Modeling and Simulation Analyses in Support of the Investigation into the Sinking of the Container / RORO Ship El Faro, on October 1st, 2015.

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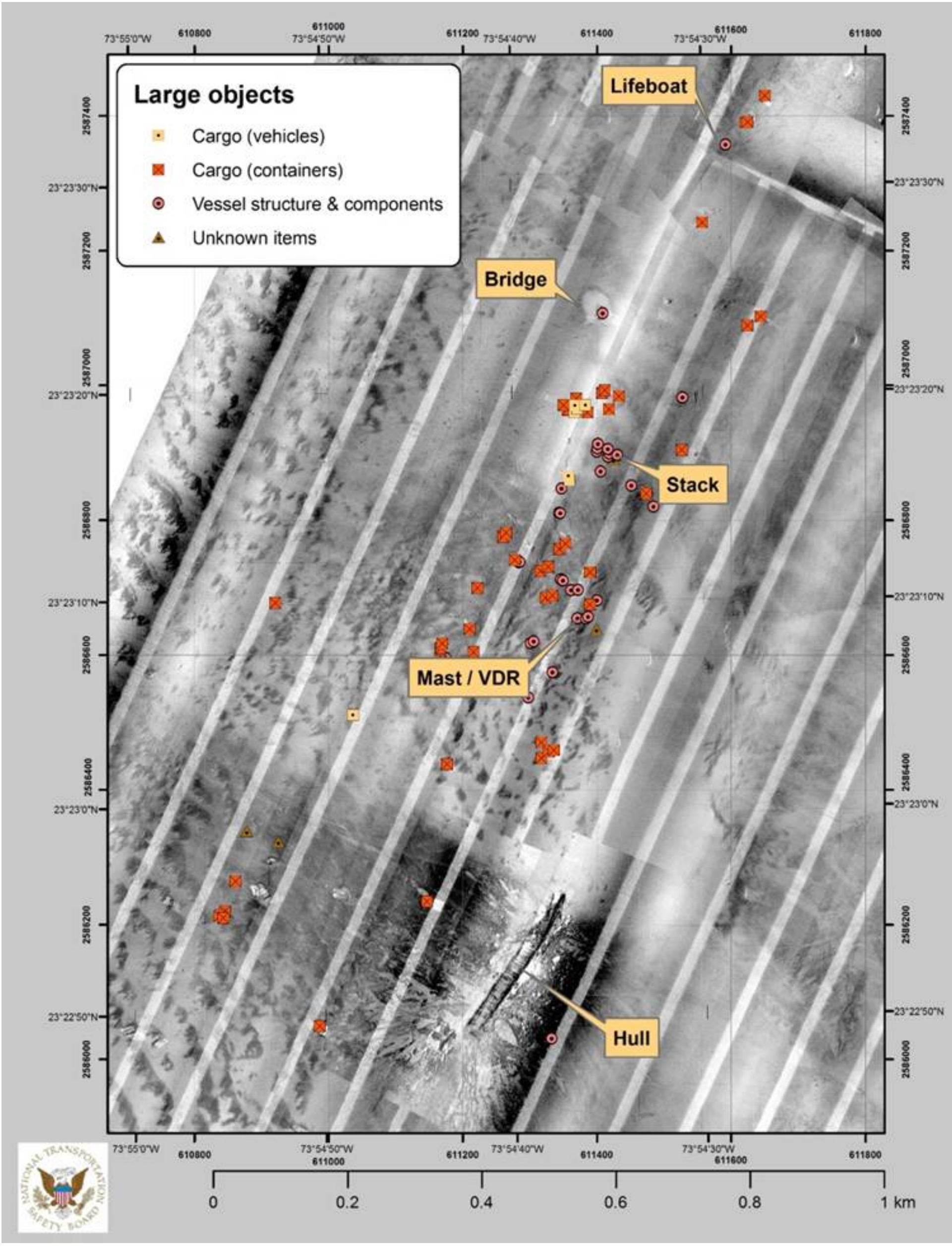

Cover Image: This is a composite debris field map as the EL Faro lies on the bottom from NTSB. The upper two stories of the deck house (labeled Bridge) are approximately half a mile from the main hull which is upright on the bottom.

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1 Executive Summary

On the morning of October 1st, 2015, the Tote Marine Container / RORO ship El Faro, was lost with all hands, (33 crew and officers) off the Bahamas during a developing category 4 hurricane Joaquin.   This report describes extensive modeling and simulation performed by CSRA, in support of the National Transportation Safety Board (NTSB) and in cooperation with the US Coast Guard Marine Safety Center (USCG_MSC) to help explain what happened to the El Faro.

Figure 1-1: Stock Photo of El Faro (Deck Load Different from Accident Voyage)

Information from phone calls and the VDR indicated that nearly two hours before the vessel was lost, the vessel lost power. Thus, the two primary questions were:
Why did the El Faro lose power, and
Why did the El Faro sink?

Prior to the start of the CSRA effort, there were a number of possible causes for the sinking that could have played out individually or acting together including but not limited to:

- Catastrophic damage by a rogue wave or group of rogue waves
- Large cargo shift with or without breech of the hull's watertight integrity
- Downflooding by waves reaching the intake and exhaust vents into the lower RORO holds
- Green water on the second weather deck downflooding through an open scuttle or scuttles
- Downflooding due to a crack or cracks in the hull
- Breaking up on the surface
- Capsizing in beam seas after broaching due to loss of power

- Loss of lube oil pressure to the steam turbine

The numerical simulation and modeling investigations done on this project were designed to answer these questions.

While this project started in spring 2016, significant data from the wreck visits and the Voyage Data Recorder (VDR) were not available until the fall. As a result, the work has progressed through three stages separated by the availability of new data as the project progressed. This is summarized here and treated more thoroughly later in the report.

- **Phase One** involved the build out and testing of the various numerical models and post processing routines. This included:
  - Study of green water reaching the vents into the RORO holds and into the 2nd deck
  - Accelerations acting on the RORO Cargo and their lashings
  - Accelerations acting on the container cargo and their lashings
  - Accelerations acting on personnel in the house
  - Accelerations acting on the lube oil reservoir feeding the steam turbine

The range of conditions modeled under this early phase were based on limited data available as the VDR data and advanced NOAA weather models were not yet available.

- **Phase Two** - NTSB requested a pause in the work while the Voyage Data Recorder (VDR) was recovered and that data was analyzed. This resulted in:
  - Two data sets from the VDR, numerical data about the speed, latitude, longitude etc. and transcript of the audio recordings from the bridge.
  - New sea state and weather Data from the NOAA WAV_III wind and wave model, which provided the weather conditions at the VDR based location of the ship every 15 minutes from the day before the sinking, through the sinking and beyond. (Chawla, 2016)
- **Phase Three** is a synthesis of all available information including:
  - The numerical and audio data from the VDR
  - Evidence provided by a review of photos and videos of the ship on the bottom
  - Additional Hydrodynamic modeling that combined all of the available information to depict the ship over the last few hours leading up to the sinking

A number of times during the night, bridge personnel complained of very poor visibility due to darkness and heavy rain and wind driven spray. The ship left Jacksonville with 396 containers aboard and there are only 2 to 3 visible aboard in the bottom footage. Within minutes of the order to abandon ship, someone noted containers in the water, but many of them may have gone over the side earlier in the storm. There were multiple comments on the VDR transcript at different times about “rumbling” and “stuff banging around”, that may have been containers going over without the crew seeing them due to the poor visibility.

Some of the modeling performed under this project shows the level of combined wind loading, heel and roll motions necessary for containers to break the twist locks and fall over the side. The accelerations acting on the containers, due to wave induced ship motions, were developed as part of the modeling process.

Some of the modeling and simulation work performed includes the effect of various cargo shifts. The accelerations at the most vulnerable RORO cargo in each hold were calculated for every run and are supplied later in this report.

There is a concern that breakaway RORO cargo may have impacted a 6 to 8 inch fire main pipe in the 3 hold that penetrates the side of the ship below the waterline. If that is the case, the pipe may have completely or partially broken, or it may have torn out of the sideshell seachest, or plating which would result in a larger hole. Unfortunately, this part of the hull is below the mud line and not visible on the wreck. None of the commercial off the shelf hydrodynamics modeling computer software available is capable of modeling water ingress of this type, and sloshing of water in a RORO hold without extensive code creation and testing, which is beyond the scope of this project.

The ship was designed to handle RORO cargo with vents bringing fresh air into and exhaust laden air out of the cargo holds. There were fire dampers fitted that might have limited the ability of green water to enter the cargo holds if closed, but NTSB informed CSRA these were not likely closed for El Faro on the accident voyage. Our modeling demonstrates that once the ship was heeled over 15 to 18 degrees in storm waves, the vents on the lower side would be submerged a significant part of the time, leading to catastrophic down-flooding.

The lube oil system for the steam turbine and reduction gear would shut down if the heel or heel combined with roll angle caused the suction pipe to rise above the surface of the oil in the sump tank. If this occurred, the loss of lube oil pressure would cause a loss of main propulsion to protect the turbine and gear, and the vessel would broach "beam to", the hurricane seas. This is studied in section 12-5 of this report.

In the VDR transcript, it is clear that the master and chief engineer were trying to shift ballast between the ramp tanks to lessen the heel angle. Our modeling provides accelerations acting on this lube oil tank as well as the instantaneous roll angle for every condition modeled and is provided below.

The El Faro has very limited ballast tank capabilities and shifting water between the ramp tanks was probably not very effective. The double-bottom ballast tanks were filled with concrete and therefore not available for ballast changes.

The Tote Marine loading manual prescribes the methods for RORO and container cargo lashing.

Our Analysis shows that in many cases, the residual buoyancy of 3 containers stacked together is enough to break the 4 corner twist locks if the containers are suddenly submerged. This was included in the Orcaflex model. If all 396 containers were modeled with a twist lock link at each corner 1584 individual links are required. Therefore, to evaluate the modeling capability, only the bottom container in each stack was lashed with twist lock links in the Orcaflex model which reduce the number to about 580 unique links. The two or three containers in each stack were simply anchored together. The Orcaflex container loading model also includes the effect of container stacks contacting / impacting one another due to ship and container motions. This capability to model containers on a ship, in storm conditions with realistic behavior in wind and waves is new to the industry as far as the software manufacturer knows.

The RORO cargo lashings were not modeled, primarily due to the lack of sufficient input information. The behavior of vehicle lashings using Orcaflex has been used to a limited degree on US NAVY RORO vessels, thus it is possible.

VDR transcript indicates that when the ship heel was first noticed on the bridge it was to starboard, and the notion was that it was due to the strong winds acting on one side of the ship. A decision to change course switched the heel angle to the other side. The heel was to port just before the ship lost power, and remained to port after the loss of propulsion from which it was no longer able to maneuver.

When the information reached the bridge that there was significant flooding in the 3 hold, and a scuttle was open on the 2nd deck, the ship was already heeling. Our modeling and simulation work in all three phases specifically addresses the before loss of power (BLOP), after loss of power (ALOP) and sinking conditions with different draft and heel conditions. While these conditions were somewhat conjectural in phase 1 due to limited data, they were refined in phase 2. The phase 3 modeling was based on a consensus covering the best available data and after discussion with NTSB and the USCG_MSC. Table 1-1 shows the best estimate available. The many different analyses and information leading up to this are described later in the report.

Table 1-1: Estimated EL Faro Conditions on the Morning of 10/1/15

Count	Description	H/13 (m)	Tm(sec)	Wave Heading		Wind Speed	Wind Heading	Draft AP	Draft FP	Mean	Trim Angle	VCGcor	Angle of Heel	TCG
	Time(local)			Degrees	Description	Knots	Degrees	m	m	Draft (m)	deg	m	deg	m
1	245	5.44	11.46	90.44	Near Beam	54.47	41.4	10.272	8.748	9.510	0.375	10.85	7	0.906
2	315	6.69	10.98	98.66	Near Beam	64.54	39.0	10.272	8.748	9.510	0.375	10.85	7	0.906
3	330	7.57	11.08	100.23	Near Beam	69.58	41.4	10.272	8.748	9.510	0.375	10.85	10	1.296
4	415	7.81	10.96	82.98	Near Beam	72.96	62.3	10.272	8.748	9.510	0.375	10.85	12	1.559
5	430	7.89	10.92	52.86	Aft Quartering	74.20	94.1	10.272	8.748	9.510	0.375	10.85	15	1.953
6	500	8.04	10.83	37.45	Stern Quartering	76.71	112.7	10.272	8.748	9.510	0.375	10.85	18	1.296
7	530	8.20	10.80	36.80	Stern Quartering	77.10	112.0	10.272	8.748	9.510	0.375	10.85	18	1.296
8	600	8.35	10.79	35.86	Stern Quartering	77.49	-177.3	10.272	8.748	9.510	0.375	10.85	18	1.296
9	615	8.43	10.91	48.74	Stern Quartering	72.90	-164.6	10.272	8.748	9.510	0.375	10.85	18	1.296
10	630	8.51	10.90	54.24	Aft Quartering	68.31	-159.6	10.272	8.748	9.510	0.375	10.85	18	1.296
11	645	8.59	10.89	58.54	Aft Quartering	63.71	-156.3	10.272	8.748	9.510	0.375	10.85	18	1.296
12	700	8.67	10.88	63.24	Aft Quartering	59.12	-153.0	10.272	8.748	9.510	0.375	10.85	20	2.623
13	715	8.75	10.81	80.10	Near Beam	61.59	-128.2	10.272	8.748	9.510	0.375	10.85	20	2.623
14	730	8.82	10.74	84.23	Near Beam	64.06	-133.7	10.272	8.748	9.510	0.375	10.85	20	2.623
15	735	8.85	10.67	87.05	Near Beam	65.48	-140.2	10.272	8.748	9.510	0.375	10.85	20	2.623

Table 1-2: Calculated Responses

Damaged Cond 2	Ship	H/13	Tm	Wave Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave	Response Period		
15 deg Set Heel	Speed	(m)	(sec)	Degrees	Description	45 min	m	m	m	deg	deg	deg	m	Ratio	Heave	Roll	Pitch
Time (local)	Knots																
245	19.30	5.44	11.46	90.44	Near Beam	Maximum	7.43	30.78	5.68	23.35	2.12	3.34	4.38	1.75	9.37	12.12	9.34
315	16.4	6.69	10.98	98.66	Near Beam	Maximum	3.88	30.08	6.54	22.67	2.74	4.37	6.06	1.76	8.81	11.75	8.94
330	16.7	6.99	11.08	100.23	Near Beam	Maximum	4.62	45.39	6.63	22.67	3.52	4.43	5.48	1.69	9.04	11.65	8.84
415	9.3	7.32	10.96	82.98	Near Beam	Maximum	6.34	34.35	7.25	25.44	3.41	3.95	5.45	1.57	9.48	11.70	9.32
430	10.0	7.44	10.92	52.86	Aft Quartering	Maximum	6.65	26.58	6.63	25.15	2.86	1.84	5.90	1.83	10.49	12.27	9.95
500	9.0	7.61	10.83	37.45	Stern Quartering	Maximum	10.28	25.71	7.09	27.63	2.75	2.14	6.46	1.74	12.03	12.64	12.14
530	4.3	7.57	10.80	36.80	Stern Quartering	Maximum	8.94	37.26	6.17	30.80	3.33	1.44	6.13	1.62	10.27	11.95	10.63
600	6.0	7.48	10.79	35.86	Stern Quartering	Maximum	7.36	37.81	5.58	27.88	3.06	1.20	5.52	1.44	10.74	12.17	11.12
615	6.9	7.57	11.94	48.74	Stern Quartering	Maximum	8.93	27.84	7.08	27.96	3.15	4.79	6.43	1.69	10.30	12.76	10.44
630	6.7	7.57	12.00	54.24	Aft Quartering	Maximum	8.66	29.89	7.72	29.45	3.29	0.55	7.85	1.82	10.17	12.07	10.00
645	6.8	7.59	12.06	58.54	Aft Quartering	Maximum	6.47	29.32	5.84	26.74	3.05	1.35	6.85	1.71	10.11	12.55	10.32
700	6.8	7.80	12.12	63.24	Aft Quartering	Maximum	8.41	33.49	7.67	28.44	3.13	0.74	5.68	1.59	10.37	12.14	10.25
715	6.7	8.02	12.18	80.10	Near Beam	Maximum	6.88	39.63	8.47	28.46	3.83	2.05	7.87	1.78	9.34	11.84	9.30
730	0.0	8.23	12.24	84.23	Near Beam	Maximum	5.90	34.64	8.60	28.26	3.78	3.93	7.15	1.75	9.82	12.00	9.71
735	0.0	8.45	12.30	87.05	Near Beam	Maximum	11.19	88.22	8.19	47.34	3.34	2.10	7.69	1.82	10.74	12.51	10.84

The responses shown in table 1-2 are single sided maxima for each surge, sway, heave, roll, pitch, yaw and the maximum wave height achieved in the time series. The wave ration is the maximum wave height in the time series minus the minimum over the significant wave height. The ratio values are within the expected range. The roll period is in fairly good agreement with the roll period shown in the VDR data of about 12 seconds.

The accelerations induced on the container deck and in the RORO holds in the transverse and vertical directions approach 8 tenths of a G while the longitudinal accelerations are lower. These are captured in great detail in the phase 3 results presented later in this report.

The ship lies upright on the bottom with severe impact damage to the stern including a crack across the ship at the aft engine room bulkhead. The bow appears to have landed more gently with not much forward motion as there are minimal dunes of sediment around the bow. The bow has settled and / or crushed about 15 feet into the bottom. The debris field is extensive but it is clear that the actual dispersion of containers must go much further than the mapped area, because only a fraction of them are to be seen in the mapped area. The pilot house is approximately 1/2 mile away while the mast and boiler exhaust stack are about half that distance away.

Conclusions:

The different kinds of computer simulations performed by CSRA in support of this investigation, have allowed us to gain a physics based understanding of how the winds, waves and stability conditions acted on the ship and during the creation of the debris field.

Our analysis, in conjunction with the videos of the wreck, the VDR data and the work of other team members has systematically narrowed down the possible causes of this El Faro Casualty as follows:

The loss being due to the action of Rogue Waves was evaluated by Dr Fedele et al at Georgia Tech and found to be very unlikely, which was corroborated by the VDR transcript

The possibility of the ship breaking up on the surface was eliminated by the VDR audio and examination of the wreck footage on the bottom.

Catastrophic capsizing in beam seas after loss of power is eliminated by the VDR transcript data, although a slower capsize in the course of sinking does seem to have occurred.

The modeling and simulation has successfully addressed:

- The effect of various heel angels as the result of several cargo shift and downflooding scenarios. This shows that the heel angles are more likely due to loss of righting moment due to flooding in holds than due to a shift of cargo on the RORO decks. Moving the vehicles around has a smaller effect than the addition of flood water does.
- Downflooding by waves reaching the intake and exhaust vents into the lower RORO holds was a likely source of flooding once the ship heeled over for a range of conditions
- Green water on the second deck (a weather deck) downflooding through an open scuttle or scuttles
- Loss of lube oil pressure to the steam turbine, was likely the primary reason for loss of power, as the heel angles exceed the pickup for the oil sump. This was studied by examining the static and moving angles at the tank surface and the 3 axes accelerations acting on the tank and the oil inside it as a function of time and ship motions, described in section 12.5 of this report

As described from when this work was first proposed, this has been a first of its kind investigation of what these simulation tools can and cannot do. The state of the art was notably advanced by the work performed herein, but much future development of the tools and techniques still lies ahead.

Future Work:

The art and science of Marine Forensic Investigation has been notably advanced by this work on the El Faro, and several avenues of investigation may proceed from this data once the NDA's are lifted.

- The GPS data from the VDR may allow us to capture or at least estimate the roll and pitch motion of the ship as a function of time as the course, speed, wind and wave conditions changed.

- The behavior of the container lashings in tensile failure is documented in several of references. This knowledge has not been fully promulgated into the Orcaflex model due to lack of time. The completion of this modeling will provide a first of its kind data set and modeling capability that will be described in a technical paper once the NDA is lifted.
- Future work may map the containers falling off, to where they landed on the bottom after falling through the current and density gradients. These could potentially be compared to the containers that are labeled in the debris field.
- There are several aspects of flood water entry and flood water sloshing around as a ship moves in waves, that there is currently no commercial off the shelf model to simulate. There is much that can be done to increase this capability by writing python or C++ code to run with Orcaflex, however this development is out of scope for the current contract. Some model testing to validate such models would probably be necessary as well.

2 Introduction to the Modeling Project

The suite of software selected for these analyses is based on their unique abilities demonstrated through prior work on other projects. These tools include:

- SHCP for hydrostatics and righting moments
- Visual SMP for low sea state, linear theory seakeeping and damping moment evaluation
- Hydro-D which is the graphical user interface for WASIM and WADAM
- WASIM (2011) is a Rankine panel code that is capable of linear theory RAO's with forward speed or non-linear time domain seakeeping at speed in up to extreme storm waves
- WADAM is a zero-speed linear theory Rankine panel code that allows the creation of Haskin RAO's which produce forces and moments instead of just motions. These are better for adding in such things as wind forces or objects moving around.
- Orcaflex is a general-purpose hydrodynamics code with a graphical user interface that allows the ship to respond to waves plus winds plus currents all acting at the same time. It also allows a wide range of other analyses of interest including:
  - Forces and moments acting on container lashings. Lashings failing at a maximum load and the containers subsequently falling off
  - Object on object collision and contact forces
  - Wind loading on specific objects
  - The action of propulsors and the action of "wings" such as rudders and ride control fins
  - The ability to model a group of objects free falling through the water column and making bottom impact
  - The ability to create .avi movie files of dynamic behaviors for illustration to a wider audience
- MATLAB and Excel are used together to capture and post process the many types of data files that must be created to set up the other software and then to post process and understand the vast amounts of data that comes out of these simulations.

The simulation and modeling investigation began with gathering information and modeling the ship and the cargo load in meticulous detail.

2.1 Gathering Information

2.1.1 CargoMax Models for Hydrostatics and Righting Moments

The CargoMax model in the departure condition was GFI from NTSB and the USCG Marine Safety Center (MSC). Eventually a number of different versions were made available to account for fuel burn off and to some degree the ingress of water into the holds.

2.1.2 Weights and Centers Accounting

A detailed and accurate accounting of weights and centers of gravity are critical in any marine forensic analysis. It provides a baseline to which the investigators can add or subtract weight from flooding and the behavior of buoyancy elements as the events progress through the failure cascade. For instance, under normal circumstances, the containers on deck provide no buoyancy because they are out of the water. If they were all to suddenly become submerged, they would initially add about 37,000 metric tonnes of buoyancy, before any flooding of the containers occurred, which is comparable to the normal navigational displacement of the ship, (34,000 metric tonnes).

The GFI CargoMax model contains a number of approximations that result in questionable resolution when studying a sinking event. For instance, all of the vehicles are at the same location in any given hold and all autos weigh the same.

- An excel spreadsheet was created to account for every vehicle in the RORO decks as accurately as the input data allowed.
- An additional sheet of the spreadsheet includes every one of the containers with their weights, centers and identification numbers. See Figure 3-4 for an example of one of these loading plans, Bay 10 in this case. Appendix 6 of this report describes how the container centers of gravity were developed.

Unfortunately, the lightship data from the CargoMax model was very coarse. David Karnes at the USCG Marine Safety Center created a blended model in Rhino-3D that provided approximate volumes for the shell and deck structure. These were included in the weights spreadsheet.

The 6 tanks in the inner bottom that are filled with permanent ballast are also included in detail. An estimated weight for the engines and outfitting and machinery was necessary to bring the weights into line with the CargoMax model. An approximate weight for the machinery, and the mooring gear, including anchors and chains, was provided by Dr. Jeff Stettler at USCG MSC.

Placing the remaining unaccounted-for weights very near the CG made it possible to bring the CG into line with the CargoMax model.

The linked file contains the detailed weights information for the RORO space and the container deck.

CSRA Dynamic-El Faro_Detailed Cargo Weights & Centers.xls

2.1.3 Buoy and Chart Based Wind and Wave Data

One of the first places to look for wind and wave data to support these sorts of analyses are the armada of NOAA/NDBC wave buoys scattered around the coasts of the United States. Figure 2-1 shows that none are within many miles of the ship at the time of interest for the sinking.

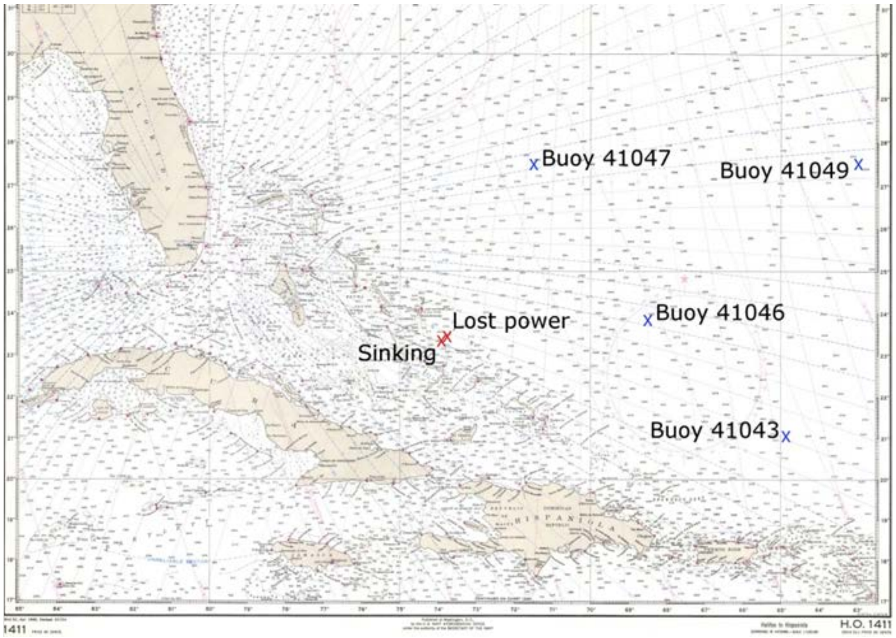

Figure 2-1: Large Scale Chart Showing the Sinking Location

2.1.4 Introduction of the NOAA WAV_III Model Wind and Wave Data

In May of 2016, some preliminary data on the probable wind and wave states in the 3 critical conditions were received from Dr. Fedele (Fedele et al 2016, Fedele personal correspondence). The data is a block of 36 headings around the compass, each with 40 spectral components, provided as a text or .csv file.

On November 23, 2016, an additional data set was received from Dr. Arun Cawla at NOAA in Silver Spring, Maryland. This data uses the ship positions from the VDR and calculates the wind and wave fields in 15-minute intervals for approximately the last 24 hours of the voyage. A Matlab routine was developed to interrogate each of the 98 data files to find the most plausible wind and wave conditions. Considerable work was required to align this data set with the limited data set provided by the VDR.

2.1.5 Introduction of the Voyage Data Recorder Data

The VDR recovered data was supplied to CSRA in the late summer of 2016. The initial data supplied included a time and date stamp, latitude, longitude, antenna height, rate of turn, and wind speed, on approximately 1 second intervals. The Latitude and Longitude were provided with sufficient decimal places to resolve motions of approximately 7 centimeters or around 3 inches.

2.1.5.1 VDR Wind Data

The wind speed from the RM Young wind anemometer looks reasonable but the wind azimuth was fixed to a single value for the entire record. These are two separate sensors in the wind sensor and it seems likely that the azimuth sensor was dead before the ship left Jacksonville.

Figure 2-2: Typical RM Young Marine Grade Wind Sensor

While figure 2-2 represents a typical sensor, it is unknown if this is an exact match for the one aboard EL Faro. The wind turns the propeller and the rate of rotation is calibrated proportional to the wind speed. The tail vane causes the sensor to rotate around the vertical shaft to align with the wind direction. The block with six screws at the joint in the shaft is the azimuth sensor. The sensor was attached to a post on a railing on the top of the pilot house. See figure 3-1 for ship geometry. This is a marine scientific grade wind sensor widely used in weather forecasting around the world.

2.1.6 VDR Audio Transcript Data.

The VDR audio data transcript was provided to the CSRA team upon public release and was reviewed in detail by S. Kery and W. Garzke. Mr. Garzke was invited because of his many years of forensic naval architecture analysis experience. An additional review and summary was provided by Mr. Stolzenberg at NTSB. The review of this data turned out to be critical in understanding some of the other data.

2.1.7 Introduction to the Investigation Video Data

Three trips were made out to the El Faro wreck by NTSB and USCG Marine Safety Center personnel, and about 4 terabytes of photos and video were recorded. Sean Payne at NTSB reviewed it all and removed the many hours of “looking at sand”, which is typical of sea bed video footage.

On January 12-13, 2017, a group of seven subject matter experts met at the NTSB Vehicle Recorder Lab to study the footage and produce a Wreckage Examination Report. The group included the following:

Chairman:	Sean Payne Mechanical Engineer National Transportation Safety Board (NTSB)
Member:	Eric Stolzenberg Senior Marine Accident Investigator National Transportation Safety Board (NTSB)

Member:	Lt. Evan Reger Naval Architect/Marine Safety Engineer United States Coast Guard (USCG)
Member:	Thomas Gruber Chief Engineer American Bureau of Shipping (ABS)
Member:	Lee Peterson Director of Operations TOTE Maritime Puerto Rico
Member:	Eugene Van Rynbach Naval Architect/Marine Engineer Vice President Herbert Engineering Corp.
Member:	Sean Kery Senior Distinguished Technologist CSRA

The group looked over a sampling of the video footage starting at the port bow, and working around the ship counterclockwise. This resulted in the official NTSB Group Chairman's Factual Report of Investigation DCA16MM001 that was provided for draft-review in mid-February. This report shows extensive damage to the ship and to the sinking related dispersion of its cargo. The damage signatures show:

- Damage that occurred at the surface prior to sinking
- Extensive damage that occurred as the ship was leaving the surface
- Damage that occurred during the plunge to the seabed some 14000 feet down.
- Extensive damage caused by bottom impact
- Some post-sinking damage due to corrosion

This will be discussed in detail in section 6 of this report.

2.2 Building the Undamaged Ship & Cargo Models

In order to understand the dynamic behavior of a vessel in a damaged condition, it is first necessary to see those behaviors in an intact condition. The intact condition is also necessary to provide objective evidence that the simulations are proceeding without gross errors and to allow tuning of the yaw behavior and the roll damping.

The first stage of the numerical analysis was to build the El Faro hull and appendages in the different analyses software packages so that its motions in waves could be modeled. This included:

- Building a 3D model in Hydro-D for use in WASIM and WADAM for linear and non-linear Seakeeping studies. (Figure 2-3) (Modeling colors are not user selectable)
- Building a simplified model in Visual SMP. This is used for a “Second Opinion” that can be used to a very limited extent to verify the higher order model results.
- Building a model in SHCP hydrostatics and stability software which is used to calculate the intact and damage stability.

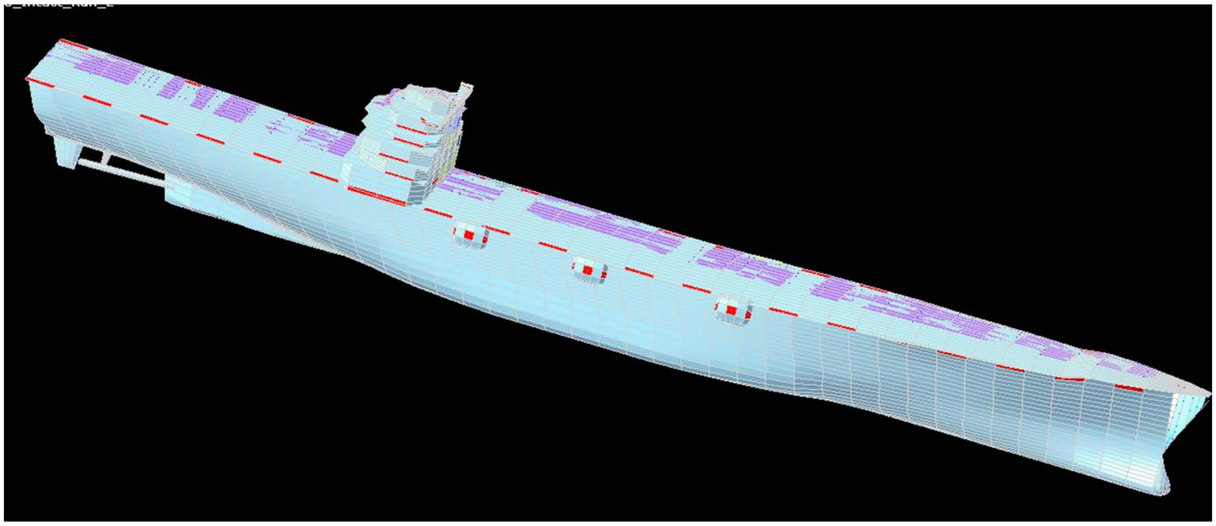

Figure 2-3: Example of WASIM Model (early)

- Building the detailed graphical OrcaFlex model. (Figure 2-4)
    - This includes all of the containers in their correct locations and each with the correct weights and centers of gravity, buoyancy and wind loading information.
    - This includes the ship's upper deck and house structure with correct wind areas and drag coefficients.
    - The many openings onto the second deck and the ventilation openings under the main deck leading down into the two lower cargo RO/RO holds
    - While OrcaFlex can model the ship acted on by wind and waves acting simultaneously, it requires motions inputs from one of the other computer codes as part of the setup of the impulse response functions required for the ship to respond to the incoming waves.

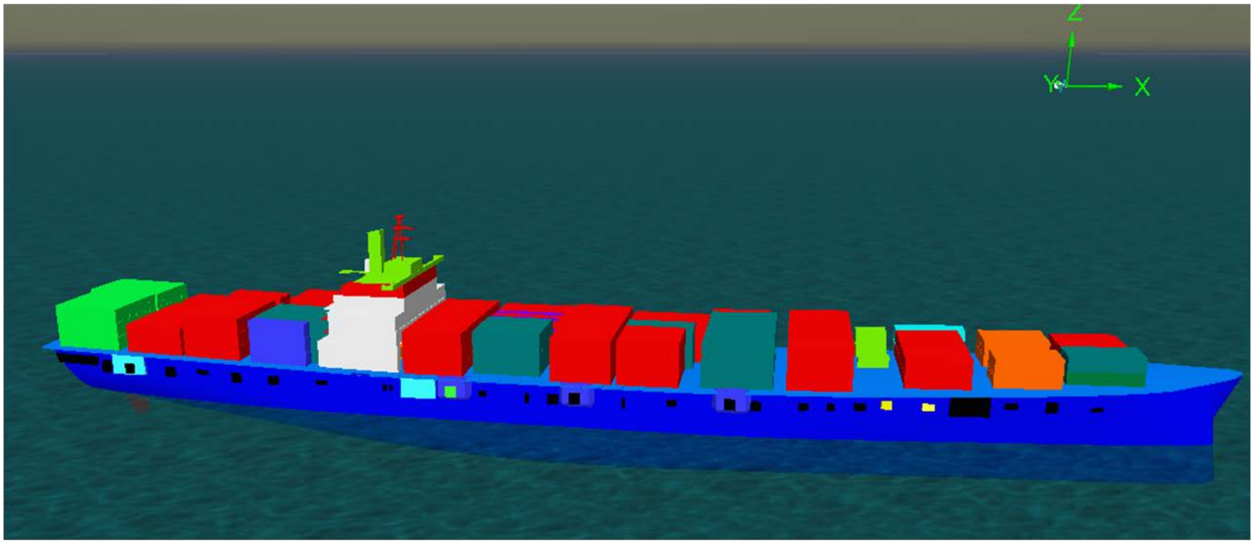

Figure 2-4: OrcaFlex Model of EL Faro with Container Load and Hull Openings (early version)

Note that the colors used in the Orcaflex model were chosen for visual effect and contrast and are not intended to represent actual colors.

2.2.1 Visual SMP

The Visual SMP linear strip theory code is limited to small amplitude waves and small amplitude ship motions responses so it is of limited use in modeling hurricane conditions where these limitations are exceeded. SMP was run in sea state 3 (1.25m H1/3 and 7.5second TM) and sea state 4 (2.5m H1/3 and 8.8 seconds Tm) to provide roll damping information and to provide a basis of comparison to the other models.

2.2.2 WASIM and WADAM Rankine Panel Codes

The non-linear time domain WASIM code and the linear theory, zero speed WADAM code share a common user interface named Hydro-D. Both utilize the same Rankine panel model of the hull and the input geometry is interchangeable. The WASIM results are used to provide the most accurate motions data available in high sea states with the ship underway at speed.

The WASIM model allows us to turn on selected panels in the models to produce time series of pressures on those panels. Those pressures are used to show when green water from waves is reaching specific hull openings around the second deck and vents leading into the lower holds.

The WASIM and WADAM codes allow selection of cut planes through the hull. The program integrates the panel pressures about those planes and returns time series data for 3 degree of freedom shear forces and 3 degree of freedom bending moments.

The WADAM code outputs several kinds of RAO's. The ship motion RAO's are similar to those coming out of SMP, except that the SMP RAO's come out with the quantities squared. The Haskin RAO's in WADAM are in a similar format but produce the forces and moments acting on the hull. When these are input into Orcaflex with the damping and righting moment matrices, the model in that program is more able to respond to external forcing such as wind, wind gusts, and cargo weights shifting around in the holds and on the upper deck.

2.2.3 SHCP (2010) Models for Hydrostatics and Righting Moments

The Ship Hull Characteristic Program (SHCP) was used to calculate damage stability properties for the required analysis. Hull section offsets were input into the program and hydrostatics were compared against Orca hydrostatic outputs to confirm that the hull was appropriately modeled. Orca is an add-in to the Rhino CAD model software used to smooth the lines and render them in 3D.

Different damage conditions were tested in SHCP to give a range of righting arm curves. The righting arm is the measure of the transverse distance between the net force of gravity on the hull acting through the hull's center of gravity and the net buoyancy force. A positive righting arm means that there is a positive restoring moment between these two forces, restoring the ship from a heeled condition back upright. A negative righting arm means that the relationship between the force of gravity and buoyancy will create an overturning moment, not uprighting the ship but instead heeling it farther over. Therefore, of main interest were conditions where the righting arm would be negative at small angles of heel, indicating instability.

The modeled conditions involved two conditions required by the customer and a range of other conditions to observe trends in the vessel's stability. Figure 2-5 illustrates a typical SHCP modeling condition

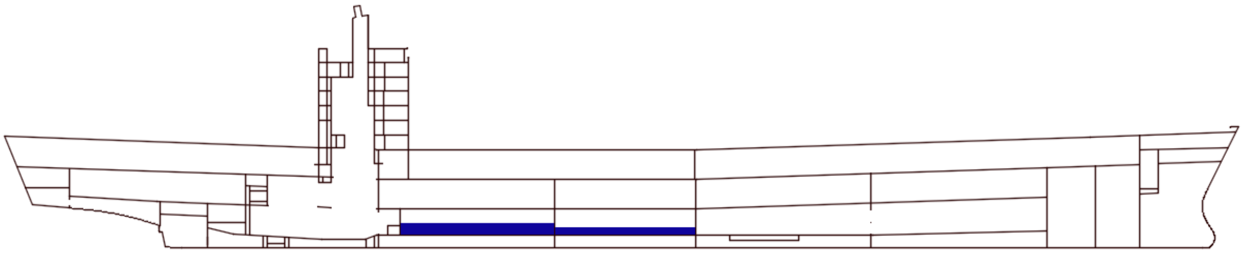

Figure 2-5: Illustration of Typical SHCP Modeling Conditions

Table 2-1 shows how SHCP was used to model the ship intact condition and with different levels of flooding. Item 1, the free flooding requirement, is a necessary setup step for the program to run but otherwise irrelevant.

While these results are expected to match the GHS model results from the USCG, having local control of the input/output allowed the analysis team to develop the righting moment curves and other relevant quantities necessary for feeding the other software packages in use. The full scope of SHCP results are contained in Appendix 4

Table 2-1: List of Conditions Modeled in SHCP

SHCP	Condition
label	
1	Free Flooding requirement
2	Hold 3 @ 20%
2A	Condition 2 with no tween deck
2B	Condition 2A with water on second deck (~1ft)
2C	Condition 2A with water on second deck (~2ft)
3	Hold 3 @ 30% Hold 2A @ 10%
3A	Condition 3 with no tween deck
3B	Condition 3A with water on second deck (~1ft)
3C	Condition 3A with water on second deck (~2ft)
4	Hold 3, 2A @ 50% on 4th deck
5	Hold 3, 2A, 2, and 1 @ 50% on 4th deck
6	Hold 3, 2A @ 100% and Hold 2, 1 @50% on 4th deck
7	Hold 3, 2A, 2, 1 @ 100% on 4th deck
8	Hold 3 @ 100% on 4th deck and 50% on 3rd deck
9	Hold 2A @ 100% on 4th deck and 50% on 3rd deck
10	Hold 2 @ 100% on 4th deck and 50% on 3rd deck
11	Hold 1 @ 100% on 4th deck and 50% on 3rd deck

3 Phase 1 Detailed Technical Approach and Data

3.1 Model Creation

The modeling process began with receiving a number of drawings and documents from NTSB. These included both original Sun Ships hand lettered documents from the 1960's and 70's as well as AutoCAD models created by Herbert Engineering. It turned out that there were numerous inconsistencies in each of them.

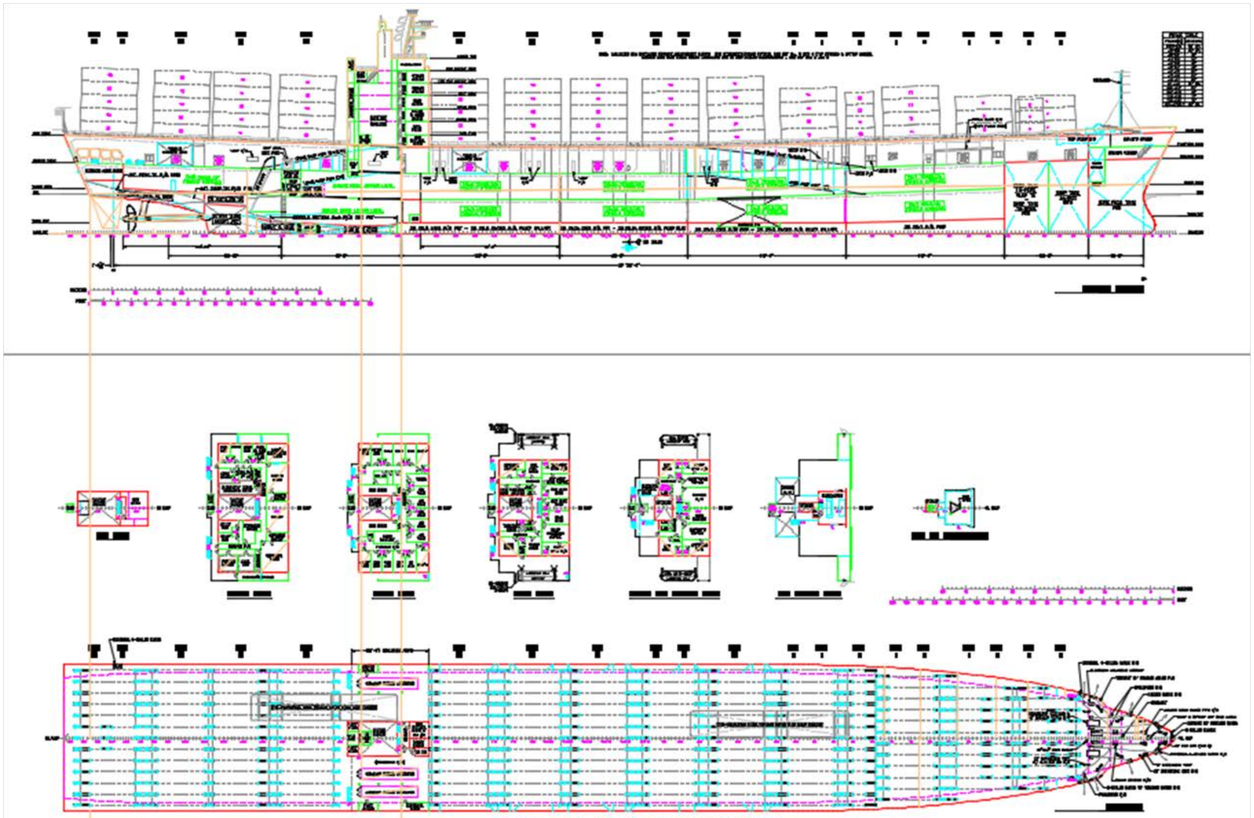

Figure 3-1: EL Faro GA Drawing (partial)

Figure 3-1 shows that the main and second deck on the forward part of the ship slope aft. The midbody is level, including but not limited to the 90 feet that was added. The stern section slopes slightly forward to about the middle of the house structure. Both the top deck and the second deck have significant camber, which means that the center is higher than the sides so that any water on them tends to flow back over the side.

While the GA drawing has many necessary details, it was discovered in the fall of 2016 after the models had been created that the deck heights are off by up to 18 inches. Many of the 60 or so openings in the side of the ship are also shown incorrectly. The deck heights from the GA for all decks had to be changed to match the very similar looking capacity plan drawing and hand-written station offsets including the deck height plan shown in figure 3-2.

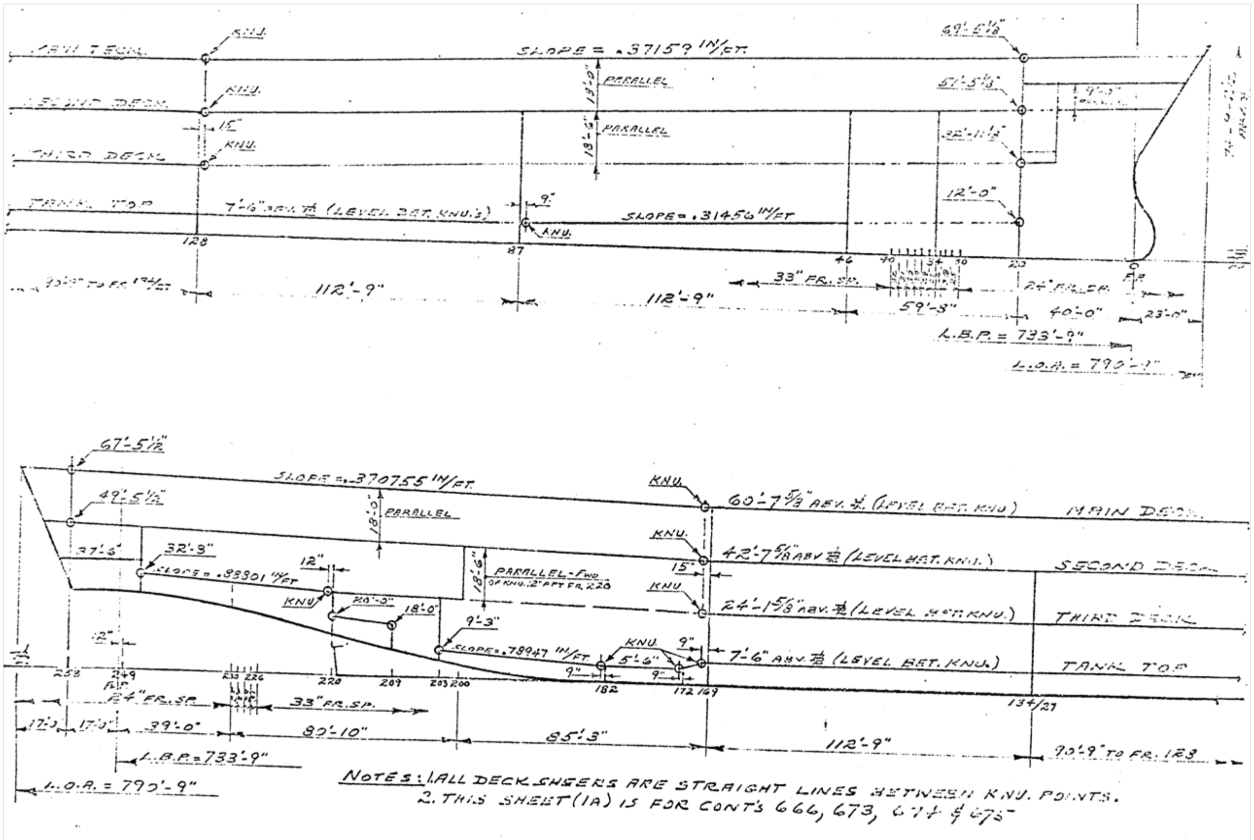

Figure 3-2: Deck Heights from Hand Lettered Drawings circa 1967

The locations of the container guides shown on both the GA (Fig 3.1 lower) and the Capacity Plan did not match or allow the loading configuration shown in the loading diagrams provided for each of the 19 container bays. These were all adjusted to allow the containers to be placed as shown in the loading plan, similar to Figure 3-4.

Difficulties like this are very common when dealing with drawings of older ships, and these were eventually resolved. The vent locations required acquiring additional drawings from Tote Marine and Herbert Engineering. Some data and photographs of the sister ship *EL Yunque*, were also viewed but it's not clear that the two ships are exactly the same at this level of detail. Even then, it was necessary to compare them to the photos of the wreck on the seabed, to make sure that the model has various details with the correct geometry and in the correct location.

3.1.1 Station Offsets in Original Sun Ships Format

The station offsets, (circa 1967) at every frame were hand lettered in feet, inches and eighths of an inch, on legal sized paper with very poor / faint copy quality. These were typed into excel and converted into metric decimal units, then plotted. It quickly became clear that many of these stations had some severe kinks and wrinkles in them, even after the input data and typing were checked for accuracy. In many cases the same kinks and wrinkles were in several adjacent frames as shown for frames 88, 92 and 96 below in Figure 3-3.

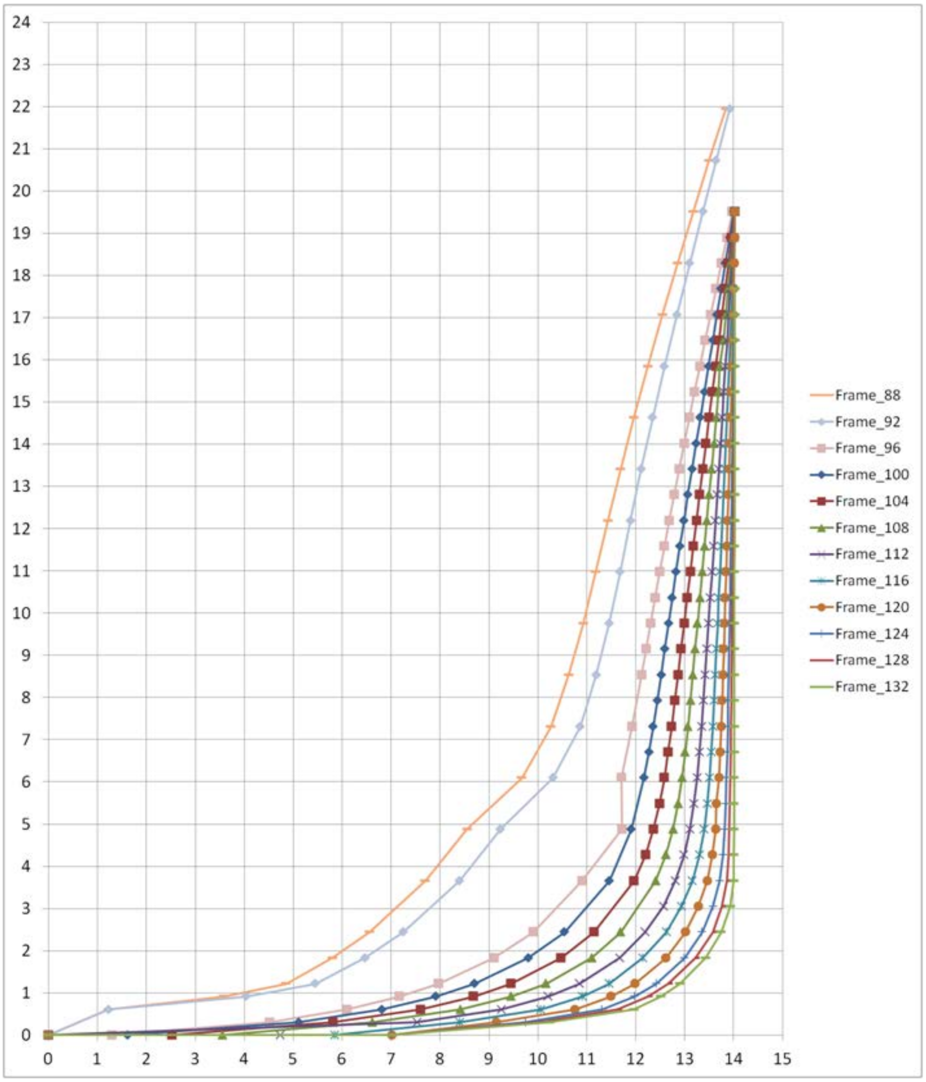

Figure 3-3: Early Plot of Sun Ship Offsets Showing Irregularities

Photographs with the ship in dry dock were used to validate that these kinks and wrinkles were a data artifact on the original drawings, and did not represent the ship as built.

A separate but similar analysis was underway by David Karnes at the USCG Marine Safety Center and he was kind enough to share his Rhino 3D Model. He independently found the same problem with the original drawings.

The models for use in Hydro_D, WADAM, WASIM, Orcaflex, Visual SMP and SHCP are all based on a composite of the hull offsets as developed by Kery and the Karnes model. The selection of which parts were used where, was chosen on the basis of the model meshes closing properly, and not on which investigator developed them. They were very similar but varied enough that some patches were problematic with one shape data set, but closed with the other and vice versa.

3.1.2 Analysis Plan

The plan, as proposed in the Statement of Work, was to develop working models of the ship in a variety of different software packages because each has specific strengths and weaknesses.

- SMP was chosen as a baseline because it is well respected within its limitations for mono-hulls like this for small amplitude motions
    - o Another reason for including SMP is because one of the outputs is an extensive array of many different types of damping matrices. These were used as part of the damping matrix development to feed the WASIM and WADAM codes
- WASIM was chosen based upon successful usage on prior ship sinking studies for its ability to model non-linear waves exciting non-linear ship motions in heavy seas. It also has the ability to model:
    - o Green water at the deck edge and impacting on specific locations on the ship
    - o Shear and bending moments at cut planes through the hull
- WADAM is a linear theory sister program to WASIM that allows the export of two types of Response Amplitude Operators (RAOs)
    - o The standard type provides 6 degree of freedom ship motions due to statistical wave spectra
    - o The Haskin RAOs develop 6 degree of freedom forces and moments acting on the ship, as well as added mass and damping matrices that are necessary for feeding Orcaflex
- Orcaflex is a general-purpose hydrodynamics modeling tool that has been used successfully to model other ships in storms and during their sinking events. (Kery et al, 2012, 2015, 2016) OrcaFlex has a graphics capability as well as the ability to model winds, waves, currents and density gradients. The graphical technique used for surface waves is a crude grid stretching algorithm, which prevents the waves from looking tall or steep, but this only effects the visualization and not the physics. The wave run-up on the side of the ship can be seen, as can the motions
- In all simulations, a goal was to model at least 100 wave encounters. The standard equation for frequency of encounter (PNA Vol 111, pp23, eqn. 69) is not applicable for short-crested seas, so a counter of the zero up crossings was added to the post processing algorithms to capture the actual number of waves encountered. In almost all cases the actual number exceeds 100 encounters and in most cases, is greater than 200.
- The WASIM program models 200 irregularly spaced frequency components with the starting phase initialized with a seeded random number generator. By changing the seed, a statistically identical but different time series of waves is developed. Experience has shown that different realizations can give substantially different results. Accordingly, critical runs were repeated a number of times with each phase seed reset referred to as an additional realization. In most cases the realization number is also the values used for the seed. I.e. realization 4 uses a seed of 4.0

3.2 Analysis Products Setup

These different analyses were setup to deliver specific results.

- The SMP and damping matrix results described in Appendix 5 were used to setup the other analyses and don't have independent deliverables accept as noted in the appendix

- The WASIM analysis produced a set of shear force and bending moments acting on the hull due to wave conditions
- Pressure panels were set up in the WASIM model at the locations where the vents leading into the second deck were located and where the vents leading down into the holds below the waterline are located
- A series of Matlab routines were developed to calculate the rigid body motions at key locations in the RORO cargo areas, in the container stacks on deck and in the Accommodations area. These routines are based on the equations for rigid body motion at a point provided in DOD-STD-1399-301A, Page 14, which have been arranged to handle the time series data and with the inclusion of sway terms missing in the original equations

3.3 Phase 1 WASIM Runs Matrix Development and Evolution

The earliest runs matrix in the WASIM code, focused on sea states 3 and 4 to provide a basis for evaluating that the model was providing plausible results with no obvious modeling artifacts. This quality control step proved useful as early runs produced an error that was traced back to the volume of some of the appendages. This was corrected in later runs. Next the runs matrix was expanded up through higher sea states.

The bulk of the higher sea state runs were focused on the critical conditions shown in Table 3-1:

1. Just Before Loss Of Power (JBLOP) at around 5:30 AM on the morning of 10/1.
2. Just After Loss Of Power (JALOP) when the ship was drifting downwind in close to beam seas.
3. In the estimated conditions as the ship was sinking. These conditions were provided by Dr. F. Fedele at Georgia Tech, based on hourly modeling of what he expected the Hurricane to produce for winds and waves.

Table 3-1: Critical Modeling Conditions, Phase 1

		H1/3 (m)	Tm (sec)
Just Before Lost of Power	JBLOP	7.45	11.168
Just after Loss of Power	JALOP	7.45	11.168
Sinking A	Sink_A	8.45	12.3
Sinking B	Sink_B	9.76	12.25

In the JALOP and sinking conditions, it is assumed that the ship would be blowing downwind in a near to beam sea condition. Most seakeeping software will give a greatly reduced pitch motion in long crested beam seas, which is partially realistic and partially a simulation artifact. To avoid this, and acknowledging that the center of wind drag is not located at the half length of the ship in this case, courses of 90 degrees and then +/- 15 degrees off 90 degrees (75 and 105 degrees) were modeled.

3.4 Phase 1 Motions Setup

The Phase 1 motions summary results are contained in Appendix 2, chapter 12

3.5 Phase 1 Accelerations Setup in the Container Stacks

The container bay load outs contained 397 containers with three additional containers loaded as permanent cargo under the house structure for ships stores. 71 containers representing all one, two or three tiers high at the outermost row of each bay on both port and starboard were selected for acceleration study. The majority of the containers were refrigerated. Only a partial listing of what they contained was made available, however the unique identifiers and the weight and size were listed on drawings like Figure 3-4 below. The RF means refrigerated, whereas HC means that they are 9.5 feet high, which most of the cargo containers were on this voyage.

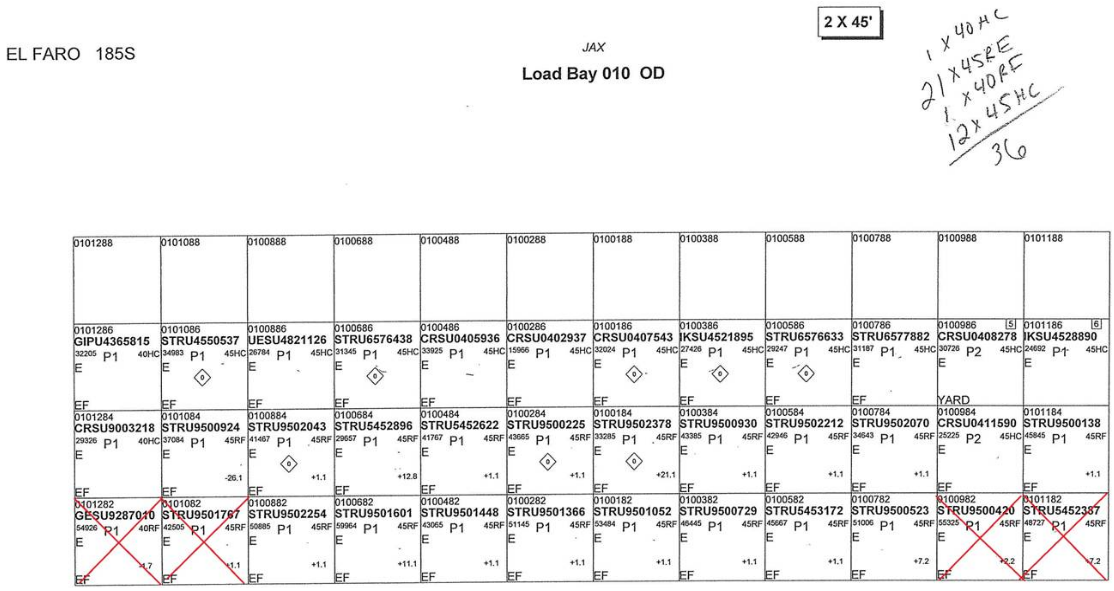

Figure 3-4: Typical Container Loading Plan

Figure 3-4 shows a typical loading plan received from Tote Marine. The handwritten notes were made by whomever was directing the loading. The red lines are the locations where Tote Personnel or their contractors applied lashing rods. Note that most of the container stacks were only held in place by the twist locks. While these sketches show 4 high, the highest loaded on this voyage was 3 high. Any block with no labels did not have a container loaded in them.

