Naval Affairs in the Senate. His position had made him aware of the developments in naval technology occurring overseas, and he recognized that the

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[1] Unless otherwise noted, all information for this section comes from three sources: Sink Before Surrender by John Quarstein, Reign of Iron by James Nelson, and Ironclad Down by Carl Park. Park's book delved into the details of the *Virginia* could have been built, while Quarstein and Nelson provided the backdrop of the *Virginia's* history.

[2] In keeping with most current day histories, the *Virginia* will be the name applied to the ship over the course of this report, rather than the *Merrimack*. The *Merrimack* may be used if there is a feature of the ironclad, notably during construction or with regards to the engine that is part of the *Virginia's* characteristics.

[3] There are examples of sailing ships and galleons that had iron plates or spikes over parts of the hull in the pre-industrial age, and of course the French floating batteries used at the Battle of Kinburn. However, as J. Richard Hill noted in War at Sea in the Ironclad, an Ironclad is usually defined as a ship with iron cladding, steam propulsion, and shell guns.

Confederate States Navy needed an ironclad vessel if they hoped to break the Union blockade made up predominately of wooden ships of war.

Mallory dispatched agents overseas to try and purchase an ironclad from the English or the French, but those efforts turned out to be fruitless. Simultaneously, he began efforts to construct an ironclad vessel within the CSA, and engaged Lieutenant John Mercer Brooke to begin developing plans. Brooke's original concept featured a sloped iron casemate built on top of a wooden hull to provide buoyancy. The wooden hull had narrow ends at the bow and stern, and was submerged two feet below the water line to protect it from cannon shot and shell, exposing only the casemate to enemy fire.

John Luke Porter, the de facto Chief Naval Constructor at Gosport Naval Shipyard, was summoned to Richmond to develop detailed plans. His relationship with Brooke as construction of the *CSS Virginia* commenced was often strained and would later erupt into a long running feud over responsibility for the *Virginia's* design[4], both wanting to take the lion's share of the credit for the historic ship from the other.

Brooke and CSN Chief Engineer William Price Williamson turned to the problem of how to power the vessel. A meeting at Tredegar Iron Works, in Richmond Virginia, yielded the disappointing news that a steam power plant for Brooke's vessel would take 12 months to build. Mallory and Brooke wanted an ironclad in the fight as soon as possible: 12 months was unacceptable. Williamson floated the idea of using the engines on the *USS Merrimack*, which had been scuttled by Union forces as they abandoned Gosport Naval Shipyard. The ship had been raised by the Confederacy shortly after capturing the yard. This idea expanded into the wholesale conversion of the steam frigate *USS Merrimack* into the ironclad *CSS Virginia,* as all concerned realized it was the fastest path towards a Confederate ironclad.

2.3 Ship Construction Begins

The *Merrimack* was already in dry dock at Gosport when the conversion began in the summer of 1861. The fact that the *Merrimack* had been set on fire *and* scuttled in a thorough attempt at its destruction was actually fortunate for the Confederacy. The scuttled ship had burned down to the waterline, and as a result the berthing deck and the hull below were preserved from the flames. Porter had the charred parts of the hull cut away, so that at the bow the hull had 19 feet of depth and at the stern it had 20 feet. He had originally intended to have the hull be 19 feet in depth fore and aft, but this would have cut into the propeller and he was forced to raise the hull cut to preserve that part of the ship, as there was not enough time to fashion a new propeller or replace it with a different one.

2.4 Casement Construction

Construction of the armored shield (typically referred to as "the casement") began in August of 1861. As shown in Figures 2 and 3, it was a thick structure consisting of two layers of 2 inch iron plating backed by courses of oak and pine planking and rafters of yellow pine. Different sources have different wood thicknesses, as noted in Park's Ironclad Down, and as shown in Figure 3. For this project it was assumed that John L. Porter's thicknesses (4 inches of iron, 4 inches of oak, 5 inches of pine, and 12 x 12 inch pine rafters) were correct. The casement began approximately 29 feet aft of the bow and extended aft for about 190 feet. By November of 1861 the wooden structure was complete and the iron plating, rolled at Tredegar Iron Works, began to arrive. Huge bolts were used to affix the plating to the wooden backing structure. The bolts went all the way through the entire casement, from the iron plating outside to the rafters inside.

The rafters backing the casement were joined to the hull by oak knees connecting the rafters to the ship's existing framing. The *Merrimack's* hull was essentially solid to the turn of the bilge, meaning there was no space between the hull framing; the frames butted up against each other. Above the turn of the bilge there was space between the frames (Isherwood, 1863). Carl Park, as described in Ironclad Down, believes that in order to support the solid casement of the *Virginia* the workers at Gosport installed filler frames so that every rafter in the solid casement could be connected to a piece of structure inside the hull, and for the purposes of analysis and weights Park's hypothesis was accepted. This essentially made the *Virginia* a vessel with a solid hull, with very small gaps between the frames, filler frames, and casement rafters.

A gun deck was built above the berth deck, backed by deep rafters and supported by iron knees. There are very few details of how the internals of the ship were built or arranged, but a notional deck framing plan was made by Park based on other framing plans of the era that features transverse rafters, smaller transverse carlings, and two deep longitudinals. The deck itself was likely about 5" thick, made of pine or oak.

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[4] The interested reader should refer to Ironclad Down, which recounts the dispute in detail.

The upper deck (the top of the casement) was actually a grid of square iron bars supported by wooden backing structure. The thought was that an open deck would allow for better ventilation and lighting inside the casement itself, but it wasn't enough to keep the inside of the *Virginia* from being dark and very hot due to the running of the engines and boilers. The casement also did nothing to stop rain from entering the ship, so it was perpetually damp. It was not a pleasant place to serve.

At the forward end of the casement was a small pilot house, a conical structure made of iron plating and cast at Tredegar Iron Works. There had originally been plans to place a pilot house on the aft end of the casement as well, but in the interest of time only one was installed.

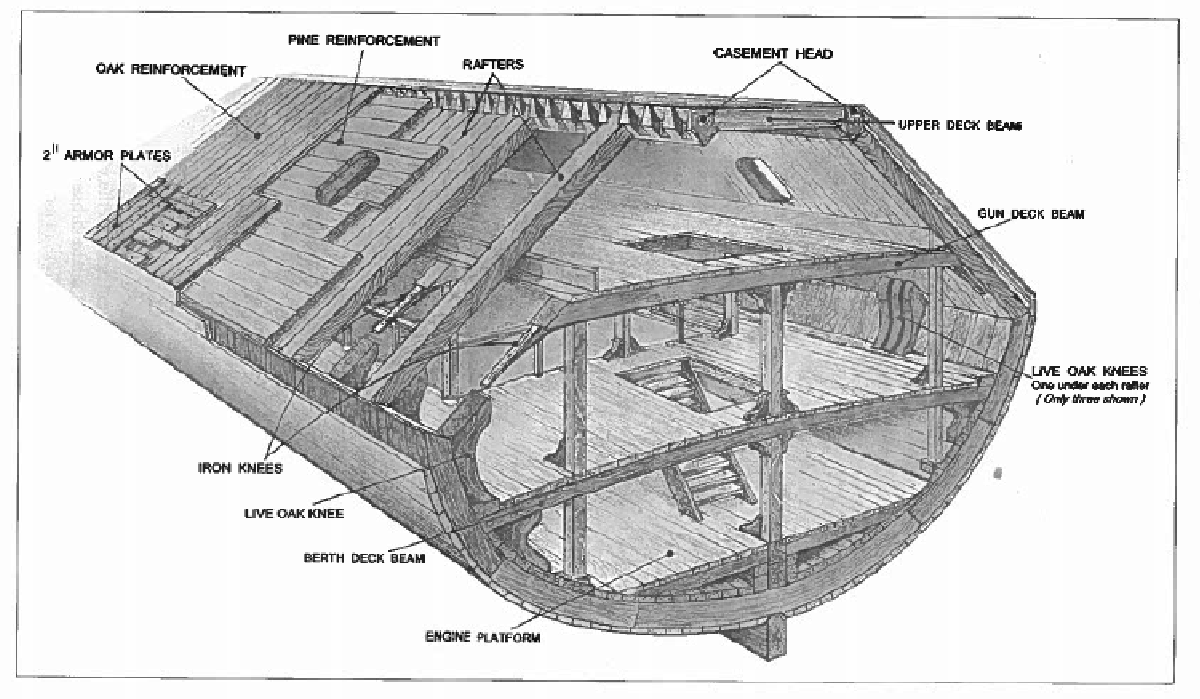
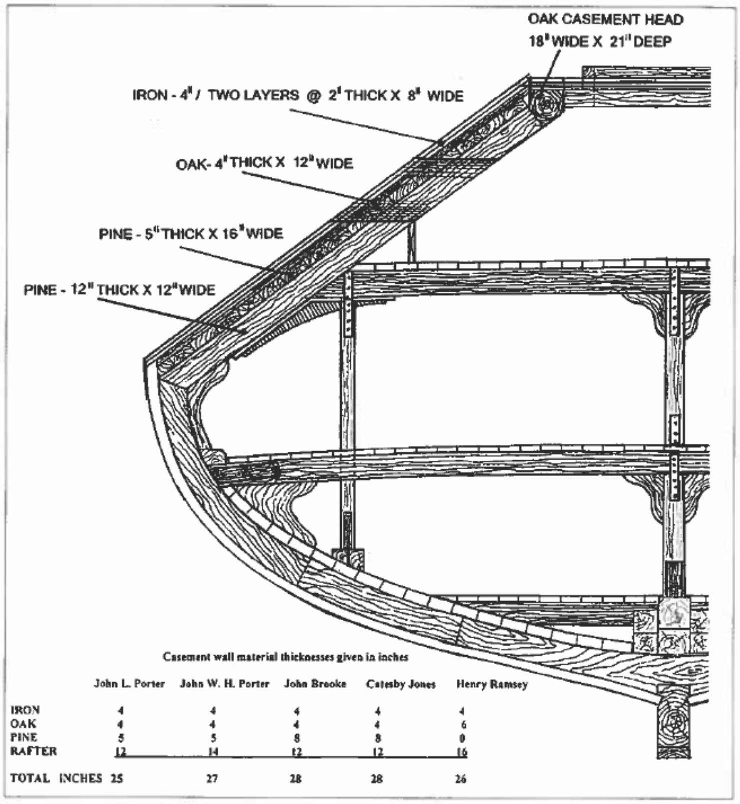


Figure 2: Structure Details of the CSS Virginia, from Ironclad Down by Carl Park



Casement wall material thicknesses given in inches

	John L. Porter	John W. H. Porter	John Brooke	Catesby Jones	Henry Ramsey
IRON	4	4	4	4	4
OAK	4	4	4	4	6
PINE	5	5	8	8	0
RAFTER	12	14	12	12	16
TOTAL INCHES	25	27	28	28	26

Figure 3: Casement Thicknesses. From Ironcad Down, by Carl Park

2.5 Upper Decks

The hull forward and aft of the casement was closed with weather decks. These decks were plated with 1inch think iron.

Atop the aft deck a fantail or platform was installed to protect the propeller and the rudder from enemy shot. The fantail was constructed of 12 inch deep timbers and covered with 1 inch of iron plate.

Breakwaters were installed on the forward weather decks. These were designed to keep water from pushing against the front of the casement and to keep water from getting into the gun ports cut into the forward end of the casement (see Figure 1). It has been assumed that limber holes were cut into the bottom of the breakwaters to allow water to enter and exit freely, meaning that the area is a free flooding space and does not contribute to ship's buoyancy and that the water inside the breakwater does not contribute to free-surface effects on the whole. The breakwaters were made out of stout timbers and I have assumed they were not armored. Most paintings of the *CSS Virginia* do not show the breakwaters, though many contemporary models include them.

2.6 Additional Armor

A band of 1 inch iron plate extended 12 inches below the knuckle line (the line between the *Merrimack's* old hull and the newly installed casement – sometimes called the "eaves of the ship" in the historical literature, but in this report referred to as a knuckle line). Additional armor was added after the Battle of Hampton Roads, so that at the end of the *CSS Virginia's* service life it had a 2 inch armor band extended 3 feet below the knuckle line. For this project the initial configuration of 1 inch iron plate was assumed.

2.7 Machinery

As mentioned previously, one of the reasons for converting the *USS Merrimack* into an ironclad was that the *Merrimack's* existing machinery could be used. The power plant was comprised of 4 Martin vertical tube boilers and 2 back acting engines. The boilers were fired by coal burning furnaces. The engines were connected to a single shaft that rotated a two bladed Griffith's screw measuring 17' – 4" in diameter. The blades were variable pitch, but Isherwood notes that the pitch was typically set at an average of 25 feet, at least for the *Merrimack*. There is no mention of what pitch the *Virginia's* propellers would have operated at that I could find. All in all the engines were capable of delivering 869 hp to the shafting after losses within the engine are taken into account (Isherwood, 1863). Isherwood's horsepower estimates are likely based on nineteenth century parametric equations that linked steam pressure and piston size to horsepower production and other such rules of thumb, and hence may not be wholly accurate.

In calm seas the engines could supposedly propel the ship at a speed of 8.69 knots, but abstracts of the *Merrimack's* logs suggest that without sails set the *Merrimack* averaged 5.25 knots (Isherwood, 1863).

The *Merrimack's* engines were really a second source of propulsion, used for getting in and out of port and allowing the ship some means of maneuver in unfavorable winds; the *Merrimack* sported three masts and could spread 48,757 square feet of canvas (Isherwood, 1863), so it was truly a sailing vessel with auxiliary steam power. Even so, the ship's engines were a disappointment and overhauling them was part of the reason that the *Merrimack* was at Gosport when the Civil War began. The engines were submerged when the ship was scuttled, and part of the conversion effort was restoring them to operability.

2.8 Armament

The *CSS Virginia* (as she was christened on Feb 17, 1862) was armed with 10 guns. The fore and aft ends of the casement sported 7" Brooke Rifles, a banded naval rifle designed by John Mercer Brooke and cast at Tredegar. These were mounted on pivots and could be fired through one of three gun ports run through the casement wall in front of the gun. On the broadside there were two additional Brooke Rifles of 6.4" caliber. The remaining guns along the broadsides were Dahlgren IX's that were captured by the Confederacy with the fall of Gosport Shipyard. All guns were mounted on Marsilly carriages, with the 7" Brooke Rifles having additional mounts below the carriage that allowed the gun to swivel.

Both Brooke Rifles and Dahlgren IX's were capable of firing explosive shells or solid shot, referred to at the time as "bolts". Because the primary mission of the Virginia was going to be breaking the Union Blockade of Hampton Roads by attacking its wooden ships, Brooke began to assemble magazines made up almost exclusively of shells, though there were some bolts reserved for two Dahlgrens that would fire hot shot, which were bolts heated in a furnace below decks, used with the intention of setting wooden ships ablaze.

Some amount of small arms (rifles, pistols, swords) would have also been onboard.

There is some mention in the historic literature on the *CSS Virginia* that the ship had small boat howitzers on its upper deck, but most believe that these guns were never installed. For this analysis it is assumed that they were not present.

Finally, the *CSS Virginia* was equipped with an iron ram fitted to the bow, a throwback to the days of galley warfare practiced before the age of sail. It was a late addition to the ship, insisted upon by Mallory and grudgingly put in place by Porter upon orders from Lieutenant Brooke.

2.9 Loads (in brief)

The *CSS Virginia* carried 150 tons of coal and 18,200 lbs (8.125 tons) of powder. Based on the charge required to propel a shell of approximately 12 – 13 lbs it can be estimated that the ship carried about 59 LT of ammunition for its guns.

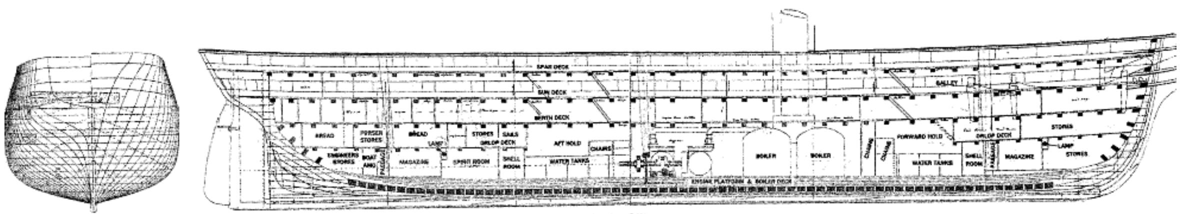
There is no mention in the existing records of the amount of provisions stored on the ship. The crew was living on board the ship once its construction was mostly complete, and the ship's galleys would have been serving meals. The *CSS Virginia* was intended only make short sallies from port to either attack or move to another port, and so it's reasonable to assume that the ship was not taking on large amounts of provisions, perhaps at most enough for a few weeks.

A more detailed discussion of loads is presented in Section 3.7 of this report, in conjunction with discussion of the weight analysis process.

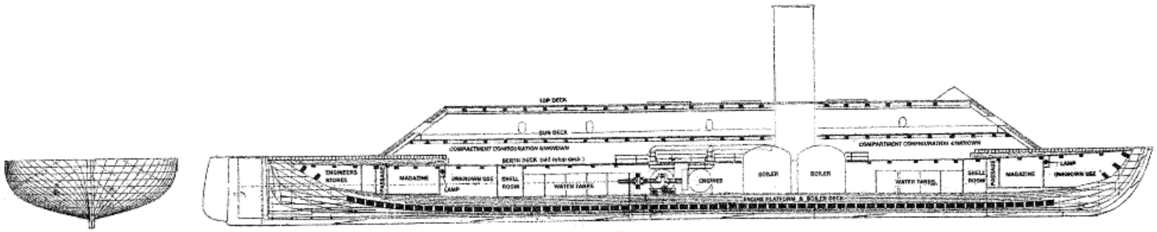
2.10 Internal Arrangements and Tankage

Aside from the gun deck layout and the position of the engines little is known about the internal arrangement of *CSS Virginia* once the conversion was complete. John Porter alludes to challenges inherent in finishing the arrangements but no drawings or descriptions exist of how the compartments within the ship were laid out.

Where necessary for loading calculations I have taken Park's assumption that the lower deck arrangements are similar to that of the *Merrimack* (see Figure 4), and these are the there are areas of the ship that would have housed the magazines, stores, and of course is where the engines, boilers, and coal was all located.



USS MERRIMACK
As built



CSS VIRGINIA
Conversion

Figure 4: Notional Internal Arrangement as Shown in Ironclad Down, Based on the Internal Arrangement of the *USS Merrimack*. Composite by Carl Park from Archival Prints

The berth deck likely provided accommodations for officers and crew, and in accordance with naval tradition at the time the officer's quarters would have been located aft and the crew's area forward. Officers would have been provided cabins separated by joiner bulkheads or canvas dividers, and the crew likely would have slept in hammocks strung from the deck above. There was probably also a sick bay and other spaces to administer the ship, and there was certainly a galley, but it's impossible to know exactly where these spaces were located[5].

There would have been little tankage on board the *Virginia*, though a contemporary cutaway of the *USS Merrimack* does show tanks fore and aft of the engines and Park has left them in his notional arrangement shown in Figure 4. At first I believed that these might be feed water tanks for the boilers, but numerous sources suggest that when the *USS Merrimack's* boilers were built in the 1850's feed water was usually ingested directly from the sea[6]. In the case of the *Virginia* is possible that they were filled with water deemed fresh or potable before the ship was launched, but that detail of her construction is unknown. Still, the tanks shown in the arrangement were probably not used as feed water tanks, as that was not the state of the art at the time.

The tanks aboard the *Virginia* are possibly water tanks used to store water. Online ship modeling forums suggest that the British began using the water tanks aboard their vessels towards the end of the Napoleonic Wars or shortly thereafter, and in his 1869 Treatise on Naval Architecture and Shipbuilding, US Navy Commander Richard Meade describes the use of metal water tanks for storage. He does state that such tanks had only been recently employed on US Naval Vessels, but in terms of naval history "recent" is a relative term, and it is therefore possible that these types of water tanks were installed on the *USS Merrimack* and in turn found use on the *CSS Virginia*. It is possible as well that they depict coal scuttles or some other stores container, but for the purposes of this analysis it was assumed that these tanks are for water.

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[5] The location of the galley and the pipe that would allow smoke to escape through the upper deck is a matter of intense speculation amongst historians.

[6] The "Marine Steam-Engine" from 1867 by Thomas J. Main and Thomas Brown notes that marine boilers were full of sea water, and describes hand pumps that could either allow water into the boiler or take water out of the boiler through a sea connection. There were feed pumps aboard that supplied water from the engine condensers to the boiler, but eventually feed water had to be pulled in from the sea to make up steam losses from blowing off the boiler.

2.11 Construction Completion and Service Life

By February 1862 the *CSS Virginia* was complete enough to be floated in the dry dock. This was not the official launching of the ship but rather a test to determine the current draft, list, and trim of the vessel and ensure that the wooden hull would bear the weight of the casement. Few who watched the ship's construction had an encouraging word for John Porter as they watched it being built. He wrote later that "Hundreds – I may say thousands – asserted she would never float. Some say she would turn bottom side up….public opinion generally around here said she would never come out of the dock."

So naturally, contrary to all expert opinion, when the ship first floated off in the dock it was not too heavy to float but rather floated all too well, lighter than expected. Porter is generally blamed for this. Most believe he must have made an error in his calculations, either neglecting the full weight of the missing spars and masts or not correctly accounting for the additional buoyancy added to the ship by raising the cut line to 20' at the propeller. However, given the difficulties of weight estimation even with today's technology, coupled with the extreme stress of converting the *Merrimack* in so little time for which Porter was wholly responsible for executing, this naval architect is willing to forgive him.

In any case, the waterline was approximately 19' above the bottom of the keel, which is the location of the knuckle line between the ship's hull and the armored casement. In the original concept this knuckle was to be two feet below the waterline. At the time of first float the *CSS Virginia* was not fully complete; work was still being done on the casement and much of the ship's loads (including guns, ammunition, and coal) had yet to be loaded, but Porter knew that the additional weight would not be enough to submerge the ship to the desired waterline. Additional ballast was therefore added to the ship in the form of pig iron placed on the fore and aft weather decks and, according to Nelson, scrap iron being placed in the ship's spirit room. This would ensure that the ship had drafts of 21' and 22' above the bottom of the keel fore and aft, respectively, and that the knuckle was at least two feet below the waterline.

The ship was officially launched on February 17, 1862, and went to a pier side berth to complete outfitting. By the beginning of March the ship was ready for service though had not been through any sea trials. Time was of the essence, and accordingly the first time the *CSS Virginia* steamed into Hampton Roads it was to do battle with the Union blockading fleet.

The battle was a two day affair. On March 8th the *Virginia* first engaged the *USS Congress*, disabling her with close range shell and hot shot and continuing on to the *USS Cumberland*. The *USS Cumberland* was rammed by the *Virginia* while both ships fired their guns furiously at point blank range. The *Virginia* lost her ram in this engagement and most accounts state that the structural damage from ramming the *Cumberland* caused a small leak in the hull up forward. After the *Cumberland* sank the *Virginia* turned its attention back to the *Congress* and set it afire after Union shore batteries hindered an attempt by the *Congress* to surrender. As the day ended the *Virginia* moved towards the grounded *USS Minnesota*, but darkness and a lowering tide forced the *Virginia* back to a friendly berth in Norfolk.

On the night of March 8th the *USS Monitor* fortuitously arrived on scene, and on March 9th the *CSS Virginia* and *USS Monitor* met in Hampton Roads and, for the better part of four hours, the two ships battered each other with neither gaining a clear advantage. The *Monitor* returned to the *Minnesota's* side and the *Virginia*, with crew exhausted and ammunition running low, returned to Sewell's Point.

The *Virginia* would never get the chance to re-engage with its nemesis. It had moderate damage to the iron plates forming the casemate, and any cracks in the hull that had been sustained from ramming the *Cumberland* had to be repaired. It was placed into dry dock and in addition to repairs the iron band around the ship's hull was reinforced with additional iron plating. The modifications increased the mean draft of the *CSS Virginia* to about 23 feet above the bottom of the keel.

It was ready for sea again on April 4th, and over the coming weeks would play a game of cat and mouse with the Union ironclad, still on station. Additional Union ironclad vessels had arrived, such as the *USS Galena* and the *USS Naugatuck*, and the new *Virginia* commander, Josiah Tattnall, was worried about being outmatched or running into engine trouble and being captured or sunk in the midst of numerically superior forces. Still, he tried his best to draw the *Monitor* out into single ship combat, but the *Monitor's* Captain exercised great discipline in never taking the bait, much to the chagrin of the *Monitor's* crew. The stalemate was most beneficial to the Union, as the US Navy maintained control over the York River and Chesapeake Bay, and the *CSS Virginia* could do nothing to prevent General George McClelland from landing 105,000 Union soldiers at Fort Monroe and beginning the Peninsular Campaign.

By May 10th Sewell's Point was in Union hands[7] and the Confederate evacuation of Norfolk and Portsmouth was well underway. A signal that should have alerted the Virginia to the Confederate retreat had never been fired, and the officers and crew of the Virginia realized that they were alone on the Chesapeake Bay. The *Virginia* had to take action of some kind or it would certainly fall into Union hands or be attacked the *Monitor* and its cohorts.

Tattnall decided to take the ship up the James River to participate in the defense of Richmond as a floating battery, though he also considered attempting to take the *Virginia* to Savannah, GA, or valiantly sallying forth to engage the Union Fleet on his own, going out in style, which likely meant sinking and capture by Union Forces, if not death for him and most of his crew. Sailing up the James was deemed the most practical and useful to the overall Confederate war effort. However, in order to do so the ship's draft would have to be lightened to 18 feet from the bottom of the keel. This would allow it to stay in shallower water, out of range of Union artillery on the opposite side of Hampton Roads, and would allow for it to pass over Harrison's Bar, a sandbar blocking the entrance to the River.

Since the battle on March 8 – 9, the ship had been modified to have more armor at the water line and was now even heavier than before, perhaps at a draft of 23 feet fore and aft. To lighten the ship the crew spent the night of 10/11 May throwing hard ballast, structure, practically anything but guns and ammunition overboard. They achieved a draft reduction of three feet before the pilots informed the crew and Tattnall that it was a hopeless effort; winds blowing out of the west had pushed water out of Hampton Roads and lowered the water depth, meaning the ship had to achieve a draft of less than 18 feet. The pilots knew the cause was hopeless. Unfortunately the draft reduction efforts had left the ship sitting too high in the water to fight effectively, with two feet of the lower hull exposed, as well as the rudder and propeller.

Tattnall, furious and accusing the pilots of cowardice, of manipulating him and the crew to put the ship in a condition where it could no longer fight, had no choice but to order the *CSS Virginia* destroyed and the crew evacuated so they could rejoin the Confederate war effort[8]. Accordingly, before dawn on May 11th, the day that Union Armies would formally occupy Norfolk, the ship was set afire and exploded when the flames reached the powder magazine. The *CSS Virginia's* short career had ended.

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[7] This was a curious event in which President Lincoln himself, in Hampton Roads to spur McClellan on to Richmond and with the help of a pilot, located an ideal place to make a landing at Willoughby's Point after his Secretary of Treasury Salmon P. Chase had led a brief military expedition and found it unopposed.

[8] A number of the crew actually engaged the *Monitor* again, this time firing artillery from land, at the Battle of Drewry's Bluff.

3 ANALYSIS PROCESS

The purpose of this thesis was to take what is known about the *CSS Virginia* and develop a model using modern naval architecture software, run analyses using that model, and gain some insight into its naval architecture characteristics, specifically in regards to hydrostatics, sea keeping, and resistance.

The overall process is relatively straight forward. A geometric model of the *CSS Virginia* was made using Paramarine software. Based on the geometric model it was possible to estimate the ship's displacement and LCB at its recorded drafts prior to the Battle of Hampton Roads.

That information aided a weight analysis whose true purpose was to estimate the VCG of the ship. The weight analysis also allowed for total weight moments of inertia and radii of gyration to be estimated from the weight distributions.

With the model, weights, and gyration radii as an input, a naval architecture analysis of hydrostatics and sea keeping characteristics was completed using Paramarine. Part of the sea keeping analysis was gauging the *Virginia*'s effectiveness in the Chesapeake Bay and in an open ocean environment with regards to sea sickness and the frequency at which the gun ports would have been wetted due to ship motions and sea conditions.

Information from the Paramarine geometry model was used as input in a NAVCAD environment to generate a resistance prediction.

The analysis was done keeping in mind that the results would be used to see if the *CSS Virginia* could have embarked on different missions aside from blockade busting in Hampton Roads. The sea keeping mission effectiveness analysis was coupled with information from the resistance data to assess if it was possible for the story of the *CSS Virginia* to have an alternative ending.

3.1 Important Assumptions

Many assumptions were made over the course of the analysis, notably in the regards to the weight estimate, which is largely based on assumptions regarding how the *Virginia* was built and the weights of the various items it carried as loads. Those assumptions are stated in the discussions of different aspects of the weight analysis.

However, there are some assumptions that have an impact beyond the weight analysis that should be stated at the outset.

1. It is assumed that the reciprocal density of water is 35.5 ft^3/LT. The *CSS Virginia* was designed for and spent all of its time in Hampton Roads, where the density varies between saltwater and freshwater. Because salinity data from 1862 is not readily available, 35.5 ft^3/LT (an average of reciprocal weight densities for salt and fresh water) is assumed.

2. Hull deflection is not accounted for in this analysis. This is a notable assumption, as many wooden vessels were subject to significant hogging when launched; eleven inches over a keel length less than 200 feet was not atypical (Kery, 2015). The structural characteristics of the *CSS Virginia* were held outside the scope of the analysis, but of course the information provided by the structural analysis with regards to hogging or sagging may alter some of the conclusions reached elsewhere in this report. Porter did have structural concerns for the vessel when weight was added to the ship after it floated too high in the water (Park, 2007), and it would have been interesting to see how well founded his concerns were.

3. The densities of the materials were undoubtedly variable to some degree. Not every plate cast at Tredegar was the same, not every piece of pine or oak has exactly the same density. However, for the purposes of this report, it is assumed that that is the case. The density of iron is taken to be 490 lb/ft^3, the density of oak is taken to be 46 lb/ft^3, and the density of yellow pine is assumed at 30 lb/ft^3.

4. Port/stbd symmetry is assumed. Transverse centers of gravity were not tracked in the weight analysis, and from the outset it is assumed that the TCG of the *Virginia* is on the CL of the ship.

5. It is assumed that the hull and the casement are essentially solid, i.e. with no spaces between frames. Isherwood (1863) reports that the *Merrimack* was solid to the turn of the bilge, with frames butting up against each other leaving no space between them. There was space between the frames above the bilge in the *Merrimack,* and during the conversion *Merrimack* had spaces between the frames but these

were filled in with additional wood framing to provide a solid foundation for the casement. This method of supporting the casement is postulated in Ironclad Down.

6. Free Surface Effects are assumed negligible. The free surface effect of the supposed water tanks (see Section 2.10, 3.7.8, and Appendix E) is too small to effect the vessel's stability. It is assumed that the breakwaters have limber holes in place to allow water to drain from the area between them and the casement, in essence making it a free flooding space that does not act as a free surface. As such, free surface effects on stability are not accounted for in this analysis.

7. As can be seen in Figure 1, the *Virginia* was outfitted with boats, stanchions, and other accoutrements on the outside of the hull. Most of these items were shot away relatively early on the first day of the Battle of Hampton roads, and were not accounted explicitly for in the weight estimate. Their weight did contribute to the initial drafts at the outset of the battle, so these items would be part of the unaccounted for weight left un-estimated due mostly to lack of information.

8. It is assumed that the *CSS Virginia* operated at a speed of 6 knots. The highest speed allotted to the craft was 8 or 9 knots, estimated by the pilots as they passed the shore while sailing towards Hampton Roads down the Elizabeth River on March 8, 1862. The tender pilots that made up part of the *Virginia's* flotilla later agreed that the ship made 7 knots (Nelson, 2004). Most observers put the speed of the *Virginia* at a far more modest 4 to 5 knots (Besse, 1996). It was decided to choose a middle path, and where a service speed was required over the course of analysis 6 knots was used.

3.2 Selection of Software

Paramarine software was used for two reasons. One was that it was readily available at Newport News Shipbuilding, whose department of Naval Architecture and Weight Engineering allowed its use for academic purposes. The second was that the parametric features of the software, the ability to make changes and have them reflect through other aspects of the model, was very attractive and typically worked quite well as new elements were added into the analysis.

When it came to making an estimate on the overall resistance of the *Virginia* the Paramarine suite produced EHP estimates that were believed to be overestimates based on comparison with a basic ITTC skin friction resistance calculation. NAVCAD software was used instead to estimate the ship's resistance, based on inputs from the Paramarine geometry model. Even then, it was realized that the antiquated nature of the hull form and the unusual aspects of its design (a rounded casement sitting on top of a completely submerged monohull) meant that any resistance analysis using powering prediction methods would only generate a gross approximation of what the required EHP may have been.

3.3 Geometric Modeling

3.3.1 Modeling the Lower Hull

Before computer modeling could begin a set of lines had to be obtained. Despite the wealth of books written on the *Virginia's* history there is actually not a great deal of information on the *Virginia* from a naval architecture perspective in the form of drawings and detailed specifications, and what information is available is occasionally contradictory as it comes from different sources. There are few original drawings in existence and those show a profile view and midship section only, and have few dimensions to work off of. Part of the reason may be the nature of the work itself – converting an existing ship under time pressure doesn't leave much time for detailed drawings.

After some preliminary research there were three options for obtaining a set of lines:

- One was to use a set of lines produced by Besse in his book C.S. Ironclad Virginia and U.S. Ironclad Monitor, with Data and References for Scale Models, readily available for purchase at the Mariner's Museum in Newport News, Virginia. The lines were initially produced in the 1930's, and have been updated by the Museum in two additional editions. They feature a profile view, a plan view, and section curves for 12 sections along the body of the hull. The profile and plan views from these lines can be seen in Figure 1, with midships set at Station 6. The lines were intended to be used for building models. There is a scale running along the bottom showing distance from the stem, but inspection shows that this scale is somewhat inconsistent along the length of the vessel.

- Second, Ironclad Down by Carl Park shows a lines plan he developed from a *USS Merrimac* lines plan obtained from the national archives, with the casement of the *CSS Virginia* imposed on top of the archival *Merrimack* lines. There is no dimensioning or scaling, though the drawing certainly appears to be to scale. Park's lines can be seen in Figure 4.

- A third option was to duplicate Park's effort by developing a lines plan of my own with help from the National Archives.

Besse's lines were used. These were readily available and, while they have fewer sections than Park's lines, they do have other details that Park's lines lack. Park notes in his book that there is nothing necessarily wrong with Besse's lines for the purpose of building models. It is also not likely that using different lines would alter the results of the analysis greatly.

Besse's lines were scanned into a PDF and that PDF was imported into AutoCAD as a PDF underlay. Polyline tracings were then made of the section lines, as shown in Figure 5.

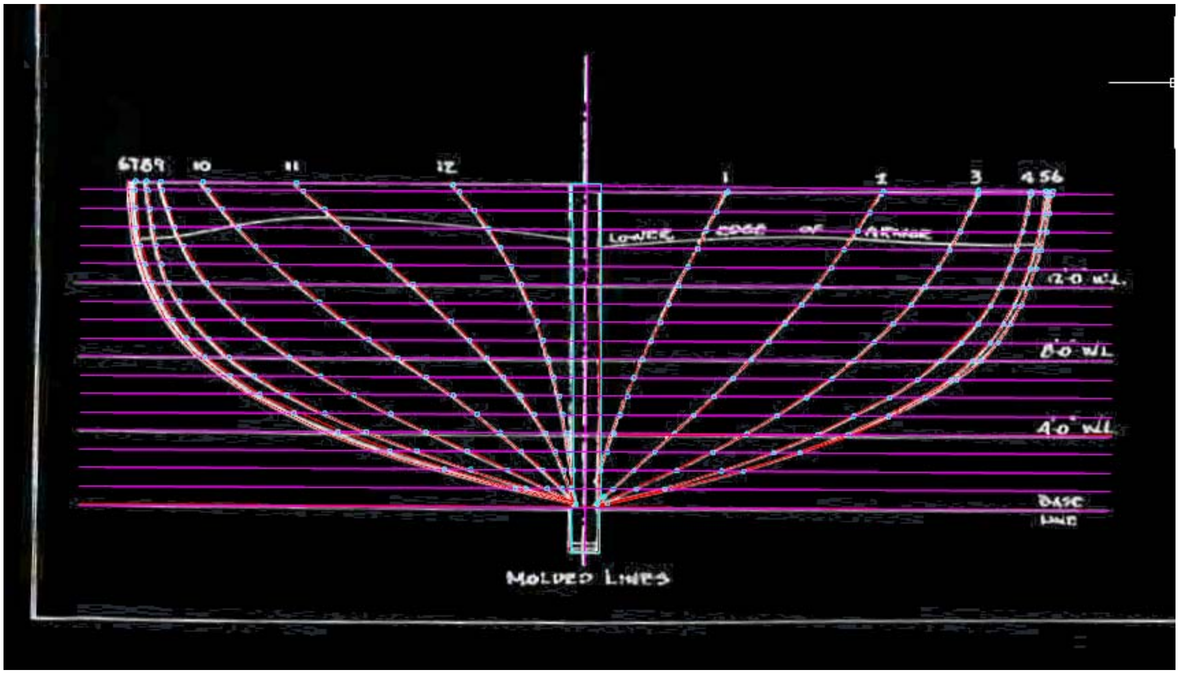

Figure 5: Polyline Tracing of Besse's Section Lines

The lines were then scaled and oriented properly using 3D AutoCAD so that the polylines could be imported into Paramarine as a .dxf file. Paramarine works in metric units (though it will take inputs and display outputs in US units) and so the lines had to be scaled based on metric dimensions. Besse's lines were made in a scale of 1/16" = 1', and the Paramarine model was made in full scale. A scaling factor of 4.8768 was found to be appropriate. The Polylines for the forward sections are shown in Figure 6 ready to be exported into Paramarine. A similar process was followed for the aft section polylines.

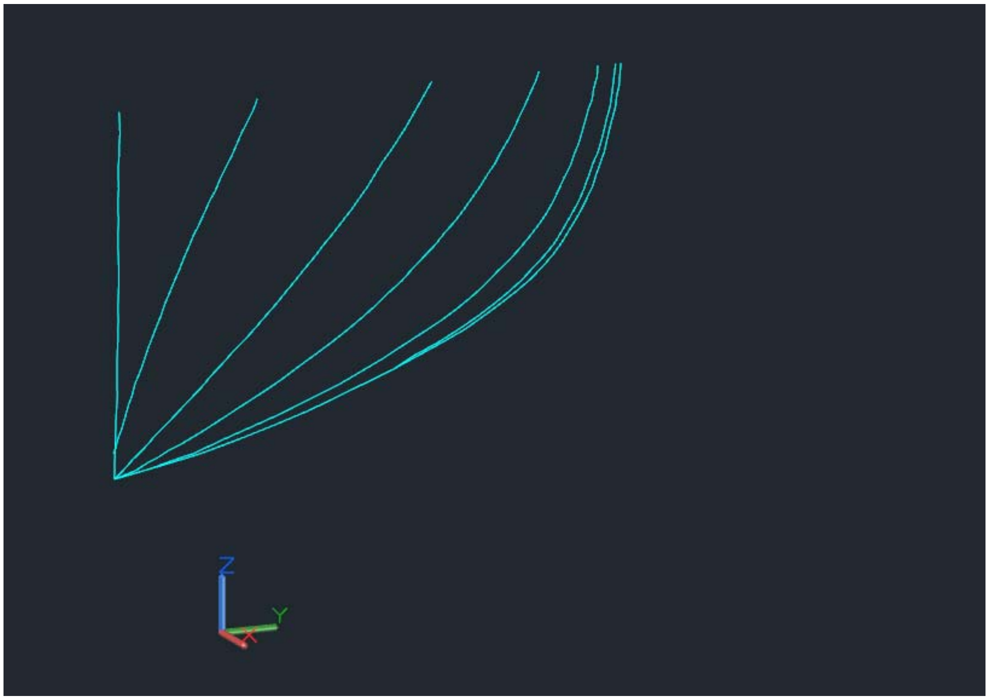

Figure 6: Fwd Section Lines Ready for Import into Paramarine

After the polylines were exported into Paramarine, X-T Curves for the section lines were made using the polylines as guides. X-T Curves are curves that Paramarine uses to build hull surfaces and solids. They are parametric and result in smooth curves, though chines and straight lines can also be modeled based on commands input by the user. After all the X-T Section Curves were made using the polylines as guides, they were spread out longitudinally based on Besse's section locations. The results are shown in Figure 7.

Figure 7: X-T Curves Spaced Longitudinally in Paramarine

The keel geometry was then added to the model in the same way. As can be seen in Figure 5, the upper part of the keel was connected to the bottom of each section. This is the "rabbet line", the point where the external planking and plates are joined to the keel. The rabbet line was established as the Baseline for this model, and for this analysis the two terms should be considered interchangeable, though Baseline is used more often. The state of the model after the keel geometry was in place can be seen in Figure 8.

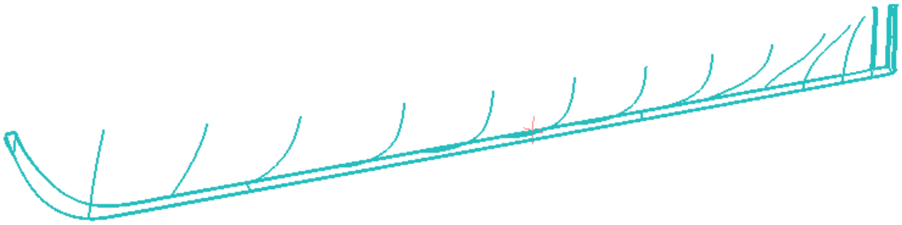

Figure 8: X-T Section Curves with Keel Geometry

The knuckle line, or the line where the lower hull meets the casement, was then established by drawing an additional X-T curve through the upper point of all the sections. Waterlines were added to the hull to create a mesh to better define the hull surface.

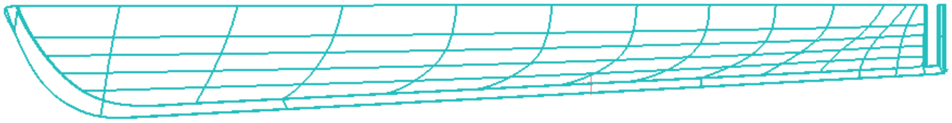

Figure 9: Hull Geometry with Knuckle Line

With all the curves defined it was now possible to make surfaces. Paramarine develops X-T Surfaces from the X-T Curves where the user defines the internal curves, the external boundary curves, and the surfacing methodology. While developing the surfaces for the *CSS Virginia* model, the surfacing method was selected that developed the best surface. For most flat surfaces (the keel, decks) a "Coons Linear Bezier" option was selected. For sections with more shape (such as the hull itself) a "Cubic Bezier" option was sometimes used.

Figure 10 shows the model shown from Figure 9 with an X-T Surface defined by the section lines, knuckle line, and rabbet line.

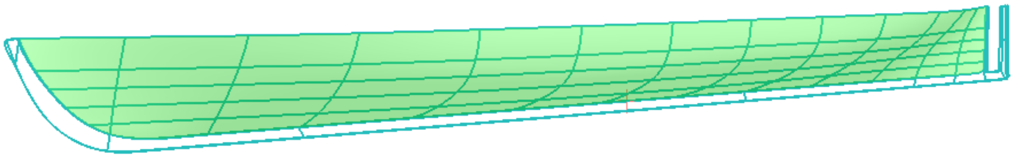

Figure 10: Lower Hull Geometry with Hull Surface Modeled

To derive solids, surfaces were knitted together into sheets and those sheets were turned into solids. Below is a patch sheet consisting of the upper deck, keel, and port side hull.

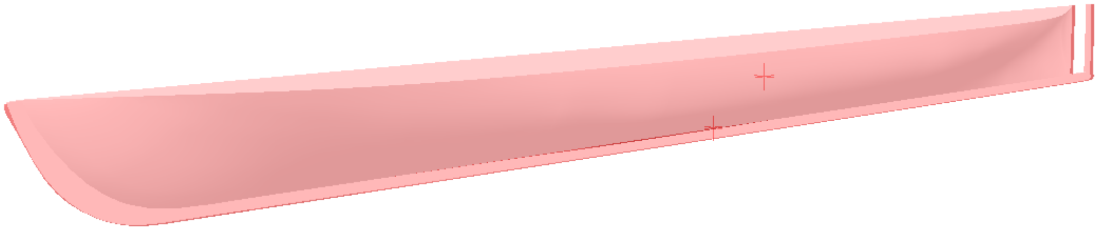

Figure 11: Patch Sheet Constructed from X-T Surfaces

Using the patch sheets shown in Figure 11, a solid was made by copying the patches and mirroring them to get a representation of the 3-D hull made by 2-D patches. This makes use of the assumption that the hull is symmetric about the CL.

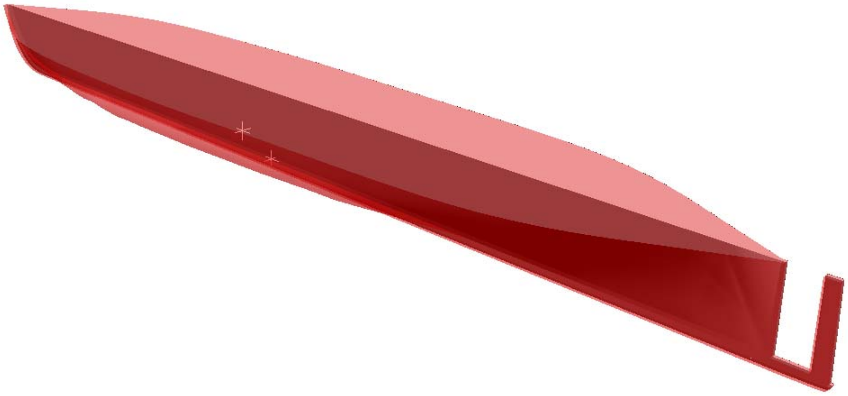

Figure 12: Mirrored Patch Sheets

From those patches finally a solid hull could be made, as shown in the Figure 13.

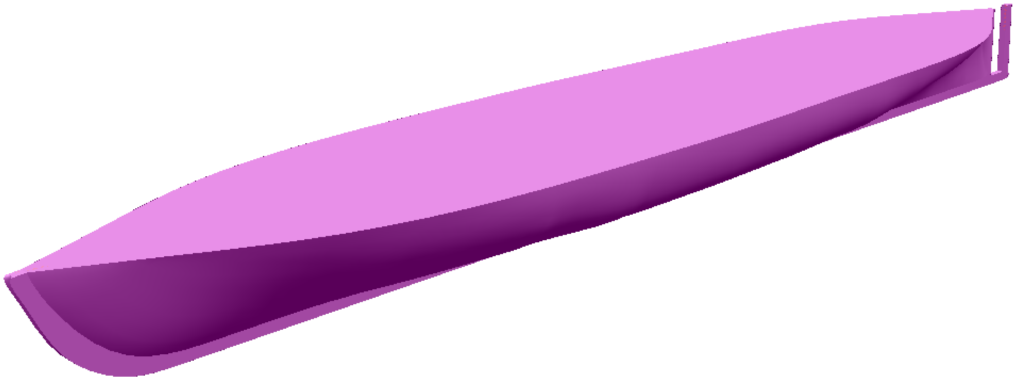

Figure 13: Solid Model of *CSS Virginia* Lower Hull

To make a brief check for hull fairness, polylines were created based on the solid lower hull geometry by essentially slicing the geometery into section, buttock, and waterlines. The results can be seen in Figures 14 – 17, and indicate that the resultant hull form modeled as described above is adequately fair.

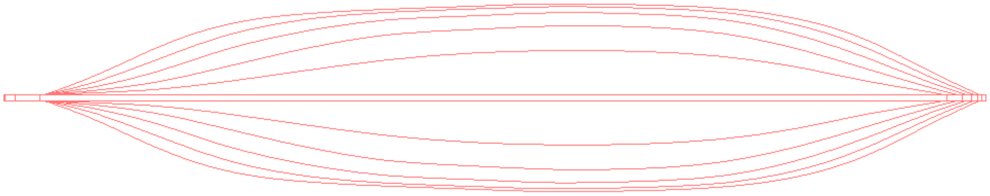

Figure 14: Waterlines for *CSS Virginia* Lower Hull, 3 ft increments

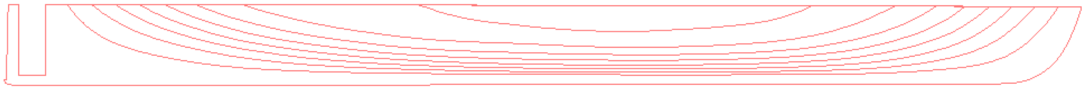

Figure 15: Buttock Lines for *CSS Virginia*, Lower Hull, 3 ft Increments

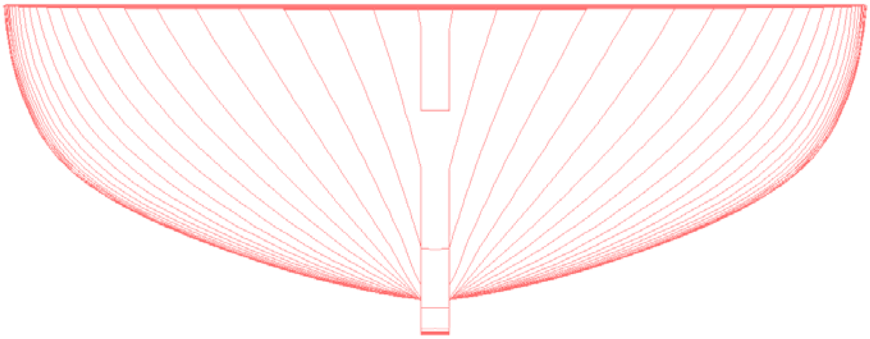

Figure 16: Fwd Section Lines for *CSS Virginia*, Lower Hull, on 5 ft Increments

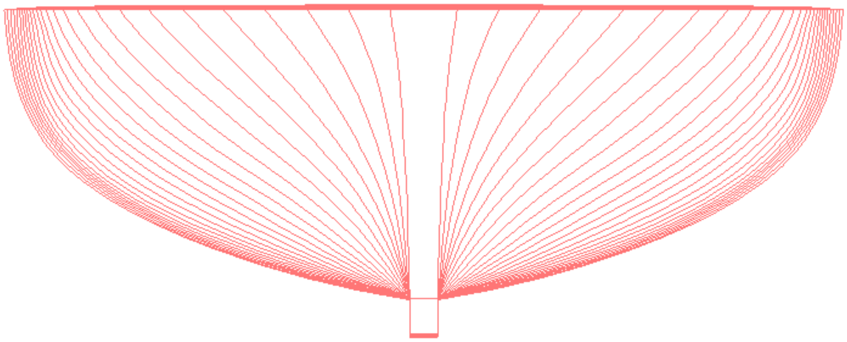

Figure 17: Aft Section Lines for *CSS Virginia*, Lower Hull on 5 ft Increments

3.3.2 Modeling the Casement

To model the casement a similar process was followed, except that instead of starting with a 2-D representation of hull sections, a 3-D panel polyline "mesh" was made in AutoCAD based both on input from Besse's lines but also some information from Ironclad Down. The mesh can be seen in Figure 18:

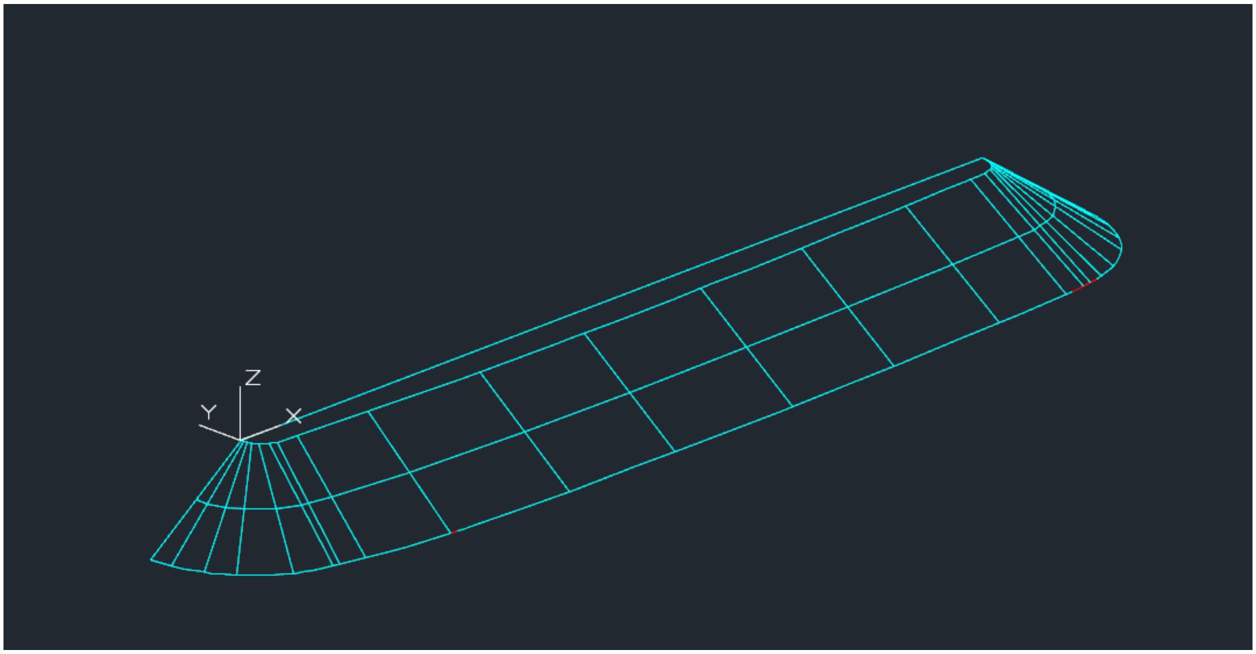

Figure 18: AutoCAD "mesh" of CSS Virginia Casement

The frame model shown in the Figure 18 was exported into Paramarine as a .dxf file and was used to guide the development of X-T Curves, in a similar manner to what was done for the section lines on the lower hull. In this case, it was important to ensure that the sides of the casement connected with the sections and the knuckle lines. Figure 19 shows the X-T Curves representing the casement and the lower hull.

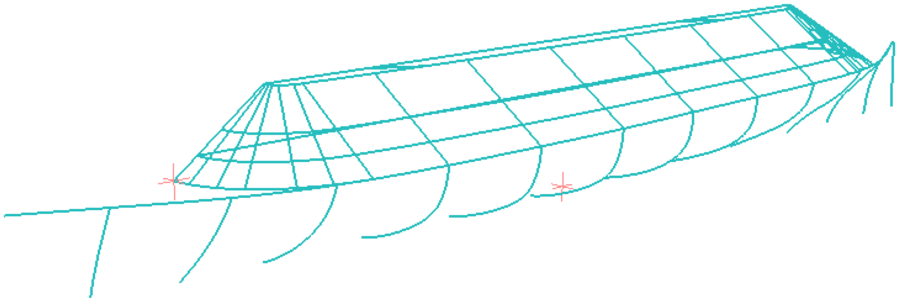

Figure 19: Modeling the *CSS Virginia* Casement

With the setting of X-T Curves there was some deviation from the previous process of tracing imported polylines exactly, as was done for the section lines. Section curves as shown in Figure 7 could be considered nearly exact tracings of Besse's lines, but the imported polylines for the casement were considered more like guidelines, and some deviation from the imported lines was necessary to conform the casement to its reported geometry.

This is particularly true of the slope of the casement's sides. When the lines shown in Figure 18 were initially exported into Paramarine and joined to the hull lines (Figure 19), the geometry of the resulting casement model was analyzed. The analysis showed that the casement had an angle forward of 35.5 degrees and aft of 34.2 degrees. The decrease in angle was due to the fact that Besse's line appear to assume that the upper deck was on a level horizontal plane located about 30'-9" above the baseline. The knuckle line varies from 19' to 20' above the bottom of the keel. Park and Besse both show that the keel gets somewhat thicker as it moves aft, but there is still variability in the location of the knuckle line above the baseline. Holding the upper deck constant would mean that the angle of the casement actually decreases going forward to aft, as was indicated by the assessment of the Paramarine geometry.

A section view in Park's book suggests that the upper deck may have been held at a constant of 13.5' above the knuckle line, meaning that the upper deck would have been sloped as was the knuckle line. When this geometry was used the angles improved: the forward casement angle was 35.5 degrees and aft it decreased to 35.1 degrees.

This is an improvement. However, the historical narrative of the *CSS Virginia* suggests that the angle of the casement was deemed very important for the deflecting of shells (Quarstein, 2012). To honor that in the model it was decided to find the horizontal level of the upper deck such that the forward and aft angles of the casement averaged 36 degrees when rounded to the nearest whole number. Placing the upper deck at a height of 31.112 feet above baseline was found to achieve an average fore and aft casement angle of 35.66 degrees. This was deemed to be better than what was achieved with the assumptions about the levelness of the upper deck that is implicit in Besse's or Park's lines, so the upper deck height of 31.11 feet constant above BL was accepted.

It is noted, of course, that with modern technology and computer modeling it is tempting to get down into such details. It is difficult to know exactly what the final form of the casement was, and what angle ultimately it ended up at. Porter himself stated after the *Virginia* was built that the casement was on a 35 degree slope (Park, 2007). Additionally, it's hard to believe that an upper deck level of 31'-1.344" above the baseline could be held with great precision in 1862. Thankfully, the difference between a casement of 34, 35, or 36 degrees should not matter much for the purposes of this analysis. This example stands as a warning of the kinds of pitfalls inherent in using modern methods to analyze historical vessels; much time can be spent diving into details that are impossible to know with great precision, and sometimes those details don't really matter in the grand scheme of an analysis, particularly given large assumptions that must be made elsewhere. One must often accept that we see through a mirror darkly when doing this sort of historical/technical analysis, make a decision, and move on.

Using a similar process to that described previously to get the lower hull solids, the solid casement was modeled as a solid joined to the lower hull and the vast majority of modeling was complete as shown in Figure 20.

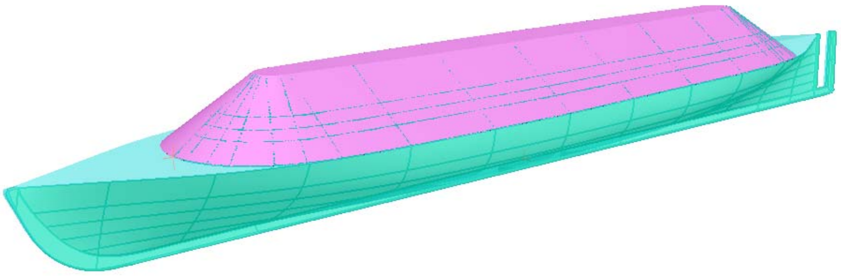

Figure 20: Casement and Lower Hull Solid Models

3.3.3 Modeling Appendages

With the main body of the ship modeled appendages were then added. The *CSS Virginia* featured bulwarks on the fwd deck, designed to keep water from sloshing up against the forward casement and into the hull through the gun ports for the forward swivel gun[9]. The bulwarks were relatively simple, just wooden courses made to form a "V" to pierce the water's surface and deflect wave action (Park), so they were modeled directly from X-T Curves in Paramarine. The ship's rudder and the aft fairing were made using the process described above for the hull and the casement, staring with polylines traced from Besse's work and moving through X-T Curves, X-T Surfaces, surface patches, and finally solids.

The pilot house was not modeled, as it is well above the waterline and does not factor into the ship's naval architecture characteristics. The weight of the pilot house was included in the weight analysis of the *Virginia*, which

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[9] Note that for this project gun ports going through the casement were not modeled for the sake of simplicity.

will be taken up in Section 3.7. For form's sake a smokestack was added the model by drawing a cylinder and attaching it in the proper place, but it to does not factor in the model's naval architecture characteristics, and was not selected as part of any of the analysis geometry.

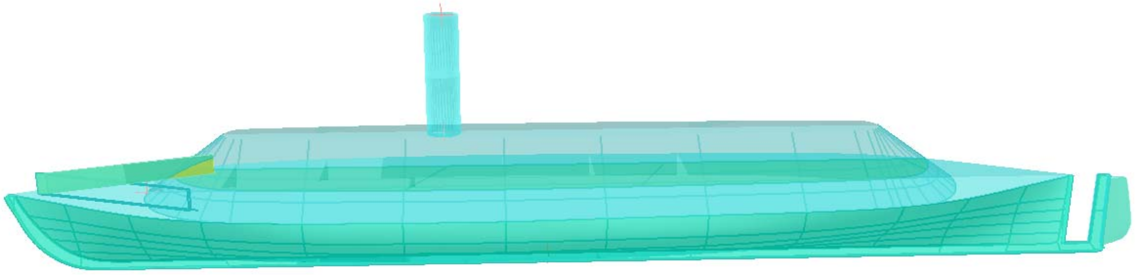

Figure 21: Final Paramarine Model of the *CSS Virginia*

3.4 Selection of Ship's Reference Points

Selection of the forward and aft perpendiculars and the placement of draft marks was done somewhat arbitrarily. With the bulk of the hull submerged it was decided to place perpendiculars that covered the length of the main hull overall. Accordingly, the forward perpendicular is placed at the very front of the stem at the baseline (extended), and the aft perpendicular is placed at the point roughly where the aft end of the hull connects with the keel, again along the baseline. Because the forward perpendicular is not really a perpendicular in the normal surface ship sense, it is referred to in the course of this analysis as the Forward Reference Point (FRP). Midships is taken to be Section 6 as located in Figure 1, about 127 feet aft of the FRP (127.008 feet is where it ended up in the model, to be exact). This is where the maximum section area of the ship is located, but as it is not exactly the midpoint between the perpendiculars it is not really a midship location in the generally approved technical sense. It did help place the sections in the Paramarine environment, and so it was adopted.

Locations for forward and aft marks are in the same locations longitudinally, but begin at the bottom of the keel so that references to drafts by marks are from the bottom of the keel rather than from baseline. It is important to note that the keel actually varies in depth. The bottom of the draft marks forward start -1.86 feet below baseline, and the draft marks for the aft end start -2.24 feet below baseline. It is noted that there is no reference to where the drafts may actually have been read from on the *CSS Virginia*.

Reference points are shown in Figure 22.

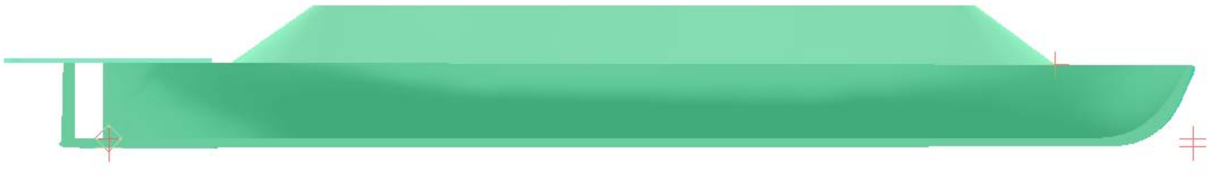

Figure 22: Ship's Reference Points. The Perpendiculars are referenced from the upper hash marks, and the Marks are referenced from the lower hash marks

3.5 Comparison of Model Characteristics with Published Characteristics

Table 1 compares the principle characteristics of the *CSS Virginia* hull form as modeled in Paramarine and as shown in the historical literature consulted for this thesis, the "Established Values". The Established Values shown in Table 1 come from Besse except for length overall, which was ventured in Nelson's Reign of Iron.

Characteristic	**Paramarine Value**	**Established Value**	**% Difference from Established Value**
Length to Aft end of Rudder Stock	265.33 feet	262.75 feet	0.98 %
Length Over all	278.80 feet	278 feet	0.29 %
Beam	51.08 feet	51.17 feet	-0.18%
Tonnage		3200 Tons	NA
Displacement	3869.37 LT[10]		NA

Table 1: Comparison of Paramarine Geometry with Established Geometry

The Tonnage measurement of 3200 Tons was the tonnage for the *CSS Virginia* as stated in the *Official Records of the Union and Confederate Navies*; it is also the tonnage listed for the *USS Merrimack* when it was commissioned (Besse, 1996). The tonnage measurement is a gross tonnage measurement of some kind, not a displacement.

Table 1 shows that the geometry of the model in Paramarine conforms very well to the overall dimensions of the vessel as established in the historical literature. It is also worth noting Besse states that any dimensions for the *CSS Virginia* were probably working figures and should not necessarily be followed to closely. But, as there is nothing else to compare with, the accepted geometry is all that one can work with.

The length to the aft end of the rudder stock, a typical length measurement of the time, has the greatest variance between the Paramarine Geometry and the established values. The Paramarine geometry was built based on Besse's line drawings and, as previously noted, there are some problems with the scaling in Besse's drawing pertaining to the length of the *Virginia*. The issue was revisited several times but it proved difficult to change the geometry, as it effected other aspects of the model which had already been established such that they no longer functioned in the Paramarine environment (Paramarine does parametrically update its models as the name implies, but that doesn't mean it is always a seamless operation; this was the one time where that proved to be case over the course of this analysis). It was decided that the dimensions were close enough to make conclusions from the analysis based on the geometry. Note that even if the 3 feet of added length occurs over the part of the ship with the maximum sectional area (615.75 ft.) the increase in the displacement of the *Virginia* is 45 LT in brackish water. That may sound like a lot, but it amounts to only 1.16% of the 3869.37 LT estimated, and should not be enough to alter any of the overall conclusions derived from this analysis.

3.6 Hydrostatics and Initial Stability Assessment

3.6.1 Hydrostatics

With the geometry fully modeled the next order of business was to create a table of hydrostatics using Paramarine functionalities. A full table of hydrostatics was made for zero trim at a range of mean drafts from 10 ft to 24.5 ft.

Of particular interest was the ship's displacement at a draft of 21 feet forward and 22 feet aft from the bottom of the keel, the oft quoted drafts at the time of the Battle of Hampton Roads. The particular hydrostatics at this draft would allow for the weight analysis to have a target weight to work towards and ultimately allow for a calculation of the unknown weights that would complete the weight and CG estimate (see section 3.7.16). While results are presented in Section 4, the hydrostatics at the battle drafts are given here in Table 2, as the displacement and LCB therein constitute an important aspect of the discussion of the weight analysis process, beginning in section 3.7. Note that the LCB is given in reference to midships.

Draft Fwd Mark	Draft Aft Mark	Displacement (LT)	LCB (ft)	LCF (ft)	TPI (LT/in)	KMt (ft)	GMt (ft)	MTI (LTft/in)
21.00	22.00	3869.37	0.69	-0.28	17.92	19.62	4.54	180.02

Table 2: Hydrostatic Characteristics of CSS Virginia at the Battle of Hampton Roads

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[10] Displacement at a draft of 21 feet forward and 22 feet aft. See section 4.1.1.

3.6.2 Righting Arm Curves

Righting arm curves (GZ Curves) were made for the ship its estimated displacement at the 21 foot fwd / 22 foot aft drafts and for the VCG estimated by the weight analysis (see section 3.7). The VCG was varied to assess how uncertainty with regards to the calculation of the CG may effect stability results by noting the changes to the GZ Curves for a VCG 10% higher than the estimated VCG. GZ Curves were produced by Paramarine by taking the buoyant ship geometry, displacement, and center of gravity as inputs.

3.7 Weight Analysis

The purpose of the weight analysis was to derive a center of gravity for the ship, particularly a vertical center of gravity, that could be used to determine the ship's stability and that also could be used in a sea keeping analysis. The weight analysis would also be used to derive weight distributions which in turn would allow for an estimate of total weight moments of inertia and gyration radii. Below is a description of the process for the various aspects of the weight analysis – more detailed calculations can be seen in Appendix A.

Generally speaking, the ship's geometry and information from the historical record were used in combination to determine weights for various parts of the ship. With the model it is possible to determine the ship's displacement at any given draft, and so a target value could be determined to guide estimation. In the end it was impossible to estimate 100% of the ship's weight; 82% of the weight was able to be estimated. The remainder was listed as an unknown weight and placed in an appropriate place aboard the ship to achieve a draft of 21 feet forward and 22 feet aft above the bottom of the keel.

3.7.1 Target Weight for Estimate

As can be seen in Table 2, Section 3.6.1, the displacement of the ship at the time of the battle of Hampton Roads, based on the Paramarine model, was 3869.37 Long Tons. The longitudinal center of gravity was 126.31 ft aft of the FRP. This was the target weight and LCG that was worked towards and used to estimate ballast and unknown weights.

3.7.2 Source Materials for Analysis / Levels of Detail

Many of the weights not connected to the geometry of the ship are mainly from second hand historical sources. An exception to this is the case of the propulsion weights, in which case most of the weights come first hand or close to it, coming from books published by BF Isherwood himself and accessed online with the help of Google Books.

The second hand sources include books, articles from websites, blogs, and so on. Much of the information was found online and on a few occasions Wikipedia was used if the article on Wikipedia cited its own source that could be traced. In one case, in a fit of laziness, a weight was taken directly from Wikipedia pertaining to the 1853 Enfield Rifled Musket. The weight quoted in Wikipedia seemed good enough, the weight in question (small arms carried on the *Virginia*) was small in comparison to the overall weight, and so it was used.

In some cases the weight estimates come from delving deeply into the sources available, but in others some quick and broad assumptions are made. As such, some of the weight estimates have the backing of several sources, while others have the backing of merely some educated guesses. Decisions as to how deeply to pursue particular weights were the author's own. In some cases, for particularly large weights, great efforts were taken to run the weights to ground. But in others, notably for the smaller weights, it was not deemed worth the effort to acquire good sources and get exact numbers. The goal was to get to a weight that seemed reasonable enough for the analysis, keeping in mind that any weight analysis for the *CSS Virgini*a and other period ships will always be something of an artful estimate, particularly when few drawings are available.

3.7.3 Armaments

The armament weight includes that of the guns and gun carriages. Small arms and the ship's ram are considered elsewhere.

Weights for the guns were actually not too easy to pin down. Different sources quote different weights for the various pieces. *CSS Virginia* carried two 6.4" Brooke Rifles, two 7" Brooke Rifles, and six Dahlgren IX guns. The Dahlgren's weighed 9000 lbs each, and the 6.4" Brooke Rifles also weighed around 9000 lbs each (Nelson). Nelson puts the weight of a 7" Brooke rifle at 14500 lbs each, but it was decided to increase the weight slightly as the weight depended on the number of bands going around the breach, and so a weight of 15000 lbs was used. This is close to a weight of 15300 lbs quoted by Quarstein in Sink Before Surrender.

All guns were housed on Marsilly Carriages. To estimate the weight a drawing of how to build a model Dahlgren IX on a Marsilly Carriage was obtained online (Green, 1976). The drawing can be seen in Appendix B. The data on the drawing was used to draw the large wooden piece parts of the gun carriage in AutoCAD. Areas were estimated in AutoCAD and, assuming a thickness based on the drawing of 6 inches, volumes of the wooden pieces were found. Weights of axles and wheels were found in a similar fashion. 100 lbs of additional metal pieces were thrown in to estimate the weight of the screws and bolts holding it all together, as well as other fittings. When the weights were summed the overall weight of a Marsilly Carriage was estimated at about 1350 lbs.

There was no such information available for the swivel gun mounts, despite an extensive search. Because of the lack of good information it was decided to simply assume the swivel carriage weight was twice the weight of a standard Marsilly Carriage. It was deemed justifiable by the fact that the swivel carriage appears to be a Marsilly Carriage placed on a moveable mount, though it may have been a low estimate. The higher weight of the 7" Brooke Rifles may have required a larger, heavier carriage. But with a shrug, we say "good enough". Here we see a good example of the type of decision making noted in Section 3.7.2. Very detailed efforts to arrive at a weight estimate for the Marsilly Carriage, but at a certain point it wasn't deemed worthwhile to apply the same level of effort to the swivel mounts.

3.7.4 Powder and Shot

Estimating the powder carried was not difficult – available records for the *CSS Virginia* suggest that she carried 18,200 lbs of powder into battle (Quarstein, 2012). It is possible she carried more but there is no other amount referenced in the literature, so it was assumed 18,200 lbs was the number.

Estimating the weight of the ammunition carried was a different matter. There were three different guns, each requiring its own shell fired with a particular charge of powder.

For the weight analysis it was assumed all the ammunition carried aboard was explosive shell. This is not quite true – two of the Dahlgren IX guns were designated as "hot shot" guns. These would have used solid shot heated in a special furnace below decks to set wooden ships ablaze (Nelson). However, even if the assumption is not quite true it is reasonable; the *CSS Virginia* set sail with the intention of destroying the Union fleet of wooden ships and accordingly loaded its magazines largely with exploding shells. The weight difference between the explosive shell and the hot shot is not likely to make a big difference, as it is believed only a small number of rounds suitable for hot shot were carried.

Estimates of the amount of ammunition carried were based on the number of shells that the 18,200 lbs of powder could effectively fire. A 7" Brooke rifle could fire a 100 pound shell 4 ½ miles using a 12 lb charge (Nelson). Based on a table of Dahlgren shell gun charges found online but attributed to Warren Ripley's Artillery and Ammunition of the Civil War, a Dahlgren IX gun could fire a 73.5 lb shell on a 13 lb service charge. For the 6.4" caliber Brooke rifle it was assumed that its shell weight and service charge was the same as the 7" Brooke rifle. As it is a different caliber the service charge and shell weight were probably different, but the amount of shells involved and the resultant differences in weight were deemed not worth the additional research.

It was then assumed that the powder would be divided based on the number of guns present, and the number of charges that could be obtained from that weight was the basis of the number and weight of shells carried for that gun. Two out of the 10 guns (20%) were Brooke 7" rifles, so 20% of the powder weight would be reserved for that gun, which results in a weight of 3640 lbs. The service charge for the 7" Brooke Rifle was 12 lbs, so that results in about 303 charges for the gun and, at 100 lbs apiece, the overall weight of shells for the 7" Brooke Rifles was about 30333 lbs. Based on the assumptions above concerning the charges for the 6.4" Brooke Rifle and its weight of shell the same is true for that piece of artillery as well.

The rest of the armament (60%) was made up of Dahlgren IX's, so 60% of the powder would have been reserved for the Dahlgrens (10920 lbs). Based on a service charge of 13lbs it amounts to 840 charges; at 73.5 lbs a piece the Virginia would have carried 61740 lbs of shells for the Dahlgrens.

In all, it was estimated that 54.65 LT of ordnance was carried by the *CSS Virginia*, not including ammunition for small arms. A table of the calculations described above can be seen in Appendix A.

The LCG and VCG of the armament was based on a proposed lower deck arrangement in Park's book (see Figure 4), showing two magazines. It is assumed that half of the weight was in the fwd magazine and half the weight was in the aft magazine. A calculation of overall VCGs and LCGs can be seen in of Appendix A.

3.7.5 Small Arms

There were certainly some small arms aboard the *CSS Virginia*. If one needs any proof: on the first day of the battle Commodore Buchanan, striding along the upper deck of the ship, angrily fired upon Union troops on the

Newport News side of the James River with a rifle (Nelson)[11]. That colorful story is submitted for evidence, but small arms would have been onboard as a matter of course to repel boarders, conduct raids, and to simply guard the ship while berthed or in dock.

There is no record of how many or what type of small arms was carried. The English made 1853 Pattern Enfield Rifled Musket was used extensively by the Confederacy, and for the analysis it was assumed that there was one Enfield per man weighing 9.5 lb each (Wikipedia, 2016). It is perhaps not the case that every man had his own rifle, but as other arms (pistols, officer's swords, axes) and associated ammunition are not accounted for it was deemed to be a reasonable assumption.

3.7.6 Personnel and Their Effects

The number of people aboard and their effects had to be accounted for as a load. There are three questions that must be answered: how many crew were present, how much did each person weigh, and how much "stuff" did they carry?

The number of crew aboard the *CSS Virginia* is not consistent depending on the source of information, but it tends to vary between 320 and 350 men. For this analysis the high side was cheated towards at times to keep unaccounted weights low, so 350 was the number chosen.

No weight record of *Virginia's* crew is readily available (if it even exists). Some kind of average weight, therefore, must be used. There are many websites devoted to the average soldier of the Civil War, and one puts his average weight at 143 lbs (World History Group, 2016). That may seem light by today's standards, but when one reflects that most soldiers in the Civil War were farmers who still relied greatly on their own strength to coax a living from their fields it's not unreasonable[12]. There is of course the past stereotype of the overweight sailor, made so by lack of exercise available on the naval ships of the day[13]. It is probably not applicable to the sailors aboard the *CSS Virginia*, as most were volunteers from the army and had not been long confined to the ship by the time of the battle.

As to the effects of the sailor these would include blankets, uniforms, letters, books, etc. Again, most websites on the "average solider" puts the weight carried by the average man at between 30 – 80 lbs, a weight that includes arms and ammunition. In the case of the *CSS Virginia* the weight of arms is accounted for elsewhere. The weight was therefore assumed to be 60 lbs per man, and is assumed an average with the enlisted men carrying less and the officers trundling slightly more aboard.

The overall weight of personnel and effects was estimated at 34.84 LT.

To estimate their location at the time of the battle a notional battle station watch bill was made. This notional watch bill can be seen in Appendix A.

3.7.7 Provisions

Regulations regarding the rationing of Confederate Sailors were not easy to find, so it was assumed that the sailors in the CSN would enjoy similar fare to their counterparts in the US Navy.

The daily ration for a US Sailor as approved in 1861 by Congress is described in The Civil War Naval Encyclopedia, edited by Spencer C. Tucker, as being:

> *"One pound of salt pork, with half a pint of beans or peas; one pound salt beef, with half a pound of flour, and two ounces of dried apples or other fruit; or three quarters of preserved [canned] meat, with half a pound of rice, two ounces of butter, and two ounces of desiccated potato; together with fourteen ounces of biscuits [hard tack], one quarter of an ounce of tea, or one ounce of coffee or cocoa, two ounces of sugar, and a gill [four ounces] of spirits; and a weekly allowance of a half a pound of pickles, half a pint of molasses, and half a pint of vinegar".*

This was taken to mean that, at the freshest, the sailors would be provided with salt pork, salt beef, peas, flour, dried fruit, hard tack, coffee, sugar, pickles, molasses, vinegar, and of course rum (Tucker states that cheaper rye

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[11] He was angered that Union Army units on the Newport News side of the James River had fired upon CSA vessels trying to remove sailors from the heavily damaged USS Congress. He was wounded in the thigh by Union rifle fire, and command for the second day of the battle passed to Lieutenant Catesby Jones.

[12] This was the explanation given for a similarly low weight presented during a lecture by Dr. James I. "Bud" Robertson for Virginia Tech Course HIST 3055 "Civil War and Reconstruction", spring 2004, which the author attended.

[13] At several points in the *Aubrey Maturin* series of books by Patrick O'Brien set during the Napoleonic Wars, Captain Aubrey was admonished by friend and surgeon Stephen Maturin to lose weight.

whiskey may have been used instead, at least in the US Navy). Not including water, this amounted to about 4.7 lbs per day per man, an ample ration for the time in quantity if not necessarily in quality. Considering that in 2011 the average American ate 1,996 lbs of food, around 5.5 lbs of food per day (NPR, 2011), 4.7 lbs seems reasonable. One must also remember that the *CSS Virginia* was berthed in friendly territory that had yet to feel the full weight of the war in 1862; the ship would probably not have had had too much trouble finding provisions. Moreover, food (or any lack thereof) does not come up very much in the *Virginia's* story. So it is assumed that the ship was adequately provisioned.

With a crew of 350 men at 4.7lbs of food per day, the *CSS Virginia* would be going through about 1635 lbs of food daily. It was never intended that the *Virginia* would go to sea for very long, though the hull of the *Merrimack*, designed to sail overseas, must have provided plenty of space to provision the ship for as long as thought necessary. For this analysis it was assumed that the *Virginia* would be relatively lightly provisioned, perhaps for three weeks (21 days). If that is assumed the overall provisions carried on board ship amounted 15.33 LT.

3.7.8 Water

Initially it was assumed that the *CSS Virginia* carried its water in casks. However, as noted in Section 2.10, evidence of tankage aboard the *Virginia* led to the assumption that the ship carried its water in tanks.

As noted previously, a cutaway view of the *USS Merrimack* shows what looks like tanks on the bottom deck of the ship. These tanks are also shown in a cutaway view of the *CSS Virginia* done by Park in his book (see Figure 4).

One would initially think that these are perhaps feed water tanks, but investigations of handbooks and technical papers on steam boilers from the late 1800s revealed that most marine steam boilers of the 1850's vintage (when the *Merrimack* was built) ingested feed water directly from sea. Additional online searches finally overturned an online discussion forum[14] on *wasserkasten,* literally German for "water box", which noted that starting around 1815 new ships built for the Royal Navy began storing water in tanks rather than casks. This was more for crew safety than water quality; instead of engaging in the back breaking work of hauling water up out of hold in wooden casks, the water could be pumped out of these metal water tanks with relative ease.

The forum helpfully pointed out a reference. In his 1869 work A Treatise on Naval Architecture and Shipbuilding, USN Commander Richard W. Meade makes note of iron water tanks for storing water. Though he notes that "a small number only now are being supplied to our cruisers" it is thought that for the *Merrimack*, built in 1855, it is plausible that they may have been in place. Meade notes that most tanks are rectangular boxes, 4 feet wide by 4 feet long and 4 to 6 feet tall.

For the purposes of the weight estimate it is assumed that the tanks shown in Park's drawing are indeed fresh water tanks (another possibility may be that they are not tanks at all, but coal scuppers). It is also assumed that they would have been filled as much as possible to act as liquid ballast to increase the draft of the ship and bring the knuckle line below the surface of the water. Based on the drawing in Park's book I have assumed that there are 8 tanks fwd and 10 tanks aft, because if we are seeing a cut away of the internals on the port side of the ship then there should be same amount of tanks on the stbd side as there are on the port side, in keeping with the assumption of port/stbd symmetry.

The weight of each empty water box was estimated at 980 lbs, and assuming it was 90% full (allowing for the fact that potable water tanks are almost never full due to usage and a seemingly inherent dislike amongst most shipbuilders and naval personnel to press tanks completely full) the amount of water carried by each was 3686 lbs. All told the structure of the tanks was estimated at 7.88 LT and the water itself estimated at 29.62 LT.

3.7.9 Propulsion Machinery

The propulsion plant of the *USS Merrimack* (and likewise the *CSS Virginia*) was massive. It consisted of four vertical tube Martin Boilers, each with their own furnaces, and two back acting engines which drove a single shaft. The propeller was a two-bladed bronze screw. The blades were designed by Robert Griffiths and was variable pitch (Quarstein, 2012).

For this analysis the weight of the propulsion plant was taken straight from values reported by BF Isherwood in his book Experimental Researches in Steam Engineering[15]. The weights for the boilers are based on a combination of information for the *USS Merrimack* and the *USS Wabash*, nominally sister ships though not as similar as two

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[14] See http://forum.sailingnavies.com/viewtopic.php?t=1277

[15] Weights from other sources appear to vastly underestimate the total weight of the machinery, especially as the weight of water in the boilers is neglected.

sister ships may be today. The weights of the engines and other machinery outside of the boilers are based on the weights of the *USS Wabash*, which are more extensive than those given for the *Merrimack*. The *Wabash*, like the *Merrimack*, had back acting engines but the *Wabash* had those of the vertical steeple type while the *Merrimack's* engines were of the horizontal type. It is assumed that the weights would be similar.

The propulsion shaft was, as Park notes, a "monster unto itself". It was fourteen inches in diameter (Park) and based on Besse's drawing about 116 feet in length. Assuming a solid casting of iron in total it weighed 29 tons (note that his includes an estimate for fitting and bearings estimated as a percentage of the weight of the shaft itself: see Appendix A).

As shown in Appendix A, the overall weight of the propulsion plant has been estimated at nearly 500 LT, not too far from the weight of the hull or the casement itself. The weigh includes water inside the boiler.

Isherwood shows no basis for the weights of these items, and it is not known how exactly the weights published in the book were arrived at and how accurate they are. It is noted that they do seem incredibly precise, almost impossibly so. However, it is the best estimate that could be found without having to try and model or rebuild the engine room, both of which were felt to be well beyond the scope of this effort. Still, the estimate of the propulsion machinery is believed to be an improvement over previous estimates made in various publications.

3.7.10 Structure and Outfitting Weights

The weight of almost all hull structure was based on geometry analysis from the model, with the exception of the pilot house. Following is a brief summary of the different aspects of the ship's structure that were estimated, and how the weight estimates were carried out.

3.7.10.1 Upper Deck Weight

The uppermost deck of the *CSS Virginia* was not solid, but rather a grid made of 2" x 2" iron bars supported by wooden beams and longitudinals (Park).

The iron grid was made by laying one set of iron bars athwartship and another on top of it running longitudinally. A sketch was made of the arrangement, presented in Figure 23. It was found that 6 linear feet of 2" square bar would be present in one square foot of deck. The area of the deck (with the appropriate deductions for hatches and smoke stacks) could be found using the Paramarine model, and was estimated at 1386 ft^2. Within that 1386 ft^2 there is accordingly 8318 linear feet of iron bar. With a weight of 13.6122 lb/linear foot the overall weight of iron bar used in the deck is estimated at 113227 lb, or about 50.5LT. Calculations can be seen in Appendix A.

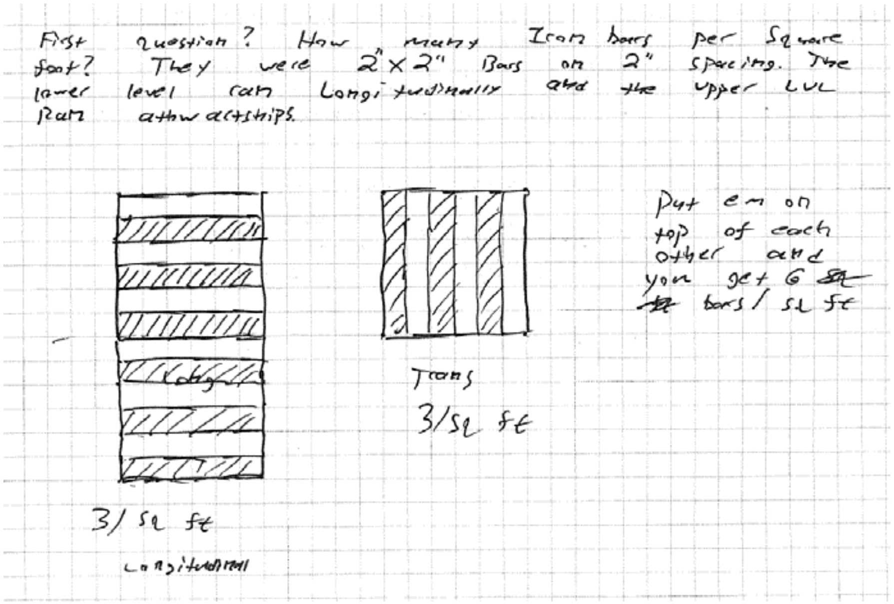

Figure 23: Sketch of Upper Deck Iron Bars[16]

Underneath the iron grid was underlying structure, and for this project a notional framing plan provided in Park's book was used to estimate the weight. The upper deck support in Park's plan is made up of approximately 25 beams and one longitudinal. It was assumed that all the beams were made of live oak, and that they were 7.5" square. The 7.5" is based on a scaled estimate from one of Mr. Park's drawings in his book. The 7.5" is a much lower depth than other beams are believed to have had within the ship, as the upper deck was not intended to bear much weight (persons and temporarily placed stores awaiting stowage, for example).

Park's framing plan showed openings for hatches and the smoke stack. For the weight estimate of the upper deck a simpler plan was made that does not allow for these openings. The extent of the upper deck was drawn in AutoCAD and 25 beams were spaced throughout with one longitudinal (Figure 24). From this plan lengths, volumes, and weights could be deduced, as well as the overall center of each beam. The overall weights of the longitudinal and beams was estimated at only about 3 LT.

Figure 24: Simplified CSS Virginia Upper Deck Framing Plan

The beams and the longitudinal were fitted into a header that defined the edges of the upper deck. A cross sectional area of the header was derived from Park's sectional view of the *CSS Virginia* and, based on the length of the header basically being the perimeter of the upper deck, an overall volume and weight could be found. The header was estimated at approximately 11 LT.

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[16] This was a sketch that I made to figure out how many 1 foot long 2" x 2" iron bars were in a square foot of decking. Each gridline is 2"

3.7.10.2 **Upper Deck Hatches**

There were three hatches on the upper deck of the ship that interrupted the grating, as can be seen in Figure 1. Estimates for the area of the hatches were made by scaling off Besse's lines. The forward and mid hatches were estimated to be 65 ft^2 and the aftermost hatch looks to be a little bit bigger, about 80 ft^2.

No one seems to be absolutely sure what the hatches were made out of or how they were constructed. If they were made of iron they would be prohibitively heavy, but if they were made of anything else they would not provide much protection against enemy shot from above.

So for the sake of manageability it was assumed that the hatches were made of 2 inch thick oak. Even then the hatches would be about 500 lbs, but there would have been ways to make the movement of those hatches manageable (they may have been split in two halves, for example). We also at times underestimate engineers from the past, but never count out mechanical engineers of the 19th century: there may have been a mechanical means to assist in raising the hatches of some kind. The overall weight of the hatches was estimated at about 0.71 LT.

3.7.10.3 **Gun Deck Structure**

The weight of the gun deck includes the weight of the planking, beams, longitudinals, and iron knees.

The weight of planking was easy enough to obtain based on the model of the ship's geometry in Paramarine. A plane was passed at the proper elevation of the gun deck and the area bounded by the ship's hull was measured. Based on Park's book the gun planking thickness was 5" (Isherwood notes the same thickness for the *Merrimack*'s gun deck). I did assume the deck would have been made of pine, which is perhaps an oversight: higher strength oak may have been used instead. The thickness and area yielded a volume, and then the density of pine yielded a weight. The deck planking of the gun deck was estimated to be nearly 33 Tons.

The weight of the underlying deck structure was made by following a process similar to that used for the support structure of the upper deck. In this case a combination of Park's nominal framing plan was used. Park includes gun deck beams and carlings, which would have been smaller beams placed in between the large gun deck beams. For the weight estimate of the gun deck only the beams and two longitudinals were considered, as including the carlings raises the weight of the underlying structure of the gun deck to be greater than the weight of the gun deck planking itself, even if the structural knees of the deck are not accounted for. Such a situation seems unlikely. Park's plan was simplified and drawn in AutoCAD, approximate lengths of the beams were found, dimensions were applied to get volumes, and a density of pine yielded an estimated weight. Again, it is possible (actually likely) that oak was used and this assumption may be an error. Overall, the weight of the beams and longitudinals amounted to about 23 LT.

The beams were assumed to be 17" deep by 14.5" wide as was the case on the *Merrimack*'s gun deck (Isherwood, 1863). The longitudinals were assumed to be 1' deep and 1' wide, based Park showing them in his layout as similar to the smaller carlings. Figure 25 shows the approximate layout drawn for the weight estimate. Beams and longitudinals are in green, the carlings are in purple.

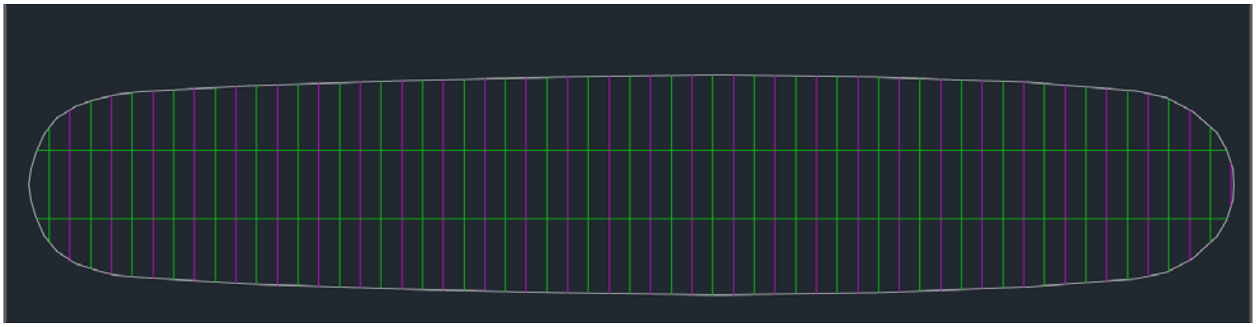

Figure 25: Simplified Gun Deck Framing Plan

Wrought iron knees connected the major gun deck beams to the casemate (see Figure 2) (Park). According to Park's work each gun deck beam had two iron knees; Park's framing plan stipulated 28 beams, so I assumed there would be 56 knees. The iron knees were drawn in AutoCAD and assumed to be 1" thick, resulting in a volume of just over 1 cubic foot of iron per knee. Based on the volume of iron required at a density of 490 lb/ft^3 it was estimated that each iron knee weighed 516 lb. Combined it is estimated that all iron knees weighed almost 13 LT.

3.7.10.4 Engine Platform Structure

The weight of the engine platform (the lowest deck on the ship) was estimated in a similar manner to the gun deck; an overall weight of the planking was found based on the area of the engine platform obtained from the Paramarine Geometry model. It was assumed that the engine deck planking was also 5 inches, as it was for the gun deck. The engine platform weight was based on the density of oak for its weight, so in this case it is indeed assumed that the engine platform is made of oak.

Park presents no framing plan for the engine. It may have been simple enough to come up with one based on the other framing plans, but instead it was decided to assume the structure of beams and longitudinals under the lower deck had the same ratio to the engine deck planking as the gun deck beams had to the gun deck planking. The gun deck beams, and longitudinals are 70% of the gun deck planking weight, so a similar factor was applied to the engine deck planking to estimate the weight of the structure beneath the engine room deck.

Overall the engine deck planking and underlying structure was estimated to weigh about 89 LT.

3.7.10.5 Berth Deck Structure

The berth deck was the deck above the engine room deck, though there was a section of the deck through which the boilers would have gone through.

The weight of the berth deck was estimated along the same lines as the engine platform. The deck planking weight was found by getting the area of the berthing deck from the Paramarine geometry and subtracting out the area required for the upper part of the boilers, about 12 ft by 14 ft according to Park's reckoning. A deck thickness of assumed 5" was assumed. The weight of the beams and any other underlying structure was estimated using the ratio of planking weight to structure weight for the gun deck. In all, the berthing deck and underlying structure had an estimated weight of about 80 LT. It was assumed that the deck was made of pine.

3.7.10.6 Casement Weight

The *Virginia's* casement was built in layers. The first layer was made up of pine rafters that defined the overall shape of the casement. On top of the rafters was another layer of pine planking and a layer of oak planking. The planks would have run perpendicular to each other. Over that two layers of 2" iron plates were placed, also run perpendicular to each other. The whole thing was held together with giant bolts going through the entire construction. The bolts were countersunk into the armor plating to create a relatively flush casement surface.

Naturally, none of the men who designed or built the *Virginia* agree retrospectively on how deep the different layers of wood are (all agree on the upper 4 inches of iron)[17]. For this project John Porter's estimate of 12 inch deep pine rafters, 4 inches of pine planking, and 5 inches of oak planking was used, for an overall casement depth of 25 inches.

To estimate the weight of the iron used on the casement the approach taken was pretty straightforward: the surface area of the casement was found from the Paramarine geometry and it was multiplied by 4 inches to get a volume. The density of iron was applied to get an overall weight of almost 638 LT. It is noted that for the casement the geometry was modeled to the molded line (or at least an assumed molded line), which makes this approach possible.

Using a similar approach to estimate the weight of the wood used for the casement could not be used, because throwing a large thickness inward from the molded line would cause erroneous results. Instead, it was decided to take a cross section of the casement and find the percent area in cross section of the different layers of wood, and assume that the same percentages applied to the volume of the casement. The overall casement volume was easily obtained in Paramarine (it is modeled as a solid) and the different volumes of wood could be estimated based on the percentages from the AutoCAD sketch. The sketch created can be seen in Figure 26, with a close up in Figure 27.

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[17] The different estimates were noted in Park's book. See Figure 3

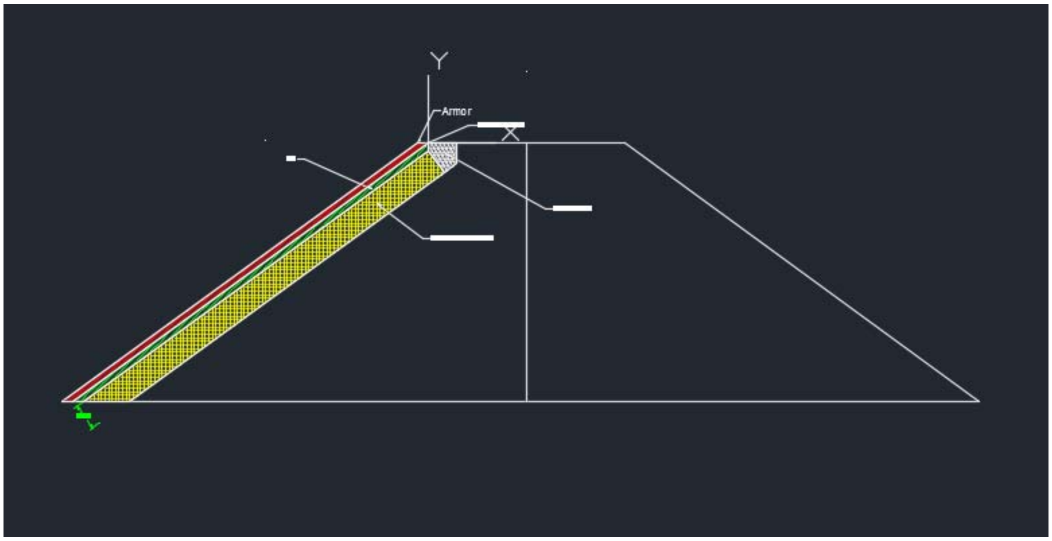

Figure 26: Casement Section Sketch

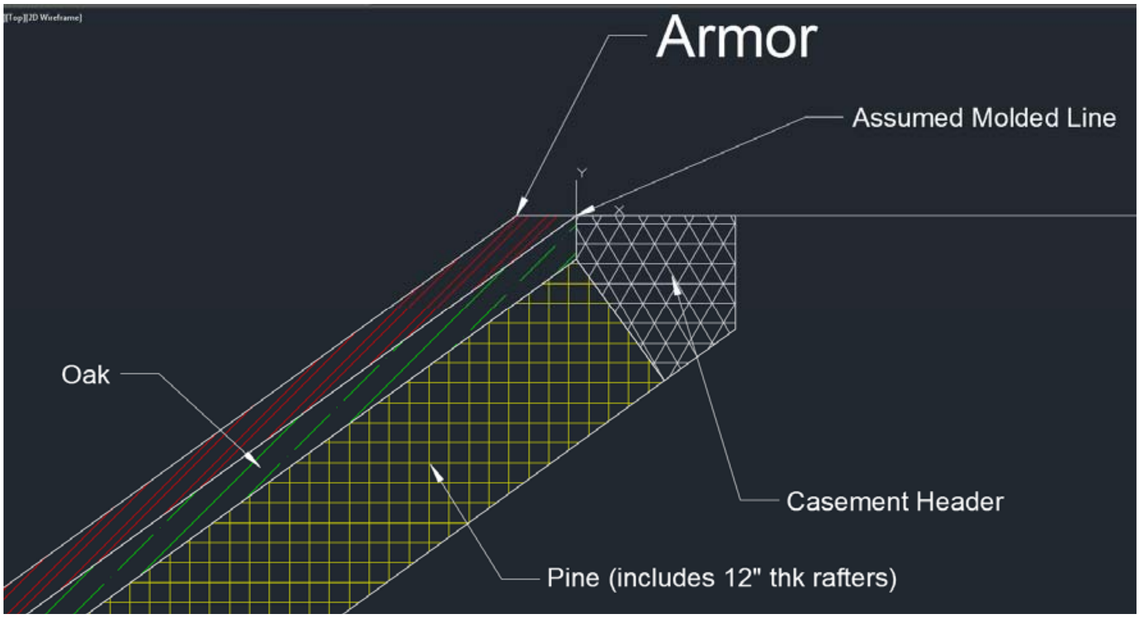

Figure 27: Close up of Armor Casement Sketch

It was found that oak made up 3.86% of the area in cross section and the pine (including the depth of the rafters) made up 15.47% of the area. The overall volume contained in the casement shape in the Paramarine model was 69092 cubic feet; applying the factors above results in 2669 ft^3 of oak and 10691 ft^3 of pine used. Overall, the weight of wood used in the casement is approximately 198 LT.

The weight of the bolts was not estimated, though it would have added slightly to the weight estimate because the wood for each driven bolt would have to be replaced by iron. Additionally, there was no accounting of the weight lost from boring the gun ports through the casement. The thought was that the changes to the weight estimate from the bolts and the missing wood for the gun ports would allow for some of the unaccountable weight to be captured.

Ironclad Down goes to some length to discuss how the casement and the lower hull might have been joined together, specifically what kind of joint was used to join the rafters to the frames and filler frames of the lower hull. One thing is for certain though: the joining of the casement to the lower hull required many, many live oak knees. Oak knees as drawn by Park can be seen in Figures 2 and 3.

Knees were used everywhere to join different pieces of structure together and give them strength. They were a very important structural feature of past ships. Knees were used, for example, to join transverse beams to stanchions or deck planking to the hull.

The weight of the knees used to secure the upper hull to the lower hull was found by first estimating the weight of each knee to be about 200 lbs each. This may seem high, but considering the lengths of the knee and the fact that each one would have been a foot thick (the thickness of hull frames and filler frames) it's clear they would have been very heavy. It's possible that more knees of lower thickness were used, (3 knees of 4 inches depth or 2 of 6 inches depth, etc.), but the effect would be the same.

The number of knees required was estimated by taking the length of the knuckle line at points where the lower hull meets the casement, both on the port side and stbd side. This total length, port and stbd, is 316 feet, meaning about 316 knees would have been required to join the casement to the lower hull. That does not include other structural knees used elsewhere in the ship for other purposes.

Overall the weight of knees for the casement alone is estimated to be 28 LT. If you account for the weight of the knees, the wood, and the iron plate, the overall weight of the casement and the knees required to join it to the lower hull was 863 LT, about 22% of the of the *Virginia's* 3869 LT displacement.

3.7.10.7 **Tail Fairing**

A fairing, or platform, was fitted onto the narrow deck aft of the casement to protect the propeller and the rudder from solid shot. It was modeled in Paramarine based on polylines drawn over Besse's lines drawing in AutoCAD. The volume of the fairing was obtained from the Paramarine model and, using the density of oak, an estimated weight of about 20 LT was obtained.

The tail fairing was clad in 1 inch thick iron. The area of the upper side of the tail fairing was easily obtained from the Paramarine geometry. The 1 inch thickness yielded the volume of iron used; applying the density of iron yielded a weight of approximately 17.6 LT.

3.7.10.8 **Bulwarks**

Bulwarks were placed ahead of the forward end of the casement as a water break to prevent waves from rolling over the Virginia's upper deck and crashing into the casement. The two bulwarks were basically walls about 5 feet tall, formed into a V-shape to pierce the water. It is assumed that limber holes were cut into the bottom of the bulwarks to allow water to drain from the area and make it a free flooding zone.

The bulwarks were modeled in Paramarine, and their volume was taken from the geometry model. Assuming they were made of oak, it was found that the two bulwarks would have weighed a total of 5.3 LT.

3.7.10.9 **Pilot House**

On top of the fwd end of the casement a pilot house made of iron was situated, a conical structure through which the pilot could see while remaining relatively protected from enemy fire. There is some indication that a similar pilot house was planned for the aft end, but all sources state the *CSS Virginia* probably only had the one on the fwd end.

The pilot house was not modeled in Paramarine, as it did not contribute to the hydrostatic properties of the ship and it was easy enough to estimate the weight by assuming it was a conical frustum with walls 12 inches thick. Its volume was estimated about 83 cubic feet and then it was reduced by 10 percent to account for the fact that slits were placed in the pilot house walls so the pilot could see. Overall, the weight estimated for the pilot house was 16.4 LT.

3.7.10.10 **Keel and Upper Keel Structure**

The keel was a prominent feature of the *USS Merrimack* and likewise the *CSS Virginia*. The keel below the hull (i.e. below the baseline or the rabbet line) was modeled in Paramarine as part of the geometry model. Its volume was found from the model and, using the density of oak, a weight of 23 LT was estimated.

There was additional structure above the keel inside the ship running down the CL, as shown in a midship section drawn by Park appearing in Ironclad Down (Figure 28). This was not modeled in Paramarine, but rather estimated. An estimate of the cross sectional area of the wood was made from Park's drawing, and that area was multiplied by the length of the hull for which the bottom is flat along the CL. An overall volume was estimated and, applying the density of oak, a weight of 32.9 LT was calculated.

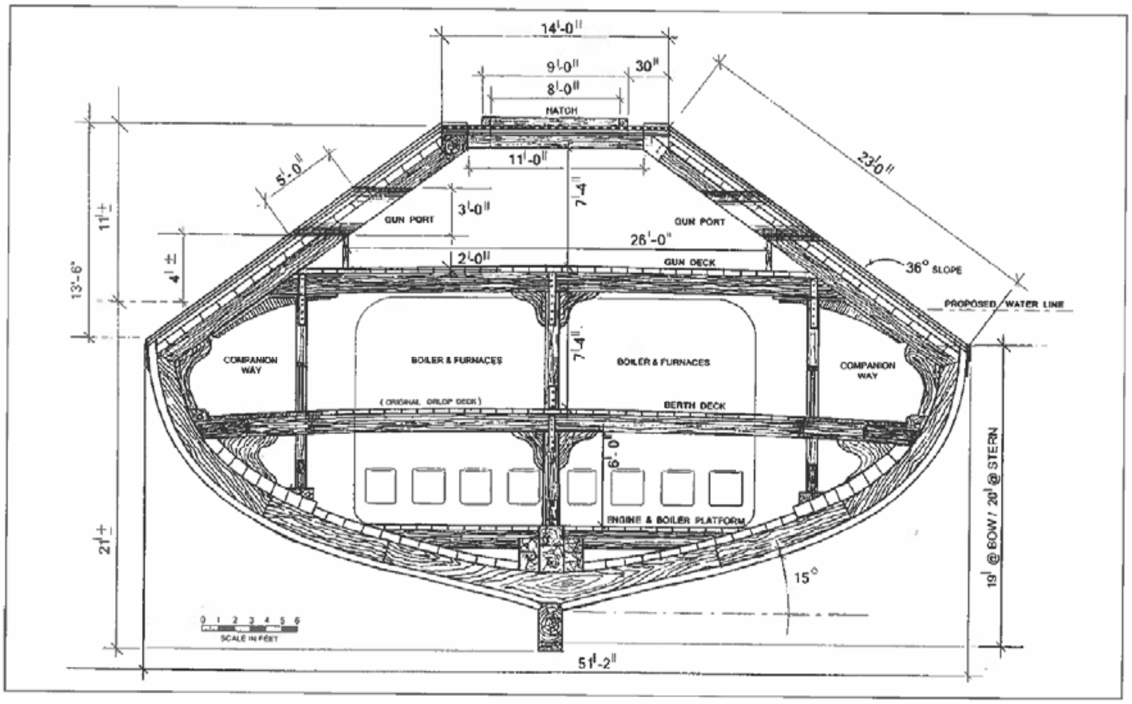

Figure 28: Midship Section of the *CSS Virginia*, as Drawn by Park and Presented in Ironclad Down

3.7.10.11 Ship's Hull and Copper Sheathing

The model of the ship's hull in Paramarine is taken to the outer line, not the molded line. To estimate the hull thickness a second Paramarine geometry model was made to the inside of the hull. It is assumed that the hull is solid and it is two feet thick, which accounts for external planking, frames, and internal planking as shown in Figure 28. To estimate the weight of the hull the volume of the hull solid in the *CSS Virginia* model was subtracted by the volume of the inner hull model solid. A density for oak was applied to the result to estimate the hull weight.

The assumption that the hull is solid is deemed acceptable by the fact that Isherwood described the *Merrimack's* hull as being solid up to the turn of the bilge. Above the turn of the bilge there would have been space between the frames; Park believes that the space in between the frames was taken up by filler frames in order to provide a solid foundation for the casement, as shown in Figure 2.

The two feet of thickness is a convenient assumption, but not an unreasonable one. Looking at Park's midship section view in Figure 28 it appears, by looking at the scale in the lower left hand corner of the drawing, that below the berth deck the entire thickness of the hull is at least 2 ft, perhaps even 3 ft. Above the berth deck the internal planking is replaced by the knees that are used to connect the casement to the hull, so the thickness of the hull declines somewhat, at least for purposes of the weight estimate as the knees are accounted for elsewhere. Because there are places where the hull thickness looks to be less than 2 ft and other places where it is more, an average of 2 feet seemed reasonable. Isherwood's description of the *Merrimack's* hull supports Park's drawing: between the framing, garboard strakes, internal bilge strakes, and planking, the hull seems to vary from 33.5 inches to 10 inches thick (Isherwood, 1863). It must be said that the 10 inch thickness per Isherwood occurs well above where Porter would have cut the burned portions of the *Merrimack* away to begin construction of the *Virginia*.

There are features of the hull that could not be estimated. There are, for example, diagonal iron braces which may or may not have been left in place for the *Virginia*, and the entire hull was held together with copper and iron bolts (Isherwood, 1863). If the 2 ft hull thickness is an overestimate in any way, the thought is that it would at least account for some of this unknown structure.

By the methods and reasoning above, the hull was estimated to have a weight of approximately 601 LT. This method was applied prior to fairing the hull solid with waterline X-T curves as shown in Figure 9[18], and in

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[18] It was only realized late in the analysis process that the hull was not properly faired. Production of waterlines, section lines, and buttocks revealed the error. Waterlines were added to better describe the hull mesh and the changes were cascaded through

consequence of that the hull volume decreased. It was decided to account for the decrease in displacement of the lower hull weight, and so after applying a deduction for the faired hull the final estimated of the hull was approximately 588 LT.

The *USS Merrimack* had copper sheathing over the hull to keep it from fouling, and there is no reason to believe it would not have been in place after the *Merrimack* was converted into the *Virginia*. It was assumed, on the advice of historian John Quarstein, to be 1/8 inch thick. The volume of copper was estimated by taking the area of the hull and multiplying by the 1/8 inch thickness. Applying a density for copper of 558 lb/ft^3, this yielded an estimated weight of 36.2 LT for the copper sheathing.

3.7.10.12 Side Shell Steel

At the time of the engagement with the *USS Monitor*, the *Virginia* had a steel armor band 1 inch thick extending 2 ft below the knuckle line for the entire length of the hull. A weight of 20.5 LT was estimated for the band by using the Paramarine geometry model to get a total volume of steel that would have been necessary.

After the battle with the *Monitor* the extent of the armor band was increased to a depth of 3.5 inches over 160 feet on each side of the vessel (Quarstein, 2012), which provided more protection for the ship, and the extra weight allowed the knuckle line to be submerged deeper in the water. That increase was not accounted for in the weight estimate for this analysis, as the weight estimate was geared towards the condition of the *CSS Virginia* during the confrontation with the Union blockade squadron and the *USS Monitor*.

3.7.10.13 Fore and Aft Weather Deck Planking, Backing Structure, and Armor

The weather decks fore and aft of the casement were armored with 1 inch iron plating (Nelson, 2004). It was difficult to find the areas of the fore and aft weather decks in Paramarine because the X-T curves defining the decks (the area forward of the casement and the area between the aft end of the casement and the tail fairing) were being used by other geometrical features. Trying to make new X-T curves over the existing ones proved problematic, for some reason. So the information from the X-T curves was used to draw the deck areas in AutoCAD and from that the volume of the decking and the weight could be obtained. It was assumed the decks were made with 5 inch thick planking. The weight of the 1 inch iron plating was also based on the AutoCAD geometry.

As for backing structure for the decks, it was assumed that the underlying deck structure was half the planking weight.

3.7.11 Ship's Ram

Late in construction the *CSS Virginia* was fitted with an iron ram on its bow. The ram broke off the ship during combat with the *USS Cumberland*. The ram has never been definitively found, but based on discussion of what it might have looked like in Park's book the weight was estimated at 1500 lbs. The ram was not modeled, as it was believed to have a minimal effect on hydrostatics.

3.7.12 Anchors

The anchors would have probably been the typical admiralty pattern type that comes to mind when most people think of anchors, and there were probably two of them, one port and one stbd (Besse). One of these anchors supposedly is at the Museum of the Confederacy in Richmond, Virginia, but that is not altogether certain (Park, 2007). An anchor is shown in Figure 1 as part of the ship.

The weight was estimated based on estimating the anchor size from Besse's drawing and assuming it was made entirely of iron. From Besse the anchor is about 12 feet in depth and the main shaft had maybe a 1ft diameter. It was assumed that the weight of the flukes would be 50% of the weight of the shaft. Above the anchor was another shaft that is smaller, maybe 4 inches in diameter and 10 ft in length.

Putting the weights of everything together, each anchor would have weighed 7354 lbs. Combined the weight of the anchors was estimated to be 6.57 LT.

The weight of the anchor chain and the capstans was not estimated. This is perhaps an oversight: it would be possible to have a used a nominal length of chain with a nominal weight. But it was decided that the chain and

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the analysis. As a result of fairing the hull, the overall displacement decreased by approximately 13 LT, and it was decided it would be most accurate to deduct it from the previously estimated hull weight as described. All results shown in this thesis are for the properly faired hull, reflected in Figures 14 – 17.

capstans would be left to be a part of the final, "unaccounted for" weight necessary to bring the weight estimate to the target weight.

3.7.13 Rudder

The *CSS Virginia* had a single rudder, and it was modeled in Paramarine based on the one shown in Besse's drawing. A volume was obtained based on the geometry, and based on the density of oak the weight was estimated to be 2.1 LT.

3.7.14 Hard Ballast

It seemed that in the winter of 1861 through 1862 a common parlor game in the city of Norfolk was speculation as to whether the *CSS Virginia* would capsize after being launched, or if indeed the ship would float at all.

So of course it is one of those ironies of history that when the *CSS Virginia* was finally floated in the dock that it floated all too well. Some accounts make it sound worse than others, but according to Nelson and Quarstein the knuckle line between the casement and the hull was at or just above the waterline. The lower hull was protected by a 1 inch armor band extending about 2 ft below the water line, but that was not enough to deflect solid shot and shell and it left the *Virginia* dangerously exposed.

Kettleridge (pig iron) was loaded on the decks fore and aft of the casement and additional pig iron was put in the spirit room (Nelson, 2004) such that the ship could attain drafts of 21 ft fwd and 22 ft aft. The ship actually had a natural drag to it as it went aft, so the casement would have been closer to an even keel.

The amount of weight necessary to bring the ship down to its final draft can be calculated from the Paramarine hydrostatics model. First, the difference between displacements and LCBs was calculated based on the two sets of drafts. Here, it is assumed that when the ship floated off the blocks it had a 19 foot draft fore and aft.

The difference between the two displacements was found to be about 631 LT:

Draft	Displacement	LCB (from FRP)	LMOM
19/19	3238.58	123.76	400807
21/22	3869.37	126.32	488767
Diff	630.79	139.45	87960

Table 3: Calculation of Weight Required to Attain 21/22 ft Drafts

Not all of the weight required to achieve the final drafts was hard ballast. At the time of first float the ship's coal, powder, and shot had yet to be loaded. Personnel and stores were also not aboard yet (Quarstein, 2012), and given the assumption that the tanks near the engine are water tanks, one could assume that the water for those tanks had not been brought aboard as well. These loads can be deducted from the above to estimate the hard ballast required to bring the ship to its final drafts:

Item	Weight	LCG (from FRP)	LMOM
Unknown Weight	630.79	139.45	87960
SUB Personnel	22.34	132.55	2962
SUB Personnel Effects	12.50	132.55	1657
SUB Variable loads	256.93	111.09	28524
TOTAL (Ballast)	339.01	161.65	54799

Table 4: Calculation of Hard Ballast Required

At a density of 490 lb/ft^3 the volume of iron required would have been 1550 cubic feet. That may seem like a lot, but it is a small fraction of the volume of the lower hull which, based on the Paramarine geometry model, has a volume of around 120000 ft^3. Even allowing for permeability factors there would still be plenty of space to stow excess iron.

In reality, there may not have been this much ballast aboard. The above analysis assumes that the *Virginia* was nominally complete at first float, and that only variable loads and personnel had to be loaded (i.e. the ship had attained its lightship weight). This may not have been the case. Even as the vessel prepared to steam out in Hampton Roads on the 8th of March, there were still shipyard workers trying to complete the outfitting of the ship (Nelson, 2004). So it is likely that there was some amount of weight to complete that is not part of the estimate, but how much is not known.

For vertical placement, it was assumed that the VCG of the ballast was in line with the estimated propulsion plant VCG, 11.04 feet above baseline. This was deemed a convenient approximation by which some of the ballast was placed on the fore and aft weather decks and some was placed in what was the *Merrimack's* spirit room, which was located on the lower level (Park).

3.7.15 Remaining Unknown Weight

In spite of the efforts to account for as much weight as possible there was still a large amount of weight that could not be estimated. Much of this weight would be for things like internal outfitting and joiner bulkheads, steering gear aside from the rudder, fittings, chains for the anchors, capstans, galley equipment, hot shot furnaces, braces, etc. The weight of the fasteners in the casement and the weight of fasteners in the hull would also be included in this remaining weight. This was listed in the weight calculations as "unknown structure", based on the assumption that a lot of it is, in fact structural (in truth, much of it is probably outfitting weight as well). It was placed longitudinally such that the final LCG of the weight estimate was equal to the LCB from the hydrostatics at a draft of 21 feet forward and 22 feet aft. The VCG of this unknown weight was placed at the center of the calculated structure.

The amount of weight estimated was 3167.51 LT. To get to the overall weight of 3869.37 LT supplied by the hydrostatics, 701.86 LT is required. This was the amount of weight that could not or otherwise was not estimated. All in all the weight analysis accounted for about 82% of the target weight.

3.7.16 Overall Weight Estimate

With the weight analysis of the different aspects of the ship as described above and shown in Appendix A completed, it remained to combine the weights into a final, overall weight estimate. The final weight estimate can be seen in Table 5 below and at the start of Appendix A.

Item	Weight (LT)	Z (vert - ft)	VMOM (LTft)	X (long - ft aft of FP)	LMOM (Ltft)
<u>Structure</u>					
Upper Deck Iron/Hatches	51.26	31.11	1595	133.96	6867
Upper Deck Longitudinals	1.93	30.41	59	128.28	247
Uppder Deck Beams	3.73	30.41	113	127.94	477
Upper Deck Header	10.99	30.50	335	128.24	1409
Gun deck Planking	32.96	23.79	784	128.39	4232
Gun deck Beams	18.80	22.98	432	128.81	2422
Gun deck Longitudinals	4.61	23.29	107	130.09	600
Gun Deck Iron Knees	12.90	22.13	285	128.81	1662
Engine Plat planking	51.93	6.00	312	121.59	6313
Engine Plat Support Struct	36.89	5.44	201	121.59	4486
Berth Deck Planking	46.04	13.50	622	128.01	5894
Berth Deck Support Strcut	32.72	12.88	421	128.01	4188
Casement armor plating	637.78	23.93	15259	128.14	81727
Casement wooden structure	197.99	23.80	4712	127.66	25275

Casement live oak knees	28.21	17.45	492	134.68	3800
Tail Fairing	19.93	18.22	363	251.79	5017
Armor on Tail Fairing	17.69	19.27	341	251.79	4454
Bulworks	5.29	19.84	105	24.39	129
Pilot House	16.41	32.43	532	56.60	929
Keel	22.80	0.83	19	143.08	3263
Upper Keel Structure	32.92	4.88	160	134.92	4442
Ship's Hull	588.89	7.23	4256	114.48	67413
Copper Sheathing	36.22	7.23	262	114.48	4147
Side Shell Steel	20.58	16.45	338	130.55	2686
Armor on fwd deck	12.26	17.24	211	22.83	280
Fwd Deck Planking	5.76	16.99	98	22.83	131
Fwd Deck Framing	2.88	16.49	47	22.83	66
Armor on Aft Deck	3.95	17.72	70	224.05	885
Aft Deck Planking	11.60	17.47	203	232.01	2691
Aft Deck Framing	5.80	16.97	98	232.01	1346
Water Tanks	7.88	9.75	77	102.51	807
Ram	0.67	17.00	11	0.00	0
Anchors	6.57	8.00	53	7.00	46
Rudder	2.11	8.12	17	267.45	563
Total Structure (Calculated)	1988.96	16.59	32993	125.14	248896

Armament	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Guns and Carriages	52.77	25.64	1353	139.27	7349
Small Arms	1.48	25.64	38	139.27	207
Total Armament	54.25	25.64	1391	139.27	7556
Propulsion	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Boilers	219.70	12.88	2829	102.51	22521
2 back acting engines	209.87	9.45	1984	135.94	28531
Screws and Fittings	15.41	10.26	158	260.00	4007
Miscellaneous	18.69	11.20	209	118.84	2221
Propulsion Shaft	29.84	9.00	269	198.00	5908
Total Propulsion	493.51	11.04	5449	128.04	63188
Loads - Fixed	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Personnel	22.34	20.20	451	139.27	3112

Personnel Effects	12.50	15.00	188	128.01	1600
Total Fixed Loads	34.84	18.33	639	135.23	4712
Loads - Variable	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Coal	150.00	9.75	1463	102.51	15376
Fwd Powder	4.06	9.75	40	42.00	171
Fwd Shot	26.93	9.75	263	50.17	1351
Aft Powder	4.06	9.75	40	211.17	858
Aft Shot	26.93	9.75	263	177.83	4789
Water in Tanks	29.62	9.75	289	102.51	3037
Provisions (food only)	15.33	9.75	149	193.17	2961
Total Variable Loads	256.93	9.75	2505	111.09	28542
Lightship and Fixed Loads	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Structure (calculated)	1988.96	16.59	32993	125.14	248896
Structure (not-calculated)	701.86	16.59	11642	115.47	81044
Armament	54.25	25.64	1391	139.27	7556
Propulsion	493.51	11.04	5449	128.04	63188
Fixed Loads	34.84	18.33	639	135.23	4712
Ballast	339.01	11.04	3743	161.65	54799
Total Lightship and Fixed Loads	3612.44	15.46	55856	127.39	460195
TOTAL	**3869.37**	**15.08**	**58361**	**126.31**	**488737**

Table 5: Overall Weight Estimate of *CSS Virginia*

3.8 Determination of Weight Moments of Inertia and Radius of Gyration

The weight analysis yielded a CG which could be used in the assessment of initial stability and in sea keeping analysis. It did not, however, yield moments of inertia that could be used to determine gyration radii. Standard gyration radii could be used, but the *CSS Virginia* is a vessel that doesn't necessarily fit well with a modern day hull form and is unique in its own right all the same. It was decided that rather than rely on standard radii for a particular hull form that didn't quite match the *Virginia's*, an attempt would be made to determine the radius of gyration based on the weight estimate. The methodology chosen was that described in (Hasnch, 2006). A summary of this method is discussed below.