Table 3-2 shows the typical file setup. There are 71 locations, each with a column for X (longitudinal), Y (transverse) and Z(Vertical) axis accelerations. Three of the data fields are shown on the right-hand side of Table 3-2. The first half of the accelerations are on the port side of the ship whereas the second half are on the starboard side.

Table 3-2: Typical Accelerations Output

									1_deck_ Port			1_2nd tier_ Port			2_deck_ Port		
		Bretschneider							207.74	7.32	22.50	207.74	7.32	25.37	203.92	9.83	22.18
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**Heading**	**Draft AP**	**Draft FP**	**Duration**	**Parameter**	**Ax_1**	**Ay_1**	**Az_1**	**Ax_2**	**Ay_2**	**Az_2**	**Ax_3**	**Ay_3**	**Az_3**
18	**5**	4.00	9.7	deg	m		**sec**		**G's**	**G's**	**G's**	**G's**	**G's**	**G's**	**G's**	**G's**	**G's**
		we	POE	**180**	**9.933**	**8.166**	**2480**	Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.2592	0.64775106	1.04390963	6.018897708	**Head Seas**				Minimum	-0.08	-0.18	-0.22	-0.09	-0.18	-0.22	-0.08	-0.18	-0.21
	Wave Encounters		**412**	Realization	**R1**	**9.0495**		Maximum	0.10	0.17	0.19	0.10	0.17	0.19	0.10	0.17	0.19
	Long Crested			**TCG=-0.052m**				Standard Deviation	0.02	0.04	0.06	0.02	0.04	0.06	0.02	0.04	0.06
								RMS	0.02	0.04	0.06	0.02	0.04	0.06	0.02	0.04	0.06
								Range	0.18	0.35	0.41	0.19	0.35	0.41	0.18	0.34	0.40

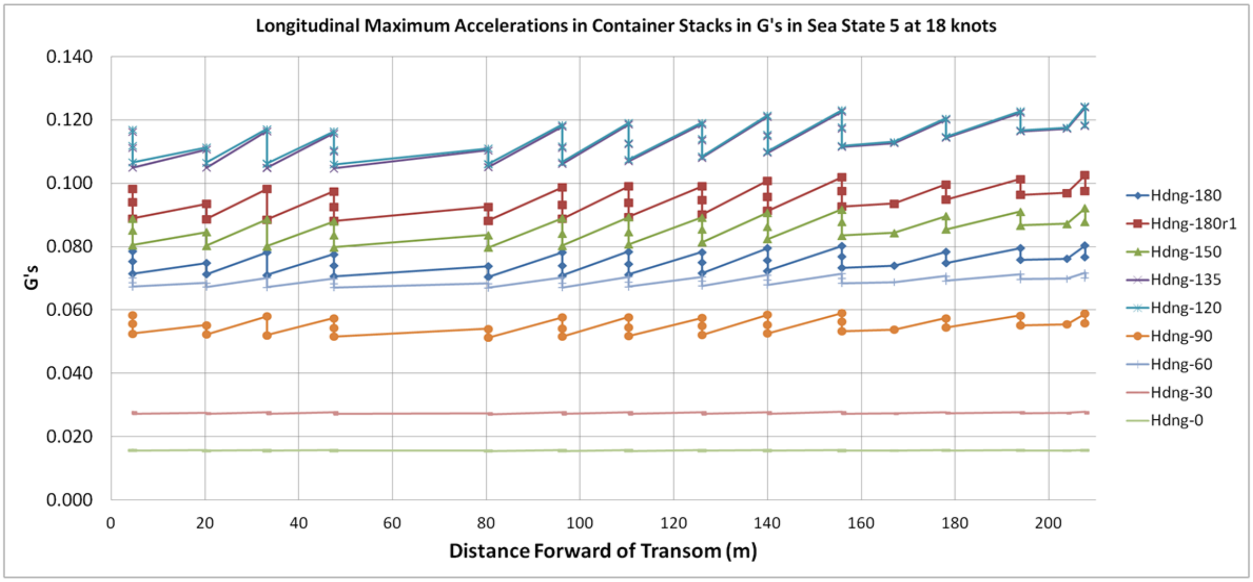

Figure 3-5: Typical Longitudinal Acceleration Maxima Plotted Versus Position on Ship (port side)

In Figure 3-5, the three data points stacked up at a single location represent the three containers stacked up at those locations. It's obvious in this view that higher containers experienced higher accelerations because they have a longer moment arm from the instantaneous center of motion. That center of motion for pitch, roll and yaw moves around as the ship moves in waves, especially very large waves.

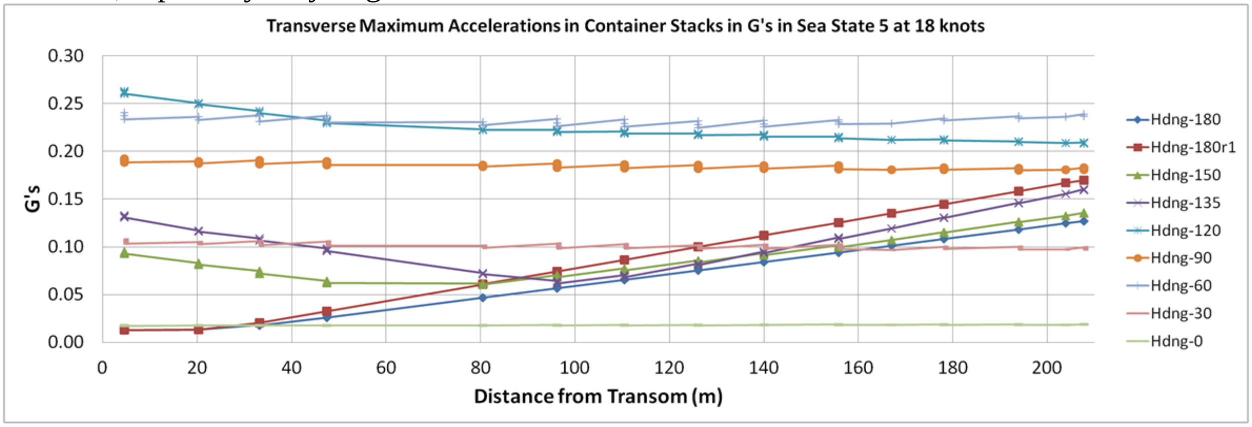

Figure 3-6: Typical Transverse Acceleration Maxima Plotted Versus Ship Position (port side)

There is similar data for the starboard side in the data files for each of the several hundred individual runs. Figure 3-6 is just an example of what the local maxima over the entire time series looks like. There was no attempt at correlating these in time but that is certainly possible from the raw data.

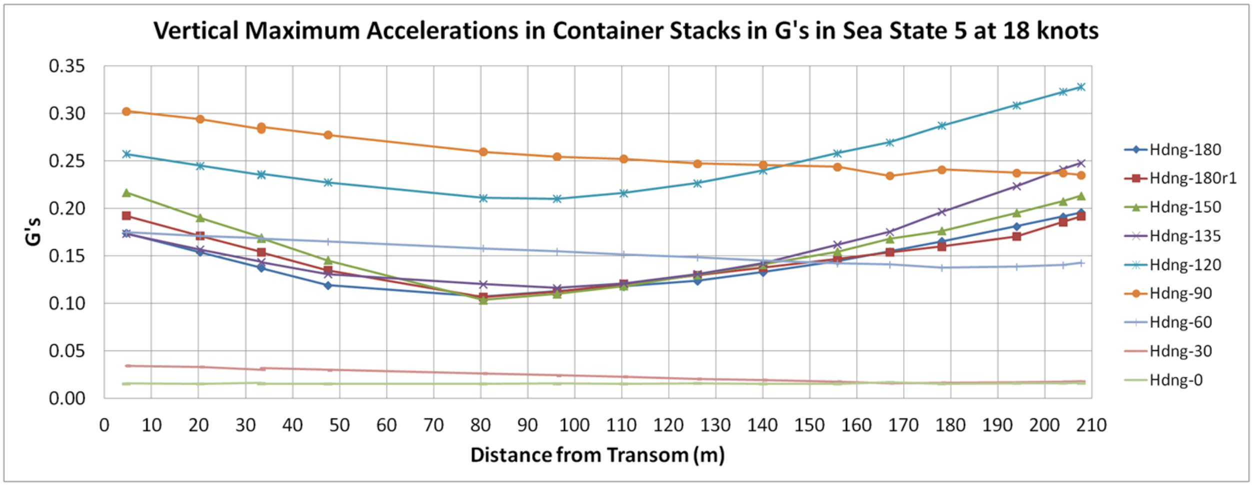

Figure 3-7: Typical Vertical Acceleration Maxima Plotted Versus Ship Position (port side)

These are for the top of sea state 5 with 4-meter waves which should be no challenge to the lashing or the twist lock connections. The accelerations later in the storm are much higher. While figures 3-5,6,7 demonstrate some of the data that is available from either the WASIM or the OrcaFlex models. Detailed study was beyond the scope of this analysis. Statistical summaries for each run are contained in the excel spreadsheets embedded later in this document. The later Orcaflex runs anchored the bottom containers with links emulating twist locks at each corner and several runs were made that show when these begin to fail and the containers begin to fall off.

3.5.1 Container Stack Data for Count, Locations and Properties

CSRA Dynamic-EL_Faro_Orcaflex_Container Setup_6-27-2017.xls

3.6 Accelerations in the RORO Cargo Spaces

The RORO spaces have a specific labeling convention as shown in Figure 3-9. Unfortunately, this does not match the descriptions used on the bridge audio, shown in Figure 3-8

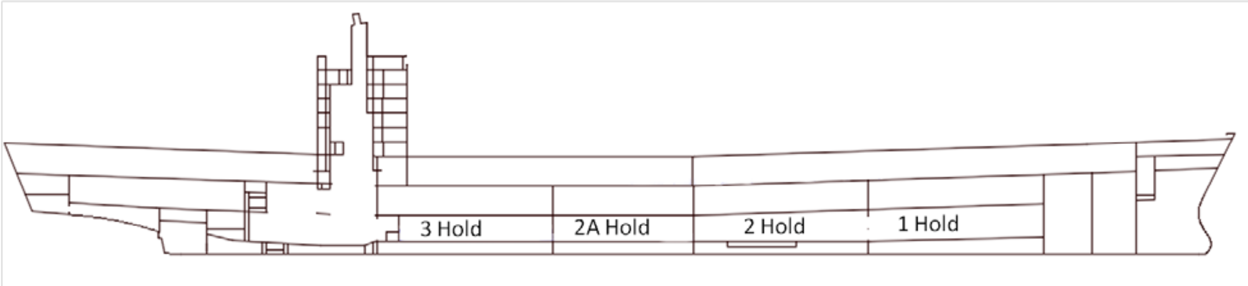

Figure 3-8: Hold Labels Used on Bridge Audio

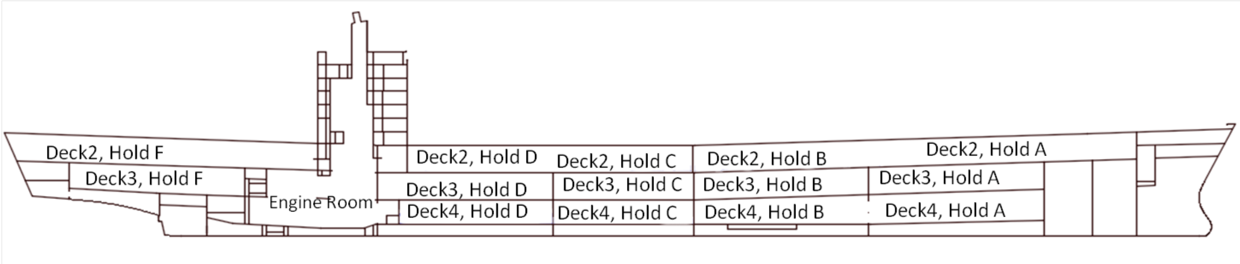

Figure 3-9: Hold Labels Used on Loading Diagrams

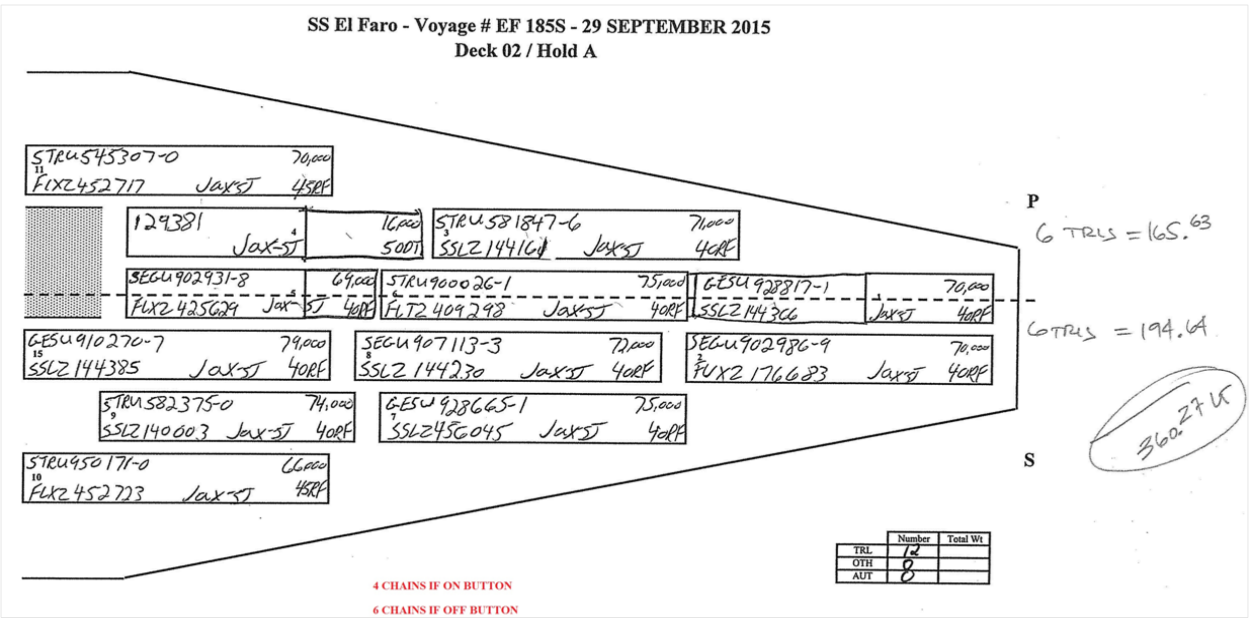

Figure 3-10: Typical El Faro Loading Diagram Deck 02, Hold A

Figure 3-10 shows a typical loading diagram used by whomever was the cargo master to load the El Faro. These are printed forms that are filled in by hand. The spacing is apparently based on the location of the tie downs and the pedestals that lock into and support the 18-wheeler hitches at the front of the containers. Longer or shorter trailers were sketched in by hand. Smaller vehicles such as cars are only shown as a string of digits in an approximate location. These were all scaled off these sketches as closely as possible and entered into the weights and centers accounting.

A total of 63 locations, as shown in Table 3-3, were selected in the various RORO spaces with the aim of modeling the 4 locations where the vehicles are farthest from the centers of roll and pitch. Experience on other ships suggests that the acceleration values are good for about 1 to 2 meters from any given location, so the exact locations are not very sensitive.

Table 3-3: RORO Spaces, Matrix Used to Calculate the Accelerations

								Vehicle BAY			
							total	Shipboard			
					Identifier	Length	Weight	CGx	CGy	CGz	
COUNT	Level	Hold No.			Number	Feet	m-tonnes	m	m	m	
1	02	A	PORT	FWD	GESU928817-1	40RF	31.75	191.440	1.524	17.470	02 A PORT FWD
2	02	A	PORT	AFT	STRU545307	45RF	31.75	165.729	7.620	16.656	02 A PORT AFT
3	02	B	PORT	AFT	STRU950038	45RF	34.02	142.302	10.668	15.938	02_B_PORT_AFT
4	02	B	PORT	FWD	R20372	AUTO	1.36	157.307	1.524	14.734	02 B PORT FWD
5	02	C	PORT	FWD	STRU950200	45RF	28.58	119.978	10.729	15.502	02 C PORT FWD
6	02	C	PORT	AFT	UPS-TRUK		4.43	107.901	7.681	14.258	02_C_PORT_AFT
7	03	D	PORT	AFT	GESU928914	40RF	32.21	86.773	10.729	15.529	02 D PORT AFT
8	03	D	PORT	FWD	SEGU9070688	40RF	25.86	97.186	10.729	15.476	02 D PORT FWD
9	03	E	PORT	AFT	Offc Trlr 35756		2.04	89.134	11.633	13.905	02_E_PORT_AFT
10	03	E	PORT	FWD	Offc Trlr 35757		2.04	69.658	11.633	14.256	02 E PORT FWD
11	03	F	PORT	AFT	UPS TRUCK		4.43	3.868	4.420	16.152	02 F PORT AFT
12	03	F	PORT	FWD	A56391	AUTO	1.36	33.172	9.144	15.130	02_F_PORT_FWD
13	03	F	PORT	FWD	SEGU902906	40RF	10.89	30.048	-4.115	16.402	02 F PORT FWD
14	03	A	PORT	AFT	UPS TRUCK	TRUCK	4.45	173.322	7.468	9.753	03 A PORT AFT
15	03	A	PORT	FWD	TSFZ567783	53CHS	13.61	191.060	2.743	11.569	03_A_PORT_FWD
16	03	B	PORT	AFT	732893	AUTO	1.36	127.787	11.064	8.013	03_B_PORT_AFT
17	03	B	PORT	FWD	734270	AUTO	1.36	161.767	9.257	9.139	03 B PORT FWD
18	03	C	PORT	AFT	FCIU808574	40HC	20.41	104.584	6.033	9.527	03_C_PORT_AFT
19	03	C	PORT	FWD	CAXU996537	40HC	32.66	123.912	10.516	9.863	03_C_PORT_FWD
20	03	D	PORT	AFT	GESU662259	40HC	23.13	78.685	9.480	9.559	03 D PORT AFT
21	03	D	PORT	FWD	BHCU4964210	40HC	24.04	95.080	10.516	9.574	03_D_PORT_FWD
22	03	E			CATB00638		23.22	59.588	7.468	13.722	03_E__
23	03	E			CATB00640		23.22	47.295	7.468	12.278	03 E
24	03	F	PORT	FWD	CATB00639		23.22	30.018	7.468	9.601	03 F PORT FWD
25	03	F	PORT	AFT	732236	AUTO	1.52	9.944	4.420	10.380	03_F_PORT_AFT
26	04	A	PORT	FWD	CCLZ1470	20TK	13.78	186.819	2.134	4.793	04 A PORT FWD
27	04	A	PORT	AFT	CCLZ1325	20TK	13.78	166.728	6.706	4.328	04 A PORT AFT
28	04	B	PORT	FWD	EMOU459293	40HC	26.76	153.689	4.296	4.815	04_B_PORT_FWD
29	04	B	PORT	AFT	732781	AUTO	1.52	132.568	4.420	3.048	04 B PORT AFT
30	04	C	PORT	AFT	736458	AUTO	1.52	104.270	11.430	3.048	04 C PORT AFT
31	04	C	PORT	FWD	406390	AUTO	1.52	127.279	11.430	3.048	04_C_PORT_FWD
32	04	D	PORT	AFT	A49032	AUTO	1.52	73.745	9.144	3.048	04 D PORT AFT
33	04	D	PORT	FWD	A99882	AUTO	1.52	99.077	11.430	3.048	04 D PORT FWD
34	02	A	STBD	FWD	SEGU902986	40RF	31.75	191.440	-1.524	17.470	02_A_STBD_FWD
35	02	A	STBD	AFT	STRU950171	45RF	29.94	165.729	-7.620	16.644	02 A STBD AFT
36	02	B	STBD	FWD	SEGU921711	40RF	35.38	160.696	-1.829	16.530	02 B STBD FWD
37	02	B	STBD	AFT	STRU950422	45RF	32.21	142.303	-10.668	15.924	02_B_STBD_AFT
38	02	C	STBD	FWD	STRU582265	40RF	31.75	124.264	-7.681	15.526	02 C STBD FWD
39	02	C	STBD	AFT	STRU9500035	40RF	31.75	115.693	-10.729	15.526	02 C STBD AFT
40	03	D	STBD	AFT	GESU910338	40RF	27.22	81.461	-7.681	15.490	02_D_STBD_AFT
41	03	D	STBD	FWD	STRU657196	45RF	22.00	95.486	-7.681	15.422	02 D STBD FWD
42	03	D	STBD	FWD	44538471	53TR	25.86	88.473	-10.729	15.476	02 D STBD FWD
43	03	E	STBD	AFT	Intership10127		4.45	72.946	-11.278	14.626	02_E_STBD_AFT
44	03	E	STBD	FWD	TRJ1660	TRUCK	4.45	83.569	-11.278	14.434	02 E STBD FWD
45	03	F	STBD	AFT	538579	53TR	25.86	3.868	-4.420	17.530	02 F STBD AFT
46	03	A	STBD	AFT	UPS TRUCK	TRUCK	4.45	173.322	-7.468	9.753	03_A_STBD_AFT
47	03	A	STBD	FWD	TSFZ567794	53CHS	13.61	191.060	-2.743	11.569	03_A_STBD_FWD
48	03	B	STBD	AFT	IKSU433300	40HC	22.23	138.599	-11.552	10.065	03 B STBD AFT
49	03	B	STBD	FWD	TCNU804750	40HC	29.03	157.134	-9.257	10.780	03_B_STBD_FWD
50	03	C	STBD	FWD	STRU409459	40HC	31.75	123.912	-4.420	9.853	03_C_STBD_FWD
51	03	C	STBD	AFT	TSFZ567762	53CHS	13.61	112.985	-10.516	9.392	03 C STBD AFT
52	03	D	STBD	AFT	CASU9319757	40HC	23.59	78.615	-8.188	9.567	03_D_STBD_AFT
53	03	D	STBD	FWD	IKSU452926	45HC	23.13	91.941	-10.516	9.559	03_D_STBD_FWD
54	03	F	STBD	FWD	BACKHOBB0027		7.26	31.086	-7.468	9.548	03 F STBD FWD
55	03	F	STBD	AFT	732573	AUTO	1.52	9.944	-7.468	10.380	03 F STBD AFT
56	04	A	STBD	FWD	SHPZ203343	Rail Car	189.83	186.819	-2.134	4.793	04_A_STBD_FWD
57	04	A	STBD	AFT	UTLZ600515	Rail Car	169.41	166.728	-6.706	4.328	04 A STBD AFT
58	04	B	STBD	FWD	IKSU433827	40HC	27.22	141.173	-1.562	4.821	04 B STBD FWD
59	04	B	STBD	AFT	731101	AUTO	1.52	132.568	-4.420	3.048	04_B_STBD_AFT
60	04	C	STBD	AFT	736038	AUTO	1.52	105.745	-11.887	3.048	04 C STBD AFT
61	04	C	STBD	FWD	732471	AUTO	1.52	126.767	-11.887	3.048	04 C STBD FWD
62	04	D	STBD	FWD	529267	AUTO	1.52	99.077	-11.887	3.048	04_D_STBD_FWD
63	04	D	STBD	AFT	C85870	AUTO	1.52	74.862	-10.058	3.048	04 D STBD AFT

3.7 Accelerations Setup in the Manned Spaces

These were setup in each of the rooms in the deck house structure. Initially this was to see how much motion the crew had to deal with and the data is capable of supporting motion sickness index and motion induced interruption index as well. Later when the possibility of the lube oil tank causing the loss of power became an issue, two locations for the lube oil were added to this post processing algorithm.

3.8 Sensitivity Study of Green Water Reaching the Vent Openings

The work described in this section was conducted early in the project before much was known about the wave climatology and how the timeline unfolded. The object of this study was to see if there was a threshold wave height below which water did not reach the second deck openings or the vents into the lower RORO holds. The study was successful in developing the pattern it set out to find. At the time this was done, there was no way to tie these observations into the storm wave data in 15-minute intervals because that data was not received until months later.

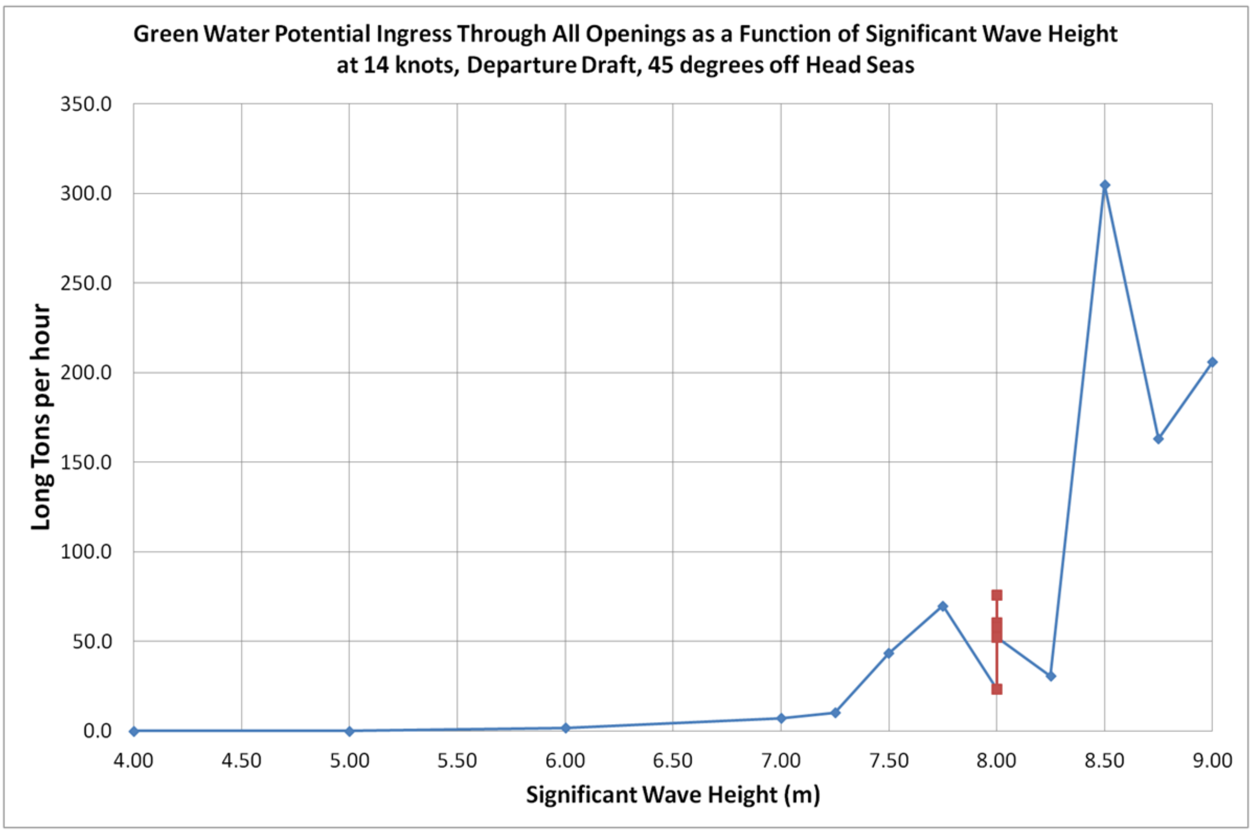

Figure 3-11: Green Water Potential from a Sensitivity Study / Systematic Series

Figure 3-11 shows an overall pattern noticed in the data, which is that below a threshold wave height there is not much green water entering the second deck or the vent's leading to the lower decks. The blue line and dots represent a series of WASIM runs at 0 heel angle, 14 knots and 45 degrees off head seas at the departure draft, where the significant wave height was increased in increments of 1.0 meter and then 0.25 meter between 7 and 9 meters. The red squares represent 5 different realization runs at the 8m wave height where the random number generator for the wave component phases was reset to a different value each time. This 8m transect of the data space demonstrates that this non linear time series data can vary across a range of values, even when several hundred waves were modeled for each run. The much higher value at 8.5 meters may be an extreme outlier or there may be something else going on that makes the 8.75 and 9m values lower. The take away point is that below a certain wave height of approximately 7m there probably was not much water coming aboard via the vents, in the intact condition with zero heel

3.9 Summary of Shear and Bending Results

The shear and bending cut planes illustrated in Figure 3-12 and listed in Table 3-4 were selected to coincide with structural bulkheads or strength discontinuities or places such as on the deck house where separation was known to have occurred. These produced Force and Moment (F&M) time series as shown in Figure 3-13.

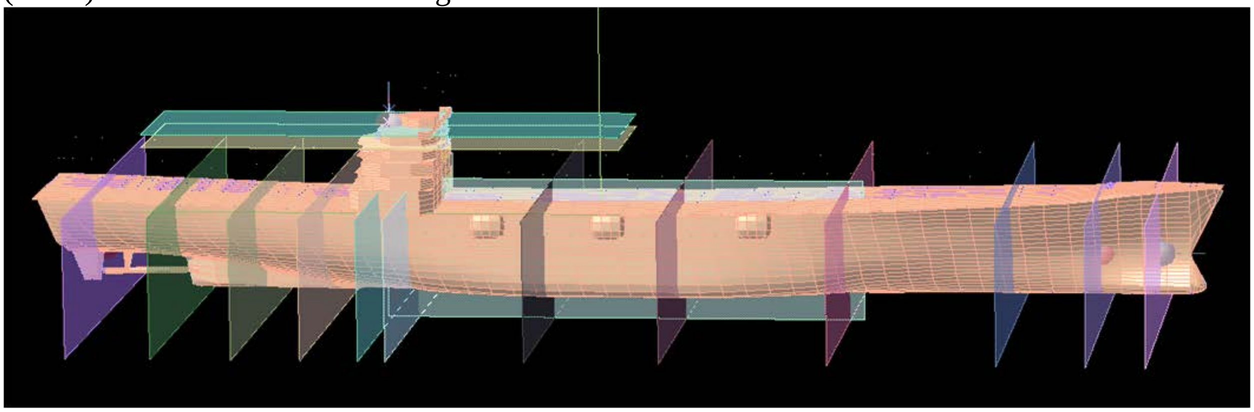

Figure 3-12: Location of Cut Planes on the EL Faro Model

Table 3-4: Cut Plane Locations Setup on Phase 1 El Faro WASIM Runs

Cut locations that coincide with internal bulkheads or external breaks				
	X	Y	Z	Description
	m	m	m	
Cut_plane_YZ_1	7.315	0.000	8.760	End of Skeg / Stern Tube
Cut_plane_YZ_2	24.943	0.000	8.760	
Cut_plane_YZ_3	41.707	0.000	8.760	Aft Engine Room Bulkhead
Cut_plane_YZ_4	55.956	0.000	8.760	fwd bulkhead of engine room
Cut_plane_YZ_5	67.920	0.000	8.760	Aft Blkhd Hold D
Cut_plane_YZ_6	73.558	0.000	8.760	Fwd end of house
Cut_plane_YZ_7	102.057	0.000	8.760	Bulkhead between holds C-D
Cut_plane_YZ_8	129.718	0.000	8.760	Bulkhead between holds B-C
Cut_plane_YZ_9	164.084	0.000	8.760	Bulkhead between holds A-B
Cut_plane_YZ_10	198.476	0.000	8.760	Blkhd between hold A & aft deep tank
Cut_plane_YZ_11	216.637	0.000	8.760	Blkhd between aft 2 deep tanks
Cut_plane_YZ_12	228.829	0.000	8.760	Blkhd aft end of fwd deep tank
Cut_plane_XY_1	67.920	0.000	18.898	House Connection to main deck
Cut_plane_XY_2	67.920	0.000	32.766	Lower Nav Bridge Deck
Cut_plane_XY_3	67.920	0.000	35.509	Nav Bridge Deck
Cut_plane_XZ_1	116.967	0.000	8.760	Longitudinal Centerline

Note that cut planes 1 through 12 are in a transverse / vertical plane, while planes XY_1 through XY_3 are horizontal at the locations the house is known to have broken. The final plane is in the longitudinal / vertical plane. Also note that the row highlighted in yellow is at the aft engine room bulkhead where the hull is cracked almost in half on the bottom. Based on the impact damages around the hull, it is almost certain that this crack happened on bottom impact.

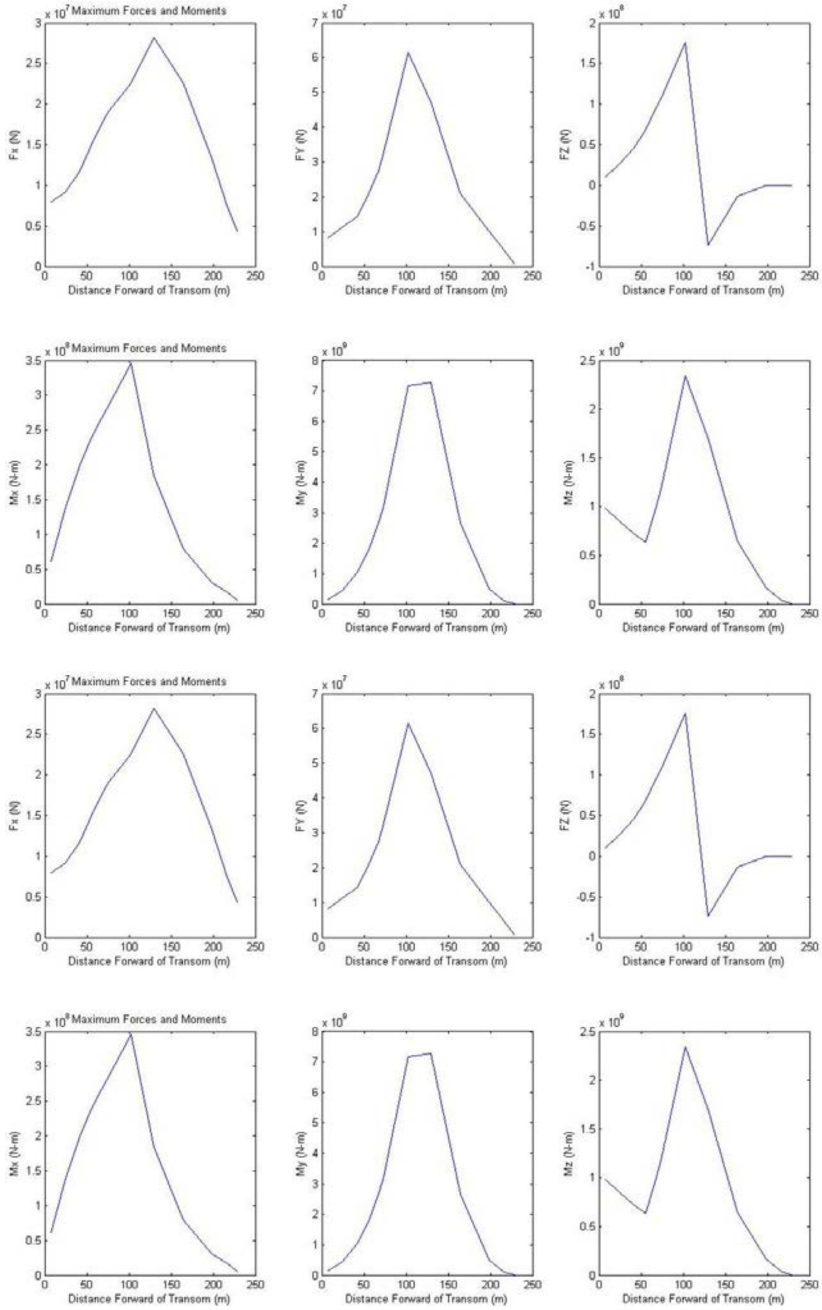

Figure 3-13: Typical F&M Output Maxima Plotted for All 6 Degrees of Freedom

Figure 3-13 is a typical set of minima and maxima output plots for all 6 degrees of freedom from the WASIM or WADAM shear force and bending moment cut plane data.

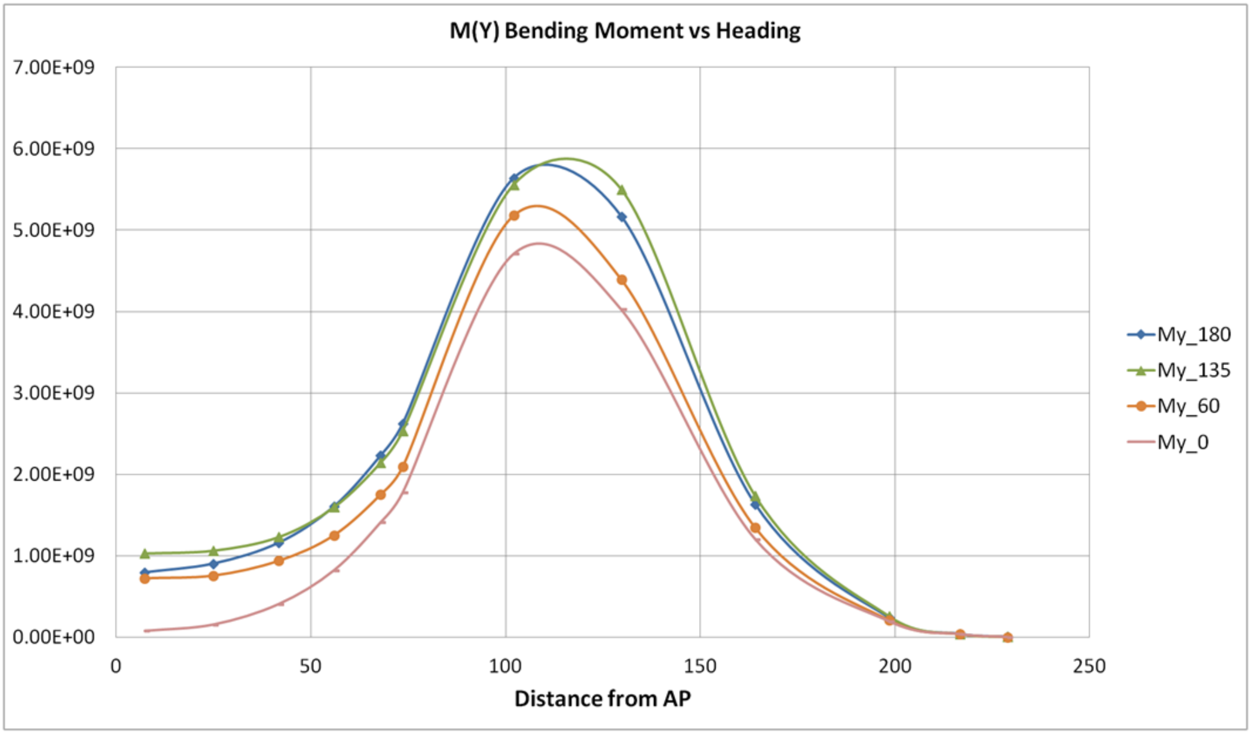

Figure 3-14: Plot of the Wave Induced Bending Stress Versus Length Position (meters) and Heading for One Sea State and Speed Condition.

Figure 3-14 is an example of what some of this data looks like versus length along the hull for a range of ship headings relative to waves.

Once the hull damage videos and the VDR voice recording were studied in Phase 2, all further work in creating and post processing F&M data was suspended, as it appears unlikely that this played a part in the casualty.

The crack in the sideshell and continuing across the main deck that was noted on the bottom is at the aft bulkhead of the engine room. The communications between the bridge and the engine room up until a few minutes before the VDR stopped recording would certainly have mentioned a crack allowing water to flood the engine room.

4 Phase 2, Detailed Technical Approach and Data

Phase 2 began with NTSB requesting a pause while the third voyage went out to recover the VDR. Once the data was received, it took some time to evaluate all the new information and evidence.

4.1 VDR Latitude and Longitude

The VDR numerical data was received at CSRA in the fall of 2016 consisted of a CSV file containing the following information in approximately 1 second intervals.

- Date
- Time, (hours, minutes, seconds) three column format
- Latitude (decimal format to 7 decimal places) (7cm resolution)
- Longitude (decimal format to 7 decimal places) (7cm resolution)
- Number of satellites in view and several similar quantities that were not useful to the investigation.
- Antenna Altitude (meters) (1cm resolution)
- Speed over the ground
- Heading
- Course over the ground
- Wind Speed
- Wind Azimuth (all the same value due to failed sensor)

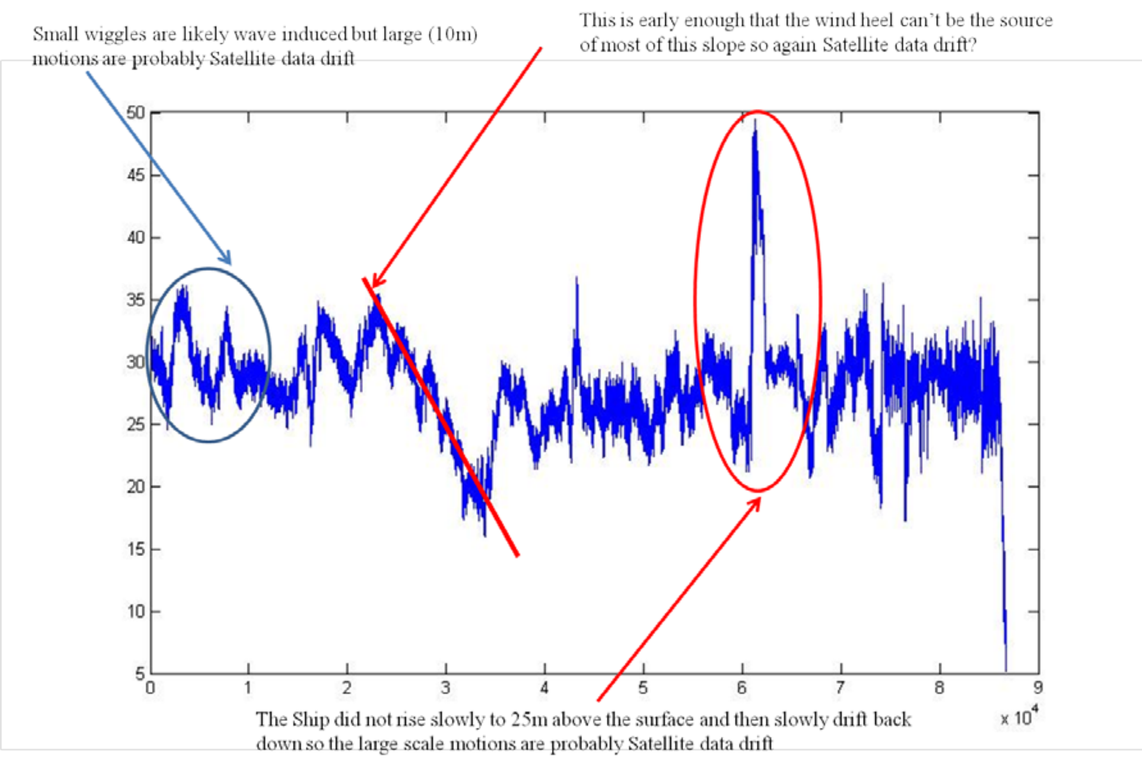

Figure 4-1: Raw Antenna Height (m) vs Time

The antenna height data plotted in Figure 4-1, shows a lot of large scale drift that cannot be attributed to anything the ship was doing, for instance the 25-meter spike would require the ship to be flying for this to be real.

4.2 WAV_III Data Set

On November 23, 2016, a data set was received from Dr. Arun Chawla from NOAA in Silver Spring, MD. This consisted of 96 data files at locations corresponding to the El Faro's positions from the VDR with a wave spectrum in 15-minute intervals and a report on his modeling of Hurricane Joaquin. (Chawla, 2016)

Figure 4-2 shows an excellent correlation at certain times and locations for this model.

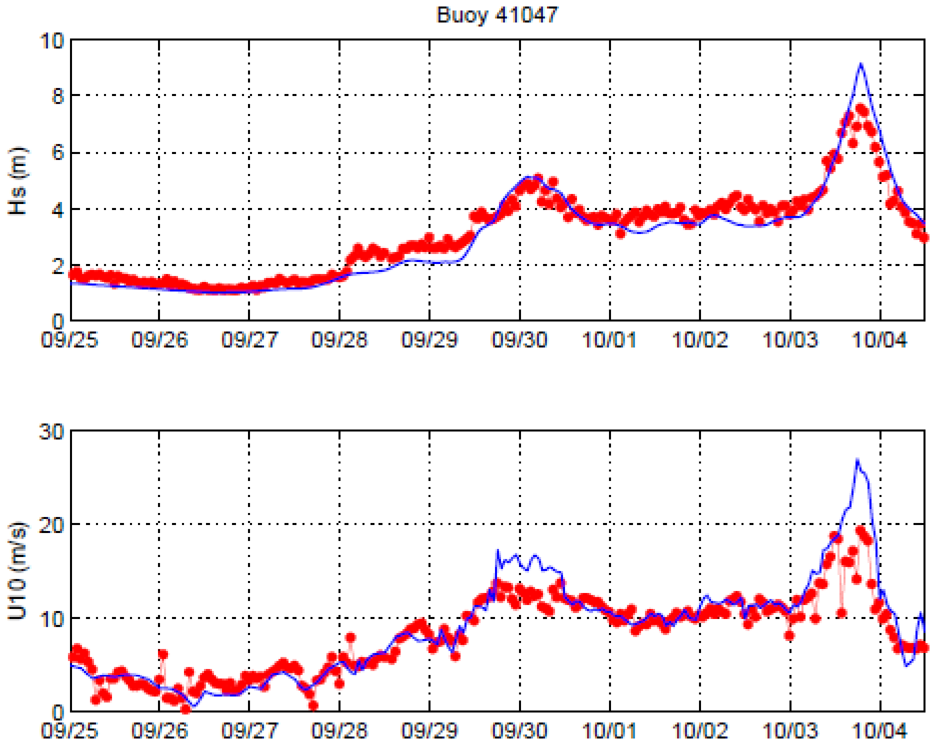

Figure 4-2: Figure 6, Page 9 showing good correlation between model and buoy data

The red is the buoy data and the blue the model data, times are UTC (Zulu). For the model grid point that sits on top of the buoy, the results are excellent.

Figures 4-3 and 4-4 illustrate a problem with using this data at face value for the sinking of the El Faro. The model progresses by dead reckoning and then updates with satellite data every 6 hours as it did at 12:00 Zulu. Note that Figure 4-3 and the next five others not shown, place the El Faro within the eye of the storm, whereas Figure 4-4 shows it within the eye wall in the northwest quadrant of the storm after the satellite update. There is an enormous difference in the wind force between the eye wall and the eye of the storm. This is discussed further in figures 4-11 through 4-16.

There is a tradition that the worst place in a hurricane is in the northwest quadrant, but that actually depends on the direction that the storm is traveling in because in reality the worst quadrant is where the storm winds and the forward speed of the storm add together. In the case shown in figures 4-3 and 4-4 the storm was headed roughly South, but in the next few hours would steer back to the Northeast and head out into the Atlantic.   At the time of the El Faro sinking the slow speed of the storm movement had a negligible effect on the wind field.

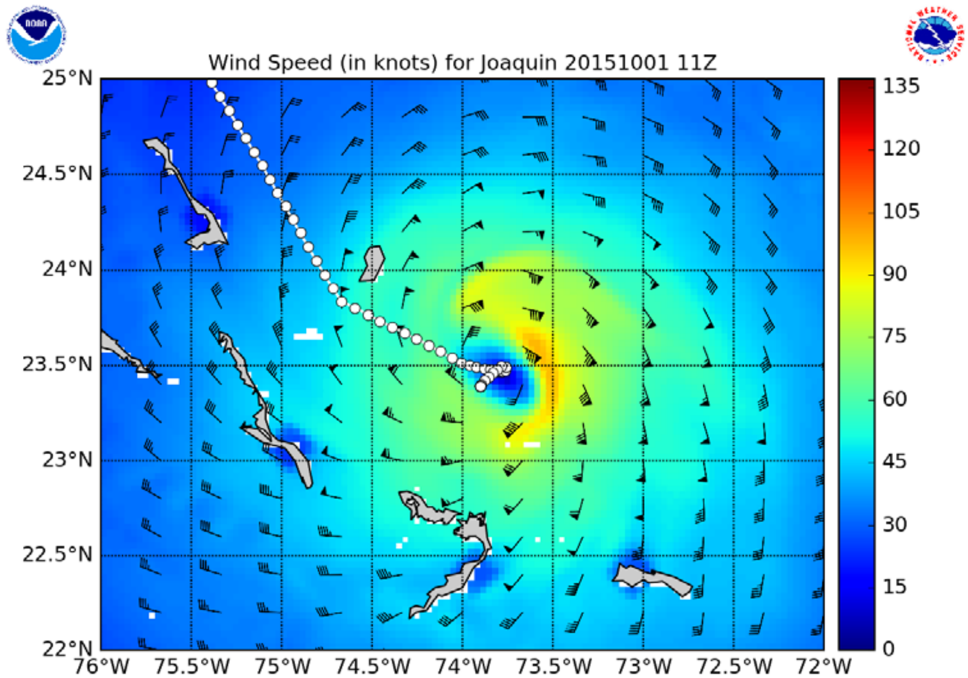

Figure 4-3: Wind Speed Data from WAV_III model at 11:00 Zulu

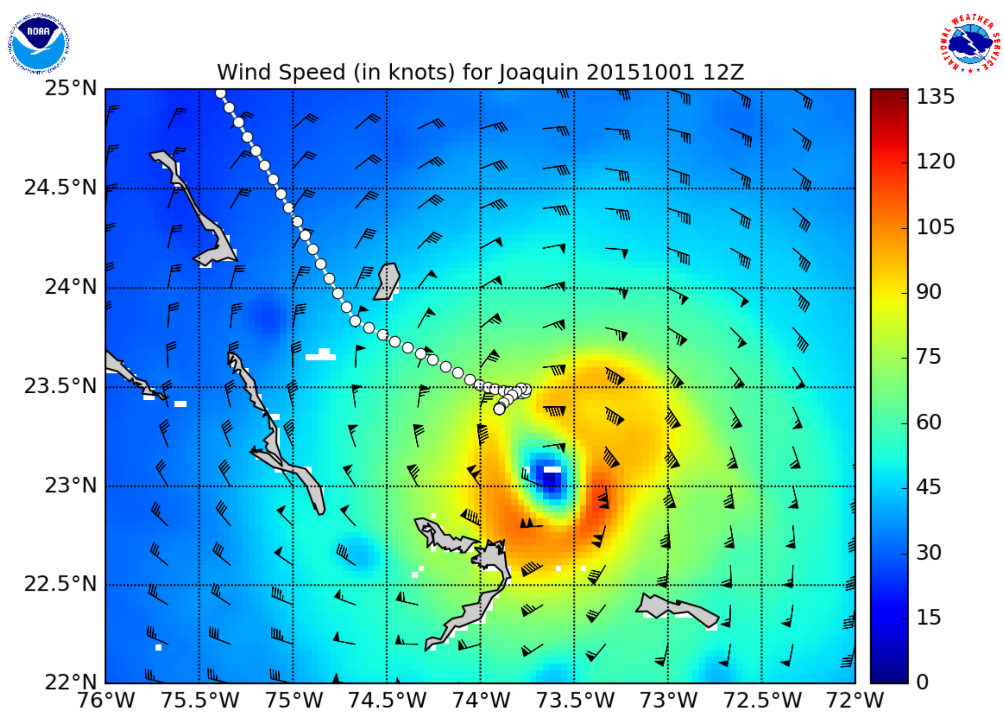

Figure 4-4: Wind Speed Data from WAV_III Model at 12:00 Zulu

The dots in Figures 4-3 and 4-4 are the EL Faro position in 15-minute intervals. Note the jump from in the eye to out in the eye wall when the satellite updated the model.

4.3 VDR Wind vs WAV_III Wind

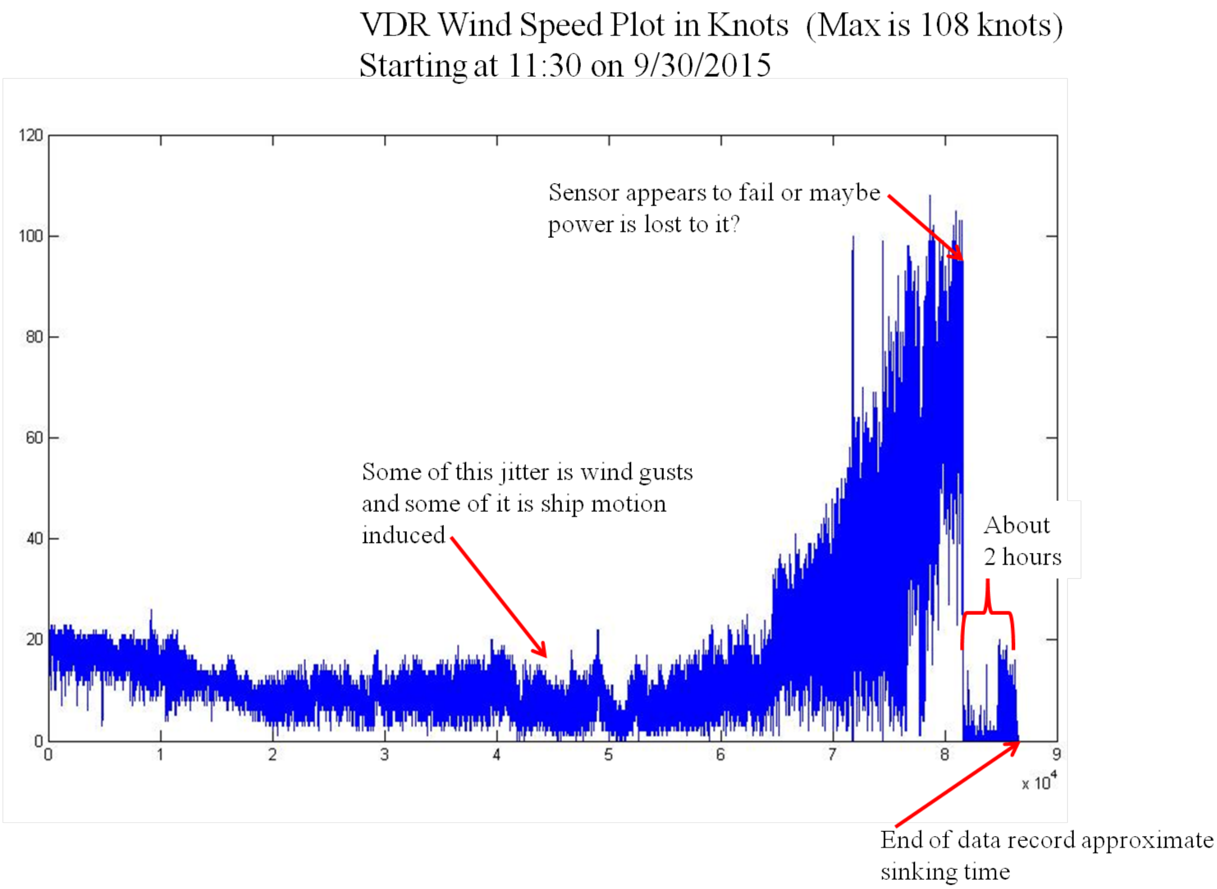

Figure 4-5: Plot of the Wind Speed Data captured on the VDR Recording

Figure 4-5 shows a plot of the VDR recording of the wind sensor data with a 1 second data rate. The width of the fuzz band gives an idea of the gusts but also includes some ship motions. The last two hours of data indicates that the sensor failed or was blown off the ship. Either way we have no data for that time period. The VDR unit continued to record but a quick look at the data over that interval shows mostly zeros with an occasional spike, which is consistent with a failed or missing sensor.

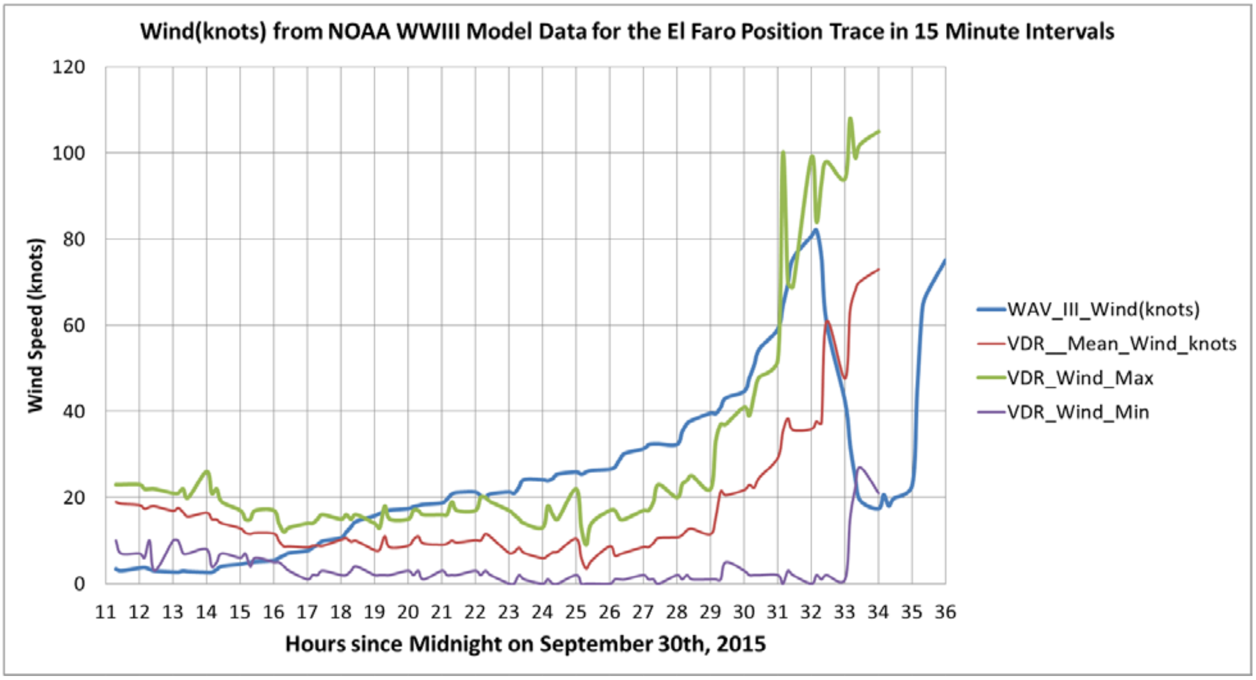

Figure 4-6: VDR Wind Trace Superimposed on the WAV_III Wind Trace

Figure 4-6 shows that the WAV_III wind trace (blue line) shows the ship in the eye of the storm consistent with Figure 4-3 but this does not agree with the maximum wind speed trace recorded on the ship shown in green. This implies that the other wind directions, wave heights, periods and directions predicted for the El Faro over that time window identified as hour 32 through hour 36 in Figure 4-6 are also incorrect.

4.3.1 Attempts at Correcting the Wind / Wave Data

Each of the 96 data files supplied by NOAA is for a specific location where the VDR says the ship was at that time. Each file contains a data set for every 15 minutes from 11:30 AM UTC on the morning of September 30th, through several hours after the El Faro sank at about 11:35 UTS (7:35 local time) on October 1st, 2015. Searching through this data set for a location that remained outside the eye was the next step.

Table 4-1: Output of Spectrum Search

	'trkpnt_75	'trkpnt_76	'trkpnt_77	'trkpnt_78	'trkpnt_79	'trkpnt_80	'trkpnt_81	'trkpnt_82	'trkpnt_83	'trkpnt_84	'trkpnt_85
Date	20151001	20151001	20151001	20151001	20151001	20151001	20151001	20151001	20151001	20151001	20151001
time	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000	100000
lat	23.77	23.73	23.70	23.67	23.64	23.61	23.57	23.54	23.52	23.50	23.49
long	-74.52	-74.46	-74.39	-74.32	-74.25	-74.18	-74.12	-74.06	-74.01	-73.96	-73.92
Depth(m)	2396.70	2529.30	1873.70	3741.70	4607.10	4810.60	4822.40	4786.20	4754.60	4731.20	4731
wind (m/s)	25.88	27.60	29.58	31.73	33.81	37.43	39.86	39.54	37.65	35.09	31.63
Wind(knots)	50.31	53.65	57.50	61.68	65.73	72.76	77.49	76.87	73.19	68.22	61.49
Wind Azimuth	357.30	353.80	350.60	348.30	346.10	343.00	341.20	341.00	341.60	342.50	343.5
Vector Azm	221.50	217.87	213.39	208.83	204.62	199.73	194.33	188.73	184.82	181.70	179.33
H1/3(m)	5.42	5.96	6.53	6.83	7.03	7.17	7.48	7.41	7.10	6.67	6.11
H1/3(feet)	17.77	19.54	21.42	22.40	23.06	23.53	24.53	24.32	23.30	21.87	20.06
Tm(seconds)	10.50	10.72	10.66	10.78	10.87	10.91	10.79	10.78	10.72	10.62	10.50

Table 4-1 shows the results at 10:00 AM Zulu of a search through all of the data files later than 10 AM. The wind speed at trkpnt81 shows the highest wind speed.

Figure 4-7 shows that the maximum wind speed from track point 81 at about 78 knots is still quite a bit lower than the 108-knot peak recorded by the VDR. The search covered all of the parameters covered by the data set and Figure 4-8 provides the significant wave height traces.