The radius of gyration about an axis is given by the equation

$$K = \sqrt{\frac{I}{\Delta}}$$

Where I is the weight moment of inertia about the axis in question and Δ is the displacement of the vessel. The displacement of the *Virginia* is known based on the hydrostatics. The question is how best to get the weight moment of inertia.

Under normal circumstances in a modern weight analysis the moment of inertia of each item can be tracked in a spreadsheet or a database and the overall moment of inertia is found by transferring those tracked moments of inertia to an axis through the CG via the parallel axis theorem. The individual moments are then summed to get the overall weight moment of inertia.

For the *CSS Virginia* this method would have proved difficult. Individual moments of inertia were not tracked during the course of the weight estimate, and making inertia estimates based on closely approximating shapes would have been extremely time intensive and difficult.

However, there is a method for using the weight distribution along the longitudinal, vertical, and transverse axes to determine overall moments of inertia. It was first proposed by Hansch in Society of Weight Engineers (SAWE) Paper 3399 and was later adopted by the SAWE as a part of Recommended Practice (RP) No. 17, Weight Distribution and Moments of Inertia for Marine Vehicles.

The method suggested in the paper and the RP states that the total weight moment of inertia can be written as an integral:

$$I_{total} = \int w(r) * rdr$$

where w(r) is weight as a function of r, the radial distance of the weight away from the axis about which the moment of inertia is being taken. If you apply the Pythagorean Theorem the equation can be re-written as

$$I_{total} = \int (w(a) * a)da + \int (w(b) * b)\, db$$

where *a* is the distance along the *a* axis from the axis about which the moment is taken and *w(a)* is the weight as a function of the distance *a*. Likewise *b* is the distance along the *b* axis about which the moment is taken and *w(b)* is the weight as a function of the distance *b*. In this case we would be seeking the moment of inertia about a third axis, *c,* which would be orthogonal to axes *a* and *b*.

Considering that roll, pitch, and yaw occur about the longitudinal (x), transverse (y), and vertical (z) axes respectively, we can then write integral equations for the different moments of inertia as shown below.

$$I_{xx} = \int (w(y) * y)dy + \int (w(z) * z)\, dz$$

$$I_{yy} = \int (w(x) * x)dx + \int (w(z) * z)\, dz$$

$$I_{zz} = \int (w(y) * y)dy + \int (w(x) * x)\, dx$$

Here, *w(x)*, *w(y)*, and *w(z)* are weight distributions along the x, y, and z axes, respectively. The weight distributions can be integrated numerically to find the moments of inertia (Hasnch, 2006).

The weight moments of inertia used to determine radius of gyration are taken about the center of gravity of the ship. Weight distributions can be found with respect to any axis and then transferred to an axis through the center of gravity by applying the parallel axis theorem

$$I_{CG} = I_{aa} - W(d^2)$$

where I_{CG} is the weight moment of inertia about an axis at the center of gravity, I_{aa} is the moment of inertia about a different axis that is parallel to the axis at the center of gravity, W is the overall weight, and d is the distance between the axis *aa* and axis *cg*.

3.8.1 Weight Distributions

The weight analysis was used to develop weight distributions along the vertical, transverse, and longitudinal axes. The weight distribution along the longitudinal axis was referenced to the FRP, the weight distribution along the transverse axis was referenced to the CL, and the weight distribution along the vertical axis was referenced to the BL. The weight distribution along the longitudinal axis was a 21 station weight distribution, the distribution about the transverse axis was based on 1 foot increments, and the vertical distribution was based on 2 foot increments.

The weights were located or split into these different incremental stations and bins. Some weights were treated as discrete loads and placed into one station, other weights were distributed over a number of stations. As an example: the weight of the wood and steel for the casement was distributed along its length based on the assumption of a constant weight per foot. The weight of things like the ram, pilot house, anchors, were all treated as discrete items and placed into a single bin that approximated their locations. Items that might be considered a distributed weight along one axis may be treated as discrete when the weight distribution along another axis is examined. All of the decks were considered to have weights distributed in the longitudinal and transverse directions, but were considered discrete weights along the vertical axis.

The resulting tabular weight distributions are included in Appendix C. The approximate longitudinal, transverse, and vertical weight distributions are shown in Figures 29, 30, and 31. It should be noted that the weight distributions did not sum up perfectly to the overall displacement of *CSS Virginia* at the time of the Battle of Hampton Roads, but are very close (less than 1% difference).

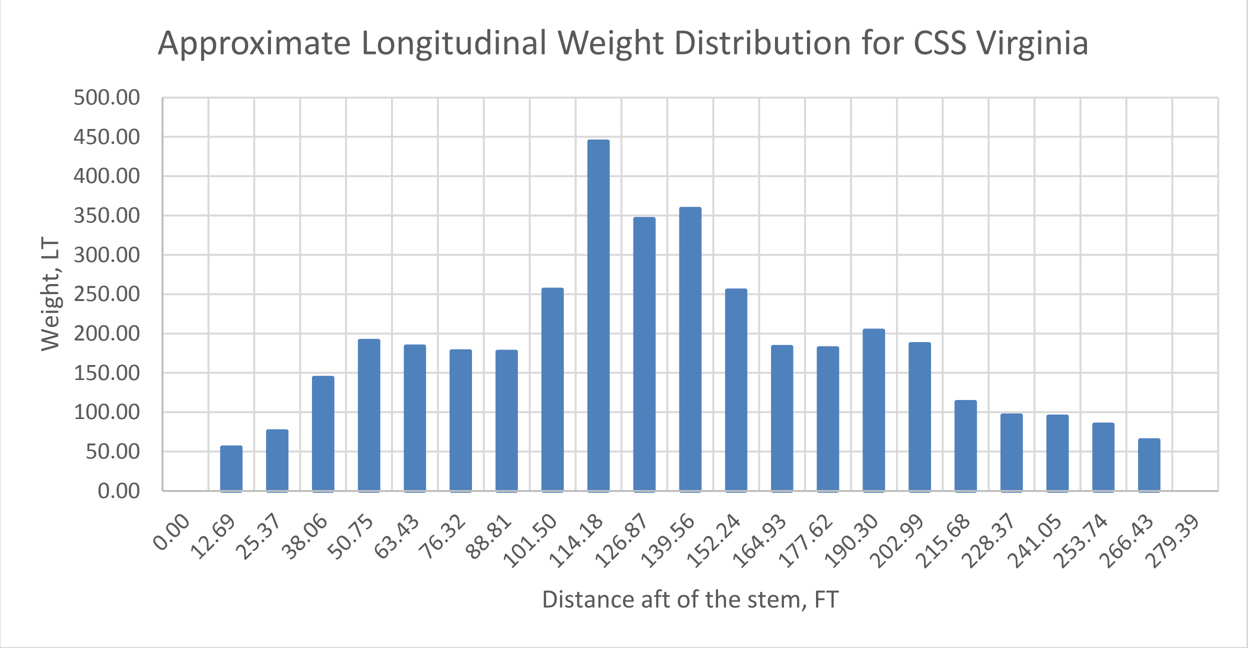

Figure 29: Approximate Longitudinal Weight Distribution for *CSS Virginia*

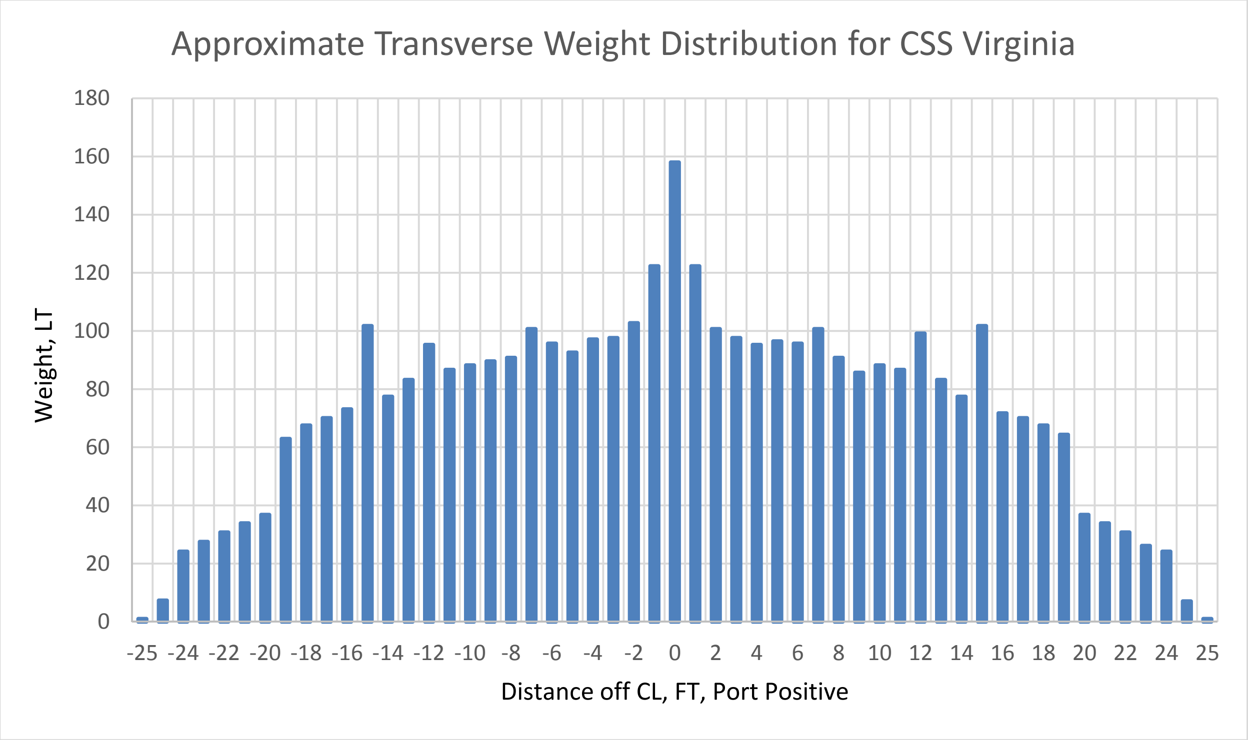

Figure 30: Approximate Transverse Weight Distribution for *CSS Virginia*

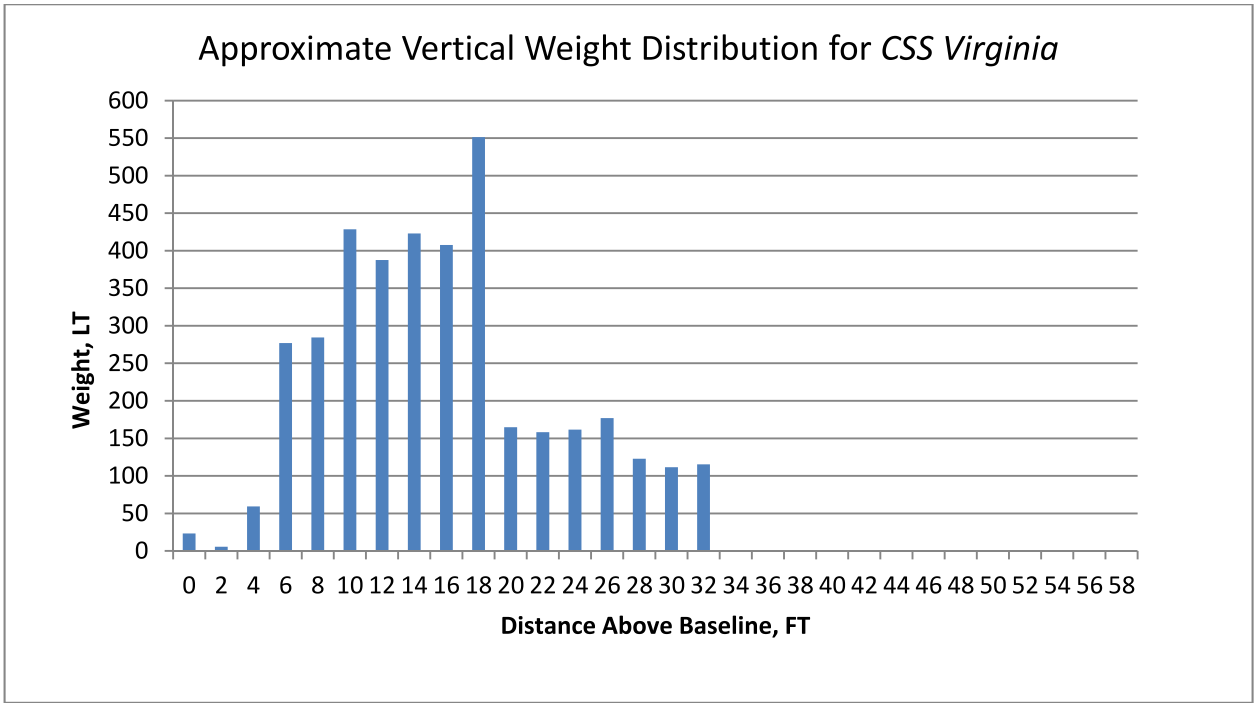

Figure 31: Approximate Vertical Weight Distribution for *CSS Virginia*

3.8.2 Inertia and Gyradius Calculations

With the weight distributions found it was then possible to numerically integrate the functions to get weight moment of inertias. Excel was used to break the weight distributions down into functions were

$$w(x) = \frac{weight}{linear\ foot} * x$$

where the weight per linear foot is a constant over a given interval, corresponding to the subdivisions used to define the weight distributions. The variable *x* is the subinterval distance that allows for the entire weight in the interval within the weight distribution to be accounted for. The weight per foot varies from one subdivision to the next. The example shown above is along the x axis; the y and z axes are similar.

To further develop the method used, set aside for a moment the notion of breaking up into intervals the length across which the weight distribution is taken, and assume that the w(x), as defined above, uses a constant weight per linear foot over the entire length of interest.

Given that the weight per linear foot is a constant, the inertial equations can be reduced into something simple enough to see using integral calculus. As an example, consider the equation for I_{yy}:

$$I_{yy} = \int (w(x) * x)dx + \int (w(z) * z)\, dz$$

If we let the weight per foot in the x direction be delineated by the constant θ and the weight per foot in the z direction be the constant α, then the weight distribution functions can be represented as

$$w(x) = \theta * x$$

$$w(z) = \alpha * z$$

Then the equation for moment of inertial about the y axis can be re-written as

$$I_{yy} = \theta \int x^2 dx + \alpha \int z^2 dz$$

Now we bring back into the mind the fact that θ and α are not constant over the entire length of the axes in question for their respective weight distributions, but only across subintervals of those distributions. If we have *n* intervals along the x axis and *k* intervals along the z axis, we can arrive at an expression that is able to be tabulated and summed.

$$I_{yy} = \sum_i^n \theta_i \int_{a_i}^{b_i} x^2 dx + \sum_i^k \alpha_i \int_{e_i}^{f_i} z^2 dz$$

Carrying out the integrals, we now have:

$$I_{yy} = \sum_i^n \theta_i \left(\frac{b_i^3}{3} - \frac{a_i^3}{3}\right) + \sum_i^k \alpha_i \left(\frac{f_i^3}{3} - \frac{e_i^3}{3}\right)$$

It remains to correct the inertial components to the center of gravity if necessary, using the parallel axis theorem. For the gyradius calculations of the *CSS Virginia* it was necessary, as the weight distributions were referenced to the FRP, CL, and BL.

To start with one example, if we let d_x be the distance in the x direction between the CG and the point about which the longitudinal inertia component was taken, and if we let d_z be the distance in the z direction between the

CG and the point about which the vertical inertia component was taken, the parallel axis theorem can be used to express I_{yy} about the CG:

$$I_{yyCG} = \left(\left[\sum_i^n \theta_i\left(\frac{b_i^3}{3}-\frac{a_i^3}{3}\right)\right] - \Delta d_x^2\right) + \left(\left[\sum_i^k \alpha_i\left(\frac{f_i^3}{3}-\frac{e_i^2}{3}\right)\right] - \Delta d_z^2\right)$$

This is an expression that, if somewhat inelegant, is well suited for use in a program such as Excel. Similar expressions can be found for I_{zz} and I_{xx}. If we denote the weight in the transverse (y) direction to be

$$w(y) = \beta * y$$

and allow it to be integrated over subintervals s_i to t_i, then we can get recast our expressions from I_{zz} and I_{xx} through the center of gravity as

$$I_{zzCG} = \left(\left[\sum_i^n \theta_i\left(\frac{b_i^3}{3}-\frac{a_i^3}{3}\right)\right] - \Delta d_x^2\right) + \sum_i^j \beta_i\left(\frac{t_i^3}{3}-\frac{s_i^t}{3}\right)$$

$$I_{xxCG} = \left(\left[\sum_i^k \alpha_i\left(\frac{f_i^3}{3}-\frac{e_i^3}{3}\right)\right] - \Delta d_z^2\right) + \sum_i^j \beta_i\left(\frac{t_i^3}{3}-\frac{s_i^t}{3}\right)$$

Note that for the transverse contribution a correction using the parallel axis theorem is not necessary for the *CSS Virginia*. Symmetry port and stbd is assumed, the TCG is on CL, and thus $d_y = 0$.

With the weight moment of inertias estimated it was then possible to estimate the gyration radii by using the formulas

$$K_x = \sqrt{\frac{I_{xxCG}}{\Delta}}$$

$$K_y = \sqrt{\frac{I_{yyCG}}{\Delta}}$$

$$K_z = \sqrt{\frac{I_{zzCG}}{\Delta}}$$

In keeping with convention the gyradii are expressed as unit less coefficients obtained by taking the gyradius and dividing it by the overall length or beam of the ship, depending on the gyradius in question.

Tabulated final results can be seen in Tables 6 and 7 below. Additional details can be seen in Appendix C.

Moments due to distribution along axis	Uncorrected Weight Moments ($LTft^2$)	Weight (based on Distribution - LT)	Distance Between the reference axis at (0,0,0) and the CG	Corrected Weight Moments ($LTft^2$)
Vertical	1066078	3868.50	15.08	186015
Longitudinal	75988516	3868.51	126.31	14270485
Transverse	543372	3869.51	0.00	543372

Table 6: Derivation of Corrected Weight Moments of Inertia

Parameter	Weight Moment (LTft^2)	Weight (LT)	Gyradius (ft)	Coefficient
Pitch	14456499	3868.50	61.13	0.22
Yaw	14813857	3869.01	61.88	0.22
Roll	729387	3869.01	13.73	0.27

Table 7: Gyradius Coefficients

3.9 Sea Keeping Analysis

With the geometry of the ship modeled and the weight, CG, and gyration radii estimated, it was now possible to use Paramarine to run various sea keeping analyses. Of particular interest was long term mission effectiveness based on sea sickness and shipping water through the gun ports, which would be a risk if the *CSS Virginia* were to run into heavy seas. Mission effectiveness was examined for three different locations in the Chesapeake Bay and in the open ocean off the Virginia coast. While the *Virginia's* theatre of operations was intended to be limited to the Chesapeake Bay area, examining open ocean effectiveness would allow for an assessment of the *Virginia's* ability to set sail for a different port in Confederate hands or attack a Union city.

To accomplish the sea keeping analysis Response Amplitude Operators (RAOs) were generated for the *CSS Virginia* based on wave heights and frequencies established from actual wave data in the Chesapeake Bay and off the Virginia Coast in 2015. Those RAOs were then used in Paramarine to carry out a long term analysis of operational effectiveness for the Virginia based on seasickness criteria and flooding through the gun ports. A more detailed description of the process follows.

3.9.1 Selection of Geometry

Paramarine requires that geometry be selected from the main geometry model for analysis. The geometry selected can be seen in Figure 32. Note that the breakwaters and rudder has been left out of the selection. Paramarine's sea keeping engine requires a solid body that can be divided into sections for its strip theory based analysis program, and the addition of the breakwater and the rudders made it difficult to create the necessary solid body sections.

Leaving the breakwater and the rudder out of the geometry seems acceptable. The breakwaters typically would be mostly above waterline and are therefore not likely to have a major impact on the overall analysis. Again, it is assumed there are limber holes in the bottom of the breakwater to allow the area enclosed by the casement and the breakwater to act as a free flooding space. Thus there is no additional buoyancy added, aside from the buoyancy due to the displacement of the breakwaters themselves, which would have a negligible contribution to the hull's sea keeping characteristics. Likewise there is no free surface effect to consider, as stipulated in Section 3.1

The rudder is also believed to be too small to make much of a difference in the analysis overall, and as it is on CL it was believed its impact on roll damping in the sea keeping analysis would be small in comparison to other aspects of the ship's geometry, such as the keel and the fantail, both of which were included as a part of the analysis geometry.

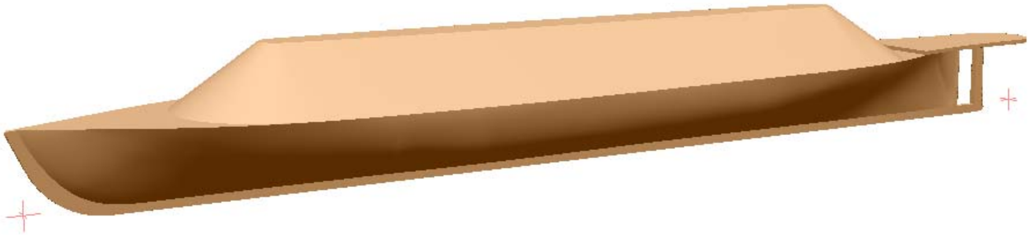

Figure 32: Geometry Selected for Sea keeping Analysis

The geometry was divided into sections by Paramarine for the sea keeping analysis, as shown in Figure 33.

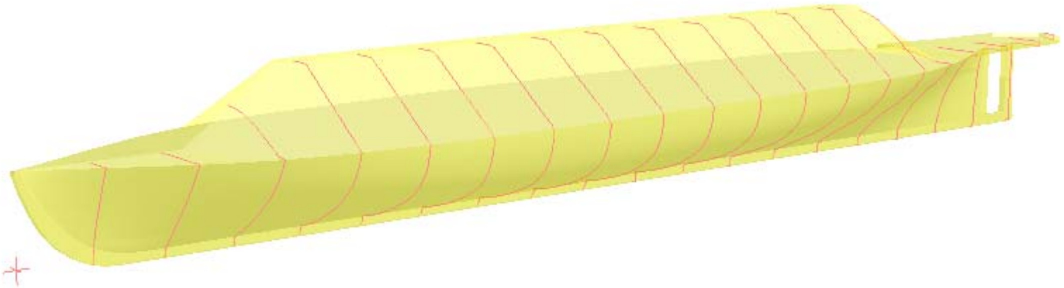

Figure 33: Geometry Divided into Sections for Sea Keeping Analysis

3.9.2 Development of Wave Data

For Paramarine to develop the RAOs a wave height and range of frequencies is required as input. To run the long term operability analysis a more comprehensive set of wave data is required concerning the probability that the vessel will encounter a certain wave height and period. Rather than use average data it was felt that it might be interesting to compile actual buoy data over a given time and use the data in the analysis.

Wave data was extracted from NOAA's National Buoy Data Center. Significant wave heights and average wave period was used; one of the buoys selected offered both average and dominant wave period data, but the others supplied only average period data, so in all cases average period was used for the sake of consistency. The time period chosen was January – May 2015. 2015 was chosen because it was the most recent compiled data available at the time when the wave data for the analysis was being developed. The months of January through May were chosen because that was about the time of year that the *CSS Virginia* was active during its short service life in 1862; using data for 5 months also made the creation of a statistical wave atlas more manageable.

Data was taken from three Chesapeake Bay buoys and one buoy located in the Atlantic Ocean approximately 64 miles east of Virginia Beach, VA. A summary of the buoys used is listed in Table 8.

Station #	Location	Latitude	Longitude	Owner
44014	64 NM East of Virginia Beach, VA	36° 36' 41'' N	74° 50' 31'' W	National Data Buoy Center
44064	First Landing (Cape Henry)	36° 58' 28'' N	76° 2' 44'' W	Chesapeake Bay Interpretive Buoy System
44058	Stingray Point (Deltaville), VA	37° 34' 2'' N	76° 15' 27'' W	Chesapeake Bay Interpretive Buoy System
44042	Potomac, MD	38° 1' 59'' N	76° 20' 8'' W	Chesapeake Bay Interpretive Buoy System

Table 8: Data Buoys Used in Sea keeping Analysis

Drawing general conclusions about the *CSS Virginia's* sea keeping characteristics based on data from such a specific time implies, implicitly, that the chosen data is representative of all other time periods, and particularly the time period in 1862 when the *Virginia* was actively operating. That assumption is admittedly problematic. However, it is noted that the significant wave data from buoy 44014 tracks fairly close to average significant wave heights from 1990 – 2008 over January through May, as shown in Figure 34. No such comparison could be made for the Chesapeake Bay buoys, but as the buoys listed above are all close enough to show the effects of major weather events that drive the wave characteristics measured, it is assumed that if Buoy 44014's data tracks close to averages than the others do as well.

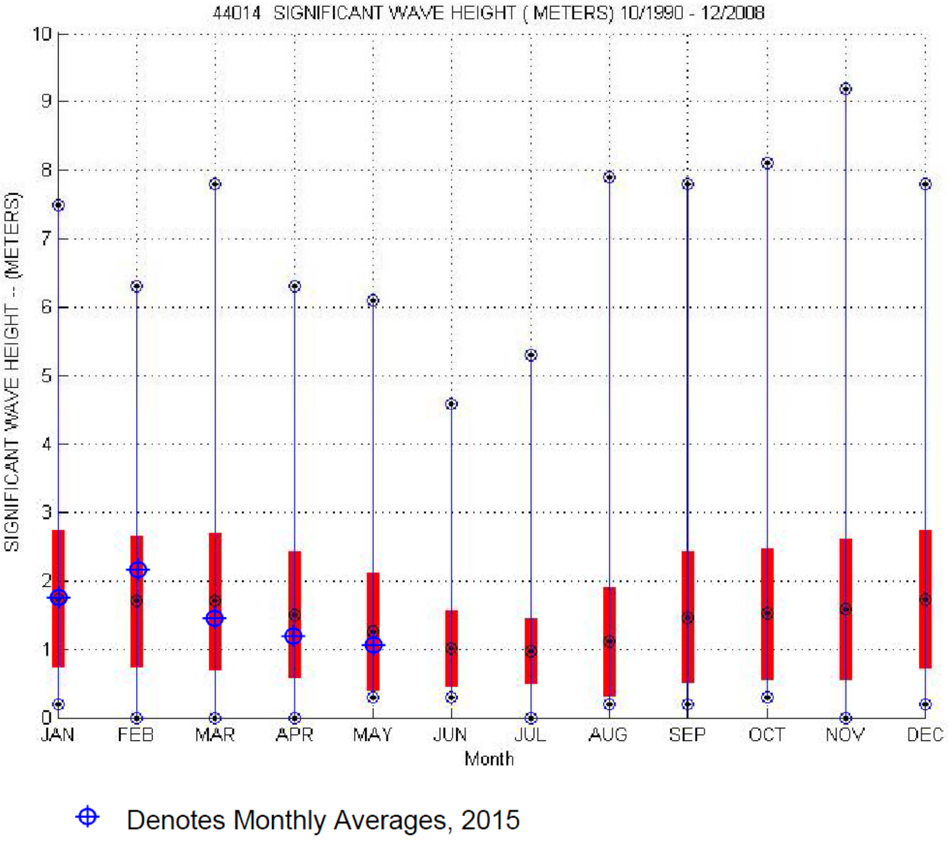

Figure 34: Average Wave Heights January - March 2015, Compared to Long Term Averages, Station 44014: Graphic from National Buoy Data Center Website

So one goes out on a limb and says that the data is representative "enough" for the purposes of this analysis. Different time periods are not likely to show vastly different characteristics, and thus measures of effectiveness derived from the wave data selected for this task are not likely to differ vastly over other periods of time. The lone exception to this would be if one just focused on wave data from June and July, which based on Figure 34 has the lowest average wave heights. But for the sake of making some general conclusions about how the *Virginia* would fare on the Bay and at sea the data selected should be acceptable to use without fear of the results being off base. In other words, if the ship does not perform well based on data taken from May – June 2015, it is likely to perform poorly over other similarly sized time periods, no matter what year the data is taken from.

The data in most cases was collected by the buoys hourly. The data points for the wave height and the average period were downloaded into Excel and then placed into histograms. The number of bins required was estimated initially using the Rice Rule[19], which in turn determined the step size of the bins. That initial estimate was adjusted so that there were enough bins to create a histogram that spanned the entire set of wave data, so the number of bins actually used did not match the Rice Rule recommendation.

If n is the number of data points, k is the number of bins, h is the bin size, and $max(x)$ and $min(x)$ are the maximum and minimum values in the data set, then the Rice Rule for estimating bin numbers and bin size can be written mathematically as

$$k = 2n^{\frac{1}{3}}$$

$$h = \frac{\max(x) - \min(x)}{k}$$

A histogram is a representation of a data distribution, based on the number of points that fit within each bin. It was possible to express the frequencies for each bin as a probability by dividing the frequency values tied to each bin by the total number of data points. As an example, Table 9 shows histograms for the open ocean wave data, both for wave height and average period, where the data is expressed as frequencies and probabilities. The same histograms can be seen in Appendix D along with the histograms for the data taken from the buoys in the Chesapeake Bay.

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[19] See http://onlinestatbook.com/2/graphing_distributions/histograms.html. The Rice Rule is presented by David Lane of Rice University as an alternative to the Sturges' Rule that typically results in more bins and a finer distribution. Lane notes that the ultimate selection of bins and step sizes for a histogram is somewhat flexible; the number of bins should be adjusted until a distribution is achieved that fits the data well.

Significant Wave Height, FT				Average Wave Period, Seconds		
Bin	*Frequency*	Probability		*Bin*	*Frequency*	*Probability*
0.33	0	0.0000		3.46	1	0.0003
0.914201	0	0.0000		3.69129	16	0.0044
1.498402	50	0.0138		3.922581	40	0.0111
2.082604	202	0.0559		4.153871	93	0.0257
2.666805	361	0.0998		4.385161	166	0.0459
3.251006	453	0.1253		4.616452	285	0.0788
3.835207	415	0.1148		4.847742	326	0.0902
4.419408	387	0.1070		5.079032	372	0.1029
5.003609	344	0.0951		5.310323	396	0.1095
5.587811	245	0.0678		5.541613	393	0.1087
6.172012	182	0.0503		5.772903	310	0.0857
6.756213	175	0.0484		6.004194	292	0.0808
7.340414	122	0.0337		6.235484	265	0.0733
7.924615	97	0.0268		6.466774	185	0.0512
8.508817	83	0.0230		6.698065	127	0.0351
9.093018	90	0.0249		6.929355	84	0.0232
9.677219	62	0.0171		7.160645	68	0.0188
10.26142	77	0.0213		7.391935	58	0.0160
10.84562	57	0.0158		7.623226	47	0.0130
11.42982	42	0.0116		7.854516	23	0.0064
12.01402	46	0.0127		8.085806	22	0.0061
12.59822	22	0.0061		8.317097	11	0.0030
13.18243	21	0.0058		8.548387	8	0.0022
13.76663	18	0.0050		8.779677	5	0.0014
14.35083	10	0.0028		9.010968	5	0.0014
14.93503	15	0.0041		9.242258	1	0.0003
15.51923	7	0.0019		9.473548	5	0.0014
16.10343	10	0.0028		9.704839	3	0.0008
16.68763	4	0.0011		9.936129	3	0.0008
17.27183	4	0.0011		10.16742	3	0.0008
17.85604	8	0.0022		10.39871	0	0.0000
18.44024	2	0.0006		10.63	3	0.0008
19.02444	3	0.0008		10.86129	0	0.0000
More	2	0.0006		More	0	0.0000
n	3616			*n*	3616	

Table 9: Histograms of Open Ocean Wave Heights and Average Periods

For use in Paramarine's long term effectiveness analysis, the probabilities were combined to express the probability that the *CSS Virginia* would see a certain wave height and period (i.e. a particular sea state). That probability is given by

$$P_{ss} = (P_{waveheight})(P_{waveperiod})$$

Every combination of wave height and period in the histograms had to be used. For the open ocean data this amounted to a table of probabilities made up of 34 rows and 34 columns. The overall sum of the entities making up the table equals 1.0. A partial example of one of the probability tables can be seen in Appendix D.

To make the Paramarine program run more efficiently, and to ease the transfer of data from Excel into Paramarine, the resulting probabilities were entered into Paramarine rounded to three decimal places. Some rounding of probabilities between 0.00030 and 0.00050 up to a value of 0.001 was done in the wave atlas so that all probabilities were to the nearest hundredth yet still summed to unity. Such rounding accounts for 0.02 to 0.07 out of a total probability of 1.0, and is not deemed to alter the results of the analysis to any great degree.

3.9.3 Generation of RAOs

With geometry selected and wave data developed, it was now possible to use Paramarine to generate RAOs. Paramarine uses PROTEUS 3, a sea keeping program developed by Safety at Sea Ltd (currently a part of the Brookes Bell Group) to develop RAOs for a variety of speeds and headings. The program uses algorithms based on strip theory. For this project RAOs were run at 0 knots and 6 knots, over headings ranging from 0 to 360 degrees on 30 degree increments. A complete set of RAOs can be seen in Appendix E.

RMS motions were generated from the RAOs based on an offshore sea state. The wave height for the RMS motion plot was set at 5.164 feet and a modal period of 8.333 seconds was used. The modal period corresponds to an encounter frequency of 0.12 Hz, at which roll resonance occurs for the 0 knot RAOs. See section 4.2.1 for further details. The wave height of 5.164 feet is the average wave height encountered based on the offshore data from station 44014. The RMS plots are therefore representative of the *CSS Virginia* sailing in the open ocean.

3.9.4 Operability Analysis

Once the RAOs were complete operability analyses could be run. A long term operability analysis combines the RAOs and the probability density tables generated from the wave buoy data. Mission effectiveness is based on the probability of meeting the given criteria based on the calculated RAOs.

For the *CSS Virginia* operability analyses were run for the three sets of wave data on the Chesapeake Bay and for the single wave data set taken at offshore station 44014. Two sets of criteria were examined against the wave data. The first was a Motion Sickness Index (MSI) criteria taken at points along the gun deck. The second was a deck wetness criteria taken at the open gun ports of the casement.

3.9.4.1 MSI Criteria

MSI was calculated based on the RAOs and wave data probability densities. MSI was taken at several points on the gun deck. The gun deck was chosen because that is where much of the crew would be while the ship was accomplishing its main mission (i.e. to fight and break the Union Blockade of Hampton Roads). It is also a place where most of the crew was made up of volunteers from Confederate artillery units, many of whom were likely not used to being at sea, and therefore more susceptible to seasickness. The crew of *Virginia* taking other posts (officers, engineers) were mostly former sailors in the Union navy and thus, in theory, more acclimated to being at sea and less susceptible to seasickness. The points at which MSI criteria were based can be seen below in Table 10 and Figures 35 and 36. For all four operability runs, MSI criteria was adjusted until the *Virginia's* effectiveness began to approach 100% to allow for good comparisons of motion sickness impacts in all operating locations defined by Table 8.

MSI Criteria Locations			
	X (ft Aft FRP)	Y (ft off CL, port +)	Z (ft abv BL)
Port Fwd	61	9.773	24.485
Stbd Fwd	76.334	-10.634	24.485
Port Aft	182.333	10.063	24.485
Stbd Aft	173	-10.41	24.485

Table 10: Points for MSI Criteria

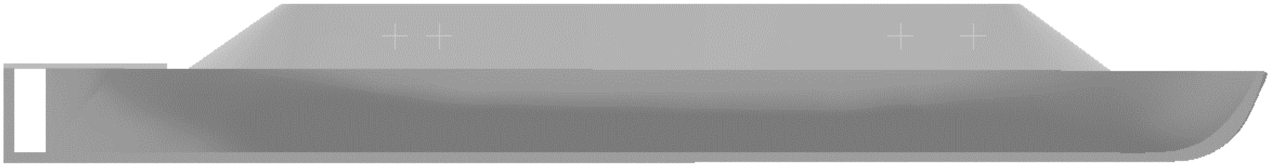

Figure 35: Profile View Showing MSI Criteria Points

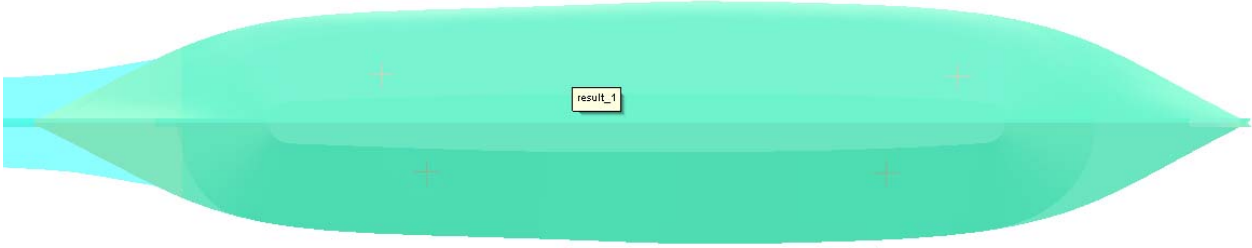

Figure 36: Plan View Showing MSI Criteria Points

3.9.4.2 Deck Wetness Criteria

It is fairly obvious that one of the main problems with the *CSS Virginia* from a safety at life at sea stand point is low freeboard to the gun ports. At the battle drafts the freeboard is only about 4 feet. In rough seas water could easily enter through these gun ports[20]. The *CSS Virginia* would have had bilge pumps of some kind onboard to remove excess water, but it is very possible for the water entering the ship to outstrip the pumps. At what point that would occur is hard to say. Nothing in the historical literature reviewed for this project pointed to a bilge pump capacity.

To honor the fact that freeboard would be the main problem with the *CSS Virginia* at sea, a deck wetness criteria was developed. As shown in Table 11, 8 points were selected approximately at the bottom of the gun ports which ring the entire ship. A deck wetness frequency of 0.004 Hz was attached to each of these points. This represents the rather arbitrary conclusion that the captain of the *Virginia* might start to get worried if he was shipping water through any of the gun ports at a rate of once every 250 seconds (about once every 4 minutes). It may very well be that the *Virginia's* pumps could compensate for that rate of water ingress through one of the gun ports, but it's difficult to know for certain. Paramarine is also indifferent to the amount of time that the gun port is wetted, as well as the portion of the gun port that is subjected to the sea. It is one thing to have it be wetted partially

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[20] It is true that the Virginia may had shutters for the gun ports made out of plate metal (Park, 2007), but these were not water tight and in any case could probably be easily lost in heavy weather

for a second, but quite another to have it fully submerged for 3 seconds. Paramarine only is looking for how often the deck wetness occurs, not its duration.

Deck Wetness Criteria Locations			
	X (ft Aft FRP)	Y (ft of CL, Port +)	Z (ft abv BL)
Fwd CL	42.143	0	24.485
Aft CL	215.792	0	24.485
Port Fwd	61	13.773	24.485
Stbd Fwd	76.334	-14.634	24.485
Port Mid	126.667	14.41	24.485
Stbd Mid	126.667	-14.41	24.485
Port Aft	182.333	14.063	24.485
Stbd Aft	173	-14.41	24.485

Table 11: Deck Wetness Criteria Locations

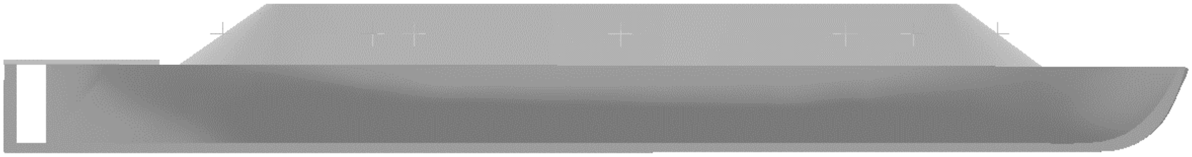

Figure 37: Elevation Showing Deck Wetness Criteria Points

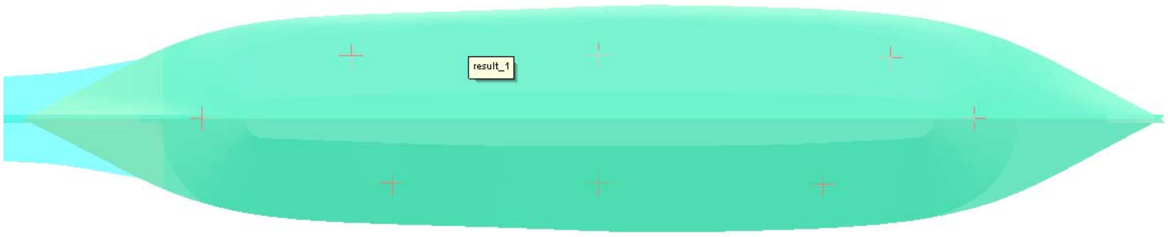

Figure 38: Plan View Showing Deck Wetness Criteria Locations

3.10 Resistance Analysis

It was originally intended that a detailed resistance and propulsion and analysis, coupled with a maneuvering analysis, would be carried out to see just how fast the *CSS Virginia* might have been able to go and how well it might have handled. The results would be compared against the historical records, such as they are.

This turned out to be a tall order. Paramarine has a suite of propulsion and maneuvering tools, but many of the tools are set up with modern day shipping in mind and will not accommodate vintage 1850's hull forms and technology very well. In addition the *CSS Virginia* hull form, which is rather unique with the lower hull completely submerged, did not have characteristics that fell within the parameters of many of the empirical resistance methods employed by Paramarine. In the one instance where it did, the Andersen resistance method was applied but the results seemed unrealistically high.

It was decided to take the parameters from the Paramarine model and use them in a NAVCAD analysis. Even then, in order to make the analysis work for NAVCAD it was thought best to analyze the ship as though it had a draft of 18.25 feet, meaning that a small portion of the lower hull would be just above the surface of the water. That makes the analysis more like that on a conventional ship, and makes an analysis at least possible. The waterline length of the ship at a draft of 18.25 feet was taken to be 265.35 feet, or the length between perpendiculars as chosen (see section 3.4). This is roughly the length of the hull. The fantail was thought best considered as an appendage. Note that the displacement was still that of the *Virginia* at its battle drafts, which is why it is correct to say the ship was analyzed as though it had a draft of 18.25 feet.

It is acknowledged that an analysis based on the parameters above will not provide an accurate result for the *CSS Virginia* in its battle condition; already the resistance of the lower hull's submerged upper decks and the form and frictional drag produced by the casement are being neglected. It is also noted that most of the powering methods used in NAVCAD are based on resistance data from other existing models and hull forms, and it's likely that the antiquated hull form, with a hard keel, bluff bow, and shaped stern, does not compare favorably with the hull forms used to build the powering methods. It might be said that the analysis shows what a modern day vessel with characteristics similar to those of the *Virginia* would require if it were to be propelled at low speed with no hotel loads.

Table 12 shows the inputs used in the NAVCAD analysis. Based on the inputs NAVCAD suggested the Holtrop and the Andersen powering methods, and was also able to run resistance analyses based on the Oortmerssen, Swift, and Kostov methods, though the latter three were not considered ideal by the software based on the model parameters. For the analyses it was assumed that wind speed was zero and there were no waves, so no allotment has been made for the weather. To account for the fact that the *CSS Virginia* was at times working in relatively shallow waters the Schlichting method was selected to add drag due to the shallows.

Input Parameter	Parameter Value or Selection
Configuration	Monohull
Chine Type	Round/multiple
Length on WL	265.35 ft
Beam	51.00 ft
Wetted Surface Area	15117.30 ft^2
LCB Fwd Transom	130.281ft
LCF Fwd Transom	127.753 ft
Max Section Area	627.026 ft^2
Waterplane Area	9792.069 ft^2
Displacement	3869.31 LT
Immersed Transom Area	30.947 ft^2
Transom Beam on Waterline	2.00 ft
Transom immersion	18.05 ft
Half Entrance Angle	26.00 deg
Bow Shape Factor	1.0 (WL Flow – Rounded Beam)
Stern Shape Factor	-1.0 (BTK Flow – V Shaped Stern)
Propulsor Type	Propeller
Count [of Propulsors]	1
Water Type	Brackish
Density	1.9647 slug/ft^3 (NAVCAD Default)
Viscosity	1.25280e-5 ft^2/s (NAVCAD Default)
Viscous Expansion	Standard
Friction Line	ITTC-57
Hull form Factor	1.0000
Correlation Allowance	ITTC-78 (v 2008) (NAVCAD Default)
Appendage Drag	Assume 5% of overall
Shallow/channel	Apply Schlichting Methodology

Table 12: NAVCAD Analysis Inputs

4 RESULTS AND DISCUSSION

4.1 Hydrostatics and Initial Stability Assessment

4.1.1 Hydrostatic Tables and Curves of Form

A summary of hydrostatics for different mean drafts between marks is shown below in Table 13. Hydrostatics for the ship in its condition during the battle are shown in Table 14.

Mean Draft	Displacement (LT)	LCB (ft)	LCF (ft)	TPI (LT/in)	KMt (ft)	GMt (ft)	MTI (LTft/in)
10.00	999.04	3.50	3.31	16.95	27.94	12.86	195.88
10.50	1102.50	3.47	3.02	17.53	27.94	12.86	205.40
11.00	1209.36	3.42	2.76	18.09	27.91	12.83	214.73
11.50	1319.42	3.35	2.54	18.59	27.76	12.68	223.73
12.00	1432.41	3.28	2.30	19.07	27.60	12.52	232.52
12.50	1548.21	3.20	2.09	19.52	27.44	12.36	241.17
13.00	1666.58	3.11	1.89	19.93	27.19	12.11	249.44
13.50	1787.31	3.02	1.68	20.31	26.95	11.87	257.54
14.00	1910.32	2.93	1.47	20.69	26.75	11.67	265.55
14.50	2035.47	2.83	1.28	21.02	26.51	11.43	273.24
15.00	2162.59	2.74	1.09	21.35	26.29	11.21	280.80
15.50	2291.60	2.64	0.93	21.65	26.09	11.01	288.23
16.00	2422.38	2.54	0.77	21.94	25.89	10.81	295.57
16.50	2554.82	2.45	0.64	22.20	25.69	10.61	302.58
17.00	2688.77	2.35	0.48	22.45	25.48	10.40	309.39
17.50	2824.15	2.26	0.33	22.68	25.31	10.23	316.19
18.00	2960.93	2.17	0.20	22.91	25.16	10.08	322.75
18.50	3098.99	2.08	0.06	23.11	25.01	9.93	329.14
19.00	3238.22	1.99	-0.01	23.30	24.88	9.80	334.68
19.50	3380.39	1.83	-12.90	22.92	24.28	9.20	344.04
20.00	3515.82	1.26	-13.23	22.23	22.92	7.84	333.88
20.50	3646.31	0.76	-0.43	19.26	21.47	6.39	198.38
21.00	3759.86	0.72	-0.36	18.59	20.48	5.40	189.06
21.50	3869.37	0.69	-0.28	17.92	19.62	4.54	180.02
22.00	3974.88	0.67	-0.20	17.25	18.87	3.79	171.27
22.50	4076.43	0.65	-0.11	16.60	18.22	3.14	162.81
23.00	4174.08	0.63	-0.02	15.95	17.66	2.58	154.63
23.50	4267.87	0.62	0.08	15.31	17.18	2.10	146.71
24.00	4357.81	0.61	0.16	14.67	16.76	1.68	138.89
24.50	4443.89	0.60	-0.77	13.90	16.38	1.30	125.65

Table 13: Hydrostatics Based on Mean Drafts

Draft Fwd Mark	Draft Aft Mark	Displacement (LT)	LCB (ft)	LCF (ft)	TPI (LT/in)	KMt (ft)	GMt (ft)	MTI (LTft/in)
21.00	22.00	3869.37	0.69	-0.28	17.92	19.62	4.54	180.02

Table 14: Hydrostatics in Battle Condition

Note that for both tables LCB and LCF are in reference to midships as shown in Figure 1 (placed at Station 6). A positive value indicates that the point is *forward* of midships. The value for GM in Table 14 is based on an assumed VCG of 15.08 ft above baseline, which is the VCG in the battle condition calculated by the weight estimate.

To better visualize the *CSS Virginia's* hydrostatic characteristics the data in Table 13 was plotted to create hydrostatic curves. The results can be seen in Figure 39. Note that the ship's mean draft, in feet, is given along the horizontal axis. The vertical axis represents the values of the different hydrostatic characteristics in accordance with the legend below the curves. Note that Displacement has been divided by 1000 to plot on the curves, and MT1 has been divided by 10.

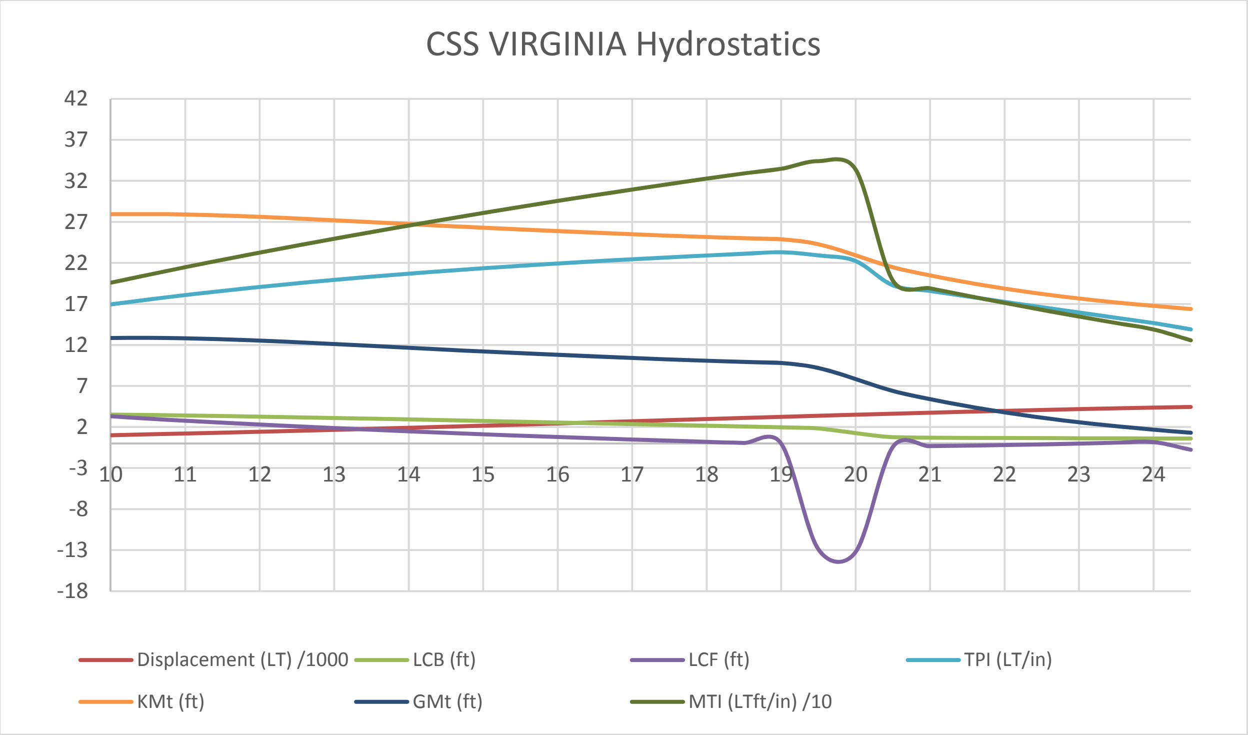

Figure 39: CSS Virginia Hydrostatics

4.1.2 Discussion

There are a few features of the hydrostatics worth noting. First is that for the mean draft hydrostatics in Table 13, the changes due to the large area of the fairwater are evident, as the LCF shifts aft very quickly through drafts 19.5ft through 21ft, and then returns to a location closer to midships once the fairwater is fully submerged. This is very clearly seen in Figure 39.

The curves of form also show that MT1 also changes rapidly after the tail fairing is submerged. KM begins to decrease after the lower hull is submerged (at a draft of approximately 19 feet) and decreases more so as draft increases, which is what would be expected with the tumblehome produced by the sloped sides of the casement.

Second, the value of GM in the battle condition is around 4.5 feet in the battle condition. That value of GM is an indication that while the ship was stable at the battle drafts it was not "overly stable", such that it would induce large accelerations on the crew in the act of righting itself after a heeling excitation.

It is also noted that based on the VCG of 15.08 the GM would only be around 2.5 feet at a draft of 23 feet, which were reportedly the drafts of the *Virginia* after the modifications completed during the post-battle dry docking period noted in Section 2.11. The hydrostatics indicate that the ship was less stable after the modifications were made. The diminishing KM of the tumblehome hull form as the draft of the *Virginia* increases makes it likely that any modifications increasing the weight of the vessel would have lowered stability. This is particularly true of the weight due to the added armor around the knuckle line, which was placed above the CG and would have had the detrimental effect of raising it very slightly. It may be possible that Porter and the other workers and engineers at the Gosport Navy Yard understood this, but decided that the increased survivability (the initial armor band at the knuckle line was felt to be insufficient and therefore a weakness) was worth the trade off.

4.1.3 An Interesting Historical Hypothesis

Another item that the hydrostatics can shed light on is the amount of weight that would have been removed by the crew during the *Virginia's* ill-fated attempt to retreat up the James River.

As noted in section 2.11, shifting winds brought the water levels at the entrance of the James River down, literally pushing water out of Hampton Roads towards the Atlantic Ocean. The pilots aboard *The Virginia* informed Captain Tattnall that in order to even clear Harrison's Bar at the mouth of the James River the draft of the *Virginia* would have to be reduced to 18 feet (Quarstein, 2012). Even from the battle drafts it would require the removal of approximately 900 LT to achieve this, but modifications to *Virginia's* iron band had resulted in a heavier ship and an even higher weight delta to be overcome for the crew. The draft was now 23 feet (Quarstein, 2012), meaning about 1200 LT would have to be removed in order to achieve the desired 18 ft draft.

It is difficult to see where a weight of this magnitude would come from, based on the weight analysis. If you could remove all the ballast, fixed loads, and variable loads, that would only add up to about 630 LT. In order to even get to 900 LT the crew would have to be removing structure, like joiner bulkheads and non-essential structural items, outfitting, maybe even pieces of the casement itself, but even then it is hard to see how that amount of weight reduction could be achieved, especially in one night. Each man, assuming a full complement of 350, would have to move 5760 lbs of material. The Confederacy arguably managed to very much with rather little over the course of the war, but that simply seems like a bridge too far.

The crew reportedly did manage to reduce the draft by 3 feet (Quarstein, 2012) by 1 AM. This would have taken, by the mean draft hydrostatics, 659 LT, which is still rather astonishing considering that the order was given at 7PM on May 10th and by 1 AM on May 11th the pilots had proclaimed the effort to be pointless, as the winds were continuing to blow out of the west and even an 18 foot draft was not light enough to get the ship over Harrison's bar. In order to achieve the 3 foot draft reduction each man would have had to have offloaded 4217 lbs of material in 6 hours.

Tattnall made scapegoats out of the pilots, as the draft reduction effort had made the vessel "no longer an ironclad", with 2 feet of its unprotected hull exposed, robbing Tattnall of the chance to take the *Virginia* out once more against the now significantly strengthened Union Fleet in a suicidal blaze of glory. However, if the ship was at 23 feet to start and the draft had been reduced by 3 feet, then the ship would have been at a mean draft of 20 feet. Not accounting for trim the ship's knuckle line would have still been submerged. Perhaps not to the desired extent but still submerged, a far cry from the two feet of exposed hull noted by Quarstein. As long as the crew had not thrown over all the coal or ammunition, Tattnall could have managed his last stand, had he really wanted to.

In spite of vaunted Southern gallantry and honor, an utterly forlorn assault on the Union Fleet doesn't quite seem in the character of the war, particularly in 1862. Is it not possible that Tattnall ordered the ship lightened knowing it was fruitless in order to shift blame for the loss of the *Virginia* to the pilots? Could he have actually not wanted to take the ship out for one last, hopeless hurrah? Could he have engineered a way to save the crew and destroy the *Virginia* without accepting all of the dishonor associated with losing the vessel?[21] The truth is lost in the sands of time, but this engineer puts it forward as an interesting hypothesis.

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[21] Mallory actually did hold Tattnall responsible for the loss of the *Virginia,* though John Mercer Brooke blamed the loss on poor communication between the evacuating Confederate Army and Tattnall, for which much of the blame shifted towards CSA General Huger. If my hypothesis was presented with a bit of tongue and cheek (though I actually do believe it is a possibility) it must be said that Tattnall's position was absolutely untenable, and there is little else he or the crew could have done.

4.1.4 Righting Arm Curves

A GZ Curve for the ship at a displacement of 3869.37 LT and a VCG of 15.08 feet can be seen in Figure 40. Note that heel to the port side is positive.

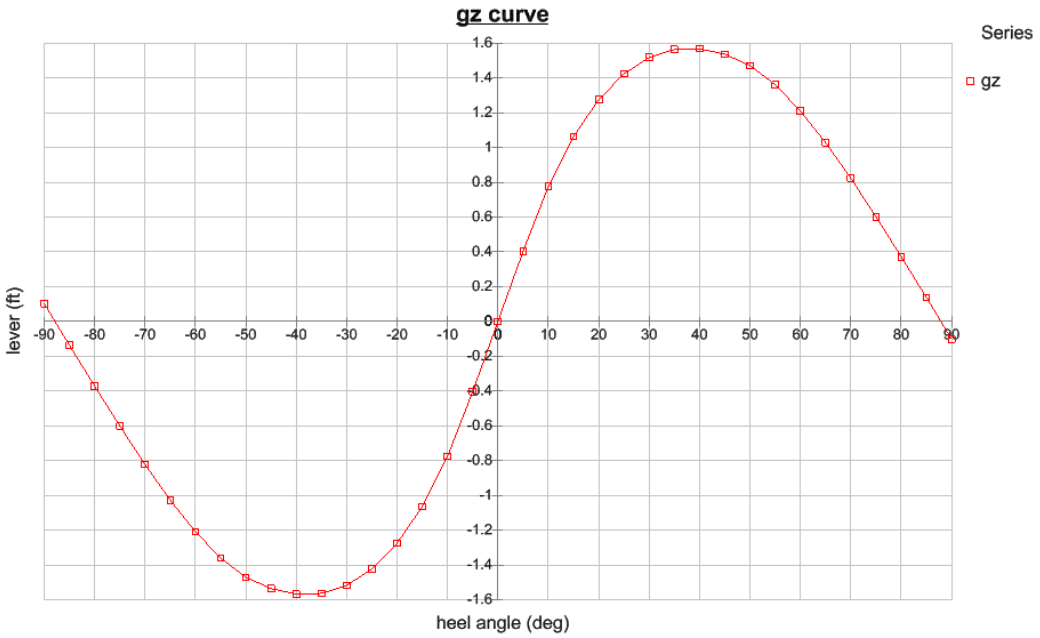

Figure 40: GZ Curve for CSS Virginia, Displacement of 3869.51LT, VCG of 15.08 feet

The relatively low maximum GZ of 1.57 feet is not surprising, but it is surprising that the point of vanishing stability does not occur until the ship has taken on a heeling angle of approximately 87 degrees.

When considering the different elements that impact ship's stability, the one with the most uncertainty in this analysis is the position of the center of gravity.

The geometry model may not represent precisely the vessel that the Confederate States Navy built at Gosport, but based on the dimensional comparison in Table 1 it is probably a close facsimile. As such, the volume of the water displaced by the vessel as it heels and the resulting changes to the hydrostatic forces acting on the vessels have a fair level of certainty.

The center of gravity and weight, however, are based on a weight analysis that was rife with assumptions and therefore carries a higher level of uncertainty. If the VCG is accurate to within, say, +/- 10%, the VCG could be as low as 13.57 feet or as high as 16.56 feet.

A shift upwards of the CG to 16.56 feet would dramatically alter the GZ Curves, as shown in Figure 41. The maximum righting arm is reduced to 0.783 feet at a heeling angle of 25 degrees, with a point of vanishing stability closer to 58 degrees port or stbd. This is more along the lines of what one might expect out of hull form that features extreme tumblehome above the waterline. This could indicate a problem for the *Virginia*; with most of its variable loads located on the bottom deck, the overall VCG of the ship would have risen as coal, powder, shot, provisions, and water were consumed. Taking all the variable loads calculated in the weight analysis and reducing them by two-thirds raises the estimated VCG by about 0.2 feet. That may not be a concern if the estimated 15.08 feet VCG proves correct. But if the VCG was actually higher, more along the lines of 16.56 feet, a 0.2 foot increase would result in a notable decrease in stability, as shown in Figure 42 and by comparison with Figure 41.

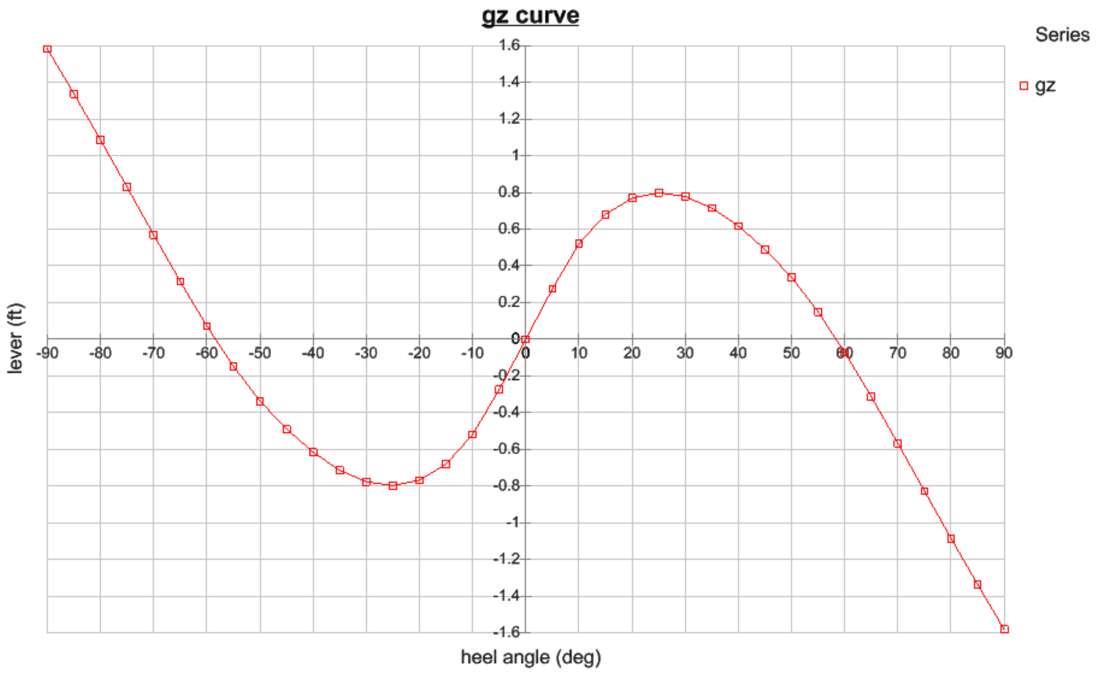

Figure 41: GZ Curve for *CSS Virginia*, Displacement of 3869.51 LT, VCG of 16.56 feet

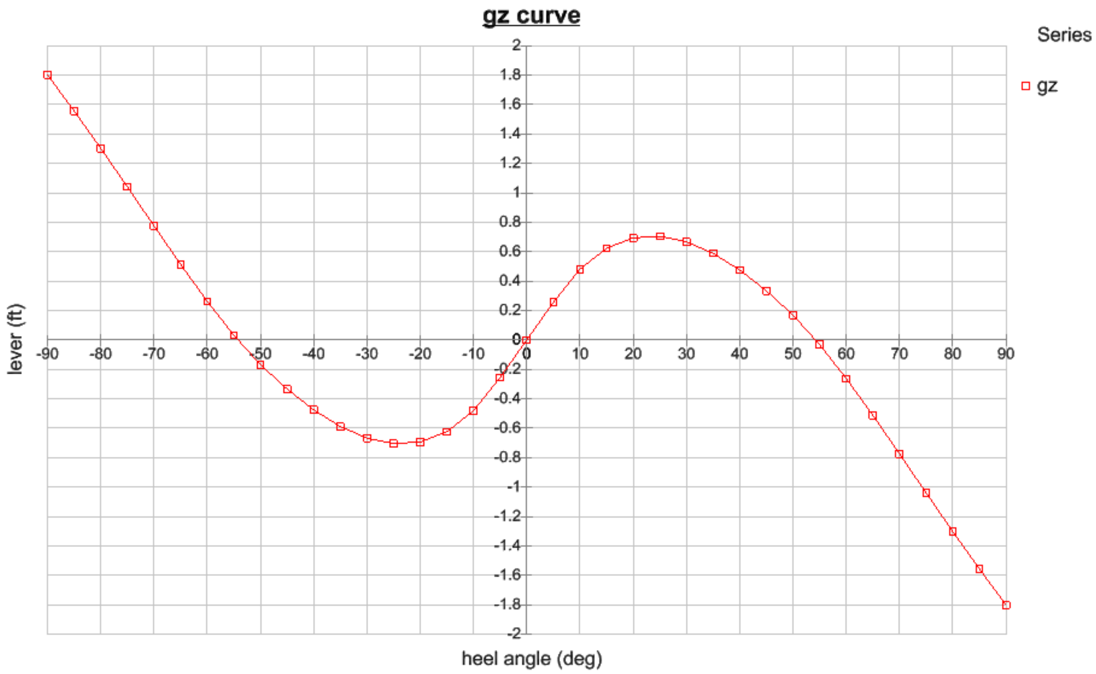

Figure 42: GZ Curve for CSS Virginia, Displacement of 3869.51 LT, VCG of 16.78 feet

Discussion of GZ curves should be taken with a large grain of salt, as achieving a heel of 58 degrees would not be possible for the *CSS Virginia*. The bottom of the gun ports go beneath the waterline at a heeling angle of approximately 16 degrees, and the upper deck is immersed at 46 degrees. While it may be possible that some limited downflooding through the gun ports may improve stability (the lowering of the VCG would have to be considered against the increase of the external waterline and any free surface effects), one must remember that the upper deck was not closed but rather a grid made of railroad ties. Upper deck edge immersion would therefore be catastrophic and likely signal the loss of the ship, even without the gun ports taking on water.

An analysis of downflooding caused by the gun ports was deemed beyond the scope of this project. However, downflooding analyses and additional examination of the stability of the ship (e.g. subjecting the ship to modern day classification and SOLAS rules, noting the effect of heel and waves on initial stability, etc.) represents an area of further study that could provide additional information about the *CSS Virginia's* capabilities or lack thereof.

4.2 Sea Keeping Analysis

4.2.1 RAOs

RAOs were run using PROTEUS 3 (see Section 3.9.3.) for encounter headings 0° to 360° on 30° increments, at speeds of 0 knots and 6 knots. A few outputs that offer insight into the general results are shown below, and the complete set of RAOs for all headings and speeds can be seen in Appendix E.

Figures 43 – 47 show RAO plots at 0 knots on headings of 0°, 30°, 90°, 150° and 180°. This sampling of RAOs paints a good picture of the results at this speed because, as can be seen in Appendix E, the RAO plots show port and stbd symmetry. Displacement motions are plotted against wave amplitude, and the angular motions are plotted against wave slope.

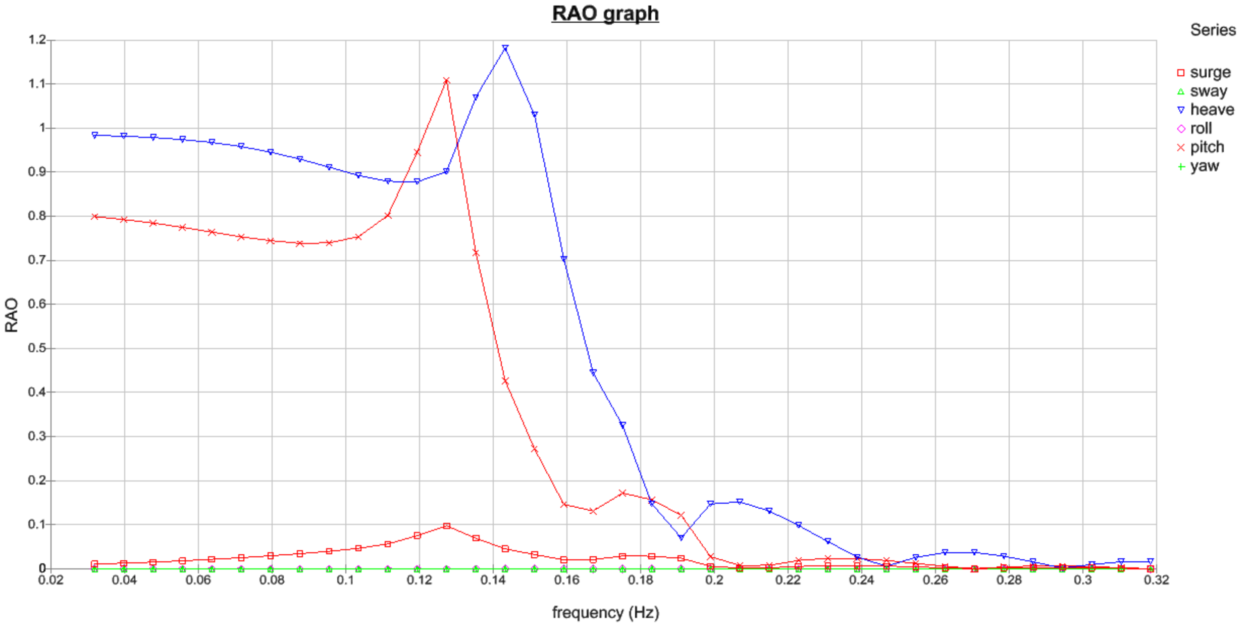

Figure 43: RAO Graph, 0 knots, 0 degree Heading

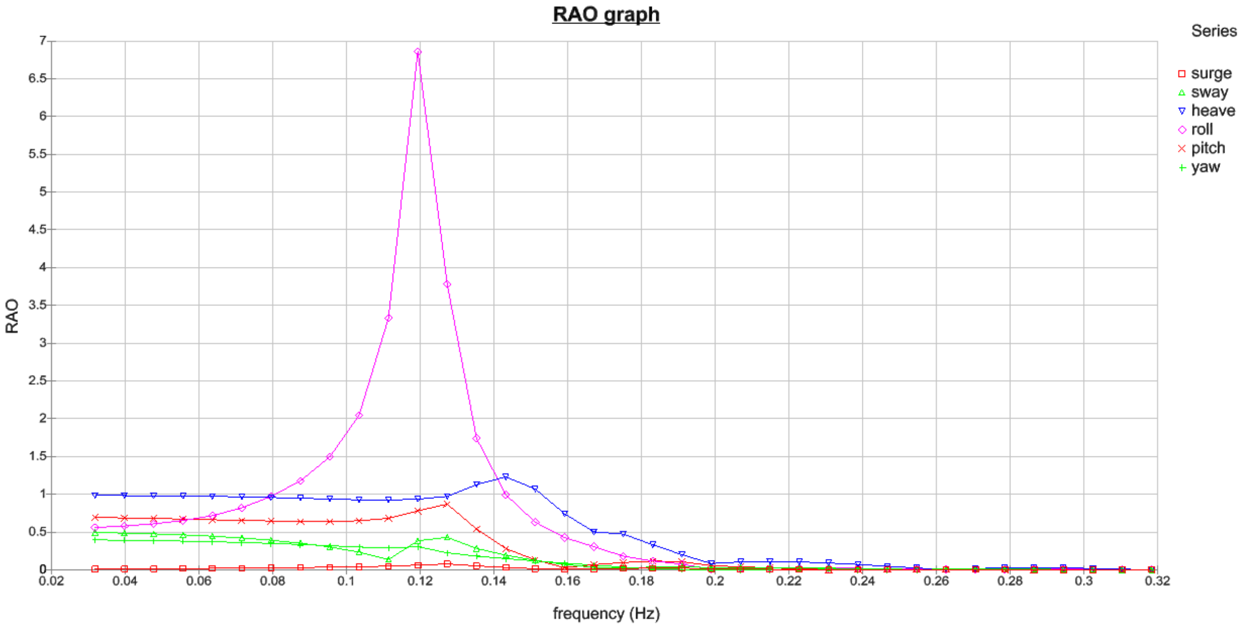

Figure 44: RAO Graph, 0 knots, 30 degree Heading

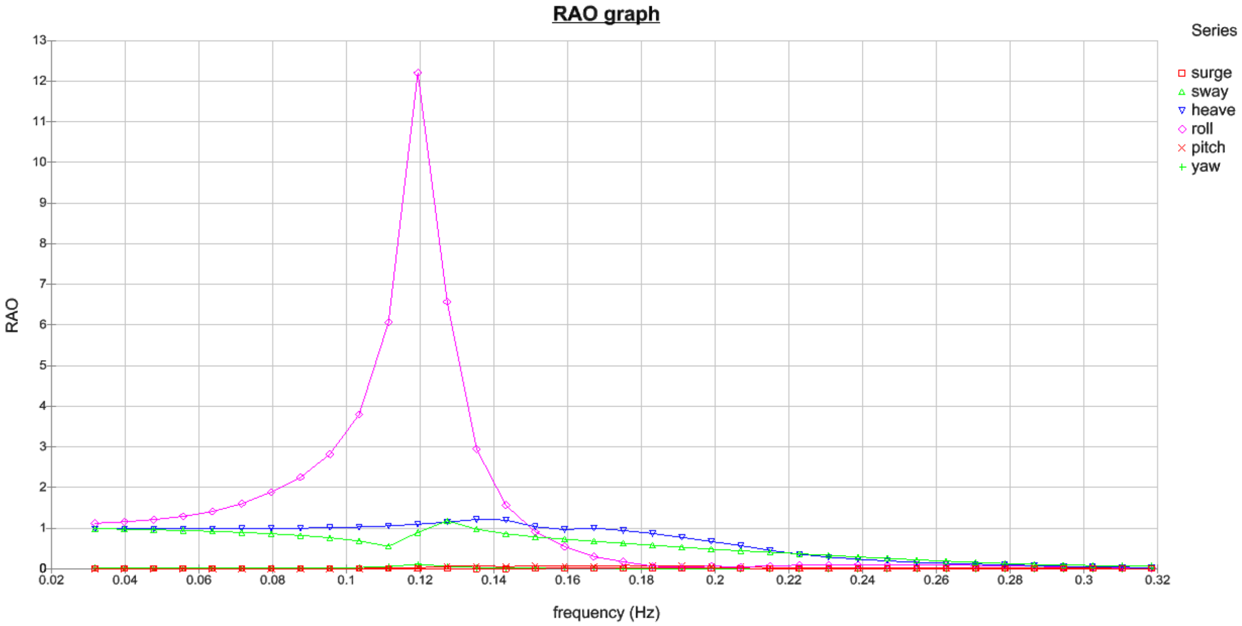

Figure 45: RAO Graph, 0 knots, 90 degree Heading

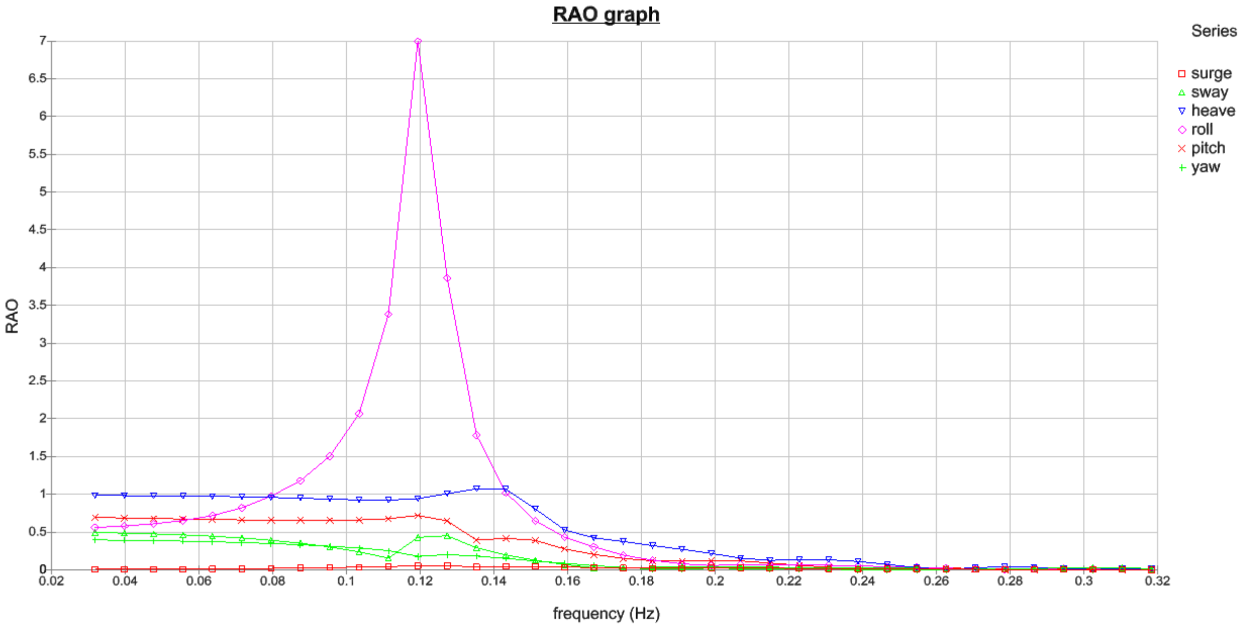

Figure 46: RAO Graph, 0 knots, 150 degree Heading

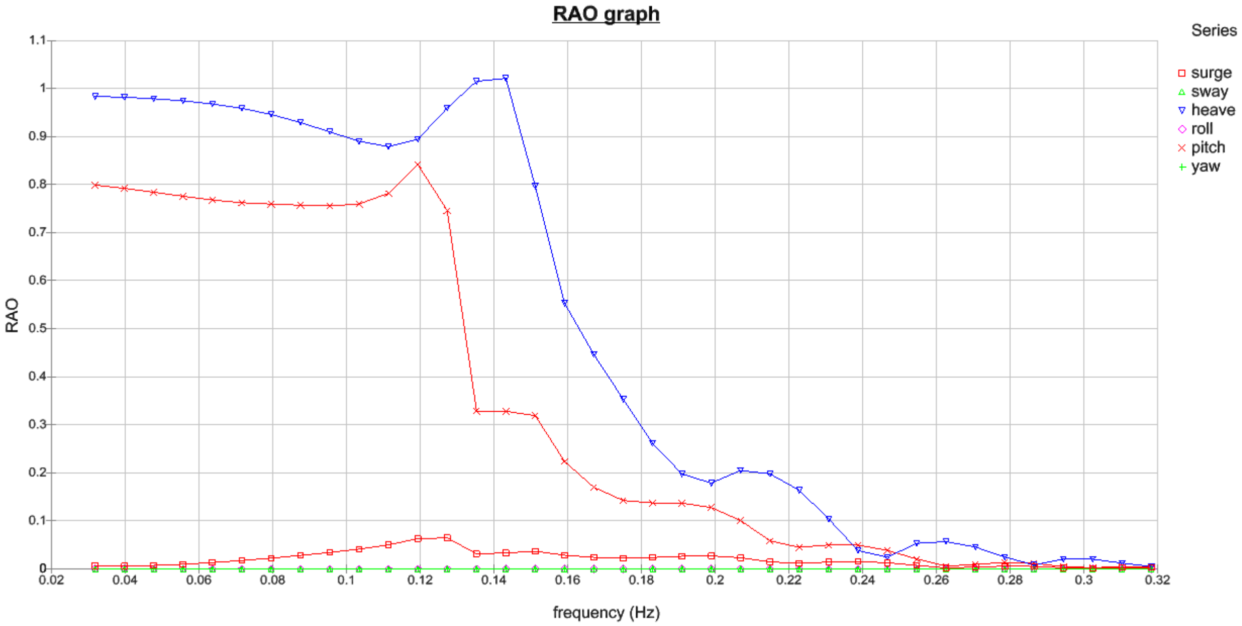

Figure 47: RAO Graph 0 knots, 180 degree heading

The RAOs show that the main motion concerns of the ship are heave, pitch, and roll. Sway, surge, and yaw motions do occur but are more modest. It is worth noting, however, that even small sway and yaw motions may have proved problematic for the *Virginia*. Though a maneuvering analysis was deemed infeasible, it is noted that the crew of the *Virginia* found it difficult to maneuver. Tenders were often required to aid in turning the ship, even in the midst of the battle of Hampton Roads (Nelson, 2004). With such sluggish steering, the *Virginia* may not have been able to easily counter even small changes in its navigational heading due to sway and yaw, which could put the ship into increasingly disadvantageous encounter headings with the dominant sea states.

Pitch motions and heave motions are as one would expect, more pronounced at lower frequency (and hence higher period, longer wavelength) waves, with a slight resonance around a frequency of 0.12Hz for pitch and approximately 0.14Hz for heave. The pitch and heave resonances are slightly out of phase, with pitch responses echoed at slightly higher frequencies in heave response.

Roll motions are quite pronounced, with a sharp resonance around 0.12Hz. The resonance peak seems not unreasonable at 12.2, in line with the "greater than 10" value noted as not atypical for modern ships with no roll damping mechanisms in Volume II of the Principles of Naval Architecture. Though, as mentioned many times previous, the *Virginia* is not a modern hull form and the hard keel and fan tail must be providing some roll damping to a certain extent. It is possible that without these features the roll resonance would be even sharper.

One feature of the roll motion shown in the RAOs is that the resonance peak is not as steep as one might expect a resonance peak to be. While the rolling motion RAO does drop off precipitously after attaining resonance as encounter frequencies increase, its rise from the lower frequencies to resonance traces a rather elegant curve that looks almost parabolic. This widens the base of the resonance peak, meaning that the *Virginia* is subject to increasingly severe rolling motions over a broader frequency spectrum, rather than being subjected to very severe rolling motion over a narrow spectrum. This makes rolling motion a greater concern as it increases the number of different sea state situations in which it can occur at large magnitudes, making it difficult to operate the ship in a way that decreases those motions.

Figures 48 – 52 show RAO plots for the same headings when the *CSS Virginia* is moving at 6 knots, for the same angles as previous.

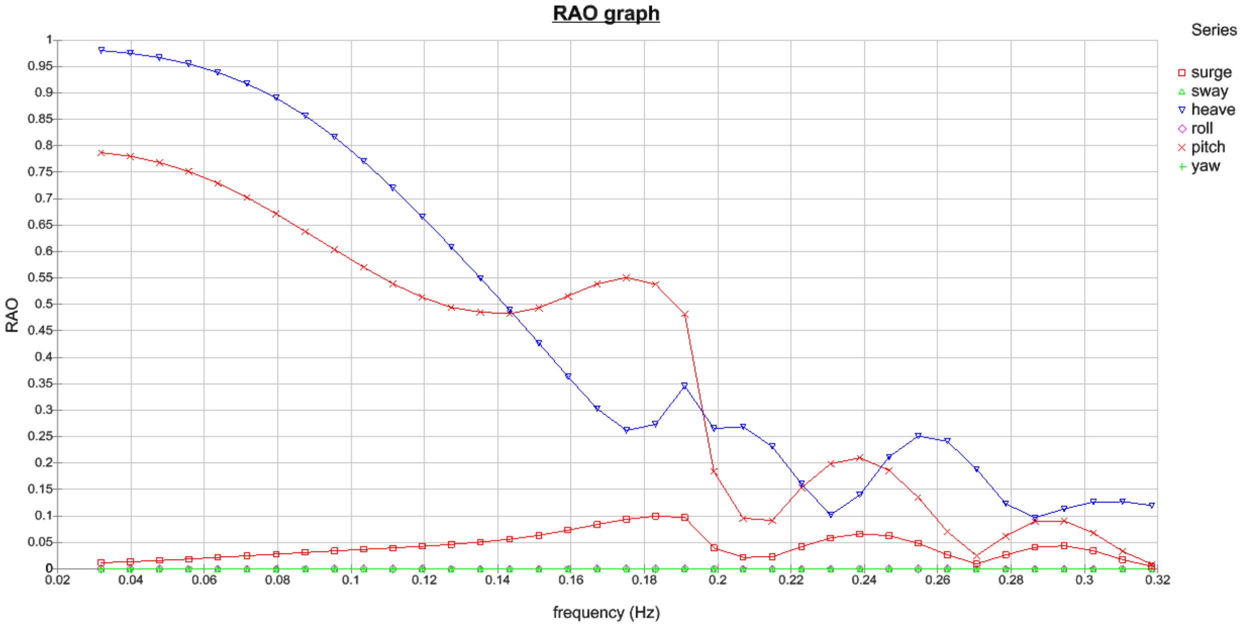

Figure 48: RAO Graph, 6 knots, 0 degree Heading

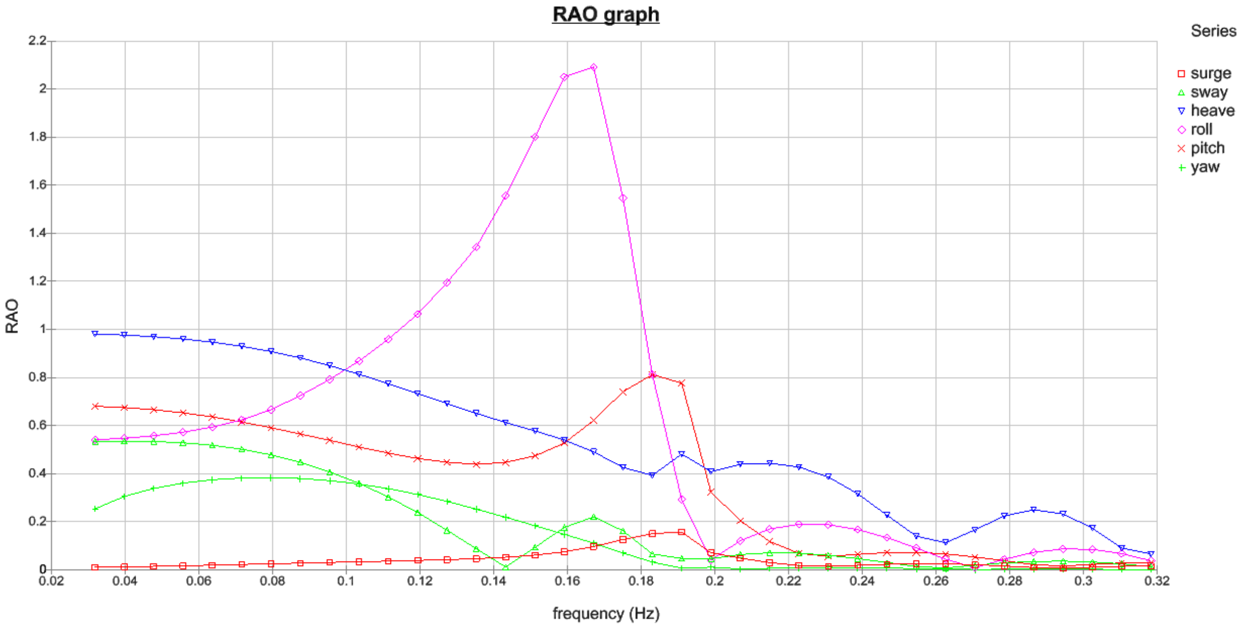

Figure 49: RAO Graph, 6 knots, 30 degree Heading

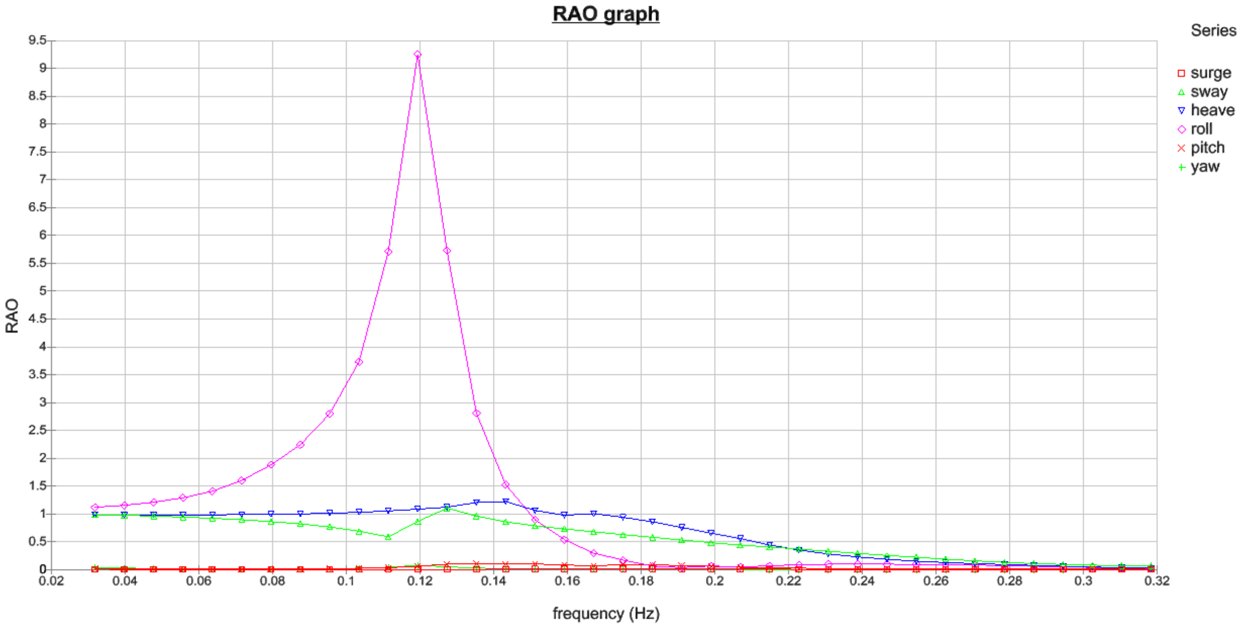

Figure 50: RAO Graph, 6 knots, 90 degree Heading

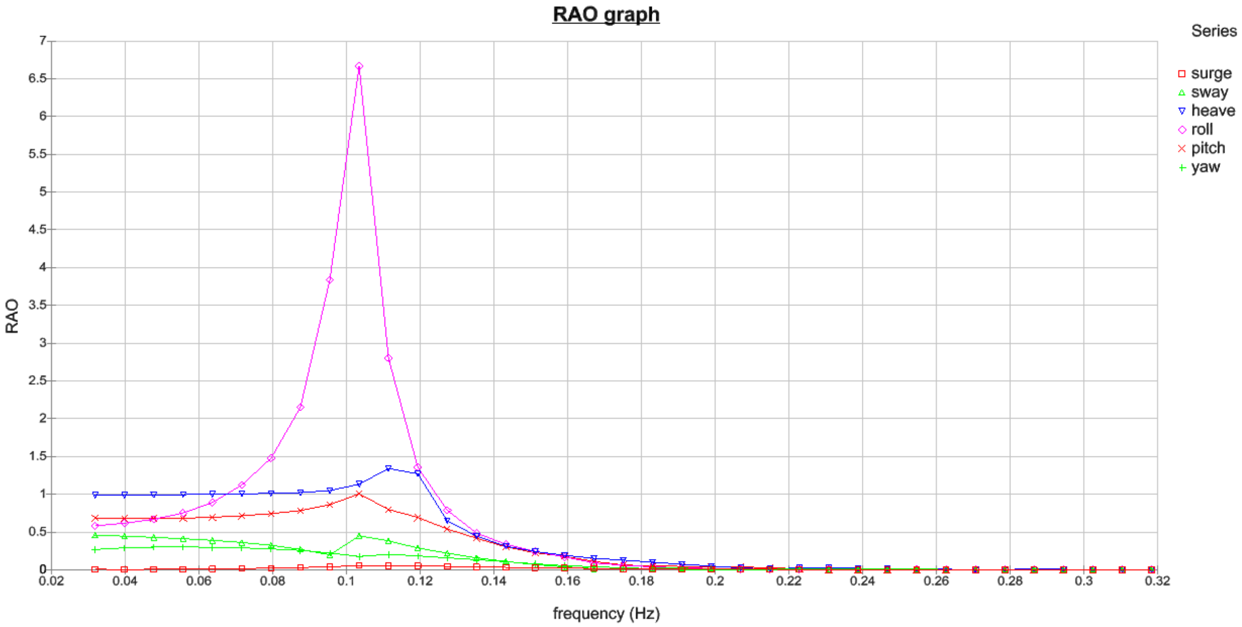

Figure 51: RAO Graph, 6 knots, 150 degree Heading

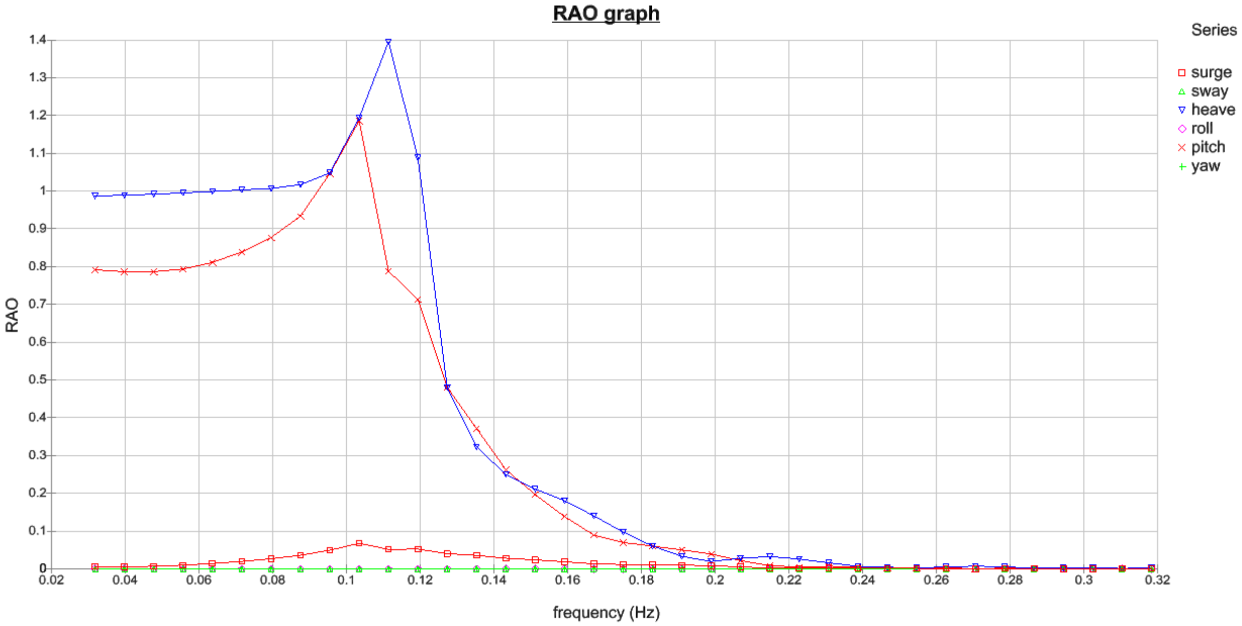

Figure 52: RAO Graph, 6 knots, 180 degree heading

Figures 48 and 49 show that while motion behavior is more complex at 6 knots than at 0 knots, the motion amplitudes are slightly more subject to damping at “high” speed then they are at zero speed when the ship finds itself in head seas or seas off the forward quarter. As the encounter heading shifts to the beam and moves aft the motions at 6 knots take on the character of the RAOs produced at zero knots. The phase differences apparent in the RAOs at zero knots for the different types of motion can also be seen at 6 knots, though the more complex nature of the motions in head and forward quartering seas gives the phase differences more visibility.

The second set of RAOs with the *Virginia* running at a speed of 6 knots show that, if possible, the *Virginia* would be best served by running at speed either in head seas or with seas on the forward quarter to keep rolling motions to a minimum. However, as noted previously, the *Virginia's* steering was poor and it may not have been able to maintain a heading in a complex seaway without help from tenders or tugs.

4.2.2 RMS Motions

The RAOs were used to plot RMS Motions for the *Virginia* in waves at a height of 5.164 feet with a modal period of 8.3333s. The wave height corresponds to the average offshore wave height from the data set collected (Station 44014, January – May, 2015). The modal period corresponds to a frequency of 0.12 Hz, the approximate frequency at which roll motion resonance occurs at zero knots, based on the RAOs. Figures 53 – 58 show the plots for all six degrees of freedom.

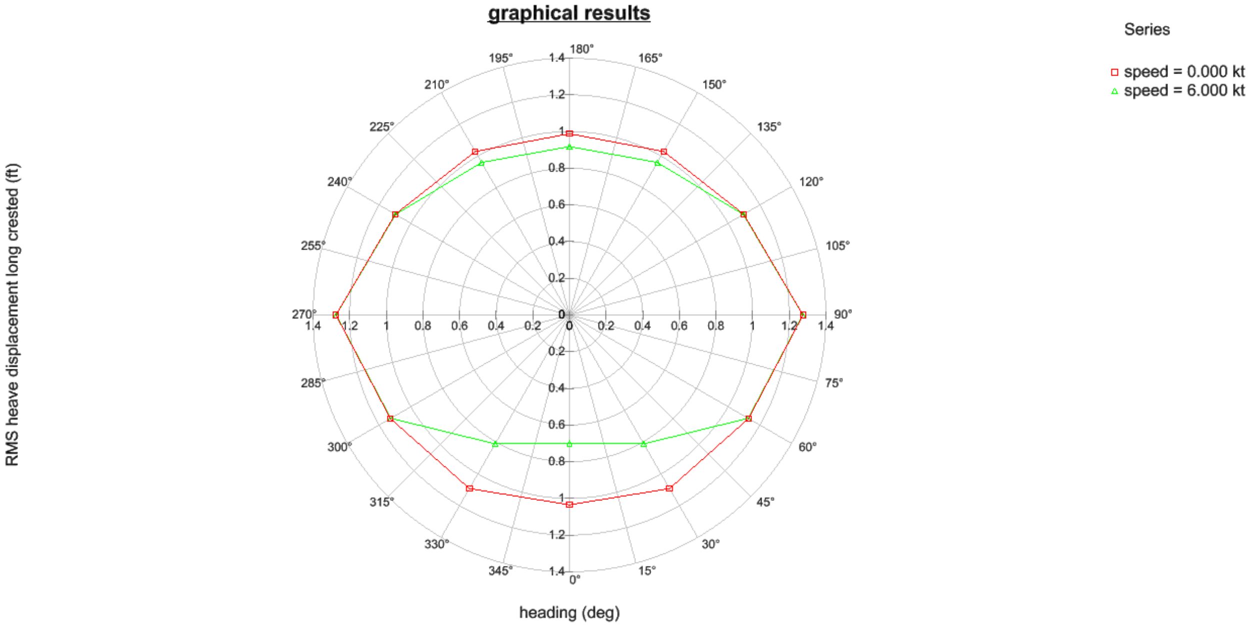

Figure 53: RMS Heave Motions in Offshore Sea State

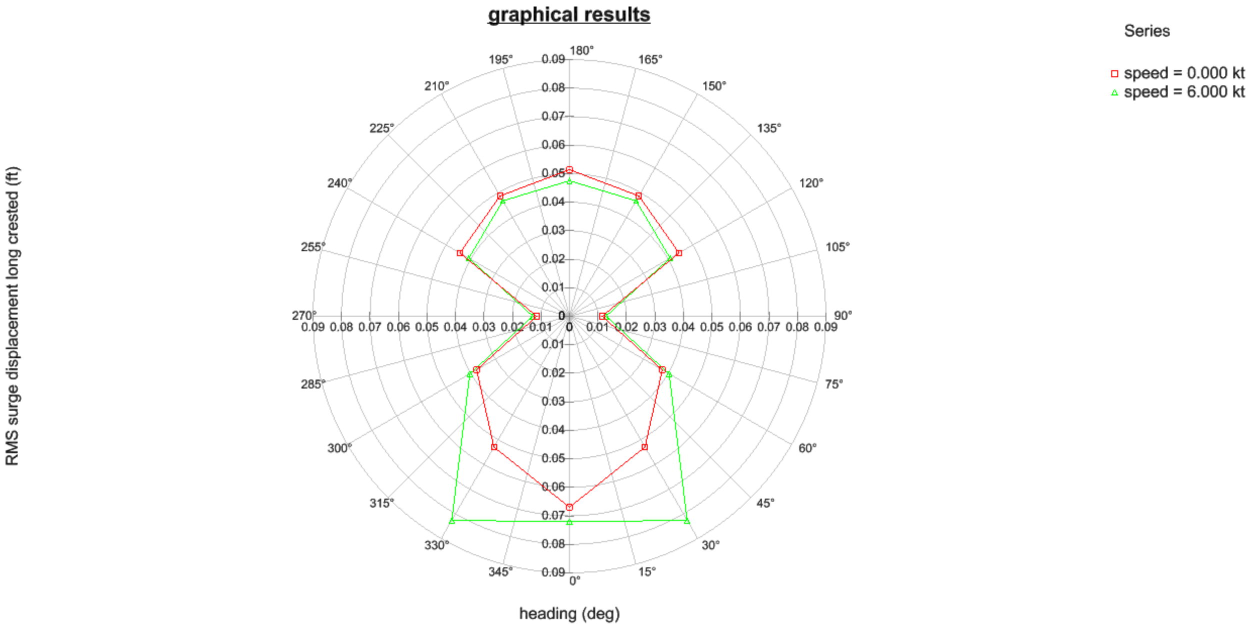

Figure 54: RMS Surge Motions in Offshore Sea State

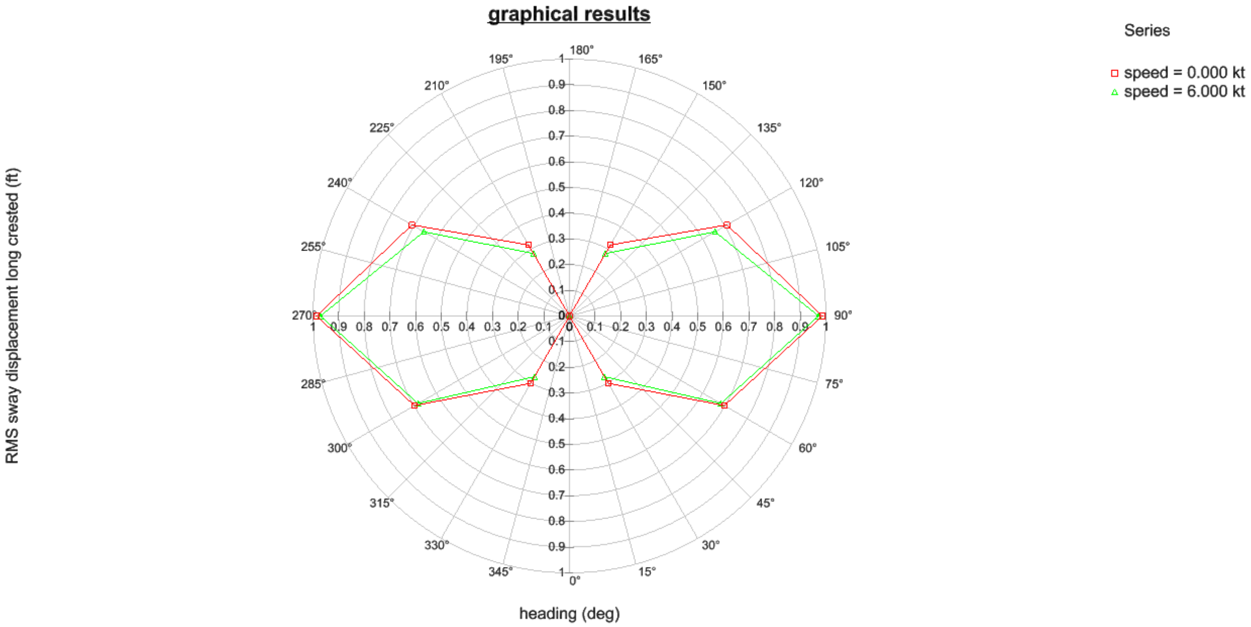

Figure 55: RMS Sway Motions in Offshore Sea State

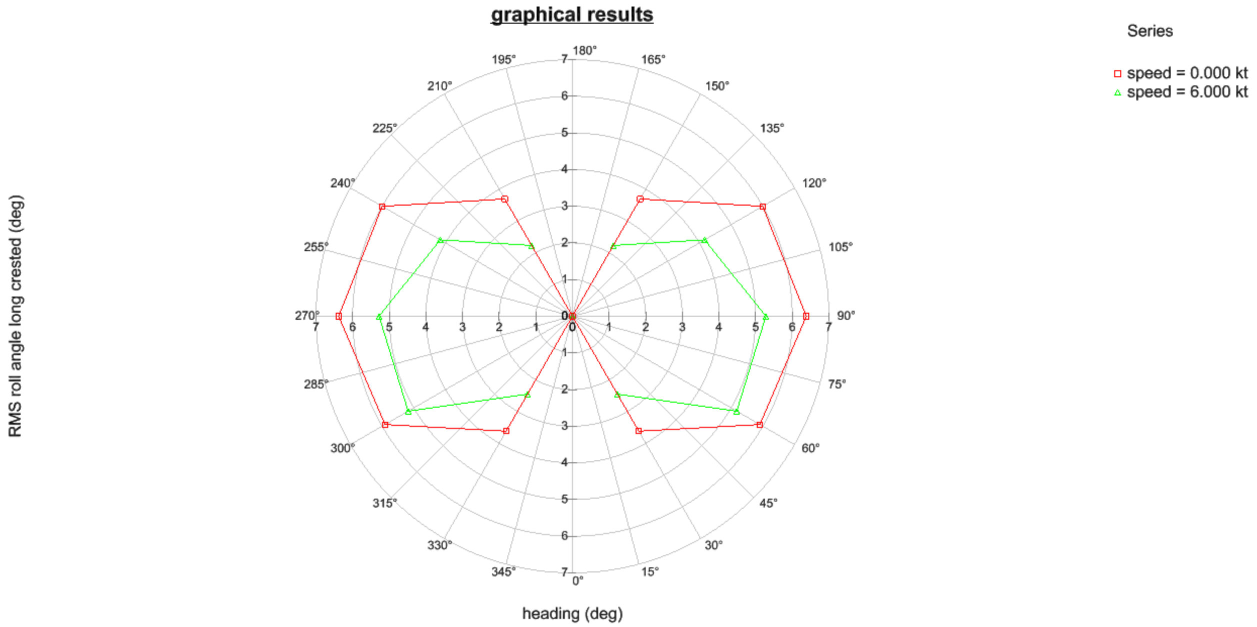

Figure 56: RMS Roll Motions in Offshore Sea State

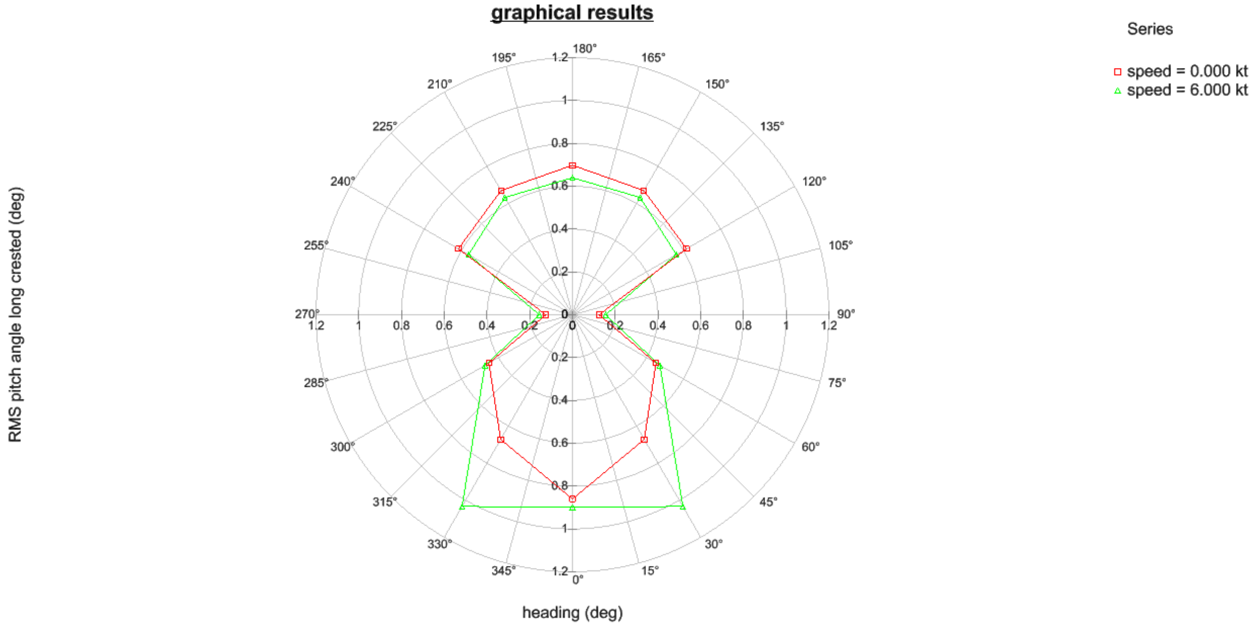

Figure 57: RMS Pitch Motions in Offshore Sea State

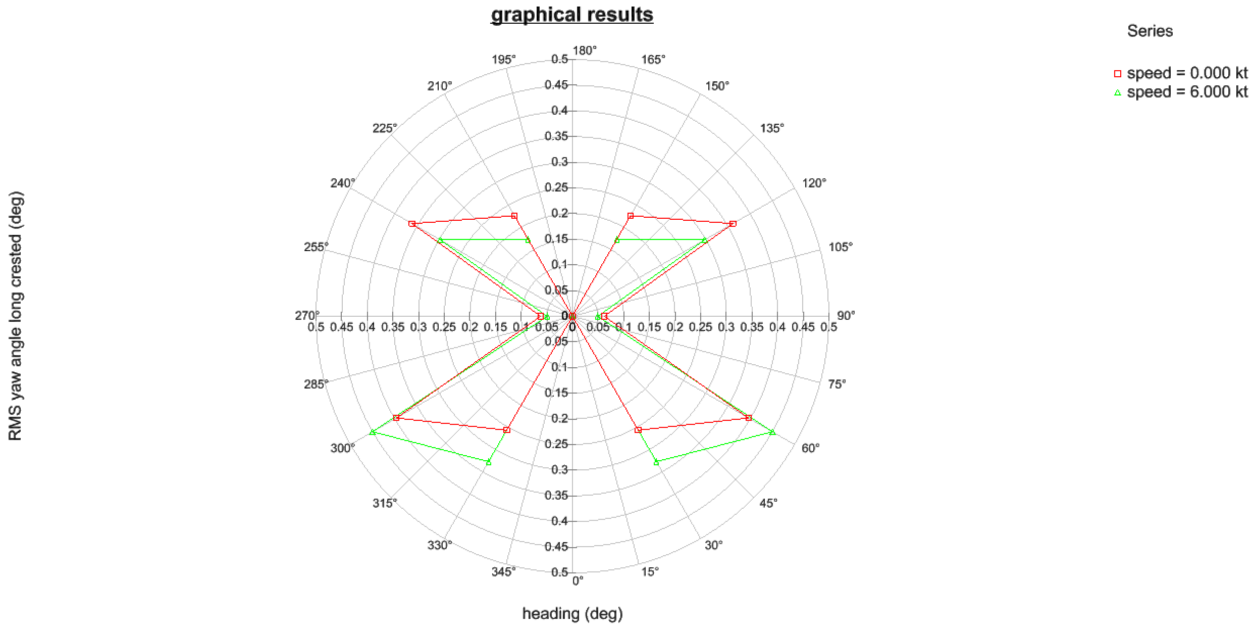

Figure 58: RMS Yaw Motions in Offshore Sea State

The RMS Motion plots give some more insight into how the *CSS Virginia* behaves at the zero knot speed and the 6 knot speed. Pitch, surge, and yaw motions are all more pronounced in head seas at 6 knots for the *Virginia;* the increase is most dramatic for pitch and surge. In following seas these degrees of freedom show greater RMS motions at zero knots, though not by a large amount over those seen at 6 knots.

Rolling motions based on the RMS plots show notable reduction when the *Virginia* is at speed as opposed to when at rest. Heave motions show some diminishing in head and following seas when the ship is operated at 6 knots. As far as sway motion is concerned there is a slight diminishing of motions for the ship at 6 knots, but the effect is not great.

4.2.3 Long Term Effectiveness Results

As noted in section 3.8.4, the long term effectiveness analyses were made based on MSI and deck immersion criteria. The analyses were made against a statistical wave atlas containing data from January – May of 2015, and taken to be representative late winter and spring in Hampton Roads.

4.2.3.1 MSI results

Based on data from the Chesapeake Bay stations, sea sickness would not have been much of an issue for the crew of the *CSS Virginia* if it stayed in the Bay or in Hampton Roads. For the Deltaville station, at an MSI index of 0.1%, the *Virginia* shows 100% long term effectiveness. Based on the statistics supplied in the wave atlas virtually no one would ever get motion sickness. For the Potomac Station, at an MSI index of 0.1%, the mission effectiveness is calculated to be 99.97%. So again, here, at a point well up the Chesapeake Bay, seasickness is not an issue.

Things change slightly in Cape Henry, which is at the entrance to the Chesapeake Bay and is less sheltered from the effects of weather. In order to obtain a 99.9% mission effectiveness rating, the MSI has to be increased to 2.5%. That would indicate that 2.5% of the crew might have motion sickness at any one time while cruising around the waters of Cape Henry. That is an overall effectiveness rating; there are plenty of wave height and period combinations that lead to 100% mission effectiveness and a number that lead to low effectiveness (around 23% for a wave height of 6.1 feet and a period of 5.610 seconds, a very heavy but not unheard of sea state for the Chesapeake Bay and Hampton Roads), but in general wave heights and periods are such that, statistically speaking, seasickness would not be much of an issue for the *Virginia* at Cape Henry.

Based on the offshore wave statistics, however, motion sickness is a more serious consideration. In order to attain the effectiveness levels seen in the Chesapeake Bay for low or very low MSI, the MSI acceptability criteria for the offshore operability run has to be increased greatly. At an MSI of 10% the overall mission effectiveness of the *CSS Virginia* is down to 93.523% based on the offshore wave data. To achieve a 99.97% mission effectiveness rating, the MSI index has to be raised to 25% for the offshore run. That means that, statistically speaking, in order to be assured of accomplishing the *CSS Virginia's* missions the crew would have to accept that fully one quarter of them might be seasick at any one time. It is difficult to imagine the ship fighting effectively if a quarter of its crew is down with seasickness, though it is possible to imagine the ship cruising to reach a friendly port and being willing to pay that kind of price to reach safe harbor.

A summary table of the results noted previously can be seen in Table 15:

Station	Location	MSI	Mission Effectiveness Rating
44014	64 NM East of Virginia Beach, VA	25%	99.97%
44064	First Landing (Cape Henry)	2.5%	99.90%
44058	Stingray Point (Deltaville,) VA	0.1%	100%
44042	Potomac, MD	0.1%	99.97%

Table 15: MSI Results at Different Wave Data Locations

4.2.3.2 Deck Wetness Results

As noted in Section 3.9.4.2, deck wetness was tied to the gun ports, and acceptance criteria was based on the bottom of the gun ports being immersed with a frequency less than 0.004 Hz (once every 250 seconds).

As one would expect, the long term analyses based on the points from the Chesapeake Bay show that immersion of the gun ports at the frequency selected is not a problem. Based on the data from Potomac, MD and Deltaville, VA, 100% mission effectiveness is achieved. Long term effectiveness based on the data from Cape Henry, VA yields an effectiveness of 99.62%. This indicates that for the most part, except in incredibly bad weather on the Chesapeake Bay, the *Virginia* could operate without any risk of shipping water through the gun ports.

Once again it is a vastly different matter in the open ocean. Based on the data from Station 44014 the *CSS Virginia* would only meet the criteria specified 64.52% of the time. This indicates that it is rather likely that the *CSS Virginia* would risk taking on water, and in extension sinking, were it to take to the open seas.

Looking closer at the open ocean results, it is apparent that in wave heights greater than 3.84 feet some of the gun ports begin to fail to meet the criteria some of the time. Interestingly, the aft CL gun port is actually the first to fail to meet the deck wetness criteria 100% of the time, as the model estimates that in waves 3.84 feet high with an encounter frequency of 0.197 Hz, the aft CL gun port only has a 92% mission effectiveness rating based on the criteria. This makes sense when the RAOs are examined; in Figures 48 and 49 it is evident that the *Virginia* is susceptible to pitch motions when moving at 6 knots when encountering waves at 0.197 Hz. The pitching motion is likely brining the aft CL gun port closer towards the sea surface and on occasion the bottom of the port is submerged more often than once every 250 seconds. As the wave heights increase the rolling motions became a greater concern, with the port and stbd gun ports meeting the submergence criteria less often, particularly the port and stbd aft ports. This is probably due to the effects of roll and pitch combined.

Based on the RAO plots the *Virginia* may have had a chance in the storm if the waves were low frequency and if it could keep a zero degree encounter heading, avoiding the rolling motions that cause reduced freeboard at the gun ports which in turn contributes to taking on water. However, as already discussed, the *Virginia* had poor steering, and it is unlikely that it would have been able to operate in a chaotic sea way and keep any sort of heading. It lacked the seaworthiness to make survival in rough weather likely, and lacked the nimbleness that may have allowed it to increase those chances to any degree.

On March 19th, 1862, newly minted CSN Admiral Buchanan wrote to Secretary Mallory and counseled him that the *Virginia's* place was guarding Norfolk in Hampton Roads (Quarstein, 2012). "The *Virginia* may probably succeed in passing Old Point Comfort and the Rip Raps," he wrote, "She [is] then to be tested in a seaway…should she encounter a gale, or a very heavy swell, I think it more than probable she would founder." The results of this analysis shows that Buchanan's feel for the ship and its sea keeping qualities was correct.

4.3 Resistance analysis

4.3.1 NAVCAD Results

Ship's parameters were placed into NAVCAD as described in Section 3.10. Figure 59 shows a speed power curve produced by using the Holtrop method in NAVCAD. Table 16 shows results from other methods.

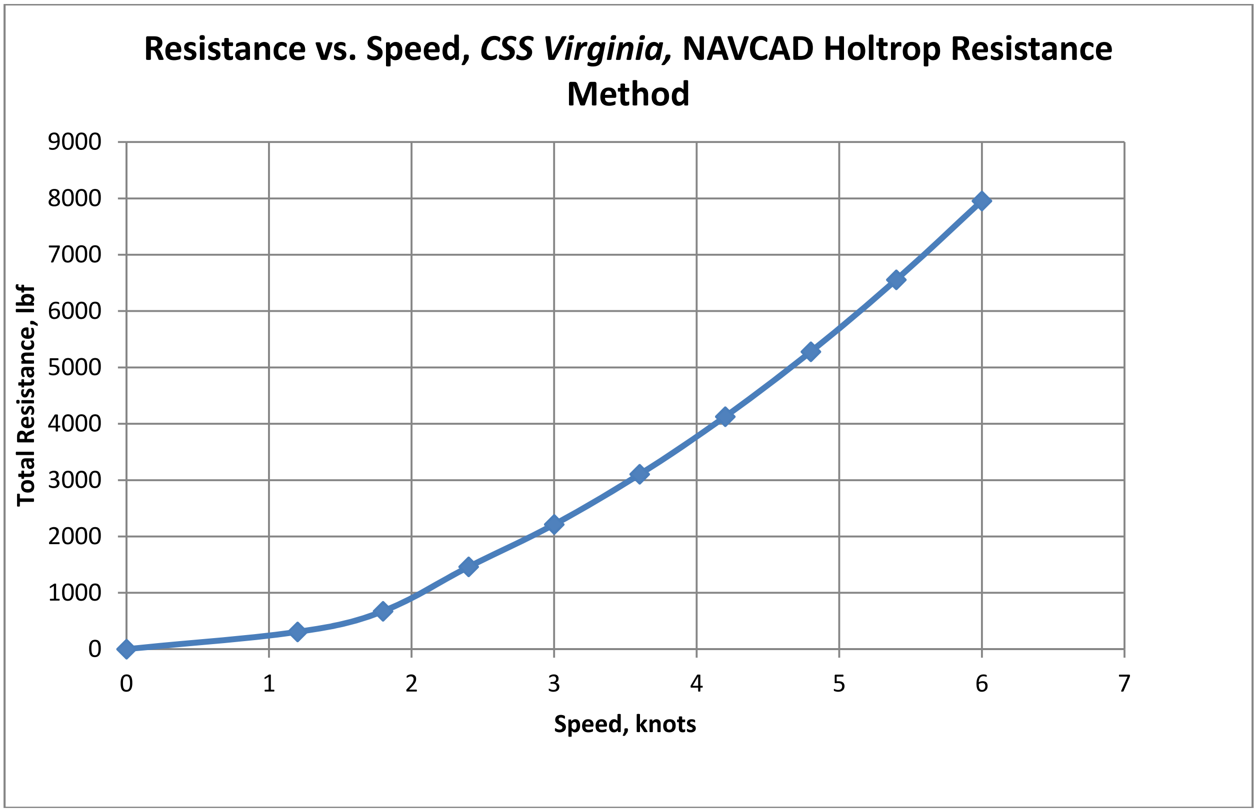

Figure 59: Resistance Curve for *CSS Virginia,* NAVCAD Analysis, Holtrop Method

Powering Method	Predicted EHP (hp)
Holtrop	146 hp
Andersen	108 hp
Oortmerssen	328 hp
Swift	175 hp
Kostov	106 hp

Table 16: NAVCAD Powering Method Predictions

As can be seen, most prediction methods put the required EHP between 106 hp and 175 hp. The Oortmerssen method is the outlier with 328 hp. The average EHP predicted by the methods above is 173 hp. Throwing out the Oortmerssen prediction, the average drops to 134 hp, which is as good an estimate as any other.

As noted in Section 3.4, the NAVCAD analysis was done with the *CSS Virginia* in an abnormally light condition, drafting only 18.25 feet. This was done to keep the *Virginia's* hull form as expressed in NAVCAD parameters more similar to a conventional ship hull form. Submerging the ship down would increase its frictional resistance due to the increase in surface area and it would also increase its form drag which is already likely considerable with so much of the ship submerged. It's hard to know how much the drag would increase, but one could see it going from about 130 hp towards the 173 hp average obtained with the Oortmerssen outlier included.

Of course, it would be a mistake to put too much faith into these numbers. Due to the uniqueness of the hull form, the best way to get resistance data for the *CSS Virginia* would be to build a model and conduct a tow tank test.

4.3.2 Comparison with Noted Horsepower

The horsepower required is worth noting and comparing with what is quoted elsewhere about the *Virginia's* engines. Most sources can be traced back to Isherwood's Experimental Researches in Steam Engineering, which quote the total horsepower developed by the engines at 1294.417 hp. It is difficult to know exactly how that horsepower was calculated (it is an incredibly precise value), or if it's a boiler horse power achieved by rules of thumb or evaporation of water at a certain temperature. But for this project we assume it is comparable to a standard hp.