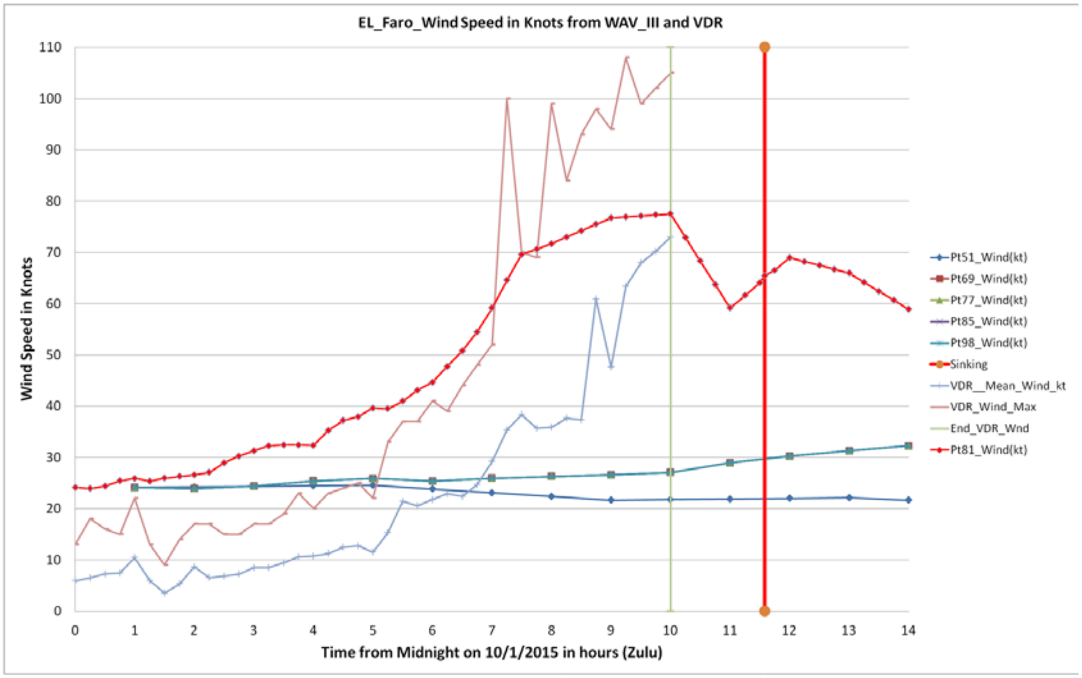

Figure 4-7: Wind Speed Search Results

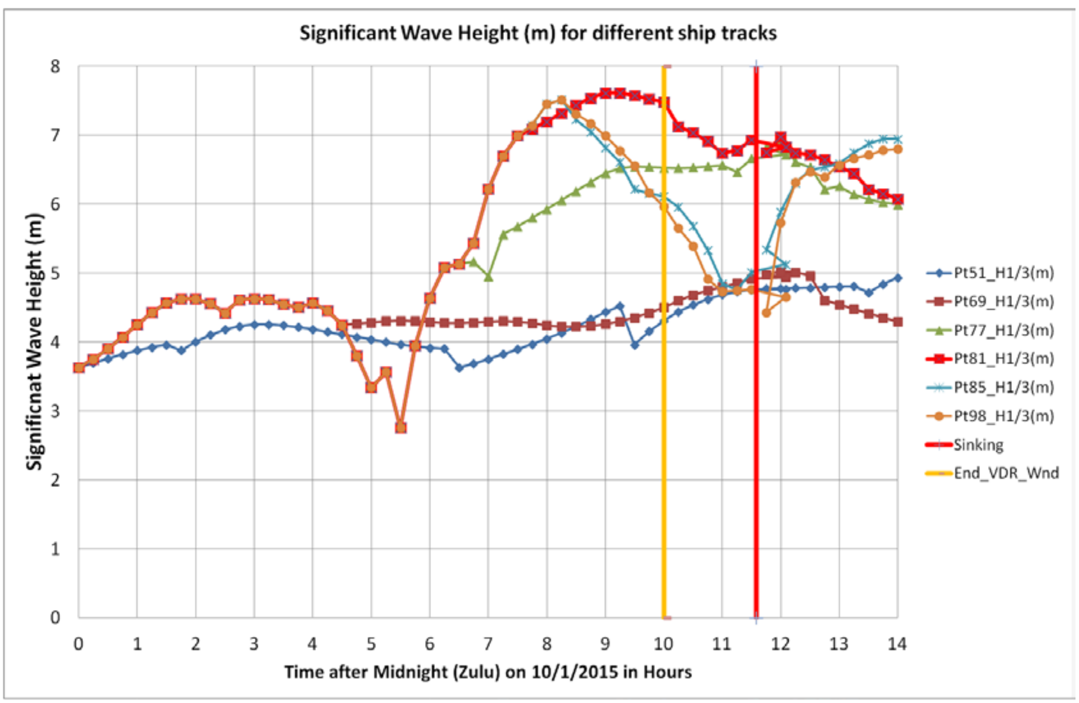

Figure 4-8: Wave Height Search Results

The P77, P81, P98 and others are traces of other locations near the storm as the wind and wave parameters progressed through the hours after midnight UTS. Many locations did not see any storm conditions over the duration of this model which is consistent with the size of the overall grid and the compact size of this storm.

4.4 Correlation with Wind / Wave Fields from Other Hurricanes

On April 7th, 2017, we received a page of a news article By Dr. S. A. HSU of Louisiana State University that uses the mathematically standard, (Y=mX + B) format for the equation of a straight line to relate wind speed and wave height in hurricanes. For Hurricane Wilma, the equation H=0.42W -2 was fitted to a set of buoy data. When contacted he also provided a similar fit to data from Hurricane Katrina.

The wind speed from the RM Young wind sensor on the El Faro was processed with this Wilma derived equation. The VDR wind data is one second recording rate data that contains a lot of gusts, so the data was sorted into the same 15-minute bins as done for the WAV_III data and the mean for each 15-minute chunk was taken.

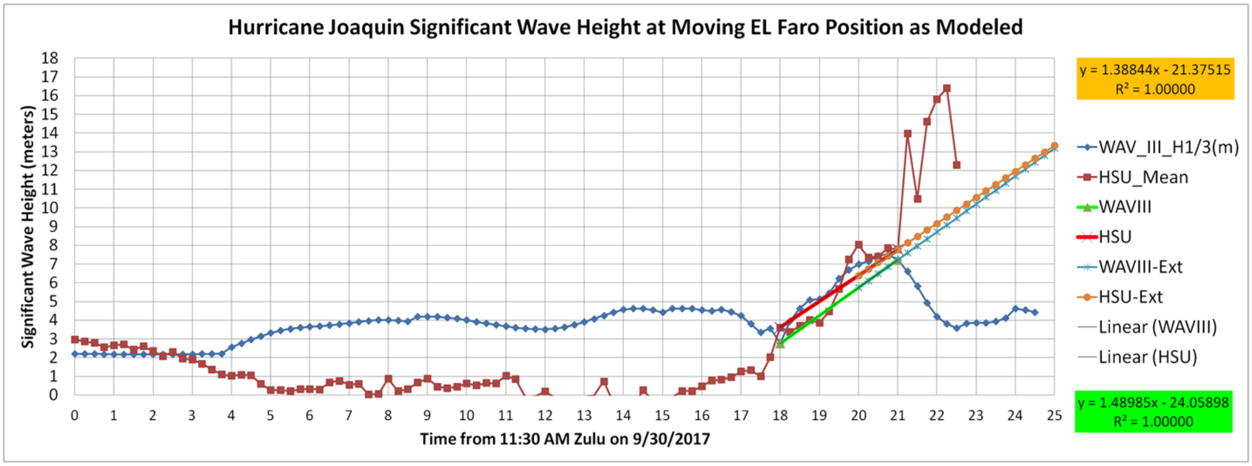

Figure 4-9: Plot of WAV_III Wave Data Against HSU Wave Data Based on VDR Winds

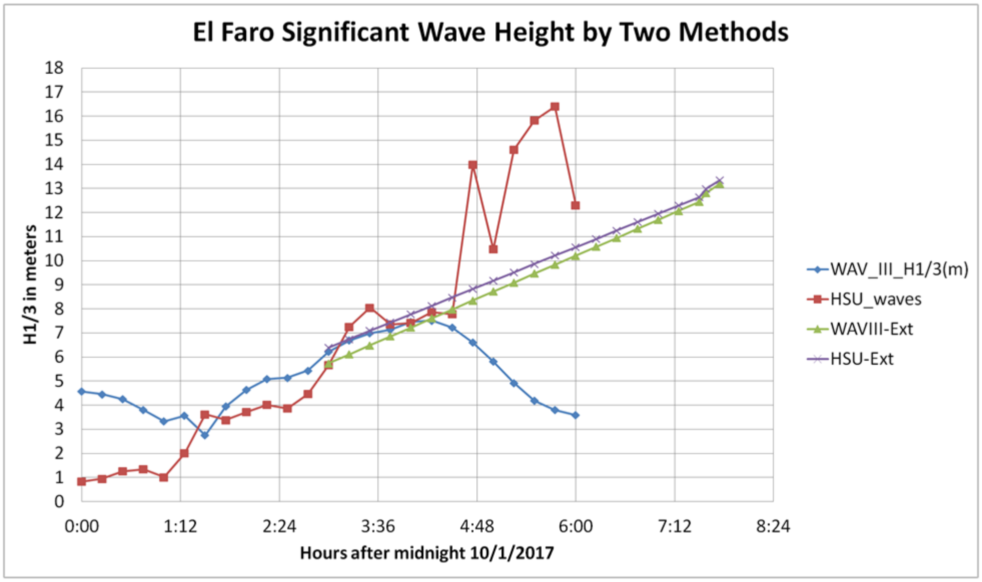

Figure 4-10: Close Up of Hurricane Time Frame

The HSU data from hour 3 to hour 18 in figure 4-9 was not as expected, but can be explained by the fact that the ship was traveling at approximately 20 knots with a following wind so the relative wind at the sensor was quite low. The period of interest begins at hour 18 in figure 4-9 which is 1:30 in the morning 10/1/2015, where the ship begins to feel the storm in earnest

Figure 4-10 shows that from about 1AM until about 4 AM local time, the WAV_III and HSU models are in pretty good agreement. A straight-line fit curve fit was made to that interval for both curves and then the linear fits were extrapolated out to the end of the VDR time series. These show pretty good agreement as well. If they were correct, then the significant wave height may have been as high as 12 or 13 meters with occasional waves as high as 16 or 17meters. Unfortunately, this is all high precision educated guesswork, and in fact we don't know what the waves were actually doing at the time.

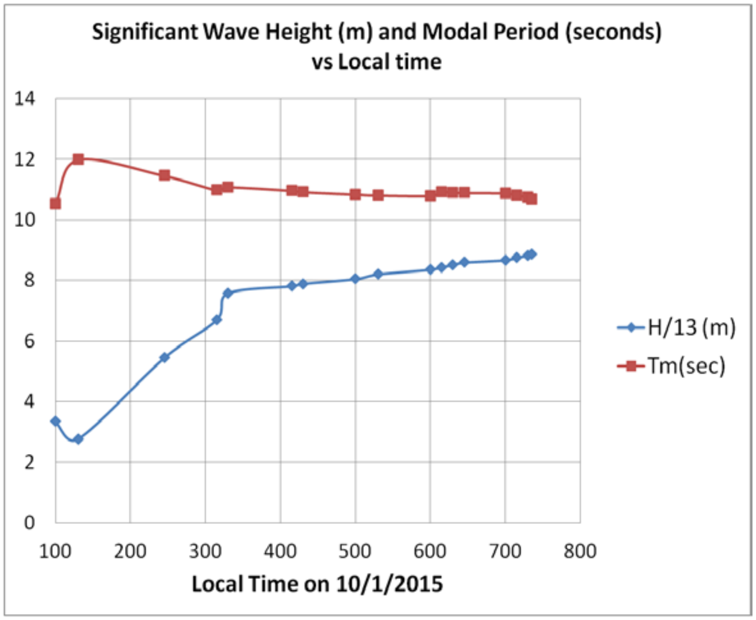

Figure 4-11: Phase 3 Best Compromise Wave Data

Figure 4-11 represents the best compromise wave data developed for the Phase 3 modeling based on all of the available inputs.

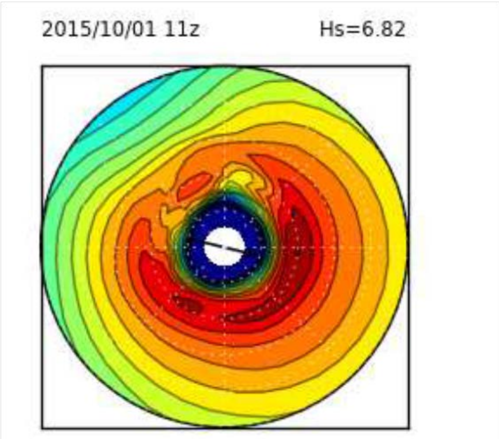

Figure 4-12: Example Plot of WAV_II Spectrum

Each WAV_III spectral file data chunk contains 36 directions times' 40 spectral components. The plot shown in Figure 4-12 has zero second period at the center and 35 second period at the outer rim. The colors show the spectral intensity although no scale was provided in the report; this was probably due to the obscure units.

Table 4-2: Wave Spectral Family Reduced from NOAA WAV_III data

Date	time	Lat	Long	207.0177038	wave heading	
20151001	6:30	23.7	-74.39	depth (m)	wind	azimuth
'trkpnt_77	peak_bracket			1873.7	26.13	337.8
Period	- 20 degrees	- 10 degrees	Center	+ 10 degrees	+ 20 degrees	
35.09	0.00000	0.00000	0.00000	0.00000	0.00000	
31.85	0.00000	0.00000	0.00000	0.00000	0.00000	
28.99	0.00000	0.00000	0.00000	0.00000	0.00000	
26.39	0.00000	0.00000	0.00000	0.00000	0.00000	
23.98	0.00000	0.00000	0.00000	0.00000	0.00000	
21.79	0.00008	0.00018	0.00024	0.00019	0.00009	
19.80	0.00623	0.01040	0.01110	0.00797	0.00425	
18.02	0.18800	0.22300	0.19100	0.12900	0.07780	
16.37	2.40000	2.28000	1.32000	0.71000	0.52600	
14.88	12.50000	12.30000	6.74000	3.00000	2.86000	
13.53	31.00000	37.30000	37.10000	20.60000	11.60000	
12.30	43.60000	61.70000	64.30000	61.90000	48.50000	
11.19	23.80000	35.80000	46.80000	55.20000	59.00000	
10.16	7.19000	11.60000	17.40000	22.80000	27.90000	
9.26	2.29000	3.62000	6.02000	9.51000	13.30000	
8.40	1.32000	1.90000	2.75000	4.50000	7.51000	
7.63	0.97300	1.33000	1.61000	2.22000	3.97000	
6.94	0.72100	1.06000	1.35000	1.65000	2.42000	
6.33	0.49000	0.76500	1.06000	1.41000	1.92000	
5.75	0.31800	0.53300	0.73000	1.02000	1.49000	
5.21	0.19100	0.37100	0.53900	0.72700	1.03000	
4.74	0.10600	0.23500	0.38800	0.55900	0.76400	
4.31	0.06200	0.14800	0.25900	0.39600	0.55100	
3.92	0.03910	0.09890	0.17600	0.26900	0.37000	
3.56	0.02560	0.06720	0.12200	0.18600	0.25100	
3.24	0.01700	0.04520	0.08240	0.12700	0.17100	
2.94	0.01150	0.03080	0.05590	0.08580	0.11400	
2.67	0.00786	0.02110	0.03820	0.05830	0.07660	
2.43	0.00528	0.01420	0.02570	0.03930	0.05140	
2.21	0.00356	0.00948	0.01720	0.02620	0.03430	
2.01	0.00239	0.00637	0.01160	0.01760	0.02300	
1.83	0.00159	0.00424	0.00774	0.01180	0.01550	
1.66	0.00104	0.00281	0.00516	0.00791	0.01040	
1.51	0.00069	0.00187	0.00347	0.00533	0.00705	
1.37	0.00045	0.00125	0.00233	0.00360	0.00477	
1.25	0.00029	0.00081	0.00154	0.00238	0.00317	
1.14	0.00019	0.00054	0.00102	0.00159	0.00211	
1.03	0.00012	0.00035	0.00068	0.00105	0.00140	
0.93	0.00008	0.00022	0.00042	0.00065	0.00087	
0.85	0.00005	0.00014	0.00026	0.00041	0.00054	

The 96 location files each with spectra every 15 minutes, were contained in text files. It was necessary to write a Matlab script that unraveled the data format and produce spectra that the modeling programs can use. Table 4-2 shows the peak spectrum where highest energy level is and the two on either side of it that are 10 and 20 degrees removed in azimuth.

The single spectrum from the center was also derived for each of the locations.

4.5 VDR Voice Transcript Data Set

Kery, Garzke and Solzenberg all studied the VDR voice data transcripts for weather and motions clues and Kery meshed them all together into the phase 3 modeling plan. This data is tricky to interpret because the voices discuss their experiences on other storms and on other ships and it's not always obvious if they are discussing the current ship / storm / situation. Some general impressions can be drawn from the overall thread of the conversations:

- The ship and some of the crew had spent years on the Puget Sound (Tacoma WA) to Cook Inlet (Anchorage AK) run across the Gulf of Alaska where stormy weather is common.
- There was some discussion regarding request that the stevedores put on storm lashings, and a question as to who had checked the lashings versus whose job it was.
- The captain felt that if they had gone south far enough, that the storm would be north of them and moving away. In fact, they were in the northwest corner of the storm at the time of the sinking and the storm was further south of their position, as indicated in Figure 4.4.
- They had conflicting weather reports from different sources, with different update times and the credibility of one versus the other was discussed.
- There was discussion between the mates on watch and the able- bodied seamen (AB's) manning the helm that they should have diverted and gone down the west side of the Bahamas Archipelago in the "Old Bahama Channel".
    - There was discussion about the narrow channels and shallow waters between the islands and how trying to pass through to the west side later in the storm would be hazardous.

CSRA Dynamic-EL_Faro_Timline (W.H.Garzke_3-2-17).xlsx

4.6 Data Consolidation and Comparison

The results of the Phase 1 and 2 modeling efforts were used to develop a final WASIM and Orcaflex runs matrix. Part of the setup for the phase three simulations was to specifically target damages found in the debris field and on the wreck.

The wind and wave data was compared to the audio transcript which removed some ambiguity from the wind and wave data. The WAV III model uses different direction conventions for wind direction and wave direction which made it look like they were coming from 180 degrees out from one another. One is defined as "going towards" and the other as "coming from". When the bridge crew mentions that the wind was out of the North, and the waves were from approximately a stated direction, the ambiguity was resolved.

These runs matrices were performed in the spring of 2017 under phase 3 described in Chapter 5.

5 Phase 3, Detailed Technical Approach and Data

The modeling in Phase 3 started with the assumption that every 15-minute wind and wave data was substantially correct. As noted in the Phase 2 discussion, the wind data can be replaced for much of the record with the amplitude from the ship's actual wind sensor and the direction from the NOAA data which roughly agrees with the VDR audio transcript.
The wave data predicted by the NOAA WAV 3 model produces a substantially lower significant wave height than the earlier Fedele data.

NTSB and the USCG MSC agreed on the three loading conditions to be modeled, shown in Table 5-1.

Table 5-1: Three Loading Conditions Agreed to by the Team

Condition	Displacement	Floodwater	KG	GM	T_f	T_a	T_{lcf}	Trim	
	LT	LT	ft	ft	ft	ft	ft	ft	
Intact at LOP (no flooding)	34,277	0	37.5	4.0	26.9	31.9	29.9	5.0	
Hold 3 @ 20% (perm 0.8)	35,860	1,585 (H3)	36.3	0.8	27.4	33.4	30.9	5.9	
Hold 3 @ 30% Hold 2A @ 10% (perm 0.8)	37,316	2,375 (H3), 665 (H2A)	35.6	-1.9	28.7	33.7	31.6	4.8	
		*Note lolling condition. Lolling angle 14 deg with minimal residual righing arms.							
Notes:									
KG is without free surface correction.									
GM is with free surface correction (i.e. the initial slope of the GZ curve)									
Length between perpendiculars	223.647								
Condition	Displacement	Floodwater	KG	GM	T_f	T_a	T_LCF	Trim	
	m-tonnes	m-tonnes	m	m	m	m	m	m	deg
Intact at LOP (no flooding)	34829.0	0.0	11.430	1.228	8.199	9.723	9.114	1.524	0.3904
Hold 3 @ 20% (perm 0.8)	36437.5	1610.5	11.064	0.256	8.352	10.180	9.418	1.798	0.4607
Hold 3 @ 30% Hold 2A @ 10% (perm 0.8)	37916.9	3089.0	10.851	-0.579	8.748	10.272	9.632	1.463	0.3748

This table was used with the time series data to develop a modeling matrix for WASIM with the non-linear seakeeping and another for Orcaflex where the wind loading and the containers could be included.

5.1 SHCP Analysis

The SHCP modeling is covered in appendix 2, chapter 13 of this report.

5.2 WADAM RAO Data

Five sets of RAO's were produced including the early work in Visual SMP and then 4 sets in WADAM at the intact departure draft and the three conditions in table 5-1. The heave and pitch don't seem to vary much with the draft condition.
All of the Roll RAO's have the same relative peak height but the roll natural periods vary with the increasing draft.
Attempts to run either SMP or WADAM with a significant heel angle were unsuccessful because the programs were not designed to handle it. WADAM produced a set of RAOs at 5 degrees of heel but the results do not appear to be credible.
The RAO's for the three conditions in figure 5-1 were prepared into Orcaflex input format.

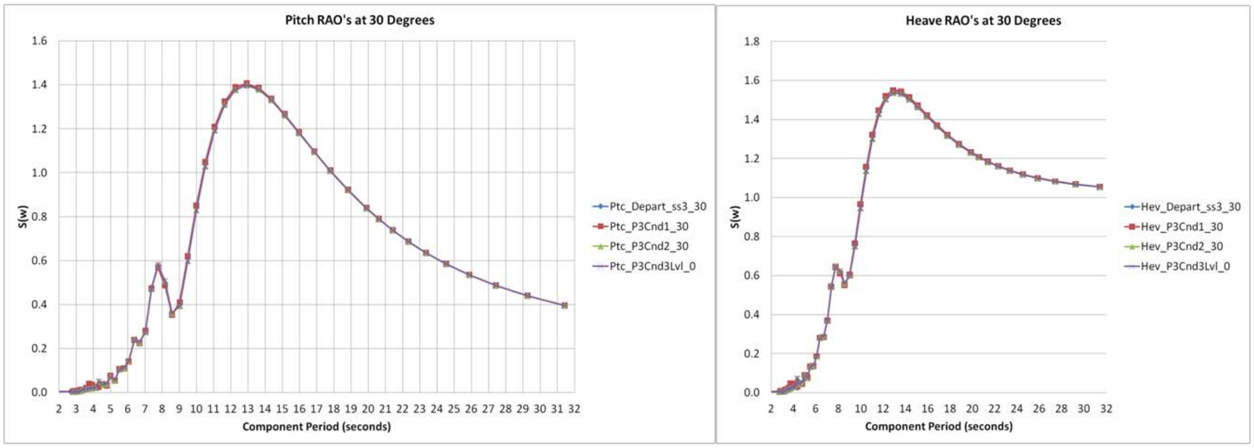

Figure 5-1: El Faro Heave & Pitch Motion RAOs at 30 degrees and Zero Speed

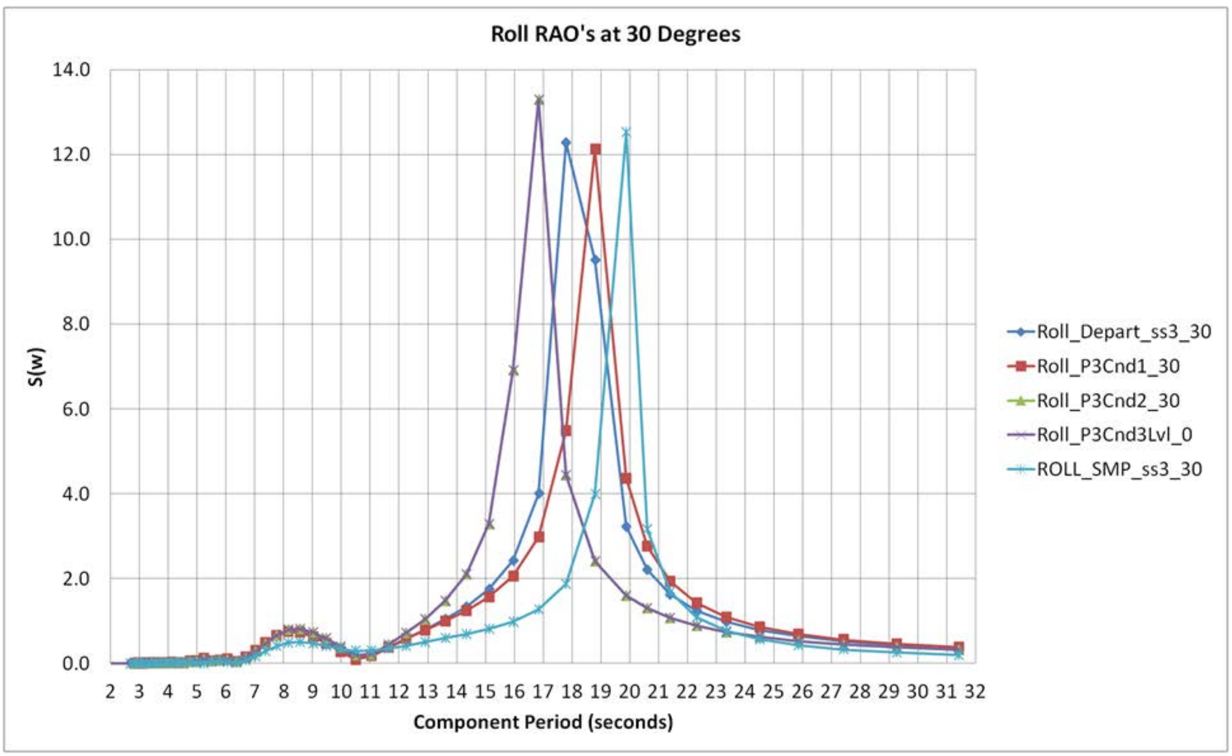

Figure 5-2: El Faro Roll Motion RAO at Zero Speed

A sensitivity study on another ship / project with SMP showed that the results can be sensitive to the number of strips the hull is broken up into, due to the trapezoidal rule used to integrate the volume and centers. A similar sensitivity study for SMP and WADAM was not performed for the El Faro as it was out of scope and time was not available.

5.3 Orcaflex Surface Runs Matrix

Orcaflex runs were made according to the sinking timeline. The wave conditions were extrapolated from the area where the wave predictions agree to the sinking wave height of 8.9 meters proposed by Dr. Fedele. These were extrapolated with a straight line fit as shown in green in Table 5-2. The heel angles are extracted from the voice recording timeline as much as possible. Once the heel angle exceeds about 15 degrees, the vents on the downhill port side are submerged on almost every wave so downflooding is uncontrolled.

Table 5-2: Orcaflex Runs Matrix

						Wind	Wind	Draft	Draft		Trim		Angle of	
Count	**Description**	**H/13 (m)**	**Tm(sec)**	**Wave Heading**		**Speed**	**Heading**	**AP**	**FP**	**Mean**	**Angle**	**VCGcor**	**Heel**	**TCG**
	Time(local)			**Degrees**	**Description**	**Knots**	**Degrees**	m	m	Draft (m)	**deg**	m	deg	m
1	100	3.34	10.52	137.05	Bow Quartering	39.60	9.3	10.272	8.748	9.510	0.375	10.85	5	0.646
2	130	2.76	11.98	104.47	Near Beam	40.94	46.3	10.272	8.748	9.510	0.375	10.85	5	0.646
3	245	5.44	11.46	90.44	Near Beam	54.47	41.4	10.272	8.748	9.510	0.375	10.85	7	0.906
4	315	6.69	10.98	98.66	Near Beam	64.54	39.0	10.272	8.748	9.510	0.375	10.85	7	0.906
5	330	7.57	11.08	100.23	Near Beam	69.58	41.4	10.272	8.748	9.510	0.375	10.85	10	1.296
6	415	7.81	10.96	82.98	Near Beam	72.96	62.3	10.272	8.748	9.510	0.375	10.85	12	1.559
7	430	7.89	10.92	52.86	Aft Quartering	74.20	94.1	10.272	8.748	9.510	0.375	10.85	15	1.953
8	500	8.04	10.83	37.45	Stern Quartering	76.71	112.7	10.272	8.748	9.510	0.375	10.85	**18**	1.296
9	530	8.20	10.80	36.80	Stern Quartering	77.10	112.0	10.272	8.748	9.510	0.375	10.85	**18**	1.296
10	600	8.35	10.79	35.86	Stern Quartering	77.49	-177.3	10.272	8.748	9.510	0.375	10.85	**18**	1.296
11	615	8.43	10.91	48.74	Stern Quartering	72.90	-164.6	10.272	8.748	9.510	0.375	10.85	**18**	1.296
12	630	8.51	10.90	54.24	Aft Quartering	68.31	-159.6	10.272	8.748	9.510	0.375	10.85	**18**	1.296
13	645	8.59	10.89	58.54	Aft Quartering	63.71	-156.3	10.272	8.748	9.510	0.375	10.85	**18**	1.296
14	700	8.67	10.88	63.24	Aft Quartering	59.12	-153.0	10.272	8.748	9.510	0.375	10.85	20	2.623
15	715	8.75	10.81	80.10	Near Beam	61.59	-128.2	10.272	8.748	9.510	0.375	10.85	20	2.623
16	730	8.82	10.74	84.23	Near Beam	64.06	-133.7	10.272	8.748	9.510	0.375	10.85	20	2.623
17	735	8.85	10.67	87.05	Near Beam	65.48	-140.2	10.272	8.748	9.510	0.375	10.85	20	2.623

These runs are typically 600 seconds, (10 minutes) long and with this complex model produce an output data file that is about 485 megabytes. While longer runs are possible the file size becomes unmanageably large.

5.3.1 Theoretical Twist Lock Failure and Container Movement modeled in Orcaflex

Study of theoretical container twist lock failure alone (without container stack lashings) and subsequent container loss in wind and wave action was examined. *To be clear, on the accident voyage El Faro containers were not only connected by twist locks, but also with lashing bars on outboard stacks, so container loss as examined below is not to be extrapolated for the accident, but rather for what might possible in Orcaflex.*

A NIST test report (Lew, Sadak and Anderson 2000) providing break test results for new and used container twist locks was found online. For examination of El Faro, each stack of 3 containers tall in Bay 15 was connected and filled with a reaction solid such that when the containers connection setting was set to free, they would not simply fall through the deck. Each bottom container was then constrained with 4 links with the strength profile of the "All Set Marine" twist locks to lock them to the deck. This required 48 links for the 12 across container loading. The coefficient of friction between the deck surface and the containers was set to a high value so that the containers would be more likely to topple than to slide.

All 146 bottom containers were eventually modeled with 584 unique links which were run for one near sinking condition. The majority of the containers fell off in 600 seconds with the remaining ones closest to amidships where the roll and pitch moment arms where shortest and hence the accelerations were lowest.

While it is possible to model the connection of each and every container using this method, to do so would be very time consuming with over 1600 links required and each with a unique geometry that would have to be developed in excel and entered by hand.

An attempt was made to include the lashing bars per the loading plan on the outboard stacks of containers. This was not successful, although with some additional trial and error tweaking, there is no reason it can’t be done. Further work to get the exact starting length and pre-tension set right is required. This is somewhat challenging because the ship and the container each use their own local reference origin. This was out of scope and could not be completed in the time available.

In these theoretical modeling conditions (with twist locks only, and the as-lashed loading on the accident voyage) the containers begin falling off as soon as the motions exceed a threshold value, however that motion threshold value was not extracted from the data due to time constraints.   They fell off both sides of the ship, as the ship rolled and not just from the side which was heeled down by the wind heel and flooding. Once the containers reach the water, they are seen bumping back into the sides of the ship.   It's possible to evaluate those impact forces but that was not pursued at this time.   There are several places in the study of the video footage where dents and scratches to the hull can be attributed to floating container strikes. Figure 5-3 is a screen grab from the Orcaflex video showing containers falling off the ship.

In the event containers entered the water, it is likely they floated for a time on the surface. One of the challenges unanswered at this time is how long the containers remained at the surface. A large number of the containers loaded on the El Faro were refrigerated containers which have to be tightly sealed. While the seals in a reefer container were never intended to keep out the sea, it is reasonable that these would take longer to sink than a container with lesser seals to hold out the water.

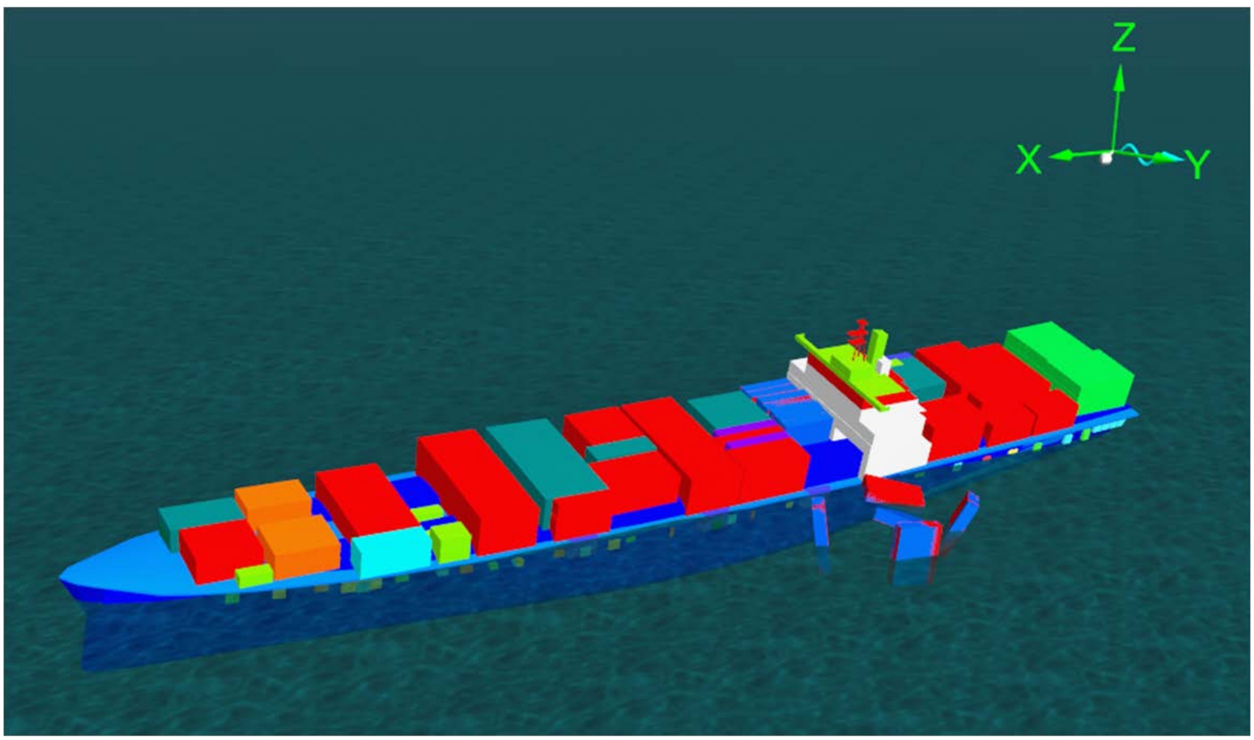

Figure 5-3: Theoretical Modeling of Containers Falling Off Vessel, Screen Grab from Orcaflex Video

5.3.2 Attempt to Model the Free Surface from Flood Water in 3 Hold (aka Hold 4D)

The orange block illustrated in Figure 5-4 slides on a surface at the level of the tank tops. It has a mass equal to the 1610 m-tonnes of flood water proposed by the USCG MSC.   It is tethered with a spring and damper at the forward and aft centerline that limit its motion in the longitudinal and transverse directions to remain roughly with in hull envelope.   The geometry of the block is somewhat arbitrary.

While this shows that Orcaflex has the ability to model moving weights, an exhaustive study of this phenomenon would require scale model tests to go much further. Specifically, the sloshing behavior of the free surface in a hold partially occupied by vehicles of various sizes will be affected by the presence of the obstructions. If the vehicles are sloshing around with the flood water in whole or in part then the picture is even more complicated.

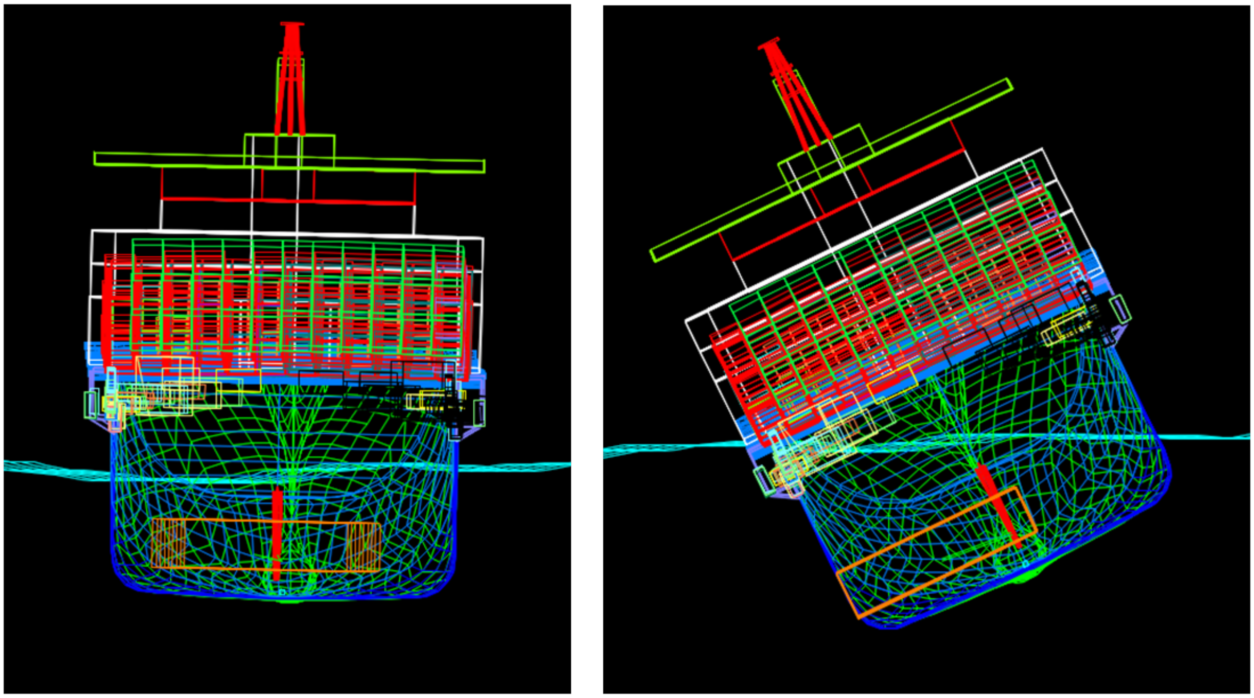

Figure 5-4: Two Screen Grabs from Orcaflex Simulation of Free Surface in the 3 Hold

5.4 Orcaflex Sinking Model

A sinking model was developed for the El Faro in Orcaflex and exercised for several different ballasting conditions at the surface.

1. The baseline case had the center of gravity of the RORO cargo on the centerline.
2. The second case had the center of gravity of the RORO cargo moved 25% of the beam to port to represent a cargo shift.
3. A case where the containers fall off over the last hour that the ship was on the surface.

Results from these sinking experiments are preliminary at this time and may be reported in a separate follow on report, except as shown below. The extreme complexity of these models is producing results but slowly and with run times of tens of hours and enormous output file sizes.

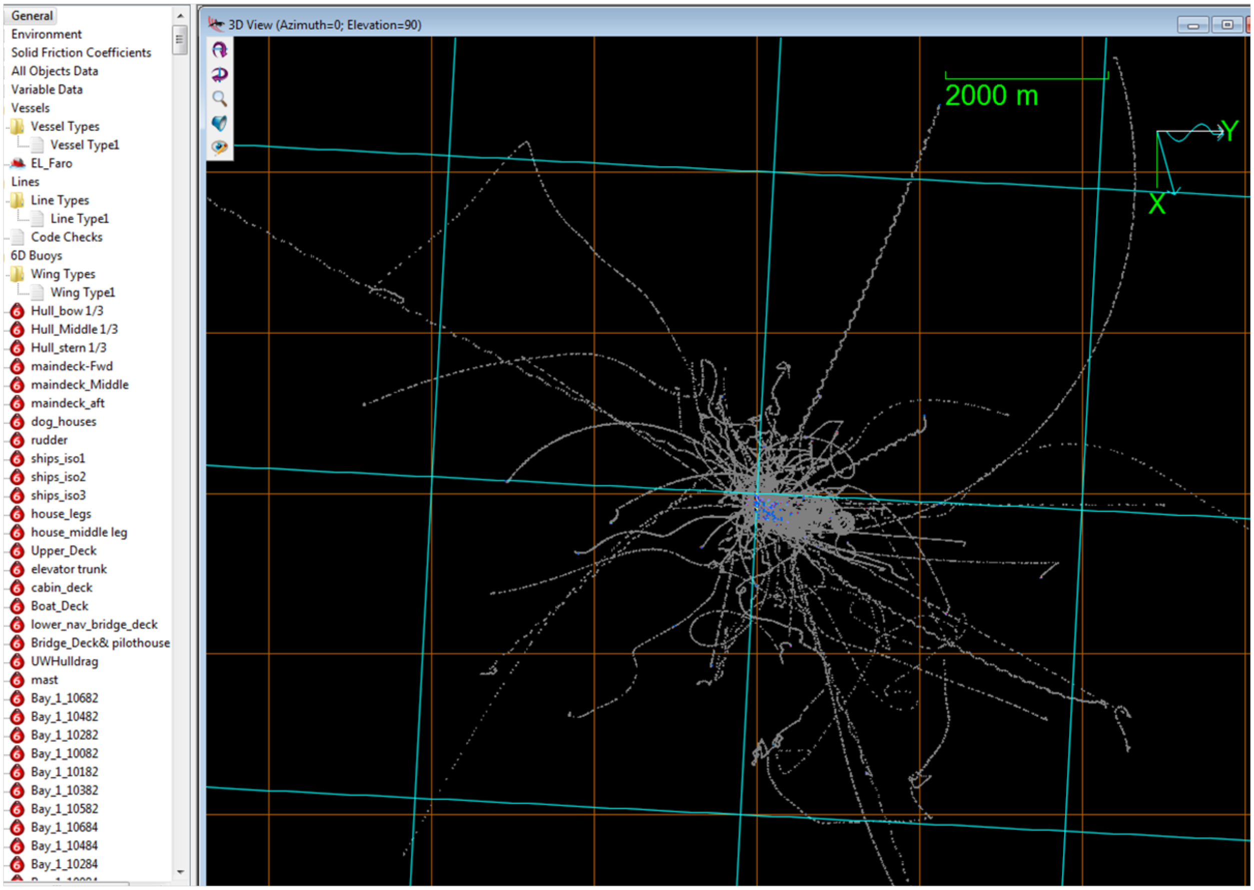

Figure 5-5: Debris Field Map from Orcaflex Simulation.

Figure 5-5 shows a concentration of containers in the center of the image but the trails show some of the more distant containers as well. This dispersion pattern is caused by the combined waves, winds and currents acting on the containers on the surface and as they flood and descend at different rates. The terminal velocity of each one is different and depends on its weight, time dependent residual buoyancy, the density of the fluid vs depth, the currents which change speed and direction vs depth, and the containers orientation relative to the direction of motion. The analyses of the path of each can be easily extracted from the Orcaflex data, however that is well beyond the scope of the current report.

6 Video and Still Footage Information

As stated in section 2.1.7, a group of subject matter experts met for two days and went over a targeted sampling of the video and still photo footage of the El Faro wreck on the bottom. The factual report contains 158 images that document many different aspects of the vessel which is largely intact in the bottom. The overall evidence is consistent with the ship striking the bottom stern first with the port side heeled down. This assertion is supported in the figures that follow.

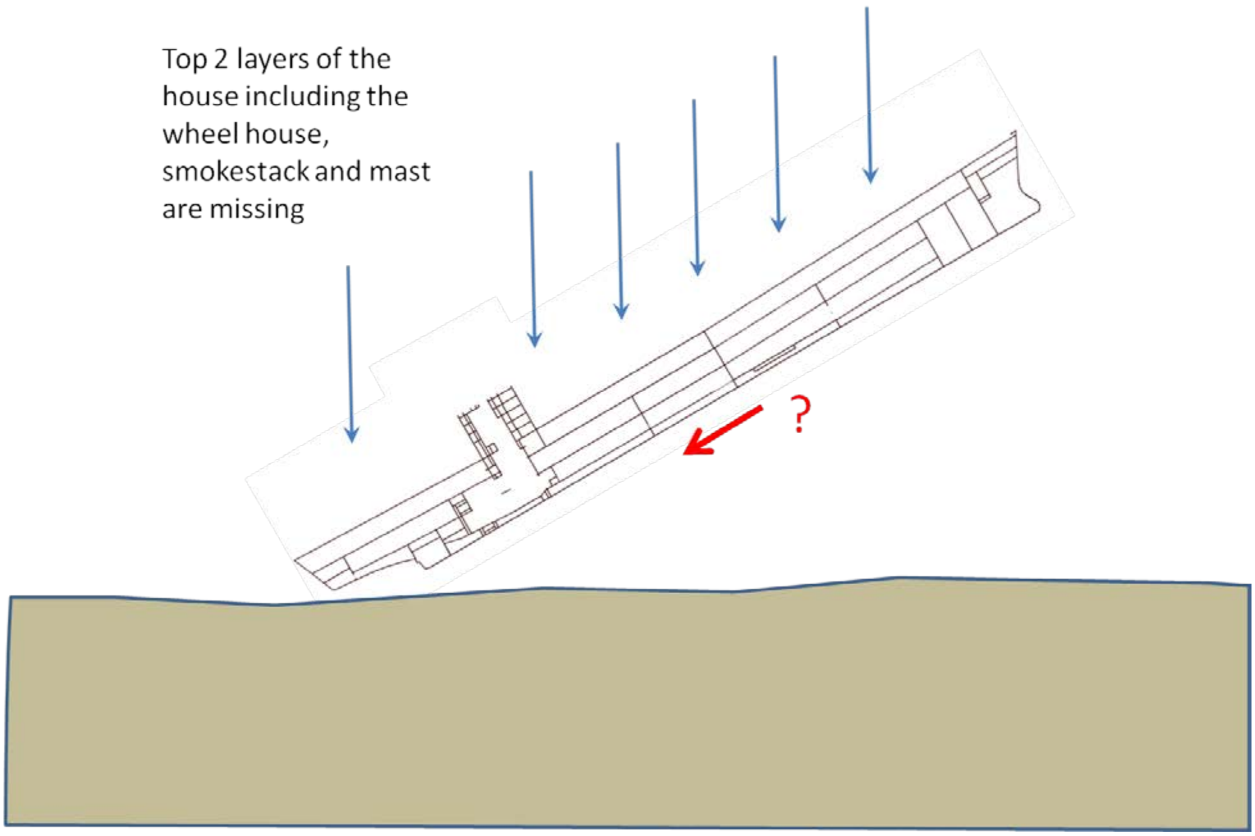

Figure 6-1: Artists Rendition of EL Faro Just Prior To Bottom Impact

Figure 6-1 shows the vessel traveling at terminal velocity just prior to bottom impact. It is unclear at this time if there would have been much aft velocity signified by the red arrow and question mark. The impact speed is estimated to be 10 to 15 knots. (4700m in 12.5 minutes is 6.3m/s which is 12.2 knots).

Figure 6-2 is an artist's rendition of the El Faro impacting the seabed. The top two levels of the house, including the wheel house, are missing and were found about 845m (.45 nautical mile) away in the debris field, slightly to port of the bow. The mast and smokestack are approximately 392 meters off the port bow in more or less a line to the bridge wreckage.

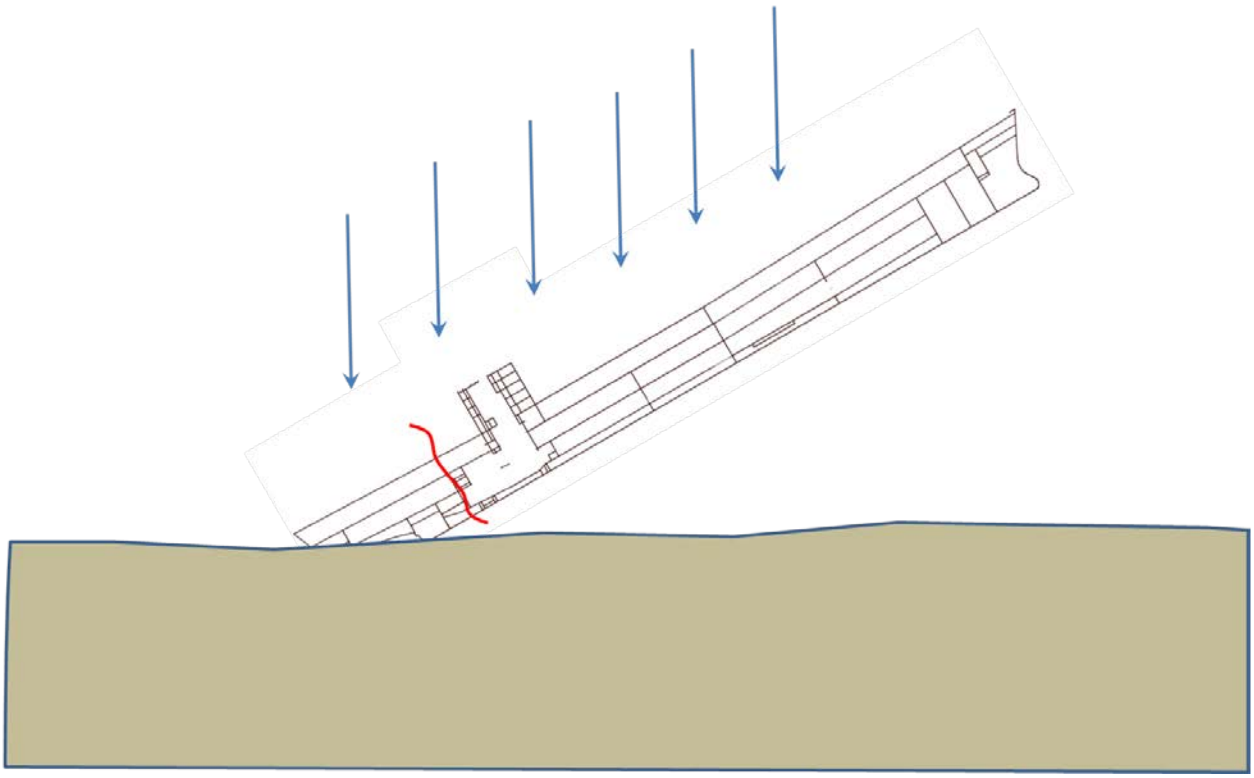

Figure 6-2: Artists Rendition of the EL Faro on Bottom Impact

There is severe damage to the stern aft of the accommodations block that is consistent with a stern first bottom impact, as depicted in Figure 6-3. There is a crack all the way through the hull just at the aft engine room bulkhead again consistent with stern first bottom impact.

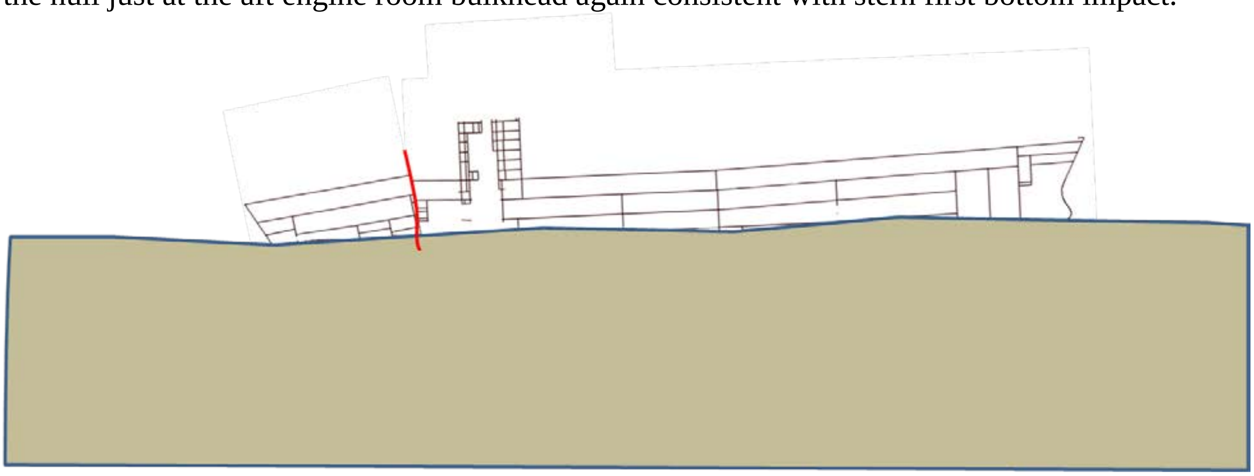

Figure 6-3: Artists Rendition of the EL Faro as Found in the Site Surveys

While the stern is badly damaged, the bow looks like it settled relatively gently to the seabed while possible moving slowly to port.

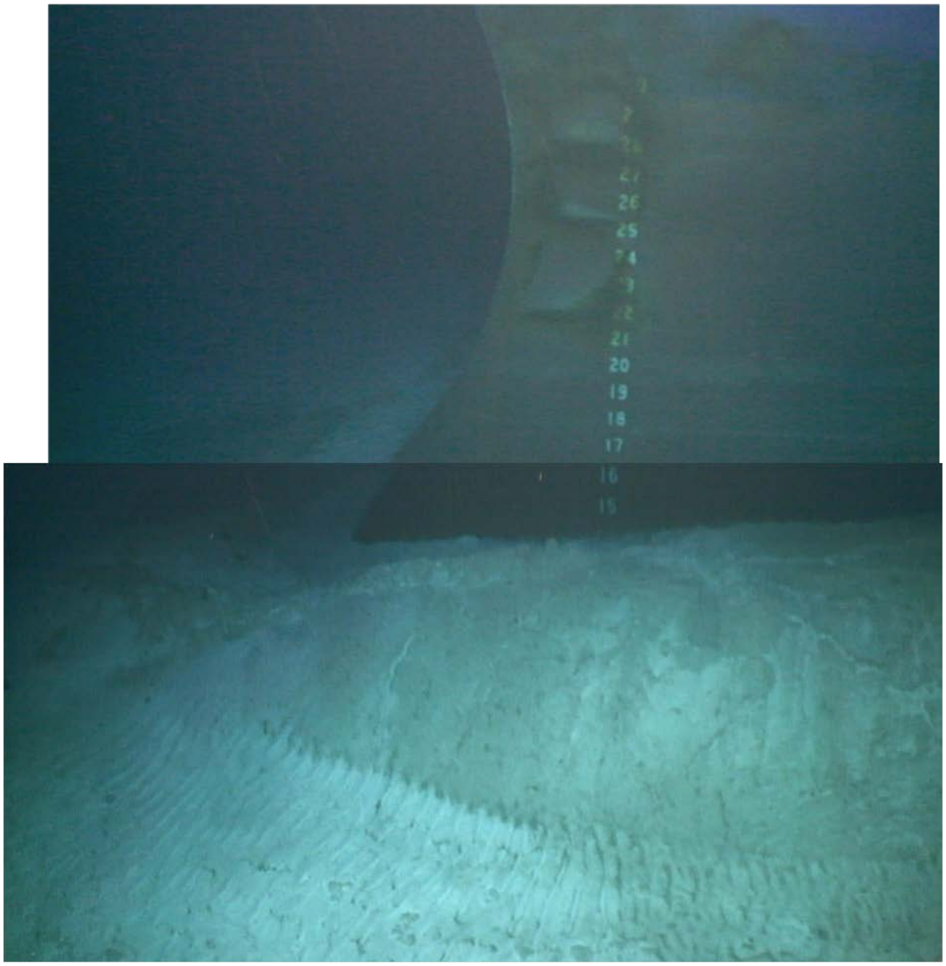

Figure 6-4: Composite View of The Port Side Bow of EL Faro

In Figure 6-4 there is a dune of sediment off the port bow but a much smaller one off the starboard bow where the ship settled down into the bottom. There is no "bow wave" where the ship pushed forward and plowed up sediment indicating that there was minimal forward speed at the time of impact. The somewhat enlarged dune on the port side suggests some small momentum in the drifting to port direction when the bow of the ship met the sea bottom. It's impossible to tell how much of the 14.5 feet that the bow is submerged into the bottom happened on impact and how much is due to the weight of the ship slowly settling into the bottom to create a semi-solid buoyant equilibrium.

In Figure 6-4, note the geometric dents in the stem starting at about the 20-foot waterline and going up. These are where the hull plating was welded over a cast steel stem piece and these dents are due to hydrostatic crushing of the voids in the stem bar which embossed the hull plating on both sides to meet in the middle.

Figure 6-5: View of the Stern of EL Faro

The video from which Figure 6-5 was developed shows that the mooring deck at the second deck level is mostly crushed under where the Juan PR lettering appears. The bulges suggest that the rudder is impaled up inside the hull. The yellow bar shown just above the broken white railing is one of the container "transfer beams" that the twist locks go into. These are displaced, broken, bent or missing completely from a number of locations on the container deck.

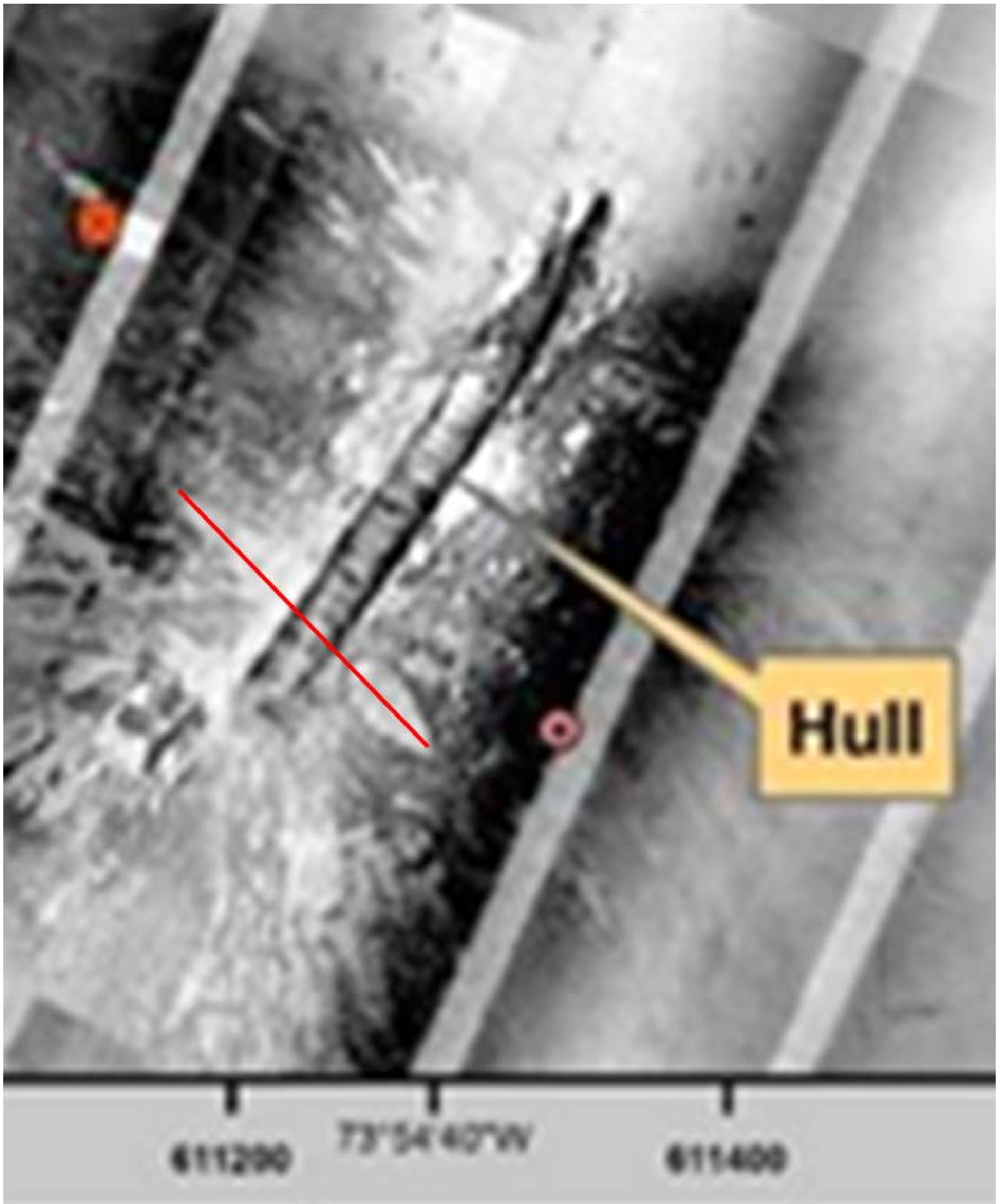

Figure 6-6: Top Sonar View of The Hull Sitting Upright On The Bottom

In Figure 6-6, notice the candle flame shaped white spots to the port and starboard aligned with the red line. These appear to be hydraulic outburst marks where the water filled stern of the ship crushed on bottom impact, causing the incompressible water that was being squeezed to find a new way to vent. The full fracture at the aft engine room bulkhead provided such a vent, and these scars in the bottom align with the crack locations quite well. They represent where a jet of fluid moved sediment around.

Figure 6-7: Top Deck Edge View of Hull Crack at Bay 16 And Aft Engine Room Bulkhead

Figure 6-8: View of Top Deck Showing Crack Traveling All the Way Across the Hull

Figure 6-7 and 6-8 show the crack extending across the hull mentioned above.

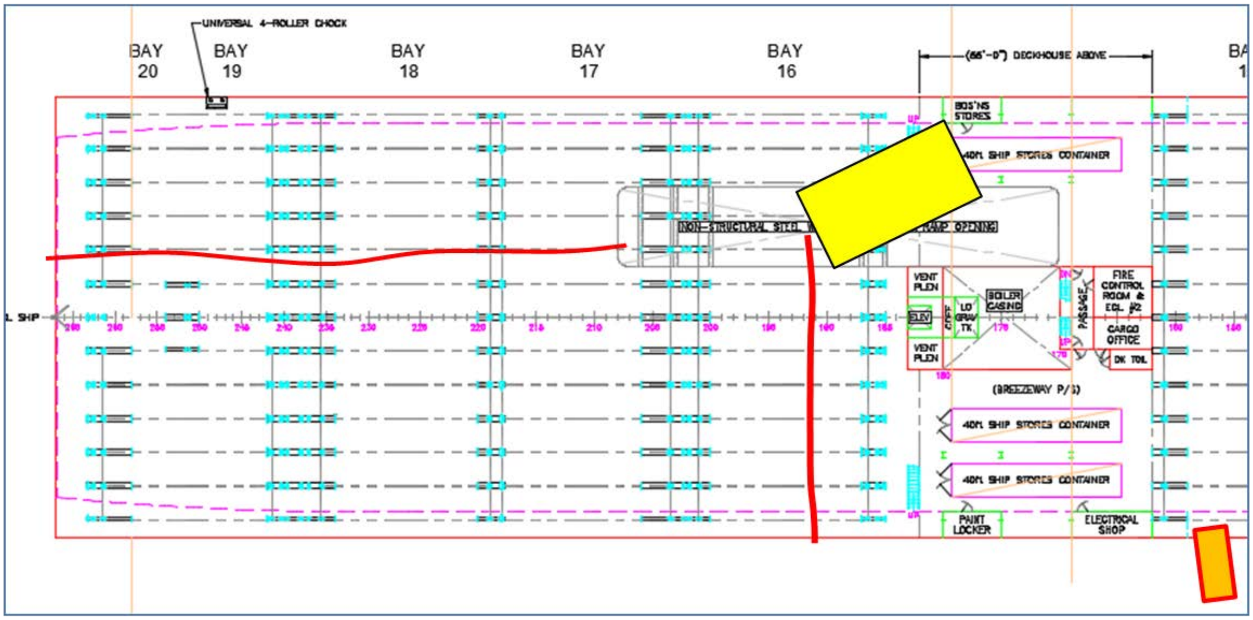

Figure 6-9: Drawing View with Damages Annotated

Further evidence of a hydraulic outburst on bottom impact is the condition of the patch that was welded over the RORO ramp. In Figure 6-10 it can be seen to be torn upwards and displaced as shown to be upside down and forward and to port of the ramp hole. The location is the yellow rectangle in Figure 6-9. Figure 6-9 has an orange rectangle sticking out of the side of the hull just forward of the house.

The stiffeners welded to the underside of the plate can be clearly seen to be on top, indicating that it's folded up and over as described.

Figure 6-10: View Showing Ramp Cover Folded Up and Over To Forward And To Port.

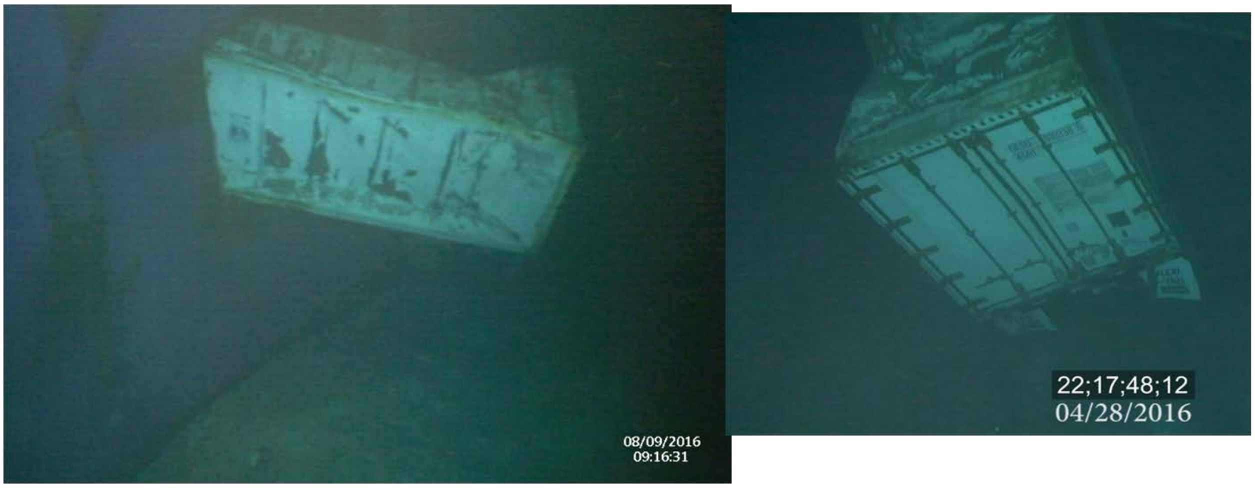

Figure 6-11: Trailer GESU910338-6 45 R1 sticking out of the side of the El Faro on the 2nd deck.

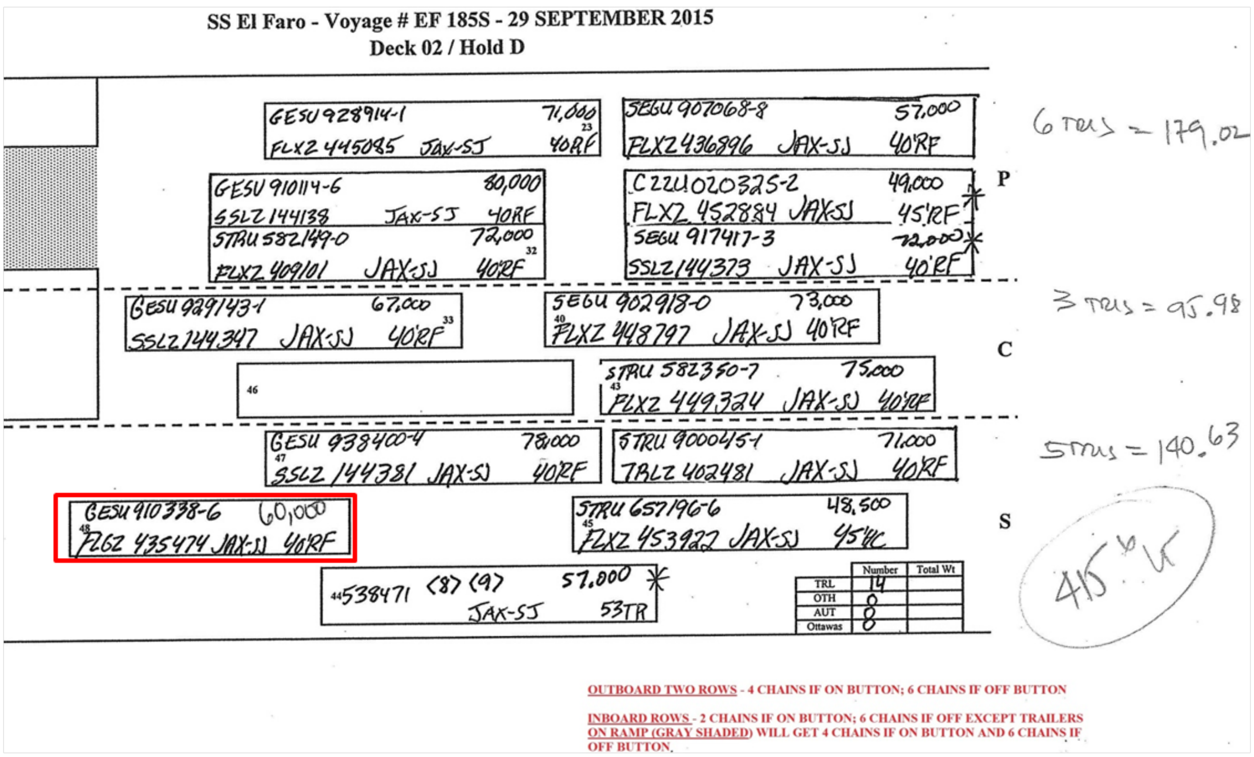

Figure 6-12: El L Faro Load Out Plan Showing the As Stowed Location of This Container

Figures 6-11 shows the trailer sticking out of the side of the hull and figure 6-12 shows where it appears on the stowage plan as matched up by the container number GESU910338-6. Figure 6-12 shows where that container was lashed, however the geometry is thought to be notional rather than geometrically precise in figure 6-12.

While it's clear that some of the RORO cargo did break loose, it's not clear why this trailer did not completely fall out. The opening is a former ramp location that had been plated over with what Tote described as a "Soft Patch". The trailer slamming around must have torn the patch off the side of the ship. The soft patch has not been identified in the debris field.

When El Faro left Jacksonville Florida, (JAX), she had 400 containers aboard of various sizes amounting to approximately 900 TEU's. There are remains of three still on the deck on the bottom.

Figure 6-13: Video Stills of Container Installations on The Bottom

In the left-hand pane of Figure 6-13 the various container twist lock sockets can be seen. At the far end where part of the port side railing appears to be intact, there is some of the yellow fiberglass grating that used to cover the deck between the container sockets. Most of it seems to be missing throughout the main deck. In the right-hand pane of Figure 6-13 one can see what looks like about a 3-inch pipe in the two container sockets. These appear to be the remains of broken twist locks, although it's not clear that they match the geometry of the All Set Marine Left Hand Twist locks that Tote Marine says the ship was equipped with. The break test specimens in Lew, Sadak and Anderson 2000 don't look like these. See Figure 6-14.

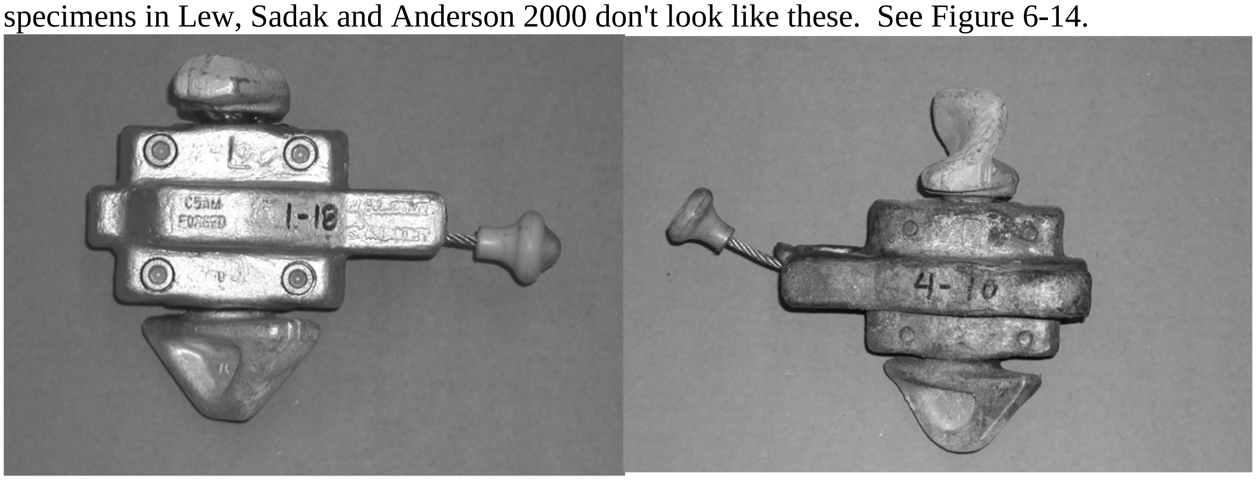

Figure 6-14: All Set Marine Twist Locks from Lew et al

The video image quality is not great so it's hard to tell what exactly is in the Figure 6-13 but something does not look right?

6.1 Damage That Most Likely Happened Near the Surface

There are many different details in the photographic and sonar evidence, backed up by hand calculations and Orcaflex simulations that are consistent with the ship plunging bow first in a sea surface with many floating containers.

- The VDR voice record clearly states that the ship was listing 18 degrees or more to port. Some of the last words were; "The bow is down" (repeated), and "We have containers in the water".
- There are scratches consistent with containers floating against the front of the house.
- The way the upper two levels of the house tore away, and reached the bottom a long way away from the rest of the ship, is explainable, especially the way the bridge wings are rolled up and aft.
- Damage to the lifeboat davits
- The way the mast tore away aft when it tore off the house top.
- The way that the stack tore away.
- The damage to joiner bulkheads inside the house and debris ejected from the back doors.

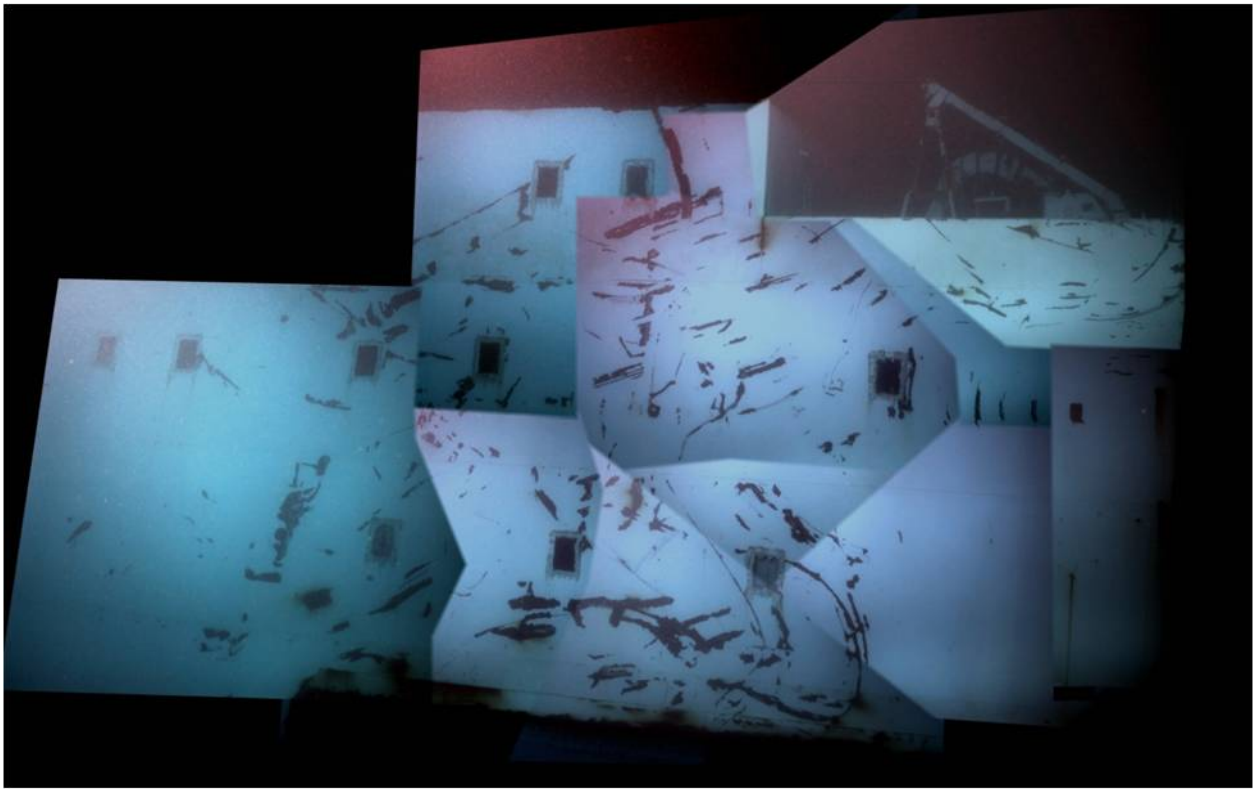

Figure 6-15: Mosaic View of Front of The House Looking Aft, With Remains of Port Lifeboat Davit In Upper Right

Figure 6-15 shows the front of the house. The scratches were most likely made by containers floating off.

6.2 Examination of the Vessel and Debris Field

There are a number of specific damage signatures found on the wreck that any plausible casualty scenario must include.

- Of the 400 containers on deck when the ship left Jacksonville, only parts of 3 remain on deck on the bottom.
    - There is one trailer noted on the main deck that is not listed in the cargo manifest.
- There is a 45-foot trailer sticking out of the second deck on the starboard side.
- The mast and stack are broken off and are lying some distance from the wreck.
- The upper two levels of the house are approximately half a mile away from the rest of the ship.
- The ship is upright on the bottom.
- The stern is severely damaged with the most extensive damage on the port side.
    - The hull is cracked across at the after-engine room bulkhead
    - The debris field photos show flow patterns on both sides that are consistent with a hydraulic outburst on bottom impact, in way of the stern crack.
    - The reinforced steel deck that covered over where a RORO ramp used to be on the port side of the top deck at the stern is pealed upwards and forwards again consistent with a hydraulic outburst on bottom impact.
- There are many scrapes on the front of the house that suggest containers floating upwards and to one side.
- The lifeboat davits appear to have been hit by floating debris as the ship went under.
- The windows on the sides and front of the ship's house appear to be intact.
- Viewed from above and from aft, it appears that most of the joiner bulkheads inside the house are missing or displaced from their original positions.
- There is a mattress and a closet door on the back walkway that appears to have come out one of the doors on the back of the house.
- There are a number of dents in the upper parts of the hull that may be due to impact with floating containers
- Large sections of the railings around the main deck are missing or are found out of place.
- Some long rolls of metal flashing that were probably in one of the containers are found on deck and draped over the side.

7 Discussion of Key Findings (Including Relevant Information Outside the Scope Of The Contract)

The El Faro was a 41-year-old ship that had undergone a lot of changes over its service life. There is insufficient documentation to establish the condition of her hull and equipment with regard to accumulated fatigue and corrosion. It is clear from the wreck that her hull girder remained intact until bottom impact. The weld area failure of the portions of the deckhouse that came off, may have been weakened by accumulated fatigue and / or corrosion damage.

The VDR transcript indicated there was a general consensus discussed among the officers that the ship had been through a lot of bad weather in the years she was on the Tacoma to Anchorage run across the stormy Gulf of Alaska. There was considerable ambiguity between the different news sources as to where the storm would track and how severe it would get. The captain believed that they were "on the back side of the storm", and that the worst of the storm has already passed them. In fact, they were in the Northwest Quadrant of the storm and still heading into it.

The ship was designed to handle RORO cargo with vents bringing fresh air into and exhaust laden air out of the cargo holds. There were fire dampers fitted that might have limited the ability of green water to enter the cargo holds if closed, but NTSB informed CSRA these were not likely closed for El Faro on the accident voyage. Our modeling demonstrates that once the ship was heeled over 15 to 18 degrees in storm waves, the vents on the lower side would be submerged a significant part of the time, leading to catastrophic flooding. See figure 7-1.

Figure 7-1: El Faro Heeled Down with Wave / Green Water Over the Vent Openings

The ship lies upright on the bottom with severe impact damage to the stern including a crack across the ship at the aft engine room bulkhead. The bow appears to have landed more gently with not much forward motion as there are minimal dunes of sediment around the bow. The bow has settled and / or crushed about 15 feet into the bottom. The debris field is extensive but it is clear that the actual dispersion of containers must go much further than the mapped area. The pilot house is approximately 1/2 mile away while the mast and boiler exhaust stack are about half that distance away.

7.1 Conclusions:

The different kinds of computer simulations performed by CSRA in support of this investigation, have allowed us to gain a physics based understanding of how the winds, waves and stability conditions acted on the ship.

As described from when this work was first proposed, this has been a first of its kind investigation of what these simulation tools can and cannot do. The state of the art was notably advanced by the work performed herein, but much future development of the tools and techniques still lies ahead.

7.2 Future Work:

The art and science of Marine Forensic Investigation has been notably advanced by this work on the El Faro, and several avenues of investigation may proceed from this data once the NDA's are lifted.

- The GPS data from the VDR may allow us to capture or at least estimate the roll and pitch motion of the ship as a function of time as the course, speed, wind and wave conditions changed.
- Future work may map the containers falling off, to where they landed on the bottom after falling through the current and density gradients. These could potentially be compared to the containers that are labeled in the debris field. The few dozen out of 396 that appear in the mapped debris field suggests that some may have fallen off earlier which would cause them to land further away. The debris field map may allow us to gain a better understanding of how and when containers came off and how they behaved in the water column. This is part of a larger effort including other ship wrecks with notable debris field maps and in one case model tests of the sinking.
- There are several aspects of flood water entry and flood water sloshing around, that there is currently no commercial off the shelf model to simulate. There is much that can be done to increase this capability by writing python or C++ code to run with Orcaflex, however this development is out of scope for the current contract. Some model testing to validate such models would probably be necessary as well.
  - Flood water in a RORO hold will interact with the cargo and lashings and may contribute to breaking the lashings and the cargo moving around.
  - The ingress of flood water through a scuttle or broken pipe or through a pipe ripped out of the side shell can be modeled and some test data already exists but it would take some work to write software that can incorporate this into Orcaflex as a routine capability.

- The ability of Orcaflex to model the compression collapse of an air pocket under increasing hydrostatic pressure either gradual or as a catastrophic implosion might also be improved by user developed software.

7.2.1 Potential Future Work

There are several sensitivity studies that were not pursued due to the limited scope of this project that may warrant further study.

- The sensitivity of ship motions to the gyradius settings was only explored at a single condition.
- The Visual SMP RAO's are known to be somewhat sensitive to the number of stations and their distribution. It is unknown if the panelization in WADAM and WASIM suffer from similar sensitivities. A study that examines the sensitivity of all three codes to this important parameterization may be worthwhile.
- The roll damping was studied quite extensively in the early stages of this project but without reaching a clear winner. A more thorough literature search would hopefully yield a methodology comparison with some sort of validation data to back up the eventual best solution. There are significant philosophical differences to the technical approaches used by the different authors consulted. Several added in parameters like block coefficient that have no direct tie to the damping of say a bilge keel but are included to extend the method to a wider range of ship sizes and shapes. Others like McTaggart, only use parameters that are directly linked to the physical situation at hand. While this physics based approach makes intuitive sense because each of the terms has a clear physical manifestation, it's not clear that these give the best answer. The difference in damping models for linear and non-linear models was not as extensively explored as it might be.
- The sinking behavior of ISO containers is not well understood in several respects. The drag coefficients were taken from (Hoerner 1967) for a simple rectangular solid. This does not account for the effects of the corrugation's or other shape elements. Several model railroad scale models are available but thus far no model testing has taken place.
    - The rate at which an ISO container will flood must differ somewhat from refer containers with greater insulation and sealing, than for simple box containers. No flooding rate data has been found for either or for that matter any type of ISO containers.
- The approximately 400 simulations performed in support of the analyses for this project created about 120 Gigabytes of data. In part because of the fact that this type of analysis has not been around long enough to fully mature, the study of this BIG DATA archive has progressed through a developmental ad hoc process. Much of this practice is shared with other US Navy ship design and analyses projects and will continue to mature under other funding. At present, we can conduct analyses targeted at answering specific technical questions quite well but, the ability to look over the larger data landscape holistically is currently lacking.

8 Avenues of Investigation That Were Not Pursued to Completion

This analysis started at a time when little or no information was available concerning the condition of the ship on the bottom and without the VDR data or the wave and wind data, except in vague terms.

8.1 Possibility of the Ship Breaking Up on the Surface

Other ships that have foundered in storms, such as the MOL Comfort, SS Edmund Fitzgerald, SS Pendleton, and SS Fort Mercer, to name a few, have done so by breaking into two or more pieces, so this was a logical avenue of investigation early on.

- The analysis of the shear and bending moments was discontinued once it became apparent from the bottom footage and the VDR data, that the El Faro did not break up on the surface.
- In order for the shear and bending values to be useful, at least a rudimentary knowledge of the ship's hull girder strength would be necessary to compare the wave induced loads against. Several months into the investigation it became apparent that no such model was available or forthcoming.
- Creating such a model is feasible up to a point. The model would create the ship "as built" and "as modified", but there is no documentation on this and most other vessels that would allow a correct strength accounting of the aged, fatigued, repaired, corroded actual condition at the time of her sinking.

8.2 Rogue Waves

The possibility that the sinking of El Faro could be attributed to encountering "Rogue Waves" was considered as part of the overall NTSB led effort. Fedele, et al used a state of the art non-linear rogue wave model and the Wavewatch III computer model to examine the probability of a rogue wave event and also the severity. (Fedele, et al 2016) This predicted a probability of occurrence of about 1/130 (0.76% probability) for a rogue wave height of 14 meters, based on a 9-meter significant wave height.

While there is nothing in the VDR audio transcript that corroborates a rogue wave, the dark of night and the storm driven spray caused very limited visibility from the bridge. There are several instances where the crew mentions larger than normal roll motions, such as 1:00AM local time, and again at around 1:45AM. Nothing is currently available to quantify the amplitude of these larger motions.

These may have been due to some sort of rogue event but did not appear to have had any catastrophic effect. Normal ship motions in this type of multi-directional seaway do occasionally produce larger motions.

The VDR audio suggests that Rogue waves were not an important factor in the sinking of EL Faro.

8.3 Vortex Shedding Vibration

The aerodynamic vortex shedding frequency from the ships 12-inch diameter mast pipes and from the 1-1/2" pipe hand rails around the wheel house occur at a frequency that is proportional to the wind speed, with some modification for the azimuth angle. A very brief analysis was done to identify those frequencies. These were supplied to NTSB to see if a Fast

Fourier Transform (FFT) of the background noise on the audio track, could be used as an indirect measure of the wind speed and direction. The audio experts did not think this was feasible due to aspects relating to the recording quality.

8.4 Parametric Roll

The conditions that can produce parametric roll are marked by a roll period that is twice the pitch period. The audio transcript of the VDR notes two episodes in the 1:00 to 1:30 AM local time frame when the crew on watch noted a single roll that was noticeably larger than they had been experiencing. The VDR speed and heading and the WAV_III wave information run in WASIM develop a mean roll zero crossing period that is 1.97 times the pitch zero crossing period, in long crested seas. This indicates that at least a brief episode of parametric roll is plausible. The re-analysis of the VDR high precision latitude and longitude data indicate that these unusual motions were recorded at some level. A further analysis beyond the scope of the current study, may be able to reach a more definitive answer concerning Parametric Roll on the El Faro. The Audio recording suggests that there was nothing with a recognizable pattern so parametric roll is not indicated as a primary cause of the sinking.

8.5 RORO Tetris

The RORO cargo could have theoretically broken free and all slid over to one side of the ship. If rectangles to scale for each vehicle in a hold were placed in their notional lashed position, and then moved over to one side with perhaps 10 to 20% compression due to collision damage, there is a maximum distance that the CG could move from the lashed position. For the trailer cargo, the geometry is fairly well known but for much of the rest of the cargo, including autos and UPS trucks, etc. the geometry is only notional. For instance, an SUV fits different than a sports car or a sub-compact and no data was provided as to what type of “Auto” was where. Given that some of the lashings would likely fail before others it was not clear how to model translation versus rotation of the vehicles. The truck sticking out of the starboard side indicates that at least some sort of lashing remains intact on the front of the truck, but that other lashings have failed.

Hence, while this seemed at first like a good idea, it was not pursued further than a notional evaluation of the concept.

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10 Appendix 1: Weights Accounting

The input data on the weights and stability parameters were supplied as a partial CargoMax output file and as a group of other PDF documents including.

- Capacity plan (PDF and AutoCAD versions)
- General Arrangement Drawing (GA) necessary for locating weight items in 3D space, which proved problematic due to drawing errors.
- NAU_viCCI_Final Stow Plan EF185JAX (48) Lashings (20 pages in several formats)
- Sea Star Line Cargo Securing Manual, (multiple documents)
- NAU_viCCI_Tote Lashing Manual
- Trim & Stability (T&S) booklet for El Faro, Revision E, Herbert Engineering 2007
- HERBERT Engineering Drawing S5L-670-100-003, Rev 1, MV Northern Lights, Fixed Ballast Installation.

Table 10-1: Departure Condition CargoMax Summary

Sea Star Line -- SS El Faro (17 Jun 2010) Printed at: 17:56 on 29 Sep 2015
CargoMax 1.21.0203 (01 Jun 2010) Voyage No. -- 185

DEPARTURE Trim & Stability Summary
JAX FINAL

ITEM	WEIGHT LTons	VCG ft-BL	LCG ft-MS	TCG ft-CL	FSmom ft-LTons
Lightship	19,943.0	27.820	45.135A	0.000	
Constant	171.9	52.859	52.932A	0.000	0.0
Containers	6,862.1	77.028	45.019A	0.102P	
RoRo Cargo	4,183.8	38.434	5.172F	0.907S	
Misc. Weight	0.0	---	---	---	
Fuel Oil	1,472.0	5.849	89.729A	0.000	10,922.3
Fresh Water	1,863.0	11.892	37.700F	0.543S	2,620.9
SW Ballast	238.0	17.510	63.674F	9.049S	228.4
Misc. Tanks	80.7	25.207	92.211F	4.176P	109.2
TOTALS	34,814.5	37.061	35.496A	0.170S	13,880.9
TOTAL DWT	14,871.6				

10.1 Goals:

The goals of this part of the study were exploratory to some extent because no-one had tried to do this sort of study using this suite of tools before. Some of the weights and centers permutations would likely be important, while others would be third or fourth order effects, and no rules of thumb or prior results exist to provide guidance as to which was critical versus not. Therefore, some goals became questions:

- How does the CG of the ship change when containers fall off?
    - How does that affect the gyradii and moments of inertia and hence the natural frequencies of the principle motions in roll, pitch and heave?
- How does movement of the RORO cargo affect the CG?
- Is the information in the CargoMax printout correct?

- What is the effect of flooding in the various holds on drafts, CG, heel and trim?

None of these sorts of questions can be tackled without a reliable weights accounting with sufficient detail such that individual components can be changed to assess the effect on the whole ship.

10.2 Challenges:

There are numerous challenges involved with applying this as input data to the various models such that it became necessary to try to recreate significant portions of the missing weights report from scratch in Excel. The deficiencies included:

- No breakdown of the lightship weight in the CargoMax model or justification that it matches the modified ship.
- The container weights were summed by cargo bay but no attempt had been made to establish a transverse or vertical center of gravity for the containers or their cargo. The CargoMax readout used generic TCG, VCG values for all of the bays.
- The RORO cargo was also summarized with standardized values for the VCG and TCG regardless of the actual cargo.
- The fuel oil burn-off was provided by Dr. Jeff Stettler and his team at the USCG MSC fairly early in the process.

10.3 Roll Gyradius Sensitivity Study

One of the plausible areas where the models might be sensitive to the weights and centers was with respect to the roll gyradius. A simple test was devised whereby the same run was repeated 3 times at the normal and then +/- 8% of the roll gyradius value. The results shown in Table 10-2 suggest that the roll gyradius does not have a huge influence. Perhaps repeating this at a higher sea state and / or speed would be worthwhile.

Table 10-2: Output data from Roll Gyradius Sensitivity Study

		Bretschneider													
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**Heading**	**Draft AP**	**Draft FP**	**Duration**		Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
10	**3**	1.25	7.5	deg	m		**sec**		m	m	m	deg	deg	deg	m
		we	POE	**135**	**9.933**	**8.166**	**2480**	Mean	-363.01	1.16	0.33	1.50	-0.17	-3.22	0.00
5.144	0.837758	1.09808	5.722	**45 Off Head Seas**				Standard Deviation	240.97	4.19	0.16	0.95	0.15	1.25	0.31
	Wave Encounters		**433**	Realization	**R1**			Minimum	-748.23	-9.71	-0.13	-1.62	-0.54	-5.03	-1.29
				TCG=-0.052m				Maximum	3.50	12.43	0.92	5.17	0.17	0.82	1.13
RGR=	10.2590							***RMS***	444.21	4.43	0.37	1.81	0.23	3.53	0.32
PGR=	56.4810	**Original Gyradius Values**													
YGR=	56.5230														
		Bretschneider													
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**Heading**	**Draft AP**	**Draft FP**	**Duration**		Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
10	**3**	1.25	7.5	deg	m		**sec**		m	m	m	deg	deg	deg	m
		we	POE	**135**	**9.933**	**8.166**	**2480**	Mean	-358.00	1.60	0.33	1.49	-0.16	-3.23	0.00
5.144	0.837758	1.09808	5.722	**45 Off Head Seas**				Standard Deviation	236.75	4.58	0.15	0.95	0.15	1.04	0.31
	Wave Encounters		**433**	Realization	**R1**			Minimum	-740.17	-11.03	-0.18	-1.81	-0.49	-4.71	-0.99
				TCG=-0.052m				Maximum	3.48	12.50	0.91	4.47	0.17	0.05	1.15
RGR=	9.4383							***RMS***	437.57	4.95	0.37	1.80	0.22	3.46	0.32
PGR=	51.9625	**Original Gyradius numbers less 8%**													
YGR=	52.0010														
		Bretschneider													
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**Heading**	**Draft AP**	**Draft FP**	**Duration**		Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
10	**3**	1.25	7.5	deg	m		**sec**		m	m	m	deg	deg	deg	m
		we	POE	**135**	**9.933**	**8.166**	**2480**	Mean	-361.44	1.56	0.33	1.49	-0.17	-3.25	0.00
5.144	0.837758	1.09808	5.722	**45 Off Head Seas**				Standard Deviation	239.48	4.63	0.15	0.95	0.15	1.09	0.31
	Wave Encounters		**433**	Realization	**R1**			Minimum	-745.13	-11.19	-0.20	-1.77	-0.50	-4.83	-0.99
				TCG=-0.052m				Maximum	3.49	12.95	0.95	4.43	0.18	0.05	1.14
RGR=	11.0797							***RMS***	442.03	4.99	0.37	1.80	0.23	3.50	0.32
PGR=	60.9994	**Original Gyradius numbers Plus 8%**													
YGR=	61.0448														

11 Appendix 2: Phase 1 Data

This Appendix contains the runs matrix comprising 170 individual 40 minute WASIM simulations, followed by:

- The Motions results
- The Container accelerations results
- The RORO cargo accelerations results
- The accelerations in the human inhabited spaces, and including the accelerations acting in the Lube Oil tank adjacent to the engine room
- The pressures results at the 60 different vent locations.

11.1 Phase 1 Runs Matrix

These results are presented from the lowest sea state to the highest.

Table 11-1: Runs Matrix in Sea States 3, 4 and 5

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Added Roll Damping	Realization	Period of Encounter	Nominal No. Waves encountered	Draft AP	Draft FP	Duration
10	3	1.25	7.5	180	Head Seas	Short	None	R0	5.21	476	9.933	8.166	2480
10	3	1.25	7.5	180	Head Seas	Long	None	R0	5.21	476	9.933	8.166	2480
10	3	1.25	7.5	150	30 Off Head Seas	Long	None	R0	5.43	457	9.933	8.166	2480
10	3	1.25	7.5	120	60 Off Head Seas	Long	None	R0	6.15	403	9.933	8.166	2480
10	3	1.25	7.5	90	Beam Seas	Long	None	R0	7.50	331	9.933	8.166	2480
10	3	1.25	7.5	60	120 Off Head Seas	Long	None	R0	9.61	258	9.933	8.166	2480
10	3	1.25	7.5	30	150 Off Head Seas	Long	None	R0	12.11	205	9.933	8.166	2480
10	3	1.25	7.5	0	Following Seas	Long	None	R0	13.38	185	9.933	8.166	2480
10	3	1.25	7.5	0	Following Seas	Short	None	R0	13.38	185	9.933	8.166	2480
10	4	2.5	8.8	180	Head Seas	Short	None	R0	6.40	387	9.933	8.166	2480
10	4	2.5	8.8	180	Head Seas	Long	None	R0	6.40	387	9.933	8.166	2480
10	4	2.5	8.8	150	30 Off Head Seas	Long	None	R0	6.64	373	9.933	8.166	2480
10	4	2.5	8.8	120	60 Off Head Seas	Long	None	R0	7.41	335	9.933	8.166	2480
10	4	2.5	8.8	90	Beam Seas	Long	None	R0	8.80	282	9.933	8.166	2480
10	4	2.5	8.8	60	120 Off Head Seas	Long	None	R0	10.83	229	9.933	8.166	2480
10	4	2.5	8.8	30	150 Off Head Seas	Long	None	R0	13.02	190	9.933	8.166	2480
10	4	2.5	8.8	0	Following Seas	Long	None	R0	14.07	176	9.933	8.166	2480
10	4	2.5	8.8	0	Following Seas	Short	None	R0	14.07	176	9.933	8.166	2480
18	5	4.00	9.7	180	Head Seas	Long	None	R0	6.02	412	9.933	8.166	2480
18	5	4.00	9.7	180	Head Seas	Long	None	R1	6.02	412	9.933	8.166	2480
18	5	4.00	9.7	150	30 Off Head Seas	Long	None	R1	6.34	391	9.933	8.166	2480
18	5	4.00	9.7	135	45 Off Head Seas	Long	None	R1	6.77	366	9.933	8.166	2480
18	5	4.00	9.7	120	60 Off Head Seas	Long	None	R1	7.43	334	9.933	8.166	2480
18	5	4.00	9.7	90	Beam Seas	Long	None	R1	9.70	256	9.933	8.166	2480
18	5	4.00	9.7	60	120 Off Head Seas	Long	None	R1	13.97	177	9.933	8.166	2480
18	5	4.00	9.7	30	150 Off Head Seas	Long	None	R1	20.62	120	9.933	8.166	2480
18	5	4.00	9.7	0	Following Seas	Long	None	R1	24.97	99	9.933	8.166	2480

Table 11-2: Runs Matrix in Sea State 6

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Period of Encounter	Nominal No. Waves encountered	Draft AP	Draft FP	Duration
10	6	6.00	12.4	180	Head Seas	Long	None	R1	9.80	253	9.933	8.166	2480
10	6	6.00	12.4	150	30 Off Head Seas	Long	None	R1	10.08	246	9.933	8.166	2480
10	6	6.00	12.4	135	45 Off Head Seas	Long	None	R1	10.44	238	9.933	8.166	2480
10	6	6.00	12.4	180	Head Seas	Short	First	R1	9.80	253	9.933	8.166	2480
10	6	6.00	12.4	180	Head Seas	Long	First	R1	9.80	253	9.933	8.166	2480
10	6	6.00	12.4	150	30 Off Head Seas	Long	First	R1	10.08	246	9.933	8.166	2480
10	6	6.00	12.4	135	45 Off Head Seas	Long	First	R1	10.44	238	9.933	8.166	2480
10	6	6.00	12.4	120	60 Off Head Seas	Long	First	R1	10.95	227	9.933	8.166	2480
10	6	6.00	12.4	90	Beam Seas	Long	First	R1	12.40	200	9.933	8.166	2480
10	6	6.00	12.4	60	120 Off Head Seas	Long	First	R1	14.30	173	9.933	8.166	2480
10	6	6.00	12.4	30	150 Off Head Seas	Long	First	R1	16.11	154	9.933	8.166	2480
10	6	6.00	12.4	0	Following Seas	Long	First	R1	16.89	147	9.933	8.166	2480
10	6	6.00	12.4	0	Following Seas	Short	First	R1	16.89	147	9.933	8.166	2480
10	6	6.00	12.4	180	Head Seas	Short	8 Deg	R1	9.80	131	9.933	8.166	1280
10	6	6.00	12.4	150	30 Off Head Seas	Long	8 Deg	R1	10.08	127	9.933	8.166	1280
10	6	6.00	12.4	135	45 Off Head Seas	Long	8 Deg	R1	10.44	123	9.933	8.166	1280
10	6	6.00	12.4	120	60 Off Head Seas	Long	8 Deg	R1	10.95	117	9.933	8.166	1280
10	6	6.00	12.4	90	Beam Seas	Long	8 Deg	R1	12.40	103	9.933	8.166	1280
10	6	6.00	12.4	60	120 Off Head Seas	Long	8 Deg	R1	14.30	90	9.933	8.166	1280
10	6	6.00	12.4	30	150 Off Head Seas	Long	8 Deg	R1	16.11	79	9.933	8.166	1280
10	6	6.00	12.4	0	Following Seas	Short	8 Deg	R1	16.89	76	9.933	8.166	1280

Table 11-3: Runs Matrix in Sea State 7

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Period of Encounter	Nominal No. Waves encountered	Draft AP	Draft FP	Duration
5	7	9.00	12.4	180	Head Seas	Short	8 Deg	R1	10.95	227	9.933	8.166	2480
4	7	7.45	11.168	180	Head Seas	Long	8 Deg	R1	9.99	248	9.933	8.166	2480
4	7	7.45	11.168	150	30 Off Head Seas	Long	8 Deg	R1	10.13	245	9.933	8.166	2480
4	7	7.45	11.168	135	45 Off Head Seas	Long	8 Deg	R1	10.31	241	9.933	8.166	2480
4	7	7.45	11.168	120	60 Off Head Seas	Long	8 Deg	R1	10.55	235	9.933	8.166	2480
4	7	7.45	11.168	90	Beam Seas	Long	8 Deg	R1	11.17	222	9.933	8.166	2480
4	7	7.45	11.168	60	120 Off Head Seas	Long	8 Deg	R1	11.87	209	9.933	8.166	2480
4	7	7.45	11.168	30	150 Off Head Seas	Long	8 Deg	R1	12.44	199	9.933	8.166	2480
4	7	7.45	11.168	0	Following Seas	Short	8 Deg	R1	12.66	196	9.933	8.166	2480
4	7	7.45	11.168	90	Beam Seas	Long	8 Deg	R1	11.17	222	9.933	8.166	2480
4	7	7.45	11.168	90	Beam Seas	Long	14 Deg	R1	11.17	161	9.933	8.166	1800
4	7	7.45	11.168	90	Beam Seas	Short	16 Deg	R0	11.17	222	9.933	8.166	2480
4	7	7.45	11.168	90	Beam Seas	Short	16 Deg	R2	11.17	222	9.933	8.166	2480
4	7	7.45	11.168	60	120 Off Head Seas	Long	8 Deg	R1	11.87	209	9.933	8.166	2480
4	7	7.45	11.168	60	120 Off Head Seas	Long	12 Deg	R1	11.87	209	9.933	8.166	2480
4	7	7.45	11.168	60	120 Off Head Seas	Long	16 Deg	R1	11.87	209	9.933	8.166	2480
4	7	7.45	11.168	30	150 Off Head Seas	Long	8 Deg	R1	12.44	199	9.933	8.166	2480
4	7	7.45	11.168	30	150 Off Head Seas	Long	12 Deg	R2	12.44	199	9.933	8.166	2480
4	7	7.45	11.168	30	150 Off Head Seas	Long	16 Deg	R3	12.44	199	9.933	8.166	2480
4	7	7.45	11.168	0	Following Seas	Short	8 Deg	R1	12.66	196	9.933	8.166	2480
4	7	7.45	11.168	0	Following Seas	Short	12 Deg	R2	12.66	196	9.933	8.166	2480
4	7	7.45	11.168	0	Following Seas	Short	16 Deg	R3	12.66	196	9.933	8.166	2480
1	7	7.45	11.168	180	Head Seas	Short	8 Deg	R1	10.85	229	9.933	8.166	2480
1	7	7.45	11.168	150	30 Off Head Seas	Long	12 Deg	R1	10.89	228	9.933	8.166	2480
1	7	7.45	11.168	135	45 Off Head Seas	Long	14 Deg	R1	10.94	227	9.933	8.166	2480
1	7	7.45	11.168	120	60 Off Head Seas	Long	14 Deg	R1	11.01	67	9.933	8.166	741.4
1	7	7.45	11.168	90	Beam Seas	Long	22 Deg	R1	11.17	222	9.933	8.166	2480
1	7	7.45	11.168	60	120 Off Head Seas	Long	40 Deg	R1	11.34	219	9.933	8.166	2480
1	7	7.45	11.168	30	150 Off Head Seas	Long	8 Deg	R1	11.46	216	9.933	8.166	2480
1	7	7.45	11.168	0	Following Seas	Short	8 Deg	R1	11.51	216	9.933	8.166	2480
1	7	7.45	11.168	75	15 off Beam Seas	Short	30 Deg	R10	11.25	220	9.933	8.166	2480
1	7	7.45	11.168	75	15 off Beam Seas	Long	30 Deg	R9	11.25	220	9.933	8.166	2480
1	7	7.45	11.168	75	15 off Beam Seas	Long	30 Deg	R0_40Comp	11.25	220	9.933	8.166	2480
1	7	7.45	11.168	90	Beam Seas	Long	30 Deg	R8	11.17	222	9.933	8.166	2480
1	7	7.45	11.168	90	Beam Seas	Short	30 Deg	R12	11.17	222	9.933	8.166	2480
1	7	7.45	11.168	90	Beam Seas	Short	30 Deg	R14	11.17	222	9.933	8.166	2480
1	7	7.45	11.168	105	15 off Beam Seas	Long	30 Deg	R11	11.08	224	9.933	8.166	2480
1	7	7.45	11.168	105	15 off Beam Seas	Long	30 Deg	R1_40Comp	11.08	224	9.933	8.166	2480

Many of the conditions in table 12-3 were investigating the sensitivity to the input roll damping parameters.

Table 11-4: Runs Matrix in Sea State 7, After Loss of Power, Near Beam Sea Conditions

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Period of Encounter	Nominal No. Waves encountered	Draft AP	Draft FP	Duration
1	7	8.45	12.3	105	-15 off Beam Seas	Long	30 Deg	R0	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Long	30 Deg	R6	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Long	30 Deg	R16	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Long	30 Deg	R24	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Long	30 Deg	R32	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Long	30 Deg	R40	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Short	30 Deg	R0	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Short	30 Deg	R11	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Short	30 Deg	R20	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Short	30 Deg	R28	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Short	30 Deg	R36	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Short	30 Deg	R44	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	105	-15 off Beam Seas	Short	30 Deg	R50	12.22	203	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R0	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R5	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R8	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R15	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R18	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R23	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R26	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R31	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R34	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R39	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R42	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R10	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R19	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R27	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R35	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R43	12.39	200	9.933	8.166	2480
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R47	12.39	200	9.933	8.166	2480

Table 11-5: Runs Matrix in Sea State 7, After Loss of Power, Beam Sea Conditions and in an Estimated Sinking Condition Seas State 8.

										Nominal			
				Heading			Roll		Period of	No. Waves			
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization	Encounter	encountered	Draft AP	Draft FP	Duration
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R0	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R2	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R7	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R17	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R25	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R34	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R37	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R41	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Long**	30 Deg	R47	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R3	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R4	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R12	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R14	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R21	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R22	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R29	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R30	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R38	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R45	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R46	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R51	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	**Short**	30 Deg	R52	12.30	202	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	105	-15 off Beam Seas	**Long**	30 Deg	**R0**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	90	Beam Seas	**Long**	30 Deg	**R0**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	75	+15 off Beam Seas	**Long**	30 Deg	**R0**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	105	-15 off Beam Seas	**Long**	30 Deg	**R2**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	90	Beam Seas	**Long**	30 Deg	**R2**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	75	+15 off Beam Seas	**Long**	30 Deg	**R2**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	90	Beam Seas	**Short**	30 Deg	**R0**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	90	Beam Seas	**Short**	30 Deg	**R2**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	105	-15 off Beam Seas	**Long**	30 Deg	**R4**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	90	Beam Seas	**Long**	30 Deg	**R5**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	75	+15 off Beam Seas	**Long**	30 Deg	**R3**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	105	-15 off Beam Seas	**Long**	30 Deg	**R7**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	90	Beam Seas	**Long**	30 Deg	**R8**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	75	+15 off Beam Seas	**Long**	30 Deg	**R6**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	90	Beam Seas	**Short**	30 Deg	**R9**	12.59	197.0	9.933	8.166	2480
1	**8**	**9.76**	**12.25**	90	Beam Seas	**Short**	30 Deg	**R10**	12.59	197.0	9.933	8.166	2480

Table 11-6: Set of Stairstep Runs Where Wave Parameters Were Increased Incrementally To Investigate The Onset Of Green Water Reaching The 2nd Deck And Vents

									Nominal				
		Stairstep		Heading			Roll		Period of	No. Waves			
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization	Encounter	encountered	Draft AP	Draft FP	Duration
14	5	4.00	9.7	135	45 Off Head Seas	Long	30 Deg	**R1**	7.3	342	9.933	8.166	2480
14	6	5.00	11.13	135	45 Off Head Seas	Long	30 Deg	**R1**	8.6	288	9.933	8.166	2480
14	6	6.00	12.4	135	45 Off Head Seas	Long	30 Deg	**R1**	9.8	253	9.933	8.166	2480
14	7	7.00	13.25	135	45 Off Head Seas	Long	30 Deg	**R1**	10.6	233	9.933	8.166	2480
14	7	7.25	13.49	135	45 Off Head Seas	Long	30 Deg	**R1**	10.9	228	9.933	8.166	2480
14	7	7.50	13.74	135	45 Off Head Seas	Long	30 Deg	**R1**	11.1	223	9.933	8.166	2480
14	7	7.75	13.97	135	45 Off Head Seas	Long	30 Deg	**R1**	11.3	219	9.933	8.166	2480
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	**R1**	11.5	215	9.933	8.166	2480
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	**R2**	11.5	215	9.933	8.166	2480
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	**R3**	11.5	215	9.933	8.166	2480
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	**R4**	11.5	215	9.933	8.166	2480
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	**R5**	11.5	215	9.933	8.166	2480
14	7	8.25	14.42	135	45 Off Head Seas	Long	30 Deg	**R1**	11.8	211	9.933	8.166	2480
14	7	8.50	14.63	135	45 Off Head Seas	Long	30 Deg	**R1**	12.0	207	9.933	8.166	2480
14	7	8.75	14.83	135	45 Off Head Seas	Long	30 Deg	**R1**	12.2	204	9.933	8.166	2480
14	**8**	9.00	15	135	45 Off Head Seas	Long	30 Deg	**R1**	12.3	201	9.933	8.166	2480

11.2 Phase 1 Motions Data Item Description

This section begins with an explanation of the data architecture in use that propagates through almost all of the data being studied.

11.2.1 Data File Nomenclature

The different analyses are grouped into separate directories by sea state, draft conditions and phase of the analyses. Each WASIM or WADAM run produces an entire directory of output and input files. Each Orcaflex File and SHCP file produce a single file. Each one of any of these 4 runs has a separate excel spreadsheet where large chunks of the data are aggregated for analysis.

The typical file naming format is El _Faro_SS6_150deg_10kn_LC_8RD_R1
Where the ship name identifies the project, the SS6 identifies the sea state in broad terms, the heading is defined by the 180 degrees = head seas nomenclature, and the speed is in knots. LC is long crested meaning all of the waves are coming from exactly the same direction. SC is short crested meaning that each of the 200 unevenly spaced spectral components are coming from randomized directions about a 90-degree arc centered on the stated direction. The 8RD identifies which roll damping parameters were in use for this run. The last term R1 identifies that this is the first realization in terms of the seed setting of the random number generator that controls the wave component phases.

11.2.2 Typical Motions Format

Table 11-7: Typical Motions Format

		Bretschneider																				
Speed	Seastate	H/13 (m)	Tm(sec)	Heading	Draft AP	Draft FP	Duration		Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave			Heave	Roll	Pitch	
10	4	2.50	8.80	deg	m		sec	Mean	5.07	0.82	0.19	2.03	0.05	-0.26	0.00	Ratio		Parameter	Period	Period	Period	POE
		we	POE	150	9.933	8.166	2480	Maximum	9.39	3.00	1.24	3.86	0.67	0.22	2.36	1.78		Mean	7.34852	15.5359	7.83687	6.64
5.14	0.71	0.95	6.64	30 deg off Head seas				Minimum	0.00	-0.57	-0.93	0.00	-0.62	-0.80	-2.09			Maximum	21.75	29.35	21.8	
	Wave Encounters		373	Realization	R3			Std Dev	1.79	0.56	0.32	0.38	0.19	0.18	0.62			Minimum	0	0	0	
								RMS	5.24	1.08	0.37	2.09	0.19	0.28	0.59			Std Dev	1.87811	5.83946	1.70125	
								Range	4.69	1.78	1.08	1.93	0.64	0.51	2.22			*Range*	21.75	29.35	21.8	

All of the data in this report begins with a single time series run in WASIM or Orcaflex. These are captured in excel in approximately the format shown in Table 11-7. The left-hand side captures the input conditions of speed, heading, wave parameters, nominal period of encounter, nominal number of wave encountered, duration, and draft conditions. The heading relative to waves is given in degrees and also in words because different conventions are in use in the hydrodynamics community and it can get confusing. Head seas are always head seas but they can be either zero or 180 degrees depending on the data source.

Each Motion degree of freedom has the mean, max, min, standard deviation, RMS and Range calculated for the time series. In general, only the maxima and either the RMS or the Standard Deviation are presented when they are lumped together. The full form version has 6 columns for the velocities and 6 for the accelerations of the rigid body as a whole. These were redacted to simplify the presentation here.

The wave ratio is simply the maximum less the minimum in the whole-time series divided by the input significant wave height. The trend is toward larger ratios with the greater number of waves encountered, however there is a large variation from one realization to the next as well.

The last block on the far left appears only in the motions tab. The post processing routine calculates the mean for each of the 3 or 4 parameters, Heave, Roll, Pitch and Wave Height? and then runs through the time series and catches each up crossing of the mean such that a "period" for each wave form is calculated. From this list of up-crossings the mean and other statistics are calculated. This was instituted to try to get a feel for the ship’s gross response and what, if any, relationship between the response periods and the periods of encounter might be. This information gets interesting when short crested seas are used. The nominal of encounter period is from a textbook equation for long crested seas and the nominal number of encounters is the run duration divided by the nominal period of encounter.

11.3 Motions Data Summary

The sea state 3 and 4 data were produced early in the study as a quality check that the program was predicting reasonable results. The weird mean heave was corrected for later runs by changing how the volume of the appendages below the water line are modeled. In problematic runs, the Yaw typically diverges by large angles and that did not occur here. There are several plots made that also allow quality control to be checked at a glance. These are not useful for anything else but are part of the CSRA programmatic quality control.