Isherwood estimates that the BHP of the engines is 869.79 hp after figuring the losses in the engine itself. Calculating loses due to friction, water resistance of the screw blades, and the amount of slip in the screw, Isherwood estimates that the power expended in production of the vessel is 590.47 hp (Isherwood, 1863).

Isherwood's estimate is much higher than anything provided by the NAVCAD software, and it results in an efficiency against Isherwood's BHP of 67%, which is outstanding even by today's standards. Against the total horsepower (1294.417 hp) the efficiency is 46%, which is still quite respectable. The 590.47 hp is unrealistic, and probably based on established understandings and parametrics of the day concerning powering calculations.

Taking Isherwood's BHP and THP estimates at face value, and if we assume that the effective horsepower required is 186 hp based on the NAVCAD analysis, then the efficiency against BHP is 21% and against THP it is 14%. Those efficiencies make more sense considering the state of technology in the 1850's and 1860's. If the ship in fact only had a speed of 4 or 5 knots, the EHP required and subsequent efficiencies would be even less.

We don't know exactly what the BHP or THP of the *Virginia*'s engines was as we peer back through time, and as already noted the NAVCAD results are only gross estimates. It's hard to make good conclusions off the results, but I think it's enough to say at least that 6 knots was plausible, though not much more. A tow tank test of a model and better estimates of the *Virginia's* engine capabilities would hold the keys to learning anything more.

4.3.3 Range

The *Merrimack's* logs suggest that the *Merrimack's* engines consumed 3283 lbs of coal per hour (Isherwood, 1863). If we assume that the *Virginia* burned coal at the same rate, then the 150 LT of coal carried would allow about 102 hours of steaming time. If a speed of 6 knots could be maintained at 3283 lbs of coal per hour, then the range of *CSS Virginia* would have amounted to about 614 nautical miles.

That is enough range to give the *Virginia* some options beyond cruising and fighting around Hampton Roads. Table 17 shows the distance from Norfolk, VA, to different points of interest in the Chesapeake Bay and the East Coast, in accordance with the US Department of Commerce.[22] Tables are based on the shortest and safest navigable sea lanes in 2012; those sea lanes may have been somewhat different in 1862 but in general terms it should suffice.

City	Distance (nautical miles)
Washington DC	185
Wilmington, NC	363
Charleston, SC	429
Savannah, GA	503
Jacksonville, FA	587
Mobile, AL	1440
New Orleans, LA	1509
New York, NY	294
Boston, MA	571

Table 17: Distance from Norfolk, VA, to other Ports

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[22] See Distances Between US Ports, 2012 (12th) Edition, US Department of Commerce, available at http://www.nauticalcharts.noaa.gov/nsd/distances-ports/distances.pdf

Could the *Virginia* have made an attack on Washington or beyond? That was certainly a concern felt deeply by President Lincoln's administration. Thanks to the invention of telegraphy, news of the serious loss suffered by the US Navy on March 8, 1862 arrived quickly in the Washington. Lincoln lamented on March 9th the loss of the *Congress* and the *Cumberland*, and asked Captain John A. Dahlgren if it was possible that the *Virginia* (though he referred to it still as the *Merrimack*) "might not have a visit here." Secretary of the War Edwin Stanton certainly shared those concerns, and feared not only for Washington but for New York and Boston as well. Stephen Mallory himself, who was more familiar with the ship than his Union counterparts, expressed a belief that an attack on New York was possible. Only the officers of the *Virginia* took the realistic view that the ship's abilities were limited (Quarstein, 2012).

Based on the *Virginia's* range of 614 nautical miles and the distances in Table 17, it can be seen that the *Virginia* would indeed have ample range to make it to Washington and back on one load of coal. It could also just barely make to New York and back on one load as well, but would not have much reserve coal left; a prudent commander would probably be against it, as no friendly re-coaling ports would be available to the North. Boston was too far away to attack for this very reason; while the *Virginia* could make it to Boston it could not get back on a single load of coal. The lack of friendly ports north of Norfolk would leave it unable to re-coal after the assault and return to friendly waters.

Another question: could the *Virginia's* commanders more seriously contemplated striking out for a friendly port to the South instead of sailing up the James River towards Richmond after Norfolk had fallen to the Union? After Norfolk began to fall to Union Forces on May 10, 1862, Commander Tattnall did consider heading into the open ocean and steaming for Savannah. His officers talked him out of it, feeling certain that the ship was likely to flounder. Table 17 does show that the *Virginia* did indeed have the range to reach Wilmington, Charleston, Savannah, or even Jacksonville on a single load of coal. Mobile and New Orleans were too far to contemplate without re-coaling somewhere, probably in Florida. All of these ports were under the Union blockade to a certain extent in 1862, so running into them would entail some risk of meeting hostile vessels.

4.4 Putting it all together – A New Con-Ops for the *Virginia*?

Having the range for different missions is one thing, but having the seaworthiness to accomplish them is quite another, and the wisdom of the various schemes is yet another consideration. Utilizing the results of the hydrostatics, sea keeping analysis, and the limited resistance analysis, it is possible to comment on different, hypothetical mission profiles for the *Virginia*. Below is a discussion of three, though the ship's limitations make it a discussion of only two: an attack on Washington DC and a transit on the open ocean, either to attack New York or to run to a friendly port to the South.

4.4.1 Attack on Washington

As shown in section 4.3.3, the *Virginia* does have ample range to make it Washington DC and back. As shown in Section 4.2.3, long term analysis based on the wave atlas created from the Cape Henry, Deltaville, and Potomac wave data shows that the ship would have nearly 100% operational effectiveness in typical weather conditions. So, barring extreme weather events (tropical storms, violent cloudbursts, etc.), the *Virginia* could arrive off of Washington DC and bombard the city from an endurance and sea keeping perspective.

One has to consider that the vessel, having consumed large amounts of coal, powder, and shot, would be drafting less as it returned to Hampton Roads. If the draft has decreased to the point where the ship's hull is no longer submerged below the knuckle line, it would leave the *Virginia* vulnerable to shot striking unprotected areas of its hull.

Below is a table estimating the condition of the *Virginia* upon return to Hampton Roads after churning its way up the Bay and the Potomac Rivers and then returning. At a speed of knots a return trip from Norfolk to Washington takes 61.67 hours. If you assume that the *Virginia* spends six hours bombarding Washington then the total time spent is 67.67 hours. Noting that it is assumed the *Virginia* is consuming 3283 lbs of coal per hour, the overall weight of coal consumed on the mission is 99.17 LT. If you assume also that the *Virginia* expends 2/3 of its power and shot, that is a further weight reduction of 44.91 LT. That yields the following displacement and center of gravity as shown in Table 18.

Item	Weight	VCG	VMOM	Long	LMOM
Initial Condition	3869.37	15.08	58361	126.31	488737
Less Fwd Powder	-2.71	9.75	-26	42.00	-114
Less Fwd Shot	-17.95	9.75	-175	50.17	-901
Less aft Powder	-2.71	9.75	-26	211.17	-572
Less Aft Shot	-17.95	9.75	-175	177.83	-3192
Less Coal Consumed	-99.17	9.75	-967	102.51	-10166
Return Condition	3728.88	15.28	56992	127.06	473792

Table 18: Condition upon Returning From an Attack on Washington DC

Based on the even keel hydrostatics presented in Table 13, the mean draft of the *Virginia* would be around 20.75 feet, so the knuckle line (19 feet above the bottom of the keel) would still be well submerged.

A better estimate can be made by getting a set of hydrostatics from Paramarine based on the displacement and LCG in Table 18. Paramarine reports that, in the condition shown in Table 18, the draft fwd is 19.6 feet above the bottom of the keel, and the draft is 22.1 feet above the bottom of the keel. The increase in aft trim is due to the assumed placement of the coal near the boilers. Based on the model it looks like at the bow the knuckle line would still be about 7” below the water line, getting close to being exposed but perhaps not a cause for major concern. Of course, these results should be taken with a large grain of salt; assumptions have been made about the placement of the different weights in the hull, where rather little is known about the *Virginia’s* internal arrangements.

Table 18 does start with the *Virginia* in the loaded condition that it began the battle of Hampton Roads in. Subsequent modifications to the ship would have certainly allowed the ship’s knuckle line to be submerged even after it had returned from an assault on Washington. However, the tradeoffs of the added armor (the added depth, the added weight, the increased surface area, the likely slower speed) may have ruled out an attack due to a number of different factors. While the increased armor band may have made the ship more impregnable, it rendered it so heavy and probably degraded its already poor performance to the extent that the CSN perhaps should have thought twice about putting it in place.

If it appears as though an attack on Washington was feasible from a naval architectural standpoint, it may still have been ill advised from a military standpoint. It would have been possible to bottle the *Virginia* up inside the Bay or on the Potomac, and shore based artillery installations on the run into Washington would have battered the casement. The *Virginia* may have proved to be impregnable at sea to shell guns, but a large amount of solid shot fired from powerful shore batteries may have been another matter. It is possible that the *Virginia* may have been able to fight its way out, but it is also possible that its deep draft would have left it grounded on a sandbank, or that the perpetual hammering from ships and shore batteries would finally start to tell. It is hard to know.

4.4.2 At Sail in the Open Ocean – Attacks on New York or Running to Friendly Ports

Attacking New York or making a run for friendly ports to the South requires a transit over the open ocean. At a speed of 6 knots, it would take the *Virginia* about 4 full days to get to New York and back to Norfolk, 3.5 days to get to Savannah, about 3 days to make it to Charleston, and 2.5 days to arrive in Wilmington. Those transit times would have been regarded as too risky by the various commanders of the *Virginia*, as the ship was generally judged to be unseaworthy. Stephen Mallory may have dreamed of the *Virginia* shelling New York, but his officers had a far more realistic view of the vessel and its limits.

With the benefit of today’s technology it is possible to back up the view of CSN commanders with some analysis, and the analysis shows that they were correct. The ship was not unstable in the lightship condition, as many “experts” thought it would be, but its low freeboard to the gun ports, its high propensity to roll, and its poor controllability made the ship unseaworthy. Based on the criteria for deck wetness, the *Virginia* only has a 64.5% mission effectiveness rate based on an actual set of open ocean data running from January 2015 – May of 2015. It is granted that on average in June and July the significant average wave height decreases at station 44014 (see Figure 34), and a brief survey of other stations along the eastern seaboard shows a similar drop in the mid-summer months. If June and July had been included the overall effectiveness may have increased. But even if it had an 80% chance in June and July, that is probably too low a rate of reliability to take the transit on lightly. An 85% effectiveness rate, after all, is equivalent to one’s car not starting every Friday.

A bold (or perhaps foolhardy) commander may have made the attempt *if* the weather forecast shows that conditions were favorable for raising the chances of success. It is possible with today's technology, after all, to predict weather over a 2 or 3 day span with some level of certainty.

However, in 1862 the technology and theory that enable today's weather predictions was nonexistent. Admiral FitzRoy, of the Royal Navy, is credited with making the first forecasts and storm warnings by using observations collected by telegraph stations spread along the British coast in 1860. From that data the first daily weather forecasts, made by FitzRoy himself, were published in The Times of London in 1861. It was a great leap forward in weather forecasting, but FitzRoy's forecasts were very often inaccurate (Moore, 2015). In the United States there were 500 telegraph stations making similar observations by 1860, but their work was interrupted by the Civil War and limited forecasting only came to the United States after the war concluded. It would be nearly a century after the Civil War before research even began on the computer based forecasting that all rely upon today (National Weather Service, n.d.), and even with today's technology there are still uncertainties involved that would make taking the *CSS Virginia* out to sea armed with anything less than a forecast for the most pristine, calm conditions a considerable risk[23].

Without accurate weather forecasting, and with the *Virginia's* seaworthiness guaranteed under only nominal conditions, both in terms of the analysis presented in this report and in the intuition of the professional sailors and engineers that the ship, one has to abandon the idea that the *Virginia's* story could have ended any differently than it ultimately did. An attack on New York or a retreat to a friendly port are considered risky at best even with the aid of today's technological analysis and weather forecasting tools. It would be simply unthinkable in 1862. There could not have been a second act for this history making vessel.

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[23] For a fascinating but fleeting glimpse into today's forecasting technology and the theory behind it see "The Weatherman is Not a Moron", by Nate Silver, published in the New York Times Magazine September 7, 2012 (http://www.nytimes.com/2012/09/09/magazine/the-weatherman-is-not-a-moron.html).

5 CONCLUSIONS AND AREAS OF FUTURE STUDY

This thesis applied modern naval architecture modeling and analysis methods to a historic ship, the Civil War Ironclad *CSS Virginia*. A geometry model was developed in Paramarine based on previous historical research (notably that provided found in Besse (1996) and Park (2007)) and a detailed weight estimate was made based on the geometry and historical information from a variety of sources.

From the weight estimate it was possible to estimate not only the CG of the vessel but also its radius of gyration. These were important for the naval architecture analysis of the ship, notably with regards to stability and to sea keeping. Through the use of Paramarine software it was possible to get not only hydrostatics but also GZ Curves, RAOs, and measures of mission effectiveness based on sea keeping performance and wave data statistics.

While Union and Confederate leadership respectively feared and placed their hopes in the *CSS Virginia*, the men who built and sailed the ship were more sanguine concerning its capabilities. While the ship did not stay fast on the blocks at the launch or turn flip over as soon as it was afloat, it was generally considered that were the ship to encounter a heavy sea in open ocean it was certain to flounder. The sea keeping analysis shows that their intuition was correct, as the low free board to the gun port opening sand propensity to roll made water ingress and down flooding likely. Further, while the ship may not have capsized upon launching, the GZ curves produced to assess stability show low righting arm values in the battle condition, particularly if the VCG is higher than predicted by the weight analysis. Given the uncertainty involved in the weight analysis that is a distinct possibility. Despite the fears and hopes of a nation at war with itself, the *CSS Virginia* was best suited to do what it was designed for; to break the Union Blockade of Hampton Roads at the entrance to the Chesapeake Bay. Asking the ship to do more would very possibly lead to disaster.

There are some areas of future study to build on. The primary focus of this thesis was on the seakeeping analysis, and the GZ curves provided just scratch the surface of a detailed stability assessment. It would be interesting to see how the *Virginia* fares when subjected to modern day stability rules per governments and classification societies. Also absent from the stability assessment is consideration of how beam winds effect the stability of the ship.

The seakeeping analysis presented by this thesis was limited in the fact that it was based on a linear strip theory method, and does not take into consideration non-linear effects. This could be particularly important with regards to roll damping, which the model in this thesis does not fully account for.

Finally, the resistance estimates presented in this thesis are a but a first step if a better understanding of the power necessary to propel the vessel. The unique hull form invites a tow tank test, as it is not likely that any current resistance method, most of which are based on experiments of more modern and conventional forms, can adequately account for a ship like the Virginia plowing through the water at slow speed.

Despite its limitations, this thesis has shown that there is much that can be learned by applying modern methods to historical vessels. Much more could be learned about the *CSS Virginia* in particular by continuing to peel back the layers of time that obscure this interesting, history making vessel.

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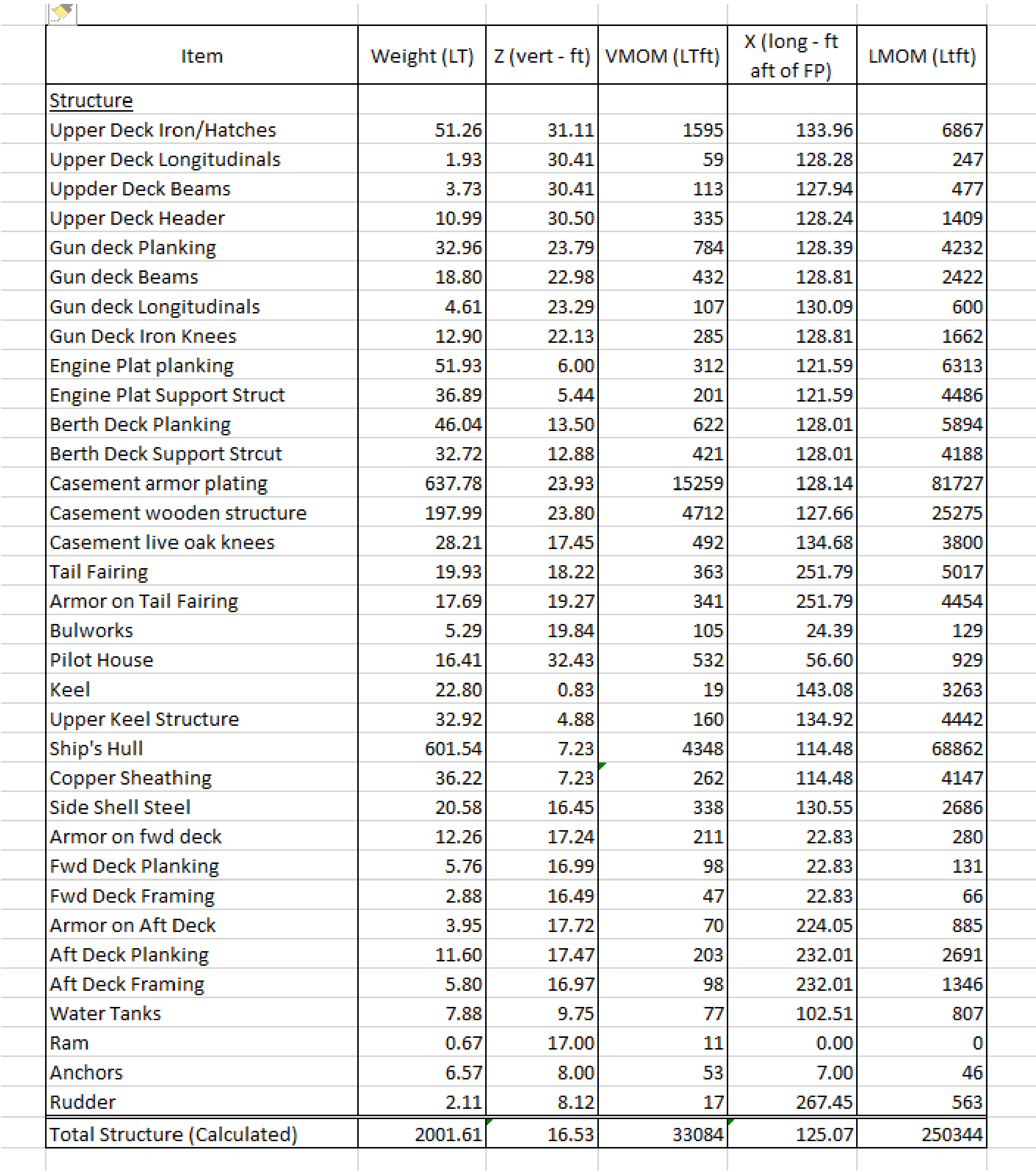
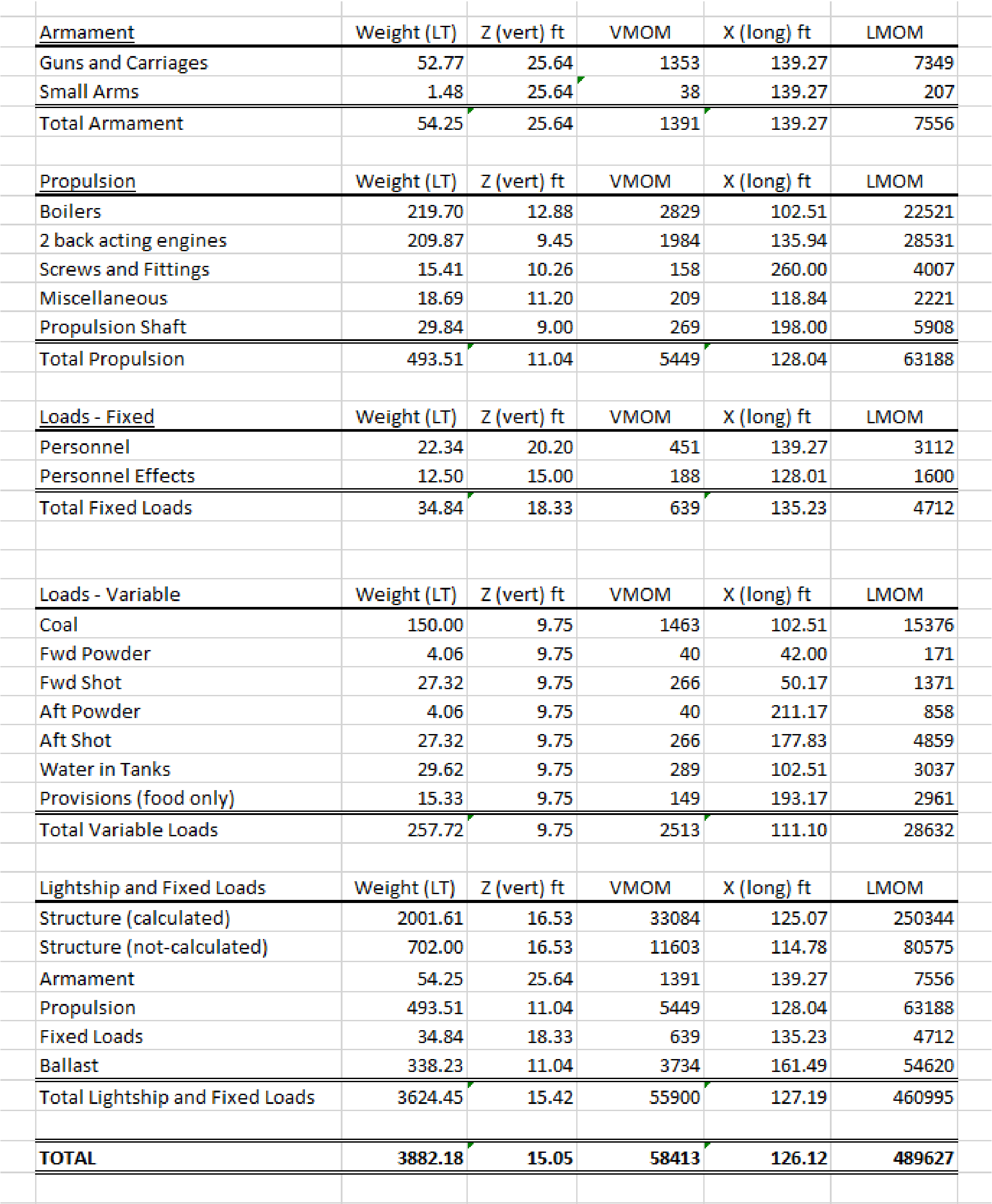
Appendix A – Weight Analysis

Below is a table of the complete weight summary. The various weight estimates made were combined into an overall weight estimate. The details of each of these items follows.



Item	Weight (LT)	Z (vert - ft)	VMOM (LTft)	X (long - ft aft of FP)	LMOM (Ltft)
Structure					
Upper Deck Iron/Hatches	51.26	31.11	1595	133.96	6867
Upper Deck Longitudinals	1.93	30.41	59	128.28	247
Uppder Deck Beams	3.73	30.41	113	127.94	477
Upper Deck Header	10.99	30.50	335	128.24	1409
Gun deck Planking	32.96	23.79	784	128.39	4232
Gun deck Beams	18.80	22.98	432	128.81	2422
Gun deck Longitudinals	4.61	23.29	107	130.09	600
Gun Deck Iron Knees	12.90	22.13	285	128.81	1662
Engine Plat planking	51.93	6.00	312	121.59	6313
Engine Plat Support Struct	36.89	5.44	201	121.59	4486
Berth Deck Planking	46.04	13.50	622	128.01	5894
Berth Deck Support Strcut	32.72	12.88	421	128.01	4188
Casement armor plating	637.78	23.93	15259	128.14	81727
Casement wooden structure	197.99	23.80	4712	127.66	25275
Casement live oak knees	28.21	17.45	492	134.68	3800
Tail Fairing	19.93	18.22	363	251.79	5017
Armor on Tail Fairing	17.69	19.27	341	251.79	4454
Bulworks	5.29	19.84	105	24.39	129
Pilot House	16.41	32.43	532	56.60	929
Keel	22.80	0.83	19	143.08	3263
Upper Keel Structure	32.92	4.88	160	134.92	4442
Ship's Hull	601.54	7.23	4348	114.48	68862
Copper Sheathing	36.22	7.23	262	114.48	4147
Side Shell Steel	20.58	16.45	338	130.55	2686
Armor on fwd deck	12.26	17.24	211	22.83	280
Fwd Deck Planking	5.76	16.99	98	22.83	131
Fwd Deck Framing	2.88	16.49	47	22.83	66
Armor on Aft Deck	3.95	17.72	70	224.05	885
Aft Deck Planking	11.60	17.47	203	232.01	2691
Aft Deck Framing	5.80	16.97	98	232.01	1346
Water Tanks	7.88	9.75	77	102.51	807
Ram	0.67	17.00	11	0.00	0
Anchors	6.57	8.00	53	7.00	46
Rudder	2.11	8.12	17	267.45	563
Total Structure (Calculated)	2001.61	16.53	33084	125.07	250344



Armament	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Guns and Carriages	52.77	25.64	1353	139.27	7349
Small Arms	1.48	25.64	38	139.27	207
Total Armament	54.25	25.64	1391	139.27	7556

Propulsion	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Boilers	219.70	12.88	2829	102.51	22521
2 back acting engines	209.87	9.45	1984	135.94	28531
Screws and Fittings	15.41	10.26	158	260.00	4007
Miscellaneous	18.69	11.20	209	118.84	2221
Propulsion Shaft	29.84	9.00	269	198.00	5908
Total Propulsion	493.51	11.04	5449	128.04	63188

Loads - Fixed	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Personnel	22.34	20.20	451	139.27	3112
Personnel Effects	12.50	15.00	188	128.01	1600
Total Fixed Loads	34.84	18.33	639	135.23	4712

Loads - Variable	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Coal	150.00	9.75	1463	102.51	15376
Fwd Powder	4.06	9.75	40	42.00	171
Fwd Shot	27.32	9.75	266	50.17	1371
Aft Powder	4.06	9.75	40	211.17	858
Aft Shot	27.32	9.75	266	177.83	4859
Water in Tanks	29.62	9.75	289	102.51	3037
Provisions (food only)	15.33	9.75	149	193.17	2961
Total Variable Loads	257.72	9.75	2513	111.10	28632

Lightship and Fixed Loads	Weight (LT)	Z (vert) ft	VMOM	X (long) ft	LMOM
Structure (calculated)	2001.61	16.53	33084	125.07	250344
Structure (not-calculated)	702.00	16.53	11603	114.78	80575
Armament	54.25	25.64	1391	139.27	7556
Propulsion	493.51	11.04	5449	128.04	63188
Fixed Loads	34.84	18.33	639	135.23	4712
Ballast	338.23	11.04	3734	161.49	54620
Total Lightship and Fixed Loads	3624.45	15.42	55900	127.19	460995

TOTAL	**3882.18**	**15.05**	**58413**	**126.12**	**489627**

Below are notes and weight estimates for the waterboxes, both their structure and the amount of water they may have carried.

Water Boxes

It was noted in the drawings of the *Merrimack* - both Park's book and sectional views from the time period - that there was space forward and aft of the engine for water tanks.

At first, it was thought that these water tanks were for feed water for the boilers. It seems though that most vintage 1850's steam engines for marine use were taking any make-up feed water directly from the sea rather than hold it in dedicated feed water tanks. It is possible that some of the water from the engine's condensers were recycled back into the boilers - I don't really know but as I have a weight of the water in the boilers the question is not overly important to me.

However, based on the "Third Report of the Committee to inquire to the Causes of the deterioration of Boilers, and to propose measures which would tend to increase their durability" which was issued in 1877 it is clear that in the British Navy sea-water was being used rather regularly in boilers on a great many ships. I am not clear as to when sea-water was no longer used in boilers, but I think it is safe to say that most, if not all, marine boilers of 1850's vintage probably relied on seawater.

So there would be no need to hold that feed water in tanks, really. In a treatise on boilers by William Henry Shock it is noted that it would help corrosion problems if you could treat feed water in tanks prior to boiler entry, but most marine vessels simply did not have the space. You probably couldn't get away from this problem until steel vessel construction was better understood and ship length could be increased.

So, what about these tanks? I finally found a forum that talked about water tanks onboard sailing vessels.
http://forum.sailingnavies.com/viewtopic.php?t=1277

These guys said around 1815 sailing navies stopped using casks to store water and started putting water in storage tanks, and pointed to a couple of references to support the notion. This was a great thing, actually; instead of haling water tanks topside it could be pumped out of the tanks. One of the references was Meade's 1869 "A Treatise on Naval Architecture and Shipbuilding" - on the Google Books scan on page 415 it addresses tanks for holding fresh water, states they are 4 x 4 footprint and 4 - 6 feet tall.

So, that seems to make sense to me. Even if it had been more water than was necessary, I'd be willing to bet that those tanks were full to drive the draft of the ship up.

Park shows 9 water tanks, 5 aft and 4 fwd. I assume they are 4x4x4'. Volume is then 64 cubic feet. Assume 1" thick iron plate. There would likely be 2 sets, one port and one stbd

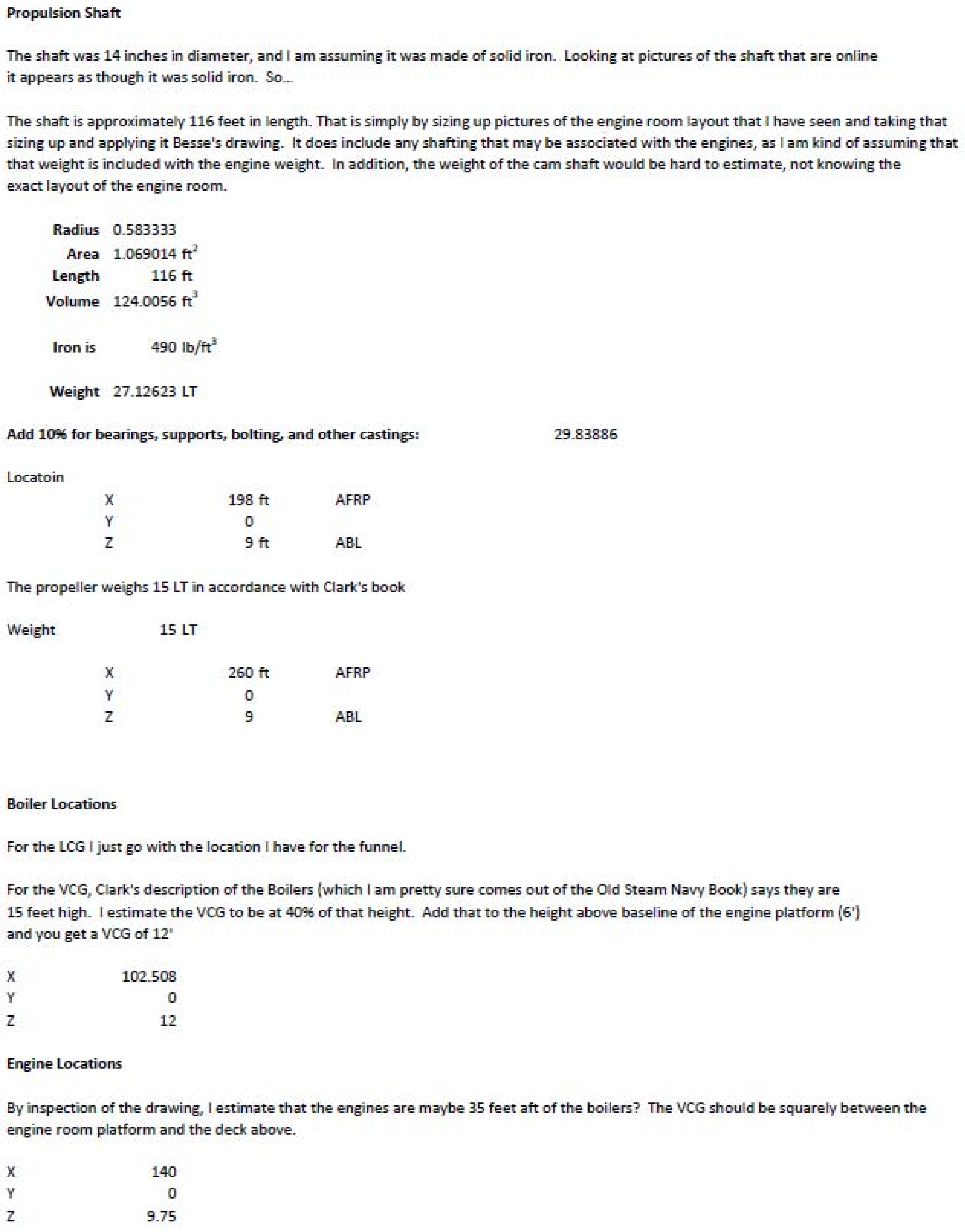
So without further ado, weights and centers.

Vol Iron	2	cubic feet
Dens Iron	490	lb/cu ft
Weight	980	lb per box

Volume of water	64	cubic feet
Weight of fresh water 90% full	3686.4	lb

	Weight (lb)	Weight (LT)
Aft Tanks	9800	4.375
Fwd Tanks	7840	3.5
Total		7.875
Aft Water	36864	16.4571429
Fwd Water	29491.2	13.1657143
Total		29.6228571

Below are the weight calculations for the engines and boilers, most of which are based on B.F. Isherwood's "Experimental Researches in Steam Engineering".



Propulsion Shaft

The shaft was 14 inches in diameter, and I am assuming it was made of solid iron. Looking at pictures of the shaft that are online it appears as though it was solid iron. So...

The shaft is approximately 116 feet in length. That is simply by sizing up pictures of the engine room layout that I have seen and taking that sizing up and applying it Besse's drawing. It does include any shafting that may be associated with the engines, as I am kind of assuming that that weight is included with the engine weight. In addition, the weight of the cam shaft would be hard to estimate, not knowing the exact layout of the engine room.

Radius	0.583333
Area	1.069014 ft^2
Length	116 ft
Volume	124.0056 ft^3
Iron is	490 lb/ft^3
Weight	27.12623 LT

Add 10% for bearings, supports, bolting, and other castings: 29.83886

Locatoin

X	198 ft	AFRP
Y	0	
Z	9 ft	ABL

The propeller weighs 15 LT in accordance with Clark's book

Weight 15 LT

X	260 ft	AFRP
Y	0	
Z	9	ABL

Boiler Locations

For the LCG I just go with the location I have for the funnel.

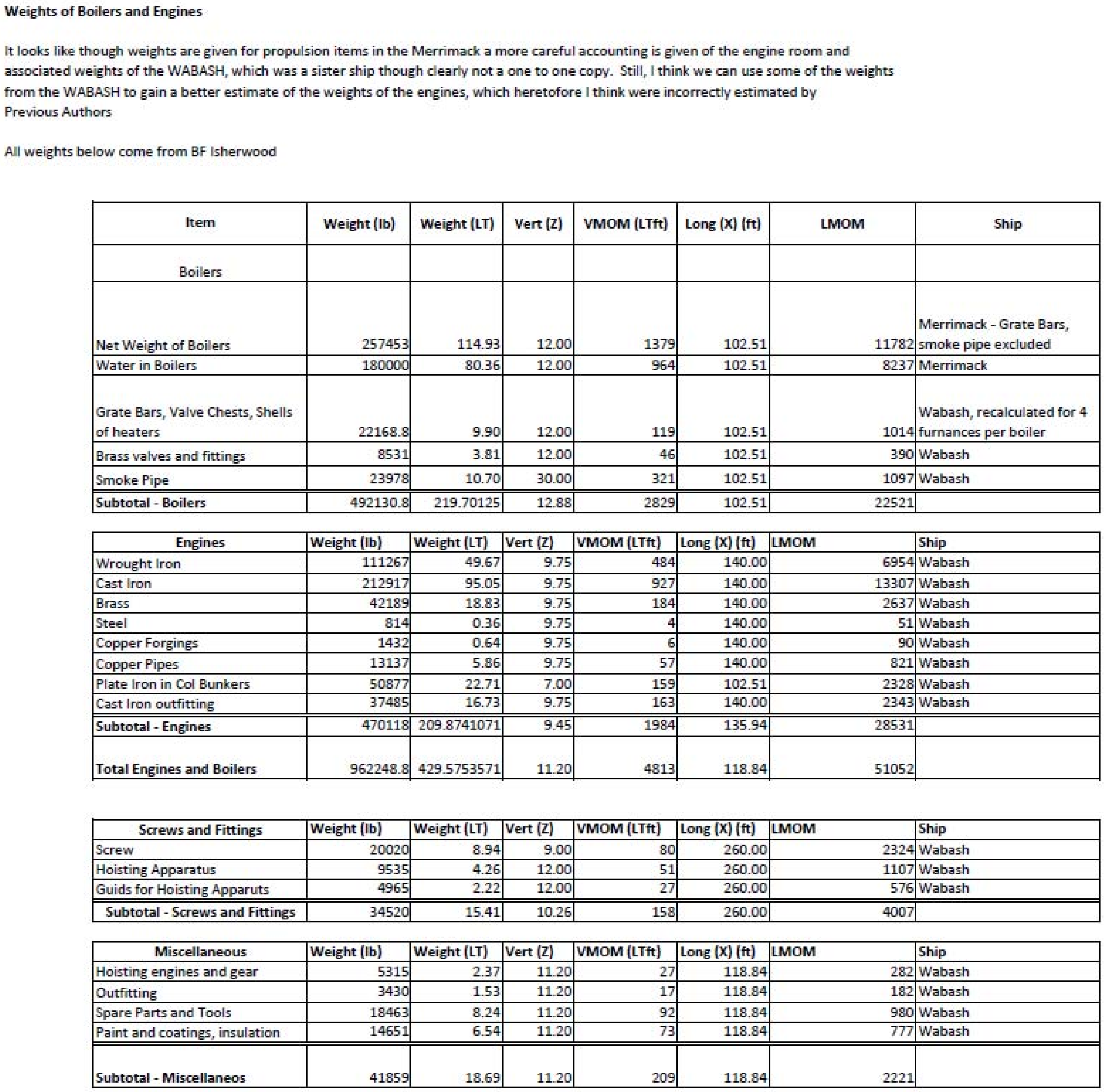
For the VCG, Clark's description of the Boilers (which I am pretty sure comes out of the Old Steam Navy Book) says they are 15 feet high. I estimate the VCG to be at 40% of that height. Add that to the height above baseline of the engine platform (6') and you get a VCG of 12'

X	102.508
Y	0
Z	12

Engine Locations

By inspection of the drawing, I estimate that the engines are maybe 35 feet aft of the boilers? The VCG should be squarely between the engine room platform and the deck above.

X	140
Y	0
Z	9.75



Weights of Boilers and Engines

It looks like though weights are given for propulsion items in the Merrimack a more careful accounting is given of the engine room and associated weights of the WABASH, which was a sister ship though clearly not a one to one copy. Still, I think we can use some of the weights from the WABASH to gain a better estimate of the weights of the engines, which heretofore I think were incorrectly estimated by Previous Authors

All weights below come from BF Isherwood

Item	Weight (lb)	Weight (LT)	Vert (Z)	VMOM (LTft)	Long (X) (ft)	LMOM	Ship
Boilers							
Net Weight of Boilers	257453	114.93	12.00	1379	102.51	11782	Merrimack - Grate Bars, smoke pipe excluded
Water in Boilers	180000	80.36	12.00	964	102.51	8237	Merrimack
Grate Bars, Valve Chests, Shells of heaters	22168.8	9.90	12.00	119	102.51	1014	Wabash, recalculated for 4 furnances per boiler
Brass valves and fittings	8531	3.81	12.00	46	102.51	390	Wabash
Smoke Pipe	23978	10.70	30.00	321	102.51	1097	Wabash
Subtotal - Boilers	492130.8	219.70125	12.88	2829	102.51	22521	

Engines	Weight (lb)	Weight (LT)	Vert (Z)	VMOM (LTft)	Long (X) (ft)	LMOM	Ship
Wrought Iron	111267	49.67	9.75	484	140.00	6954	Wabash
Cast Iron	212917	95.05	9.75	927	140.00	13307	Wabash
Brass	42189	18.83	9.75	184	140.00	2637	Wabash
Steel	814	0.36	9.75	4	140.00	51	Wabash
Copper Forgings	1432	0.64	9.75	6	140.00	90	Wabash
Copper Pipes	13137	5.86	9.75	57	140.00	821	Wabash
Plate Iron in Col Bunkers	50877	22.71	7.00	159	102.51	2328	Wabash
Cast Iron outfitting	37485	16.73	9.75	163	140.00	2343	Wabash
Subtotal - Engines	470118	209.8741071	9.45	1984	135.94	28531	
Total Engines and Boilers	962248.8	429.5753571	11.20	4813	118.84	51052	

Screws and Fittings	Weight (lb)	Weight (LT)	Vert (Z)	VMOM (LTft)	Long (X) (ft)	LMOM	Ship
Screw	20020	8.94	9.00	80	260.00	2324	Wabash
Hoisting Apparatus	9535	4.26	12.00	51	260.00	1107	Wabash
Guids for Hoisting Apparuts	4965	2.22	12.00	27	260.00	576	Wabash
Subtotal - Screws and Fittings	34520	15.41	10.26	158	260.00	4007	

Miscellaneous	Weight (lb)	Weight (LT)	Vert (Z)	VMOM (LTft)	Long (X) (ft)	LMOM	Ship
Hoisting engines and gear	5315	2.37	11.20	27	118.84	282	Wabash
Outfitting	3430	1.53	11.20	17	118.84	182	Wabash
Spare Parts and Tools	18463	8.24	11.20	92	118.84	980	Wabash
Paint and coatings, insulation	14651	6.54	11.20	73	118.84	777	Wabash
Subtotal - Miscellaneos	41859	18.69	11.20	209	118.84	2221	

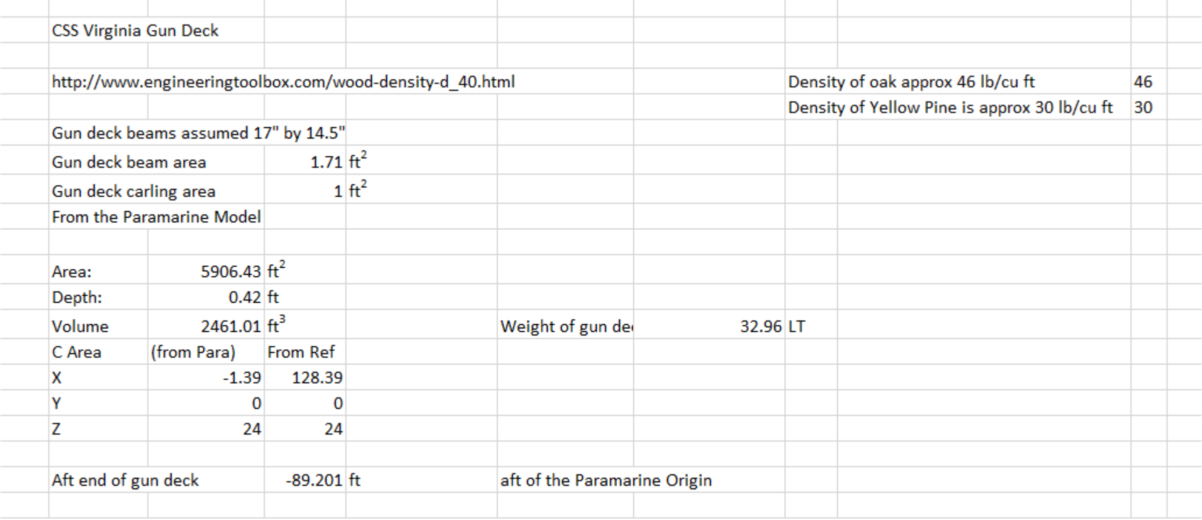
Below is the weight estimate for the Rudder. It is based on the square footage of the rudder and an assumed thickness. The square footage of the rudder is based on information extracted from the Paramarine Geometry.

Rudder

The Rudder is	102.558	cu. Ft	From Paramarine Geometry
Density oak	46	lb./cu.ft	
Weight	2.106102	LT	

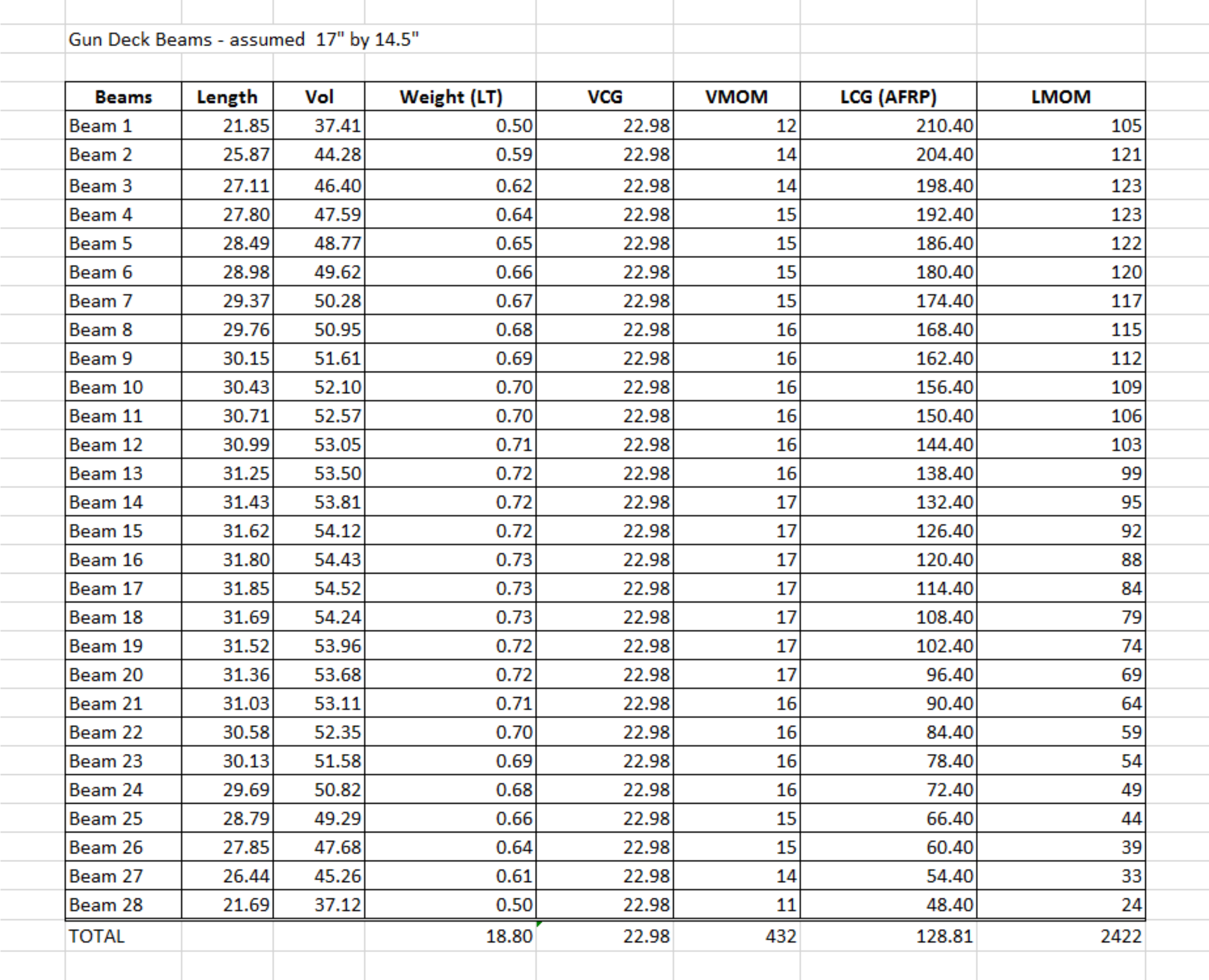
From Ref		
VCG	8.116	
LCG	267.447	FT AFRP
TCG	0	

Below is a calculation of the weight of the gun deck itself. A volume of the gun deck was found by getting the square foot area in Paramarine and then multiplying the assumed thickness of 5". Note that it was assumed that pine was used for the deck at an assumed density of 30 lb/ft^3. It probably should be assumed oak, which has an assumed density of 46 lb/ft^3. This is a difference in weight of nearly 17 LT! But in the end it would have only lowered the amount of uncalculated weight in the analysis.



CSS Virginia Gun Deck								
http://www.engineeringtoolbox.com/wood-density-d_40.html						Density of oak approx 46 lb/cu ft		46
						Density of Yellow Pine is approx 30 lb/cu ft		30
Gun deck beams assumed 17" by 14.5"								
Gun deck beam area		1.71	ft^2					
Gun deck carling area		1	ft^2					
From the Paramarine Model								
Area:	5906.43	ft^2						
Depth:	0.42	ft						
Volume	2461.01	ft^3		Weight of gun de	32.96	LT		
C Area	(from Para)	From Ref						
X	-1.39	128.39						
Y	0	0						
Z	24	24						
Aft end of gun deck		-89.201	ft	aft of the Paramarine Origin				

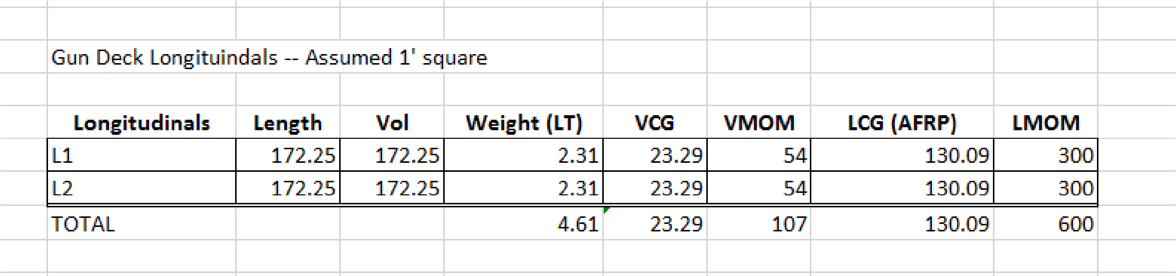
Calculation for the Gun Deck Beams…the beams weight, like the gun deck, was also assumed made of pine. They probably should have been assumed to be oak. Even if the gun deck was made of pine, it is likely that the beams would have been made of oak as they are stronger.



Gun Deck Beams - assumed 17" by 14.5"

Beams	Length	Vol	Weight (LT)	VCG	VMOM	LCG (AFRP)	LMOM
Beam 1	21.85	37.41	0.50	22.98	12	210.40	105
Beam 2	25.87	44.28	0.59	22.98	14	204.40	121
Beam 3	27.11	46.40	0.62	22.98	14	198.40	123
Beam 4	27.80	47.59	0.64	22.98	15	192.40	123
Beam 5	28.49	48.77	0.65	22.98	15	186.40	122
Beam 6	28.98	49.62	0.66	22.98	15	180.40	120
Beam 7	29.37	50.28	0.67	22.98	15	174.40	117
Beam 8	29.76	50.95	0.68	22.98	16	168.40	115
Beam 9	30.15	51.61	0.69	22.98	16	162.40	112
Beam 10	30.43	52.10	0.70	22.98	16	156.40	109
Beam 11	30.71	52.57	0.70	22.98	16	150.40	106
Beam 12	30.99	53.05	0.71	22.98	16	144.40	103
Beam 13	31.25	53.50	0.72	22.98	16	138.40	99
Beam 14	31.43	53.81	0.72	22.98	17	132.40	95
Beam 15	31.62	54.12	0.72	22.98	17	126.40	92
Beam 16	31.80	54.43	0.73	22.98	17	120.40	88
Beam 17	31.85	54.52	0.73	22.98	17	114.40	84
Beam 18	31.69	54.24	0.73	22.98	17	108.40	79
Beam 19	31.52	53.96	0.72	22.98	17	102.40	74
Beam 20	31.36	53.68	0.72	22.98	17	96.40	69
Beam 21	31.03	53.11	0.71	22.98	16	90.40	64
Beam 22	30.58	52.35	0.70	22.98	16	84.40	59
Beam 23	30.13	51.58	0.69	22.98	16	78.40	54
Beam 24	29.69	50.82	0.68	22.98	16	72.40	49
Beam 25	28.79	49.29	0.66	22.98	15	66.40	44
Beam 26	27.85	47.68	0.64	22.98	15	60.40	39
Beam 27	26.44	45.26	0.61	22.98	14	54.40	33
Beam 28	21.69	37.12	0.50	22.98	11	48.40	24
TOTAL			18.80	22.98	432	128.81	2422

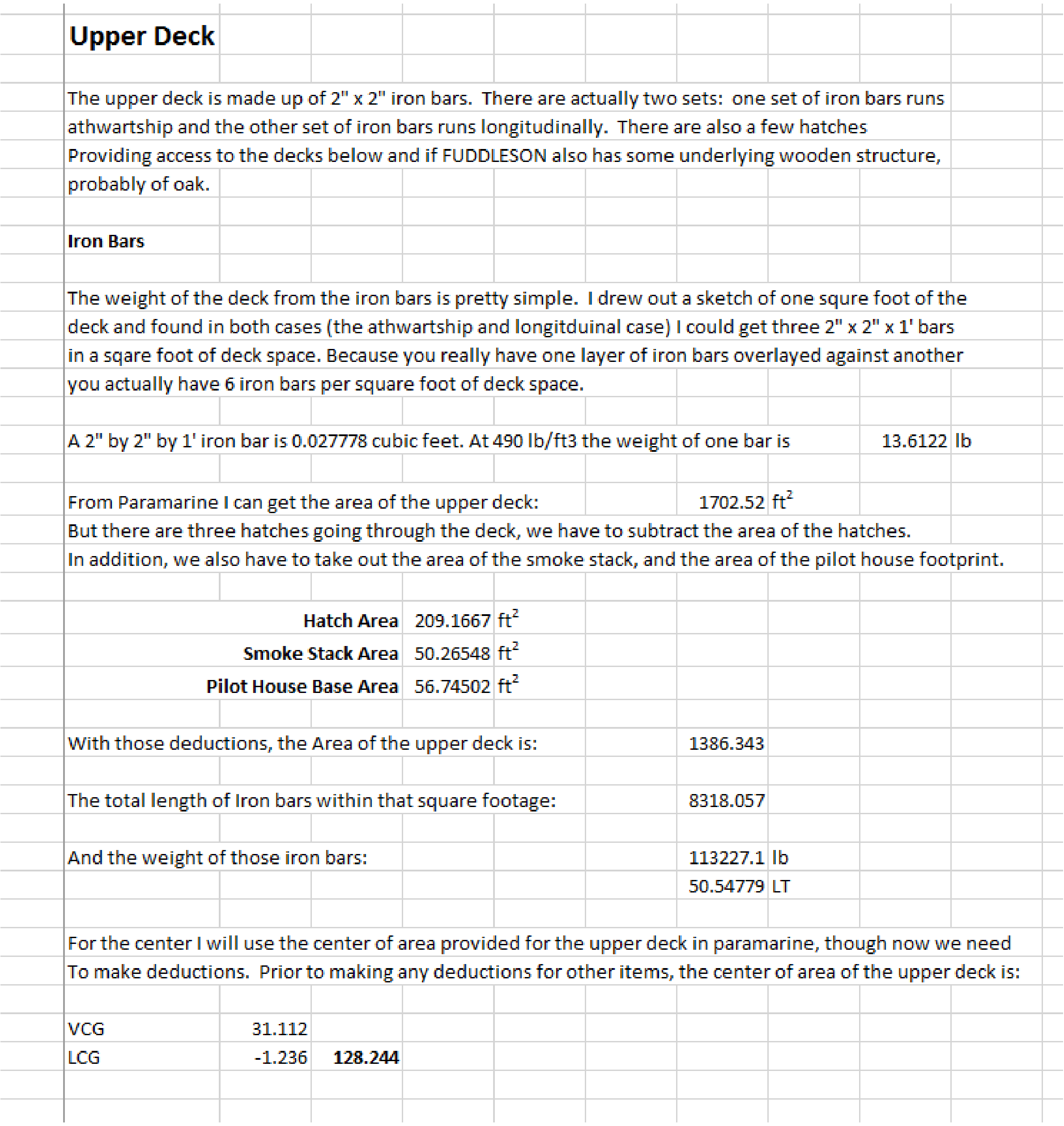
And the longitudinals, assumed 1' square.



Gun Deck Longituindals -- Assumed 1' square

Longitudinals	Length	Vol	Weight (LT)	VCG	VMOM	LCG (AFRP)	LMOM
L1	172.25	172.25	2.31	23.29	54	130.09	300
L2	172.25	172.25	2.31	23.29	54	130.09	300
TOTAL			4.61	23.29	107	130.09	600

Here are the calculation for the upper deck iron bars, hatches, and the header of oak that bounds the upper deck.



Upper Deck

The upper deck is made up of 2" x 2" iron bars. There are actually two sets: one set of iron bars runs athwartship and the other set of iron bars runs longitudinally. There are also a few hatches Providing access to the decks below and if FUDDLESON also has some underlying wooden structure, probably of oak.

Iron Bars

The weight of the deck from the iron bars is pretty simple. I drew out a sketch of one squre foot of the deck and found in both cases (the athwartship and longitduinal case) I could get three 2" x 2" x 1' bars in a sqare foot of deck space. Because you really have one layer of iron bars overlayed against another you actually have 6 iron bars per square foot of deck space.

A 2" by 2" by 1' iron bar is 0.027778 cubic feet. At 490 lb/ft3 the weight of one bar is 13.6122 lb

From Paramarine I can get the area of the upper deck: 1702.52 ft^2

But there are three hatches going through the deck, we have to subtract the area of the hatches.

In addition, we also have to take out the area of the smoke stack, and the area of the pilot house footprint.

Hatch Area	209.1667	ft^2
Smoke Stack Area	50.26548	ft^2
Pilot House Base Area	56.74502	ft^2

With those deductions, the Area of the upper deck is: 1386.343

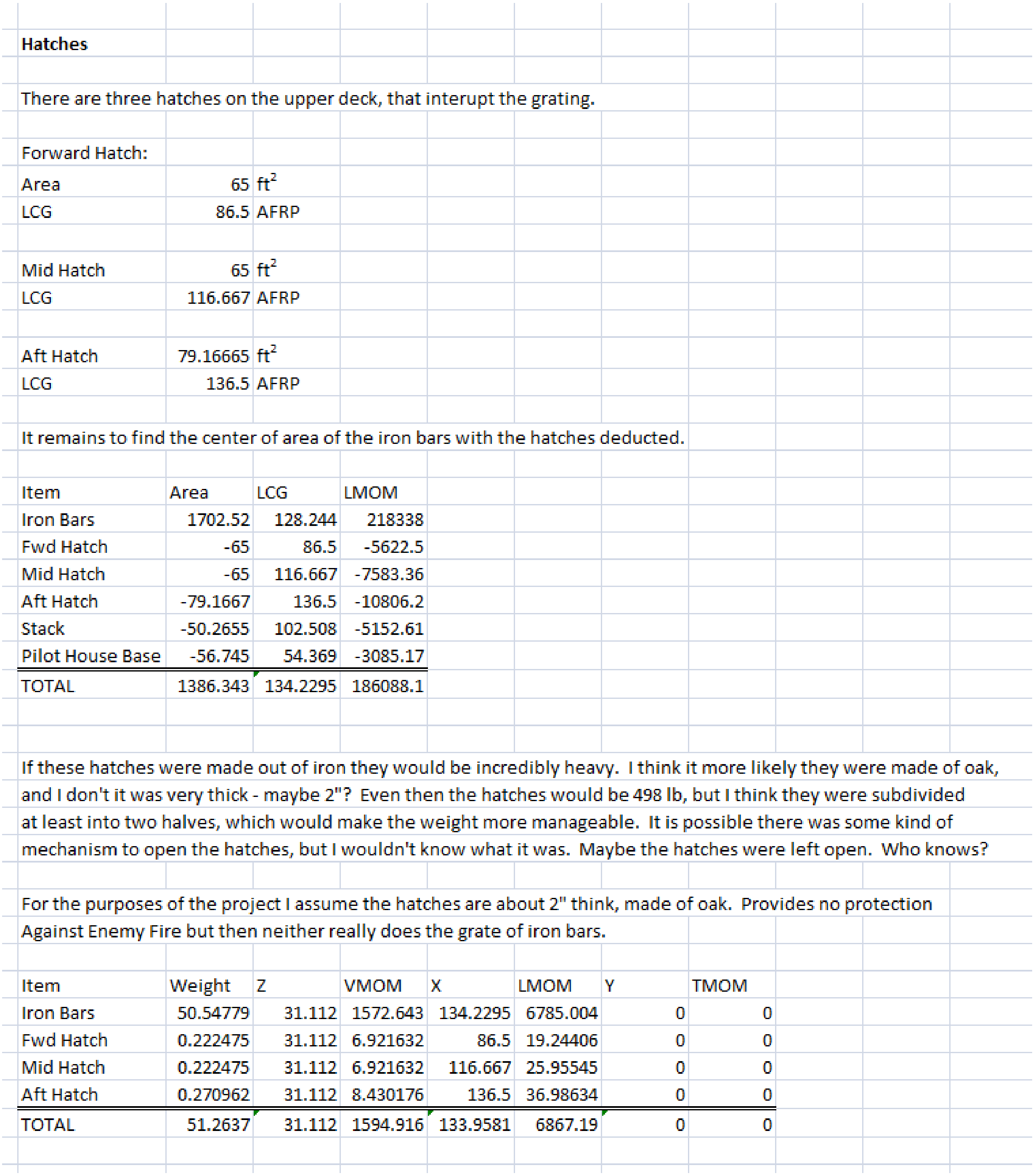
The total length of Iron bars within that square footage: 8318.057

And the weight of those iron bars: 113227.1 lb

50.54779 LT

For the center I will use the center of area provided for the upper deck in paramarine, though now we need To make deductions. Prior to making any deductions for other items, the center of area of the upper deck is:

VCG	31.112	
LCG	-1.236	**128.244**



Hatches

There are three hatches on the upper deck, that interupt the grating.