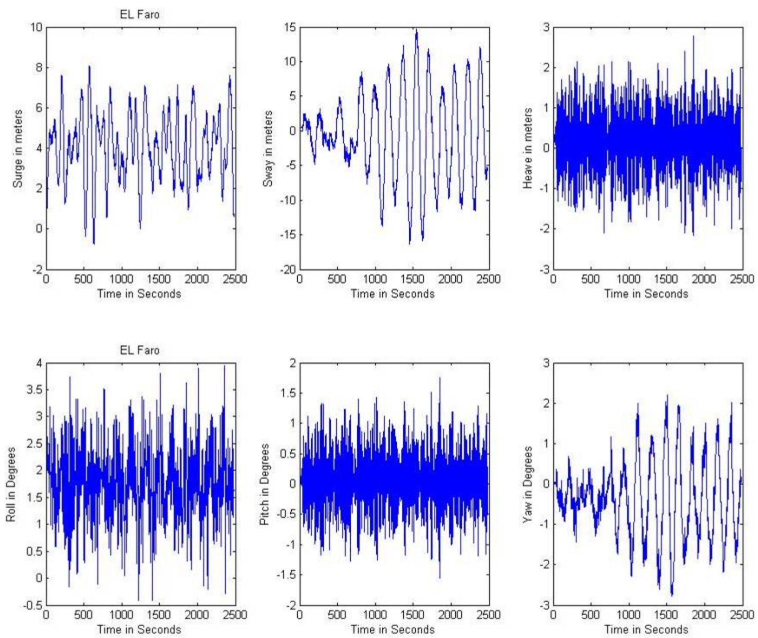


Figure 11-1: Typical 6 DOF Quality Control Plot

Table 11-8: El Faro Motions in Sea State 3, from WASIM Non-Linear

															Mean			
				Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave	Heave	Roll	Pitch	
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**Words**	**deg**		m	m	m	deg	deg	deg	m	Ratio	Period	Period	Period	POE
10	**3**	**1.25**	**7.50**	**Head seas**	**180**	Maximum	7.10	0.00	0.46	0.00	0.19	0.00	1.12	2.15	6.09	20.61	6.36	5.21
knots				**30 deg off Head seas**	**150**	Maximum	7.18	2.08	0.52	3.86	0.24	0.17	1.35	1.93	6.29	9.09	6.58	5.43
				60 deg off Head seas	**120**	Maximum	7.28	3.49	1.02	2.99	0.47	0.47	1.42	2.04	6.65	9.84	6.91	6.15
				Beam seas	**90**	Maximum	7.18	3.04	1.26	2.99	0.38	0.46	1.14	1.93	7.00	11.58	6.57	7.50
				120 deg off Head seas	**60**	Maximum	6.96	9.36	0.87	3.11	0.39	2.68	1.10	1.79	9.98	10.95	9.94	9.61
				150 deg off Head seas	**30**	Maximum	7.79	3.37	0.63	3.00	0.25	0.82	1.32	1.99	12.35	12.54	12.17	12.11
				Following seas	**0**	Maximum	7.36	3.07	0.46	2.99	0.18	0.15	1.02	1.63	13.50	34.30	13.57	13.38
															Mean			
				Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave		Heave	Roll	Pitch	
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**Words**	**deg**		m	m	m	deg	deg	deg	m		Period	Period	Period	
10	**3**	**1.25**	**7.50**	**Head seas**	**180**	Std Dev	0.61	0.00	0.08	0.00	0.04	0.00	0.31	Std Dev	1.25	7.78	1.51	
knots				**30 deg off Head seas**	**150**	Std Dev	0.63	0.25	0.10	0.15	0.05	0.03	0.31	Std Dev	1.50	5.24	1.51	
				60 deg off Head seas	**120**	Std Dev	0.65	0.47	0.23	0.13	0.13	0.08	0.31	Std Dev	1.31	5.39	1.30	
				Beam seas	**90**	Std Dev	0.62	0.45	0.32	0.12	0.09	0.07	0.31	Std Dev	1.38	6.93	1.03	
				120 deg off Head seas	**60**	Std Dev	0.76	1.93	0.21	0.22	0.11	0.43	0.32	Std Dev	2.06	7.86	1.89	
				150 deg off Head seas	**30**	Std Dev	0.89	0.54	0.11	0.21	0.05	0.13	0.34	Std Dev	1.91	1.73	1.95	
				Following seas	**0**	Std Dev	0.76	0.53	0.08	0.10	0.04	0.10	0.31	Std Dev	2.46	56.91	2.38	

Table 11-9: El Faro Motions in Sea State 4, from WASIM Non-Linear

				Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave		Heave	Roll	Pitch	
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**Words**	**deg**		m	m	m	deg	deg	deg	m	Ratio		Period	Period	Period	POE
10	**4**	**2.50**	**8.80**	**Head seas**	**180**	Maximum	8.78	0.00	0.89	0.00	0.51	0.00	2.06	1.70	Mean	7.4	20.5258	7.86952	6.40
knots				**30 deg off Head seas**	**150**	Maximum	9.39	3.00	1.24	3.86	0.67	0.22	2.36	1.78	Mean	7.34852	15.5359	7.83687	6.64
				60 deg off Head seas	**120**	Maximum	8.49	6.09	2.22	3.17	1.22	1.29	2.27	1.81	Mean	7.3686	13.0601	7.57217	7.41
				Beam seas	**90**	Maximum	8.657227	4.150063	2.42911	3.00	0.63	0.72	1.98	1.75	Mean	7.55	12.01	6.82	8.80
				120 deg off Head seas	**60**	Maximum	7.96	11.74	1.74	3.71	0.85	4.23	2.30	1.78	Mean	11.1473	12.2257	11.2991	10.83
				150 deg off Head seas	**30**	Maximum	10.81	6.58	1.06	3.93	0.50	2.26	2.01	1.65	Mean	13.4277	13.2653	13.7994	13.02
				Following seas	**0**	Maximum	10.48	3.47	0.88	3.00	0.40	0.14	2.51	1.90	Mean	14.0951	15.1497	14.0926	14.07
																Mean			
				Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave		Heave	Roll	Pitch		
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**Words**	**deg**		m	m	m	deg	deg	deg	m		Period	Period	Period		
10	**4**	**2.50**	**8.80**	**Head seas**	**180**	Std Dev	1.60	0.00	0.25	0.00	0.15	0.00	0.62	Std Dev	2.23502	8.27248	1.88155		
knots				**30 deg off Head seas**	**150**	Std Dev	1.79	0.56	0.32	0.38	0.19	0.18	0.62	Std Dev	1.87811	5.83946	1.70125		
				60 deg off Head seas	**120**	Std Dev	1.13	0.98	0.60	0.28	0.36	0.24	0.62	Std Dev	1.81904	6.57934	1.54617		
				Beam seas	**90**	Std Dev	1.059369093	0.6093816	0.67182	0.23	0.17	0.13	0.61	Std Dev	1.81	4.77	1.21		
				120 deg off Head seas	**60**	Std Dev	1.16	2.39	0.52	0.48	0.28	0.69	0.61	Std Dev	2.23546	5.09779	2.19819		
				150 deg off Head seas	**30**	Std Dev	2.41	1.33	0.29	0.58	0.15	0.45	0.66	Std Dev	2.53225	2.68675	2.48224		
				Following seas	**0**	Std Dev	1.88	0.71	0.24	0.14	0.12	0.23	0.69	Std Dev	2.94768	8.34141	3.04364		

Table 11-10: El Faro Motions in Sea State 5, from WASIM Non-Linear

		Bretschneider		Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave		Heave	Roll	Pitch	Waves
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**deg**	**Words**		m	m	m	deg	deg	deg	m	Ratio	Period	Sec	Sec	Sec	Sec
18	**5**	4.00	9.7	**180**	**Head Seas**	Maximum	12.67	2.00	2.29	2.63	1.39	0.19	3.66	1.91	Maximum	21.20	100.25	20.55	8.25
				150	**30 Off Head Seas**	Maximum	9.46	14.78	2.18	3.55	1.31	2.14	3.96	1.99	Maximum	31.45	54.75	18.90	9.70
				135	**45 Off Head Seas**	Maximum	8.09	14.66	2.78	3.95	1.76	2.20	4.32	1.98	Maximum	18.35	47.00	18.05	8.50
				120	**60 Off Head Seas**	Maximum	46.11	173.66	3.49	9.49	1.71	27.35	3.16	1.77	Maximum	35.30	175.20	18.00	10.60
				90	**Beam Seas**	Maximum	8.57	11.21	3.75	5.01	0.85	1.45	3.34	1.79	Maximum	14.70	40.50	11.00	12.55
				60	**120 Off Head Seas**	Maximum	93.91	228.82	2.93	13.43	1.50	36.99	3.18	1.69	Maximum	76.00	179.35	77.15	27.65
				30	**150 Off Head Seas**	Maximum	11.68	7.29	1.38	7.25	0.68	0.79	3.56	1.60	Maximum	36.95	37.45	36.60	42.85
				0	**Following Seas**	Maximum	10.14	3.55	0.96	2.62	0.45	0.35	3.46	1.60	Maximum	60.70	127.90	61.35	53.45
		Bretschneider		**Heading**			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave			Heave	Roll	Pitch	Waves
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**deg**	**Words**		m	m	m	deg	deg	deg	m		Period	Sec	Sec	Sec	Sec
18	**5**	4.00	9.7	**180**	**Head Seas**	Standard Deviation	2.97	0.57	0.53	0.12	0.34	0.08	0.99		Std Dev	1.79	15.48	1.74	1.701535
				150	**30 Off Head Seas**	Standard Deviation	2.08	6.45	0.60	0.51	0.39	0.92	0.99		Std Dev	2.18	8.10	1.74	1.713186
				135	**45 Off Head Seas**	Standard Deviation	1.68	6.45	0.72	0.67	0.46	0.97	0.99		Std Dev	1.73	8.58	1.66	1.853557
				120	**60 Off Head Seas**	Standard Deviation	12.53	59.27	0.94	2.26	0.50	9.18	0.99		Std Dev	2.50	35.89	1.81	2.225457
				90	**Beam Seas**	Standard Deviation	1.32	4.41	1.14	0.69	0.23	0.65	1.00		Std Dev	1.97	5.39	1.20	2.39167
				60	**120 Off Head Seas**	Standard Deviation	21.39	85.67	0.95	3.60	0.45	13.45	0.98		Std Dev	6.30	26.50	6.29	5.01743
				30	**150 Off Head Seas**	Standard Deviation	4.31	2.04	0.58	1.76	0.29	0.30	0.97		Std Dev	4.03	3.29	3.13	8.915924
				0	**Following Seas**	Standard Deviation	3.49	1.48	0.33	0.27	0.15	0.22	1.02		Std Dev	7.89	16.87	8.04	10.52437

Table 11-11: El Faro Motions in Sea State 6, from WASIM Non-Linear (First Cut at Damping Evaluation)

		Bretschneider		Heading				Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave		Heave	Roll	Pitch
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**deg**	**Words**			m	m	m	deg	deg	deg	m	Ratio		Period	Period	Period
10	**6**	6.00	12.4	**180**	**Head Seas**	**Short Crested**	Maximum	15.82	13.84	4.70	4.89	3.11	2.10	5.37	1.78	Maximum	23.90	43.05	18.15
				180	**Head Seas**	**Long Crested**	Maximum	17.97	1.10	5.60	3.01	3.39	0.14	5.12	1.79	Maximum	32.35	55.55	23.65
	FIRST_Damping			**150**	**30 Off Head Seas**	**Long Crested**	Maximum	13.50	16.46	6.05	4.75	3.36	1.69	5.12	1.71	Maximum	27.85	38.30	26.75
	TCG=-0.052m			**135**	**45 Off Head Seas**	**Long Crested**	Maximum	12.86	26.15	5.64	5.55	3.56	3.53	5.82	1.77	Maximum	21.75	45.45	21.20
				120	**60 Off Head Seas**	**Long Crested**	Maximum	11.23	32.01	7.74	8.22	4.10	5.33	5.51	1.73	Maximum	29.85	28.30	22.75
				90	**Beam Seas**	**Long Crested**	Maximum	8.77	12.57	6.59	10.06	0.80	1.94	5.99	1.98	Maximum	19.80	25.85	33.10
				60	**120 Off Head Seas**	**Long Crested**	Maximum	10.97	14.16	6.16	6.95	2.74	4.24	5.26	1.88	Maximum	21.25	37.85	18.70
				30	**150 Off Head Seas**	**Long Crested**	Maximum	14.74	12.32	5.09	5.80	2.59	3.93	4.84	1.63	Maximum	41.35	35.85	24.80
				0	**Following Seas**	**Long Crested**	Maximum	15.88	5.03	3.33	2.58	1.65	0.07	4.35	1.41	Maximum	42.85	75.05	25.40
				0	**Following Seas**	**Short Crested**	Maximum	13.72	18.34	3.95	7.66	2.09	4.76	5.36	1.77	Maximum	22.40	41.00	23.30
		Bretschneider		**Heading**				Surge	Sway	Heave	Roll	Pitch	Yaw	Wave					
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**deg**	**Words**			m	m	m	deg	deg	deg	m					
10	**6**	6.00	12.4	**180**	**Head Seas**	**Short Crested**	*RMS*	3.94	3.11	1.34	2.13	0.79	0.75	1.36					
				180	**Head Seas**	**Long Crested**	*RMS*	6.07	0.45	1.37	1.90	0.84	0.10	1.44					
	FIRST_Damping			**150**	**30 Off Head Seas**	**Long Crested**	*RMS*	5.17	6.17	1.53	2.05	0.93	1.35	1.44					
	TCG=-0.052m			**135**	**45 Off Head Seas**	**Long Crested**	*RMS*	4.26	9.61	1.61	2.18	0.96	1.70	1.41					
				120	**60 Off Head Seas**	**Long Crested**	*RMS*	4.09	13.00	1.73	2.55	0.98	1.80	1.41					
				90	**Beam Seas**	**Long Crested**	*RMS*	4.98	4.57	1.57	2.90	0.22	0.84	1.45					
				60	**120 Off Head Seas**	**Long Crested**	*RMS*	5.65	4.50	1.68	2.44	0.79	1.15	1.42					
				30	**150 Off Head Seas**	**Long Crested**	*RMS*	5.11	3.80	1.27	2.33	0.63	1.41	1.44					
				0	**Following Seas**	**Long Crested**	*RMS*	5.46	1.62	1.12	1.85	0.55	0.61	1.32					
				0	**Following Seas**	**Short Crested**	*RMS*	5.04	4.03	1.27	2.62	0.62	1.00	1.40					

Note Transverse CG based on CargoMax data for departure condition.
The roll damping in this first pass is based on the speed with no adjustment for the maximum roll damping. The intent was to establish a baseline for further refinement.

Table 11-12: El Faro Motions in Sea State 6, from WASIM Non-Linear, 8 degree Roll Damping

				Heading			Roll	Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave		Heave	Roll	Pitch	
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping		m	m	m	deg	deg	deg	m	Ratio	Parameter	Period	Period	Period	POE
10	6	6.00	12.4	180	Head Seas	Short	8 Deg	Maximum	11.70	8.71	6.28	7.36	3.83	2.39	5.34	1.78	Mean	9.91	18.26	9.34	9.80
				150	30 Off Head Seas	Long	8 Deg	Maximum	15.38	14.99	6.34	8.48	3.71	1.93	5.13	1.68	Mean	9.89	17.62	9.90	10.08
	TCG=-0.052m			135	45 Off Head Seas	Long	8 Deg	Maximum	14.66	27.76	7.82	7.55	4.69	3.71	5.59	1.80	Mean	9.70	16.76	9.35	10.44
				120	60 Off Head Seas	Long	8 Deg	Maximum	12.95	35.42	6.07	7.45	3.20	4.11	5.10	1.70	Mean	9.26	16.18	9.06	10.95
				90	Beam Seas	Long	8 Deg	Maximum	8.20	12.58	5.49	10.14	0.65	1.42	5.23	1.71	Mean	9.59	14.63	7.24	12.40
				60	120 Off Head Seas	Long	8 Deg	Maximum	9.62	16.49	6.63	17.58	2.95	3.84	5.42	1.67	Mean	12.62	15.78	12.38	14.30
				30	150 Off Head Seas	Long	8 Deg	Maximum	12.03	9.89	3.96	16.28	1.97	5.20	5.45	1.76	Mean	16.10	16.98	15.71	16.11
				0	Following Seas	Short	8 Deg	Maximum	14.51	13.37	3.80	17.09	1.80	3.15	3.68	1.25	Mean	14.86	16.47	15.40	16.89
				Heading			Roll	Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave						
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping		m	m	m	deg	deg	deg	m						
10	6	6.00	12.4	180	Head Seas	Short	8 Deg	RMS	3.89	2.90	1.39	2.32	0.80	0.70	1.32						
				150	30 Off Head Seas	Long	8 Deg	RMS	4.95	6.10	1.45	2.35	0.88	1.26	1.38						
	TCG=-0.052m			135	45 Off Head Seas	Long	8 Deg	RMS	4.84	11.30	1.61	2.56	0.95	1.80	1.38						
				120	60 Off Head Seas	Long	8 Deg	RMS	3.89	13.56	1.70	2.66	0.95	1.68	1.38						
				90	Beam Seas	Long	8 Deg	RMS	4.81	4.17	1.51	2.92	0.21	0.86	1.38						
				60	120 Off Head Seas	Long	8 Deg	RMS	5.10	4.45	1.63	4.56	0.78	1.24	1.36						
				30	150 Off Head Seas	Long	8 Deg	RMS	4.69	2.54	1.24	5.00	0.62	1.58	1.43						
				0	Following Seas	Short	8 Deg	RMS	5.03	3.27	1.22	4.27	0.59	0.90	1.33						

Based on the results for the previous damping, this set was run with roll damping set for an 8 degree roll.   The first 5 courses look like this is about right, but the cases where the waves are from aft the beam require more.

Table 11-13: El Faro Motions in Sea State 7, from WASIM Non-Linear, 8 degree Roll Damping

				Heading			Roll		Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave		Heave	Roll	Pitch	
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Parameter	m	m	m	deg	deg	deg	m	Ratio	Parameter	Period	Period	Period	POE
4	7	7.45	11.168	180	Head Seas	Long	8 Deg	Maximum	13.06	16.79	7.22	9.74	4.46	4.12	6.39	1.69	Mean	10.00	17.21	10.12	9.99
				150	30 Off Head Seas	Long	8 Deg	Maximum	14.70	13.57	6.04	13.07	3.35	6.61	7.02	1.85	Mean	10.63	17.14	10.54	10.13
	TCG=-0.052m			135	45 Off Head Seas	Long	8 Deg	Maximum	12.11	18.40	8.49	13.75	4.48	18.03	6.56	1.78	Mean	9.86	16.78	9.79	10.31
				120	60 Off Head Seas	Long	8 Deg	Maximum	14.18	22.36	8.74	14.44	4.93	12.97	7.41	1.88	Mean	9.21	17.06	8.70	10.55
				90	Beam Seas	Long	8 Deg	Maximum	12.65	29.52	7.44	24.34	1.58	3.03	6.67	1.73	Mean	9.26	15.79	7.22	11.17
				60	120 Off Head Seas	Long	8 Deg	Maximum	17.80	27.49	10.57	44.19	5.05	1.49	7.21	2.07	Mean	10.73	16.22	10.11	11.87
				30	150 Off Head Seas	Long	8 Deg	Maximum	15.64	1.03	5.89	8.62	2.97	2.58	6.62	1.74	Mean	12.41	16.08	12.35	12.44
				0	Following Seas	Short	8 Deg	Maximum	13.18	16.42	6.06	10.62	2.85	4.32	6.88	1.66	Mean	11.77	16.44	11.94	12.66
				Heading			Roll		Surge	Sway	Heave	Roll	Pitch	Yaw	Wave						
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Parameter	m	m	m	deg	deg	deg	m						
4	7	7.45	11.168	180	Head Seas	Long	8 Deg	Minimum	-11.14	-9.64	-5.58	-7.91	-3.27	-6.13	-6.21						
				150	30 Off Head Seas	Long	8 Deg	Minimum	-12.04	-6.88	-5.15	-7.87	-2.93	-1.14	-6.76						
	TCG=-0.052m			135	45 Off Head Seas	Long	8 Deg	Minimum	-7.25	-15.35	-8.59	-8.90	-4.49	-0.66	-6.69						
				120	60 Off Head Seas	Long	8 Deg	Minimum	-8.41	-11.31	-9.57	-12.26	-4.39	-0.25	-6.57						
				90	Beam Seas	Long	8 Deg	Minimum	-4.03	-4.68	-7.61	-21.46	-1.32	-1.85	-6.23						
				60	120 Off Head Seas	Long	8 Deg	Minimum	-4.13	-12.58	-8.63	-43.41	-4.06	-10.03	-8.19						
				30	150 Off Head Seas	Long	8 Deg	Minimum	-8.40	-19.31	-7.26	-6.79	-3.38	-2.89	-6.31						
				0	Following Seas	Short	8 Deg	Minimum	-6.03	-12.28	-6.38	-8.25	-3.26	-4.21	-5.50						
				Heading			Roll		Surge	Sway	Heave	Roll	Pitch	Yaw	Wave						
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Parameter	m	m	m	deg	deg	deg	m						
4	7	7.45	11.168	180	Head Seas	Long	8 Deg	RMS	4.38	4.38	1.65	2.90	0.95	1.51	1.80						
				150	30 Off Head Seas	Long	8 Deg	RMS	4.64	4.59	1.67	3.31	0.97	1.71	1.80						
	TCG=-0.052m			135	45 Off Head Seas	Long	8 Deg	RMS	3.84	5.28	2.10	3.88	1.18	4.23	1.80						
				120	60 Off Head Seas	Long	8 Deg	RMS	4.01	6.27	2.40	4.38	1.29	4.60	1.81						
				90	Beam Seas	Long	8 Deg	RMS	4.68	5.49	1.95	4.51	0.39	0.89	1.81						
				60	120 Off Head Seas	Long	8 Deg	RMS	6.97	5.95	2.60	11.82	1.19	2.85	1.85						
				30	150 Off Head Seas	Long	8 Deg	RMS	5.11	7.80	1.68	2.43	0.84	0.71	1.82						
				0	Following Seas	Short	8 Deg	RMS	5.26	4.01	1.66	3.44	0.81	1.18	1.85						

The ship got into trouble in hurricane conditions so the lower sea states were differed at this point to focus on the more critical large wave conditions.   This group represents the first pass for damping in these conditions.

Table 11-14: El Faro Motions in Sea State 7, from WASIM Non-Linear, Targeted Roll Damping

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization		Surge m	Sway m	Heave m	Roll deg	Pitch deg	Yaw deg	Wave m	Wave Ratio	Parameter	Heave Period	Roll Period	Pitch Period	POE
4	7	7.45	11.168	90	Beam Seas	Long	8 Deg	R1	Maximum	12.65	29.52	7.44	24.34	1.58	3.03	6.67	1.73	Mean	9.26	15.79	7.22	11.17
4	7	7.45	11.168	90	Beam Seas	Short	16 Deg	R0	Maximum	15.82	18.25	9.68	22.47	3.89	7.88	8.08	2.01	Mean	10.23	16.66	9.82	11.17
4	7	7.45	11.168	90	Beam Seas	Short	16 Deg	R2	Maximum	16.23	20.60	9.48	31.81	5.04	7.25	8.97	2.36	Mean	10.16	16.86	9.96	11.17
4	7	7.45	11.168	60	120 Off Head Seas	Long	8 Deg	R1	Maximum	17.80	27.49	10.57	44.19	5.05	1.49	7.21	2.07	Mean	10.73	16.22	10.11	11.87
4	7	7.45	11.168	60	120 Off Head Seas	Long	12 Deg	R1	Maximum	17.18	14.39	8.15	25.64	3.97	1.32	6.49	1.77	Mean	10.64	16.59	10.24	11.87
4	7	7.45	11.168	60	120 Off Head Seas	Long	16 Deg	R1	Maximum	12.89	14.31	8.33	25.72	4.06	1.51	6.95	1.88	Mean	10.72	16.07	10.45	11.87
4	7	7.45	11.168	30	150 Off Head Seas	Long	8 Deg	R1	Maximum	15.64	1.03	5.89	8.62	2.97	2.58	6.62	1.74	Mean	12.41	16.08	12.35	12.44
4	7	7.45	11.168	30	150 Off Head Seas	Long	12 Deg	R2	Maximum	12.90	2.25	5.37	9.04	2.74	2.43	6.20	1.82	Mean	12.64	15.98	12.90	12.44
4	7	7.45	11.168	30	150 Off Head Seas	Long	16 Deg	R3	Maximum	14.21	2.12	6.52	11.42	3.18	2.51	6.64	1.75	Mean	12.35	16.57	12.35	12.44
4	7	7.45	11.168	0	Following Seas	Short	8 Deg	R1	Maximum	13.18	16.42	6.06	10.62	2.85	4.32	6.88	1.66	Mean	11.77	16.44	11.94	12.66
4	7	7.45	11.168	0	Following Seas	Short	12 Deg	R2	Maximum	11.21	16.66	4.98	9.52	2.38	4.07	5.44	1.53	Mean	11.84	15.91	11.78	12.66
4	7	7.45	11.168	0	Following Seas	Short	16 Deg	R3	Maximum	12.78	14.75	6.03	8.03	2.94	3.70	6.40	1.71	Mean	11.67	15.72	11.25	12.66

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization		Surge m	Sway m	Heave m	Roll deg	Pitch deg	Yaw deg	Wave m
4	7	7.45	11.168	90	Beam Seas	Long	8 Deg	R1	*RMS*	4.68	5.49	1.95	4.51	0.39	0.89	1.81
4	7	7.45	11.168	90	Beam Seas	Short	16 Deg	R0	*RMS*	5.24	4.92	2.42	5.85	1.08	1.94	1.94
4	7	7.45	11.168	90	Beam Seas	Short	16 Deg	R2	*RMS*	5.89	5.33	2.58	7.10	1.18	1.96	2.02
4	7	7.45	11.168	60	120 Off Head Seas	Long	8 Deg	R1	*RMS*	6.97	5.95	2.60	11.82	1.19	2.85	1.85
4	7	7.45	11.168	60	120 Off Head Seas	Long	12 Deg	R1	*RMS*	6.21	3.50	2.34	6.09	1.13	2.25	1.75
4	7	7.45	11.168	60	120 Off Head Seas	Long	16 Deg	R1	*RMS*	6.10	3.71	2.48	5.78	1.21	2.35	1.86
4	7	7.45	11.168	30	150 Off Head Seas	Long	8 Deg	R1	*RMS*	5.11	7.80	1.68	2.43	0.84	0.71	1.82
4	7	7.45	11.168	30	150 Off Head Seas	Long	12 Deg	R2	*RMS*	4.86	7.67	1.60	2.59	0.80	0.90	1.71
4	7	7.45	11.168	30	150 Off Head Seas	Long	16 Deg	R3	*RMS*	4.86	8.16	1.74	2.60	0.88	0.75	1.86
4	7	7.45	11.168	0	Following Seas	Short	8 Deg	R1	*RMS*	5.26	4.01	1.66	3.44	0.81	1.18	1.85
4	7	7.45	11.168	0	Following Seas	Short	12 Deg	R2	*RMS*	4.93	4.42	1.74	2.84	0.86	1.38	1.77
4	7	7.45	11.168	0	Following Seas	Short	16 Deg	R3	*RMS*	4.82	4.66	1.65	2.74	0.79	1.38	1.76

This group focuses on a narrower range of headings while the damping is swept through a range of values to see how hard or relevant it might be to try to dial in the correct numbers. This was also a first attempt at modeling the ship just before and through losing power and the ability to control heading.

Table 11-15: El Faro Motions in Sea State 7, from WASIM Non-Linear, Targeted Roll Damping, Just After Loss of Power.

Just After loss of power				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave		Heave	Roll	Pitch	
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m	Ratio	Parameter	Period	Period	Period	POE
1	7	7.45	11.168	180	Head Seas	Short	8 Deg	R1	Maximum	15.84	37.32	7.55	34.98	3.66	7.33	6.21	1.77	Mean	10.88	16.23	10.51	10.85
1	7	7.45	11.168	150	30 Off Head Seas	Long	12 Deg	R1	Maximum	14.36	10.89	7.05	24.67	3.88	11.86	6.07	1.68	Mean	11.42	17.22	10.96	10.89
1	7	7.45	11.168	135	45 Off Head Seas	Long	14 Deg	R1	Maximum	13.68	21.35	7.77	37.84	3.96	18.73	5.99	1.71	Mean	10.59	16.50	10.42	10.94
1	7	7.45	11.168	90	Beam Seas	Long	22 Deg	R1	Maximum	18.07	26.81	10.48	41.15	4.23	11.55	6.82	1.77	Mean	9.19	15.55	7.31	11.17
1	7	7.45	11.168	60	120 Off Head Seas	Long	40 Deg	R1	Maximum	14.81	38.33	11.56	46.15	4.90	2.63	6.02	1.74	Mean	9.78	16.70	9.55	11.34
1	7	7.45	11.168	30	150 Off Head Seas	Long	8 Deg	R1	Maximum	12.15	19.83	7.02	20.37	3.40	2.74	6.90	1.77	Mean	11.46	17.19	11.46	11.46
1	7	7.45	11.168	0	Following Seas	Short	8 Deg	R1	Maximum	13.87	28.01	6.49	35.82	2.86	6.27	7.53	1.87	Mean	11.28	16.49	11.22	11.51

Just After loss of power				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m
1	7	7.45	11.168	180	Head Seas	Short	8 Deg	R1	Minimum	-13.91	-25.23	-5.34	-33.61	-3.05	-11.04	-7.00
1	7	7.45	11.168	150	30 Off Head Seas	Long	12 Deg	R1	Minimum	-12.46	-21.11	-4.96	-20.65	-2.80	-3.55	-6.48
1	7	7.45	11.168	135	45 Off Head Seas	Long	14 Deg	R1	Minimum	-11.94	-37.42	-6.75	-37.11	-3.58	-7.15	-6.75
1	7	7.45	11.168	90	Beam Seas	Long	22 Deg	R1	Minimum	-17.50	-19.10	-7.56	-39.39	-3.22	-5.74	-6.36
1	7	7.45	11.168	60	120 Off Head Seas	Long	40 Deg	R1	Minimum	-10.64	-7.26	-7.78	-45.17	-4.09	-13.64	-6.97
1	7	7.45	11.168	30	150 Off Head Seas	Long	8 Deg	R1	Minimum	-4.97	-14.56	-7.94	-18.37	-3.78	-9.62	-6.26
1	7	7.45	11.168	0	Following Seas	Short	8 Deg	R1	Minimum	-6.10	-24.27	-5.66	-32.92	-2.80	-5.93	-6.42

Just After loss of power				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m
1	7	7.45	11.168	180	Head Seas	Short	8 Deg	R1	*RMS*	3.86	8.42	1.74	11.13	0.91	2.59	1.76
1	7	7.45	11.168	150	30 Off Head Seas	Long	12 Deg	R1	*RMS*	4.60	4.51	1.69	4.81	0.96	2.37	1.80
1	7	7.45	11.168	135	45 Off Head Seas	Long	14 Deg	R1	*RMS*	3.85	8.35	2.21	8.72	1.17	4.71	1.80
1	7	7.45	11.168	90	Beam Seas	Long	22 Deg	R1	*RMS*	4.47	6.59	2.26	12.63	0.60	2.54	1.81
1	7	7.45	11.168	60	120 Off Head Seas	Long	40 Deg	R1	*RMS*	5.75	11.35	2.70	8.80	1.29	4.21	1.86
1	7	7.45	11.168	30	150 Off Head Seas	Long	8 Deg	R1	*RMS*	5.03	4.64	1.85	5.86	0.92	1.92	1.81
1	7	7.45	11.168	0	Following Seas	Short	8 Deg	R1	*RMS*	4.75	6.41	1.95	8.96	0.93	1.84	1.82

The sweeps through the roll damping showed that the value set had very little effect in this no forward speed condition. A value of 1 knot was kept because the ship was drifting sideways downwind at about 6 knots so the flow over the damping appendages was not zero. This was a judgment call that "some" damping was more realistic than a mathematically artificial zero.

Table 11-16: El Faro Motions in Sea State 7, from WASIM Non-Linear, 30 degree Roll Damping, After Loss of Power.

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Parameter	Surge m	Sway m	Heave m	Roll deg	Pitch deg	Yaw deg	Wave m	Wave Ratio	Parameter	Heave Period	Roll Period	Pitch Period	POE
1	7	7.45	11.168	75	15 off Beam Seas	Short	30 Deg	R10	Maximum	14.04	20.11	8.29	26.67	4.07	6.77	6.87	1.79	Mean	9.47	16.33	9.29	11.25
1	7	7.45	11.168	75	15 off Beam Seas	Long	30 Deg	R9	Maximum	14.03	42.57	12.43	46.19	4.57	4.63	6.44	1.70	Mean	9.36	15.80	8.36	11.25
1	7	7.45	11.168	75	15 off Beam Seas	Long	30 Deg	R0 40comp	Maximum	11.50	26.35	9.44	17.73	4.43	3.10	6.63	1.84	Mean	8.88	16.03	8.25	11.25
1	7	7.45	11.168	90	Beam Seas	Long	30 Deg	R8	Maximum	11.54	15.76	7.09	26.17	1.59	3.91	6.80	1.99	Mean	9.29	16.12	7.00	11.17
1	7	7.45	11.168	90	Beam Seas	Short	30 Deg	R12	Maximum	12.55	18.72	7.90	21.83	3.52	5.83	6.58	1.64	Mean	9.66	16.15	9.59	11.17
1	7	7.45	11.168	90	Beam Seas	Short	30 Deg	R14	Maximum	13.90	22.13	7.58	29.03	3.53	5.31	6.85	1.80	Mean	9.73	16.44	9.65	11.17
1	7	7.45	11.168	105	15 off Beam Seas	Long	30 Deg	R11	Maximum	12.08	20.40	8.82	19.94	3.86	6.85	6.67	1.81	Mean	8.80	16.40	8.33	11.08
1	7	7.45	11.168	105	15 off Beam Seas	Long	30 Deg	R1 40comp	Maximum	13.03	20.18	8.41	16.85	3.94	7.89	5.78	1.91	Mean	9.50	16.55	9.17	11.08

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Parameter	Surge m	Sway m	Heave m	Roll deg	Pitch deg	Yaw deg	Wave m
1	7	7.45	11.168	75	15 off Beam Seas	Short	30 Deg	R10	Minimum	-5.67	-16.92	-8.21	-24.04	-4.16	-6.62	-6.44
1	7	7.45	11.168	75	15 off Beam Seas	Long	30 Deg	R9	Minimum	-0.64	-9.81	-8.92	-40.85	-4.03	-9.41	-6.21
1	7	7.45	11.168	75	15 off Beam Seas	Long	30 Deg	R0 40comp	Minimum	-0.50	-7.38	-9.22	-14.77	-4.06	-7.06	-7.09
1	7	7.45	11.168	90	Beam Seas	Long	30 Deg	R8	Minimum	-2.65	-13.03	-5.86	-21.97	-1.37	-1.52	-8.05
1	7	7.45	11.168	90	Beam Seas	Short	30 Deg	R12	Minimum	-5.76	-12.73	-7.64	-18.81	-3.34	-6.84	-5.63
1	7	7.45	11.168	90	Beam Seas	Short	30 Deg	R14	Minimum	-7.12	-17.30	-7.87	-29.40	-3.89	-5.52	-6.55
1	7	7.45	11.168	105	15 off Beam Seas	Long	30 Deg	R11	Minimum	-6.77	-7.91	-8.85	-17.38	-3.98	-3.51	-6.78
1	7	7.45	11.168	105	15 off Beam Seas	Long	30 Deg	R1 40comp	Minimum	-7.44	-15.30	-7.83	-14.12	-3.86	-5.20	-8.43

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Parameter	Surge m	Sway m	Heave m	Roll deg	Pitch deg	Yaw deg	Wave m
1	7	7.45	11.168	75	15 off Beam Seas	Short	30 Deg	R10	*RMS*	5.39	6.53	2.23	7.97	1.06	2.07	1.70
1	7	7.45	11.168	75	15 off Beam Seas	Long	30 Deg	R9	*RMS*	5.29	10.51	2.78	12.49	1.21	2.42	1.83
1	7	7.45	11.168	75	15 off Beam Seas	Long	30 Deg	R0 40comp	*RMS*	5.17	8.49	2.59	4.17	1.20	1.91	1.80
1	7	7.45	11.168	90	Beam Seas	Long	30 Deg	R8	*RMS*	4.10	4.65	1.94	6.92	0.40	0.88	1.81
1	7	7.45	11.168	90	Beam Seas	Short	30 Deg	R12	*RMS*	4.78	5.26	2.25	4.91	1.02	1.76	1.75
1	7	7.45	11.168	90	Beam Seas	Short	30 Deg	R14	*RMS*	4.37	5.60	2.26	8.24	1.04	1.83	1.74
1	7	7.45	11.168	105	15 off Beam Seas	Long	30 Deg	R11	*RMS*	4.34	5.74	2.38	5.93	1.10	2.10	1.83
1	7	7.45	11.168	105	15 off Beam Seas	Long	30 Deg	R1 40comp	*RMS*	4.49	4.57	2.28	4.78	1.13	1.93	1.81

This block begins to focus on the motions expected in the time after the ship lost power. At the time this was created, there was no specific data on the ship's heading while adrift, so beam seas and (+/-) 15 degrees from beam seas seemed logical to capture the range of plausible motions. After the VDR and WAV_III became available, the best estimated wave heading was about 83 degrees so between the 75 and 90-degree guesstimate used here.

The next step was to sweep through a bunch of realizations at these three courses of 75, 90 and 105 degrees and try to capture the range of variation, and to try to capture the effect of long crested versus short crested waves.

Several of these runs produce capsizing event where the maximum or minimum roll reached 180 degrees indicating that the ship was upside down. While the capacity of this software to accurately model inclinations that large is doubtful, this did raise the possibility that the ship might have capsized due to wind and wave conditions.

Table 11-17: EL Faro Sea State 7 Motions at 15 degrees Aft of Beam Seas After Loss of Power

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Parameter	Surge m	Sway m	Heave m	Roll deg	Pitch deg	Yaw deg	Wave m	Wave Ratio	Parameter	Heave Period	Roll Period	Pitch Period	POE	
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R0	Maximum	14.70	22.10	8.79	20.59	3.51	6.43	7.18	1.69	Mean	9.212082	16.81905	8.852679	12.2153	R0
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R6	Maximum	13.29	17.00	8.44	14.32	3.71	7.43	6.66	1.57	Mean	9.168889	16.03084	8.569377	12.2153	R6
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R16	Maximum	11.31	19.30	8.87	15.99	3.86	5.43	6.94	1.66	Mean	9.320301	15.66266	8.640593	12.2153	R16
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R24	Maximum	10.70	27.33	11.29	33.95	3.90	8.15	9.14	1.98	Mean	9.343397	16.36854	8.512371	12.2153	R24
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R32	Maximum	11.03	37.63	8.51	28.51	4.20	7.23	6.86	1.82	Mean	9.459925	16.42967	8.759541	12.2153	R32
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R40	Maximum	11.70	21.45	10.21	14.71	4.18	7.05	8.47	1.86	Mean	9.245896	16.22336	8.578201	12.2153	R40
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R0	Maximum	17.61	16.43	10.78	29.27	4.88	7.00	6.71	1.73	Mean	9.600776	16.67939	9.63502	12.2153	R0
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R11	Maximum	14.62	16.19	9.18	22.01	4.30	9.56	6.65	1.86	Mean	9.962097	16.90651	9.723426	12.2153	R11
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R20	Maximum	13.76	15.00	10.60	17.15	4.98	10.30	8.12	1.86	Mean	9.926507	16.36821	9.505	12.2153	R20
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R28	Maximum	13.55	18.01	9.41	25.76	5.10	9.38	7.51	1.73	Mean	10.20556	16.6	9.651368	12.2153	R28
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R36	Maximum	16.38	17.84	10.85	20.01	4.41	8.70	6.91	1.75	Mean	10.11	16.24013	9.605427	12.2153	R36
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R44	Maximum	18.32	20.05	8.26	25.56	4.86	8.78	7.91	1.74	Mean	10.12275	16.06851	9.500001	12.2153	R44
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R50	Maximum	13.25	15.56	11.16	24.98	4.62	8.61	6.73	1.63	Mean	10.00547	16.29309	9.72157	12.2153	R50

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Parameter	Surge m	Sway m	Heave m	Roll deg	Pitch deg	Yaw deg	Wave m
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R0	Minimum	-8.14	-8.73	-9.03	-18.24	-3.28	-3.74	-7.10
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R6	Minimum	-7.77	-9.85	-9.48	-11.16	-3.63	-3.61	-6.58
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R16	Minimum	-5.24	-10.04	-9.80	-12.74	-3.74	-3.63	-7.07
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R24	Minimum	-5.73	-16.69	-8.83	-30.93	-3.31	-3.69	-7.60
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R32	Minimum	-6.41	-15.49	-9.16	-27.91	-3.81	-4.76	-8.56
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R40	Minimum	-7.10	-5.98	-10.02	-11.84	-4.46	-3.63	-7.24
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R0	Minimum	-11.49	-18.68	-10.59	-22.74	-5.11	-4.86	-7.94
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R11	Minimum	-8.17	-22.32	-9.13	-20.34	-4.39	-5.29	-9.05
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R20	Minimum	-8.00	-20.28	-9.34	-15.03	-4.70	-3.72	-7.59
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R28	Minimum	-6.99	-16.78	-8.21	-25.76	-4.45	-3.86	-7.13
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R36	Minimum	-10.02	-15.59	-10.05	-15.09	-4.55	-3.44	-7.85
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R44	Minimum	-12.75	-14.26	-7.13	-21.75	-3.96	-4.78	-6.79
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R50	Minimum	-7.77	-21.80	-9.86	-19.60	-3.85	-4.38	-7.01

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Parameter	Surge m	Sway m	Heave m	Roll deg	Pitch deg	Yaw deg	Wave m
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R0	*RMS*	4.59	5.11	2.47	5.70	1.07	1.86	1.95
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R6	*RMS*	4.28	3.88	2.52	4.11	1.08	1.97	1.98
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R16	*RMS*	4.24	4.65	2.64	3.78	1.12	2.00	2.09
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R24	*RMS*	4.35	5.46	2.54	6.43	1.10	2.11	1.99
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R32	*RMS*	3.99	4.97	2.58	6.29	1.10	1.99	2.03
1	7	8.45	12.3	105	-15 of Beam Seas	Long	30 Deg	R40	*RMS*	3.92	5.43	2.50	4.12	1.09	2.08	1.96
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R0	*RMS*	5.21	5.08	2.54	6.33	1.21	1.83	1.93
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R11	*RMS*	4.74	4.81	2.55	5.44	1.27	2.15	2.01
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R20	*RMS*	5.09	5.77	2.60	4.84	1.25	2.38	1.91
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R28	*RMS*	4.31	4.99	2.44	5.26	1.19	2.19	1.99
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R36	*RMS*	4.98	4.73	2.59	4.91	1.24	1.80	2.00
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R44	*RMS*	5.41	5.50	2.40	6.36	1.20	2.10	1.93
1	7	8.45	12.3	105	-15 of Beam Seas	Short	30 Deg	R50	*RMS*	4.41	5.23	2.67	5.72	1.22	2.15	1.98

Table 11-18: EL Faro Sea State 7 Motions in Beam Seas After Loss of Power

				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave		Heave	Roll	Pitch
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m	Ratio	Parameter	Period	Period	Period
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R0	Maximum	12.49	19.75	9.69	25.68	5.32	5.73	7.20	1.68	Mean	10.03	16.63	9.53
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R2	Maximum	12.72	17.87	7.36	28.62	1.42	4.13	7.10	1.66	Mean	9.75	16.16	7.05
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R7	Maximum	9.51	26.97	7.61	34.89	1.92	4.63	6.70	1.69	Mean	9.89	16.38	7.06
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R17	Maximum	11.86	49.28	7.82	38.02	1.81	7.92	7.25	1.71	Mean	9.87	15.76	7.26
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R25	Maximum	11.45	25.45	7.36	23.90	2.38	4.33	6.37	1.51	Mean	9.65	16.23	7.17
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R34	Maximum	9.76	32.91	7.65	32.02	1.64	3.79	7.01	1.59	Mean	9.83	16.02	6.99
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R37	Maximum	24.53	17.15	9.34	23.94	4.45	7.03	7.31	1.65	Mean	10.33	15.89	9.99
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R41	Maximum	11.33	36.07	7.74	28.82	2.24	4.59	7.66	1.89	Mean			
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R47	Maximum	12.44	30.53	6.79	30.70	1.82	4.24	6.88	1.66	Mean	9.80	16.27	7.16
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R3	Maximum	13.47	20.19	8.64	24.90	4.13	6.38	6.95	1.68	Mean	10.52	16.83	9.83
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R4	Maximum	13.48	23.40	9.41	27.26	4.17	7.61	7.56	1.89	Mean	10.22	16.95	9.97
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R12	Maximum	16.95	15.16	9.25	24.49	3.33	7.69	6.87	1.77	Mean	10.36	16.50	9.92
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R14	Maximum	15.05	22.42	9.43	23.47	4.01	6.90	8.34	1.79	Mean	10.09	16.78	9.93
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R21	Maximum	13.58	22.28	10.21	33.37	4.56	6.60	6.64	1.68	Mean	10.45	16.59	9.86
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R22	Maximum	15.02	29.78	9.36	39.12	3.95	7.82	6.96	1.70	Mean	10.37	16.27	9.72
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R29	Maximum	15.77	25.75	8.69	23.35	4.28	8.87	8.37	1.79	Mean	10.01	16.27	9.74
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R30	Maximum	14.44	16.41	9.41	19.25	4.36	8.87	7.73	1.98	Mean	10.43	15.95	10.43
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R38	Maximum	12.90	23.02	9.65	15.42	4.15	8.02	7.23	1.88	Mean	10.19	16.85	9.98
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R45	Maximum	17.72	18.04	9.52	24.16	3.51	7.16	6.90	1.67	Mean	10.32	16.24	9.63
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R46	Maximum	15.12	36.45	8.93	36.47	4.66	8.85	7.40	1.74	Mean	10.11	16.42	9.75
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R51	Maximum	15.34	30.56	9.57	22.17	4.61	8.70	6.70	1.59	Mean	10.31	16.72	10.01
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R52	Maximum	16.70	22.08	9.79	32.37	4.15	7.45	7.23	1.86	Mean			

				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R0	Minimum	-5.01	-13.37	-8.27	-24.95	-4.88	-7.67	-6.98
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R2	Minimum	-4.83	-9.83	-7.41	-27.37	-1.27	-2.25	-6.89
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R7	Minimum	-1.34	-10.62	-6.98	-31.84	-1.31	-2.80	-7.56
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R17	Minimum	-5.14	-20.89	-6.77	-35.72	-1.64	-9.40	-7.18
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R25	Minimum	-3.85	-13.35	-6.49	-22.68	-2.29	-3.61	-6.41
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R34	Minimum	-3.53	-12.53	-6.20	-29.90	-1.59	-3.34	-6.44
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R37	Minimum	-17.96	-15.14	-8.76	-18.45	-3.70	-5.17	-6.60
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R41	Minimum	-3.80	-12.42	-7.93	-26.29	-1.62	-3.55	-8.31
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R47	Minimum	-5.29	-12.19	-6.64	-26.29	-1.48	-4.08	-7.13
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R3	Minimum	-7.02	-13.62	-8.42	-23.61	-3.60	-7.03	-7.22
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R4	Minimum	-5.95	-17.67	-7.22	-25.19	-4.07	-6.85	-8.43
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R12	Minimum	-11.51	-15.09	-8.85	-21.02	-3.58	-4.56	-8.05
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R14	Minimum	-9.49	-15.32	-8.73	-19.23	-3.40	-5.55	-6.76
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R21	Minimum	-5.10	-20.21	-8.90	-28.50	-3.93	-6.25	-7.54
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R22	Minimum	-7.33	-24.92	-8.56	-39.11	-3.19	-7.84	-7.40
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R29	Minimum	-9.23	-17.60	-9.09	-20.45	-3.79	-6.45	-6.76
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R30	Minimum	-7.83	-18.21	-8.25	-15.03	-3.96	-5.74	-9.03
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R38	Minimum	-4.37	-19.97	-9.86	-12.74	-4.18	-8.70	-8.69
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R45	Minimum	-9.44	-18.68	-8.45	-23.24	-3.40	-5.88	-7.21
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R46	Minimum	-8.90	-17.62	-9.41	-32.00	-3.89	-10.55	-7.28
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R51	Minimum	-9.94	-19.13	-10.07	-19.23	-4.04	-9.58	-6.75
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R52	Minimum	-6.62	-16.37	-9.10	-29.21	-4.48	-5.86	-8.50

				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R0	*RMS*	5.39	5.38	2.55	4.86	1.24	1.88	1.84
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R2	*RMS*	4.55	4.60	2.11	7.07	0.36	0.85	1.98
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R7	*RMS*	4.27	5.31	2.09	8.74	0.37	1.05	1.97
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R17	*RMS*	4.35	8.44	2.12	10.13	0.40	1.46	1.97
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R25	*RMS*	4.57	6.39	2.07	9.06	0.39	1.18	1.90
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R34	*RMS*	4.44	5.78	2.08	6.84	0.37	0.73	1.98
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R37	*RMS*	6.11	5.55	2.48	4.14	1.13	1.99	1.93
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R41	*RMS*	4.44	4.39	2.08	6.15	0.37	0.86	1.99
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R47	*RMS*	4.54	5.29	2.07	6.53	0.36	0.90	1.98
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R3	*RMS*	4.75	6.32	2.52	7.03	1.14	2.08	1.96
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R4	*RMS*	4.58	5.93	2.42	5.60	1.11	2.32	2.03
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R12	*RMS*	5.69	4.65	2.46	3.94	1.12	1.93	2.02
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R14	*RMS*	4.69	5.20	2.44	5.97	1.04	1.89	2.02
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R21	*RMS*	5.03	5.91	2.58	7.06	1.17	1.73	1.97
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R22	*RMS*	5.38	7.30	2.67	11.48	1.15	2.20	1.98
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R29	*RMS*	5.32	6.33	2.59	5.17	1.22	2.59	1.91
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R30	*RMS*	5.12	5.55	2.58	4.95	1.15	2.21	2.00
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R38	*RMS*	4.74	5.61	2.54	4.75	1.19	2.20	2.03
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R45	*RMS*	5.78	4.54	2.34	5.40	1.10	1.73	1.90
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R46	*RMS*	5.13	7.30	2.53	7.45	1.12	2.49	2.03
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R51	*RMS*	4.98	5.77	2.46	5.53	1.12	2.16	1.87
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R52	*RMS*	5.05	5.97	2.56	6.54	1.10	1.94	2.02

Table 11-19: EL Faro Sea State 7 Motions 15 degrees forward of Beam Seas After Loss of Power

				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave		Heave	Roll	Pitch	
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m	Ratio	Parameter	Period	Period	Period	POE
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R0	Maximum	12.54	30.81	10.76	21.56	4.57	2.72	6.85	1.71	Mean	9.44	15.83	8.46	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R5	Maximum	14.86	28.52	9.91	29.03	3.71	3.96	6.92	1.72	Mean	9.21	16.17	8.62	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R8	Maximum	18.31	55.40	13.08	50.22	4.10	7.72	8.52	1.88	Mean	9.69	15.64	8.49	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R15	Maximum	10.79	24.40	9.67	17.35	4.28	2.38	6.84	1.65	Mean	9.46	16.28	8.66	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R18	Maximum	17.46	50.64	11.52	53.56	4.35	7.22	7.34	1.83	Mean	9.51	16.13	8.35	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R23	Maximum	11.30	25.39	10.28	27.85	4.25	3.52	6.80	1.67	Mean	9.49	16.12	8.45	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R26	Maximum	18.19	75.81	19.67	67.12	5.24	12.64	6.95	1.70	Mean	9.59	16.03	8.39	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R31	Maximum	12.98	41.55	12.63	44.39	5.01	4.91	7.39	1.68	Mean	9.41	15.95	8.42	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R34	Maximum	13.92	61.23	14.78	54.53	5.02	14.29	9.07	1.96	Mean	9.31	16.00	8.45	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R39	Maximum	12.01	36.07	11.62	47.14	3.86	5.55	8.27	1.78	Mean	9.37	16.26	8.55	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R42	Maximum	12.87	39.47	10.09	41.45	4.22	5.38	6.46	1.65	Mean	9.32	16.18	8.46	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R48	Maximum	27.24	65.80	34.18	60.46	5.30	9.06	8.06	1.89	Mean	9.52	15.88	8.68	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R10	Maximum	15.63	23.87	10.56	30.32	4.25	7.63	6.91	1.61	Mean	9.95	16.48	9.52	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R19	Maximum	17.41	19.64	8.84	26.85	4.09	5.58	7.21	1.73	Mean	9.96	16.29	9.69	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R27	Maximum	17.93	24.38	9.20	27.76	3.95	5.72	7.19	1.66	Mean	10.19	16.62	9.70	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R35	Maximum	13.13	20.89	9.08	26.75	4.48	6.15	7.35	1.69	Mean	10.18	16.39	9.82	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R43	Maximum	14.64	19.01	9.34	25.53	3.93	4.70	7.25	1.71	Mean	10.36	15.77	9.74	12.39
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R47	Maximum	17.82	21.67	10.58	22.06	4.17	7.13	7.74	1.76	Mean	10.20	16.37	9.53	12.39

				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R0	Minimum	-1.18	-5.04	-10.03	-16.87	-4.01	-6.09	-7.62
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R5	Minimum	-3.90	-8.56	-9.16	-27.77	-3.87	-7.11	-7.62
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R8	Minimum	-1.65	-14.51	-8.91	-44.46	-4.28	-8.73	-7.35
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R15	Minimum	0.00	-5.39	-9.72	-12.89	-3.83	-7.79	-7.14
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R18	Minimum	-5.77	-17.72	-8.88	-47.26	-4.14	-10.10	-8.12
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R23	Minimum	-1.15	-7.36	-9.03	-23.39	-4.21	-6.58	-7.30
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R26	Minimum	-6.74	-21.62	-10.95	-49.36	-4.89	-12.67	-7.41
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R31	Minimum	-1.17	-16.31	-8.81	-38.34	-4.78	-8.18	-6.77
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R34	Minimum	-1.85	-36.26	-9.08	-48.12	-4.00	-17.46	-7.52
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R39	Minimum	-1.68	-12.21	-8.75	-45.38	-4.06	-7.51	-6.79
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R42	Minimum	0.00	-13.85	-8.89	-37.79	-4.09	-10.40	-7.48
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R48	Minimum	0.00	-6.24	-10.35	-180.75	-3.21	-11.24	-7.93
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R10	Minimum	-2.61	-18.31	-7.92	-27.93	-4.19	-8.25	-6.68
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R19	Minimum	-6.51	-15.35	-8.27	-22.99	-3.62	-7.43	-7.44
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R27	Minimum	-8.05	-15.12	-9.39	-28.20	-4.50	-9.55	-6.81
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R35	Minimum	-3.94	-12.12	-8.61	-26.19	-4.10	-6.86	-6.97
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R43	Minimum	-4.01	-12.68	-8.59	-23.00	-4.61	-7.20	-7.22
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R47	Minimum	-6.55	-19.02	-9.56	-18.02	-4.55	-6.96	-7.09

				Heading			Roll		Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping	Realization		m	m	m	deg	deg	deg	m
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R0	*RMS*	5.51	9.66	2.80	4.77	1.21	2.07	2.03
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R5	*RMS*	5.46	9.44	2.73	6.29	1.19	1.94	1.97
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R8	*RMS*	5.60	11.68	2.97	13.07	1.22	2.36	1.99
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R15	*RMS*	5.27	9.14	2.88	4.76	1.24	2.04	2.07
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R18	*RMS*	5.78	10.96	2.90	12.95	1.18	2.37	2.00
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R23	*RMS*	5.14	8.89	2.84	6.97	1.25	2.10	2.01
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R26	*RMS*	5.88	11.52	2.84	10.11	1.18	2.29	2.03
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R31	*RMS*	5.49	10.29	2.91	10.04	1.23	2.34	2.04
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R34	*RMS*	5.67	11.13	2.86	11.92	1.21	2.75	1.99
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R39	*RMS*	5.50	9.03	2.78	8.66	1.19	2.10	1.98
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R42	*RMS*	5.25	9.94	2.82	10.13	1.20	2.24	2.00
1	7	8.45	12.3	75	+15 off Beam Seas	Long	30 Deg	R48	*RMS*	4.37	5.57	2.28	7.72	1.02	1.31	1.56
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R10	*RMS*	5.38	5.58	2.60	6.80	1.20	2.06	1.99
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R19	*RMS*	5.55	4.69	2.44	4.44	1.16	1.56	1.90
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R27	*RMS*	5.80	5.08	2.53	6.19	1.15	1.66	2.07
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R35	*RMS*	5.23	6.33	2.73	4.90	1.23	2.18	1.93
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R43	*RMS*	5.44	6.08	2.81	5.93	1.21	1.88	1.91
1	7	8.45	12.3	75	+15 off Beam Seas	Short	30 Deg	R47	*RMS*	5.50	5.78	2.62	5.17	1.18	2.21	1.89

Table 11-20: Additional Sea State 7 runs in Beam Seas and Sinking Conditions Runs in Sea State 8

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	words	Crested	Roll Damping	Realization	Period of Encounter	Nominal No. Waves encountered	Draft AP	Draft FP	Duration
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R0	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R2	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R7	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R17	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R25	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R34	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R37	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R41	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Long	30 Deg	R47	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R3	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R4	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R12	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R14	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R21	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R22	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R29	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R30	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R38	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R45	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R46	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R51	12.30	202	9.933	8.166	2480
1	7	8.45	12.3	90	Beam Seas	Short	30 Deg	R52	12.30	202	9.933	8.166	2480
1	8	9.76	12.25	105	-15 off Beam Seas	Long	30 Deg	R0	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	90	Beam Seas	Long	30 Deg	R0	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	75	+15 off Beam Seas	Long	30 Deg	R0	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	105	-15 off Beam Seas	Long	30 Deg	R2	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	90	Beam Seas	Long	30 Deg	R2	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	75	+15 off Beam Seas	Long	30 Deg	R2	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	90	Beam Seas	Short	30 Deg	R0	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	90	Beam Seas	Short	30 Deg	R2	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	105	-15 off Beam Seas	Long	30 Deg	R4	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	90	Beam Seas	Long	30 Deg	R5	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	75	+15 off Beam Seas	Long	30 Deg	R3	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	105	-15 off Beam Seas	Long	30 Deg	R7	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	90	Beam Seas	Long	30 Deg	R8	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	75	+15 off Beam Seas	Long	30 Deg	R6	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	90	Beam Seas	Short	30 Deg	R9	12.59	197.0	9.933	8.166	2480
1	8	9.76	12.25	90	Beam Seas	Short	30 Deg	R10	12.59	197.0	9.933	8.166	2480

Table 11-21: EL Faro Motions as H1/3 is Swept from Low To High To Look For Thresholds

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	Words	Crested	Roll Damping	Realization	Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave	Wave Ratio		Heave	Roll	Pitch	Waves	POE	# Waves
14	5	4.00	9.7	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	10.45	7.30	2.76	5.20	1.66	2.05	3.34	1.80	Mean	7.63	18.28	7.85	4.50	7.26	342
14	6	5.00	11.13	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	13.11	11.55	3.44	6.14	2.21	1.07	5.21	2.09	Mean	7.82	19.03	7.97	4.45	8.61	288
14	6	6.00	12.4	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	11.25	26.66	6.42	6.76	3.78	3.34	5.31	1.79	Mean	8.69	17.72	8.60	5.93	9.82	253
14	7	7.00	13.25	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	14.17	38.92	6.82	10.57	4.18	5.50	5.32	1.63	Mean	9.37	18.15	9.20	6.00	10.63	233
14	7	7.25	13.49	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	13.83	41.38	7.11	9.39	4.25	4.81	6.28	1.79	Mean	9.15	19.38	8.94	5.97	10.87	228
14	7	7.50	13.74	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	22.42	37.87	7.45	11.75	4.35	7.49	6.28	1.70	Mean	8.97	18.08	8.87	6.10	11.10	223
14	7	7.75	13.97	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	14.96	43.36	7.81	10.78	4.98	6.23	6.97	1.89	Mean	9.09	18.33	8.90	6.37	11.33	219
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	15.56	44.42	7.97	12.48	4.69	7.11	6.48	1.77	Mean	9.35	17.99	9.24	6.32	11.55	215
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R2	Maximum	15.87	48.75	7.76	16.92	4.90	7.54	7.73	1.92	Mean	9.23	18.37	9.09	6.10	11.55	215
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R3	Maximum	16.12	50.24	7.10	11.14	4.64	6.59	7.32	1.82	Mean	9.28	17.76	9.01	6.14	11.55	215
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R4	Maximum	22.28	57.29	8.06	10.06	5.06	10.99	7.15	1.81	Mean	9.46	18.29	9.11	6.45	11.55	215
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R5	Maximum	25.53	83.50	8.56	9.69	5.17	17.34	6.53	1.67	Mean	9.46	18.21	9.42	6.46	11.55	215
14	7	8.25	14.42	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	17.62	63.82	7.92	11.39	4.76	10.58	8.16	1.75	Mean	9.42	17.44	9.35	6.34	11.76	211
14	7	8.50	14.63	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	133.18	217.25	7.28	15.82	4.90	50.06	7.73	1.76	Mean	9.06	20.93	9.16	6.59	11.96	207
14	7	8.75	14.83	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	18.21	47.27	9.37	10.24	5.56	7.42	8.09	1.75	Mean	9.68	17.90	9.18	6.51	12.16	204
14	7	9.00	15	135	45 Off Head Seas	Long	30 Deg	R1	Maximum	17.65	54.25	9.23	14.63	6.00	8.10	8.37	1.76	Mean	9.08	18.02	8.84	6.12	12.32	201

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	Words	Crested	Roll Damping	Realization	Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
14	5	4.00	9.7	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-3.10	-11.19	-2.37	-2.12	-1.60	-2.65	-3.87
14	6	5.00	11.13	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-8.77	-6.93	-3.49	-3.75	-2.04	-4.18	-5.26
14	6	6.00	12.4	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-10.45	-10.01	-5.18	-3.92	-3.48	-3.95	-5.41
14	7	7.00	13.25	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-15.48	-11.72	-6.00	-4.08	-3.56	-5.26	-6.12
14	7	7.25	13.49	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-17.96	-14.69	-6.43	-5.15	-3.79	-5.54	-6.72
14	7	7.50	13.74	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-23.59	-12.17	-6.91	-7.07	-4.19	-5.67	-6.46
14	7	7.75	13.97	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-15.74	-10.72	-7.52	-7.34	-4.68	-5.30	-7.70
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-21.58	-8.67	-7.28	-5.76	-4.20	-5.04	-7.65
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R2	Minimum	-17.87	-12.52	-7.50	-9.48	-4.26	-6.10	-7.66
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R3	Minimum	-15.66	-6.47	-7.44	-6.70	-4.22	-5.35	-7.26
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R4	Minimum	-31.96	-13.61	-7.84	-4.34	-4.48	-6.20	-7.31
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R5	Minimum	-28.04	-10.53	-8.88	-5.13	-5.20	-6.51	-6.85
14	7	8.25	14.42	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-22.18	-12.42	-7.66	-4.52	-4.57	-6.32	-6.31
14	7	8.50	14.63	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-105.45	-45.14	-8.79	-8.91	-4.93	-19.90	-7.22
14	7	8.75	14.83	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-21.45	-15.21	-8.26	-5.03	-4.87	-6.30	-7.25
14	7	9.00	15	135	45 Off Head Seas	Long	30 Deg	R1	Minimum	-22.62	-16.04	-9.07	-9.78	-5.17	-6.78	-7.49

Speed	Seastate	H/13 (m)	Tm(sec)	Heading deg	Words	Crested	Roll Damping	Realization	Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
14	5	4.00	9.7	135	45 Off Head Seas	Long	30 Deg	R1	RMS	4.16	3.34	0.77	2.07	0.49	0.98	0.96
14	6	5.00	11.13	135	45 Off Head Seas	Long	30 Deg	R1	RMS	4.70	3.23	0.97	2.18	0.62	1.08	1.18
14	6	6.00	12.4	135	45 Off Head Seas	Long	30 Deg	R1	RMS	4.18	8.91	1.58	2.58	0.95	1.44	1.44
14	7	7.00	13.25	135	45 Off Head Seas	Long	30 Deg	R1	RMS	5.51	11.77	1.82	2.60	1.11	1.84	1.65
14	7	7.25	13.49	135	45 Off Head Seas	Long	30 Deg	R1	RMS	5.89	13.57	1.88	2.59	1.15	1.96	1.71
14	7	7.50	13.74	135	45 Off Head Seas	Long	30 Deg	R1	RMS	8.48	14.50	2.01	3.05	1.22	2.14	1.81
14	7	7.75	13.97	135	45 Off Head Seas	Long	30 Deg	R1	RMS	5.11	14.78	2.07	2.85	1.25	2.15	1.87
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R1	RMS	6.95	15.85	2.14	3.07	1.28	2.03	1.90
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R2	RMS	6.41	15.32	2.12	2.99	1.28	2.09	1.86
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R3	RMS	5.09	14.10	2.05	3.02	1.24	1.96	1.84
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R4	RMS	6.41	14.79	2.13	2.99	1.29	2.34	1.90
14	7	8.00	14.2	135	45 Off Head Seas	Long	30 Deg	R5	RMS	6.98	15.83	2.13	2.99	1.28	2.36	1.88
14	7	8.25	14.42	135	45 Off Head Seas	Long	30 Deg	R1	RMS	7.38	17.38	2.22	3.09	1.33	2.29	1.96
14	7	8.50	14.63	135	45 Off Head Seas	Long	30 Deg	R1	RMS	49.93	84.92	2.45	4.86	1.23	20.85	2.06
14	7	8.75	14.83	135	45 Off Head Seas	Long	30 Deg	R1	RMS	6.20	17.22	2.43	3.08	1.44	2.51	2.12
14	7	9.00	15	135	45 Off Head Seas	Long	30 Deg	R1	RMS	7.36	19.29	2.37	3.48	1.45	2.78	2.17

11.4 Container Deck Accelerations

CSRA Dynamic-El_Faro_Container deck Accelerations_4_9_2017.xlsx

The file attached/linked contains all of the phase 1 container accelerations.

11.5 Phase 1 Accelerations in the RORO Cargo Holds

CSRA Dynamic-El_Faro_WASIM_RORO_Accelerations_4_9_2017.xlsx

The locations chosen for the RORO spaces were at the extreme corners of each hold. Prior work has shown that the highest accelerations occur at the points farthest from the center of rotation. For a ship in high seas the center of rotation is not the CG as on a typical rigid body, but rather a point that is constantly moving because the hydrostatic and hydrodynamic, and wind forces all play a role.

11.6 Accelerations in the Accommodation Spaces, Navigation Bridge and at the Lube Oil Tank

CSRA Dynamic-El_Faro_WASIM_Accommodation & LO _Accelerations_4_9_2017.xlsx

11.7 Phase 1 Pressures at Vents And 2nd Deck Openings

CSRA Dynamic-El_Faro_WASIM_Phase 1 pressures_4-10-17.xls

11.7.1 Phase 1 Pressures versus Significant Wave Height Sweep

CSRA Dynamic-El_Faro_WASIM_stairstep pressures_4_9_2017.xlsx

12 Appendix 3 Phase 3 Data

12.1 WASIM Phase 3 Runs Matrix

Table 12-1: Condition 1 and Condition 2 Level Heel Runs

					Wasim						
Count	Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Draft_AP	Draft_FP	VCG	Trim	Set_Heel
	Intact Condition	Knots			Degrees	Description	m	m	m	deg	deg
	Time(local)										
1	11:15	19.45	2.22	10.42	59.64	Aft Quartering	9.723	8.199	11.430	-0.39043	0.0
2	1:00	19.30	3.54	11.76	54.46	Aft Quartering	9.723	8.199	11.430	-0.39043	0.0
3	4:30	19.30	4.19	11.34	58.16	Aft Quartering	9.723	8.199	11.430	-0.39043	0.0
4	6:15	19.30	3.76	10.84	67.00	Aft Quartering	9.723	8.199	11.430	-0.39043	0.0
5	6:45	19.30	3.61	10.72	80.37	Near Beam	9.723	8.199	11.430	-0.39043	0.0
6	1045	19.30	4.61	11.10	93.00	Near Beam	9.723	8.199	11.430	-0.39043	0.0
7	15	19.30	4.45	11.04	111.91	Broad Quartering	9.723	8.199	11.430	-0.39043	0.0
8	45	19.30	3.80	10.90	126.46	Quartering	9.723	8.199	11.430	-0.39043	0.0
9	100	19.30	3.34	10.52	137.05	Bow Quartering	9.723	8.199	11.430	-0.39043	0.0
10	130	19.30	2.76	11.98	104.47	Near Beam	9.723	8.199	11.430	-0.39043	0.0
11	200	19.30	4.63	11.99	83.79	Near Beam	9.723	8.199	11.430	-0.39043	0.0
12	245	19.30	5.44	11.46	90.44	Near Beam	9.723	8.199	11.430	-0.39043	0.0
13	315	16.4	6.69	10.98	98.66	Near Beam	9.723	8.199	11.430	-0.39043	0.0
14	330	16.7	6.99	11.08	100.23	Near Beam	9.723	8.199	11.430	-0.39043	0.0
15	415	9.3	7.32	10.96	82.98	Near Beam	9.723	8.199	11.430	-0.39043	0.0
16	430	10.0	7.44	10.92	52.86	Aft Quartering	9.723	8.199	11.430	-0.39043	0.0
17	500	9.0	7.61	10.83	37.45	Stern Quartering	9.723	8.199	11.430	-0.39043	0.0
18	530	4.3	7.57	10.80	36.80	Stern Quartering	9.723	8.199	11.430	-0.39043	0.0
19	600	6.0	7.48	10.79	35.86	Stern Quartering	9.723	8.199	11.430	-0.39043	0.0
20	615	6.8	7.13	10.91	48.74	Stern Quartering	9.723	8.199	11.430	-0.39043	0.0
21	630	6.9	7.04	10.90	54.24	Aft Quartering	9.723	8.199	11.430	-0.39043	0.0
22	645	6.7	6.91	10.89	58.54	Aft Quartering	9.723	8.199	11.430	-0.39043	0.0
23	700	6.8	6.74	10.88	63.24	Aft Quartering	9.723	8.199	11.430	-0.39043	0.0
24	715	6.8	6.78	10.81	80.10	Near Beam	9.723	8.199	11.430	-0.39043	0.0
25	730	6.7	6.93	10.74	84.23	Near Beam	9.723	8.199	11.430	-0.39043	0.0
26	735	0.00	6.83	10.67	87.05	Near Beam	9.723	8.199	11.430	-0.39043	0.0
Count	Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Draft_AP	Draft_FP	VCG	Trim	Set_Heel
	Damaged Cond 2	Knots			Degrees	Description	m	m	m	deg	deg
	Time(local)										
27	245	19.30	5.44	11.46	90.44	Near Beam	10.180	9.266	11.060	-0.43350	0.0
28	315	16.4	6.69	10.98	98.66	Near Beam	10.180	9.266	11.060	-0.43350	0.0
29	330	16.7	6.99	11.08	100.23	Near Beam	10.180	9.266	11.060	-0.43350	0.0
30	415	9.3	7.32	10.96	82.98	Near Beam	10.180	9.266	11.060	-0.43350	0.0
31	430	10.0	7.44	10.92	52.86	Aft Quartering	10.180	9.266	11.060	-0.43350	0.0
32	500	9.0	7.61	10.83	37.45	Stern Quartering	10.180	9.266	11.060	-0.43350	0.0
33	530	4.3	7.57	10.80	36.80	Stern Quartering	10.180	9.266	11.060	-0.43350	0.0
34	600	6.0	7.48	10.79	35.86	Stern Quartering	10.180	9.266	11.060	-0.43350	0.0
35	615	6.8	7.13	10.91	48.74	Stern Quartering	10.180	9.266	11.060	-0.43350	0.0
36	630	6.9	7.04	10.90	54.24	Aft Quartering	10.180	9.266	11.060	-0.43350	0.0
37	645	6.7	6.91	10.89	58.54	Aft Quartering	10.180	9.266	11.060	-0.43350	0.0
38	700	6.8	6.74	10.88	63.24	Aft Quartering	10.180	9.266	11.060	-0.43350	0.0
39	715	6.8	6.78	10.81	80.10	Near Beam	10.180	9.266	11.060	-0.43350	0.0
40	730	6.7	6.93	10.74	84.23	Near Beam	10.180	9.266	11.060	-0.43350	0.0
41	735	0.00	6.83	10.67	87.05	Near Beam	10.180	9.266	11.060	-0.43350	0.0

The condition 1 runs were chosen to ramp up from a nominal sea state to the most severe such that any threshold points could be seen in either the pressure or the accelerations data.
The condition 2 and 3 runs had some of the lower sea state runs redacted such that they were truncated to 15 runs which is the number that the current WASIM installation can process in a 12-hour period.

Table 12-2: Condition 2 with 3 "Set" Heel Angles

Count	Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Draft_AP	Draft_FP	VCG	Trim	Set_Heel
	Damaged Cond 2	Knots			Degrees	Description	m	m	m	deg	deg
	Time(local)										
42	245	19.30	5.44	11.46	90.44	Near Beam	10.180	9.266	11.060	-0.43350	15.0
43	315	16.4	6.69	10.98	98.66	Near Beam	10.180	9.266	11.060	-0.43350	15.0
44	330	16.7	6.99	11.08	100.23	Near Beam	10.180	9.266	11.060	-0.43350	15.0
45	415	9.3	7.32	10.96	82.98	Near Beam	10.180	9.266	11.060	-0.43350	15.0
46	430	10.0	7.44	10.92	52.86	Aft Quartering	10.180	9.266	11.060	-0.43350	15.0
47	500	9.0	7.61	10.83	37.45	Stern Quartering	10.180	9.266	11.060	-0.43350	15.0
48	530	4.3	7.57	10.80	36.80	Stern Quartering	10.180	9.266	11.060	-0.43350	15.0
49	600	6.0	7.48	10.79	35.86	Stern Quartering	10.180	9.266	11.060	-0.43350	15.0
50	615	6.8	7.13	10.91	48.74	Stern Quartering	10.180	9.266	11.060	-0.43350	15.0
51	630	6.9	7.04	10.90	54.24	Aft Quartering	10.180	9.266	11.060	-0.43350	15.0
52	645	6.7	6.91	10.89	58.54	Aft Quartering	10.180	9.266	11.060	-0.43350	15.0
53	700	6.8	6.74	10.88	63.24	Aft Quartering	10.180	9.266	11.060	-0.43350	15.0
54	715	6.8	6.78	10.81	80.10	Near Beam	10.180	9.266	11.060	-0.43350	15.0
55	730	6.7	6.93	10.74	84.23	Near Beam	10.180	9.266	11.060	-0.43350	15.0
56	735	0.00	6.83	10.67	87.05	Near Beam	10.180	9.266	11.060	-0.43350	15.0
Count	Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Draft_AP	Draft_FP	VCG	Trim	Set_Heel
	Damaged Cond 2	Knots			Degrees	Description	m	m	m	deg	deg
	Time(local)										
57	245	19.30	5.44	11.46	90.44	Near Beam	10.180	9.266	11.060	-0.43350	9.4
58	315	16.4	6.69	10.98	98.66	Near Beam	10.180	9.266	11.060	-0.43350	9.4
59	330	16.7	6.99	11.08	100.23	Near Beam	10.180	9.266	11.060	-0.43350	9.4
60	415	9.3	7.32	10.96	82.98	Near Beam	10.180	9.266	11.060	-0.43350	9.4
61	430	10.0	7.44	10.92	52.86	Aft Quartering	10.180	9.266	11.060	-0.43350	9.4
62	500	9.0	7.61	10.83	37.45	Stern Quartering	10.180	9.266	11.060	-0.43350	9.4
63	530	4.3	7.57	10.80	36.80	Stern Quartering	10.180	9.266	11.060	-0.43350	9.4
64	600	6.0	7.48	10.79	35.86	Stern Quartering	10.180	9.266	11.060	-0.43350	9.4
65	615	6.8	7.13	10.91	48.74	Stern Quartering	10.180	9.266	11.060	-0.43350	9.4
66	630	6.9	7.04	10.90	54.24	Aft Quartering	10.180	9.266	11.060	-0.43350	9.4
67	645	6.7	6.91	10.89	58.54	Aft Quartering	10.180	9.266	11.060	-0.43350	9.4
68	700	6.8	6.74	10.88	63.24	Aft Quartering	10.180	9.266	11.060	-0.43350	9.4
69	715	6.8	6.78	10.81	80.10	Near Beam	10.180	9.266	11.060	-0.43350	9.4
70	730	6.7	6.93	10.74	84.23	Near Beam	10.180	9.266	11.060	-0.43350	9.4
71	735	0.00	6.83	10.67	87.05	Near Beam	10.180	9.266	11.060	-0.43350	9.4
Count	Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Draft_AP	Draft_FP	VCG	Trim	Set_Heel
	Damaged Cond 2	Knots			Degrees	Description	m	m	m	deg	deg
	Time(local)										
72	245	19.30	5.44	11.46	90.44	Near Beam	10.180	9.266	11.060	-0.43350	5.0
73	315	16.4	6.69	10.98	98.66	Near Beam	10.180	9.266	11.060	-0.43350	5.0
74	330	16.7	6.99	11.08	100.23	Near Beam	10.180	9.266	11.060	-0.43350	5.0
75	415	9.3	7.32	10.96	82.98	Near Beam	10.180	9.266	11.060	-0.43350	5.0
76	430	10.0	7.44	10.92	52.86	Aft Quartering	10.180	9.266	11.060	-0.43350	5.0
77	500	9.0	7.61	10.83	37.45	Stern Quartering	10.180	9.266	11.060	-0.43350	5.0
78	530	4.3	7.57	10.80	36.80	Stern Quartering	10.180	9.266	11.060	-0.43350	5.0
79	600	6.0	7.48	10.79	35.86	Stern Quartering	10.180	9.266	11.060	-0.43350	5.0
80	615	6.8	7.13	10.91	48.74	Stern Quartering	10.180	9.266	11.060	-0.43350	5.0
81	630	6.9	7.04	10.90	54.24	Aft Quartering	10.180	9.266	11.060	-0.43350	5.0
82	645	6.7	6.91	10.89	58.54	Aft Quartering	10.180	9.266	11.060	-0.43350	5.0
83	700	6.8	6.74	10.88	63.24	Aft Quartering	10.180	9.266	11.060	-0.43350	5.0
84	715	6.8	6.78	10.81	80.10	Near Beam	10.180	9.266	11.060	-0.43350	5.0
85	730	6.7	6.93	10.74	84.23	Near Beam	10.180	9.266	11.060	-0.43350	5.0
86	735	0.00	6.83	10.67	87.05	Near Beam	10.180	9.266	11.060	-0.43350	5.0

The partially flooded condition 2 was modeled upright and then with 3 different set heel angles. The "Set Heel" is the static load condition input into the mass model in the WASIM run loading condition. These turn out to produce a dynamic mean roll of larger amplitudes.

Table 12-3: Condition 3 with 9.4 degree Set Heel

Count	Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Draft_AP	Draft_FP	VCG	Trim	Set_Heel
	Damaged Cond 3	Knots			Degrees	Description	m	m	m	deg	deg
	Time(local)										
87	245	19.30	5.44	11.46	90.44	Near Beam	10.272	8.748	10.85	-0.37481	0.0
88	315	16.4	6.69	10.98	98.66	Near Beam	10.272	8.748	10.85	-0.37481	0.0
89	330	16.7	6.99	11.08	100.23	Near Beam	10.272	8.748	10.85	-0.37481	0.0
90	415	9.3	7.32	10.96	82.98	Near Beam	10.272	8.748	10.85	-0.37481	0.0
91	430	10.0	7.44	10.92	52.86	Aft Quartering	10.272	8.748	10.85	-0.37481	0.0
92	500	9.0	7.61	10.83	37.45	Stern Quartering	10.272	8.748	10.85	-0.37481	0.0
93	530	4.3	7.57	10.80	36.80	Stern Quartering	10.272	8.748	10.85	-0.37481	0.0
94	600	6.0	7.48	10.79	35.86	Stern Quartering	10.272	8.748	10.85	-0.37481	0.0
95	615	6.8	7.13	10.91	48.74	Stern Quartering	10.272	8.748	10.85	-0.37481	0.0
96	630	6.9	7.04	10.90	54.24	Aft Quartering	10.272	8.748	10.85	-0.37481	0.0
97	645	6.7	6.91	10.89	58.54	Aft Quartering	10.272	8.748	10.85	-0.37481	0.0
98	700	6.8	6.74	10.88	63.24	Aft Quartering	10.272	8.748	10.85	-0.37481	0.0
99	715	6.8	6.78	10.81	80.10	Near Beam	10.272	8.748	10.85	-0.37481	0.0
100	730	6.7	6.93	10.74	84.23	Near Beam	10.272	8.748	10.85	-0.37481	0.0
101	735	0.00	6.83	10.67	87.05	Near Beam	10.272	8.748	10.85	-0.37481	0.0
Count	**Description**	**Ship Speed**	**H/13 (m)**	**Tm(sec)**	**Wave Heading**		**Draft_AP**	**Draft_FP**	**VCG**	**Trim**	**Set_Heel**
	Damaged Cond 3	Knots			Degrees	Description	m	m	m	deg	deg
	Time(local)										
102	615	6.8	7.57	11.94	**48.7**	Stern Quartering	10.272	8.748	10.85	-0.37481	9.4
103	630	6.9	7.57	12.00	**54.2**	Aft Quartering	10.272	8.748	10.85	-0.37481	9.4
104	645	6.7	7.59	12.06	**58.5**	Aft Quartering	10.272	8.748	10.85	-0.37481	9.4
105	700	6.8	7.80	12.12	**63.2**	Aft Quartering	10.272	8.748	10.85	-0.37481	9.4
106	715	6.8	8.02	12.18	**80.1**	Near Beam	10.272	8.748	10.85	-0.37481	9.4
107	730	6.7	8.23	12.24	**84.2**	Near Beam	10.272	8.748	10.85	-0.37481	9.4
108	735	0.00	8.45	12.30	**87.0**	Near Beam	10.272	8.748	10.85	-0.37481	9.4
109	615	6.8	7.57	11.94	**228.7**	Stern Quartering	10.272	8.748	10.85	-0.37481	9.4
110	630	6.9	7.57	12.00	**234.2**	Aft Quartering	10.272	8.748	10.85	-0.37481	9.4
111	645	6.7	7.59	12.06	**238.5**	Aft Quartering	10.272	8.748	10.85	-0.37481	9.4
112	700	6.8	7.80	12.12	**243.2**	Aft Quartering	10.272	8.748	10.85	-0.37481	9.4
113	715	6.8	8.02	12.18	**260.1**	Near Beam	10.272	8.748	10.85	-0.37481	9.4
114	730	6.7	8.23	12.24	**264.2**	Near Beam	10.272	8.748	10.85	-0.37481	9.4
115	735	0.00	8.45	12.30	**267.0**	Near Beam	10.272	8.748	10.85	-0.37481	9.4

The first group do not produce much in the way of water reaching the vents meaning that these really could not be the source of downflooding. The second set are a repeat with the significant wave heights increased to the value of 8.45 meters that Fedele proposed for the sinking condition. The first 7 are with the waves hitting one side and the second 7 are with the waves hitting the opposite side of the ship just to see if there was some profound difference in terms of green water reaching the vents. The opposite side produced negligible results.

12.2 Phase 3 WASIM Motions Data

The motions data are summarized in the following tables. The full spreadsheet of results is attached at the end of the section. These were all run in wave conditions that are based on the NOAA WAV_III model adjusted to the time frame 81 wave data. The times in the early part of the runs was chosen to sweep up through increasing wave heights to try to illuminate where thresholds might occur. The Phase 1 data analysis suggest that there are thresholds were container lashings might begin to fail or where RORO cargo may begin to break their lashings and start rolling or sliding around or where trailers might tip over. The wave height sweep in Phase 1 identified a threshold for green water reaching the second deck openings and the vent openings. In Phase 3 we are trying to find those thresholds with the very best estimates of course, speed, and wind and wave conditions from the VDR data, which was not available during Phase 1.

Table 12-4: EL Faro Phase 3 Motions in the Intact Condition

Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading									
Intact Condition	Knots	Short		Degrees	Description		Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
Time(local)		Crested					m	m	m	deg	deg	deg	m
11:15	19.45	2.22	10.42	59.64	Aft Quartering	Maximum	7.82	20.37	1.81	3.37	0.71	3.02	2.01
1:00	19.30	3.54	11.76	54.46	Aft Quartering	Maximum	8.31	45.09	3.34	7.07	1.11	5.30	3.06
4:30	19.30	4.19	11.34	58.16	Aft Quartering	Maximum	11.78	33.15	3.77	6.77	1.39	4.57	3.16
6:15	19.30	3.76	10.84	67.00	Aft Quartering	Maximum	8.10	41.30	3.03	4.20	1.20	5.97	3.07
6:45	19.30	3.61	10.72	80.37	Near Beam	Maximum	12.89	103.35	3.30	8.55	1.47	15.24	3.76
1045	19.30	4.61	11.10	93.00	Near Beam	Maximum	7.54	30.64	4.52	4.80	1.96	4.30	4.19
15	19.30	4.45	11.04	111.91	Broad Quartering	Maximum	9.45	21.23	4.01	3.17	1.72	3.05	3.98
45	19.30	3.80	10.90	126.46	Quartering	Maximum	7.50	11.94	3.27	2.35	1.52	1.71	3.28
100	19.30	3.34	10.52	137.05	Bow Quartering	Maximum	7.04	12.75	2.59	1.91	1.51	1.53	3.11
130	19.30	2.76	11.98	104.47	Near Beam	Maximum	7.13	14.77	2.87	3.31	1.30	2.28	2.25
200	19.30	4.63	11.99	83.79	Near Beam	Maximum	7.76	23.02	4.20	5.52	1.85	5.91	4.25
245	19.30	5.44	11.46	90.44	Near Beam	Maximum	7.89	31.76	4.49	5.67	1.81	4.84	4.50
315	16.4	6.69	10.98	98.66	Near Beam	Maximum	7.44	30.30	6.81	5.69	2.45	4.14	6.61
330	16.7	6.99	11.08	100.23	Near Beam	Maximum	7.78	38.61	7.21	4.99	2.56	4.52	6.48
415	9.3	7.32	10.96	82.98	Near Beam	Maximum	9.44	15.50	7.70	5.00	2.90	4.77	5.86
430	10.0	7.44	10.92	52.86	Aft Quartering	Maximum	9.73	20.09	6.46	5.68	2.62	5.77	6.83
500	9.0	7.61	10.83	37.45	Stern Quartering	Maximum	10.09	12.45	6.60	8.22	2.71	4.79	6.80
530	4.3	7.57	10.80	36.80	Stern Quartering	Maximum	10.11	6.98	6.12	5.12	3.07	3.80	5.89
600	6.0	7.48	10.79	35.86	Stern Quartering	Maximum	9.19	5.77	5.20	6.26	2.71	4.20	5.58
615	6.8	7.13	10.91	48.74	Stern Quartering	Maximum	9.32	4.40	5.63	4.74	3.27	4.44	6.06
630	6.9	7.04	10.90	54.24	Aft Quartering	Maximum	8.25	6.06	5.99	5.18	2.78	4.04	5.91
645	6.7	6.91	10.89	58.54	Aft Quartering	Maximum	10.11	6.12	5.45	4.57	2.69	4.12	5.94
700	6.8	6.74	10.88	63.24	Aft Quartering	Maximum	10.52	9.14	5.99	4.69	2.90	4.41	5.31
715	6.8	6.78	10.81	80.10	Near Beam	Maximum	9.19	12.15	5.48	2.97	2.73	3.78	5.16
730	6.7	6.93	10.74	84.23	Near Beam	Maximum	9.21	12.03	6.87	4.88	3.13	6.40	6.72
735	0.00	6.83	10.67	87.05	Near Beam	Maximum	8.80	13.64	9.11	8.74	3.73	4.84	5.32

Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Maximum	Mean	Minimum	Range
Intact Condition	Knots	Short		Degrees	Description	Roll	Roll	Roll	Roll
Time(local)		Crested				deg	deg	deg	deg
11:15	19.45	2.22	10.42	59.64	Aft Quartering	3.37	-0.03	-3.50	6.86
1:00	19.30	3.54	11.76	54.46	Aft Quartering	7.07	1.97	-4.38	11.46
4:30	19.30	4.19	11.34	58.16	Aft Quartering	6.77	2.02	-2.84	9.60
6:15	19.30	3.76	10.84	67.00	Aft Quartering	4.20	-0.21	-6.82	11.03
6:45	19.30	3.61	10.72	80.37	Near Beam	8.55	-0.12	-7.17	15.72
1045	19.30	4.61	11.10	93.00	Near Beam	4.80	-0.38	-6.13	10.93
15	19.30	4.45	11.04	111.91	Broad Quartering	3.17	-0.36	-5.14	8.31
45	19.30	3.80	10.90	126.46	Quartering	2.35	-0.32	-3.09	5.44
100	19.30	3.34	10.52	137.05	Bow Quartering	1.91	-0.16	-2.23	4.15
130	19.30	2.76	11.98	104.47	Near Beam	3.31	-0.09	-2.94	6.25
200	19.30	4.63	11.99	83.79	Near Beam	5.52	-0.06	-5.10	10.62
245	19.30	5.44	11.46	90.44	Near Beam	5.67	-0.20	-7.00	12.68
315	16.4	6.69	10.98	98.66	Near Beam	5.69	-0.14	-6.05	11.74
330	16.7	6.99	11.08	100.23	Near Beam	4.99	-0.30	-6.03	11.02
415	9.3	7.32	10.96	82.98	Near Beam	5.00	0.04	-4.58	9.58
430	10.0	7.44	10.92	52.86	Aft Quartering	5.68	-0.07	-6.81	12.49
500	9.0	7.61	10.83	37.45	Stern Quartering	8.22	-0.14	-7.52	15.74
530	4.3	7.57	10.80	36.80	Stern Quartering	5.12	-0.31	-6.45	11.57
600	6.0	7.48	10.79	35.86	Stern Quartering	6.26	-0.24	-5.48	11.74
615	6.8	7.13	10.91	48.74	Stern Quartering	4.74	-0.35	-5.77	10.51
630	6.9	7.04	10.90	54.24	Aft Quartering	5.18	-0.30	-4.82	9.99
645	6.7	6.91	10.89	58.54	Aft Quartering	4.57	-0.25	-4.97	9.54
700	6.8	6.74	10.88	63.24	Aft Quartering	4.69	-0.28	-6.17	10.86
715	6.8	6.78	10.81	80.10	Near Beam	2.97	-0.23	-4.35	7.31
730	6.7	6.93	10.74	84.23	Near Beam	4.88	-0.09	-6.63	11.51
735	0.00	6.83	10.67	87.05	Near Beam	8.74	-0.18	-8.83	17.58

Table 12-5: EL Faro Phase 3 Motions In the First Damaged Condition

Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
Damaged Cond 1	Knots			Degrees	Description	45 minute	m	m	m	deg	deg	deg	m
245	19.30	5.44	11.46	90.44	Near Beam	Maximum	8.15	19.90	4.68	5.83	1.88	3.56	4.59
315	16.4	6.69	10.98	98.66	Near Beam	Maximum	4.87	24.07	5.34	4.54	2.45	3.69	5.73
330	16.7	6.99	11.08	100.23	Near Beam	Maximum	4.29	28.50	5.70	4.67	3.23	3.88	6.23
415	9.3	7.32	10.96	82.98	Near Beam	Maximum	4.36	20.58	6.53	7.55	2.97	4.39	5.15
430	10.0	7.44	10.92	52.86	Aft Quartering	Maximum	4.45	9.79	5.76	5.61	2.64	2.60	5.79
500	9.0	7.61	10.83	37.45	Stern Quartering	Maximum	7.55	9.11	6.42	5.52	2.60	3.25	6.50
530	4.3	7.57	10.80	36.80	Stern Quartering	Maximum	6.47	8.21	5.82	5.33	3.09	1.19	5.79
600	6.0	7.48	10.79	35.86	Stern Quartering	Maximum	5.32	6.33	4.83	7.24	2.71	2.06	5.63
615	6.8	7.13	10.91	48.74	Stern Quartering	Maximum	2.56	0.99	3.91	2.27	1.66	1.87	3.43
630	6.9	7.04	10.90	54.24	Aft Quartering	Maximum	7.48	12.29	6.38	4.93	2.53	1.67	5.06
645	6.7	6.91	10.89	58.54	Aft Quartering	Maximum	5.39	14.39	5.82	6.64	2.83	1.73	6.29
700	6.8	6.74	10.88	63.24	Aft Quartering	Maximum	4.27	9.17	5.42	6.03	2.27	2.22	6.11
715	6.8	6.78	10.81	80.10	Near Beam	Maximum	3.84	14.67	6.31	5.84	3.20	2.39	6.01
730	6.7	6.93	10.74	84.23	Near Beam	Maximum	5.72	15.68	6.48	5.90	3.11	3.61	6.43
735	0.00	6.83	10.67	87.05	Near Beam	Maximum	6.63	10.30	7.90	8.56	3.65	2.82	5.26

Description	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Maximum Roll	Mean Roll	Minimum Roll
Damaged Cond 1	Knots			Degrees	Description	deg	deg	deg
245	19.30	5.44	11.46	90.44	Near Beam	5.83	-0.12	-5.41
315	16.4	6.69	10.98	98.66	Near Beam	4.54	-0.20	-4.80
330	16.7	6.99	11.08	100.23	Near Beam	4.67	-0.21	-5.06
415	9.3	7.32	10.96	82.98	Near Beam	7.55	0.02	-5.99
430	10.0	7.44	10.92	52.86	Aft Quartering	5.61	-0.07	-6.63
500	9.0	7.61	10.83	37.45	Stern Quartering	5.52	-0.17	-6.39
530	4.3	7.57	10.80	36.80	Stern Quartering	5.33	-0.16	-6.10
600	6.0	7.48	10.79	35.86	Stern Quartering	7.24	-0.15	-6.43
615	6.8	7.13	10.91	48.74	Stern Quartering	2.27	-0.11	-2.34
630	6.9	7.04	10.90	54.24	Aft Quartering	4.93	-0.29	-6.95
645	6.7	6.91	10.89	58.54	Aft Quartering	6.64	-0.15	-6.63
700	6.8	6.74	10.88	63.24	Aft Quartering	6.03	-0.11	-6.75
715	6.8	6.78	10.81	80.10	Near Beam	5.84	-0.04	-5.23
730	6.7	6.93	10.74	84.23	Near Beam	5.90	-0.01	-8.03
735	0.00	6.83	10.67	87.05	Near Beam	8.56	-0.10	-8.24

Table 12-6: EL Faro Phase 3 Motions In the 2nd Damaged Condition with 15 degree "Set Heel"

Damaged Cond 2	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
15 deg Set Heel	Knots			Degrees	Description	45 minute	m	m	m	deg	deg	deg	m
Time (local)													
245	19.30	5.44	11.46	90.44	Near Beam	Maximum	7.34	45.25	5.71	33.02	2.19	5.67	4.43
315	16.4	6.69	10.98	98.66	Near Beam	Maximum	4.55	40.35	7.23	32.88	3.00	3.26	6.05
330	16.7	6.99	11.08	100.23	Near Beam	Maximum	5.50	43.42	7.19	32.87	3.80	3.87	6.09
415	9.3	7.32	10.96	82.98	Near Beam	Maximum	9.84	55.93	7.18	36.90	3.50	0.95	5.19
430	10.0	7.44	10.92	52.86	Aft Quartering	Maximum	9.03	43.20	7.01	36.37	3.15	0.57	5.82
500	9.0	7.61	10.83	37.45	Stern Quartering	Maximum	16.70	50.79	7.45	39.45	2.71	0.00	7.01
530	4.3	7.57	10.80	36.80	Stern Quartering	Maximum	18.10	86.51	8.28	45.88	3.34	1.69	5.45
600	6.0	7.48	10.79	35.86	Stern Quartering	Maximum	14.48	74.80	6.60	43.79	3.01	0.00	5.60
615	6.8	7.13	10.91	48.74	Stern Quartering	Maximum	3.88	31.10	4.60	37.57	1.95	0.14	3.31
630	6.9	7.04	10.90	54.24	Aft Quartering	Maximum	12.96	56.10	6.62	38.12	3.04	0.00	5.30
645	6.7	6.91	10.89	58.54	Aft Quartering	Maximum	11.30	62.14	7.13	38.15	2.97	0.00	5.84
700	6.8	6.74	10.88	63.24	Aft Quartering	Maximum	10.34	58.73	6.14	38.13	2.54	0.00	5.60
715	6.8	6.78	10.81	80.10	Near Beam	Maximum	9.10	66.86	7.73	38.50	3.41	0.51	5.70
730	6.7	6.93	10.74	84.23	Near Beam	Maximum	10.15	59.23	7.76	38.52	3.27	0.78	6.62

Damaged Cond 2	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Maximum	Mean	Minimum
15 deg Set Heel	Knots			Degrees	Description	Roll	Roll	Roll
Time (local)						deg	deg	deg
245	19.30	5.44	11.46	90.44	Near Beam	33.02	25.06	0.00
315	16.4	6.69	10.98	98.66	Near Beam	32.88	23.59	0.00
330	16.7	6.99	11.08	100.23	Near Beam	32.87	23.48	0.00
415	9.3	7.32	10.96	82.98	Near Beam	36.90	23.82	0.00
430	10.0	7.44	10.92	52.86	Aft Quartering	36.37	23.90	0.00
500	9.0	7.61	10.83	37.45	Stern Quartering	39.45	24.12	0.00
530	4.3	7.57	10.80	36.80	Stern Quartering	45.88	23.86	-3.21
600	6.0	7.48	10.79	35.86	Stern Quartering	43.79	24.13	0.00
615	6.8	7.13	10.91	48.74	Stern Quartering	37.57	24.67	0.00
630	6.9	7.04	10.90	54.24	Aft Quartering	38.12	23.89	0.00
645	6.7	6.91	10.89	58.54	Aft Quartering	38.15	23.98	0.00
700	6.8	6.74	10.88	63.24	Aft Quartering	38.13	24.04	0.00
715	6.8	6.78	10.81	80.10	Near Beam	38.50	24.16	0.00
730	6.7	6.93	10.74	84.23	Near Beam	38.52	24.13	0.00

Table 12-7 EL Faro Phase 3 Motions In the 2nd Damaged Condition with 9.4 degree "Set Heel"

Damaged Cond 2	**Ship Speed**	**H/13 (m)**	**Tm(sec)**	**Wave Heading**			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
9.4 deg "Set" heel	**Knots**			**Degrees**	**Description**	**45 minute**	m	m	m	deg	deg	deg	m
Time (local)													
245	19.30	5.44	11.46	90.44	Near Beam	Maximum	7.29	29.15	5.63	24.49	2.20	2.98	4.47
315	16.4	6.69	10.98	98.66	Near Beam	Maximum	4.07	32.24	6.66	23.65	2.77	4.31	6.03
330	16.7	6.99	11.08	100.23	Near Beam	Maximum	4.70	47.21	6.87	24.36	3.56	4.38	5.49
415	9.3	7.32	10.96	82.98	Near Beam	Maximum	6.68	36.91	7.47	27.29	3.48	3.82	5.47
430	10.0	7.44	10.92	52.86	Aft Quartering	Maximum	7.21	28.71	6.85	26.90	2.94	1.50	5.79
500	9.0	7.61	10.83	37.45	Stern Quartering	Maximum	11.21	28.87	7.31	29.24	2.80	1.72	6.51
530	4.3	7.57	10.80	36.80	Stern Quartering	Maximum	9.58	42.38	6.28	32.81	3.35	1.46	5.91
600	6.0	7.48	10.79	35.86	Stern Quartering	Maximum	7.97	44.08	5.81	30.28	3.13	0.99	5.60
615	6.8	7.13	10.91	48.74	Stern Quartering	Maximum	2.84	16.94	4.34	28.06	1.85	0.31	3.32
630	6.9	7.04	10.90	54.24	Aft Quartering	Maximum	10.73	34.73	6.58	28.30	2.74	0.51	5.24
645	6.7	6.91	10.89	58.54	Aft Quartering	Maximum	7.86	34.78	5.89	29.13	2.91	1.20	6.39
700	6.8	6.74	10.88	63.24	Aft Quartering	Maximum	6.83	35.28	6.13	29.17	2.60	0.59	5.97
715	6.8	6.78	10.81	80.10	Near Beam	Maximum	5.86	37.11	7.33	28.63	3.44	1.22	5.85
730	6.7	6.93	10.74	84.23	Near Beam	Maximum	8.75	38.34	7.20	28.64	3.53	1.41	6.79
735	0.00	6.83	10.67	87.05	Near Beam	Maximum	12.42	52.18	8.91	39.99	4.12	3.22	5.67

Damaged Cond 2	**Ship Speed**	**H/13 (m)**	**Tm(sec)**	**Wave Heading**		Maximum	Mean	Minimum
9.4 deg "Set" heel	**Knots**			**Degrees**	**Description**	Roll	Roll	Roll
Time (local)						deg	deg	deg
245	19.30	5.44	11.46	90.44	Near Beam	24.49	18.68	0.00
315	16.4	6.69	10.98	98.66	Near Beam	23.65	17.01	0.00
330	16.7	6.99	11.08	100.23	Near Beam	24.36	17.46	0.00
415	9.3	7.32	10.96	82.98	Near Beam	27.29	17.52	0.00
430	10.0	7.44	10.92	52.86	Aft Quartering	26.90	17.62	0.00
500	9.0	7.61	10.83	37.45	Stern Quartering	29.24	17.64	-1.34
530	4.3	7.57	10.80	36.80	Stern Quartering	32.81	17.31	0.00
600	6.0	7.48	10.79	35.86	Stern Quartering	30.28	17.51	0.00
615	6.8	7.13	10.91	48.74	Stern Quartering	28.06	18.54	0.00
630	6.9	7.04	10.90	54.24	Aft Quartering	28.30	17.55	0.00
645	6.7	6.91	10.89	58.54	Aft Quartering	29.13	17.59	-2.08
700	6.8	6.74	10.88	63.24	Aft Quartering	29.17	17.66	0.00
715	6.8	6.78	10.81	80.10	Near Beam	28.63	17.86	0.00
730	6.7	6.93	10.74	84.23	Near Beam	28.64	17.84	0.00
735	0.00	6.83	10.67	87.05	Near Beam	39.99	16.74	-10.99

Table 12-8: EL Faro Phase 3 Motions In the 2nd Damaged Condition with 5 degree "Set Heel"

Damaged Cond 2	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
5.0 deg "Set" heel	Knots			Degrees	Description	45 minute	m	m	m	deg	deg	deg	m
Time (local)													
245	19.30	5.44	11.46	90.44	Near Beam	Maximum	8.07	30.45	5.40	17.90	2.02	3.50	4.63
315	16.4	6.69	10.98	98.66	Near Beam	Maximum	4.14	29.70	6.08	15.29	2.58	4.32	5.49
330	16.7	6.99	11.08	100.23	Near Beam	Maximum	4.71	44.13	6.31	16.33	3.34	5.73	5.38
415	9.3	7.32	10.96	82.98	Near Beam	Maximum	5.25	27.19	7.10	16.77	3.26	3.83	5.49
430	10.0	7.44	10.92	52.86	Aft Quartering	Maximum	5.46	20.56	6.30	17.72	2.82	2.02	5.86
500	9.0	7.61	10.83	37.45	Stern Quartering	Maximum	9.43	20.11	6.81	18.61	2.70	3.33	6.43
530	4.3	7.57	10.80	36.80	Stern Quartering	Maximum	7.39	24.50	6.07	20.33	3.32	1.54	5.72
600	6.0	7.48	10.79	35.86	Stern Quartering	Maximum	6.22	23.38	5.06	20.38	2.82	1.80	5.65
615	6.8	7.13	10.91	48.74	Stern Quartering	Maximum	2.55	10.39	4.20	17.74	1.75	0.73	3.31
630	6.9	7.04	10.90	54.24	Aft Quartering	Maximum	8.26	17.70	6.34	17.92	2.58	1.00	5.01
645	6.7	6.91	10.89	58.54	Aft Quartering	Maximum	6.14	20.60	5.43	18.43	2.91	1.70	6.27
700	6.8	6.74	10.88	63.24	Aft Quartering	Maximum	4.87	22.10	6.03	19.37	2.45	2.07	6.02
715	6.8	6.78	10.81	80.10	Near Beam	Maximum	4.94	22.26	6.93	18.05	3.31	2.44	6.10
730	6.7	6.93	10.74	84.23	Near Beam	Maximum	7.16	25.11	7.11	17.85	3.46	3.50	6.52
735	0.00	6.83	10.67	87.05	Near Beam	Maximum	7.69	19.34	8.36	20.87	3.85	2.75	5.25

Damaged Cond 2	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Maximum	Mean	Minimum
5.0 deg "Set" heel	Knots			Degrees	Description	Roll	Roll	Roll
Time (local)						deg	deg	deg
245	19.30	5.44	11.46	90.44	Near Beam	17.90	12.06	0.00
315	16.4	6.69	10.98	98.66	Near Beam	15.29	10.60	0.00
330	16.7	6.99	11.08	100.23	Near Beam	16.33	10.58	0.00
415	9.3	7.32	10.96	82.98	Near Beam	16.77	10.63	0.00
430	10.0	7.44	10.92	52.86	Aft Quartering	17.72	10.59	0.00
500	9.0	7.61	10.83	37.45	Stern Quartering	18.61	10.54	0.00
530	4.3	7.57	10.80	36.80	Stern Quartering	20.33	10.38	-2.23
600	6.0	7.48	10.79	35.86	Stern Quartering	20.38	10.47	-2.24
615	6.8	7.13	10.91	48.74	Stern Quartering	17.74	11.33	0.00
630	6.9	7.04	10.90	54.24	Aft Quartering	17.92	10.48	-1.73
645	6.7	6.91	10.89	58.54	Aft Quartering	18.43	10.54	0.00
700	6.8	6.74	10.88	63.24	Aft Quartering	19.37	10.60	-2.74
715	6.8	6.78	10.81	80.10	Near Beam	18.05	10.83	0.00
730	6.7	6.93	10.74	84.23	Near Beam	17.85	10.84	0.00
735	0.00	6.83	10.67	87.05	Near Beam	20.87	10.68	-0.40

Table 12-9: EL Faro Phase 3 Motions In the 3rd Damaged Condition with 9.4 degree "Set Heel"

Damaged Cond 3	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
18 degree heel	Knots			Degrees	Description	45 minute	m	m	m	deg	deg	deg	m
Time (local)													
245	19.30	5.44	11.46	90.44	Near Beam	Maximum	7.43	30.78	5.68	23.35	2.12	3.34	4.38
315	16.4	6.69	10.98	98.66	Near Beam	Maximum	3.88	30.08	6.54	22.67	2.74	4.37	6.06
330	16.7	6.99	11.08	100.23	Near Beam	Maximum	4.62	45.39	6.63	22.67	3.52	4.43	5.48
415	9.3	7.32	10.96	82.98	Near Beam	Maximum	6.34	34.35	7.25	25.44	3.41	3.95	5.45
430	10.0	7.44	10.92	52.86	Aft Quartering	Maximum	6.65	26.58	6.63	25.15	2.86	1.84	5.90
500	9.0	7.61	10.83	37.45	Stern Quartering	Maximum	10.28	25.71	7.09	27.63	2.75	2.14	6.46
530	4.3	7.57	10.80	36.80	Stern Quartering	Maximum	8.94	37.26	6.17	30.80	3.33	1.44	6.13
600	6.0	7.48	10.79	35.86	Stern Quartering	Maximum	7.36	37.81	5.58	27.88	3.06	1.20	5.52
615	6.8	7.13	10.91	48.74	Stern Quartering	Maximum	2.85	14.55	3.77	26.35	1.41	0.28	3.33
630	6.9	7.04	10.90	54.24	Aft Quartering	Maximum	5.38	28.12	6.45	30.15	2.75	1.44	5.86
645	6.7	6.91	10.89	58.54	Aft Quartering	Maximum	7.54	30.29	5.67	27.37	2.90	1.37	6.41
700	6.8	6.74	10.88	63.24	Aft Quartering	Maximum	6.21	31.31	5.98	27.29	2.55	0.78	6.05
715	6.8	6.78	10.81	80.10	Near Beam	Maximum	5.61	33.44	7.20	26.68	3.43	1.59	5.99
730	6.7	6.93	10.74	84.23	Near Beam	Maximum	8.30	35.07	7.06	26.70	3.51	1.92	6.71
735	0.00	6.83	10.67	87.05	Near Beam	Maximum	12.51	50.65	8.63	40.12	3.82	2.78	5.09

Damaged Cond 3	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Maximum	Mean	Minimum
18 degree heel	Knots			Degrees	Description	Roll	Roll	Roll
Time (local)						deg	deg	deg
245	19.30	5.44	11.46	90.44	Near Beam	23.35	17.18	0.00
315	16.4	6.69	10.98	98.66	Near Beam	22.67	16.10	0.00
330	16.7	6.99	11.08	100.23	Near Beam	22.67	16.04	0.00
415	9.3	7.32	10.96	82.98	Near Beam	25.44	16.07	0.00
430	10.0	7.44	10.92	52.86	Aft Quartering	25.15	16.17	0.00
500	9.0	7.61	10.83	37.45	Stern Quartering	27.63	16.19	0.00
530	4.3	7.57	10.80	36.80	Stern Quartering	30.80	15.93	-1.34
600	6.0	7.48	10.79	35.86	Stern Quartering	27.88	16.09	0.00
615	6.8	7.13	10.91	48.74	Stern Quartering	26.35	16.98	0.00
630	6.9	7.04	10.90	54.24	Aft Quartering	30.15	16.25	-0.53
645	6.7	6.91	10.89	58.54	Aft Quartering	27.37	16.13	0.00
700	6.8	6.74	10.88	63.24	Aft Quartering	27.29	16.20	-2.59
715	6.8	6.78	10.81	80.10	Near Beam	26.68	16.38	0.00
730	6.7	6.93	10.74	84.23	Near Beam	26.70	16.37	0.00
735	0.00	6.83	10.67	87.05	Near Beam	40.12	15.06	-14.75

Table 12-10 EL Faro Phase 3 Motions In the 3rd Damaged Condition with 9.4 degree "Set Heel" and with the Significant Wave Height Scaled up to a Higher Maximum

Damaged Cond 2	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading			Surge	Sway	Heave	Roll	Pitch	Yaw	Wave
15 deg Set Heel	Knots			Degrees	Description	45 minute	m	m	m	deg	deg	deg	m
Time (local)													
615	6.9	7.57	11.94	48.74	Stern Quartering	Maximum	8.93	27.84	7.08	27.96	3.15	4.79	6.43
630	6.7	7.57	12.00	54.24	Aft Quartering	Maximum	8.66	29.89	7.72	29.45	3.29	0.55	7.85
645	6.8	7.59	12.06	58.54	Aft Quartering	Maximum	6.47	29.32	5.84	26.74	3.05	1.35	6.85
700	6.8	7.80	12.12	63.24	Aft Quartering	Maximum	8.41	33.49	7.67	28.44	3.13	0.74	5.68
715	6.7	8.02	12.18	80.10	Near Beam	Maximum	6.88	39.63	8.47	28.46	3.83	2.05	7.87
730	0.0	8.23	12.24	84.23	Near Beam	Maximum	5.90	34.64	8.60	28.26	3.78	3.93	7.15
735	0.0	8.45	12.30	87.05	Near Beam	Maximum	11.19	88.22	8.19	47.34	3.34	2.10	7.69
		Course reflected about the CL from Port to Starboard											
615	6.9	7.57	11.94	228.74	Stern Quartering	Maximum	3.24	7.72	8.14	27.00	3.56	1.31	6.95
630	6.7	7.57	12.00	234.24	Aft Quartering	Maximum	5.11	25.69	8.76	35.82	4.08	0.54	7.24
645	6.8	7.59	12.06	238.54	Aft Quartering	Maximum	4.03	11.13	7.54	26.71	4.14	1.12	7.08
700	6.8	7.80	12.12	243.24	Aft Quartering	Maximum	5.16	8.31	7.88	27.88	4.12	1.52	6.25
715	6.7	8.02	12.18	260.10	Near Beam	Maximum	5.56	12.89	6.44	28.39	3.14	2.05	5.94
730	0.0	8.23	12.24	264.23	Near Beam	Maximum	5.30	13.13	8.01	30.16	3.53	2.07	7.31
735	0.0	8.45	12.30	267.05	Near Beam	Maximum	6.67	21.09	8.95	31.68	3.40	4.45	7.44

Damaged Cond 2	Ship Speed	H/13 (m)	Tm(sec)	Wave Heading		Maximum	Mean	Minimum
15 deg Set Heel	Knots			Degrees	Description	Roll	Roll	Roll
Time (local)						deg	deg	deg
615	6.9	7.57	11.94	48.74	Stern Quartering	27.96	16.81	0.00
630	6.7	7.57	12.00	54.24	Aft Quartering	29.45	16.08	-0.46
645	6.8	7.59	12.06	58.54	Aft Quartering	26.74	16.21	0.00
700	6.8	7.80	12.12	63.24	Aft Quartering	28.44	16.00	-3.63
715	6.7	8.02	12.18	80.10	Near Beam	28.46	15.88	0.00
730	0.0	8.23	12.24	84.23	Near Beam	28.26	15.93	-0.52
735	0.0	8.45	12.30	87.05	Near Beam	47.34	14.59	-20.07
		Course reflected about the CL from Port to Starboard						
615	6.9	7.57	11.94	228.74	Stern Quartering	27.00	16.10	0.00
630	6.7	7.57	12.00	234.24	Aft Quartering	35.82	15.45	-13.93
645	6.8	7.59	12.06	238.54	Aft Quartering	26.71	16.09	0.00
700	6.8	7.80	12.12	243.24	Aft Quartering	27.88	16.06	0.00
715	6.7	8.02	12.18	260.10	Near Beam	28.39	16.12	-1.76
730	0.0	8.23	12.24	264.23	Near Beam	30.16	16.33	-0.78
735	0.0	8.45	12.30	267.05	Near Beam	31.68	16.17	-4.64

CSRA Dynamic-EL Faro_Phase 3 Motions.xlsx

12.3 Phase 3 Accelerations at the Container Deck

The accelerations data was plotted for 15 runs ranging from 2:45 AM to 7:35 AM on the morning of October 1st, 2015. The sea conditions from 2:45 through 6:00 AM are based on the WAV 3 data from NOAA. The direction data is a best fit between the NOAA data and the VDR data for all of the runs. For 6:15 through 7:35 the wave heights and periods are extrapolated as described in figure 4-11. These were all run assuming the Condition 3 ballasting with flooding in the 3 and 2A holds are described above. The heel angles were as described in table 5-1.

Table 12-11: Conditions Modeled for Last Container Data

	Ship				
Damaged Cond 3	**Speed**	**H/13 (m)**	**Tm(sec)**	**Wave Heading**	
15-18 deg Heel	**Knots**			**Degrees**	**Description**
Time(local)					
245	19.30	5.44	11.46	90.44	Near Beam
315	16.4	6.69	10.98	98.66	Near Beam
330	16.7	6.99	11.08	100.23	Near Beam
415	9.3	7.32	10.96	82.98	Near Beam
430	10.0	7.44	10.92	52.86	Aft Quartering
500	9.0	7.61	10.83	37.45	Stern Quartering
530 ~Loss of Power	4.3	**7.57**	10.80	36.80	Stern Quartering
600	6.0	**7.48**	10.79	35.86	Stern Quartering
615	6.9	**7.57**	11.94	48.74	Stern Quartering
630	6.7	**7.57**	12.00	54.24	Aft Quartering
645	6.8	**7.59**	12.06	58.54	Aft Quartering
700	6.8	**7.80**	12.12	63.24	Aft Quartering
715	6.7	**8.02**	12.18	80.10	Near Beam
730	0.0	**8.23**	12.24	84.23	Near Beam
735	0.0	**8.45**	12.30	87.05	Near Beam

The container deck accelerations were modeled in WASIM and Matlab and the maxima to port and starboard were plotted two ways. The first is the maximum acceleration at a location on the ship versus the time series for each of the three degrees of freedom, longitudinal, transverse and vertical. The down heel side is closer to the center of roll and so the accelerations are a bit lower than on the up-heel side as shown in figures 12-1, 12-2, and 12-3.

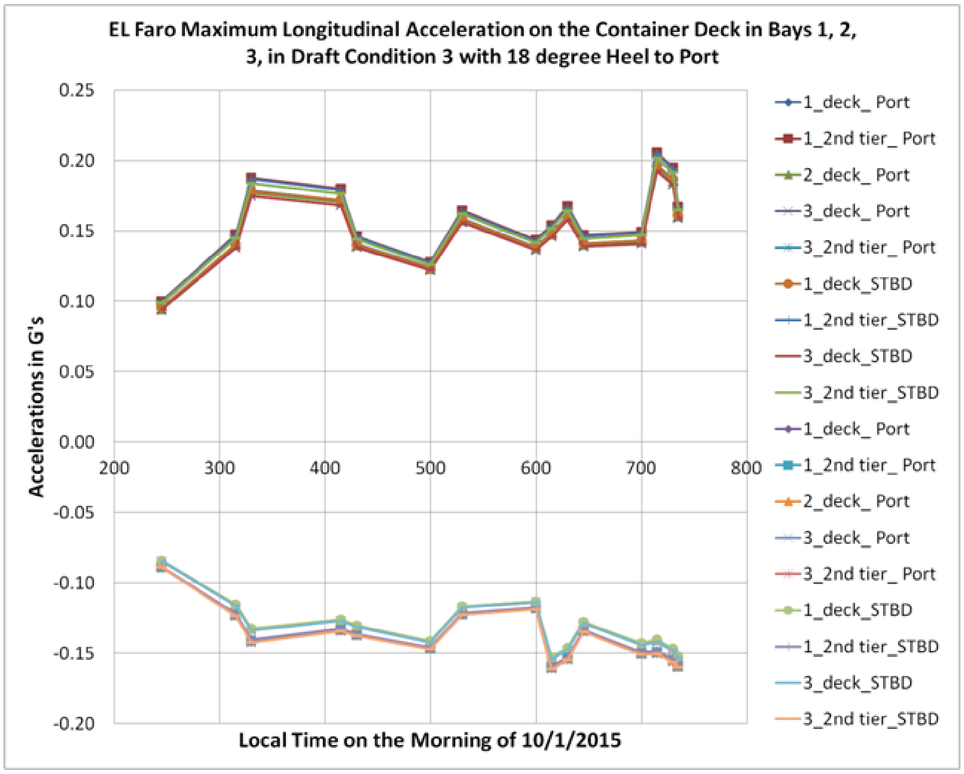


Figure 12-1: Longitudinal Acceleration Maxima in Front 3 Container Bays

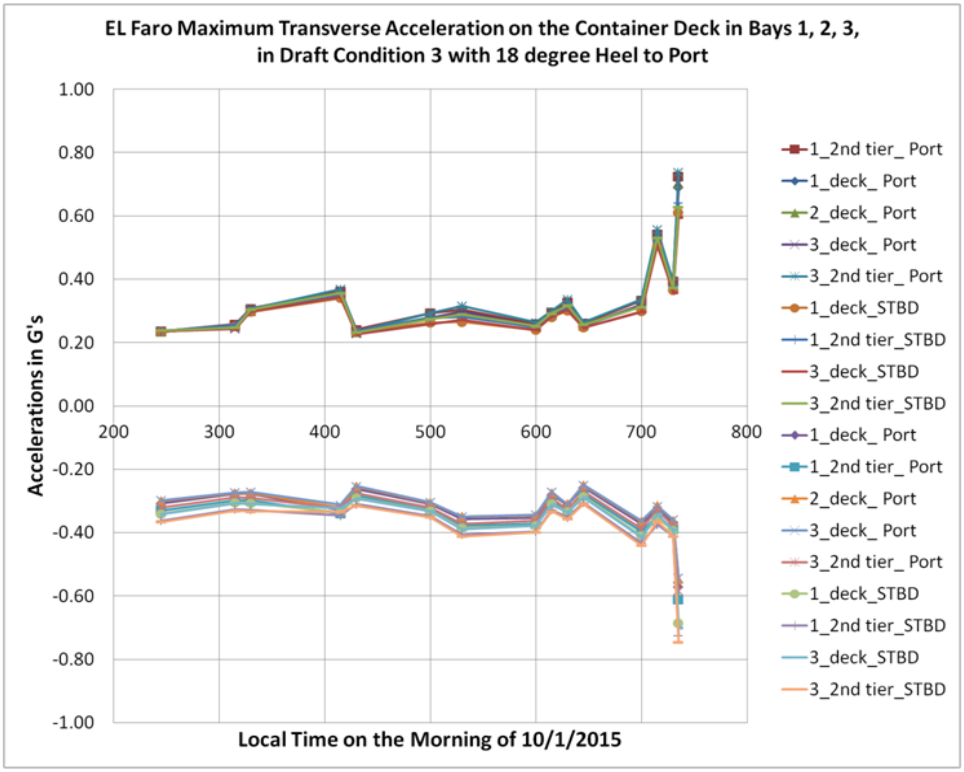


Figure 12-2: Transverse Acceleration Maxima in Front 3 Container Bays

In general, the transverse accelerations are the most severe, the vertical are next and the longitudinal are lowest. The maxima shown are the positive and negative maxima in the whole-time series and there is no wave on wave correlation between them. The raw time series data supports that level of study but it was not studied at that level of detail in the WASIM/MATLAB analyses owing to the vast amount of data created. The Orcaflex modeling data where individual container stacks are shown to break free goes into greater detail in that regard.

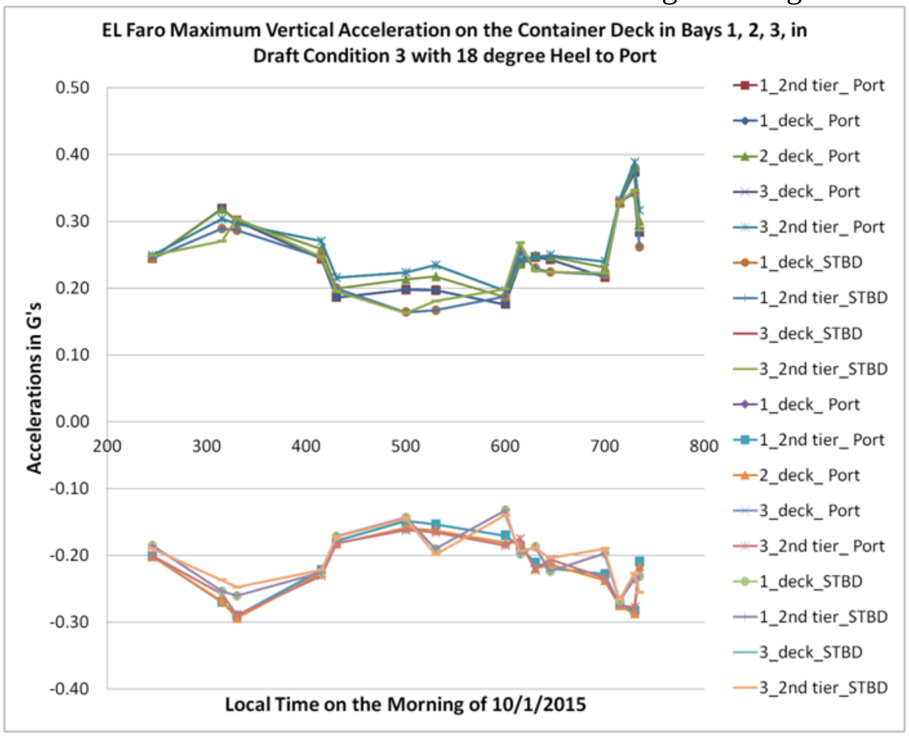


Figure 12-3 Vertical Acceleration Maxima In Front 3 Container Bays

These were created for groups of 3 or 4 container bays and are all included in the attached file.

CSRA Dynamic-EL_Faro_Phase 3 Accelerations at container stacks 6-22-17.xlsx

The other types of plots created from this data set show the acceleration maxima along the length of the vessel as the storm intensifies, again in three degrees of freedom, but it was useful to break the port and starboard side motions onto separate plots as the data was already very busy.