Forward Hatch:

Area	65	ft^2
LCG	86.5	AFRP
Mid Hatch	65	ft^2
LCG	116.667	AFRP
Aft Hatch	79.16665	ft^2
LCG	136.5	AFRP

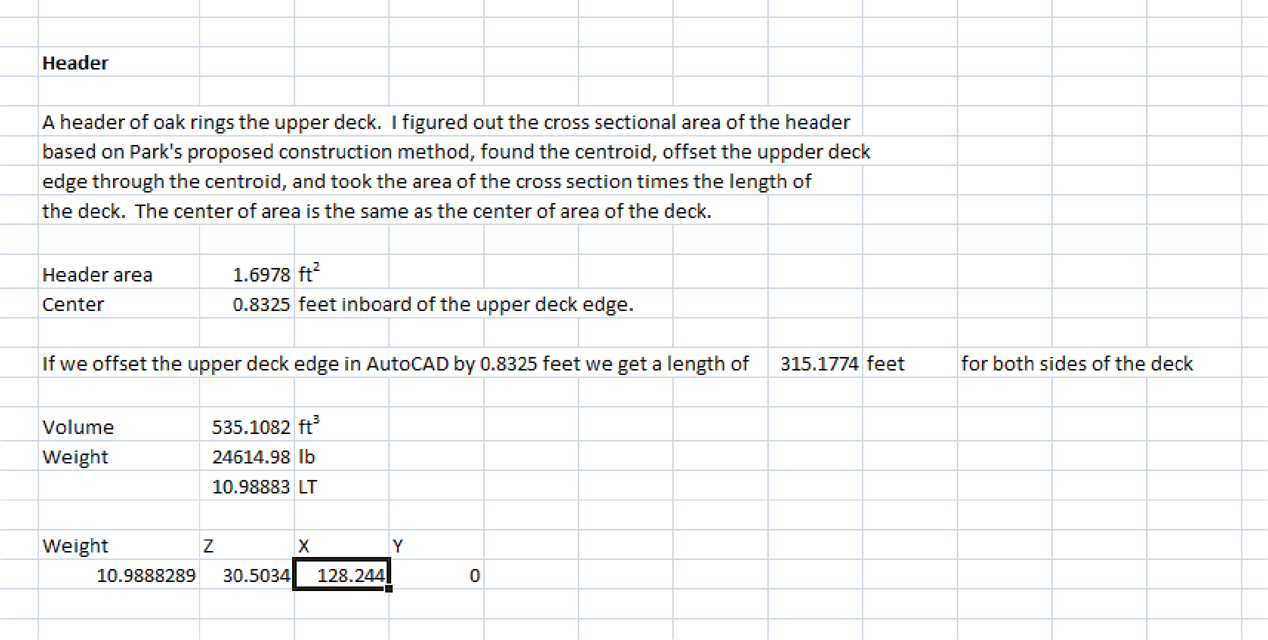
It remains to find the center of area of the iron bars with the hatches deducted.

Item	Area	LCG	LMOM
Iron Bars	1702.52	128.244	218338
Fwd Hatch	-65	86.5	-5622.5
Mid Hatch	-65	116.667	-7583.36
Aft Hatch	-79.1667	136.5	-10806.2
Stack	-50.2655	102.508	-5152.61
Pilot House Base	-56.745	54.369	-3085.17
TOTAL	1386.343	134.2295	186088.1

If these hatches were made out of iron they would be incredibly heavy. I think it more likely they were made of oak, and I don't it was very thick - maybe 2"? Even then the hatches would be 498 lb, but I think they were subdivided at least into two halves, which would make the weight more manageable. It is possible there was some kind of mechanism to open the hatches, but I wouldn't know what it was. Maybe the hatches were left open. Who knows?

For the purposes of the project I assume the hatches are about 2" think, made of oak. Provides no protection Against Enemy Fire but then neither really does the grate of iron bars.

Item	Weight	Z	VMOM	X	LMOM	Y	TMOM
Iron Bars	50.54779	31.112	1572.643	134.2295	6785.004	0	0
Fwd Hatch	0.222475	31.112	6.921632	86.5	19.24406	0	0
Mid Hatch	0.222475	31.112	6.921632	116.667	25.95545	0	0
Aft Hatch	0.270962	31.112	8.430176	136.5	36.98634	0	0
TOTAL	51.2637	31.112	1594.916	133.9581	6867.19	0	0



Header

A header of oak rings the upper deck. I figured out the cross sectional area of the header based on Park's proposed construction method, found the centroid, offset the uppder deck edge through the centroid, and took the area of the cross section times the length of the deck. The center of area is the same as the center of area of the deck.

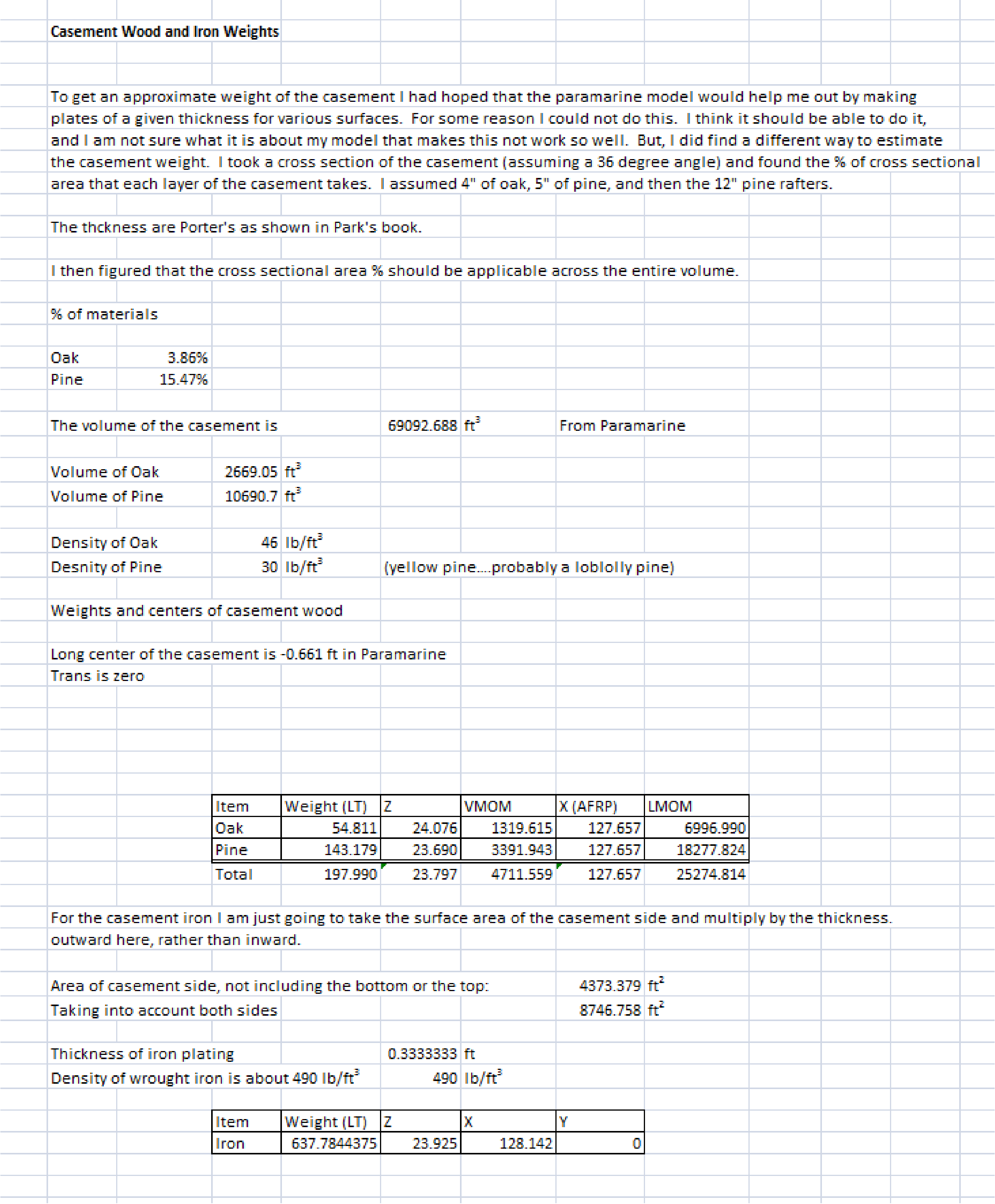
Header area	1.6978	ft^2
Center	0.8325	feet inboard of the upper deck edge.

If we offset the upper deck edge in AutoCAD by 0.8325 feet we get a length of 315.1774 feet for both sides of the deck

Volume	535.1082	ft^3
Weight	24614.98	lb
	10.98883	LT

Weight	Z	X	Y
10.9888289	30.5034	128.244	0

The weight of the casement. Note that the sketch of the cross section referenced in the first paragraph of the casement weight calculation notes is the sketch of the casement cross section shown in section 3.7.10.6



Casement Wood and Iron Weights

To get an approximate weight of the casement I had hoped that the paramarine model would help me out by making plates of a given thickness for various surfaces. For some reason I could not do this. I think it should be able to do it, and I am not sure what it is about my model that makes this not work so well. But, I did find a different way to estimate the casement weight. I took a cross section of the casement (assuming a 36 degree angle) and found the % of cross sectional area that each layer of the casement takes. I assumed 4" of oak, 5" of pine, and then the 12" pine rafters.

The thckness are Porter's as shown in Park's book.

I then figured that the cross sectional area % should be applicable across the entire volume.

% of materials

Oak	3.86%
Pine	15.47%

The volume of the casement is 69092.688 ft^3 From Paramarine

Volume of Oak	2669.05	ft^3
Volume of Pine	10690.7	ft^3

Density of Oak	46	lb/ft^3	
Desnity of Pine	30	lb/ft^3	(yellow pine....probably a loblolly pine)

Weights and centers of casement wood

Long center of the casement is -0.661 ft in Paramarine
Trans is zero

Item	Weight (LT)	Z	VMOM	X (AFRP)	LMOM
Oak	54.811	24.076	1319.615	127.657	6996.990
Pine	143.179	23.690	3391.943	127.657	18277.824
Total	197.990	23.797	4711.559	127.657	25274.814

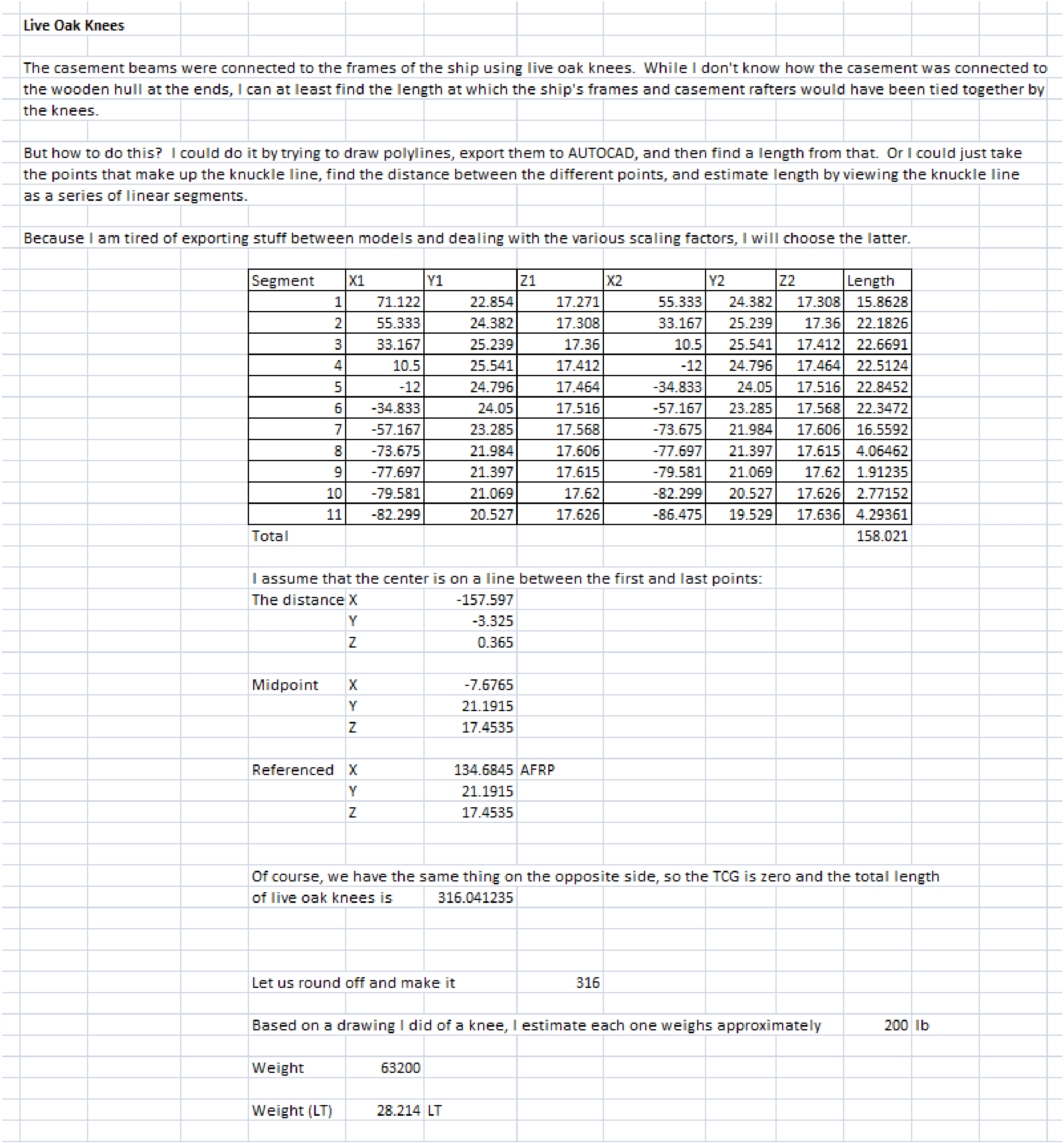
For the casement iron I am just going to take the surface area of the casement side and multiply by the thickness. outward here, rather than inward.

Area of casement side, not including the bottom or the top:	4373.379	ft^2
Taking into account both sides	8746.758	ft^2

Thickness of iron plating	0.3333333	ft
Density of wrought iron is about 490 lb/ft^3	490	lb/ft^3

Item	Weight (LT)	Z	X	Y
Iron	637.7844375	23.925	128.142	0

Here is an estimate of the number and weight of live oak knees.



Live Oak Knees

The casement beams were connected to the frames of the ship using live oak knees. While I don't know how the casement was connected to the wooden hull at the ends, I can at least find the length at which the ship's frames and casement rafters would have been tied together by the knees.

But how to do this? I could do it by trying to draw polylines, export them to AUTOCAD, and then find a length from that. Or I could just take the points that make up the knuckle line, find the distance between the different points, and estimate length by viewing the knuckle line as a series of linear segments.

Because I am tired of exporting stuff between models and dealing with the various scaling factors, I will choose the latter.

Segment	X1	Y1	Z1	X2	Y2	Z2	Length
1	71.122	22.854	17.271	55.333	24.382	17.308	15.8628
2	55.333	24.382	17.308	33.167	25.239	17.36	22.1826
3	33.167	25.239	17.36	10.5	25.541	17.412	22.6691
4	10.5	25.541	17.412	-12	24.796	17.464	22.5124
5	-12	24.796	17.464	-34.833	24.05	17.516	22.8452
6	-34.833	24.05	17.516	-57.167	23.285	17.568	22.3472
7	-57.167	23.285	17.568	-73.675	21.984	17.606	16.5592
8	-73.675	21.984	17.606	-77.697	21.397	17.615	4.06462
9	-77.697	21.397	17.615	-79.581	21.069	17.62	1.91235
10	-79.581	21.069	17.62	-82.299	20.527	17.626	2.77152
11	-82.299	20.527	17.626	-86.475	19.529	17.636	4.29361
Total							158.021

I assume that the center is on a line between the first and last points:

The distance	X	-157.597	
	Y	-3.325	
	Z	0.365	
Midpoint	X	-7.6765	
	Y	21.1915	
	Z	17.4535	
Referenced	X	134.6845	AFRP
	Y	21.1915	
	Z	17.4535	

Of course, we have the same thing on the opposite side, so the TCG is zero and the total length of live oak knees is 316.041235

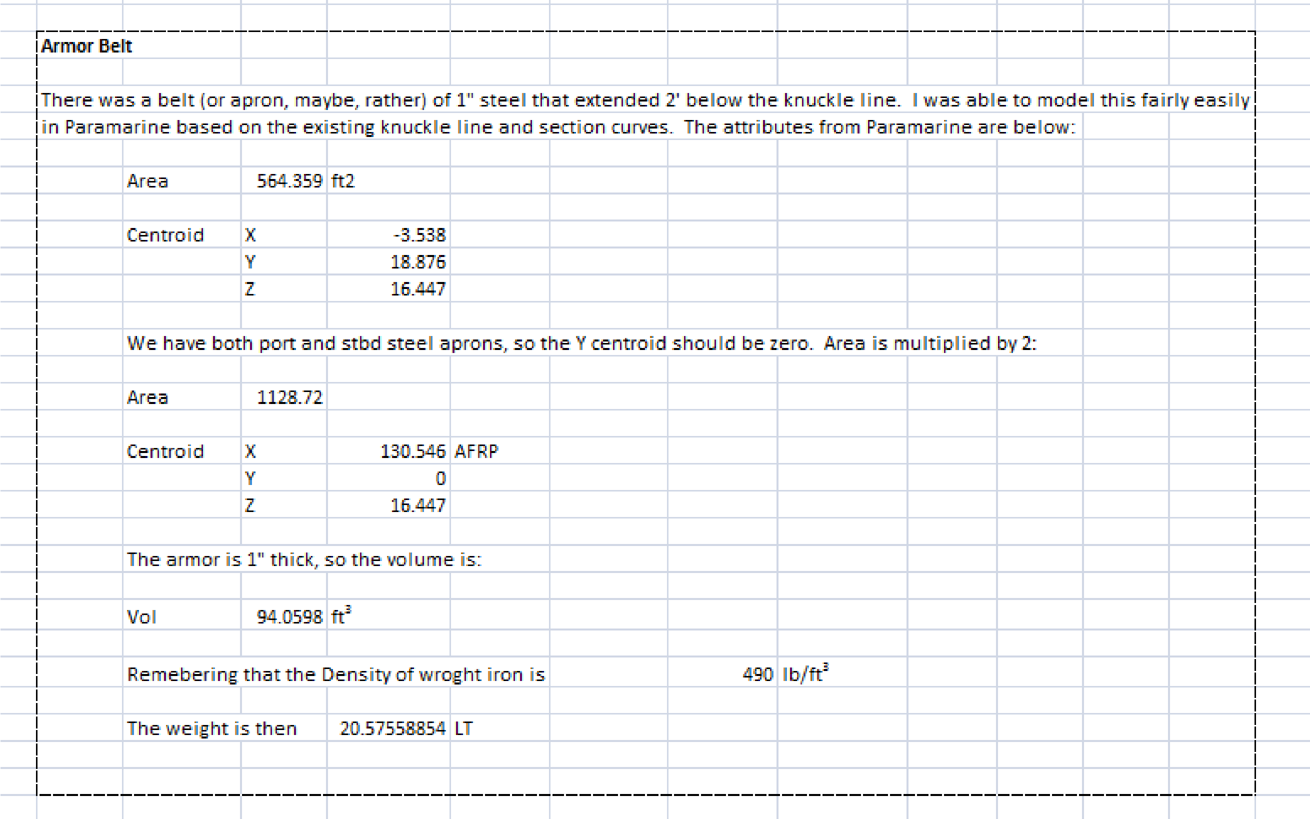
Let us round off and make it 316

Based on a drawing I did of a knee, I estimate each one weighs approximately 200 lb

Weight 63200

Weight (LT) 28.214 LT

Below is the weight estimate for the 1" thick iron band extending below the knuckle line:



Armor Belt

There was a belt (or apron, maybe, rather) of 1" steel that extended 2' below the knuckle line. I was able to model this fairly easily in Paramarine based on the existing knuckle line and section curves. The attributes from Paramarine are below:

Area	564.359	ft2	
Centroid	X	-3.538	
	Y	18.876	
	Z	16.447	

We have both port and stbd steel aprons, so the Y centroid should be zero. Area is multiplied by 2:

Area	1128.72		
Centroid	X	130.546	AFRP
	Y	0	
	Z	16.447	

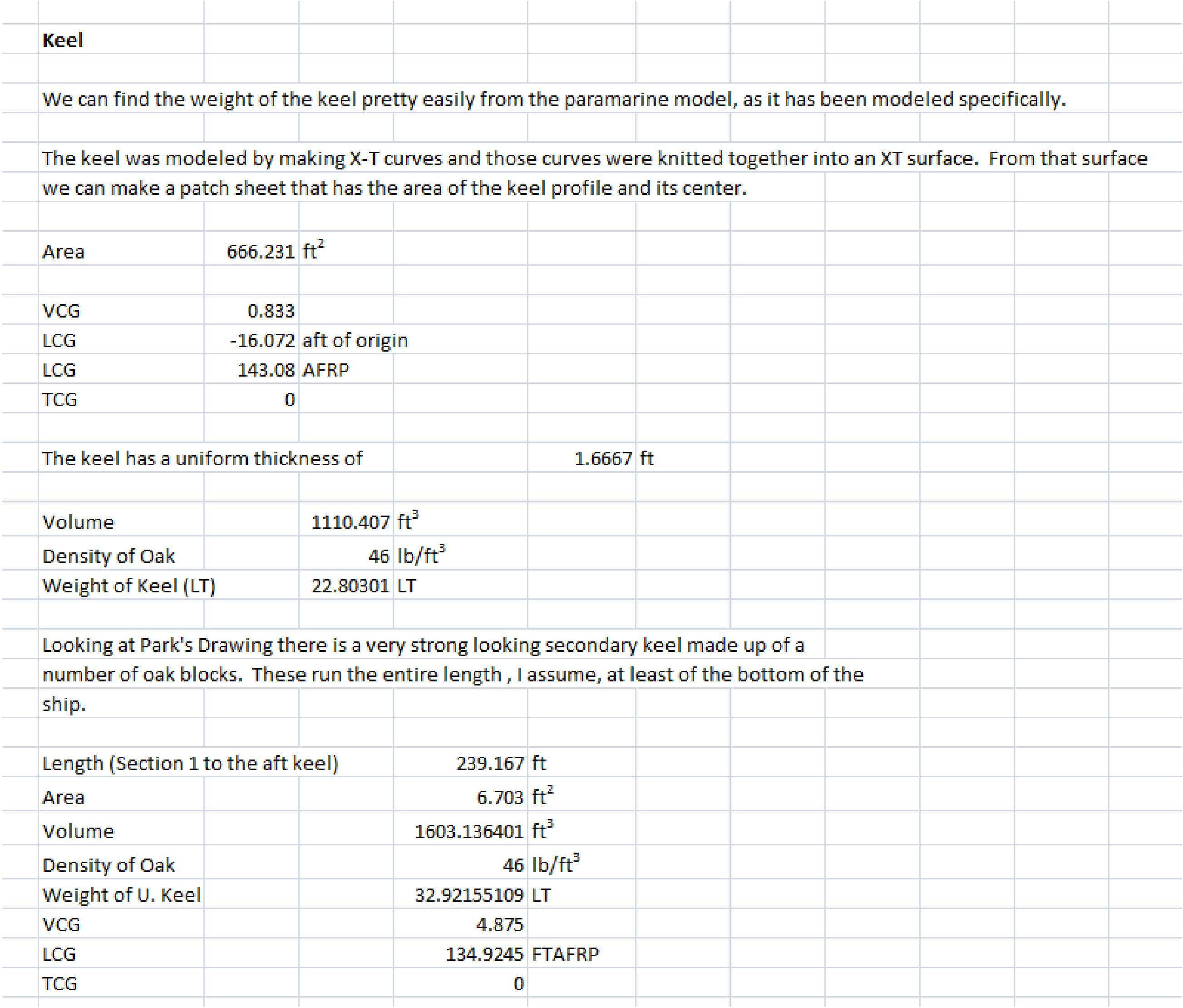
The armor is 1" thick, so the volume is:

Vol 94.0598 ft^3

Remebering that the Density of wroght iron is 490 lb/ft^3

The weight is then 20.57558854 LT

The calculations below are the weight estimates for the keel and the upper keel structure (the keelson, I think it's called). The keel calculations were based on the Paramarine geometry – the keelson calculations were based on Park's midship section drawing.



Keel

We can find the weight of the keel pretty easily from the paramarine model, as it has been modeled specifically.

The keel was modeled by making X-T curves and those curves were knitted together into an XT surface. From that surface we can make a patch sheet that has the area of the keel profile and its center.

Area	666.231	ft^2
VCG	0.833	
LCG	-16.072	aft of origin
LCG	143.08	AFRP
TCG	0	

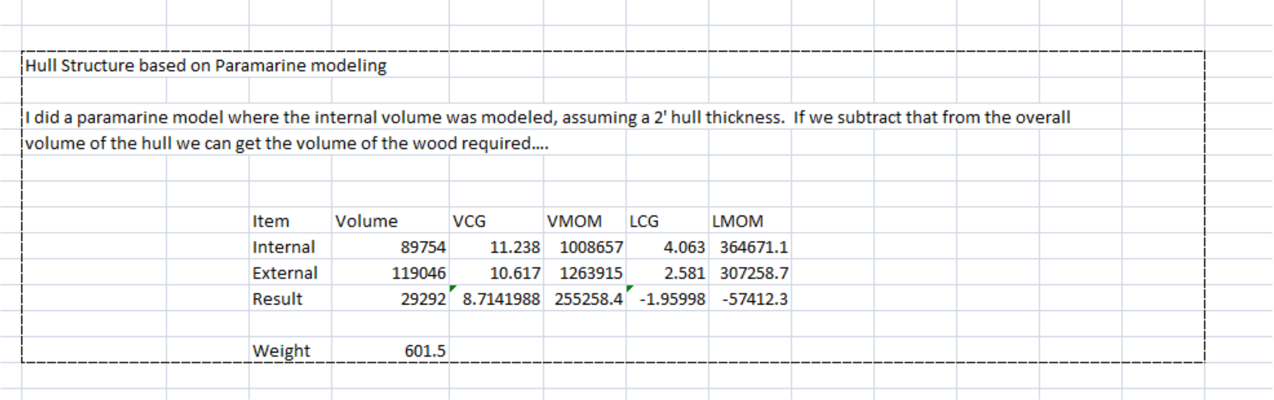
The keel has a uniform thickness of 1.6667 ft

Volume	1110.407	ft^3
Density of Oak	46	lb/ft^3
Weight of Keel (LT)	22.80301	LT

Looking at Park's Drawing there is a very strong looking secondary keel made up of a number of oak blocks. These run the entire length , I assume, at least of the bottom of the ship.

Length (Section 1 to the aft keel)	239.167	ft
Area	6.703	ft^2
Volume	1603.136401	ft^3
Density of Oak	46	lb/ft^3
Weight of U. Keel	32.92155109	LT
VCG	4.875	
LCG	134.9245	FTAFRP
TCG	0	

And below is a calculation for the hull weight itself, based on making a second Paramarine model with extents to the molded line. It is assumed that the hull thickness was about 2'. Based on the external planking, framing, and internal planking, and additionally considering the weight of other structure (cross braces and the like) not captured in the analysis, it is probably not a bad estimate. It was assumed that the hull was made of oak.

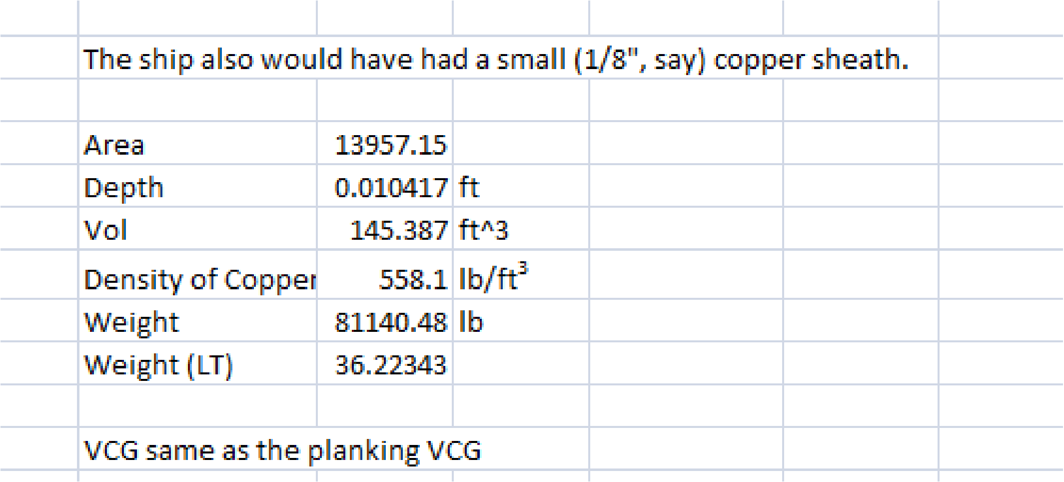


Hull Structure based on Paramarine modeling

I did a paramarine model where the internal volume was modeled, assuming a 2' hull thickness. If we subtract that from the overall volume of the hull we can get the volume of the wood required....

Item	Volume	VCG	VMOM	LCG	LMOM
Internal	89754	11.238	1008657	4.063	364671.1
External	119046	10.617	1263915	2.581	307258.7
Result	29292	8.7141988	255258.4	-1.95998	-57412.3
Weight	601.5				

The CSS Virginia would have had some copper sheathing on the hull – applied with it was still the Merrimack. Below is a weight estimate based on the surface area of the hull from the Paramarine geometry. It was assumed that it would be 1/8" thick based on conversation with John Quarstein, author of <u>Sink Before Surrender</u>.

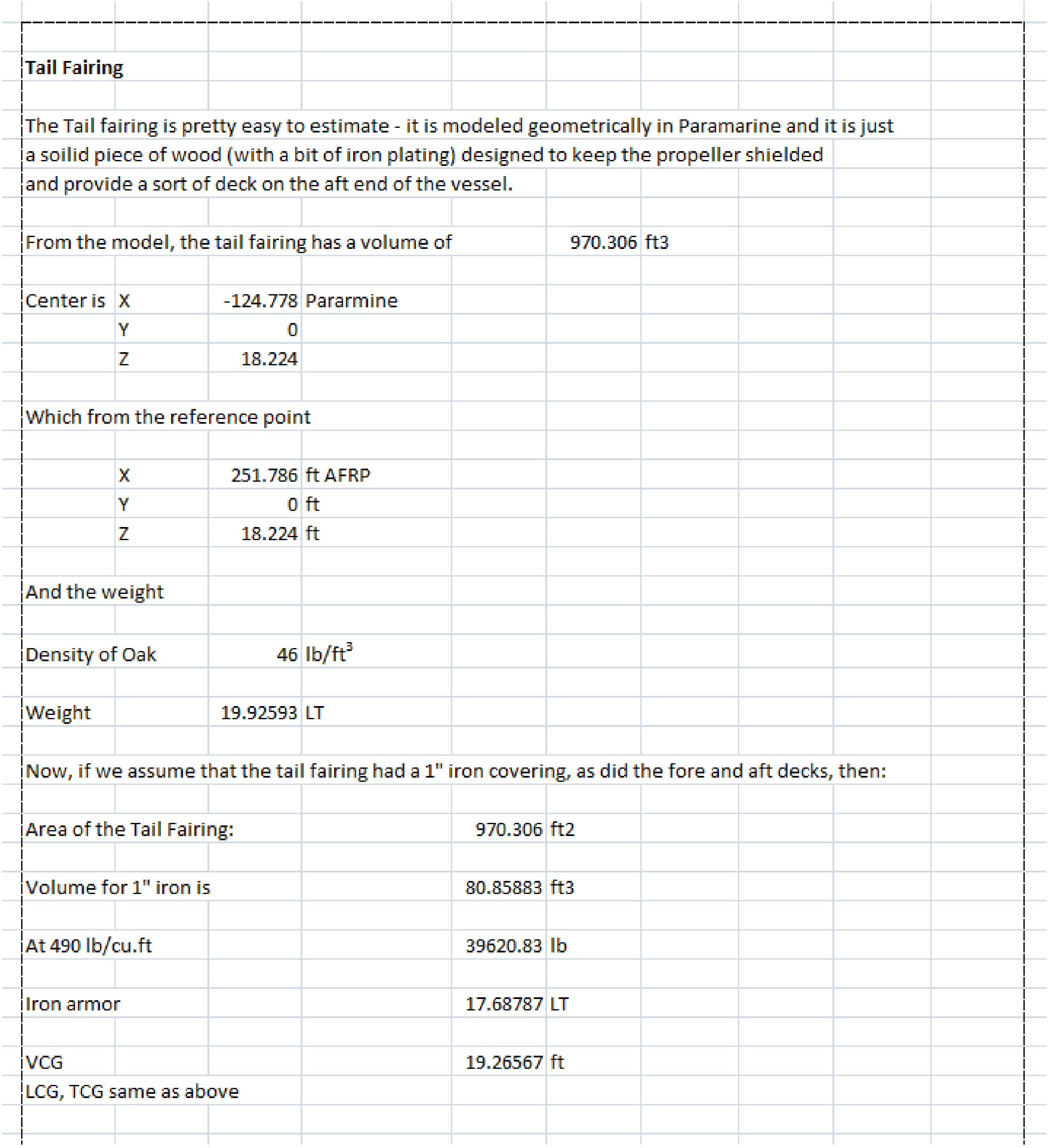


The ship also would have had a small (1/8", say) copper sheath.

Area	13957.15	
Depth	0.010417	ft
Vol	145.387	ft^3
Density of Copper	558.1	lb/ft^3
Weight	81140.48	lb
Weight (LT)	36.22343	

VCG same as the planking VCG

Here are the estimates for the Tail Fairing (sometimes referred to as the fairwater – it is the aft platform on the ship protecting the rudder). The estimate is simply based on the Paramarine Geometry.



Tail Fairing

The Tail fairing is pretty easy to estimate - it is modeled geometrically in Paramarine and it is just
a soilid piece of wood (with a bit of iron plating) designed to keep the propeller shielded
and provide a sort of deck on the aft end of the vessel.

From the model, the tail fairing has a volume of 970.306 ft3

Center is	X	-124.778	Pararmine
	Y	0	
	Z	18.224	

Which from the reference point

X	251.786	ft AFRP
Y	0	ft
Z	18.224	ft

And the weight

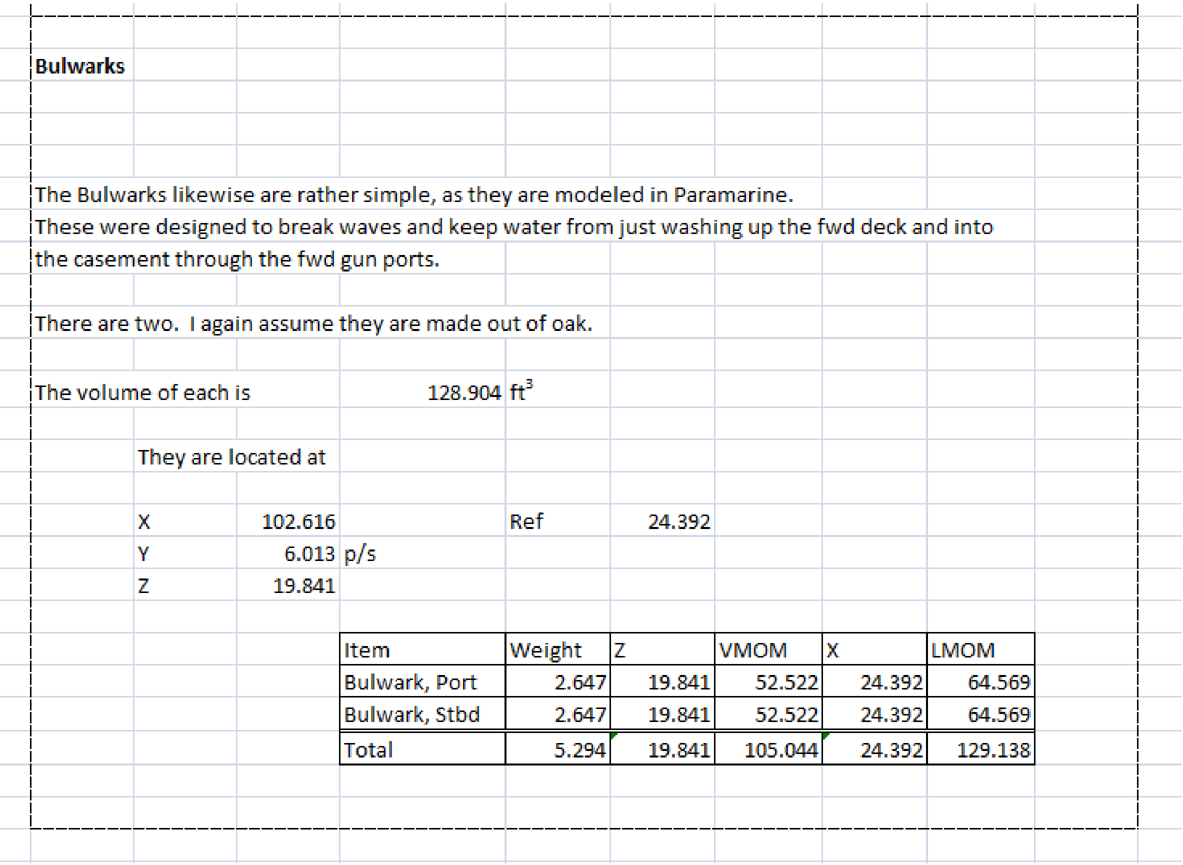
Density of Oak	46	lb/ft^3
Weight	19.92593	LT

Now, if we assume that the tail fairing had a 1" iron covering, as did the fore and aft decks, then:

Area of the Tail Fairing:	970.306	ft2
Volume for 1" iron is	80.85883	ft3
At 490 lb/cu.ft	39620.83	lb
Iron armor	17.68787	LT
VCG	19.26567	ft

LCG, TCG same as above

And the weight of the bulwarks. Also based on the Paramarine Geometry.



Bulwarks

The Bulwarks likewise are rather simple, as they are modeled in Paramarine.
These were designed to break waves and keep water from just washing up the fwd deck and into the casement through the fwd gun ports.

There are two. I again assume they are made out of oak.

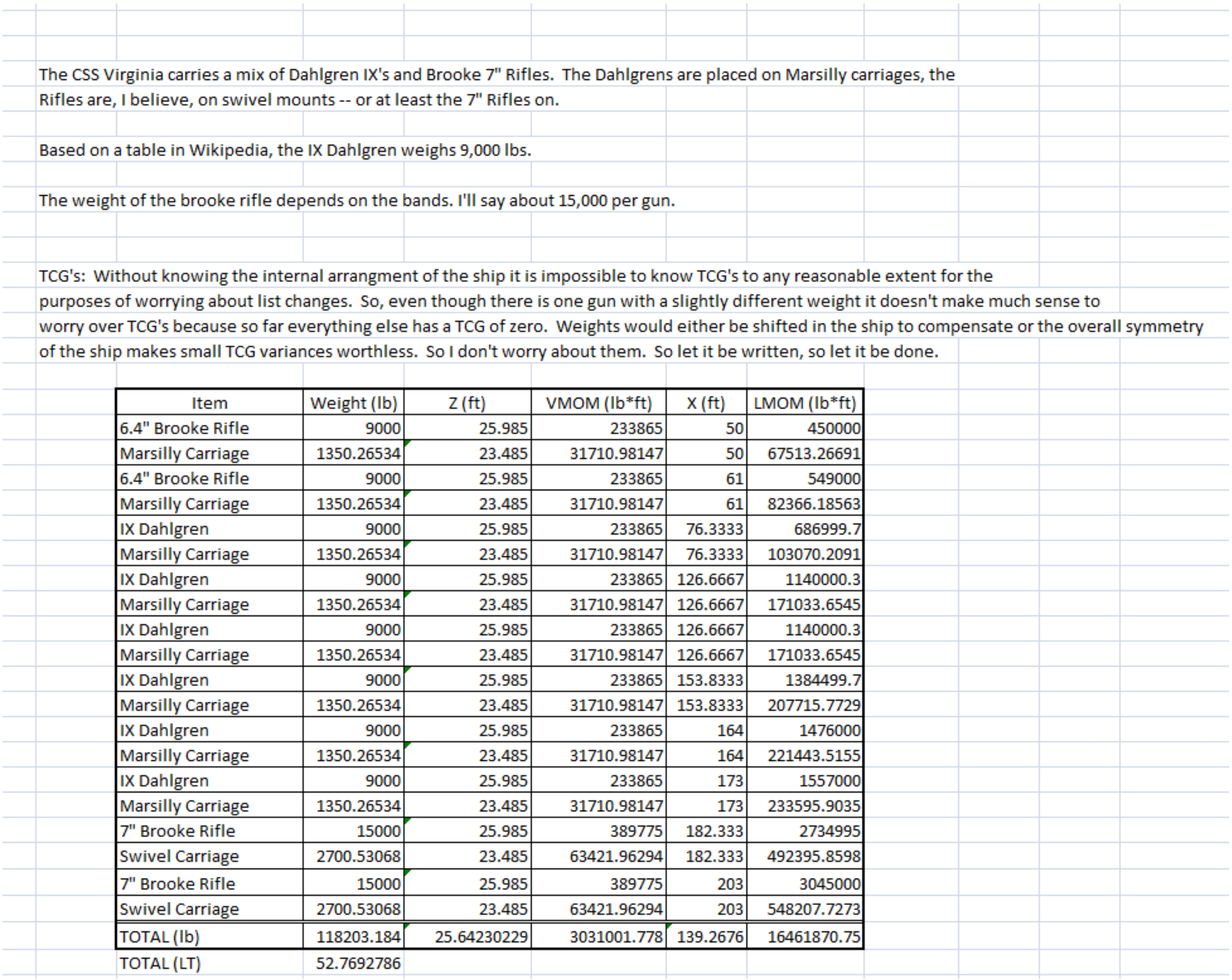
The volume of each is 128.904 ft^3

They are located at

X	102.616		Ref	24.392
Y	6.013	p/s		
Z	19.841			

Item	Weight	Z	VMOM	X	LMOM
Bulwark, Port	2.647	19.841	52.522	24.392	64.569
Bulwark, Stbd	2.647	19.841	52.522	24.392	64.569
Total	5.294	19.841	105.044	24.392	129.138

Below is the weight of guns, carriages (based on the layout of a Marsilly Carriage in Appendix B), powder, and shot.



The CSS Virginia carries a mix of Dahlgren IX's and Brooke 7" Rifles. The Dahlgrens are placed on Marsilly carriages, the Rifles are, I believe, on swivel mounts -- or at least the 7" Rifles on.

Based on a table in Wikipedia, the IX Dahlgren weighs 9,000 lbs.

The weight of the brooke rifle depends on the bands. I'll say about 15,000 per gun.

TCG's: Without knowing the internal arrangment of the ship it is impossible to know TCG's to any reasonable extent for the purposes of worrying about list changes. So, even though there is one gun with a slightly different weight it doesn't make much sense to worry over TCG's because so far everything else has a TCG of zero. Weights would either be shifted in the ship to compensate or the overall symmetry of the ship makes small TCG variances worthless. So I don't worry about them. So let it be written, so let it be done.

Item	Weight (lb)	Z (ft)	VMOM (lb*ft)	X (ft)	LMOM (lb*ft)
6.4" Brooke Rifle	9000	25.985	233865	50	450000
Marsilly Carriage	1350.26534	23.485	31710.98147	50	67513.26691
6.4" Brooke Rifle	9000	25.985	233865	61	549000
Marsilly Carriage	1350.26534	23.485	31710.98147	61	82366.18563
IX Dahlgren	9000	25.985	233865	76.3333	686999.7
Marsilly Carriage	1350.26534	23.485	31710.98147	76.3333	103070.2091
IX Dahlgren	9000	25.985	233865	126.6667	1140000.3
Marsilly Carriage	1350.26534	23.485	31710.98147	126.6667	171033.6545
IX Dahlgren	9000	25.985	233865	126.6667	1140000.3
Marsilly Carriage	1350.26534	23.485	31710.98147	126.6667	171033.6545
IX Dahlgren	9000	25.985	233865	153.8333	1384499.7
Marsilly Carriage	1350.26534	23.485	31710.98147	153.8333	207715.7729
IX Dahlgren	9000	25.985	233865	164	1476000
Marsilly Carriage	1350.26534	23.485	31710.98147	164	221443.5155
IX Dahlgren	9000	25.985	233865	173	1557000
Marsilly Carriage	1350.26534	23.485	31710.98147	173	233595.9035
7" Brooke Rifle	15000	25.985	389775	182.333	2734995
Swivel Carriage	2700.53068	23.485	63421.96294	182.333	492395.8598
7" Brooke Rifle	15000	25.985	389775	203	3045000
Swivel Carriage	2700.53068	23.485	63421.96294	203	548207.7273
TOTAL (lb)	118203.184	25.64230229	3031001.778	139.2676	16461870.75
TOTAL (LT)	52.7692786				

Weight of Marsilly Carriage:

To estimate the weight I found a drawing online of how build a 9" Dahlgren Shell gun on a Marsilly carrige.
The model is 1/2" = 1'. So I drew up the pieces in autocad, which has no scale factor, in accordance with the drawing.
So I had a drawing that was 1/2 size. I then scaled it up by 2 to get the pieces in full scale.

Based on the drawings pretty much all the pieces were taken to be 0.5 feet in depth or thick. So we can just take the area and multiply it by 0.5 ft to get a density. The axles and wheels require just a little more calculation, but not much.

Marsilly carriages could be made of wood or iron. Most that I see in pictures are wood. I assume oak.

Density of oak	46	lb/ft^3
Density of Iron	490	lb/ft^3

Weight of the Axle:

The axle is made up of a block of wood 9" square and 3.5 feet in length through which runs an axle
(I am assuming is it solid iron) that is 6" in diamter. The axle is longer, extending for 5.25 feet

Area of wood	0.5625	ft^2
Area of Axle	0.19634954	ft^2
Remainding area of wood	0.36615046	ft2

Weight of wood	58.9502239	lb
Weight of axle	505.109194	lb
TOTAL	564.059418	

Weight of wheels

The wheels I am assuming are also made of wood. I think its possible they have may been
banded by iron but I am not sure and I don't think that weight will be of much consequence.

The drawing bears out that we have a wheel 0.5625 feet in radius, through which goes the 3" radius axle.
We already have the area of the axle, so

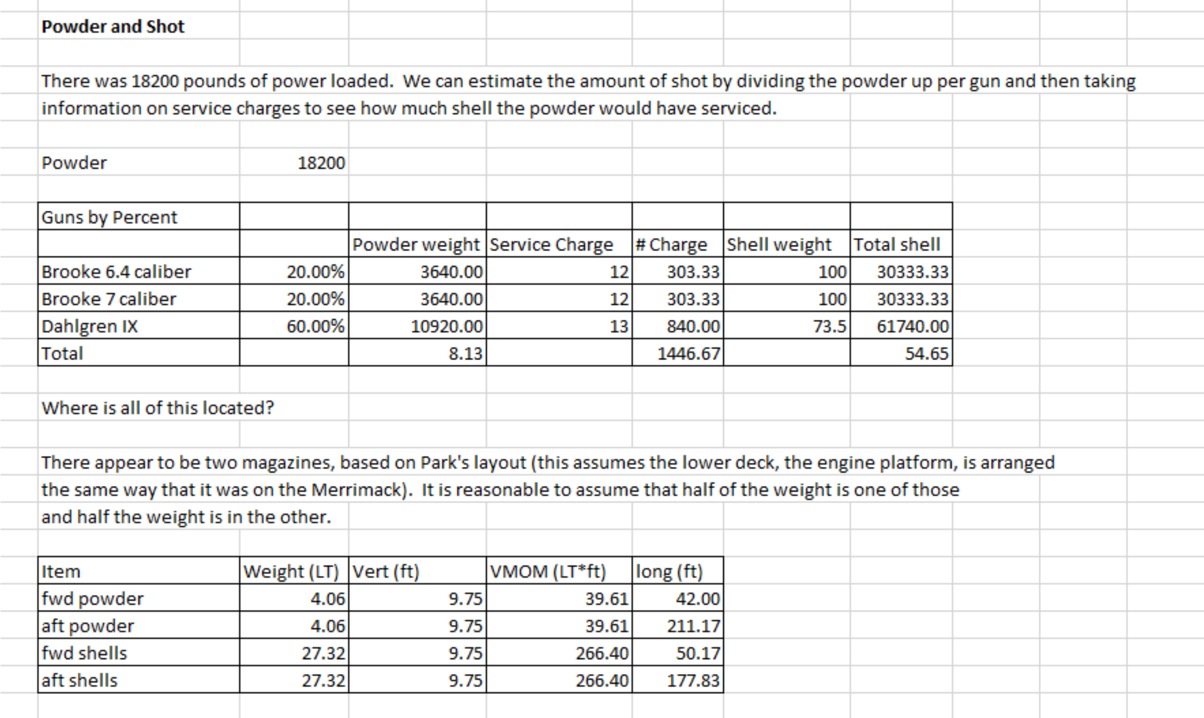
Area of wheel (no axle)	0.99401955	ft^2
Area of axle	0.19634954	
Area of wheel	0.79767001	

The wheel is 6" in depth, so

Weight	18.3464102	lb

So now we can start to put everthing together

ITEM	Area (ft^2)	Depth (ft)	Volume (ft^3)	Weight
Axle				564.0594
Wheels (2)				36.69282
Rear Transom	3.5237	0.5	1.76185	81.0451
Front Transom	1.9571	0.5	0.97855	45.0133
Breast Piece	1.4591	0.5	0.72955	33.5593
Sides (2)	21.2998	0.5	10.6499	489.8954
Additional Metal				100
Total				1350.265



Powder and Shot

There was 18200 pounds of power loaded. We can estimate the amount of shot by dividing the powder up per gun and then taking information on service charges to see how much shell the powder would have serviced.

Powder	18200

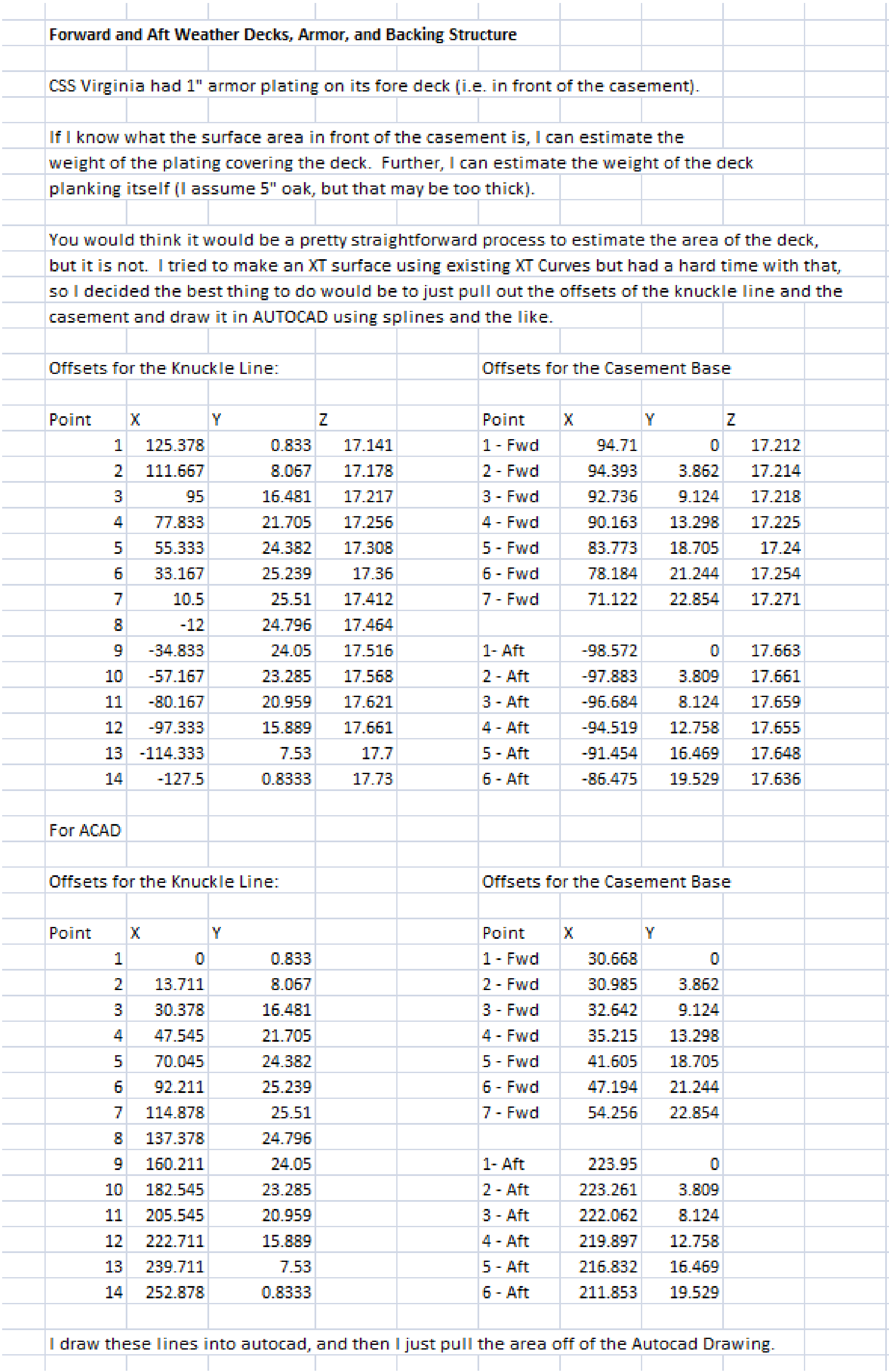
Guns by Percent						
		Powder weight	Service Charge	# Charge	Shell weight	Total shell
Brooke 6.4 caliber	20.00%	3640.00	12	303.33	100	30333.33
Brooke 7 caliber	20.00%	3640.00	12	303.33	100	30333.33
Dahlgren IX	60.00%	10920.00	13	840.00	73.5	61740.00
Total		8.13		1446.67		54.65

Where is all of this located?

There appear to be two magazines, based on Park's layout (this assumes the lower deck, the engine platform, is arranged the same way that it was on the Merrimack). It is reasonable to assume that half of the weight is one of those and half the weight is in the other.

Item	Weight (LT)	Vert (ft)	VMOM (LT*ft)	long (ft)
fwd powder	4.06	9.75	39.61	42.00
aft powder	4.06	9.75	39.61	211.17
fwd shells	27.32	9.75	266.40	50.17
aft shells	27.32	9.75	266.40	177.83

Next is the weight of the weather decks fore and aft of the casement. Also included is the armor plating on those decks. Note that due to some quirk of the geometry, it was very difficult to create new XT Curves in these areas to estimate the areas and volumes and weights directly. So the decks were drawn in AutoCAD based on information on the geometry from the Paramarine Model.



Forward and Aft Weather Decks, Armor, and Backing Structure

CSS Virginia had 1" armor plating on its fore deck (i.e. in front of the casement).

If I know what the surface area in front of the casement is, I can estimate the weight of the plating covering the deck. Further, I can estimate the weight of the deck planking itself (I assume 5" oak, but that may be too thick).

You would think it would be a pretty straightforward process to estimate the area of the deck, but it is not. I tried to make an XT surface using existing XT Curves but had a hard time with that, so I decided the best thing to do would be to just pull out the offsets of the knuckle line and the casement and draw it in AUTOCAD using splines and the like.

Offsets for the Knuckle Line:

Point	X	Y	Z
1	125.378	0.833	17.141
2	111.667	8.067	17.178
3	95	16.481	17.217
4	77.833	21.705	17.256
5	55.333	24.382	17.308
6	33.167	25.239	17.36
7	10.5	25.51	17.412
8	-12	24.796	17.464
9	-34.833	24.05	17.516
10	-57.167	23.285	17.568
11	-80.167	20.959	17.621
12	-97.333	15.889	17.661
13	-114.333	7.53	17.7
14	-127.5	0.8333	17.73

Offsets for the Casement Base

Point	X	Y	Z
1 - Fwd	94.71	0	17.212
2 - Fwd	94.393	3.862	17.214
3 - Fwd	92.736	9.124	17.218
4 - Fwd	90.163	13.298	17.225
5 - Fwd	83.773	18.705	17.24
6 - Fwd	78.184	21.244	17.254
7 - Fwd	71.122	22.854	17.271
1- Aft	-98.572	0	17.663
2 - Aft	-97.883	3.809	17.661
3 - Aft	-96.684	8.124	17.659
4 - Aft	-94.519	12.758	17.655
5 - Aft	-91.454	16.469	17.648
6 - Aft	-86.475	19.529	17.636

For ACAD

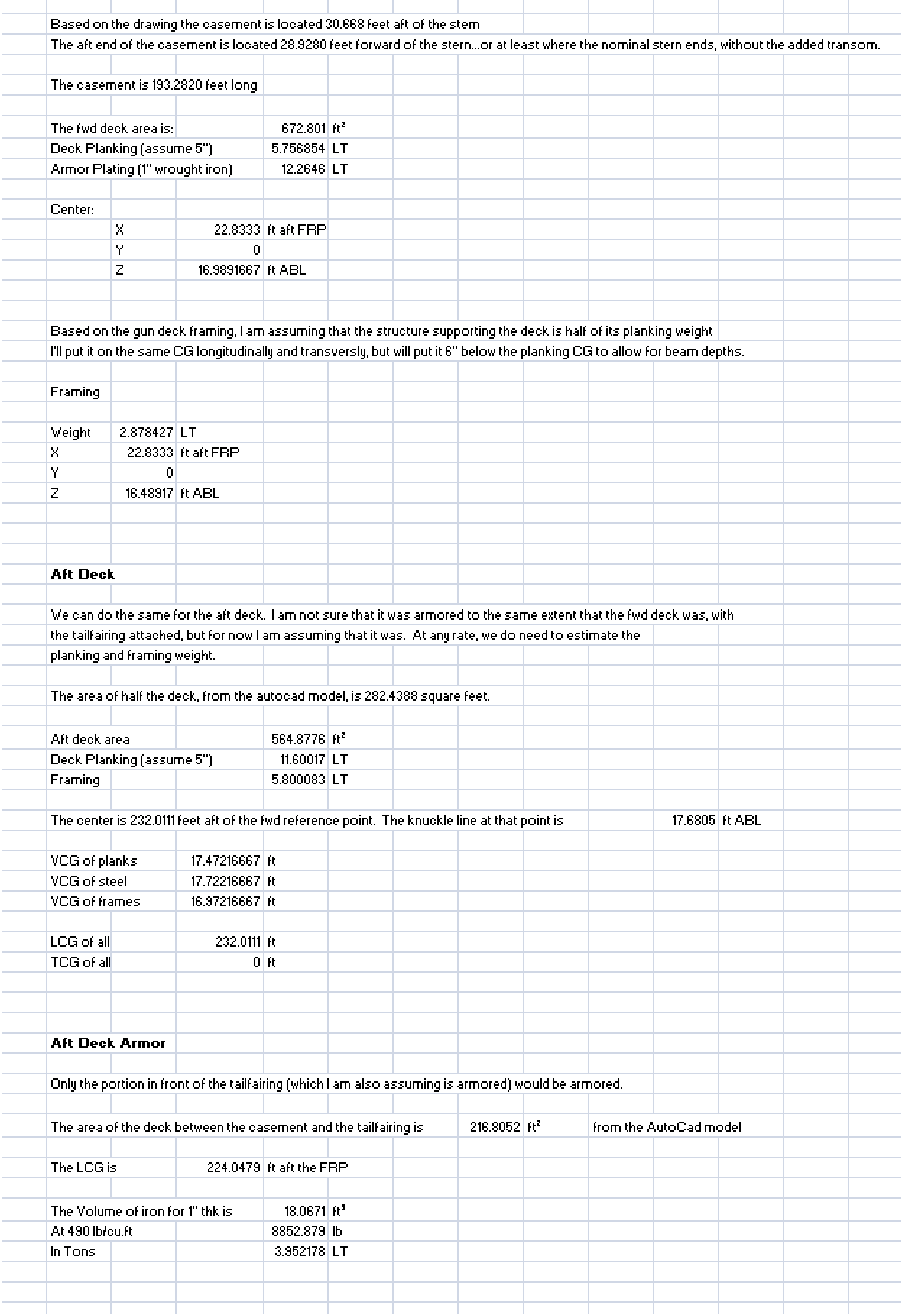
Offsets for the Knuckle Line:

Point	X	Y
1	0	0.833
2	13.711	8.067
3	30.378	16.481
4	47.545	21.705
5	70.045	24.382
6	92.211	25.239
7	114.878	25.51
8	137.378	24.796
9	160.211	24.05
10	182.545	23.285
11	205.545	20.959
12	222.711	15.889
13	239.711	7.53
14	252.878	0.8333

Offsets for the Casement Base

Point	X	Y
1 - Fwd	30.668	0
2 - Fwd	30.985	3.862
3 - Fwd	32.642	9.124
4 - Fwd	35.215	13.298
5 - Fwd	41.605	18.705
6 - Fwd	47.194	21.244
7 - Fwd	54.256	22.854
1- Aft	223.95	0
2 - Aft	223.261	3.809
3 - Aft	222.062	8.124
4 - Aft	219.897	12.758
5 - Aft	216.832	16.469
6 - Aft	211.853	19.529

I draw these lines into autocad, and then I just pull the area off of the Autocad Drawing.