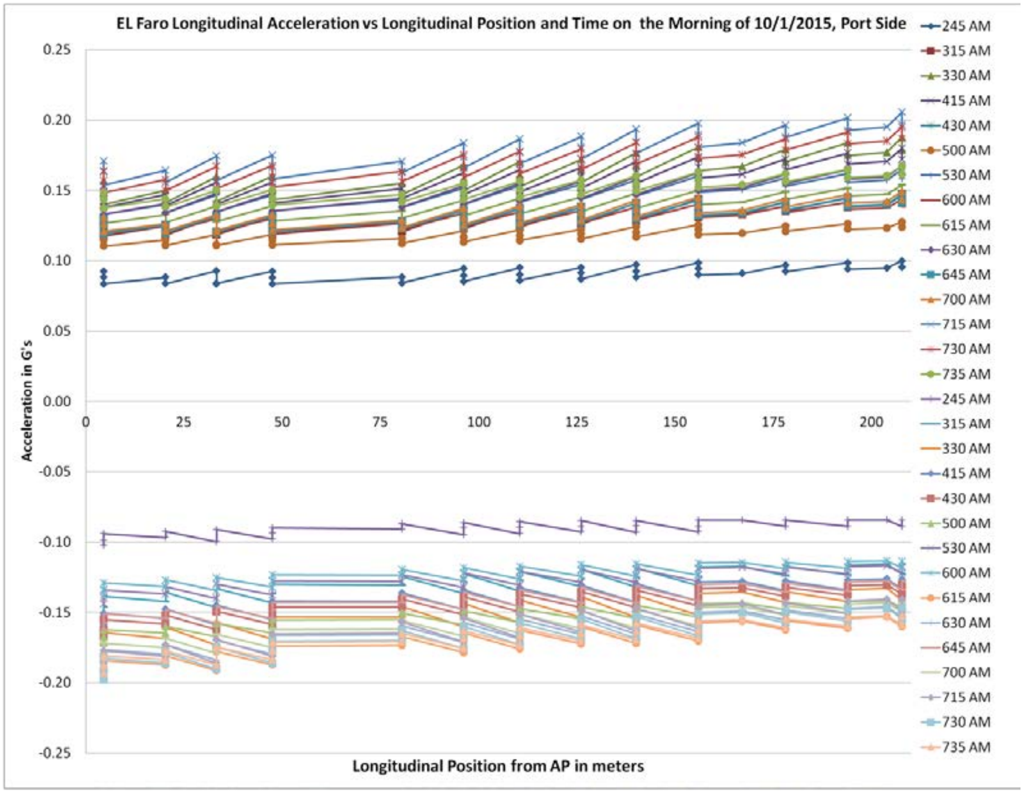


Figure 12-4: Longitudinal Container Acceleration vs Location and Time, Port Side

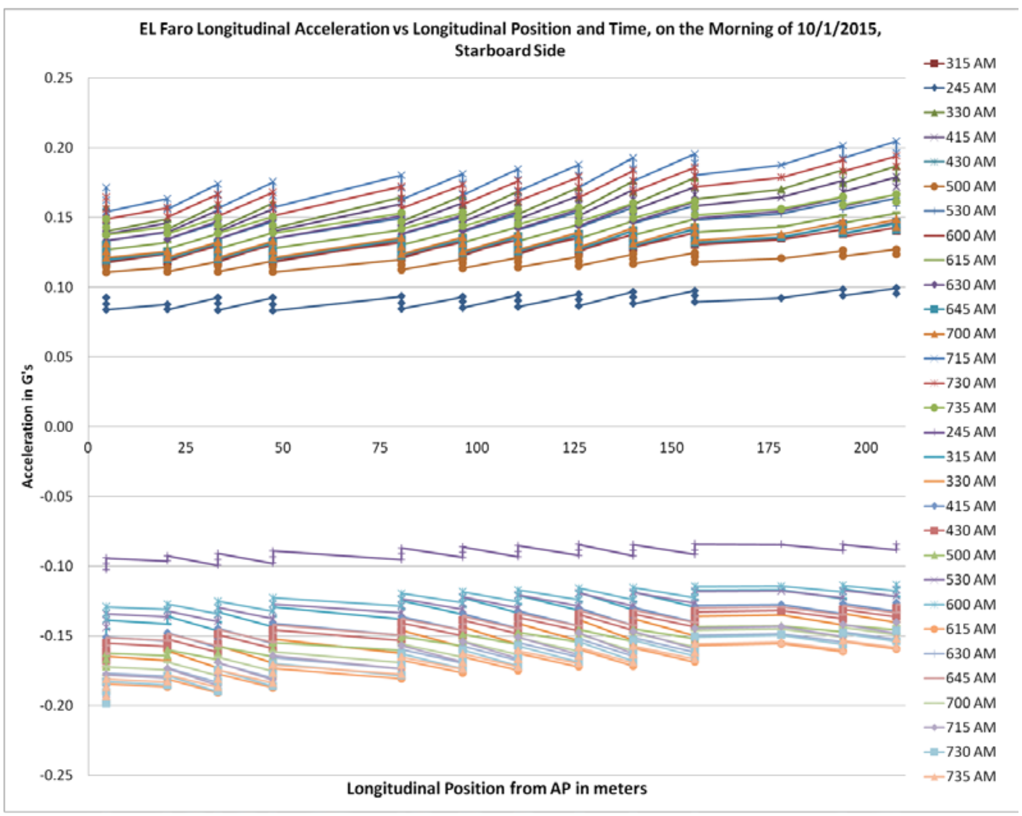


Figure 12-5: Longitudinal Container Acceleration vs Location and Time, Stbd Side

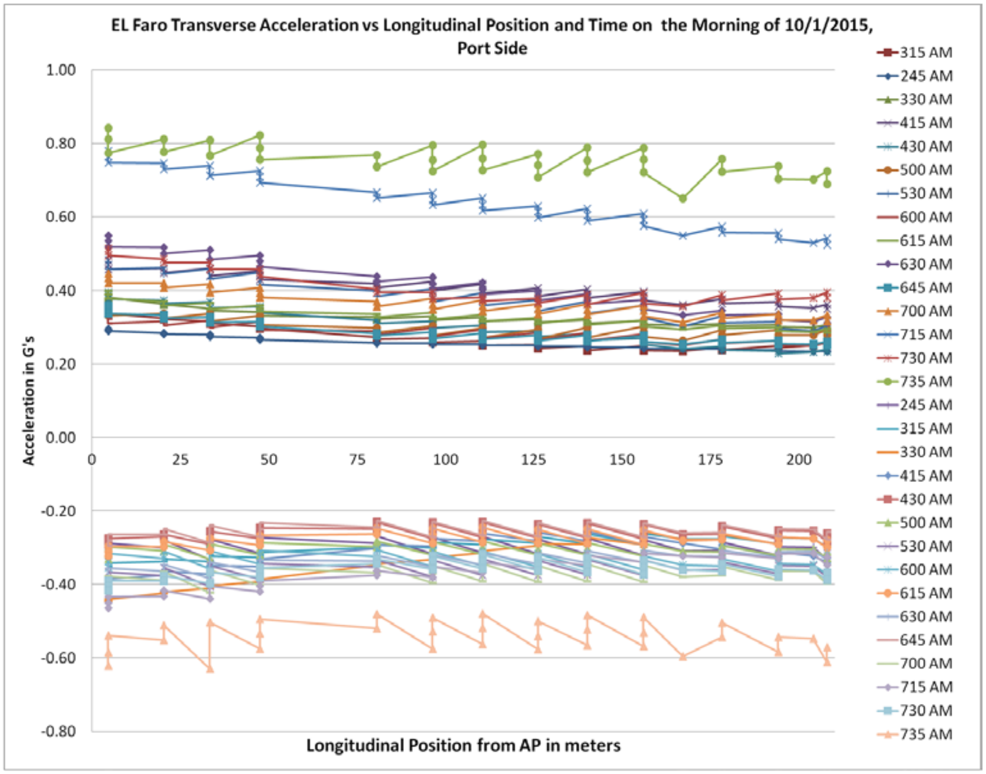


Figure 12-6: Transverse Container Acceleration vs Location and Time, Port Side

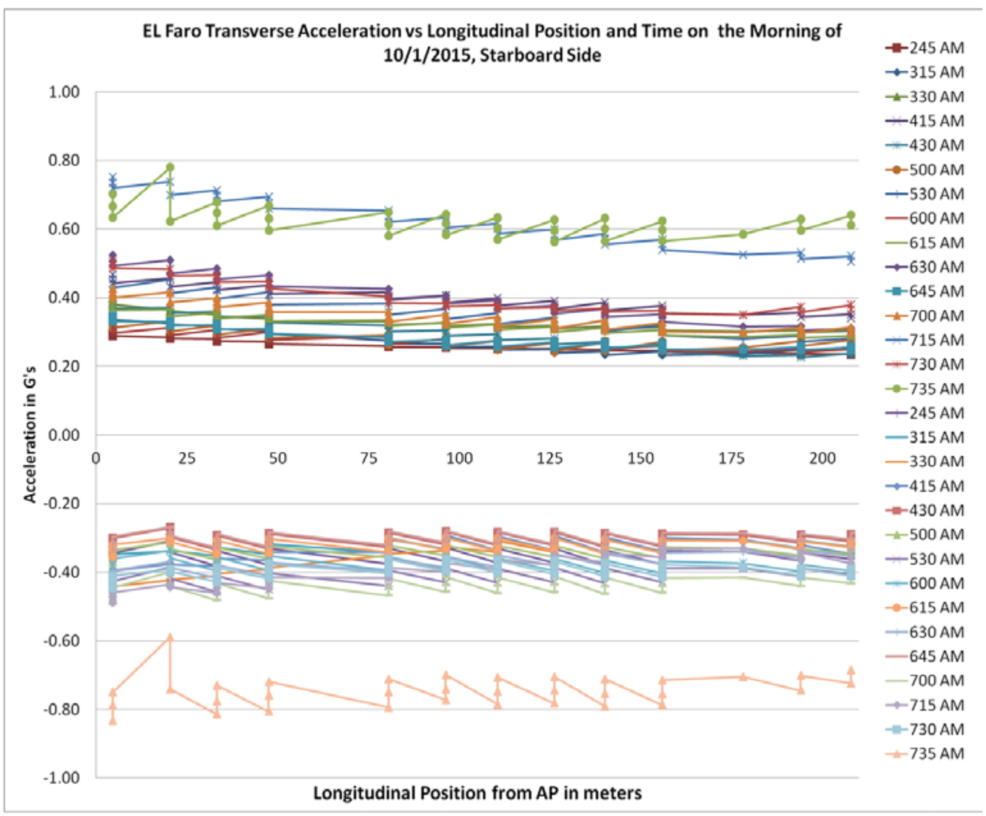


Figure 12-7: Transverse Container Acceleration vs Location and Time, Stbd Side

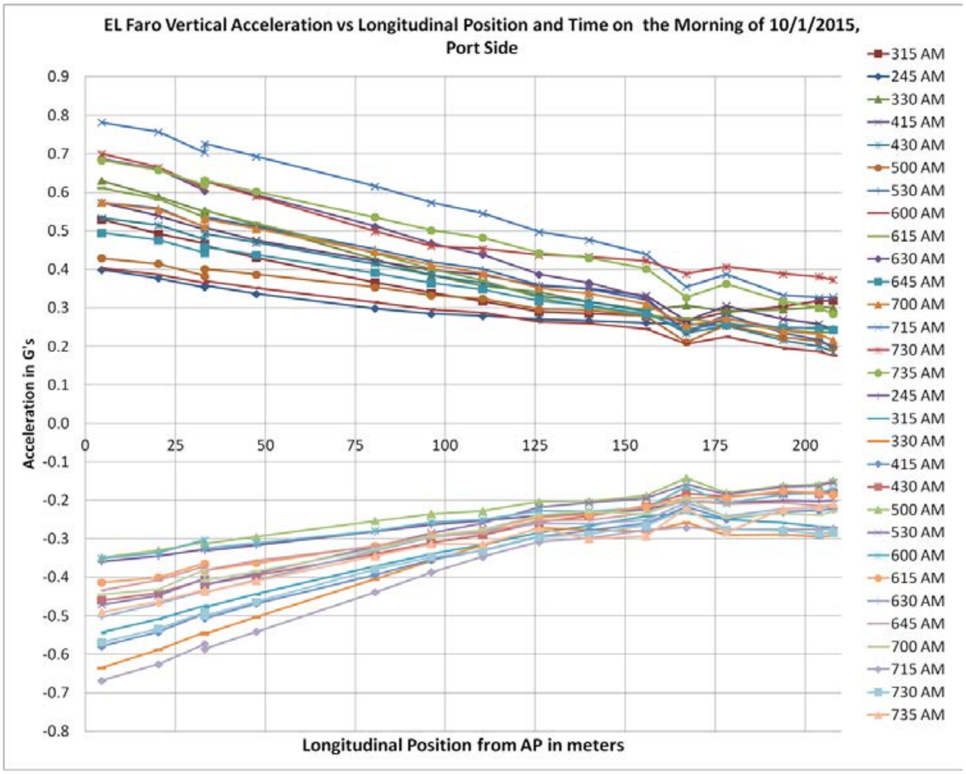


Figure 12-8: Vertical Container Acceleration vs Location and Time, Port Side

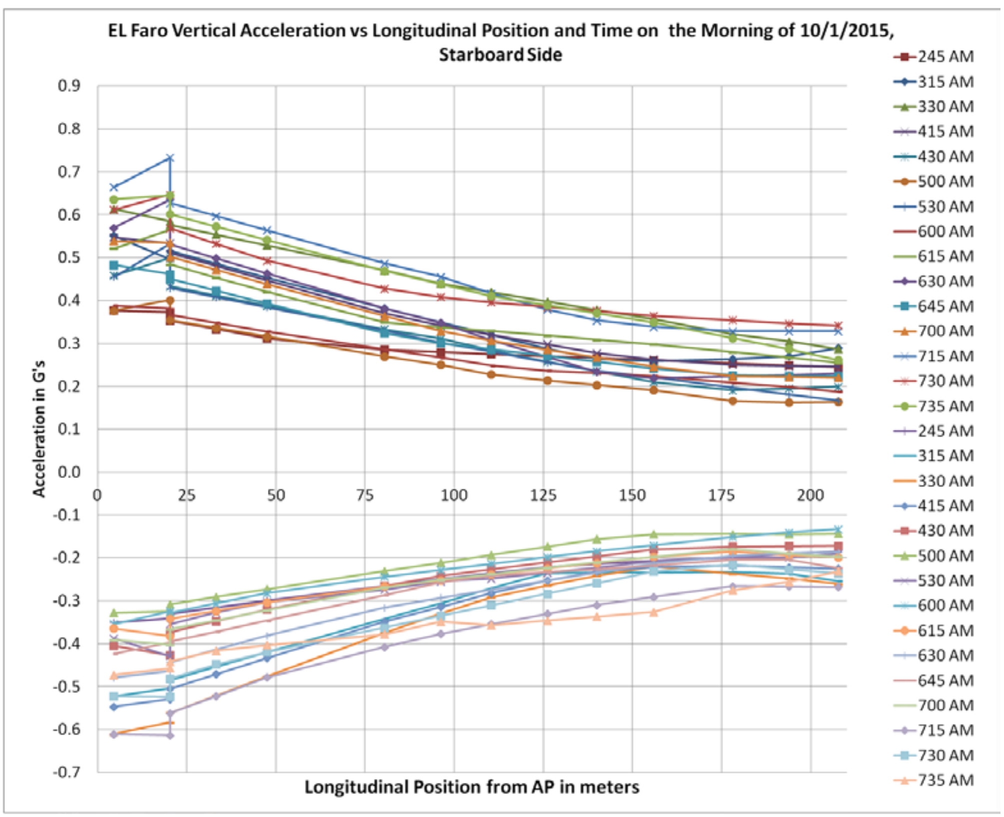


Figure 12-9: Vertical Container Acceleration vs Location and Time, Stbd Side

The two and three step "ladders" in the longitudinal and transverse acceleration traces represent that the accelerations are larger the higher you get in the container stacks. This is the same as saying that the accelerations increase with distance from the instantaneous center of rotation, although we can't state with any certainty where that dynamic center is at any given instant without further analysis.

12.4 Phase 3 Accelerations in the RORO Holds

Plots similar to those provided for the containers were prepared for the RORO spaces.

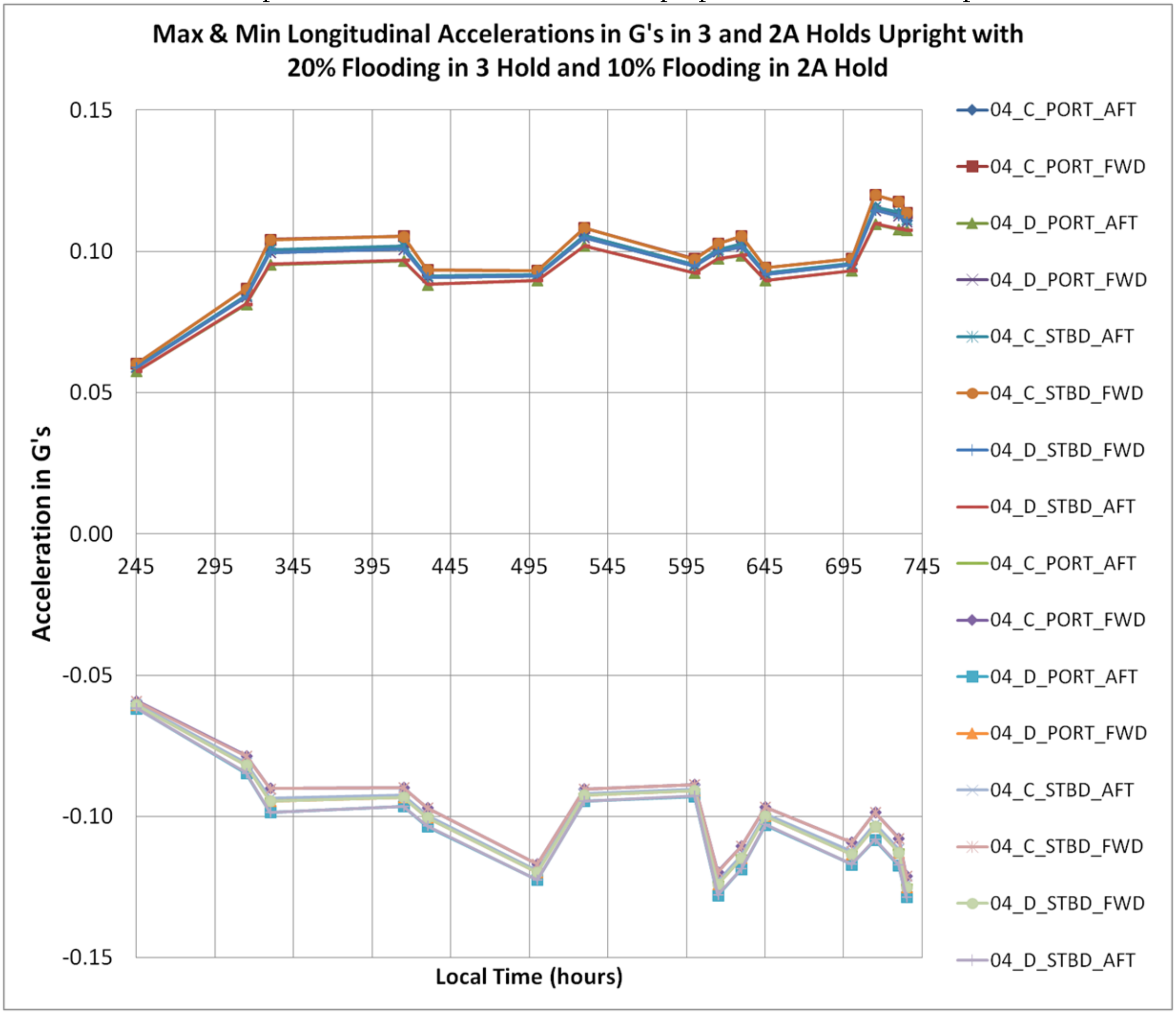


Figure 12-10: Longitudinal Accelerations Acting on the Corner Vehicles in Holds 3 and 2A vs Time into the Storm

Figure 12-10 shows that there is a little scatter with vehicle location but not much.

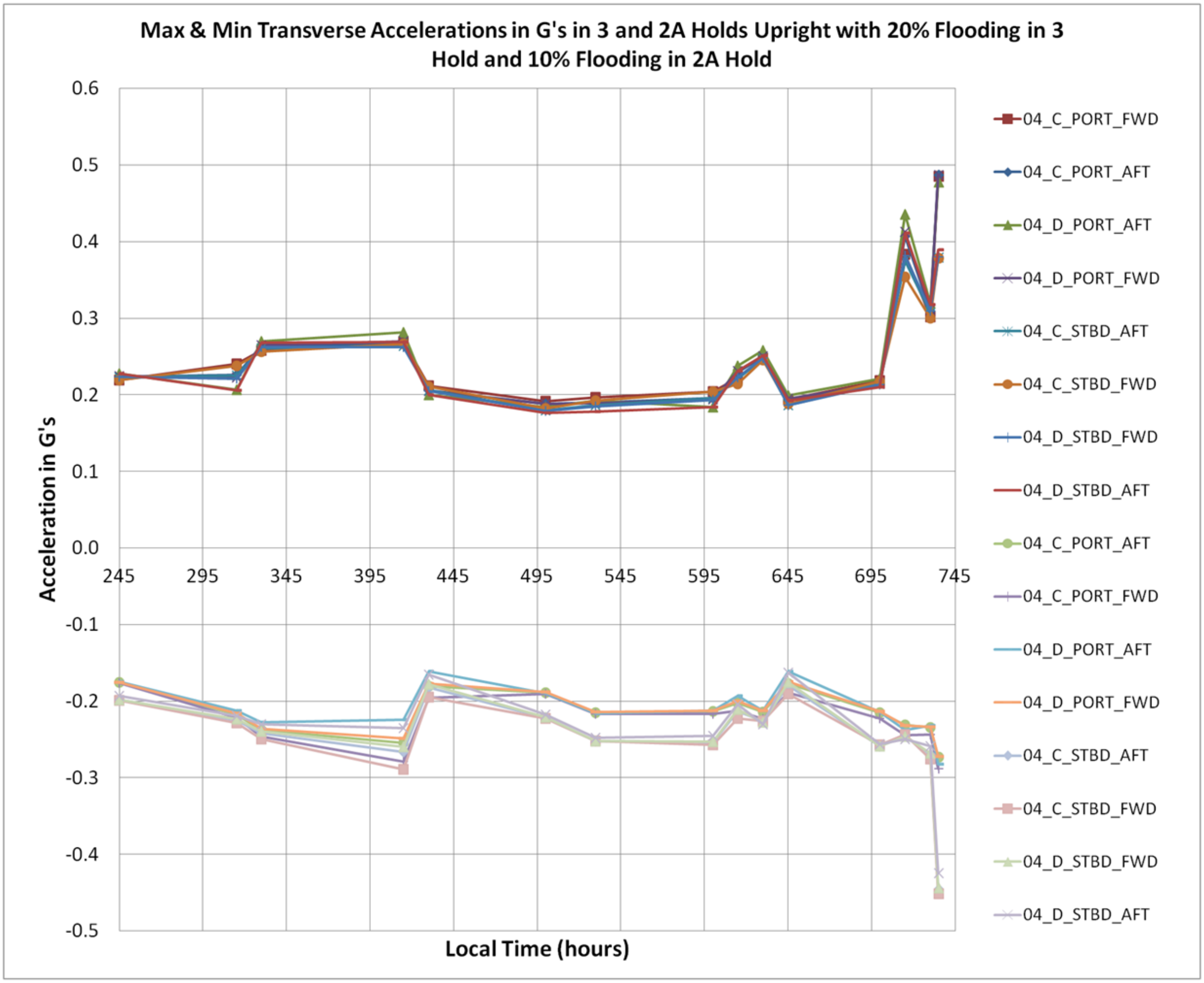


Figure 12-11: Transverse Accelerations Acting on the Corner Vehicles in Holds 3 and 2A vs Time into the Storm

Figure 12-11 shows a strong port to starboard bias due to the increasing heel angle as the time series unfolds.

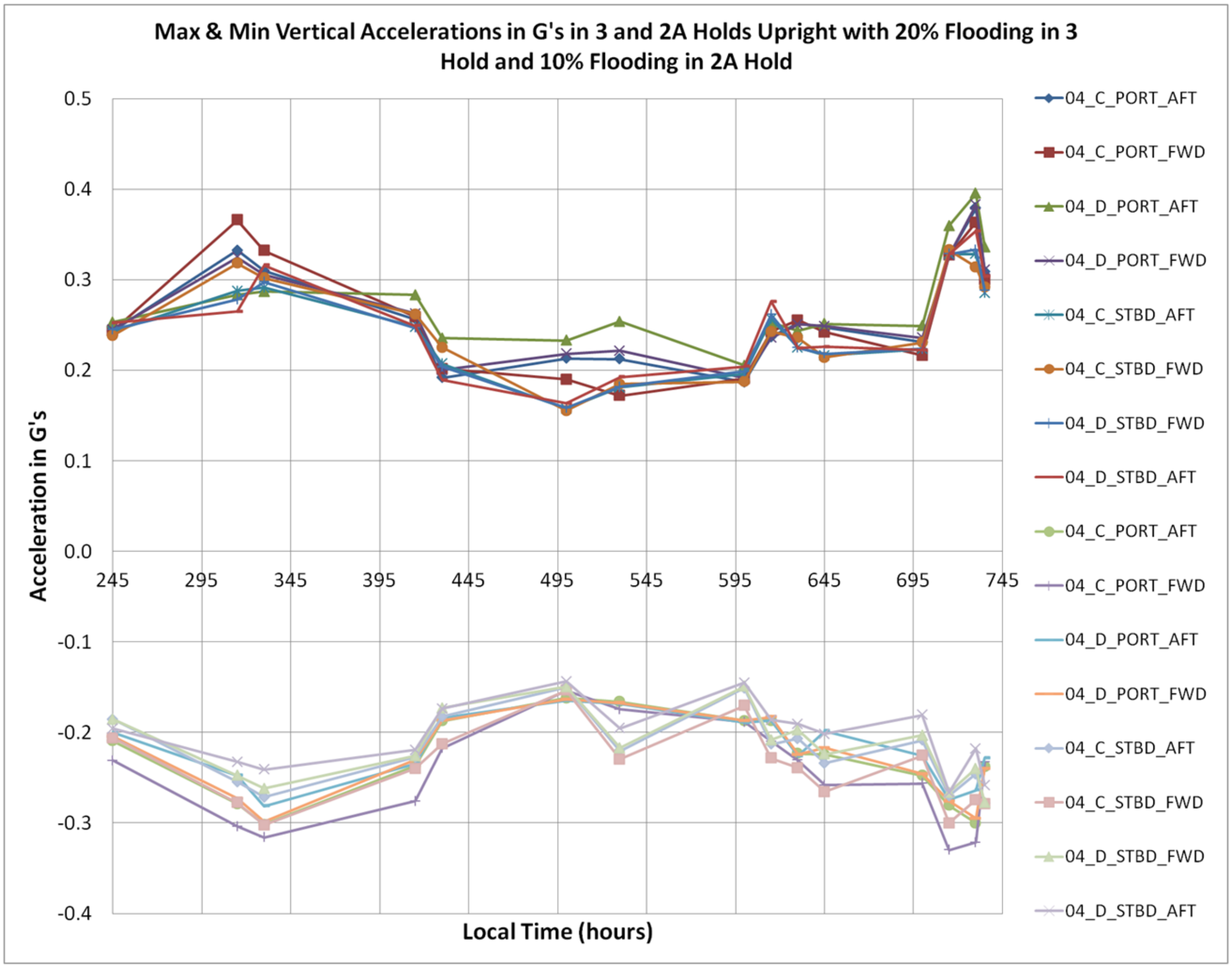


Figure 12-12: Vertical Accelerations Acting on the Corner Vehicles in Holds 3 and 2A vs Time into the Storm

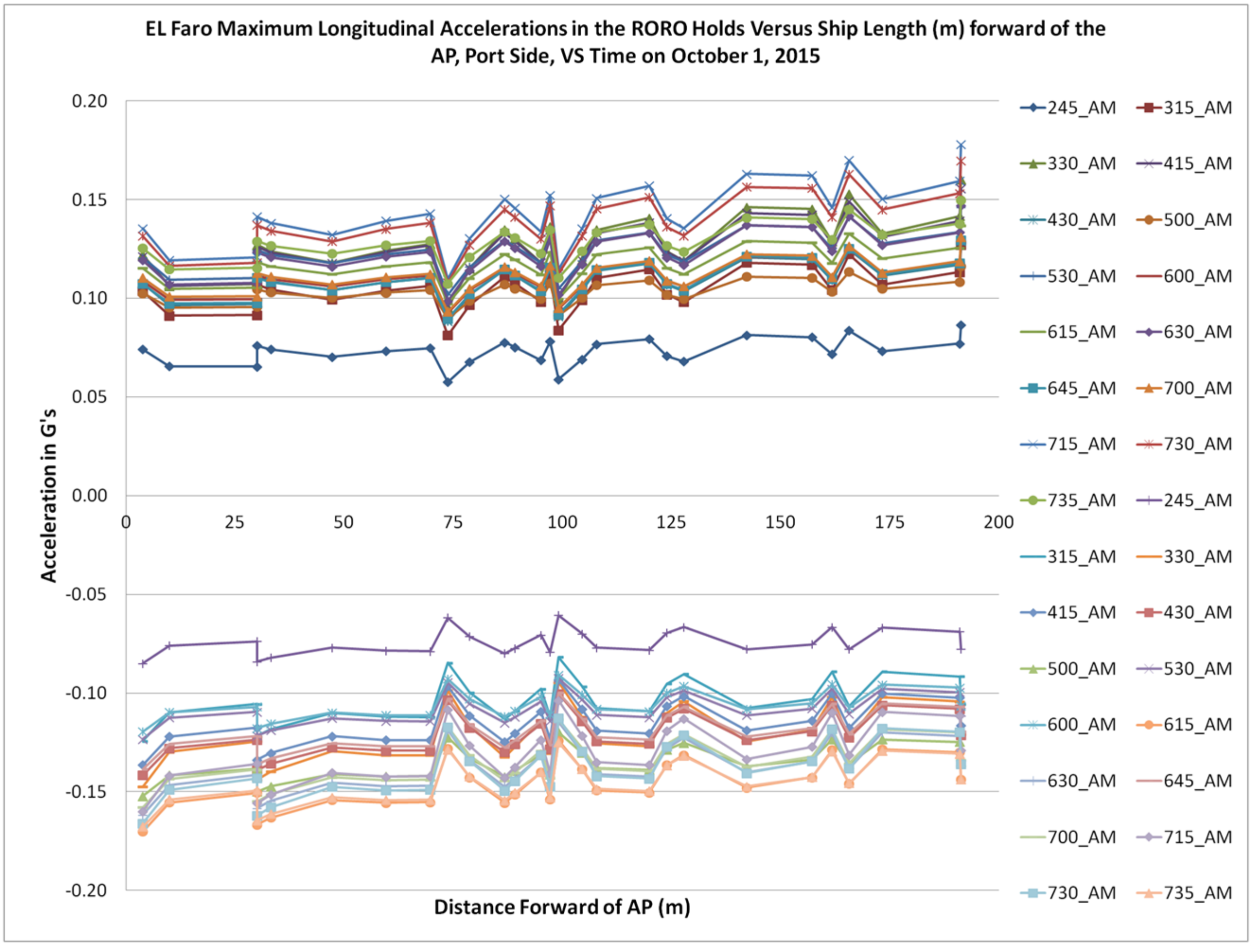


Figure 12-13: RORO Holds Maximum Longitudinal Acceleration vs Length Forward of AP and Time for Vehicles on the Port Side

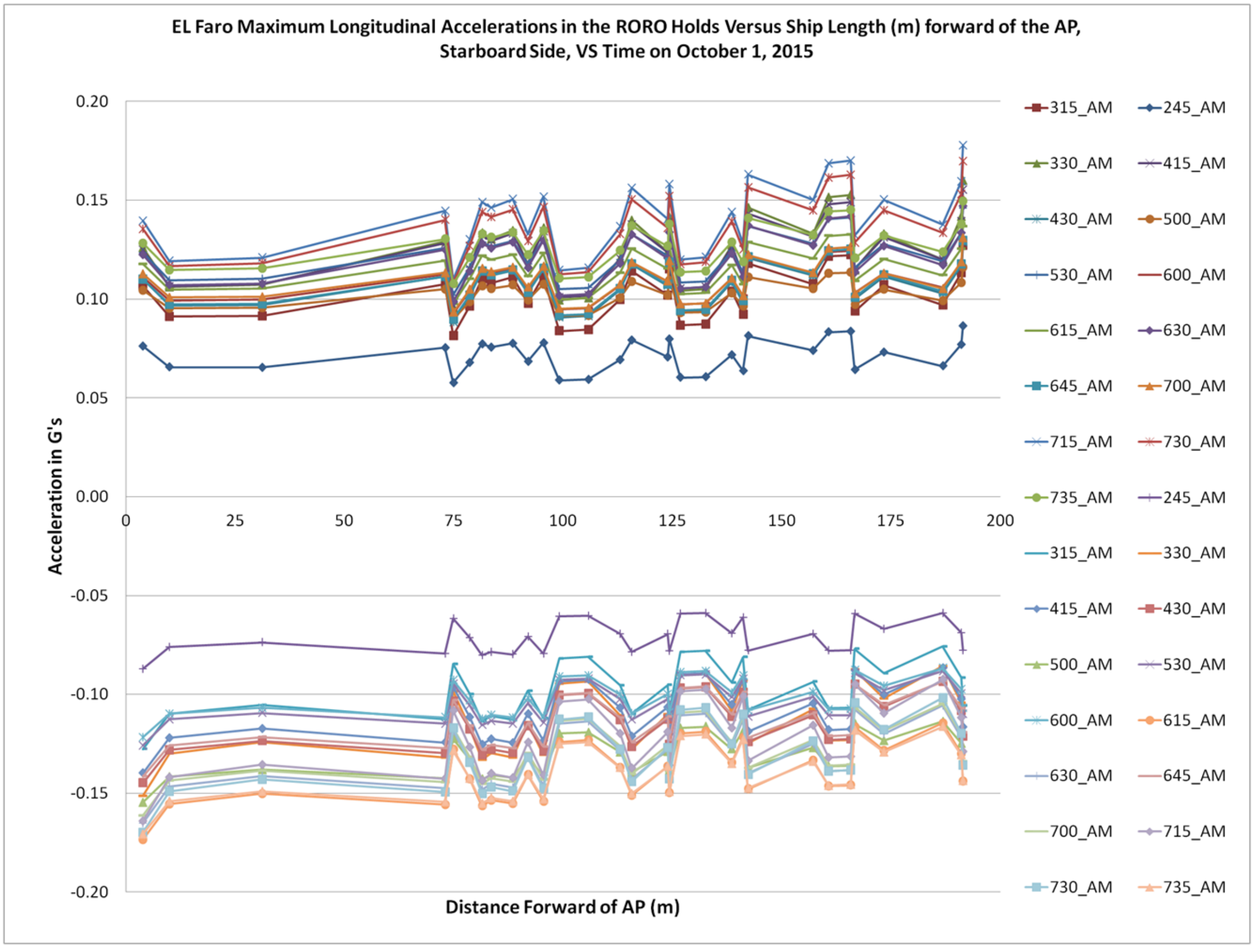


Figure 12-14: RORO Holds Maximum Longitudinal Acceleration vs Length Forward of AP and Time for Vehicles on the Starboard Side

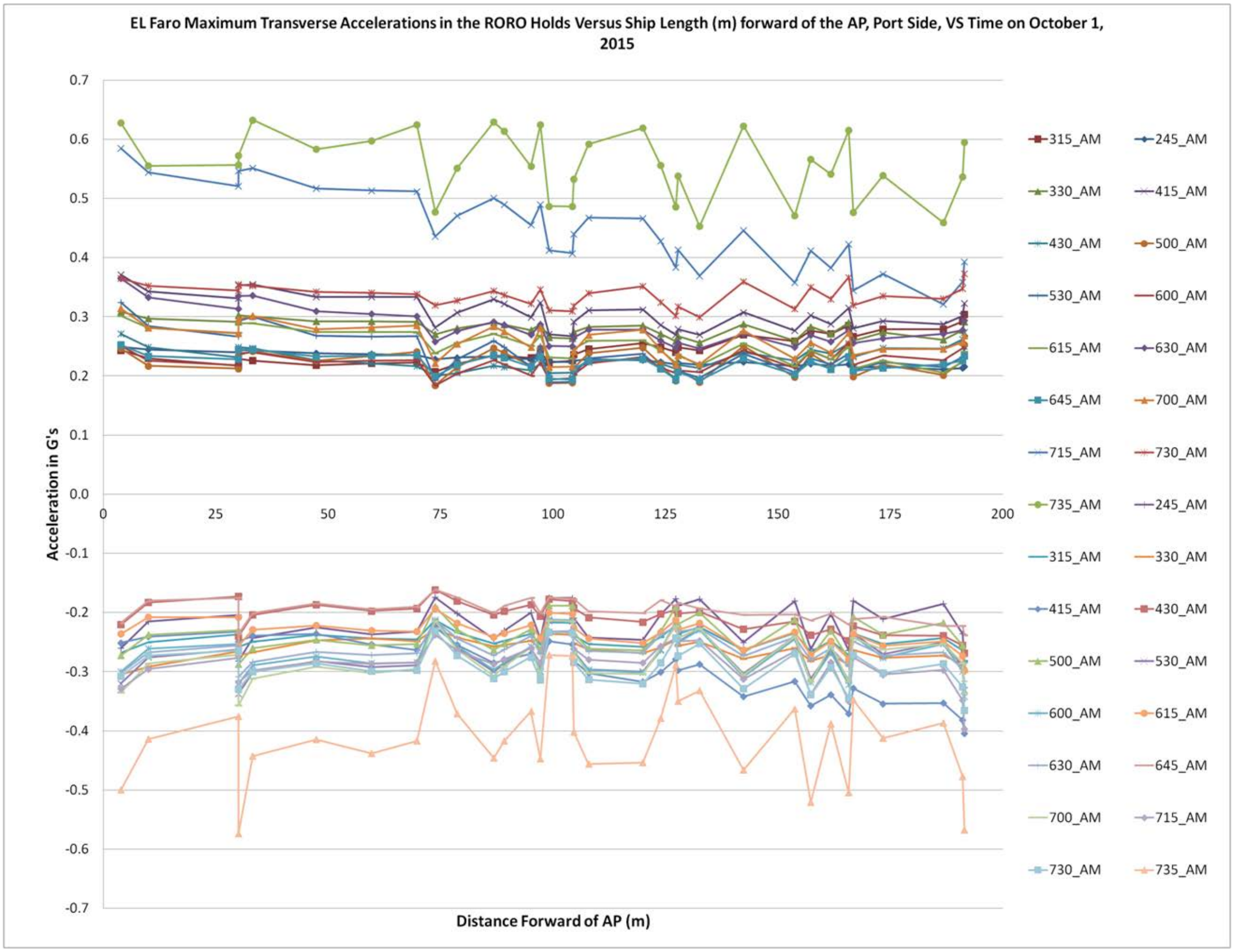


Figure 12-15: RORO Holds Maximum Transverse Acceleration vs Length Forward of AP and Time for Vehicles on the Port Side

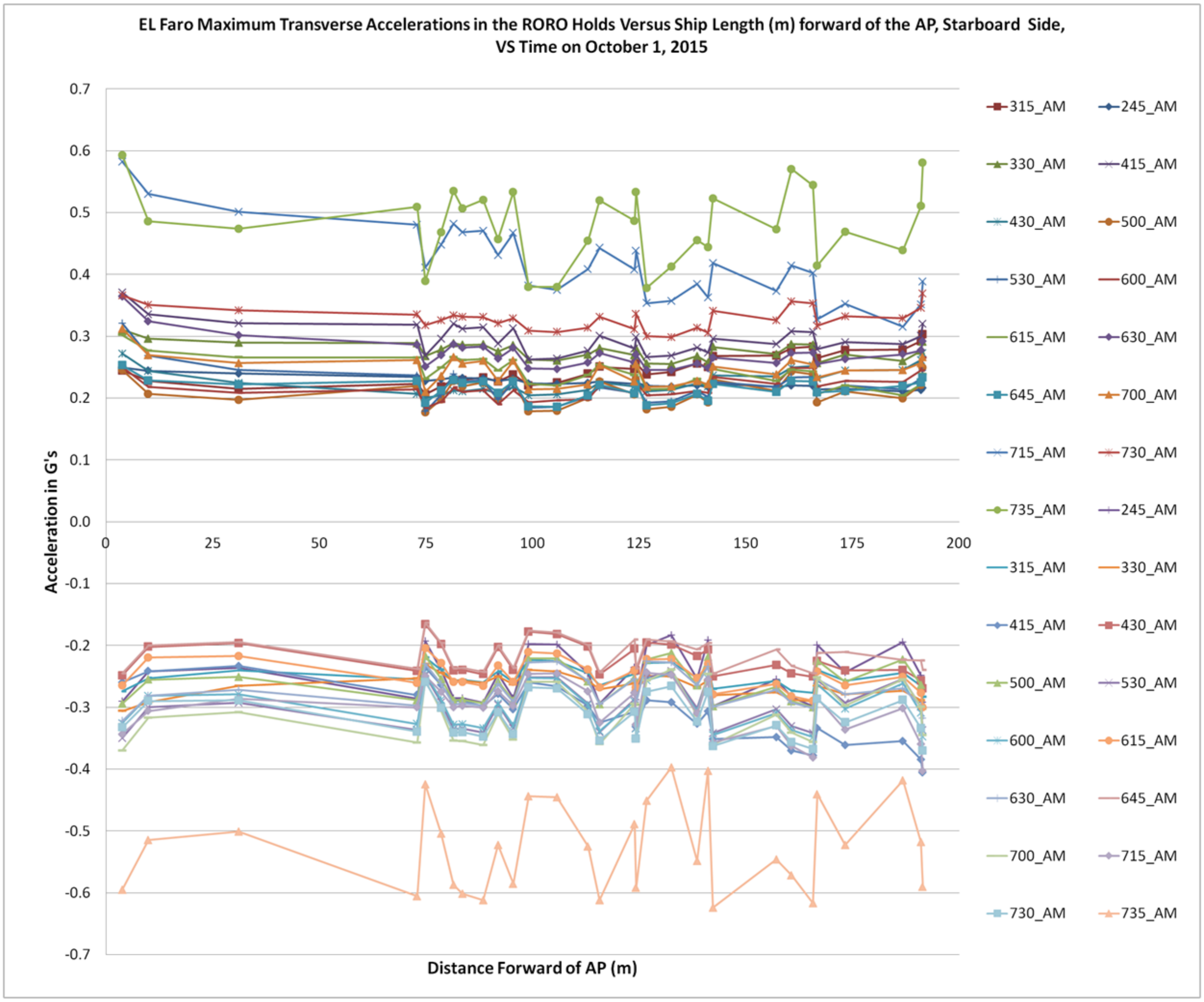


Figure 12-16: RORO Holds Maximum Transverse Acceleration vs Length Forward of AP and Time for Vehicles on the Starboard Side

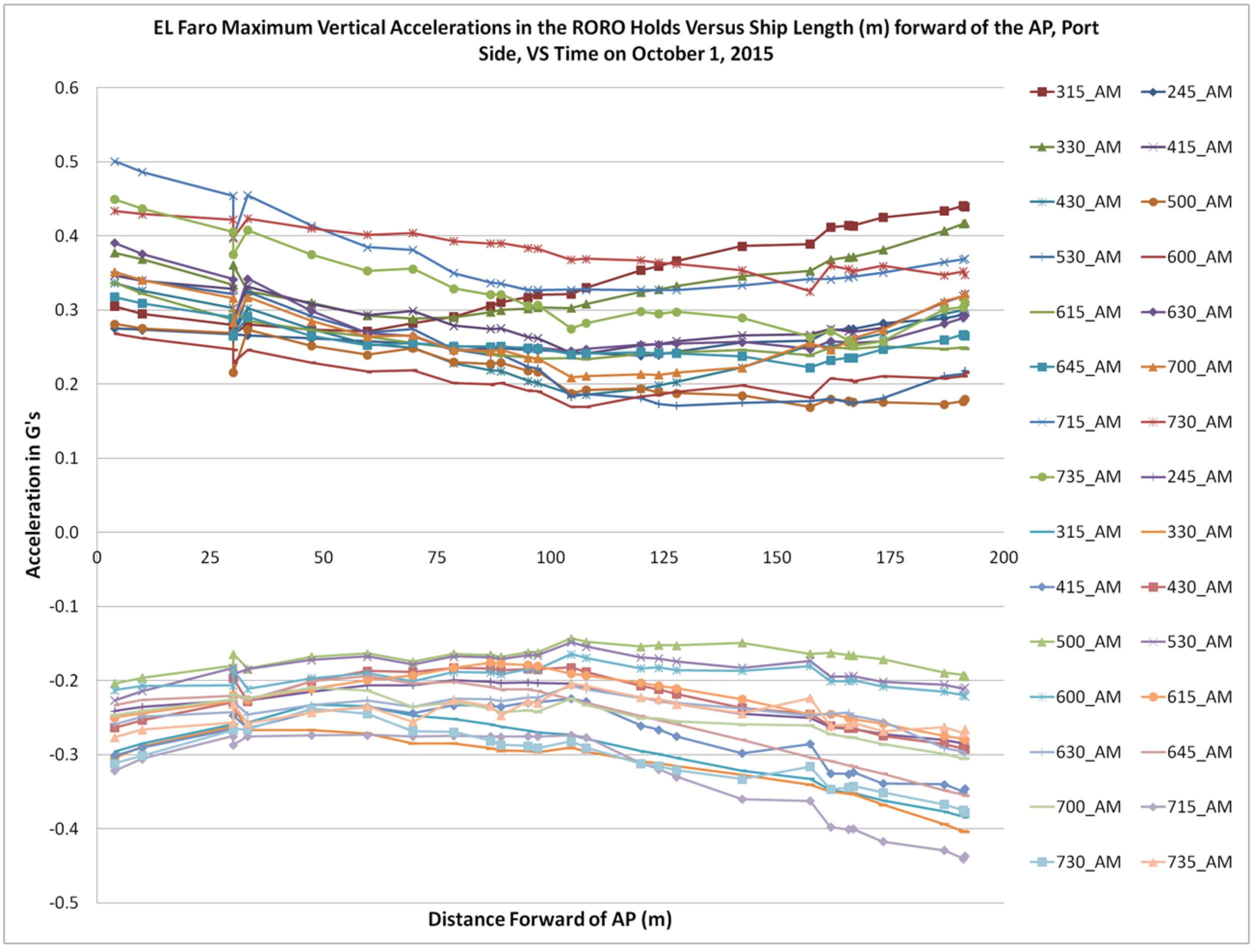


Figure 12-17: RORO Holds Maximum Vertical Acceleration vs Length Forward of AP and Time for Vehicles on the Port Side

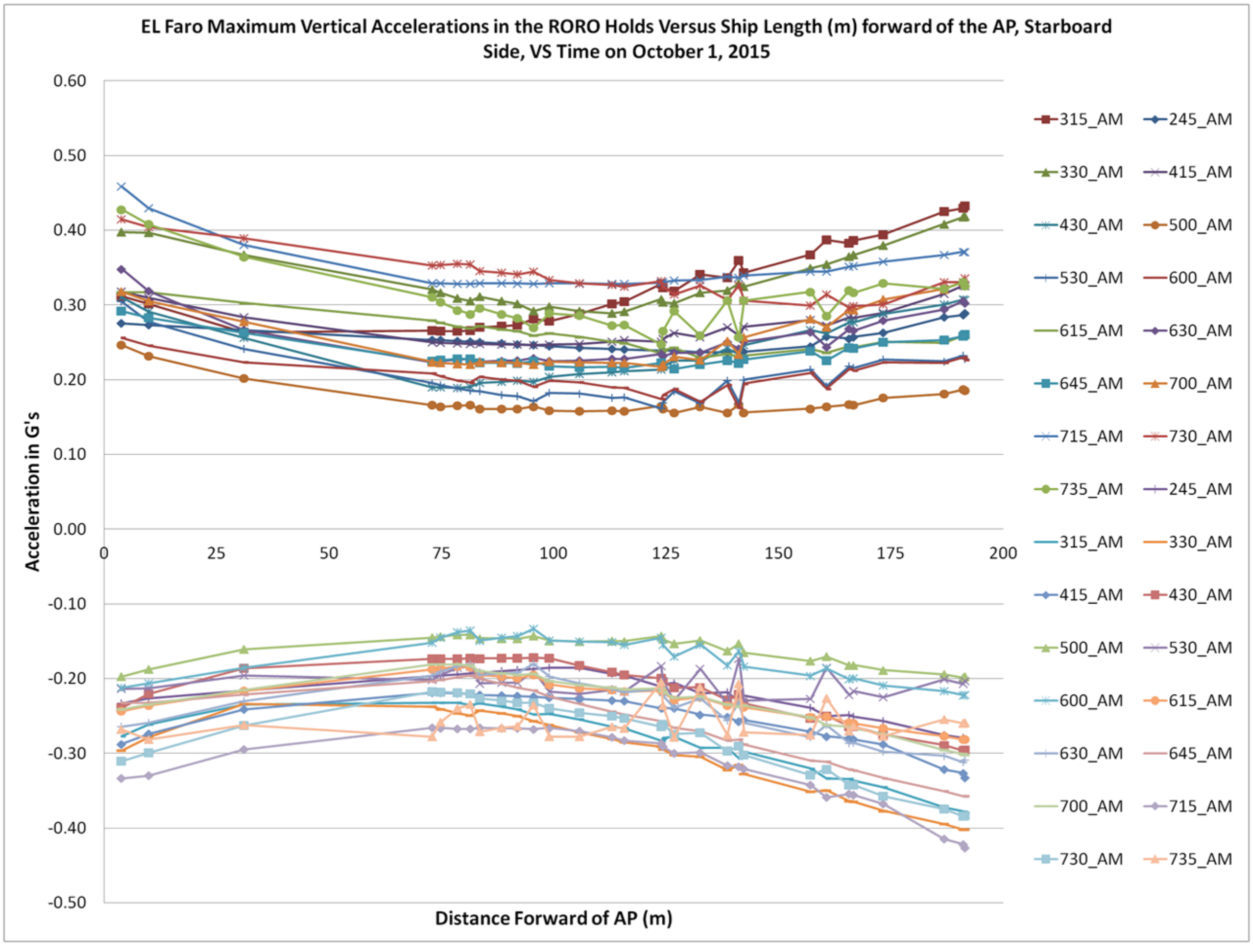


Figure 12-18: RORO Holds Maximum Vertical Acceleration vs Length Forward of AP and Time for Vehicles on the Starboard Side

The greater vertical accelerations at the ends of the ship are due to the pitching motions. Interestingly this suggests that vehicles may have broken free at the ends of the ship before they did in the 3 hold which is near the low point one these curves.

CSRA Dynamic-EL_Faro_Phase 3 Accelerations in RORO Holds_6-27-17.xlsx

12.5 Phase 3 Accelerations in the Deck House and Lube Oil Tank

Of the 30 different locations covered in this set of data, the accelerations at the Lube Oil Tanks feeding the steam turbine and reduction gear are the most important.

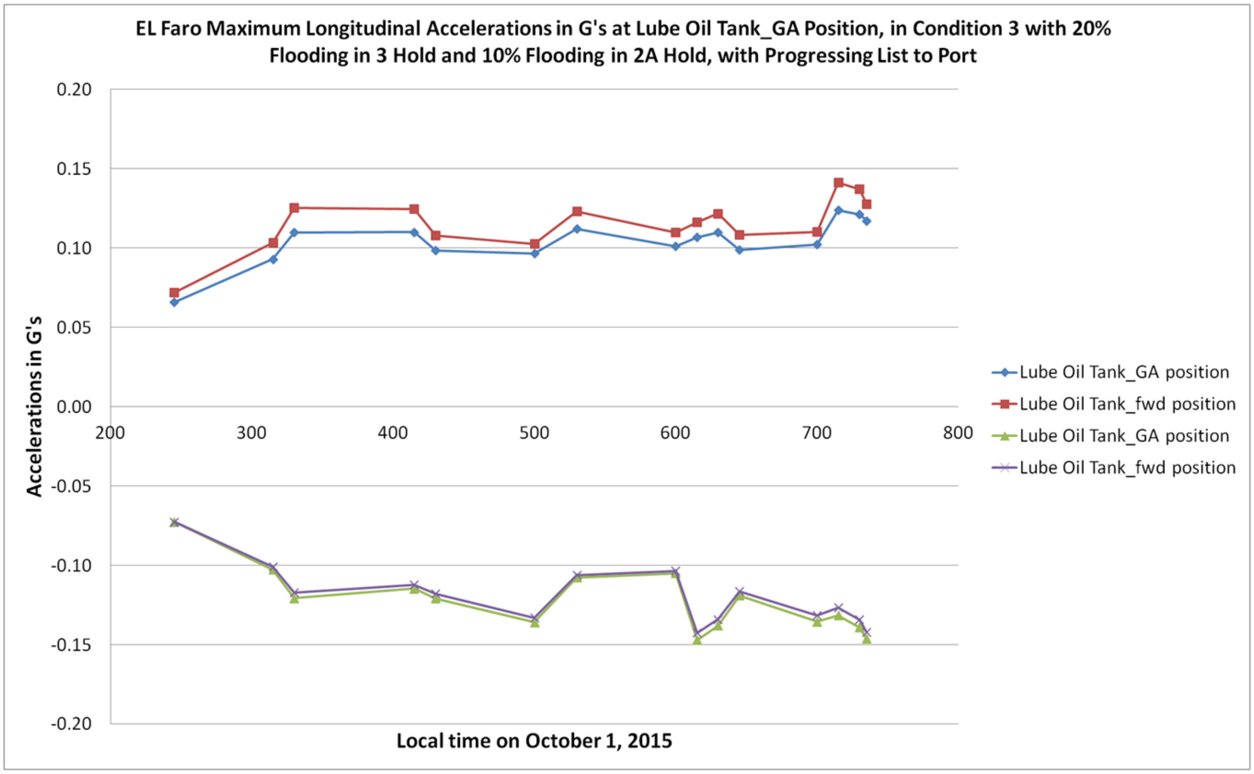


Figure 12-19: Longitudinal Acceleration Maxima at the location of the Lube Oil Tank

There is an offset of a few meters between the two positions scaled off the drawings so both were modeled.

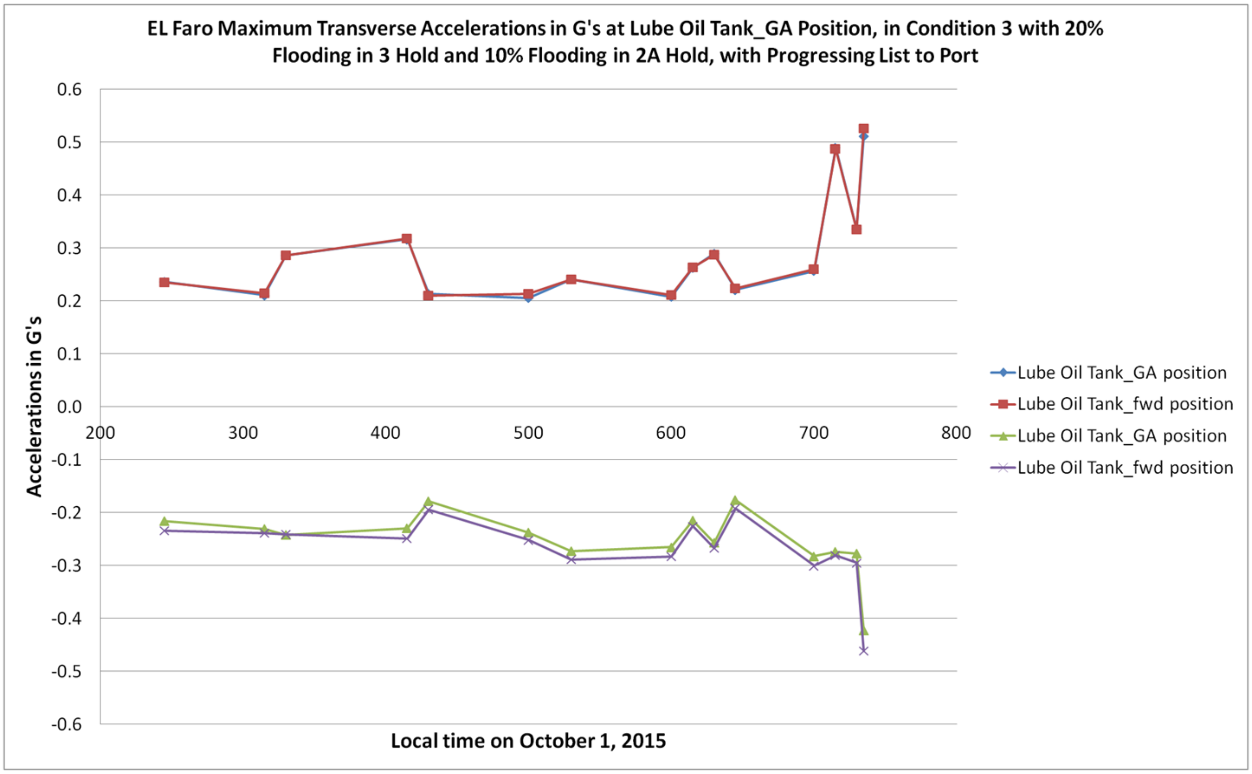


Figure 12-20: Transverse Acceleration Maxima at the location of the Lube Oil Tank

The transverse acceleration is understandably larger than the longitudinal.

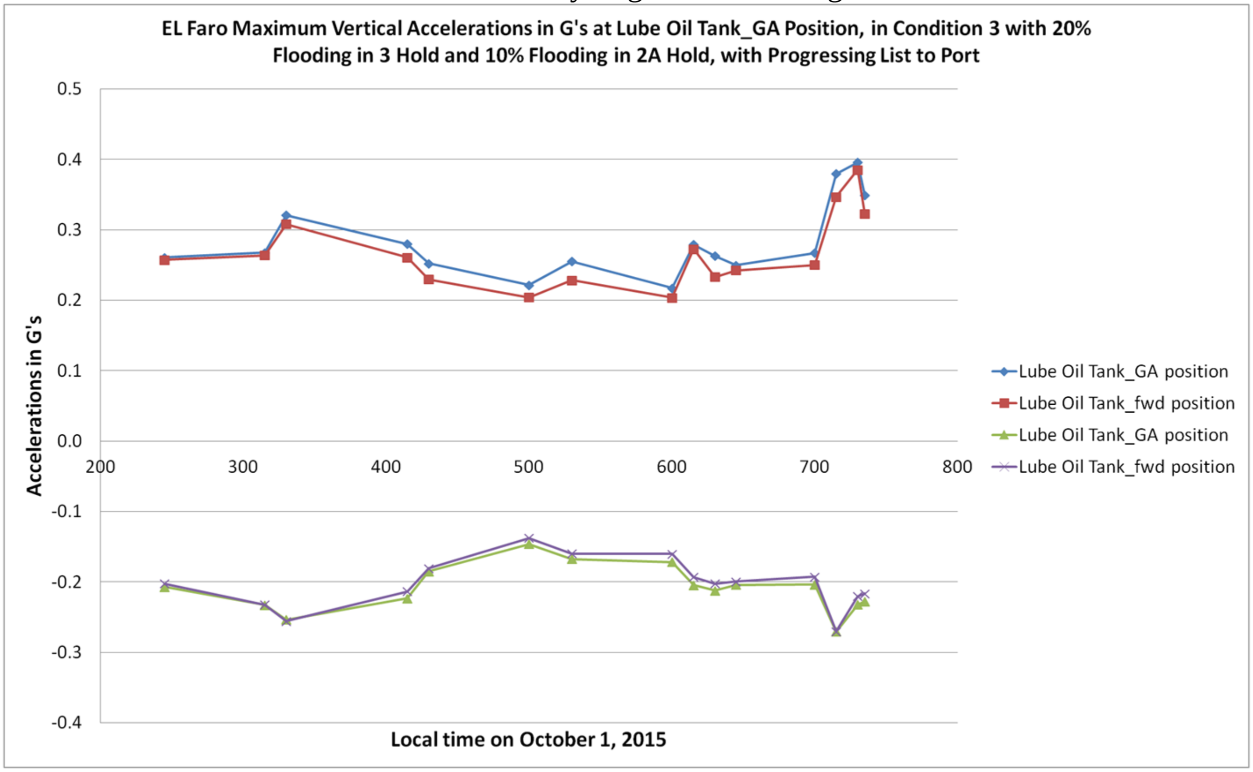


Figure 12-21: Vertical Acceleration Maxima at the location of the Lube Oil Tank

These traces fail to supply a "Smoking Gun" by themselves for the time of loss of power. That time 5:30 can be seen in table 12-11 to be at the junction between the unaltered NOAA WAV3 data and the later area where the sea conditions were estimated for remaining outside the eye of the storm. The Heel angle was about 18 degrees at 5:30AM local time so an acceleration of 3 or 4 tenths of a G on top of that may be enough to cause problems. Any tendency of the oil to foam up when sloshed about at that rate may also have played a role in the loss of oil pressure to critical equipment and the loss of power.

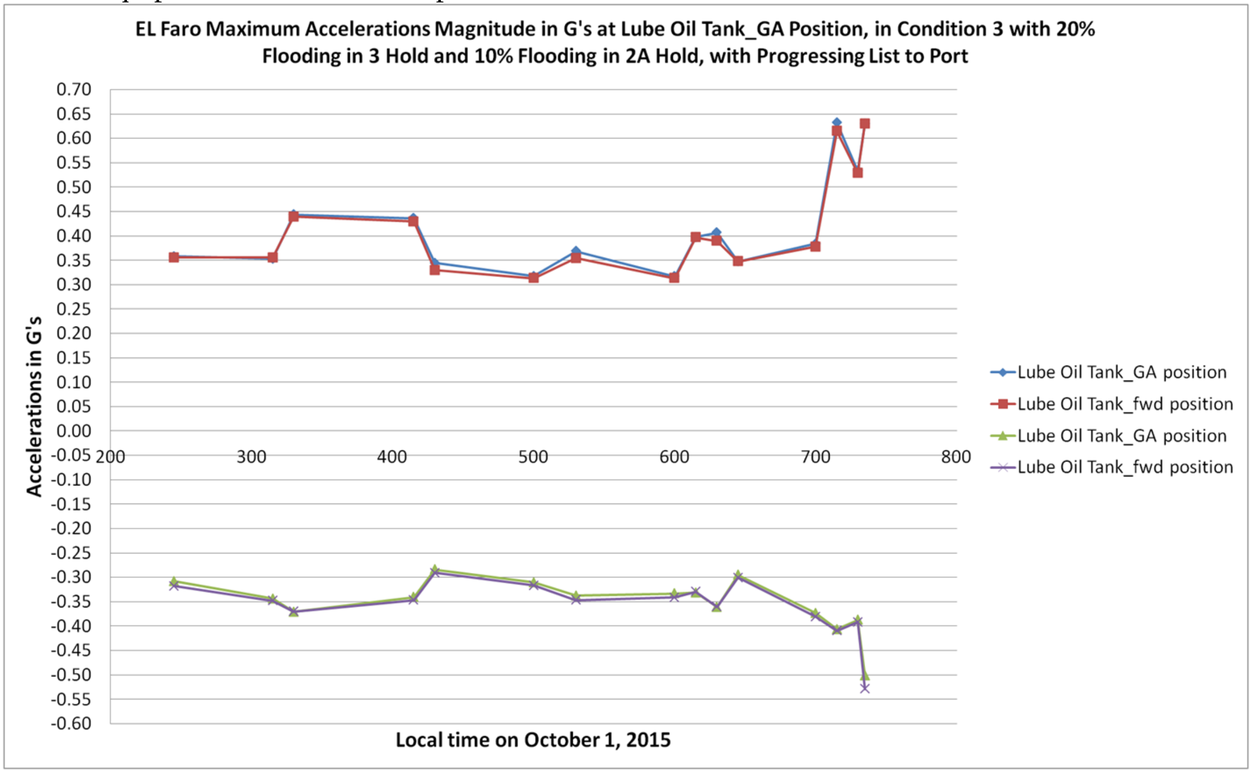


Figure 12-22: Vector Magnitude of Acceleration Maxima at Lube Oil Tank

CSRA Dynamic-EL_Faro_Phase 3 Accelerations in Accom & LO Tank_6-28-2017.xlsx

12.6 Phase 3 Pressures at the Vents and Hull Openings

CSRA Dynamic-EL_Faro_Phase 3 Pressures at Vents & Hull Openings_7-1-17.xlsx

13 Appendix 4: SHCP Modeling Results

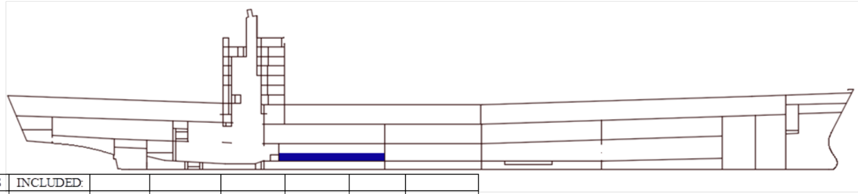
Table 13-1: Summary of Conditions Modeled

SHCP label	Condition
1	Free Flooding requirement
2	Hold 3 @ 20%
2A	Condition 2 with no tween deck
2B	Condition 2A with water on second deck (~1ft)
2C	Condition 2A with water on second deck (~2ft)
3	Hold 3 @ 30% Hold 2A @ 10%
3A	Condition 3 with no tween deck
3B	Condition 3A with water on second deck (~1ft)
3C	Condition 3A with water on second deck (~2ft)
4	Hold 3, 2A @ 50% on 4th deck
5	Hold 3, 2A, 2, and 1 @ 50% on 4th deck
6	Hold 3, 2A @ 100% and Hold 2, 1 @50% on 4th deck
7	Hold 3, 2A, 2, 1 @ 100% on 4th deck
8	Hold 3 @ 100% on 4th deck and 50% on 3rd deck
9	Hold 2A @ 100% on 4th deck and 50% on 3rd deck
10	Hold 2 @ 100% on 4th deck and 50% on 3rd deck
11	Hold 1 @ 100% on 4th deck and 50% on 3rd deck

Each condition that follows shows graphically where the water is presumed to be, the SHCP output table and a graph of the Righting Arm (RA) that results as a function of heel angle.