Based on the drawing the casement is located 30.668 feet aft of the stem

The aft end of the casement is located 28.9280 feet forward of the stern...or at least where the nominal stern ends, without the added transom.

The casement is 193.2820 feet long

The fwd deck area is:	672.801	ft^2
Deck Planking (assume 5")	5.756854	LT
Armor Plating (1" wrought iron)	12.2646	LT

Center:

X	22.8333	ft aft FRP
Y	0	
Z	16.9891667	ft ABL

Based on the gun deck framing, I am assuming that the structure supporting the deck is half of its planking weight

I'll put it on the same CG longitudinally and transversly, but will put it 6" below the planking CG to allow for beam depths.

Framing

Weight	2.878427	LT
X	22.8333	ft aft FRP
Y	0	
Z	16.48917	ft ABL

Aft Deck

We can do the same for the aft deck. I am not sure that it was armored to the same extent that the fwd deck was, with the tailfairing attached, but for now I am assuming that it was. At any rate, we do need to estimate the planking and framing weight.

The area of half the deck, from the autocad model, is 282.4388 square feet.

Aft deck area	564.8776	ft^2
Deck Planking (assume 5")	11.60017	LT
Framing	5.800083	LT

The center is 232.0111 feet aft of the fwd reference point. The knuckle line at that point is 17.6805 ft ABL

VCG of planks	17.47216667	ft
VCG of steel	17.72216667	ft
VCG of frames	16.97216667	ft

LCG of all	232.0111	ft
TCG of all	0	ft

Aft Deck Armor

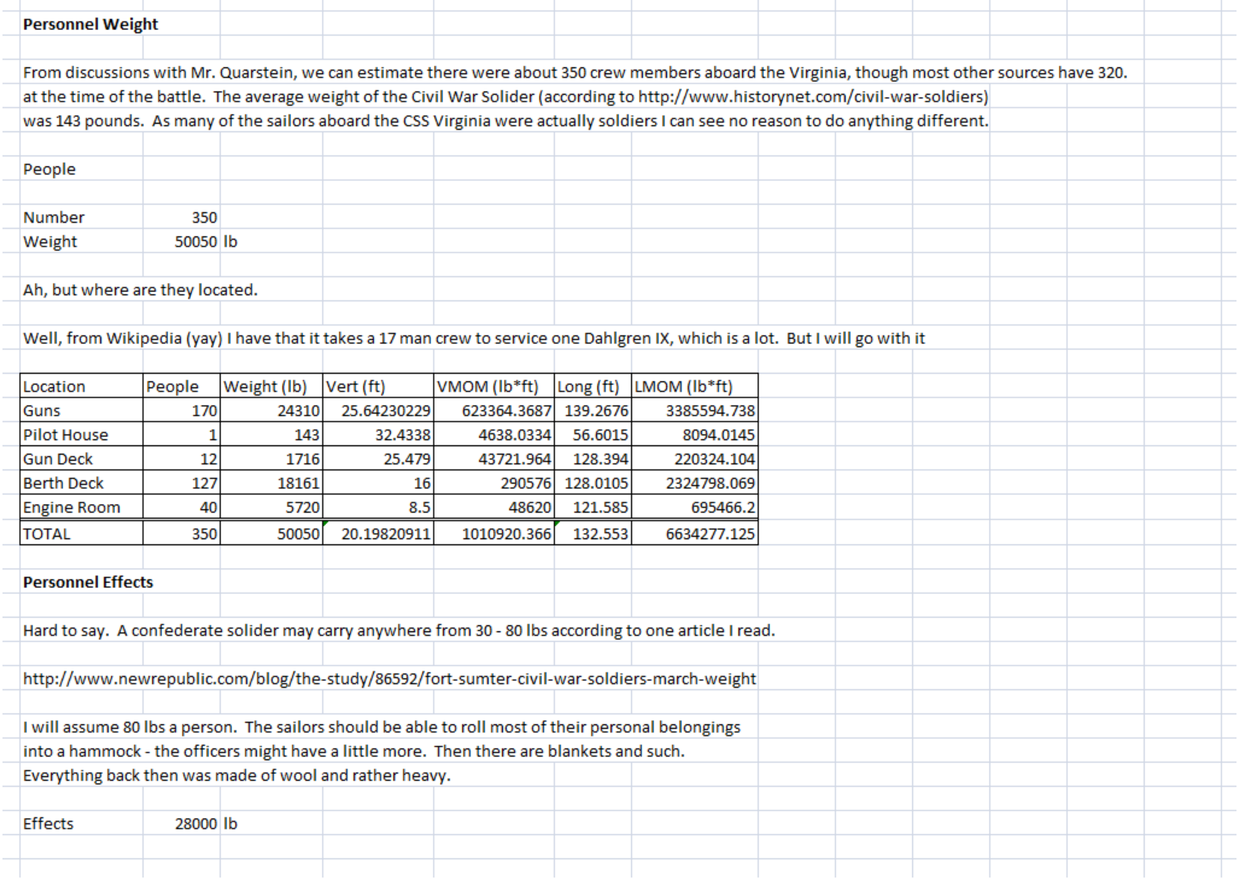
Only the portion in front of the tailfairing (which I am also assuming is armored) would be armored.

The area of the deck between the casement and the tailfairing is 216.8052 ft^2 from the AutoCad model

The LCG is 224.0479 ft aft the FRP

The Volume of iron for 1" thk is	18.0671	ft^3
At 490 lb/cu.ft	8852.879	lb
In Tons	3.952178	LT

Now people, effects, and provisions:



Personnel Weight

From discussions with Mr. Quarstein, we can estimate there were about 350 crew members aboard the Virginia, though most other sources have 320.
at the time of the battle. The average weight of the Civil War Solider (according to http://www.historynet.com/civil-war-soldiers)
was 143 pounds. As many of the sailors aboard the CSS Virginia were actually soldiers I can see no reason to do anything different.

People

Number	350	
Weight	50050	lb

Ah, but where are they located.

Well, from Wikipedia (yay) I have that it takes a 17 man crew to service one Dahlgren IX, which is a lot. But I will go with it

Location	People	Weight (lb)	Vert (ft)	VMOM (lb*ft)	Long (ft)	LMOM (lb*ft)
Guns	170	24310	25.64230229	623364.3687	139.2676	3385594.738
Pilot House	1	143	32.4338	4638.0334	56.6015	8094.0145
Gun Deck	12	1716	25.479	43721.964	128.394	220324.104
Berth Deck	127	18161	16	290576	128.0105	2324798.069
Engine Room	40	5720	8.5	48620	121.585	695466.2
TOTAL	350	50050	20.19820911	1010920.366	132.553	6634277.125

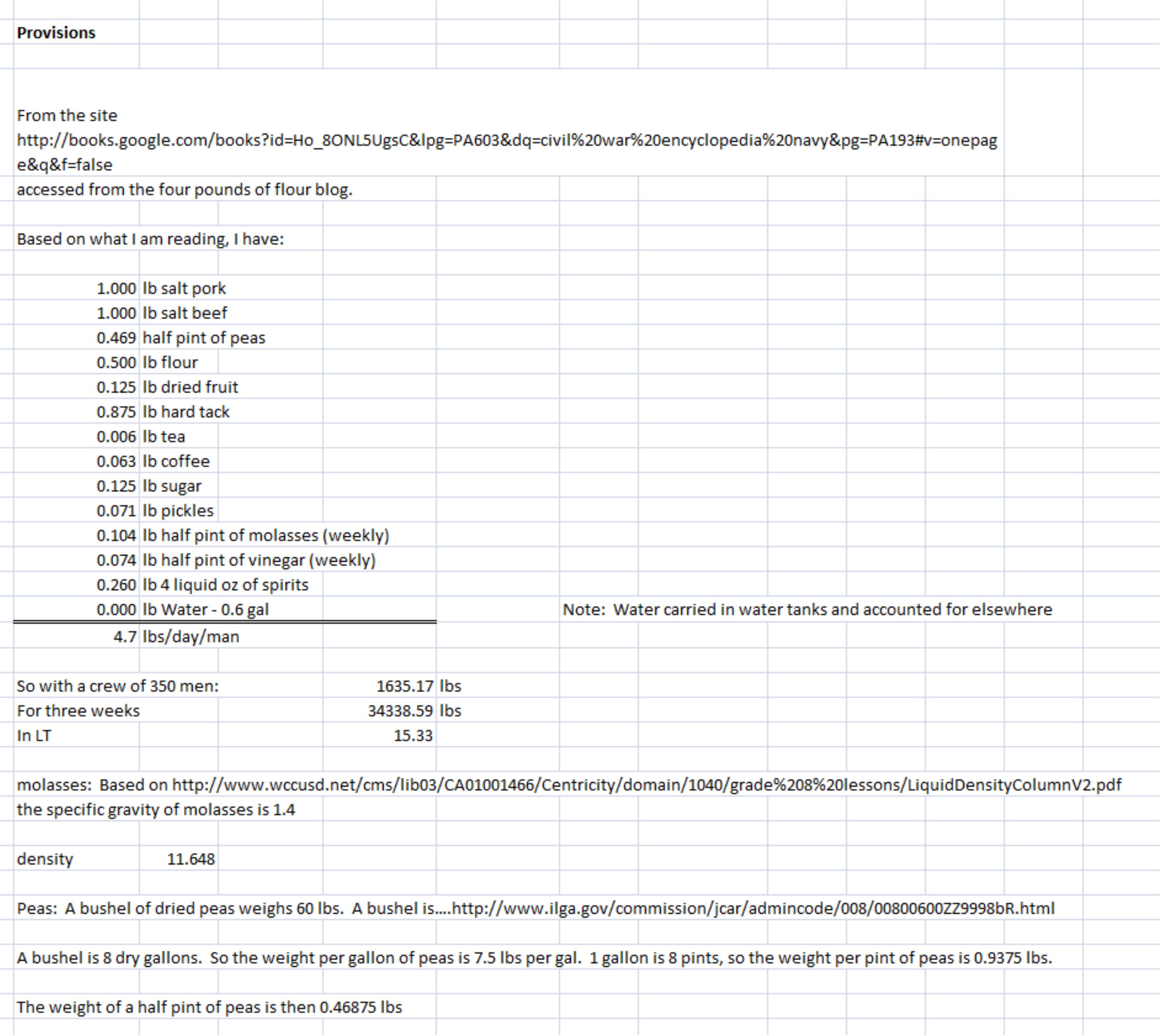
Personnel Effects

Hard to say. A confederate solider may carry anywhere from 30 - 80 lbs according to one article I read.

http://www.newrepublic.com/blog/the-study/86592/fort-sumter-civil-war-soldiers-march-weight

I will assume 80 lbs a person. The sailors should be able to roll most of their personal belongings
into a hammock - the officers might have a little more. Then there are blankets and such.
Everything back then was made of wool and rather heavy.

Effects	28000	lb



Provisions

From the site
http://books.google.com/books?id=Ho_8ONL5UgsC&lpg=PA603&dq=civil%20war%20encyclopedia%20navy&pg=PA193#v=onepage&q&f=false
accessed from the four pounds of flour blog.

Based on what I am reading, I have:

1.000	lb salt pork
1.000	lb salt beef
0.469	half pint of peas
0.500	lb flour
0.125	lb dried fruit
0.875	lb hard tack
0.006	lb tea
0.063	lb coffee
0.125	lb sugar
0.071	lb pickles
0.104	lb half pint of molasses (weekly)
0.074	lb half pint of vinegar (weekly)
0.260	lb 4 liquid oz of spirits
0.000	lb Water - 0.6 gal
4.7	lbs/day/man

Note: Water carried in water tanks and accounted for elsewhere

So with a crew of 350 men:	1635.17	lbs
For three weeks	34338.59	lbs
In LT	15.33	

molasses: Based on http://www.wccusd.net/cms/lib03/CA01001466/Centricity/domain/1040/grade%208%20lessons/LiquidDensityColumnV2.pdf
the specific gravity of molasses is 1.4

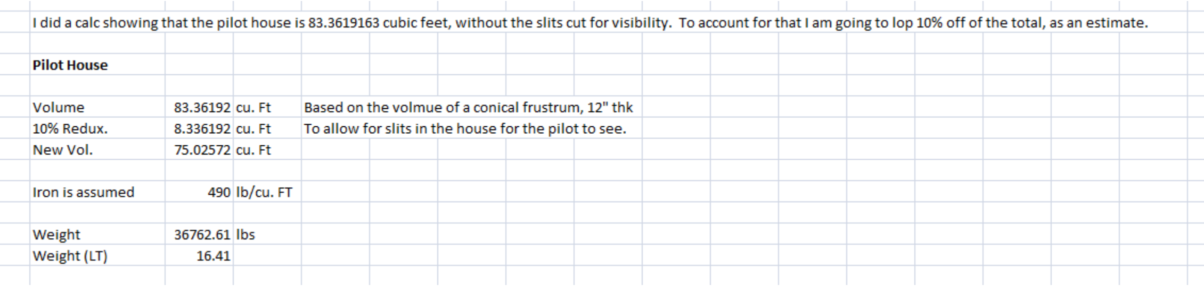
density 11.648

Peas: A bushel of dried peas weighs 60 lbs. A bushel is....http://www.ilga.gov/commission/jcar/admincode/008/00800600ZZ9998bR.html

A bushel is 8 dry gallons. So the weight per gallon of peas is 7.5 lbs per gal. 1 gallon is 8 pints, so the weight per pint of peas is 0.9375 lbs.

The weight of a half pint of peas is then 0.46875 lbs

The weight of the pilot house:

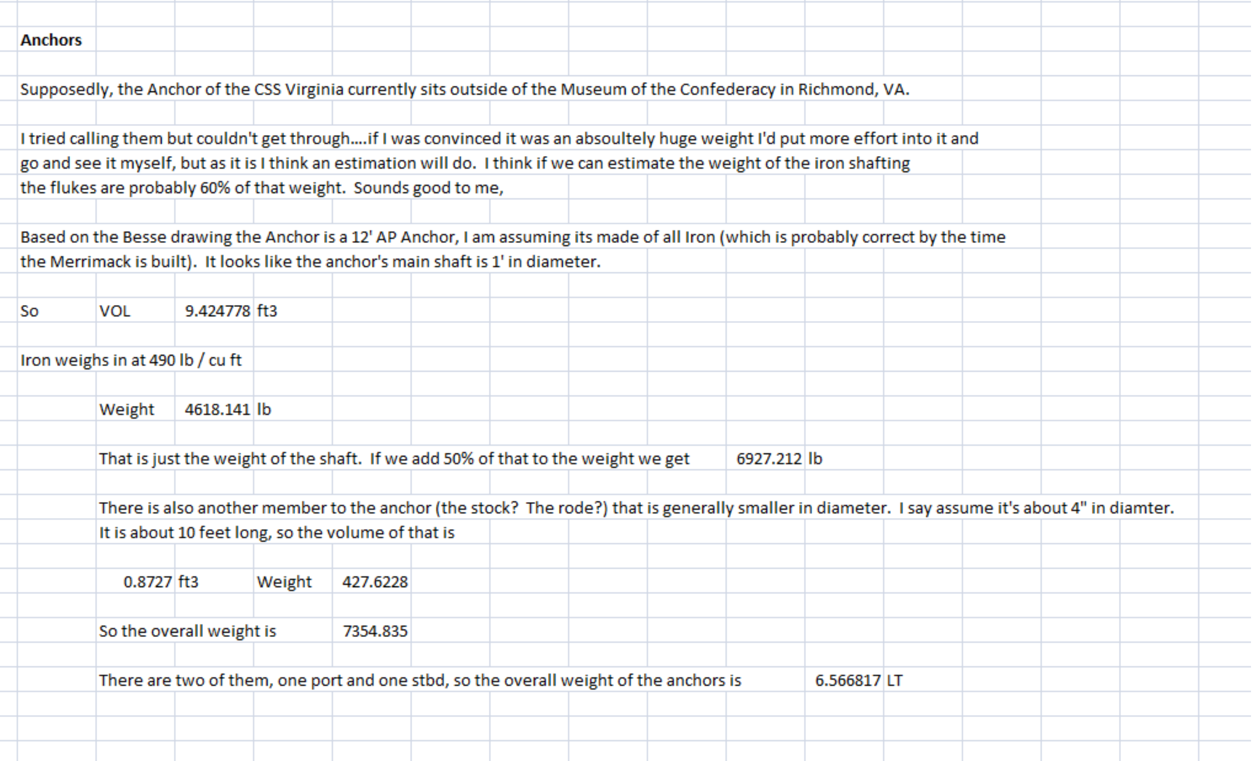


I did a calc showing that the pilot house is 83.3619163 cubic feet, without the slits cut for visibility. To account for that I am going to lop 10% off of the total, as an estimate.

Pilot House

Volume	83.36192	cu. Ft	Based on the volmue of a conical frustrum, 12" thk
10% Redux.	8.336192	cu. Ft	To allow for slits in the house for the pilot to see.
New Vol.	75.02572	cu. Ft	
Iron is assumed	490	lb/cu. FT	
Weight	36762.61	lbs	
Weight (LT)	16.41		

An Estimate for the anchors. Note that an estimate for the chains was not made.



Anchors

Supposedly, the Anchor of the CSS Virginia currently sits outside of the Museum of the Confederacy in Richmond, VA.

I tried calling them but couldn't get through....if I was convinced it was an absoultely huge weight I'd put more effort into it and
go and see it myself, but as it is I think an estimation will do. I think if we can estimate the weight of the iron shafting
the flukes are probably 60% of that weight. Sounds good to me,

Based on the Besse drawing the Anchor is a 12' AP Anchor, I am assuming its made of all Iron (which is probably correct by the time
the Merrimack is built). It looks like the anchor's main shaft is 1' in diameter.

So VOL 9.424778 ft3

Iron weighs in at 490 lb / cu ft

Weight 4618.141 lb

That is just the weight of the shaft. If we add 50% of that to the weight we get 6927.212 lb

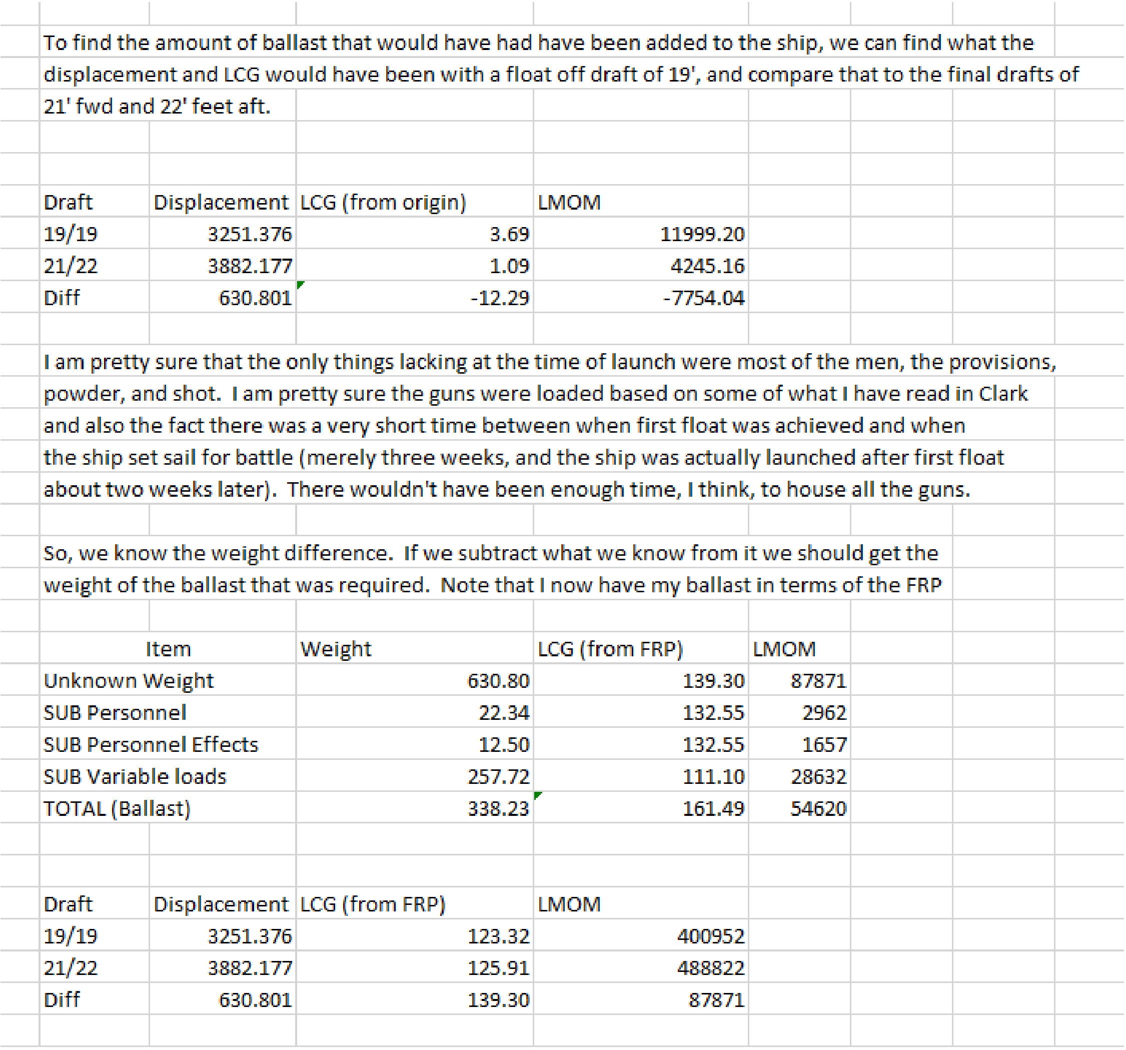
There is also another member to the anchor (the stock? The rode?) that is generally smaller in diameter. I say assume it's about 4" in diamter.
It is about 10 feet long, so the volume of that is

0.8727 ft3 Weight 427.6228

So the overall weight is 7354.835

There are two of them, one port and one stbd, so the overall weight of the anchors is 6.566817 LT

And finally the ballasting calculation, which figures out how much difference in displacement between the estimated weights and the target weight (Displacement at a draft of 21 feet forward and 22 feet aft and the initial float off draft of 19 feet no trim), and how much of that difference is accounted for in loads that had yet to be onboard at the time of initial float. The remainder is the amount of ballast required. Note that here the LCG is given from the origin to find the overall weight required to increase the draft to 21ft fwd / 22 ft aft; this is because hydrostatics are reported as an LCG from the origin. As noted in Section 3.4, the origin is about 127 feet aft of the forward reference point (stem). It was easy to take the LCG information from the hydrostatics and convert it later. The table in Section 3.7.14 shows the LCGs converted into distance aft of the FRP for the sake of consistency.



To find the amount of ballast that would have had have been added to the ship, we can find what the displacement and LCG would have been with a float off draft of 19', and compare that to the final drafts of 21' fwd and 22' feet aft.

Draft	Displacement	LCG (from origin)	LMOM
19/19	3251.376	3.69	11999.20
21/22	3882.177	1.09	4245.16
Diff	630.801	-12.29	-7754.04

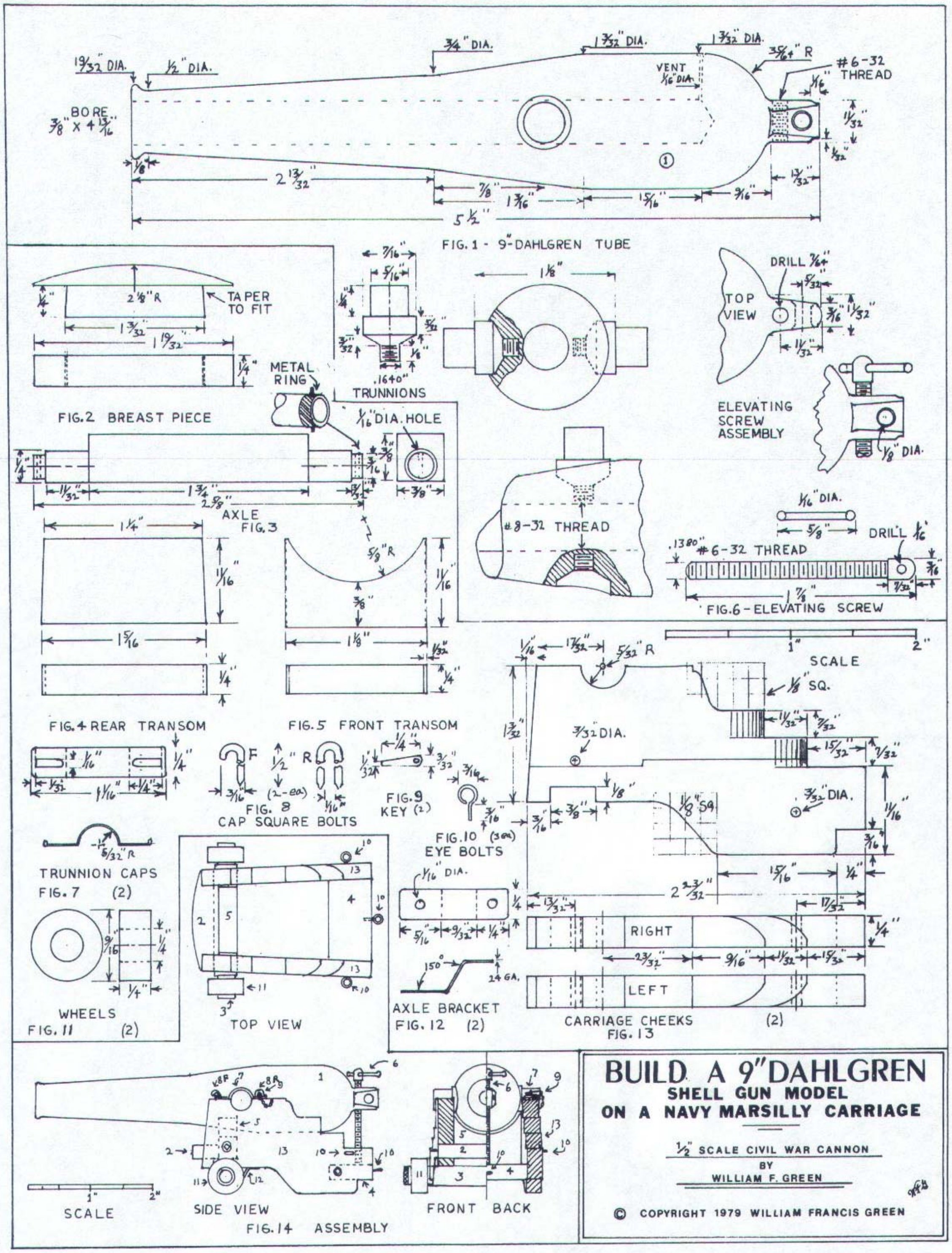
I am pretty sure that the only things lacking at the time of launch were most of the men, the provisions, powder, and shot. I am pretty sure the guns were loaded based on some of what I have read in Clark and also the fact there was a very short time between when first float was achieved and when the ship set sail for battle (merely three weeks, and the ship was actually launched after first float about two weeks later). There wouldn't have been enough time, I think, to house all the guns.

So, we know the weight difference. If we subtract what we know from it we should get the weight of the ballast that was required. Note that I now have my ballast in terms of the FRP

Item	Weight	LCG (from FRP)	LMOM
Unknown Weight	630.80	139.30	87871
SUB Personnel	22.34	132.55	2962
SUB Personnel Effects	12.50	132.55	1657
SUB Variable loads	257.72	111.10	28632
TOTAL (Ballast)	338.23	161.49	54620

Draft	Displacement	LCG (from FRP)	LMOM
19/19	3251.376	123.32	400952
21/22	3882.177	125.91	488822
Diff	630.801	139.30	87871

Appendix B – Marsilly Carriage



BUILD A 9"DAHLGREN
SHELL GUN MODEL
ON A NAVY MARSILLY CARRIAGE

½" SCALE CIVIL WAR CANNON
BY
WILLIAM F. GREEN

Appendix C – Radius of Gyration Calculations

First, the weight distributions were found. To do this I took the weight estimate from Appendix A and, for items distributed over a certain length of the vessel, found weight per unit length values as well as fore and aft extents. For the hull in the longitudinal distribution I based the weight of each station on the ratio of the station area to the maximum station area. For the transverse and vertical hull weight distribution a parabolic weight distribution was assumed.

The different weights were stacked up into a broad Excel Table that broke the dimension across which the weight distribution was taken into its various stations, much like one would break up a range of values for a histogram.

But that only gave the weight at a certain point. For longitudinal distribution, the weight placed in a bin bounded by points A and B had to be smeared across that interval. So it was assumed, for the weight in a given bin, that the weight was distributed linearly across the interval. It was assumed the weight was placed at the aft end of the interval (point B).

For example, by the method above, at a point 12.687 feet aft of the FRP, 55.73 LT of weight was placed in the longitudinal distribution. This 55.73 LT accounts for all the weight between 0 and 12.687 feet aft of the FRP. A linear distribution was found across the interval by taking 55.73LT and dividing it by 12.687, meaning that between 0 and 12.687 feet the distribution of the *Virginia* is about 4.39 LT/ft. The next point is between 12.687 feet and 25.374 feet. At 25.364 feet we placed a weight of 76.356 LT. In order to achieve that weight across the interval of 12.687 feet to 25.374 feet a weight/ft of 6.02 LT/ft was found to be necessary. And so on.

It was not necessary to do this for the transverse weight distribution, as the intervals were only 1 foot in length. It was necessary to do it for the vertical distribution, which had intervals 2 feet in length.

Table C-1, C-2, and C-3 shows the weights resulting from the grouping analysis, and the resulting LT/ft of the ship over the grouping intervals.

Distance Aft of FP	Weight (LT)	Distribution W(x) (LT/ft)
0.00	0.00	4.39
12.69	55.74	6.02
25.37	76.36	11.38
38.06	144.34	15.08
50.75	191.37	14.51
63.43	184.08	13.81
76.32	178.03	14.21
88.81	177.39	20.21
101.50	256.37	35.06
114.18	444.76	27.29
126.87	346.24	28.30
139.56	359.09	20.14
152.24	255.45	14.47
164.93	183.63	14.34
177.62	181.89	16.11
190.30	204.36	14.77
202.99	187.32	8.95
215.68	113.55	7.61
228.37	96.56	7.49
241.05	95.09	6.70
253.74	84.94	5.12
266.43	64.96	0.00
279.39	0.00	0.00

Table C-1: Longitudinal Weight Distribution

Distance off CL	Distribution W(x) (LT/ft)
-25.239	1.000
-25.000	7.326
-24.000	24.406
-23.000	27.790
-22.000	31.030
-21.000	34.126
-20.000	37.078
-19.000	63.189
-18.000	67.826
-17.000	70.346
-16.000	73.369
-15.000	101.986
-14.000	77.689
-13.000	83.491
-12.000	95.535
-11.000	86.947
-10.000	88.459
-9.000	89.827
-8.000	91.051
-7.000	100.939
-6.000	95.944
-5.000	92.873
-4.000	97.384
-3.000	97.888
-2.000	102.981
-1.000	122.596
0.000	158.258
1.000	122.596
2.000	100.969
3.000	97.888
4.000	95.533
5.000	96.736
6.000	95.944
7.000	100.939
8.000	91.051
9.000	85.963
10.000	88.459
11.000	86.947
12.000	99.398
13.000	83.491

14.000	77.689
15.000	101.986
16.000	71.954
17.000	70.346
18.000	67.826
19.000	64.603
20.000	37.078
21.000	34.126
22.000	31.030
23.000	26.375
24.000	24.406
25.000	7.326
25.239	1.000

Table C-2: Transverse Weight Distribution

Distance above BL	Weight (LT)	Distribution W(X) (LT/ft)
0.000	24.542	0.000
2.000	6.958	3.479
4.000	60.752	30.376
6.000	278.241	139.120
8.000	285.861	142.930
10.000	429.830	214.915
12.000	389.078	194.539
14.000	424.392	212.196
16.000	408.947	204.474
18.000	552.759	276.380
20.000	164.904	82.452
22.000	158.307	79.153
24.000	161.543	80.771
26.000	176.981	88.491
28.000	122.728	61.364
30.000	111.445	55.723
32.000	115.283	57.642
34.000	0.780	0.390
36.000	0.780	0.390
38.000	0.780	0.390
40.000	0.780	0.390
42.000	0.780	0.390
44.000	0.780	0.390
46.000	0.780	0.390
48.000	0.780	0.390
50.000	0.780	0.390
52.000	0.780	0.390
54.000	0.780	0.390
56.000	0.780	0.390
58.000	0.390	0.195

Table C-3: Vertical Weight Distribution

With the weight distributions completed it remained to perform the integrals discussed in Section 3.8. This involved taking the distribution in LT/ft of each interval (a,b) and finding the term

$$\theta_i\left(\frac{b^3}{3}-\frac{a^3}{3}\right)$$

where θ_i is the LT/ft weight distribution. Tables C-1, C-2, and C-3 lend themselves to easy application of the expression above. As shown in Section 3.8, these terms are summed to perform the integrations necessary for calculating the radii of gyrations for a given axis.

Below are Tables C-1, C-2, and C-3 with the integral terms added.

Distance Aft of FP	Weight	Distribution W(x)	Integral
0.00	0.00	4.39	2990
12.69	55.74	6.02	28678
25.37	76.36	11.38	147136
38.06	144.34	15.08	379877
50.75	191.37	14.51	602450
63.43	184.08	13.81	871745
76.32	178.03	14.21	1211543
88.81	177.39	20.21	2324533
101.50	256.37	35.06	5178144
114.18	444.76	27.29	5034279
126.87	346.24	28.30	6377101
139.56	359.09	20.14	5441201
152.24	255.45	14.47	4620788
164.93	183.63	14.34	5338026
177.62	181.89	16.11	6918557
190.30	204.36	14.77	7246377
202.99	187.32	8.95	4977395
215.68	113.55	7.61	4761109
228.37	96.56	7.49	5239410
241.05	95.09	6.70	5200062
253.74	84.94	5.12	4395196
266.43	64.96	0.00	0
279.39	0.00	0.00	
		SUM INTEGRAL	76296599

Table C-4: Longitudinal Weight Distribution With Integrals

Distance off CL	Distribution W(x) Lt/ft	Integral
-25.239	1.000	1105
-25.000	7.326	14652
-24.000	24.406	15349
-23.000	27.790	15712
-22.000	31.030	15778
-21.000	34.126	15585
-20.000	37.078	24033
-19.000	63.189	23219
-18.000	67.826	21549
-17.000	70.346	19981
-16.000	73.369	24511
-15.000	101.986	16341
-14.000	77.689	15223
-13.000	83.491	14935
-12.000	95.535	11506
-11.000	86.947	9760
-10.000	88.459	8114
-9.000	89.827	6586
-8.000	91.051	5686
-7.000	100.939	4062
-6.000	95.944	2817
-5.000	92.873	1980
-4.000	97.384	1207
-3.000	97.888	652
-2.000	102.981	286
-1.000	122.596	53
0.000	158.258	41
1.000	122.596	236
2.000	100.969	620
3.000	97.888	1178
4.000	95.533	1967
5.000	96.736	2910
6.000	95.944	4273
7.000	100.939	5129
8.000	91.051	6218
9.000	85.963	7991
10.000	88.459	9593
11.000	86.947	13154

12.000	99.398	13052
13.000	83.491	14165
14.000	77.689	21451
15.000	101.986	17293
16.000	71.954	19158
17.000	70.346	20777
18.000	67.826	22116
19.000	64.603	14102
20.000	37.078	14344
21.000	34.126	14346
22.000	31.030	13355
23.000	26.375	13480
24.000	24.406	4398
25.000	7.326	151
25.239	1.000	
	Sum Integral	546181

Table C-5: Transverse Weight Distribution with Integrals

Distance above CL	Weight (LT)	Distribution W(X) LT/ft	Integral
0.000	24.542	0.000	9
2.000	6.958	3.479	567
4.000	60.752	30.376	7049
6.000	278.241	139.120	14102
8.000	285.861	142.930	34959
10.000	429.830	214.915	47208
12.000	389.078	194.539	71864
14.000	424.392	212.196	92149
16.000	408.947	204.474	159932
18.000	552.759	276.380	59585
20.000	164.904	82.452	69866
22.000	158.307	79.153	85510
24.000	161.543	80.771	110672
26.000	176.981	88.491	89509
28.000	122.728	61.364	93762
30.000	111.445	55.723	110825
32.000	115.283	57.642	850
34.000	0.780	0.390	956
36.000	0.780	0.390	1069
38.000	0.780	0.390	1187
40.000	0.780	0.390	1312
42.000	0.780	0.390	1443
44.000	0.780	0.390	1581
46.000	0.780	0.390	1724
48.000	0.780	0.390	1874
50.000	0.780	0.390	2030
52.000	0.780	0.390	2193
54.000	0.780	0.390	2361
56.000	0.780	0.390	1268
58.000	0.390	0.195	
		SUM	1067419

Table C-6: Vertical Weight Distribution with Integrals

The sums of the integrals are the weight moments of inertia about the FRP, CL, and BL. They have to be corrected to an axis through the CG using the parallel axis theorem. This correction can be seen in Table 6, section 3.8.2. After the moments are corrected they have to be combined as described in in Section 3.7.2 to get the gyration radii. The radii are described as coefficients over LBP or the Beam of the ship; LBP for the gyration analysis was taken to be 278 feet (the length overall), and the beam was taken to be 51.082 feet. Final results are shown in Table 7, Section 3.8.2.

Appendix D – Wave Data Histograms and Statistical Atlases

For Paramarine to calculate measures of long term effectiveness, a wave atlas must be loaded into the program. The wave atlas is actually a collection of the probabilities that the ship will meet a particular wave height at a particular frequency, as discussed in Section 3.9.2. For this report the *CSS Virginia's* effectiveness was analyzed at four different stations, three inside the Chesapeake Bay and one on the open ocean, as noted in Section 3.9.2.

To create the statistical wave atlas for the four different stations, the wave data from the stations taken from January 2015 – May 2015 was placed into an excel spreadsheet and histograms were made of the data. Probabilities of the waves falling within certain "bins" of height and period were calculated by taking the number of data points in each bin and dividing it by the total number of points.

Histograms for all four stations are shown on the following pages.

Deltaville VA Average Wave Heights

Bin	*Frequency*	*Probability*
0.124	58	0.018
0.248	271	0.084
0.372	254	0.078
0.496	193	0.060
0.62	184	0.057
0.744	226	0.070
0.868	204	0.063
0.992	211	0.065
1.116	204	0.063
1.24	145	0.045
1.364	193	0.060
1.488	141	0.044
1.612	163	0.050
1.736	118	0.036
1.86	97	0.030
1.984	104	0.032
2.108	102	0.031
2.232	76	0.023
2.356	45	0.014
2.48	54	0.017
2.604	50	0.015
2.728	31	0.010
2.852	34	0.010
2.976	28	0.009
3.1	26	0.008
3.224	10	0.003
3.348	10	0.003
3.472	2	0.001
3.596	3	0.001
3.72	2	0.001
More	0	0
n	3239	

Deltaville VA Average Wave Period

Bin	*Frequency*	*Probability*
0.254	0	0.000
0.508	0	0.000
0.762	0	0.000
1.016	0	0.000
1.27	0	0.000
1.524	0	0.000
1.778	10	0.003
2.032	492	0.152
2.286	630	0.195
2.54	949	0.293
2.794	445	0.138
3.048	454	0.140
3.302	197	0.061
3.556	42	0.013
3.81	11	0.003
4.064	1	0.000
4.318	2	0.001
4.572	0	0.000
4.826	0	0.000
5.08	1	0.000
5.334	0	0.000
5.588	0	0.000
5.842	0	0.000
6.096	0	0.000
6.35	1	0.000
6.604	0	0.000
6.858	0	0.000
7.112	0	0.000
7.366	0	0.000
9.4	1	0.000
More	0	0.000
n	3236	

Table D-1: Deltaville VA Wave Data Histograms

Potomac MD Average Wave Height

Bin	*Frequency*	*Probability*
0.271	162	0.165
0.542	139	0.142
0.813	109	0.111
1.084	169	0.172
1.355	102	0.104
1.626	108	0.110
1.897	47	0.048
2.168	46	0.047
2.439	35	0.036
2.71	16	0.016
2.981	4	0.004
3.252	18	0.018
3.523	3	0.003
3.794	4	0.004
4.065	4	0.004
4.336	8	0.008
4.607	6	0.006
4.878	0	0.000
5.149	0	0.000
5.42	1	0.001
More	0	0.000
n	981	

Potomac MD Average Wave Period

Bin	*Frequency*	*Probability*
0.272	0	0.000
0.544	0	0.000
0.816	0	0.000
1.088	0	0.000
1.36	0	0.000
1.632	0	0.000
1.904	34	0.035
2.176	166	0.169
2.448	379	0.386
2.72	180	0.183
2.992	82	0.084
3.264	66	0.067
3.536	29	0.030
3.808	22	0.022
4.08	12	0.012
4.352	7	0.007
4.624	4	0.004
4.896	0	0.000
5.168	0	0.000
5.44	0	0.000
More	0	0.000
n	981	

Table D-2: Potomac MD Wave Data Histograms

Cape Henry VA Average Wave Height

Bin	*Frequency*	*Probability*
0.292	0	0.000
0.584	35	0.012
0.876	279	0.096
1.168	439	0.151
1.46	456	0.157
1.752	371	0.128
2.044	304	0.105
2.336	247	0.085
2.628	161	0.055
2.92	118	0.041
3.212	97	0.033
3.504	70	0.024
3.796	66	0.023
4.088	55	0.019
4.38	38	0.013
4.672	35	0.012
4.964	46	0.016
5.256	33	0.011
5.548	16	0.006
5.84	10	0.003
6.132	11	0.004
6.424	5	0.002
6.716	5	0.002
7.008	4	0.001
7.3	1	0.000
7.592	0	0.000
7.884	0	0.000
8.176	2	0.001
8.7	2	0.001
More	0	0.000
n	2906	

Cape Henry VA Average Wave Period

Bin	*Frequency*	*Probability*
0.33	0	0.000
0.66	0	0.000
0.99	0	0.000
1.32	0	0.000
1.65	0	0.000
1.98	0	0.000
2.31	34	0.012
2.64	190	0.065
2.97	361	0.124
3.3	630	0.217
3.63	459	0.158
3.96	317	0.109
4.29	254	0.087
4.62	219	0.075
4.95	164	0.056
5.28	97	0.033
5.61	62	0.021
5.94	33	0.011
6.27	32	0.011
6.6	22	0.008
6.93	11	0.004
7.26	5	0.002
7.59	4	0.001
7.92	4	0.001
8.25	3	0.001
8.58	2	0.001
8.91	2	0.001
9.24	1	0.000
9.57	0	0.000
More	0	0.000
n	2906	

Table D-3: Cape Henry VA Wave Data Histograms

Open Ocean (VA Beach) Average Wave Height

Bin	*Frequency*	*Probability*
0.330	0	0.000
0.914	0	0.000
1.498	50	0.014
2.083	202	0.056
2.667	361	0.100
3.251	453	0.125
3.835	415	0.115
4.419	387	0.107
5.004	344	0.095
5.588	245	0.068
6.172	182	0.050
6.756	175	0.048
7.340	122	0.034
7.925	97	0.027
8.509	83	0.023
9.093	90	0.025
9.677	62	0.017
10.261	77	0.021
10.846	57	0.016
11.430	42	0.012
12.014	46	0.013
12.598	22	0.006
13.182	21	0.006
13.767	18	0.005
14.351	10	0.003
14.935	15	0.004
15.519	7	0.002
16.103	10	0.003
16.688	4	0.001
17.272	4	0.001
17.856	8	0.002
18.440	2	0.001
19.024	3	0.001
More	2	0.001
n	3616	

Open Ocean (VA Beach) Average Wave Period

Bin	*Frequency*	*Probability*
3.460	1	0.000
3.691	16	0.004
3.923	40	0.011
4.154	93	0.026
4.385	166	0.046
4.616	285	0.079
4.848	326	0.090
5.079	372	0.103
5.310	396	0.110
5.542	393	0.109
5.773	310	0.086
6.004	292	0.081
6.235	265	0.073
6.467	185	0.051
6.698	127	0.035
6.929	84	0.023
7.161	68	0.019
7.392	58	0.016
7.623	47	0.013
7.855	23	0.006
8.086	22	0.006
8.317	11	0.003
8.548	8	0.002
8.780	5	0.001
9.011	5	0.001
9.242	1	0.000
9.474	5	0.001
9.705	3	0.001
9.936	3	0.001
10.167	3	0.001
10.399	0	0.000
10.630	3	0.001
10.861	0	0.000
More	0	0.000
n	3616	

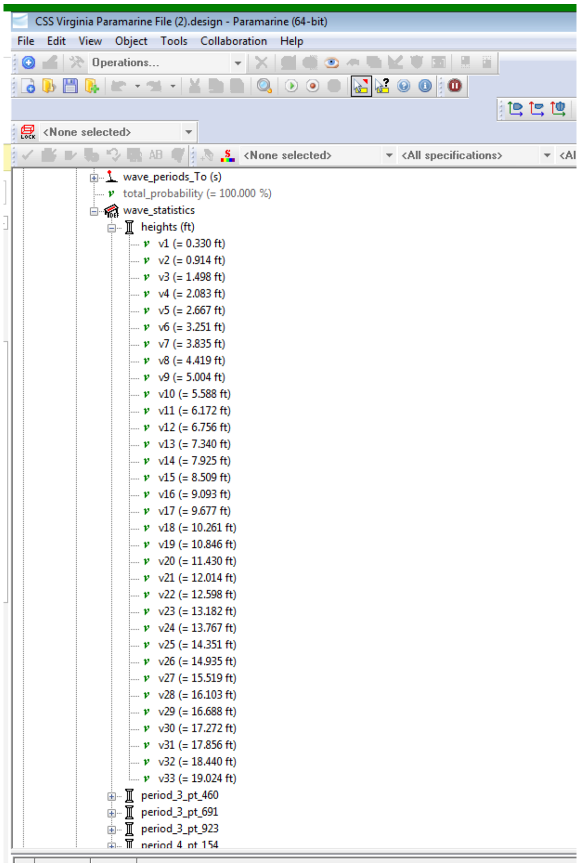
Table D-4: Open Ocean (East of VA Beach) Wave Histogram Data

With the histograms made, it was then possible to make tables of the probability of encountering a certain wave period AND a certain wave height, as described in Section 3.9.2. The operation is best described by noticing that the probabilities the tables above can be described as Matrices. If we let the wave period probability be a (m x 1) matrix **P** and the wave heights be an (1 x m) matrix **H**, where m is the number of bins used in the histograms, then the probabilities required for the long term analysis are given by multiplying the two matrices together, such that

$$[Prob] = [P][H]$$

The result is a (m x m) matrix containing all the required probabilities of the ship encountering particular wave heights at particular wave periods as defined by the histograms. The sum of all probabilities in the resulting (m x m) matrix is 1.0. The tables can be reproduced with the histograms above. Screen shots of the resulting tables can be seen at the end of this appendix.

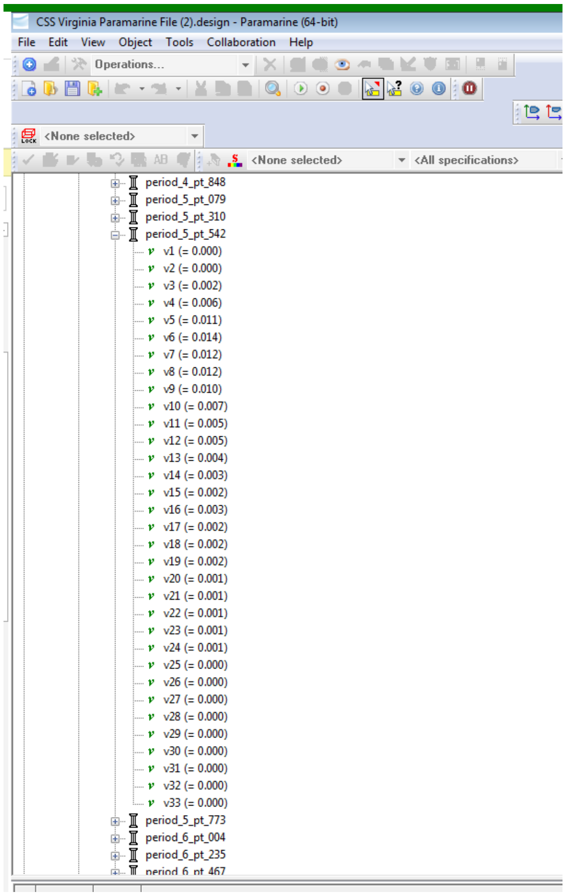
The resulting table was very painstakingly entered in as data into Paramarine. Figure D-1 shows a breakout of the wave statistics folder in the long term operability analysis placeholder within the Sea Keeping set up. Shown in Figure D-1 are the variables that correspond to the different wave heights defined by the open water data histogram.



wave_periods_To (s)
total_probability (= 100.000 %)
wave_statistics
heights (ft)
v1 (= 0.330 ft)
v2 (= 0.914 ft)
v3 (= 1.498 ft)
v4 (= 2.083 ft)
v5 (= 2.667 ft)
v6 (= 3.251 ft)
v7 (= 3.835 ft)
v8 (= 4.419 ft)
v9 (= 5.004 ft)
v10 (= 5.588 ft)
v11 (= 6.172 ft)
v12 (= 6.756 ft)
v13 (= 7.340 ft)
v14 (= 7.925 ft)
v15 (= 8.509 ft)
v16 (= 9.093 ft)
v17 (= 9.677 ft)
v18 (= 10.261 ft)
v19 (= 10.846 ft)
v20 (= 11.430 ft)
v21 (= 12.014 ft)
v22 (= 12.598 ft)
v23 (= 13.182 ft)
v24 (= 13.767 ft)
v25 (= 14.351 ft)
v26 (= 14.935 ft)
v27 (= 15.519 ft)
v28 (= 16.103 ft)
v29 (= 16.688 ft)
v30 (= 17.272 ft)
v31 (= 17.856 ft)
v32 (= 18.440 ft)
v33 (= 19.024 ft)
period_3_pt_460
period_3_pt_691
period_3_pt_923
period_4_pt_154

Figure D-1: Open Water Wave Height Variables

Figure D-2 shows a breakout of one of the periods that can be seen at the bottom of Figure D-1. In this case it is wave period 5.542 seconds for the open water case.



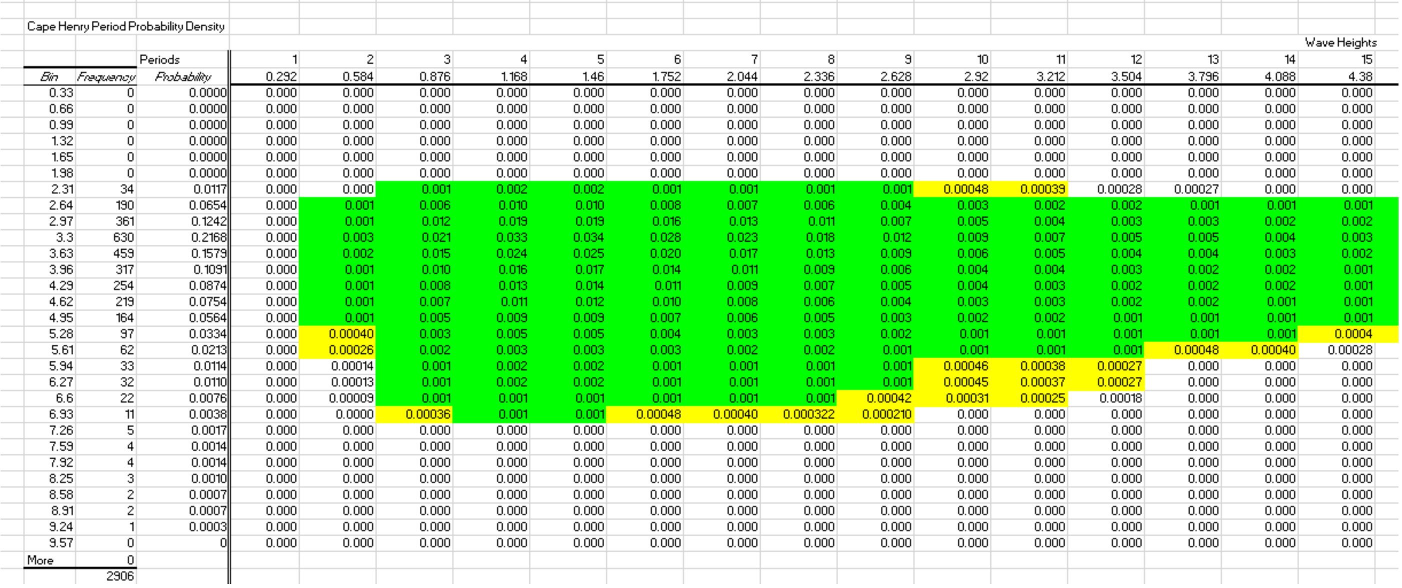
```
period_4_pt_848
period_5_pt_079
period_5_pt_310
period_5_pt_542
    v1 (= 0.000)
    v2 (= 0.000)
    v3 (= 0.002)
    v4 (= 0.006)
    v5 (= 0.011)
    v6 (= 0.014)
    v7 (= 0.012)
    v8 (= 0.012)
    v9 (= 0.010)
    v10 (= 0.007)
    v11 (= 0.005)
    v12 (= 0.005)
    v13 (= 0.004)
    v14 (= 0.003)
    v15 (= 0.002)
    v16 (= 0.003)
    v17 (= 0.002)
    v18 (= 0.002)
    v19 (= 0.002)
    v20 (= 0.001)
    v21 (= 0.001)
    v22 (= 0.001)
    v23 (= 0.001)
    v24 (= 0.001)
    v25 (= 0.000)
    v26 (= 0.000)
    v27 (= 0.000)
    v28 (= 0.000)
    v29 (= 0.000)
    v30 (= 0.000)
    v31 (= 0.000)
    v32 (= 0.000)
    v33 (= 0.000)
period_5_pt_773
period_6_pt_004
period_6_pt_235
period_6_pt_467
```

Figure D-2: Probabilities of Encountering Wave Heights, as Defined in Figure D-1, at a Given Period; in this Case a Period of 5.542 seconds

So for example: the screen shot shown in Figure D-1 states that v1 is tied to the wave height of 0.330ft, v2 is tied to the wave height of 0.914ft, and so on. So in D-2, what we see is that for a period of 5.542 seconds at a wave height of 0.330ft (v1), we have a probability of encounter of 0.000. That means, essentially, the wave data does not support seeing that combination of height and frequency at all. However, at a period of 5.542 seconds and a wave height of 3.251 feet (v6), there is a probability of encounter of 0.014. That means that, based on the open water wave data collected, there is a 1.4% chance that we will see a wave height of 3.251 feet at a wave period of 5.542 seconds.

Every probability was transcribed "by hand" from the Excel spreadsheets to the Paramarine software. Precision was kept to three decimal places (i.e. the nearest thousandth) to speed up the transcription, so the smallest probability entered was 0.001. It also kept the analysis run time lower. This meant that after all the data points with a probability greater than 0.001 when rounded to the nearest thousandth were placed into Paramarine, there was still a probability less than 1.0. It was close, between 0.93 and 0.98, but in all cases due to round of error the entered data did not equal 1.0. So additional data entries were made where probabilities that were not rounded up to 0.001 were taken to be 0.001. These points were generally greater than 0.0003, and were kept close to the areas of the tables were probabilities could be rounded to 0.001. An example of this can be seen in Figure D-3 – the green cells are the cells that had their probabilities entered into Paramarine, the yellow cells are data points rounded up to 0.001 in order to achieve a sum of all probabilities in the data set equal to 1.0. This admittedly has some effect on results, but it is likely to be miniscule and does not alter the overall conclusions of the operability analysis.

Paramarine does have functionality that allows it to tie into Excel Spreadsheets, and that may have made this process easier and may have allowed for data of a more exact precision to be utilized. But due to my own proficiency with Paramarine the Excel functionalities were not exploited here or elsewhere. Paramarine is flexible enough to allow one to do things the hard way.



Cape Henry Period Probability Density

																	Wave Heights
		Periods	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Bin	*Frequency*	*Probability*	0.292	0.584	0.876	1.168	1.46	1.752	2.044	2.336	2.628	2.92	3.212	3.504	3.796	4.088	4.38
0.33	0	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.66	0	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.99	0	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.32	0	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.65	0	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.98	0	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.31	34	0.0117	0.000	0.000	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.00048	0.00039	0.00028	0.00027	0.000	0.000
2.64	190	0.0654	0.000	0.001	0.006	0.010	0.010	0.008	0.007	0.006	0.004	0.003	0.002	0.002	0.001	0.001	0.001
2.97	361	0.1242	0.000	0.001	0.012	0.019	0.019	0.016	0.013	0.011	0.007	0.005	0.004	0.003	0.003	0.002	0.002
3.3	630	0.2168	0.000	0.003	0.021	0.033	0.034	0.028	0.023	0.018	0.012	0.009	0.007	0.005	0.005	0.004	0.003
3.63	459	0.1579	0.000	0.002	0.015	0.024	0.025	0.020	0.017	0.013	0.009	0.006	0.005	0.004	0.004	0.003	0.002
3.96	317	0.1091	0.000	0.001	0.010	0.016	0.017	0.014	0.011	0.009	0.006	0.004	0.004	0.003	0.002	0.002	0.001
4.29	254	0.0874	0.000	0.001	0.008	0.013	0.014	0.011	0.009	0.007	0.005	0.004	0.003	0.002	0.002	0.002	0.001
4.62	219	0.0754	0.000	0.001	0.007	0.011	0.012	0.010	0.008	0.006	0.004	0.003	0.003	0.002	0.002	0.001	0.001
4.95	164	0.0564	0.000	0.001	0.005	0.009	0.009	0.007	0.006	0.005	0.003	0.002	0.002	0.001	0.001	0.001	0.001
5.28	97	0.0334	0.000	0.00040	0.003	0.005	0.005	0.004	0.003	0.003	0.002	0.001	0.001	0.001	0.001	0.001	0.0004
5.61	62	0.0213	0.000	0.00026	0.002	0.003	0.003	0.003	0.002	0.002	0.001	0.001	0.001	0.001	0.00048	0.00040	0.00028
5.94	33	0.0114	0.000	0.00014	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.00046	0.00038	0.00027	0.000	0.000	0.000
6.27	32	0.0110	0.000	0.00013	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.00045	0.00037	0.00027	0.000	0.000	0.000
6.6	22	0.0076	0.000	0.00009	0.001	0.001	0.001	0.001	0.001	0.001	0.00042	0.00031	0.00025	0.00018	0.000	0.000	0.000
6.93	11	0.0038	0.000	0.0000	0.00036	0.001	0.001	0.00048	0.00040	0.000322	0.000210	0.000	0.000	0.000	0.000	0.000	0.000
7.26	5	0.0017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7.59	4	0.0014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7.92	4	0.0014	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8.25	3	0.0010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8.58	2	0.0007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8.91	2	0.0007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9.24	1	0.0003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9.57	0	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
More	0																
	2906																

Figure D-3: Partial Table of Probabilities for Wave Height and Period, Cape Henry VA Data

Appendix E – RAO Input and Output Sets, *CSS Virginia*, Paramarine

RAO Inputs:

RAOs shown in the appendix were generated by Paramarine v. 8.3.1. Inputs for the RAOs are as follows:

AP Baseline (X, Y, Z) = (-151.000 ft, 0 ft, 0 ft)
FP Baseline (X, Y, Z) = (127.008 ft, 0 ft, 0 ft)

Displacement = 3869.510 LT
CG (X, Y, Z) = (0.698 ft, 0 ft, 15.080 ft)

GM Fluid = 2.00 ft

Gyration Definitions:
Roll over Beam: 0.27
Pitch over LBP: 0.22
Yaw over LBP: 0.22

Density:
Reciprocal weight density of 35.5 ft^3/LT

Speeds: 0 knots, 6 knots

Headings: 0 through 360 degrees on a 30 degree increment

Wave Definitions:
Type: Bretschneider
Frequencies: 0.032 Hz through 0.318 Hz on a 0.008 Hz increment
Waves assumed to be long crested

The GM Fluid input appears to be a Paramarine input with a default value of 2.00 feet. Because the *CSS Virginia* has no tankage modeled it appears as though changing this input makes no input on the overall result. While it was assumed for the purposes of the weight estimate that the *CSS Virginia* was equipped with water tanks, the free surface effect of said water tanks was not figured as part of the analysis. If each water tank is 4 feet square and holds fresh water, the free surface effect of each tank is 0.005 feet. For this project we assumed there were 18 tanks, which would result in a total free surface effect of 0.09 feet, or about 1 inch. That is too small to change the overall results of the rest of the analysis, and as there is apparently no other significant tankage onboard, free surface effects can safely be neglected.

Below are the RAO outputs for the above inputs. Angular displacements (roll, pitch, and yaw) are plotted as the angular displacement over wave slope, whereas the linear displacements (sway, heave, and surge) are plotted as the linear displacement over wave amplitude.

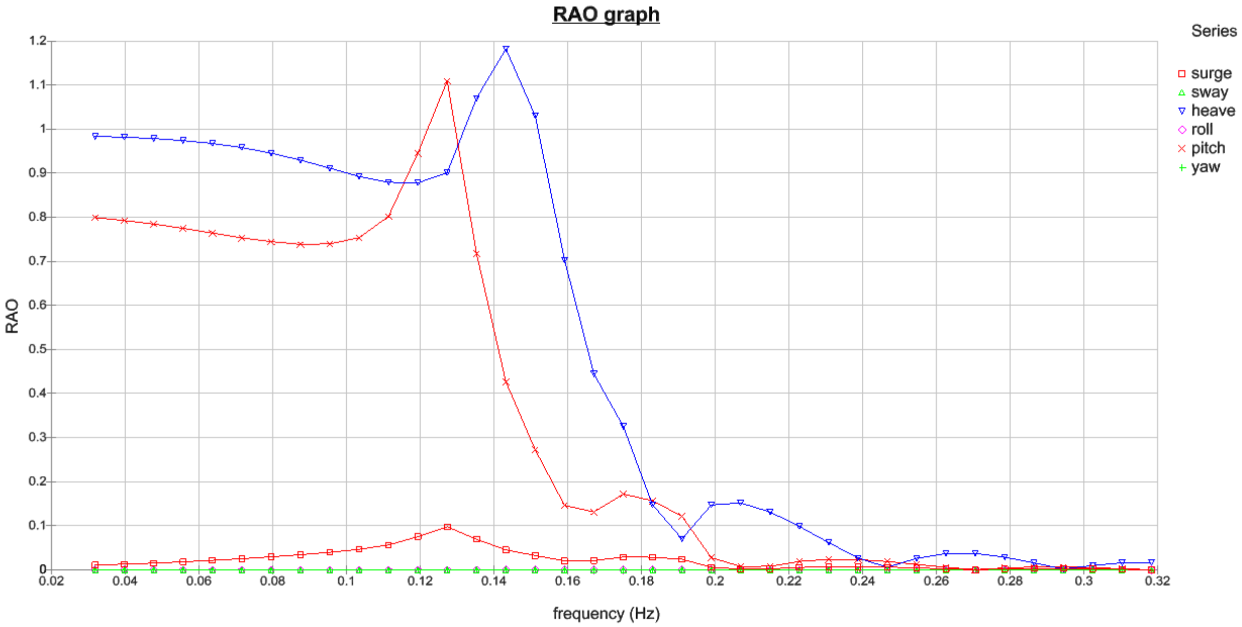


Figure E-1: RAO Graph, 0 knots, 0 degree Heading

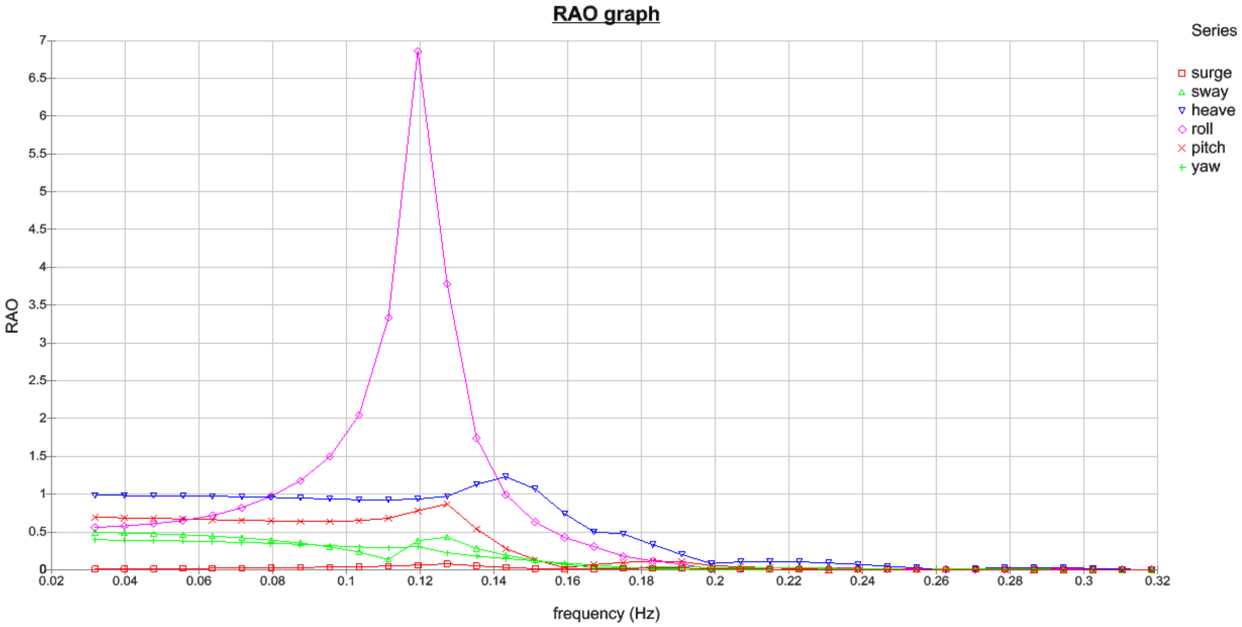


Figure E-2: RAO Graph, 0 knots, 30 degree Heading

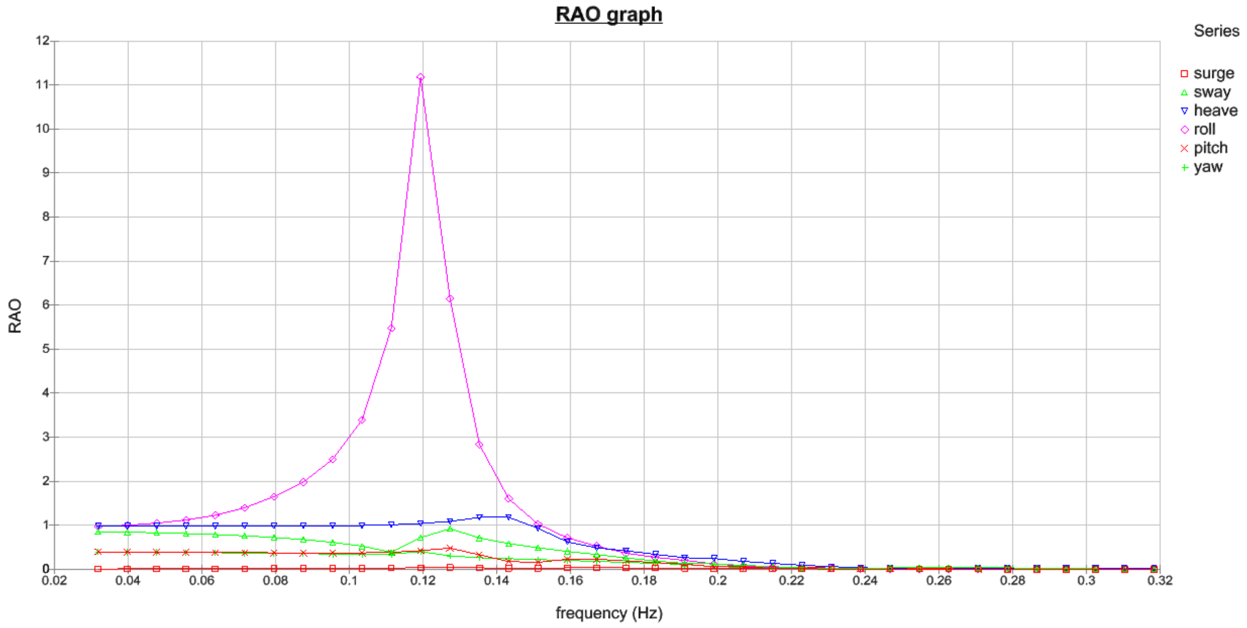


Figure E-3: RAO Graph, 0 knots, 60 degree Heading

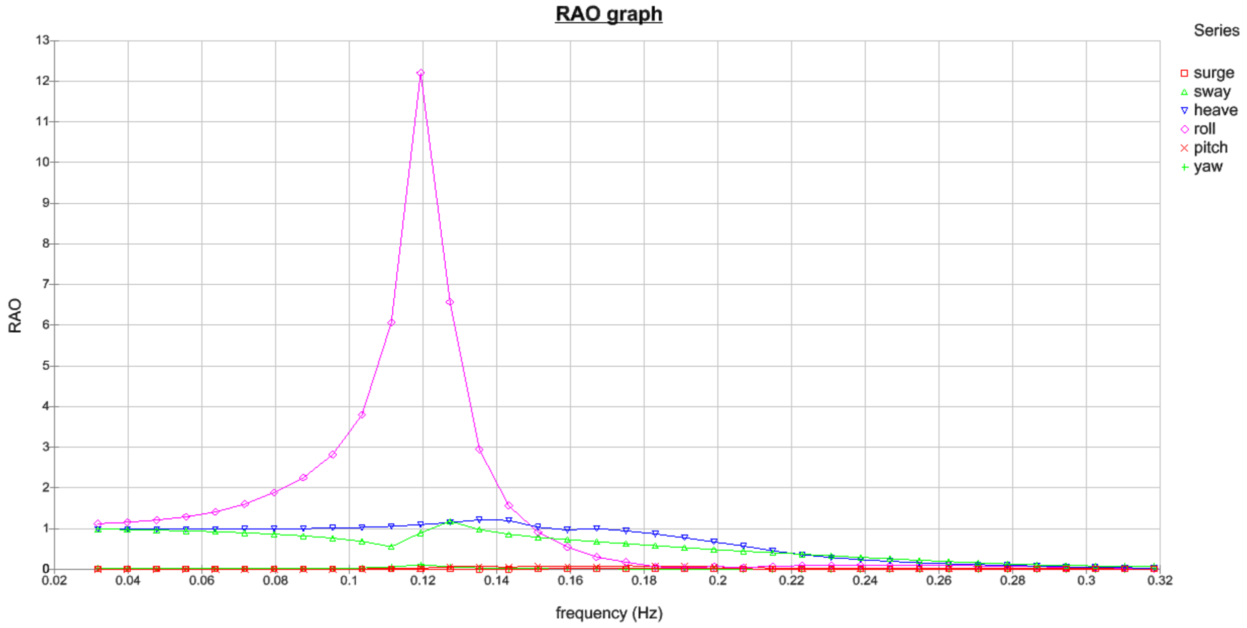


Figure E-4: RAO Graph, 0 knots, 90 degree Heading

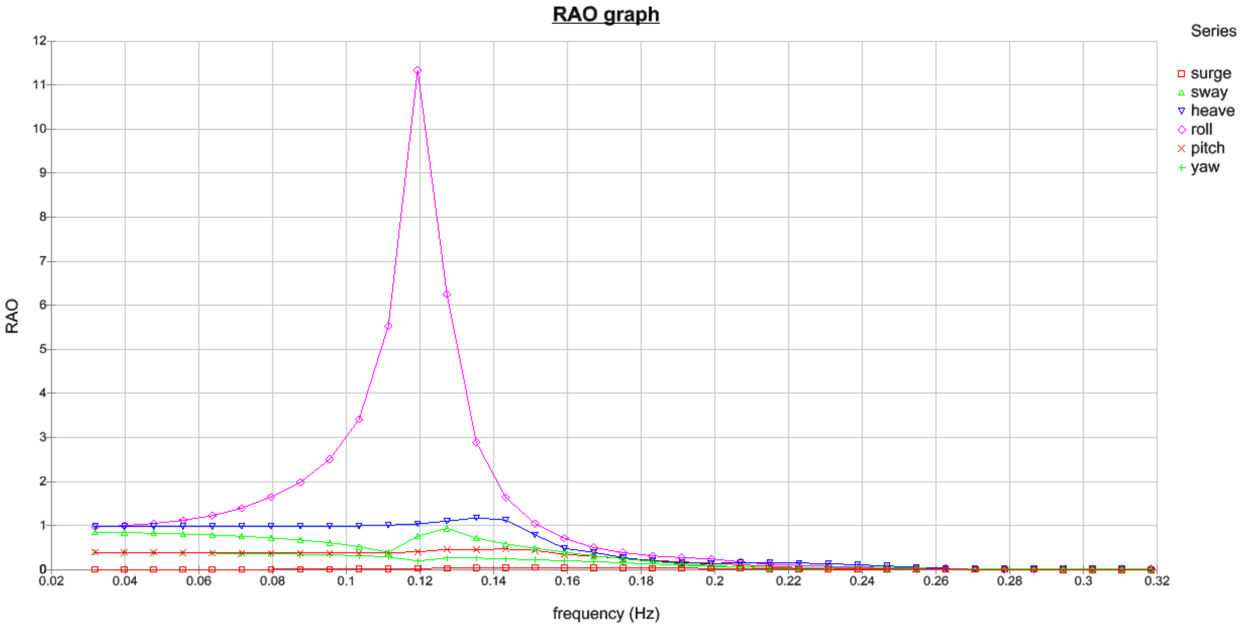


Figure E-5: RAO Graph, 0 knots, 120 degree Heading

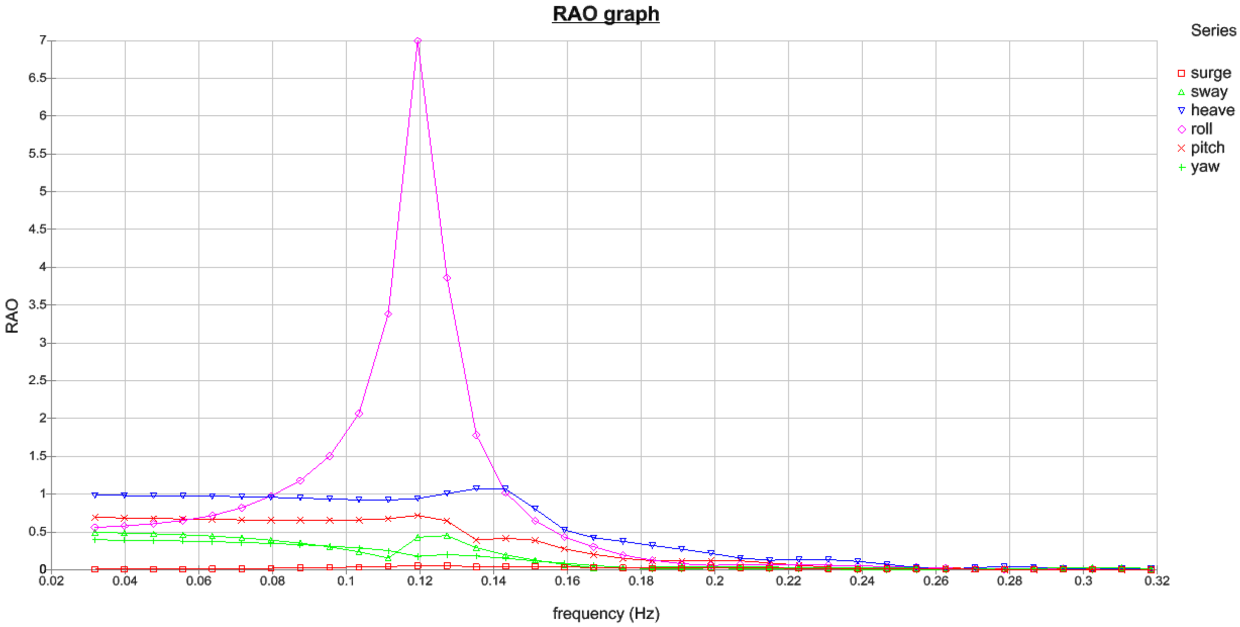


Figure E-6: RAO Graph, 0 knots, 150 degree Heading

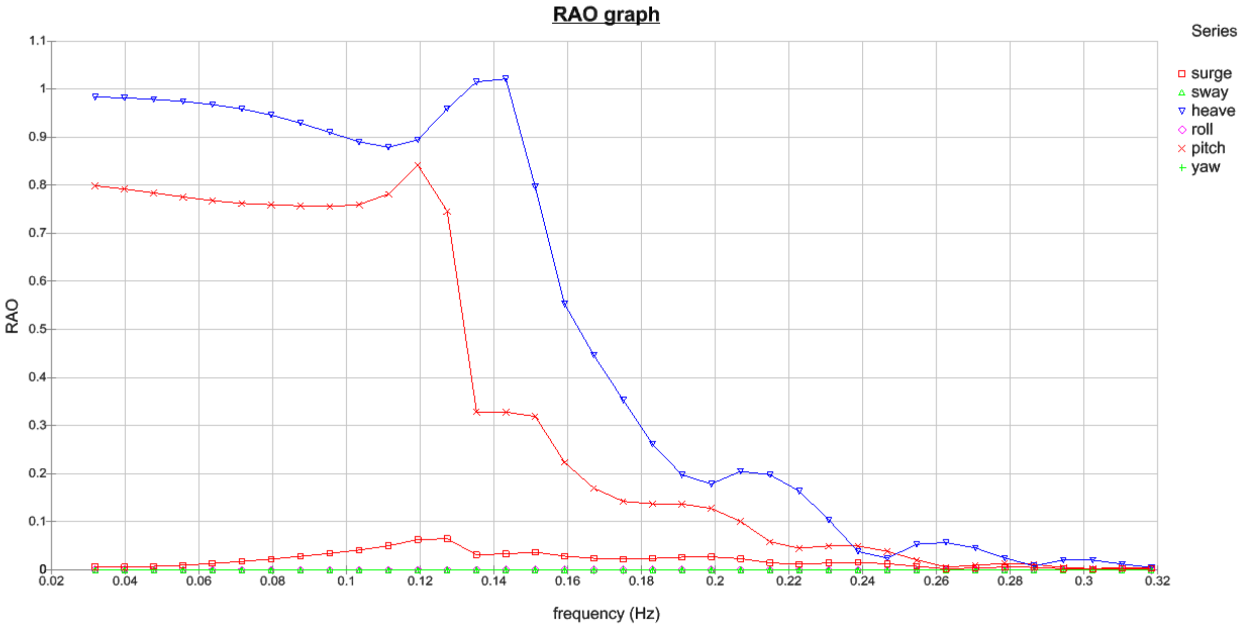


Figure E-7: RAO Graph, 0 knots, 180 degree Heading

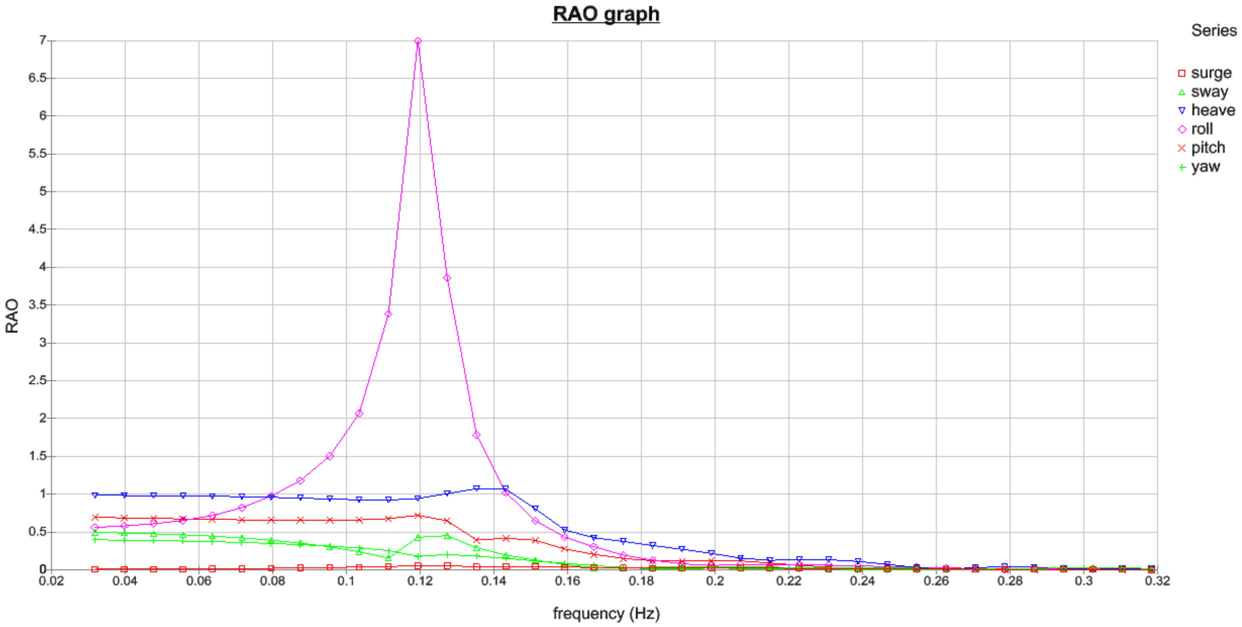


Figure E-8: RAO Graph, 0 knots, 210 degree Heading

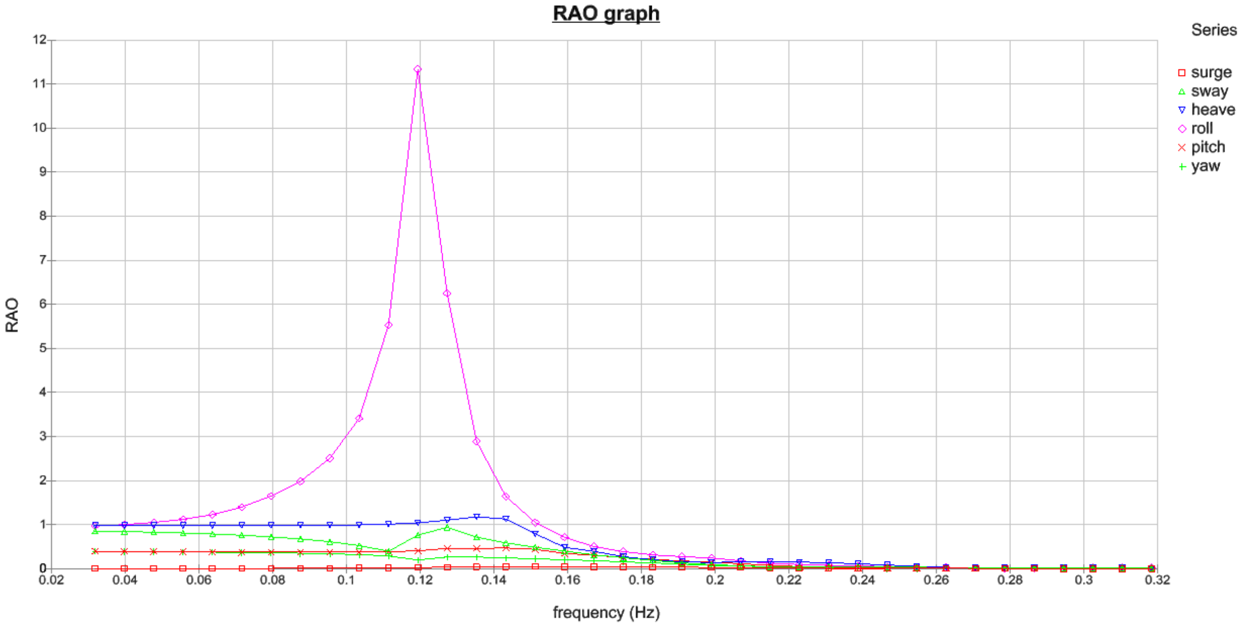


Figure E-9: RAO Graph, 0 knots, 240 degree Heading

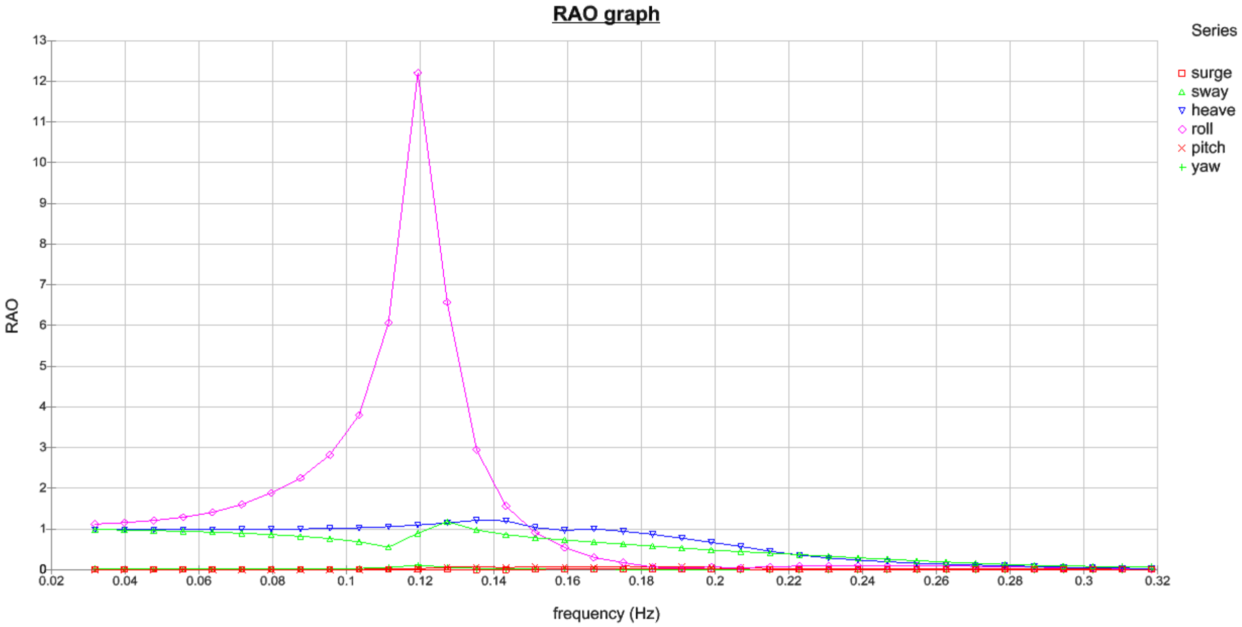


Figure E-10: RAO Graph, 0 knots, 270 degree Heading

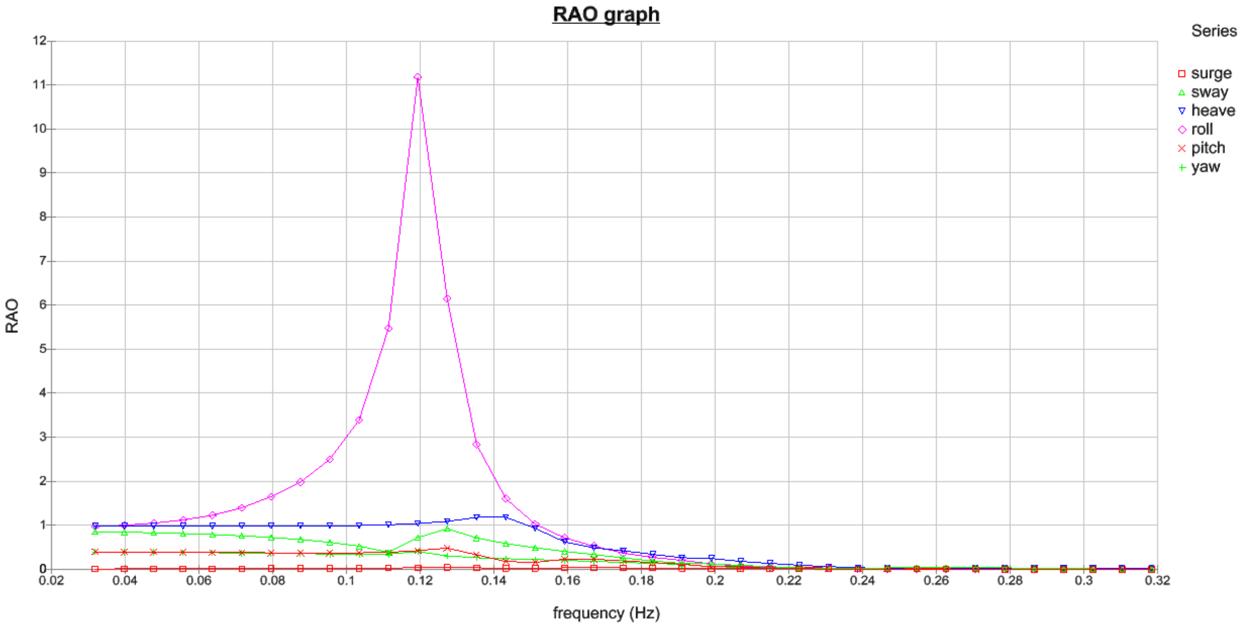


Figure E-11: RAO Graph, 0 knots, 300 degree Heading

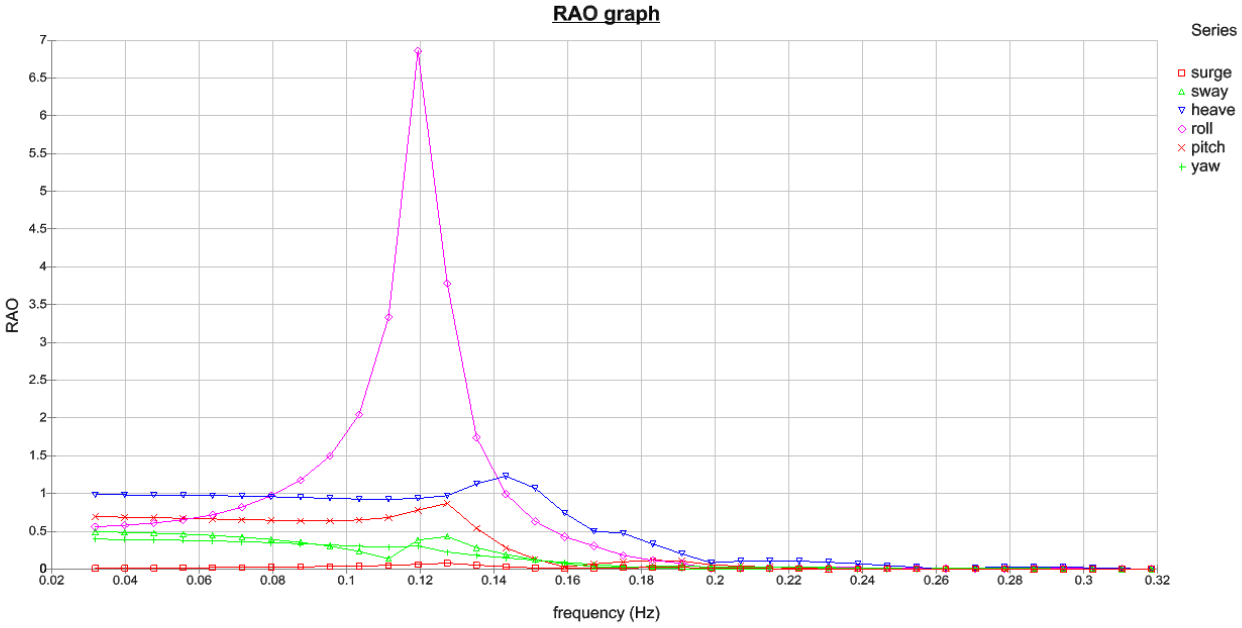


Figure E-12: RAO Graph, 0 knots, 330 degree Heading

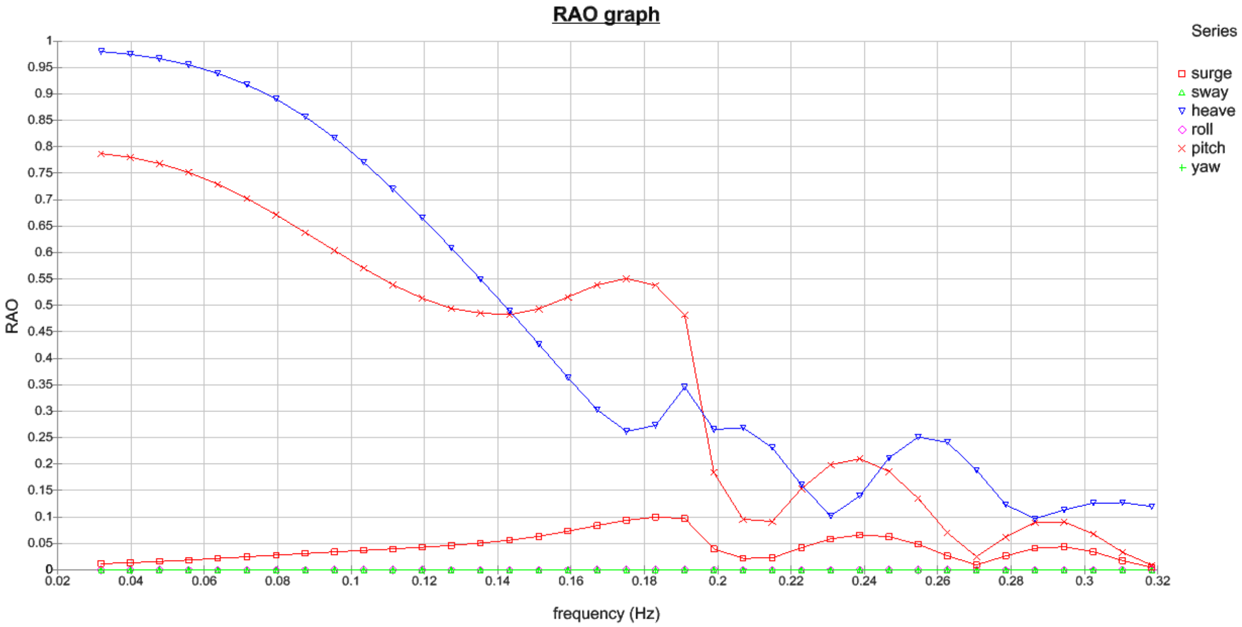


Figure E-13: RAO Graph, 6 knots, 0 degree Heading

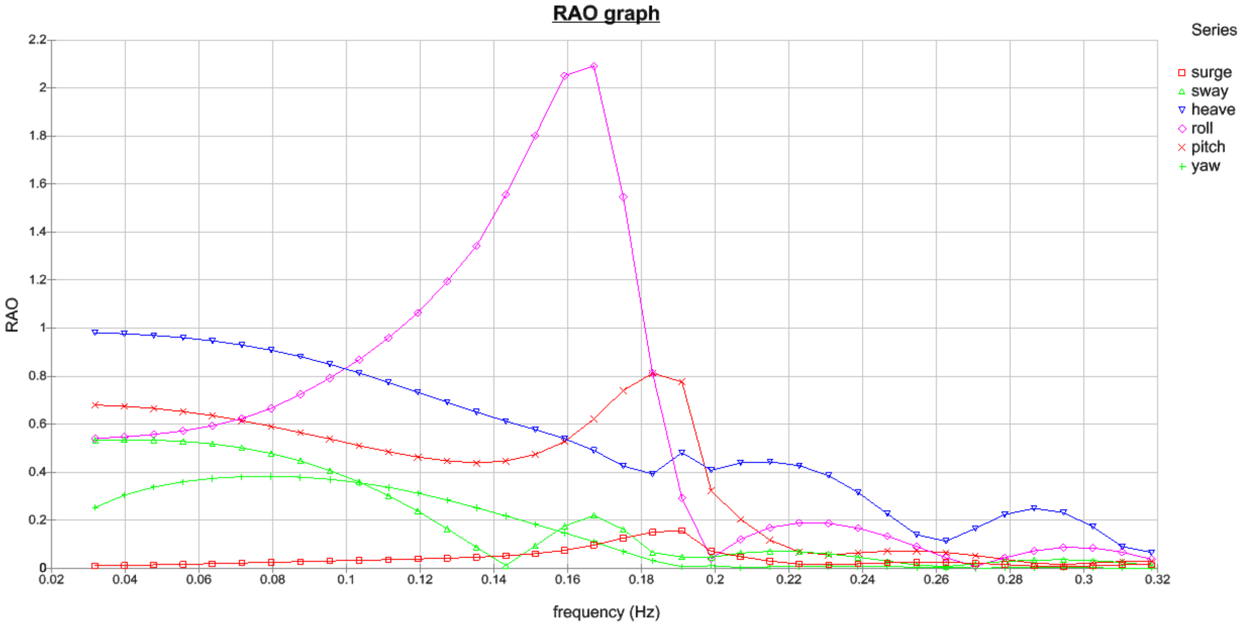


Figure E-14: RAO Graph, 6 knots, 30 degree Heading

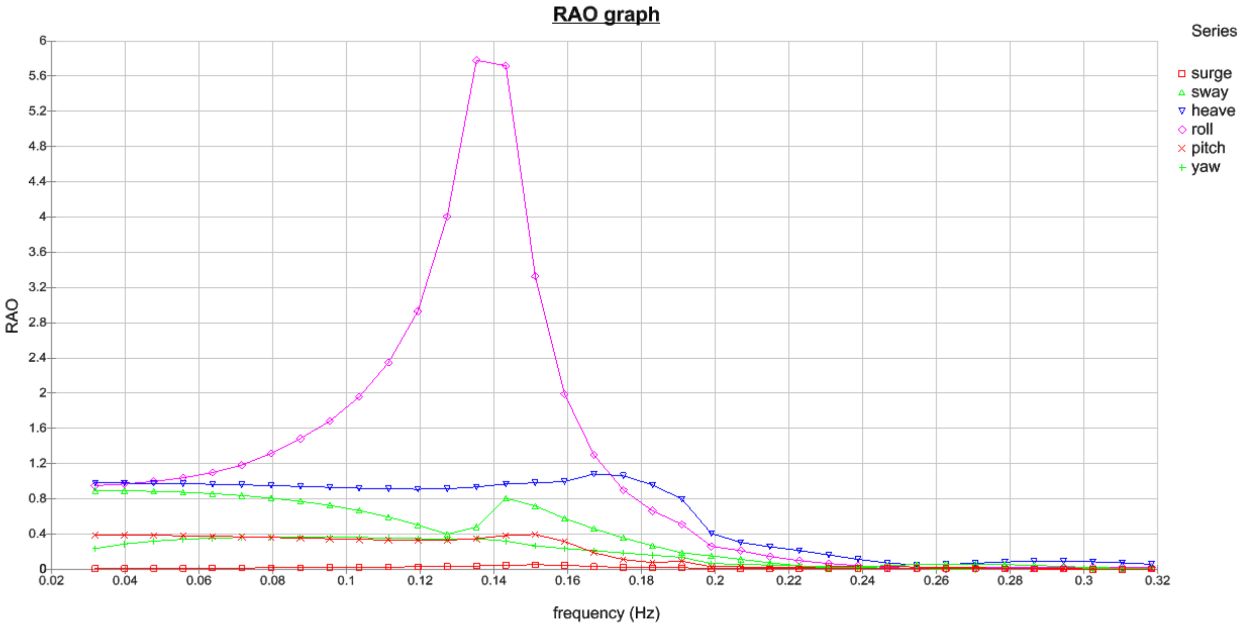


Figure E-15: RAO Graph, 6 knots, 60 degree Heading

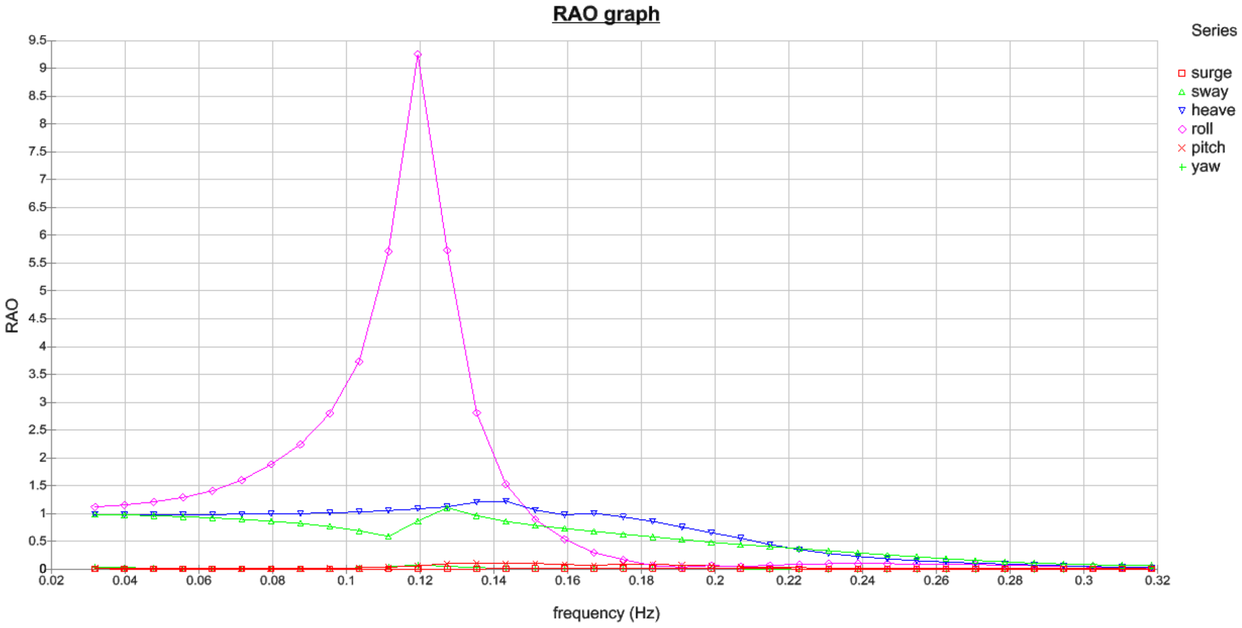


Figure E-16: RAO Graph, 6 knots, 90 degree Heading

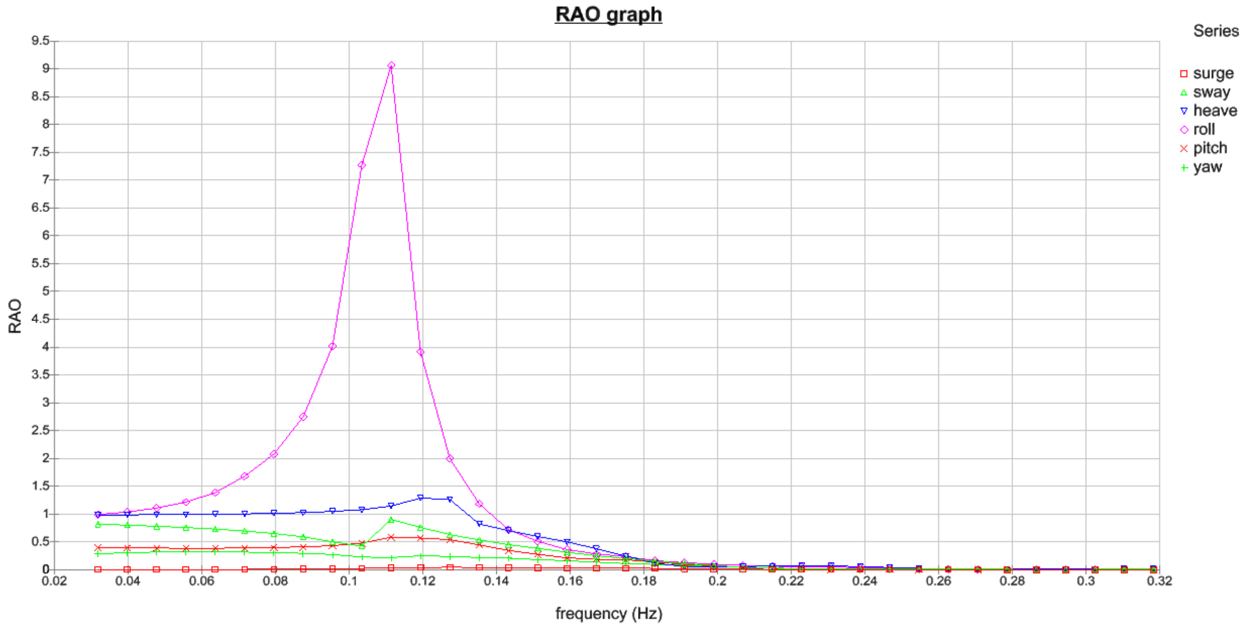


Figure E-17: RAO Graph, 6 knots, 120 degree Heading

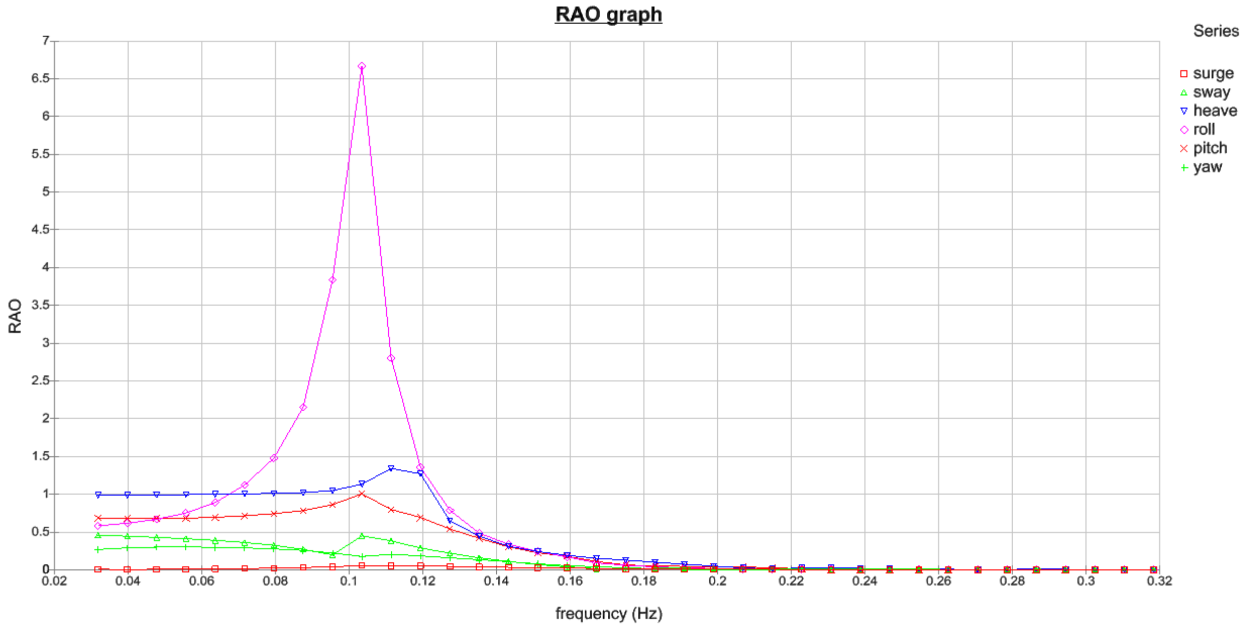


Figure E-18: RAO Graph, 6 knots, 150 degree Heading

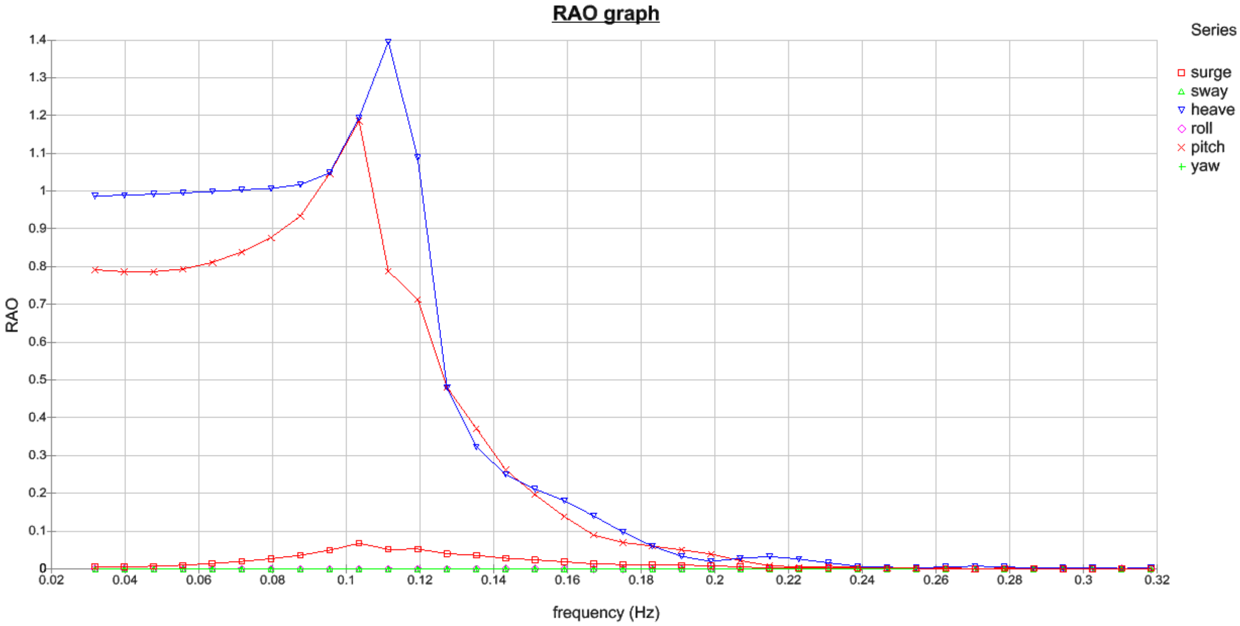


Figure E-19: RAO Graph, 6 knots, 180 degree Heading

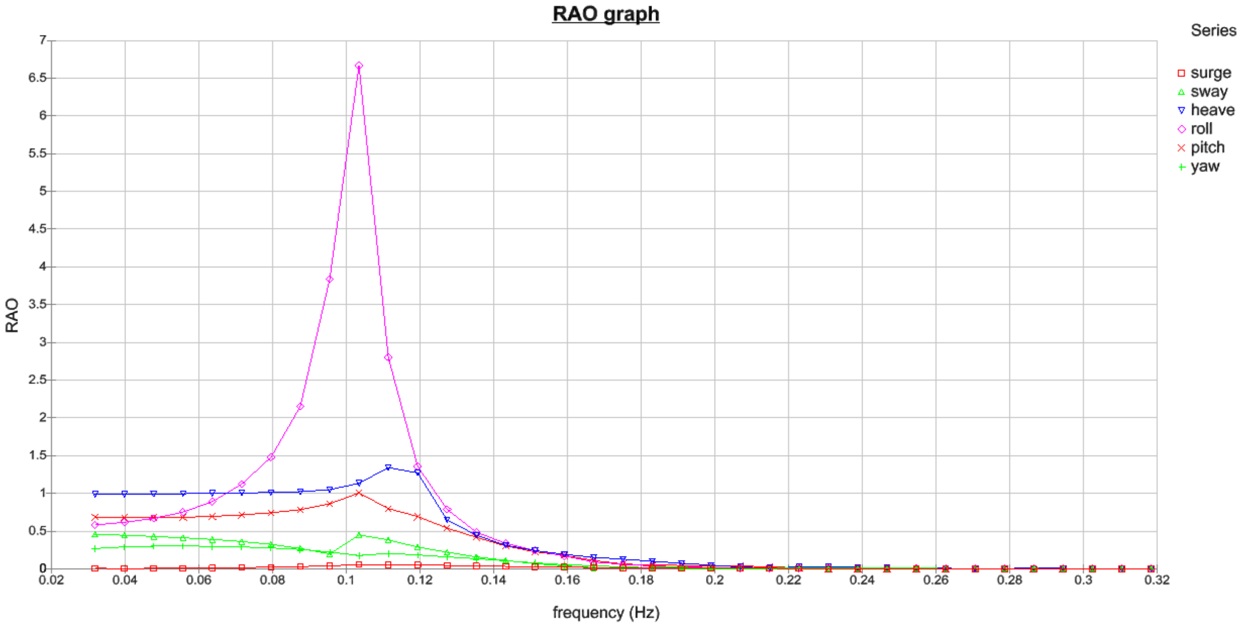


Figure E-20: RAO Graph, 6 knots, 210 degree Heading

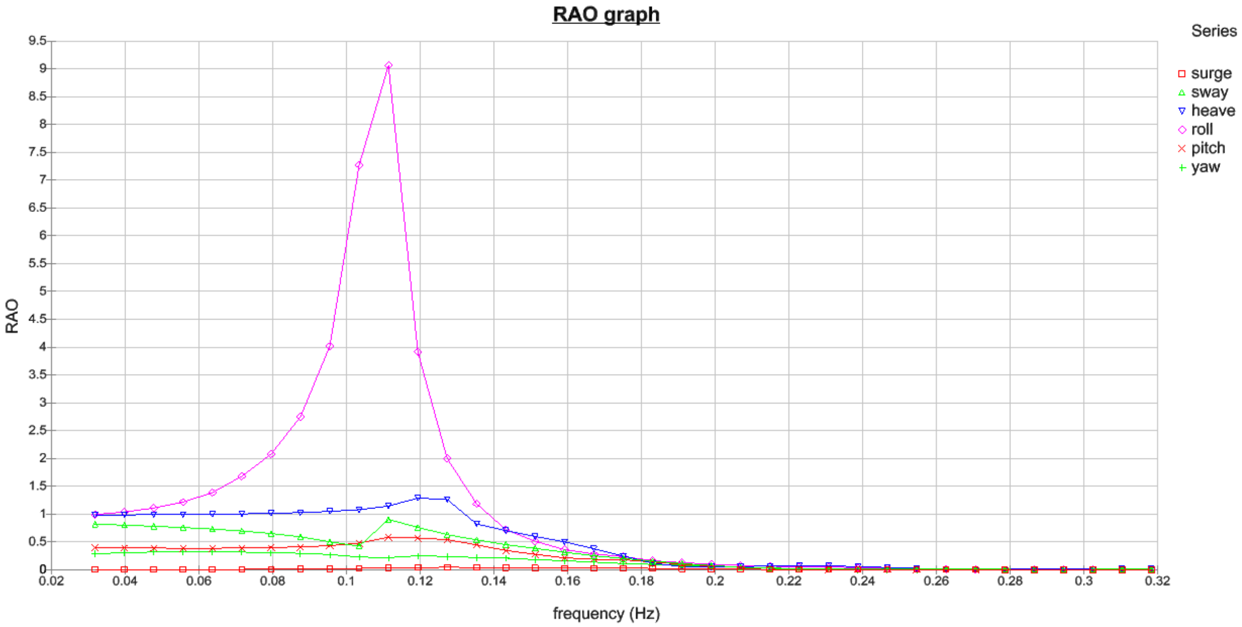


Figure E-21: RAO Graph, 6 knots 240 degree Heading

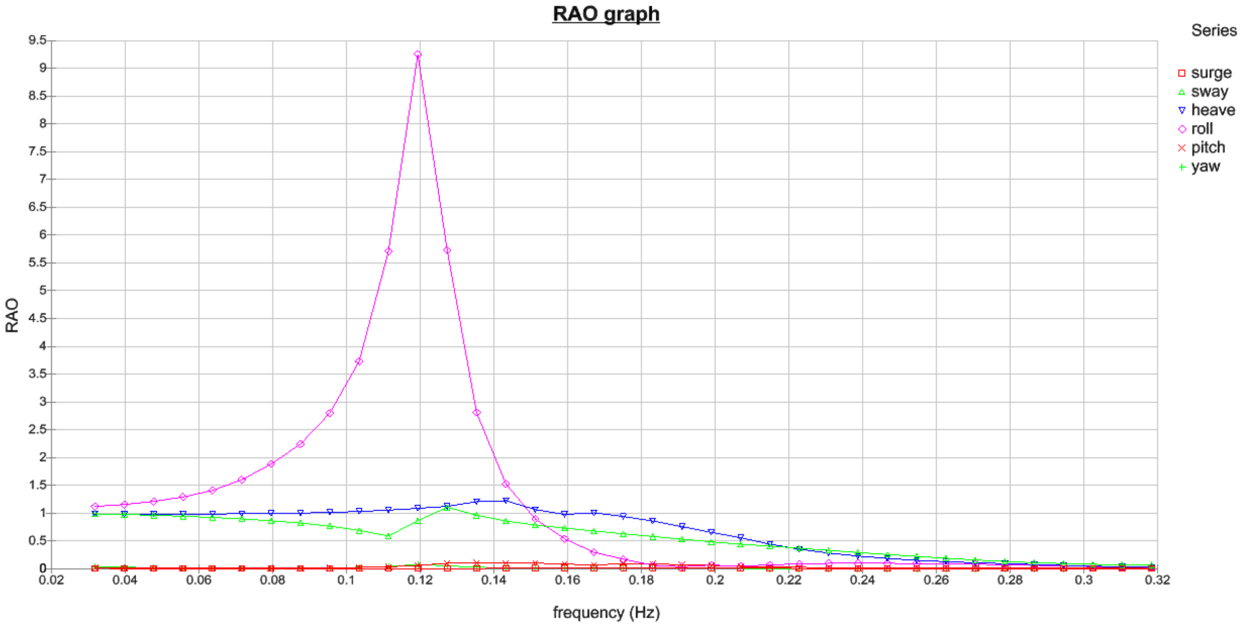


Figure E-22: RAO Graph, 6 knots, 270 degree Heading

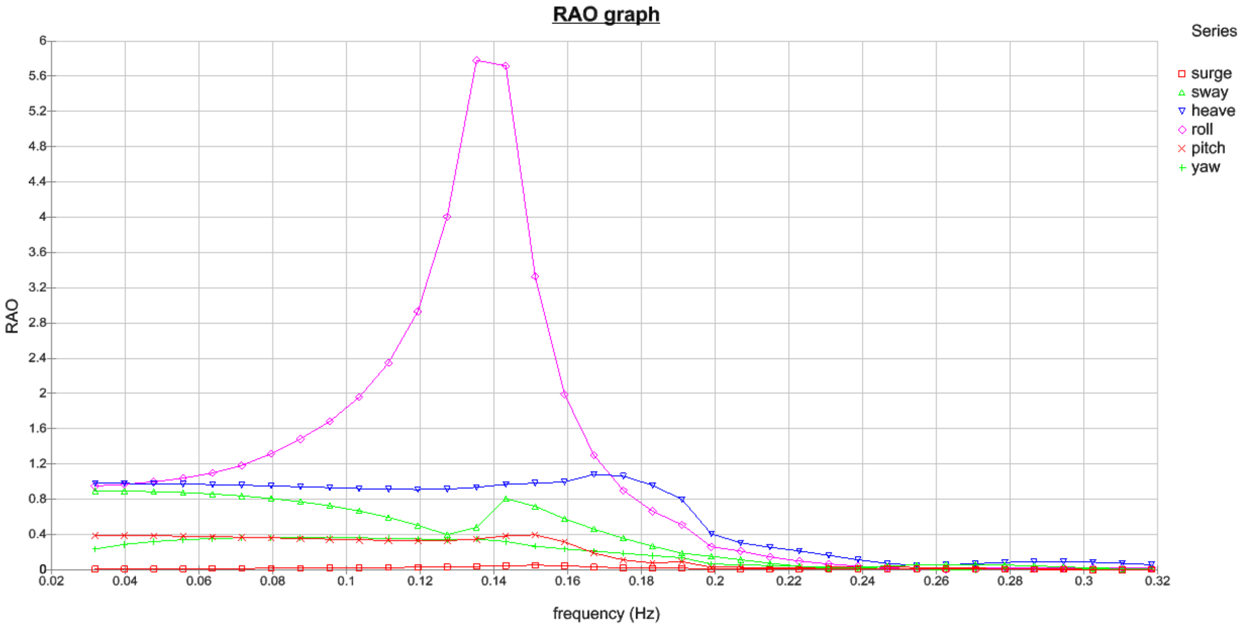


Figure E-23: RAO Graph, 6 knots, 300 degree Heading

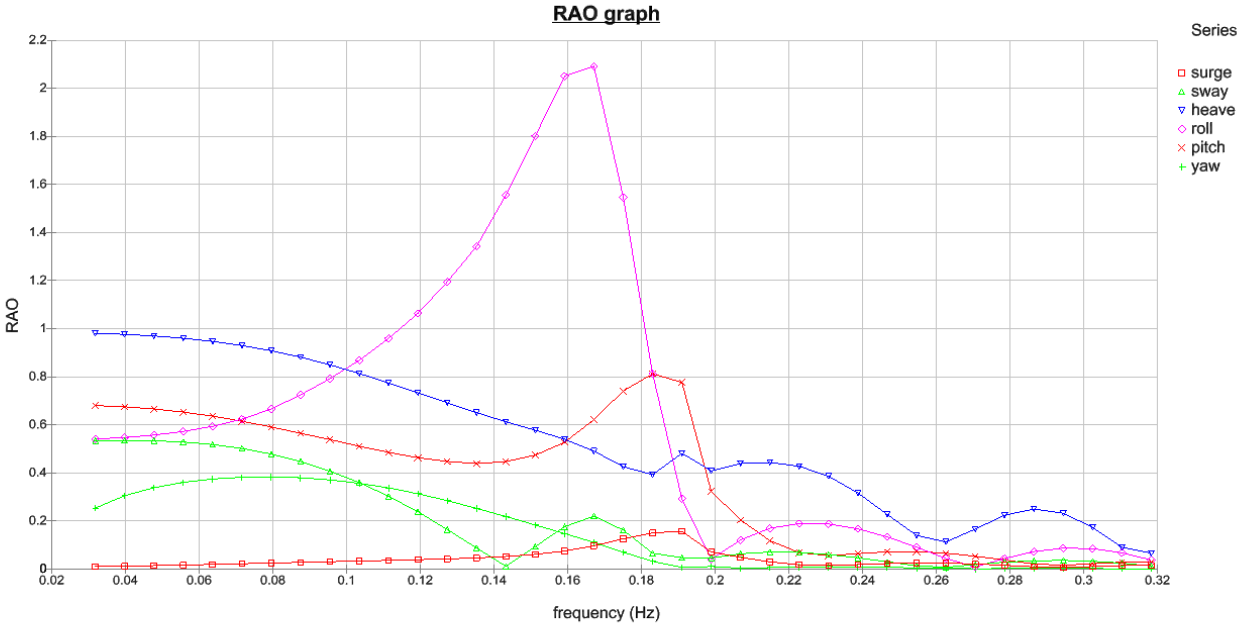


Figure E-24: RAO Graph, 6 knots, 330 degree Heading