Table 13-2: Compartment Nomenclature use in SHCP Modeling

Compartment Labels		
103	No.1	3A
203	No.2	3B
2031	No.2A	3C
303	No.3	3D
104	No.1	4A
204	No.2	4B
2041	No.2A	4C
304	No.3	4D



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH					
304	0.975	46.64	1610.5	4.814					
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
35141.94	-10.847	11	-20	-0.478	-2.647	5.882	-10.875	9.282	1.01
			-15	-0.287	-1.972	5.669	-10.885	9.346	1.316
			-10	-0.166	-1.308	5.522	-10.895	9.389	1.527
			-5	-0.103	-0.652	5.435	-10.899	9.413	1.646
			0	-0.05	0	5.407	-10.898	9.421	1.684
			5	0.004	0.652	5.435	-10.899	9.413	1.646
			10	0.068	1.308	5.522	-10.895	9.389	1.527
			15	0.191	1.972	5.669	-10.885	9.346	1.316
			20	0.384	2.647	5.882	-10.875	9.282	1.01
			25	0.63	3.34	6.169	-10.863	9.187	0.606
			30	0.918	4.043	6.536	-10.851	9.042	0.111
			35	1.238	4.742	6.981	-10.84	8.816	-0.465
			40	1.547	5.397	7.484	-10.829	8.479	-1.093
			45	1.758	5.942	7.982	-10.823	8.042	-1.753
			50	1.855	6.373	8.452	-10.818	7.508	-2.482
			55	1.846	6.706	8.884	-10.814	6.859	-3.325
			60	1.764	6.968	9.294	-10.813	6.029	-4.298
			70	1.473	7.342	10.095	-10.815	3.35	-7.32
			80	1.044	7.548	10.857	-10.83	-4.288	-17.001
			85	0.791	7.597	11.223	-10.87	-19.46	-36.038

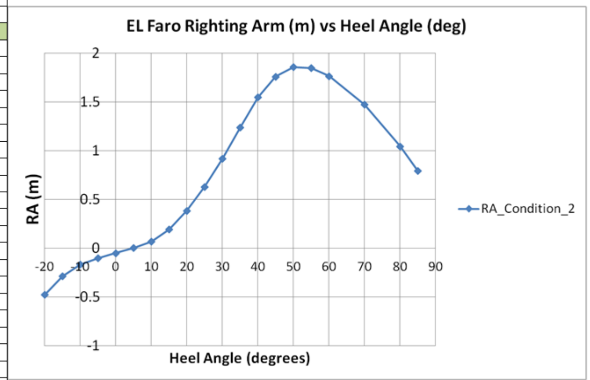
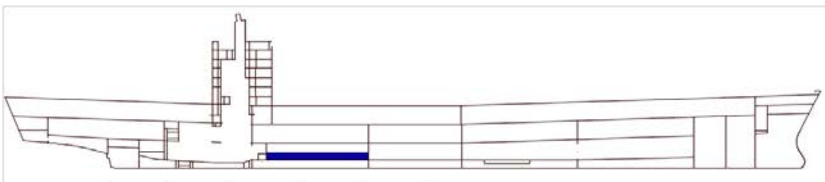


Figure 13-1: Condition 2



FIXED	FLOODED	SPACES	NCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH					
304	0.975	21.55	1610.5	4.814					
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
35141.94	-10.847	11.08	-20	-0.439	-2.647	5.882	-10.876	9.282	1.01
			-15	-0.274	-1.972	5.669	-10.886	9.346	1.317
			-10	-0.166	-1.308	5.522	-10.895	9.389	1.527
			-5	-0.103	-0.652	5.435	-10.899	9.413	1.646
			0	-0.05	0	5.407	-10.898	9.421	1.684
			5	0.004	0.652	5.435	-10.899	9.413	1.646
			10	0.068	1.308	5.522	-10.895	9.389	1.527
			15	0.178	1.972	5.669	-10.886	9.346	1.317
			20	0.345	2.647	5.882	-10.876	9.282	1.01
			25	0.566	3.34	6.169	-10.864	9.187	0.607
			30	0.832	4.043	6.536	-10.851	9.042	0.111
			35	1.132	4.742	6.981	-10.839	8.816	-0.465
			40	1.424	5.397	7.484	-10.828	8.479	-1.094
			45	1.619	5.942	7.982	-10.82	8.042	-1.755
			50	1.705	6.373	8.452	-10.814	7.508	-2.485
			55	1.691	6.706	8.884	-10.81	6.86	-3.329
			60	1.606	6.968	9.294	-10.807	6.029	-4.303
			70	1.316	7.342	10.095	-10.807	3.351	-7.329
			80	0.896	7.548	10.857	-10.817	-4.288	-17.033
			85	0.648	7.597	11.223	-10.846	-19.46	-36.158

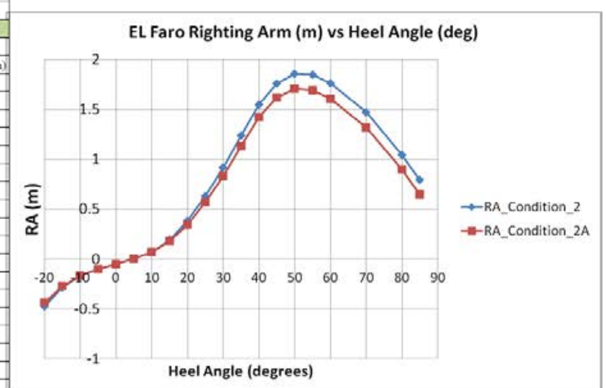
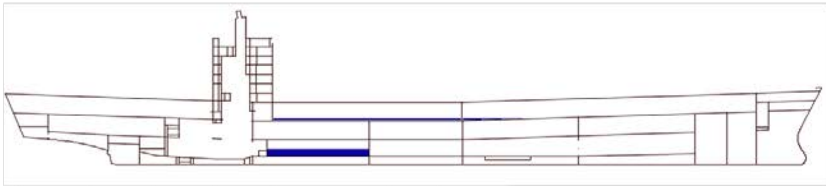


Figure 13-2:Condition 2A



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	21.55	1610.5	4.814	100	0.975	3.28	491.9	13.604
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
35633.80	-10.832	11.03	-20	-0.27	-2.623	5.935	-10.802	9.392	0.899
			-15	-0.111	-1.953	5.723	-10.832	9.455	1.21
			-10	-0.013	-1.296	5.578	-10.864	9.496	1.429
			-5	0.027	-0.646	5.492	-10.906	9.518	1.566
			0	-0.049	0	5.465	-10.98	9.522	1.643
			5	-0.124	0.646	5.492	-10.906	9.518	1.566
			10	-0.083	1.296	5.578	-10.864	9.496	1.429
			15	0.016	1.953	5.723	-10.832	9.455	1.21
			20	0.178	2.623	5.935	-10.802	9.392	0.899
			25	0.396	3.31	6.219	-10.774	9.299	0.492
			30	0.664	4.009	6.584	-10.747	9.157	-0.005
			35	0.97	4.706	7.029	-10.721	8.934	-0.581
			40	1.265	5.359	7.528	-10.698	8.604	-1.204
			45	1.462	5.898	8.021	-10.68	8.182	-1.864
			50	1.551	6.323	8.484	-10.664	7.667	-2.595
			55	1.541	6.651	8.911	-10.651	7.041	-3.435
			60	1.46	6.908	9.314	-10.64	6.242	-4.419
			70	1.182	7.275	10.1	-10.619	3.662	-7.43
			80	0.784	7.478	10.853	-10.586	-3.654	-17.181
			85	0.55	7.526	11.215	-10.582	-18.18	-36.609

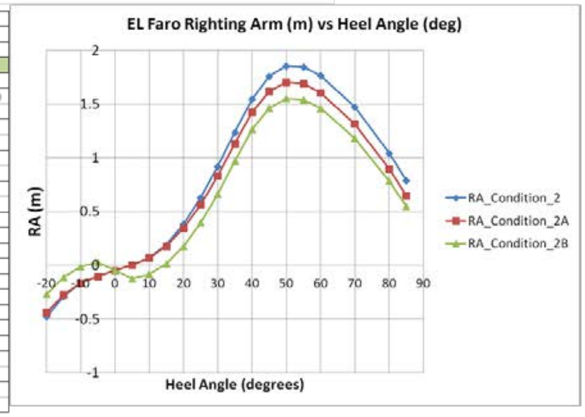
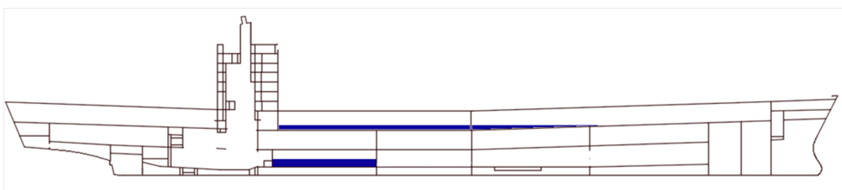


Figure 13-3:Condition 2B



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	21.55	1610.5	4.814	100	0.975	6.57	983.8	13.903
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stem)
36125.71	-10.753	11.07	-20	-0.124	-2.594	5.986	-10.646	9.507	0.74
			-15	0.025	-1.934	5.777	-10.69	9.568	1.056
			-10	0.105	-1.284	5.633	-10.744	9.608	1.283
			-5	0.108	-0.64	5.549	-10.827	9.627	1.44
			0	-0.048	0	5.521	-10.937	9.63	1.535
			5	-0.204	0.64	5.549	-10.827	9.627	1.44
			10	-0.2	1.284	5.633	-10.744	9.608	1.283
			15	-0.118	1.934	5.777	-10.69	9.568	1.056
			20	0.033	2.597	5.986	-10.646	9.507	0.74
			25	0.244	3.279	6.269	-10.606	9.414	0.333
			30	0.509	3.974	6.631	-10.569	9.274	-0.164
			35	0.817	4.671	7.075	-10.534	9.053	-0.737
			40	1.113	5.319	7.572	-10.505	8.731	-1.352
			45	1.309	5.852	8.06	-10.48	8.323	-2.012
			50	1.396	6.272	8.516	-10.456	7.827	-2.746
			55	1.387	6.595	8.937	-10.432	7.224	-3.593
			60	1.312	6.848	9.334	-10.398	6.458	-4.607
			70	1.046	7.207	10.105	-10.352	3.975	-7.638
			80	0.67	7.408	10.849	-10.301	-3.023	-17.467
			85	0.449	7.454	11.206	-10.275	-16.908	-37.269

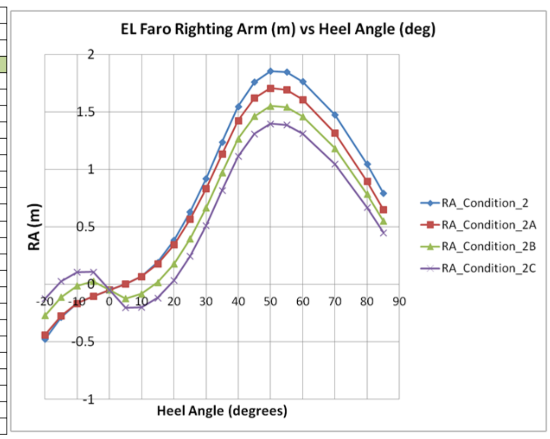
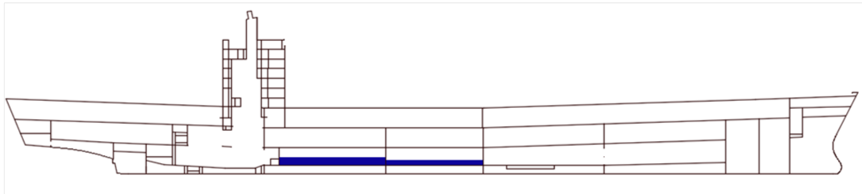


Figure 13-4: Condition 2C



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	69.96	2415.8	5.977	2041	0.975	21.15	673.2	3.515
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
36620.36	-10.984	10.73	-20	-0.45	-2.58	6.043	-11.01	9.595	0.875
			-15	-0.247	-1.921	5.835	-11.019	9.658	1.161
			-10	-0.095	-1.274	5.691	-11.026	9.699	1.356
			-5	-0.03	-0.635	5.607	-11.034	9.722	1.468
			0	-0.048	0	5.579	-11.035	9.73	1.505
			5	-0.065	0.635	5.607	-11.034	9.722	1.468
			10	0.001	1.274	5.691	-11.026	9.699	1.356
			15	0.155	1.921	5.835	-11.019	9.658	1.161
			20	0.361	2.58	6.043	-11.01	9.595	0.875
			25	0.621	3.258	6.324	-10.999	9.503	0.496
			30	0.933	3.952	6.685	-10.988	9.364	0.027
			35	1.286	4.647	7.129	-10.977	9.146	-0.518
			40	1.617	5.291	7.622	-10.969	8.834	-1.101
			45	1.84	5.818	8.103	-10.964	8.44	-1.717
			50	1.948	6.231	8.553	-10.96	7.963	-2.387
			55	1.951	6.549	8.966	-10.958	7.385	-3.154
			60	1.882	6.797	9.357	-10.957	6.65	-4.055
			70	1.611	7.151	10.112	-10.962	4.273	-6.751
			80	1.226	7.351	10.853	-10.985	-2.37	-15.351
			85	0.99	7.398	11.206	-11.038	-15.581	-32.605

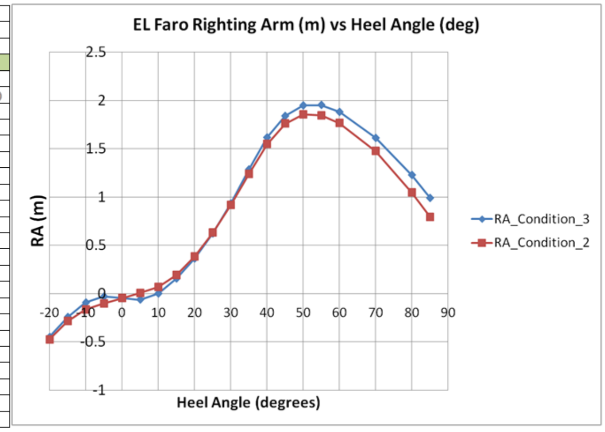
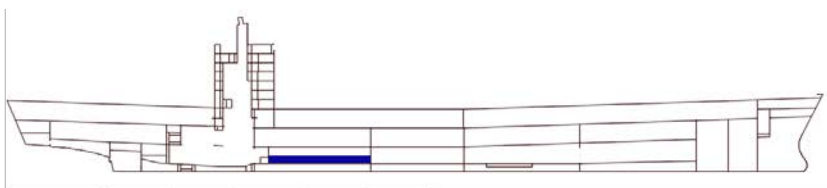


Figure 13-5: Condition 3



FIXED	FLOODED	SPACES	NCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH					
304	0.975	21.55	1610.5	4.814					
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
35141.94	-10.847	11.08	-20	-0.439	-2.647	5.882	-10.876	9.282	1.01
			-15	-0.274	-1.972	5.669	-10.886	9.346	1.317
			-10	-0.166	-1.308	5.522	-10.895	9.389	1.527
			-5	-0.103	-0.652	5.435	-10.899	9.413	1.646
			0	-0.05	0	5.407	-10.898	9.421	1.684
			5	0.004	0.652	5.435	-10.899	9.413	1.646
			10	0.068	1.308	5.522	-10.895	9.389	1.527
			15	0.178	1.972	5.669	-10.886	9.346	1.317
			20	0.345	2.647	5.882	-10.876	9.282	1.01
			25	0.566	3.34	6.169	-10.864	9.187	0.607
			30	0.832	4.043	6.536	-10.851	9.042	0.111
			35	1.132	4.742	6.981	-10.839	8.816	-0.465
			40	1.424	5.397	7.484	-10.828	8.479	-1.094
			45	1.619	5.942	7.982	-10.82	8.042	-1.755
			50	1.705	6.373	8.452	-10.814	7.508	-2.485
			55	1.691	6.706	8.884	-10.81	6.86	-3.329
			60	1.606	6.968	9.294	-10.807	6.029	-4.303
			70	1.316	7.342	10.095	-10.807	3.351	-7.329
			80	0.896	7.548	10.857	-10.817	-4.288	-17.033
			85	0.648	7.597	11.223	-10.846	-19.46	-36.158

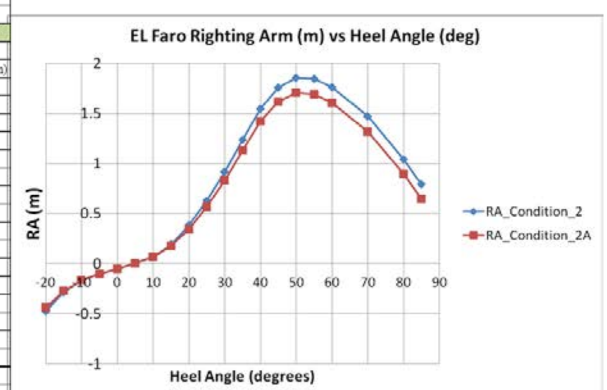
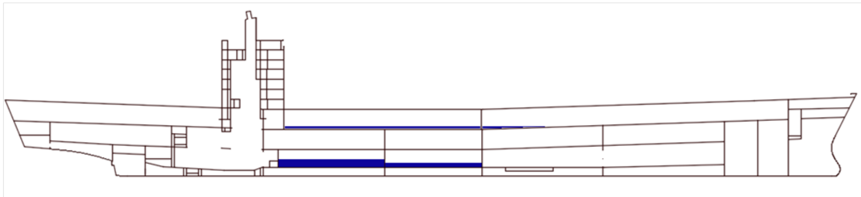


Figure 13-6: Condition 3A



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	21.55	1610.5	4.814	2041	0.975	9.81	673.2	3.515
100	0.975	3.28	491.9	13.604					
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
37112.22	-10.968	10.76	-20	-0.126	-2.557	6.095	-10.935	9.705	0.764
			-15	0.007	-1.904	5.889	-10.963	9.766	1.055
			-10	0.078	-1.263	5.746	-10.99	9.806	1.256
			-5	0.094	-0.63	5.663	-11.03	9.827	1.385
			0	-0.047	0	5.636	-11.102	9.831	1.458
			5	-0.188	0.63	5.663	-11.03	9.827	1.385
			10	-0.17	1.263	5.746	-10.99	9.806	1.256
			15	-0.098	1.904	5.889	-10.963	9.766	1.055
			20	0.037	2.557	6.095	-10.935	9.705	0.764
			25	0.244	3.23	6.374	-10.909	9.614	0.382
			30	0.513	3.92	6.733	-10.884	9.477	-0.087
			35	0.838	4.614	7.176	-10.86	9.262	-0.631
			40	1.151	5.253	7.665	-10.84	8.957	-1.207
			45	1.363	5.773	8.141	-10.824	8.579	-1.824
			50	1.466	6.18	8.585	-10.811	8.121	-2.494
			55	1.473	6.493	8.992	-10.799	7.567	-3.262
			60	1.411	6.738	9.376	-10.79	6.864	-4.173
			70	1.166	7.085	10.118	-10.774	4.585	-6.871
			80	0.831	7.282	10.85	-10.752	-1.739	-15.509
			85	0.627	7.328	11.198	-10.757	-14.312	-33.134

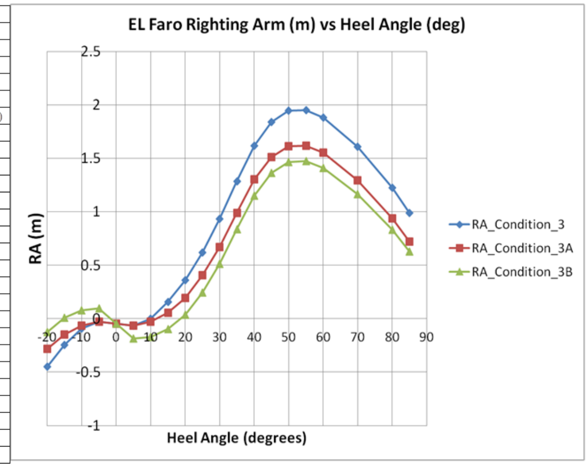
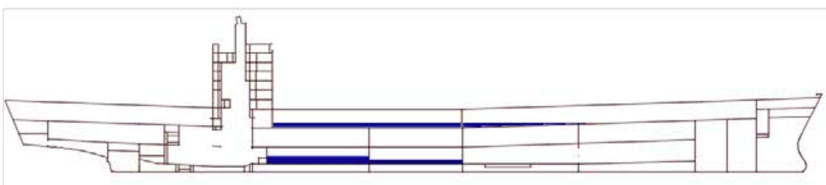


Figure 13-7: Condition 3B



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	21.55	1610.5	4.814	2041	0.975	9.81	673.2	3.515
100	0.975	6.57	983.8	13.903					
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
37604.13	-10.89	10.8	-20	0.012	-2.534	6.146	-10.78	9.818	0.606
			-15	0.135	-1.886	5.942	-10.82	9.878	0.9
			-10	0.19	-1.251	5.801	-10.868	9.917	1.11
			-5	0.171	-0.624	5.719	-10.947	9.936	1.258
			0	-0.046	0	5.692	-11.052	9.938	1.35
			5	-0.264	0.624	5.719	-10.947	9.936	1.258
			10	-0.281	1.251	5.801	-10.868	9.917	1.11
			15	-0.225	1.886	5.942	-10.82	9.878	0.9
			20	-0.099	2.534	6.146	-10.78	9.818	0.606
			25	0.101	3.201	6.423	-10.743	9.728	0.224
			30	0.368	3.887	6.781	-10.709	9.592	-0.244
			35	0.694	4.579	7.222	-10.678	9.38	-0.782
			40	1.006	5.213	7.708	-10.653	9.083	-1.35
			45	1.216	5.728	8.178	-10.631	8.719	-1.965
			50	1.317	6.129	8.615	-10.61	8.281	-2.641
			55	1.325	6.437	9.017	-10.589	7.751	-3.418
			60	1.27	6.678	9.396	-10.559	7.08	-4.353
			70	1.036	7.019	10.123	-10.518	4.9	-7.096
			80	0.72	7.213	10.846	-10.482	-1.112	-15.765
			85	0.528	7.258	11.19	-10.467	-13.051	-33.716

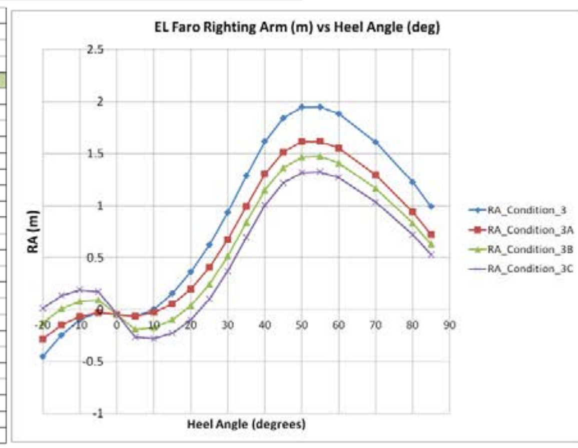
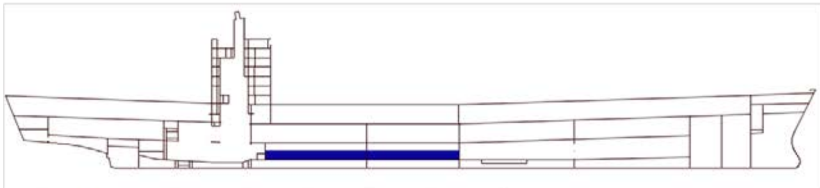


Figure 13-8: Condition 3C



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	50	1726.6	4.982	2041	0.975	50	1591.2	4.964
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
36849.18	-10.367	10.67	-20	-0.311	-2.561	6.062	-10.381	9.676	0.486
			-15	-0.114	-1.906	5.855	-10.391	9.739	0.777
			-10	-0.025	-1.264	5.713	-10.4	9.78	0.976
			-5	-0.032	-0.63	5.629	-10.404	9.804	1.088
			0	-0.047	0	5.602	-10.404	9.812	1.124
			5	-0.062	0.63	5.629	-10.404	9.804	1.088
			10	-0.069	1.264	5.713	-10.4	9.78	0.976
			15	0.022	1.906	5.855	-10.391	9.739	0.777
			20	0.222	2.561	6.062	-10.381	9.676	0.486
			25	0.488	3.235	6.342	-10.371	9.583	0.104
			30	0.808	3.926	6.702	-10.361	9.443	-0.367
			35	1.172	4.621	7.145	-10.352	9.224	-0.911
			40	1.516	5.264	7.638	-10.345	8.913	-1.493
			45	1.749	5.788	8.117	-10.34	8.524	-2.13
			50	1.868	6.199	8.564	-10.337	8.056	-2.837
			55	1.884	6.515	8.976	-10.335	7.488	-3.65
			60	1.828	6.763	9.364	-10.335	6.766	-4.617
			70	1.583	7.114	10.114	-10.342	4.43	-7.486
			80	1.223	7.312	10.847	-10.368	-2.088	-16.693
			85	1.003	7.359	11.198	-10.428	-15.014	-35.253

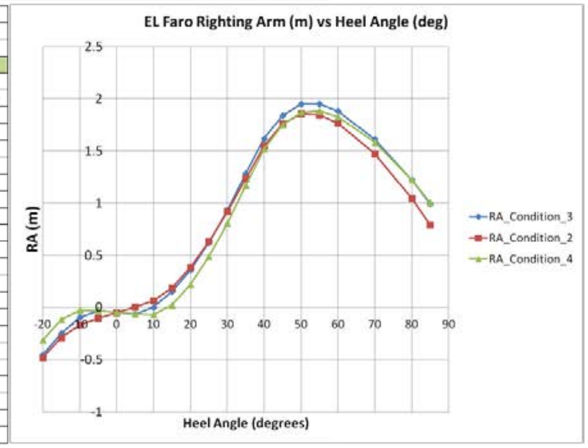
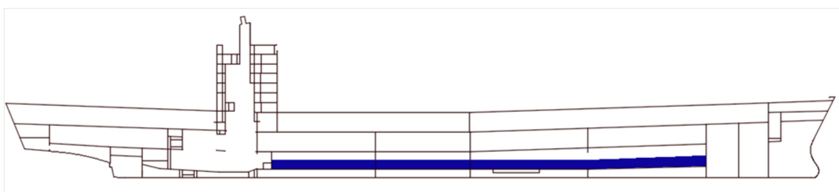


Figure 13-9: Condition 4



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	50	1726.6	4.982	2041	0.975	50	1591.2	4.964
204	0.975	50	1818.9	5.339	104	0.975	50	967.1	6.333
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
39635.14	-6.677	10.21	-20	-0.181	-2.393	6.359	-6.594	10.449	-2.132
			-15	0.008	-1.778	6.165	-6.605	10.517	-1.842
			-10	0.062	-1.179	6.032	-6.613	10.562	-1.635
			-5	0.013	-0.588	5.954	-6.618	10.587	-1.515
			0	-0.044	0	5.928	-6.619	10.595	-1.477
			5	-0.1	0.588	5.954	-6.618	10.587	-1.515
			10	-0.149	1.179	6.032	-6.613	10.562	-1.635
			15	-0.093	1.778	6.165	-6.605	10.517	-1.842
			20	0.098	2.393	6.359	-6.594	10.449	-2.132
			25	0.373	3.032	6.624	-6.586	10.349	-2.501
			30	0.723	3.699	6.973	-6.579	10.204	-2.943
			35	1.132	4.381	7.407	-6.573	9.986	-3.436
			40	1.494	4.988	7.872	-6.568	9.721	-4.034
			45	1.747	5.478	8.32	-6.565	9.412	-4.787
			50	1.888	5.858	8.734	-6.564	9.05	-5.717
			55	1.939	6.154	9.119	-6.565	8.612	-6.797
			60	1.922	6.387	9.483	-6.569	8.053	-8.058
			70	1.741	6.707	10.166	-6.585	6.295	-12.141
			80	1.432	6.885	10.82	-6.639	1.405	-24.253
			85	1.243	6.929	11.139	-6.75	-8.101	-49.463

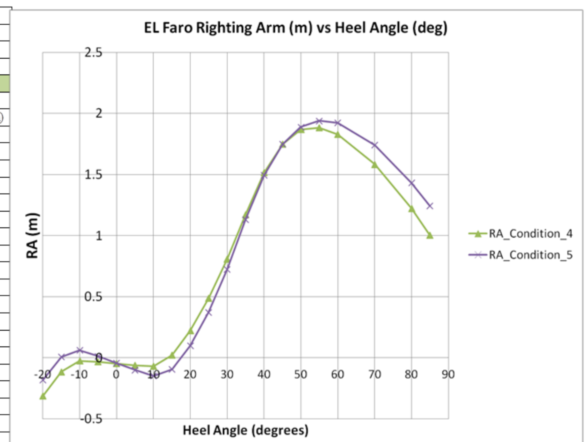
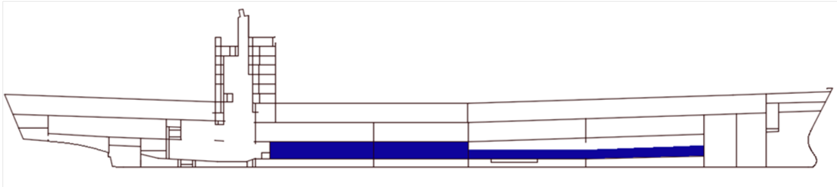


Figure 13-10: Condition 5



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	100	3453.1	0	2041	0.975	100	3182.4	0
204	0.975	50	1818.9	5.339	104	0.975	50	967.1	6.333
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
42952.9	-7.209	9.9	-20	-0.851	-2.286	6.719	-7.141	11.118	-2.299
			-15	-0.595	-1.697	6.533	-7.151	11.184	-2.059
			-10	-0.39	-1.124	6.406	-7.16	11.226	-1.89
			-5	-0.212	-0.56	6.331	-7.164	11.25	-1.793
			0	-0.041	0	6.307	-7.165	11.258	-1.761
			5	0.131	0.56	6.331	-7.164	11.25	-1.793
			10	0.31	1.124	6.406	-7.16	11.226	-1.89
			15	0.516	1.697	6.533	-7.151	11.184	-2.059
			20	0.775	2.286	6.719	-7.141	11.118	-2.299
			25	1.089	2.899	6.974	-7.136	11.021	-2.606
			30	1.469	3.547	7.312	-7.131	10.879	-2.97
			35	1.875	4.191	7.722	-7.127	10.695	-3.398
			40	2.208	4.749	8.149	-7.125	10.503	-3.953
			45	2.432	5.197	8.559	-7.124	10.299	-4.646
			50	2.544	5.544	8.937	-7.125	10.069	-5.45
			55	2.567	5.814	9.287	-7.128	9.794	-6.353
			60	2.516	6.023	9.614	-7.134	9.455	-7.475
			70	2.259	6.309	10.224	-7.155	8.41	-11.089
			80	1.88	6.471	10.823	-7.218	5.731	-21.201
			85	1.653	6.512	11.115	-7.346	0.578	-42.115

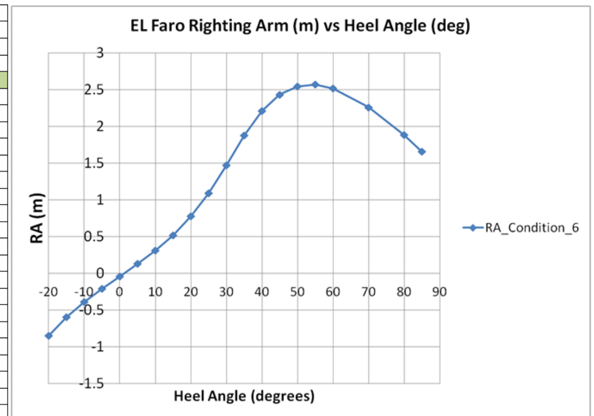
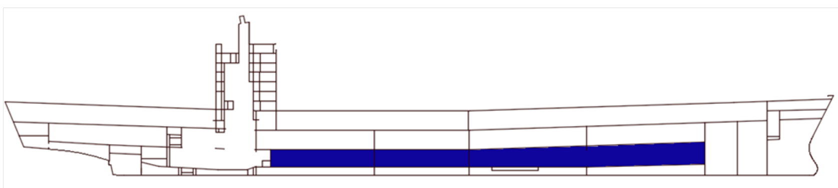


Figure 13-11: Condition 6



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	100	3453.1	0	2041	0.975	100	3182.4	0
204	0.975	100	3637.8	0	104	0.975	100	1934.1	0
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stern)
45738.86	-4.094	9.73	-20	-1.159	-2.168	7.056	-4.04	11.813	-4.555
			-15	-0.851	-1.606	6.879	-4.04	11.887	-4.336
			-10	-0.568	-1.063	6.758	-4.039	11.935	-4.177
			-5	-0.3	-0.529	6.688	-4.039	11.962	-4.086
			0	-0.038	0	6.665	-4.039	11.97	-4.056
			5	0.224	0.529	6.688	-4.039	11.962	-4.086
			10	0.493	1.063	6.758	-4.039	11.935	-4.177
			15	0.777	1.606	6.879	-4.04	11.887	-4.336
			20	1.087	2.168	7.056	-4.04	11.813	-4.555
			25	1.439	2.759	7.302	-4.042	11.705	-4.824
			30	1.844	3.382	7.626	-4.046	11.556	-5.136
			35	2.224	3.966	7.998	-4.052	11.411	-5.601
			40	2.529	4.469	8.383	-4.057	11.289	-6.279
			45	2.741	4.883	8.761	-4.063	11.174	-7.141
			50	2.854	5.209	9.116	-4.072	11.051	-8.156
			55	2.873	5.459	9.44	-4.082	10.922	-9.394
			60	2.819	5.653	9.743	-4.094	10.777	-10.962
			70	2.548	5.916	10.302	-4.134	10.401	-16.175
			80	2.142	6.064	10.842	-4.244	9.659	-30.897
			85	1.895	6.103	11.101	-4.452	8.256	-59.796

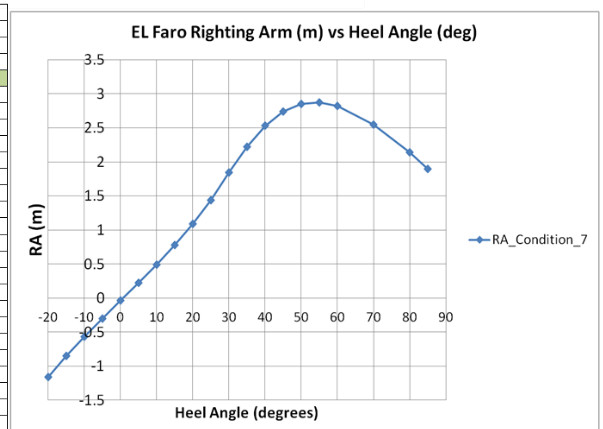
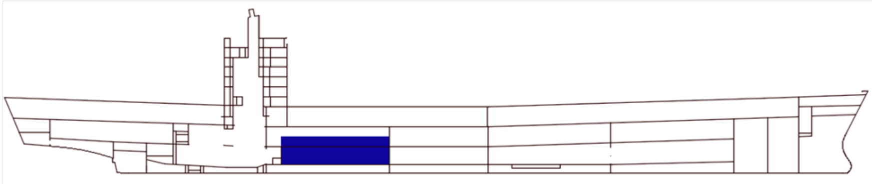


Figure 13-12: Condition 7



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
304	0.975	100	3453.1	0	303	0.975	50	2010.7	10.365
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stem)
38995.28	-12.486	10.66	-20	-0.581	-2.497	6.31	-12.518	10.024	1.424
			-15	-0.37	-1.858	6.108	-12.527	10.082	1.665
			-10	-0.236	-1.232	5.969	-12.534	10.119	1.828
			-5	-0.138	-0.614	5.888	-12.538	10.141	1.922
			0	-0.045	0	5.861	-12.538	10.148	1.952
			5	0.049	0.614	5.888	-12.538	10.141	1.922
			10	0.148	1.232	5.969	-12.534	10.119	1.828
			15	0.283	1.858	6.108	-12.527	10.082	1.665
			20	0.497	2.497	6.31	-12.518	10.024	1.424
			25	0.768	3.157	6.584	-12.508	9.938	1.096
			30	1.093	3.837	6.938	-12.498	9.809	0.685
			35	1.46	4.522	7.375	-12.489	9.61	0.206
			40	1.778	5.136	7.845	-12.482	9.346	-0.277
			45	1.979	5.63	8.297	-12.477	9.028	-0.749
			50	2.063	6.013	8.714	-12.474	8.648	-1.211
			55	2.048	6.307	9.096	-12.472	8.191	-1.733
			60	1.963	6.537	9.457	-12.471	7.611	-2.343
			70	1.654	6.859	10.145	-12.473	5.729	-4.126
			80	1.268	7.049	10.852	-12.488	0.704	-9.404
			85	1.035	7.094	11.19	-12.524	-9.321	-20.43

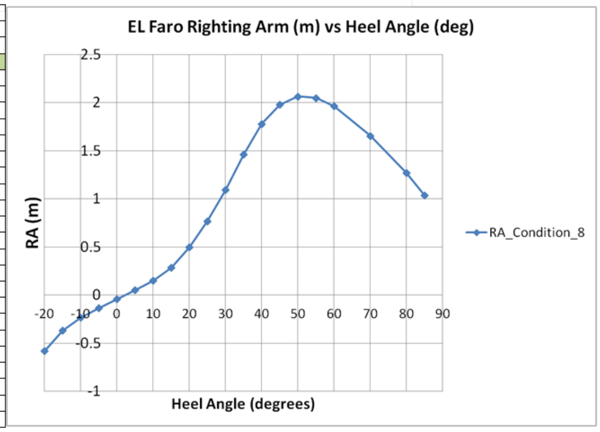
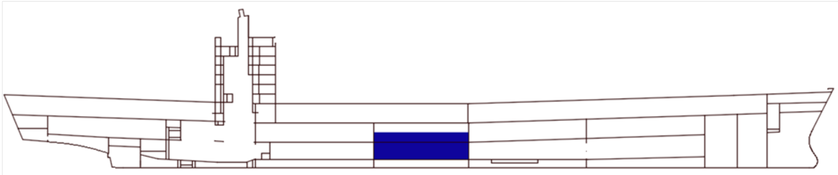


Figure 13-13: Condition 8



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
2041	0.975	100	3182.4	0	2031	0.975	50	1840.8	10.366
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stem)
38554.65	-8.553	10.71	-20	-0.532	-2.462	6.239	-8.535	10.13	-0.83
			-15	-0.336	-1.831	6.039	-8.54	10.196	-0.545
			-10	-0.216	-1.214	5.902	-8.544	10.238	-0.347
			-5	-0.128	-0.605	5.822	-8.547	10.263	-0.234
			0	-0.045	0	5.796	-8.548	10.27	-0.198
			5	0.038	0.605	5.822	-8.547	10.263	-0.234
			10	0.126	1.214	5.902	-8.544	10.238	-0.347
			15	0.249	1.831	6.039	-8.54	10.196	-0.545
			20	0.447	2.462	6.239	-8.535	10.13	-0.83
			25	0.704	3.116	6.51	-8.529	10.035	-1.2
			30	1.018	3.792	6.862	-8.522	9.894	-1.653
			35	1.381	4.481	7.301	-8.518	9.678	-2.164
			40	1.705	5.105	7.78	-8.515	9.393	-2.734
			45	1.914	5.61	8.241	-8.512	9.051	-3.41
			50	2.005	6.001	8.667	-8.511	8.648	-4.21
			55	1.999	6.304	9.062	-8.512	8.162	-5.139
			60	1.92	6.54	9.432	-8.513	7.547	-6.259
			70	1.622	6.872	10.138	-8.523	5.556	-9.604
			80	1.212	7.059	10.83	-8.555	0.049	-19.86
			85	0.971	7.104	11.164	-8.62	-10.745	-41.349

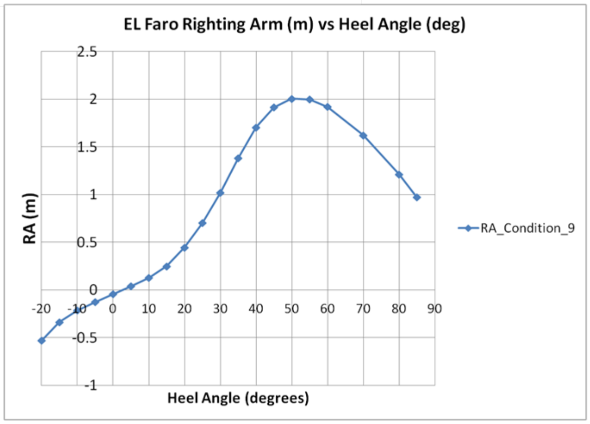
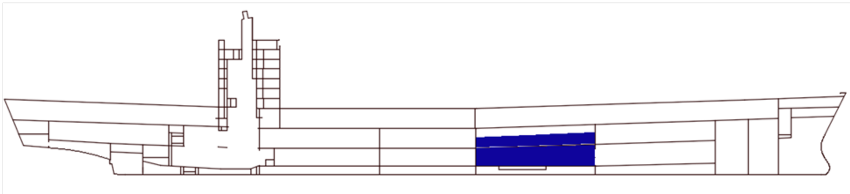


Figure 13-14: Condition 9



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
204	0.975	100	3637.8	0	203	0.975	50	2074.9	10.934
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stem)
39244.1	-4.053	10.69	-20	-0.482	-2.368	6.335	-3.939	10.475	-3.636
			-15	-0.303	-1.757	6.142	-3.952	10.55	-3.319
			-10	-0.197	-1.164	6.01	-3.964	10.599	-3.084
			-5	-0.118	-0.58	5.933	-3.968	10.627	-2.94
			0	-0.045	0	5.907	-3.97	10.636	-2.891
			5	0.03	0.58	5.933	-3.968	10.627	-2.94
			10	0.11	1.164	6.01	-3.964	10.599	-3.084
			15	0.217	1.757	6.142	-3.952	10.55	-3.319
			20	0.398	2.368	6.335	-3.939	10.475	-3.636
			25	0.646	3.004	6.599	-3.931	10.368	-4.027
			30	0.961	3.672	6.948	-3.926	10.212	-4.481
			35	1.33	4.356	7.384	-3.924	9.983	-4.984
			40	1.643	4.962	7.847	-3.923	9.708	-5.642
			45	1.844	5.451	8.294	-3.923	9.389	-6.52
			50	1.938	5.836	8.714	-3.923	9.01	-7.629
			55	1.947	6.139	9.108	-3.924	8.545	-8.945
			60	1.882	6.375	9.477	-3.928	7.963	-10.577
			70	1.607	6.703	10.176	-3.945	6.119	-15.84
			80	1.173	6.877	10.815	-3.99	0.903	-31.872
			85	0.925	6.92	11.126	-4.083	-9.234	-64.398

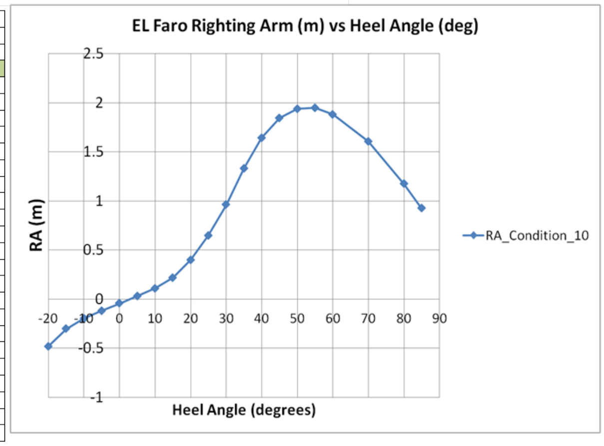
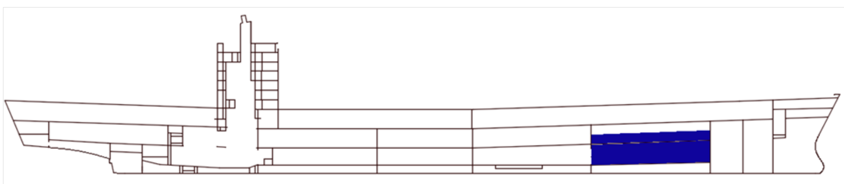


Figure 13-15: Condition 10



FIXED	FLOODED	SPACES	INCLUDED:						
ID	SP VOL	%	m-tonnes	DEPTH	ID	SP VOL	%	m-tonnes	DEPTH
104	0.975	100	1934.1	0	103	0.975	50	1287.5	12.197
DISPL	LCG	POLE HT	HEEL	RA	TCB	VCB	LCB	DRAFT	TRIM
m-tonnes	m aft MS	m	deg	m	m (+ stbd)	m abv BL	m aft MS	m	m (+ stem)
36753	-3.539	11.06	-20	-0.537	-2.453	6.056	-3.434	9.958	-3.507
			-15	-0.379	-1.82	5.856	-3.448	10.034	-3.153
			-10	-0.255	-1.205	5.72	-3.456	10.086	-2.889
			-5	-0.148	-0.601	5.64	-3.46	10.115	-2.721
			0	-0.048	0	5.614	-3.462	10.125	-2.659
			5	0.053	0.601	5.64	-3.46	10.115	-2.721
			10	0.161	1.205	5.72	-3.456	10.086	-2.889
			15	0.287	1.82	5.856	-3.448	10.034	-3.153
			20	0.447	2.453	6.056	-3.434	9.958	-3.507
			25	0.66	3.111	6.33	-3.421	9.848	-3.945
			30	0.932	3.794	6.686	-3.413	9.688	-4.456
			35	1.259	4.492	7.131	-3.408	9.443	-5.013
			40	1.555	5.131	7.62	-3.406	9.115	-5.686
			45	1.739	5.65	8.095	-3.404	8.72	-6.572
			50	1.814	6.06	8.542	-3.402	8.247	-7.725
			55	1.804	6.386	8.966	-3.401	7.664	-9.147
			60	1.724	6.643	9.368	-3.403	6.917	-10.861
			70	1.404	6.998	10.123	-3.412	4.516	-16.539
			80	0.915	7.182	10.805	-3.435	-2.387	-33.984
			85	0.649	7.228	11.145	-3.489	-15.784	-69.454

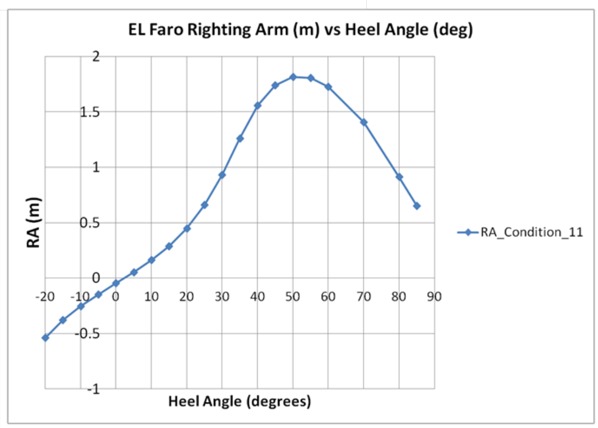


Figure 13-16: Condition 11

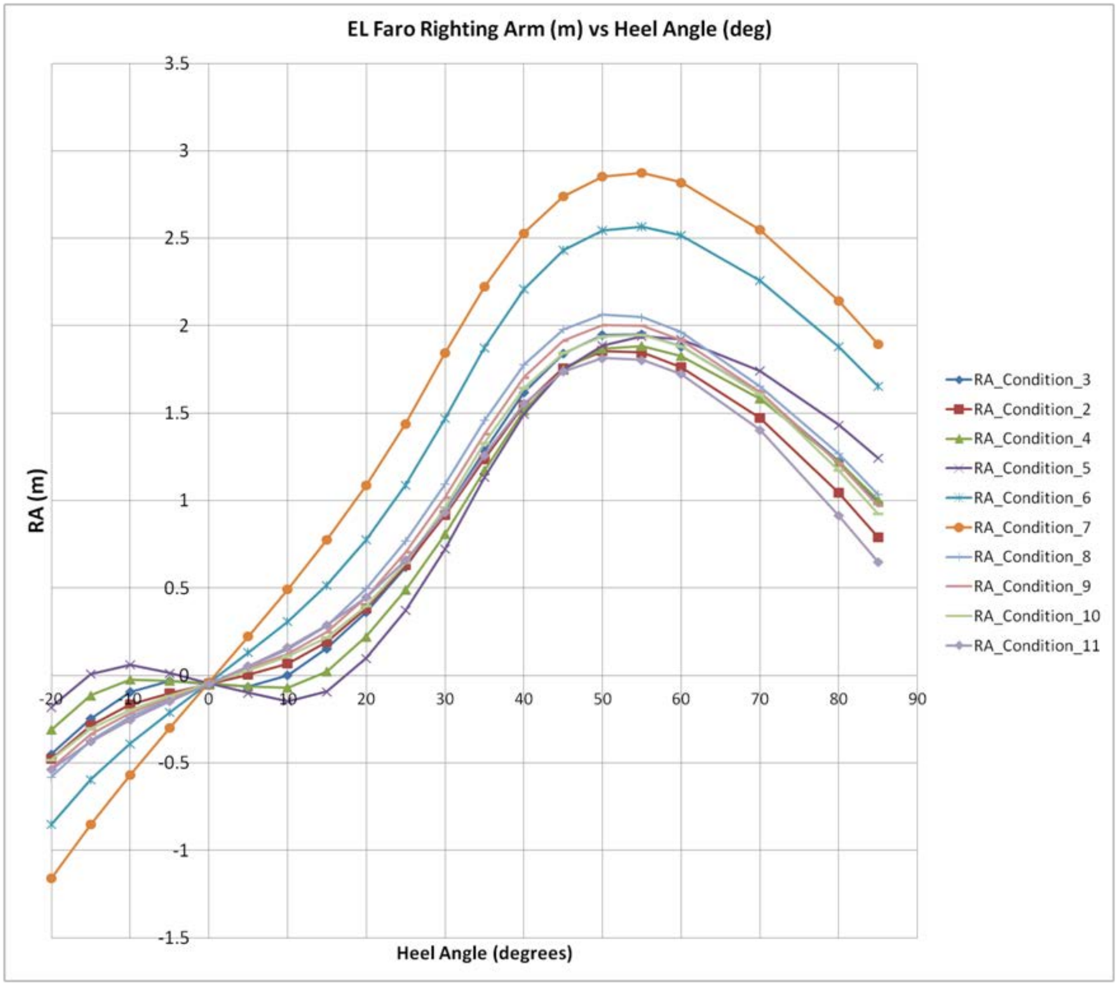


Figure 13-17: Summary Graph of Conditions Modeled in SHCP

14 Appendix 5: Roll Damping Investigation

This appendix describes how the roll damping coefficients are derived, however some of them depend on the roll angle as well as the speed the ship is traveling at.
While the section title is roll damping, pitch, heave and yaw damping were also included at some level.

When setting up dynamic simulations in general, we are using software to solve a system of differential equations with three main terms.

(M+M added)Xdd + CXd + KX where:

Xdd is the acceleration term multiplied by the mass plus added mass due to hydrodynamic effects.

Xd is a velocity times a damping coefficient. For lift and drag terms however this needs to be expressed as Xd^2 times a constant C.

KX is a restoring force caused by displacing the system from equilibrium such that the restoring force K acts proportional to the distance X.

In linear systems like SMP and WADAM the squared term in the velocity is ignored and the equations can be simplified using a simple and convenient LaPlace transform. WASIM actually uses the full Xd^2 term which is one of the important layers of non-linearity in the solution mathematics. The difficult part is in coming up with the correct coefficients.

Damping is important in all dynamic models as it is the way that energy is removed from the system. Without adequate damping the motions predicted would be unrealistically large. With too much damping the motions would be too small.

Damping in ship motions can be split into a number of different parts including friction, eddy making, wave making and speed dependant lift induced damping.
Damping is further separated out for the various physical objects that contribute to the damping including:

- Bilge keels
- Rudders
- Skegs
- Propeller shafts
- Shaft struts
- Skin friction of hull surface itself.

El Faro has all of these underwater hull features that contribute to the damping.

14.1 Roll Damping Models Considered

Damping models from a number of credible authorities were considered and compared to try to find the most plausible damping for the EL Faro. These models included:

- The models built into Visual SMP
- Schmitke (1978)

- Faltensen (2005)
- Miller (in PNA 1989)
- McTaggart (2003)

Figure 14-1 shows some of the many different damping curves that notably do not agree with one another.
To further complicate the problem, there are different formulations for linear theory calculations than for non-linear time series calculations.
The required result of these calculations was one set of damping coefficients for the WADAM linear theory Rankine panel code and another for the Non-Linear WASIM time series code.
Some of the damping is computed internally to these codes so it was necessary to break the damping from the different models into parts. For the WASIM case, it is the viscous term that is missing that needed to be added back in as a damping matrix.
The viscous terms were developed as a matrix for different roll angle magnitudes and for different ship speeds.

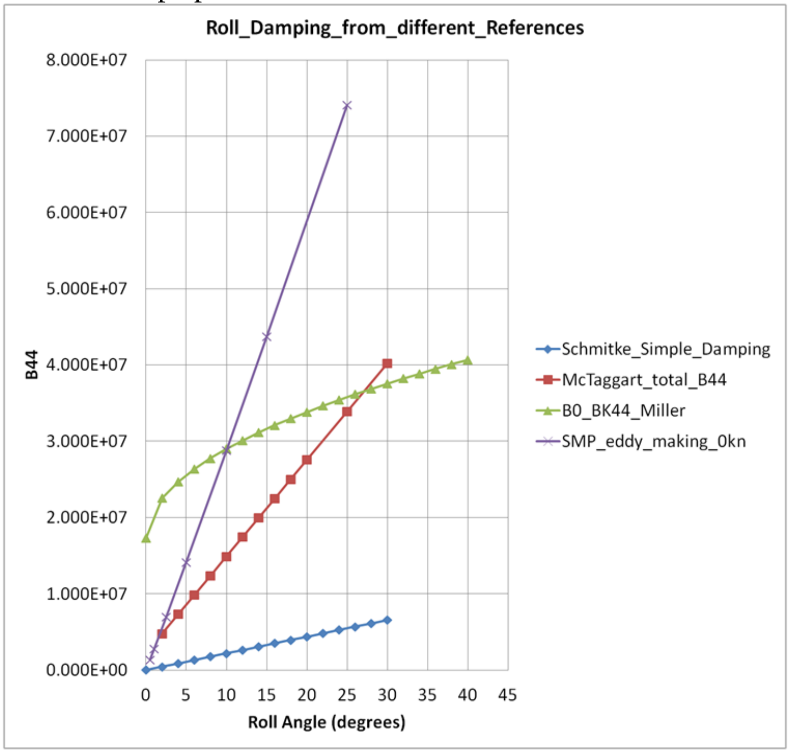


Figure 14-1: Damping as a Function of Roll Angle

The nominal speed is known for each WASIM run because it's a user specified parameter. The roll angle however is an unknown before the run has been simulated. A number of sensitivity cases were run where the only difference from one run to the next was the assumed amount of roll to be expected and therefore the roll damping value that was input.

The many runs performed under Phase 1 include those that are labeled as having a specific amount of roll damping. These damping values are arrived at by guessing how much roll the ship will experience and then using that level of damping for the first run. Theoretically, if 8 degrees of roll damping produces about 8 degrees of roll, then one has estimated correctly.

Table 14.1 below shows that 8-degree roll damping matches well for headings from head seas to about 120 degree off head seas when more damping is required.

Table 14-1: Roll Damping Matching Illustration

				Heading			Roll	Parameter	Surge	Sway	Heave	Roll
Speed	Seastate	H/13 (m)	Tm(sec)	deg	words	Crested	Damping		m	m	m	deg
10	6	6.00	12.4	180	Head Seas	Short	8 Deg	Maximum	11.70	8.71	6.28	7.36
10	6	6.00	12.4	150	30 Off Head Seas	Long	8 Deg	Maximum	15.38	14.99	6.34	8.48
10	6	6.00	12.4	135	45 Off Head Seas	Long	8 Deg	Maximum	14.66	27.76	7.82	7.55
10	6	6.00	12.4	120	60 Off Head Seas	Long	8 Deg	Maximum	12.95	35.42	6.07	7.45
10	6	6.00	12.4	90	Beam Seas	Long	8 Deg	Maximum	8.20	12.58	5.49	10.14
10	6	6.00	12.4	60	120 Off Head Seas	Long	8 Deg	Maximum	9.62	16.49	6.63	17.58
10	6	6.00	12.4	30	150 Off Head Seas	Long	8 Deg	Maximum	12.03	9.89	3.96	16.28
10	6	6.00	12.4	0	Following Seas	Short	8 Deg	Maximum	14.51	13.37	3.80	17.09

Some of these runs were done to evaluate the sensitivity of the roll motions to the damping setting and to the speed, heading and wave parameters. For hurricane wave conditions, it quickly became obvious that this approach no longer worked and there was no discernible link or pattern between actual roll motion and the roll damping number input.

Table 14-2 shows that changing the damping value has some effect on the output maximum roll, but there seems to be a lot of noise when different headings and speeds are considered. There is also considerable noise between two statistically identical runs when the only thing that changes is the random number generator setting on the 200 unevenly spaced wave components.

14.2 Sensitivity Runs

Table 14-2: Sensitivity Study Results

				Heading			Roll	Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**deg**	**words**	**Crested**	**Damping**		m	m	m	deg	deg	deg
10	6	6.00	12.4	180	Head Seas	**Short**	8 Deg	Maximum	11.70	8.71	6.28	7.36	3.83	2.39
10	6	6.00	12.4	150	30 Off Head Seas	**Long**	8 Deg	Maximum	15.38	14.99	6.34	8.48	3.71	1.93
10	6	6.00	12.4	135	45 Off Head Seas	**Long**	8 Deg	Maximum	14.66	27.76	7.82	7.55	4.69	3.71
10	6	6.00	12.4	120	60 Off Head Seas	**Long**	8 Deg	Maximum	12.95	35.42	6.07	7.45	3.20	4.11
10	6	6.00	12.4	90	Beam Seas	**Long**	8 Deg	Maximum	8.20	12.58	5.49	10.14	0.65	1.42
10	6	6.00	12.4	60	120 Off Head Seas	**Long**	8 Deg	Maximum	9.62	16.49	6.63	17.58	2.95	3.84
10	6	6.00	12.4	30	150 Off Head Seas	**Long**	8 Deg	Maximum	12.03	9.89	3.96	16.28	1.97	5.20
10	6	6.00	12.4	0	Following Seas	**Short**	8 Deg	Maximum	14.51	13.37	3.80	17.09	1.80	3.15
				Heading			**Roll**		Surge	Sway	Heave	Roll	Pitch	Yaw
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**deg**	**words**	**Crested**	**Damping**	**Parameter**	m	m	m	deg	deg	deg
4	7	7.45	11.168	180	Head Seas	**Long**	8 Deg	Maximum	13.06	16.79	7.22	9.74	4.46	4.12
4	7	7.45	11.168	150	30 Off Head Seas	**Long**	8 Deg	Maximum	14.70	13.57	6.04	13.07	3.35	6.61
4	7	7.45	11.168	135	45 Off Head Seas	**Long**	8 Deg	Maximum	12.11	18.40	8.49	13.75	4.48	18.03
4	7	7.45	11.168	120	60 Off Head Seas	**Long**	8 Deg	Maximum	14.18	22.36	8.74	14.44	4.93	12.97
4	7	7.45	11.168	90	Beam Seas	**Long**	8 Deg	Maximum	12.65	29.52	7.44	24.34	1.58	3.03
4	7	7.45	11.168	60	120 Off Head Seas	**Long**	8 Deg	Maximum	17.80	27.49	10.57	44.19	5.05	1.49
4	7	7.45	11.168	30	150 Off Head Seas	**Long**	8 Deg	Maximum	15.64	1.03	5.89	8.62	2.97	2.58
4	7	7.45	11.168	0	Following Seas	**Short**	8 Deg	Maximum	13.18	16.42	6.06	10.62	2.85	4.32
				Heading			**Roll**		Surge	Sway	Heave	Roll	Pitch	Yaw
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**deg**	**words**	**Crested**	**Damping**		m	m	m	deg	deg	deg
4	7	7.45	11.168	90	Beam Seas	**Long**	8 Deg	Maximum	12.65	29.52	7.44	24.34	1.58	3.03
4	7	7.45	11.168	90	Beam Seas	**Long**	14 Deg	Maximum	3.68	81.02	3.02	16.25	0.93	0.14
4	7	7.45	11.168	90	Beam Seas	**Short**	16 Deg	Maximum	15.82	18.25	9.68	22.47	3.89	7.88
4	7	7.45	11.168	90	Beam Seas	**Short**	16 Deg	Maximum	16.23	20.60	9.48	31.81	5.04	7.25
4	7	7.45	11.168	60	120 Off Head Seas	**Long**	8 Deg	Maximum	17.80	27.49	10.57	44.19	5.05	1.49
4	7	7.45	11.168	60	120 Off Head Seas	**Long**	12 Deg	Maximum	17.18	14.39	8.15	25.64	3.97	1.32
4	7	7.45	11.168	60	120 Off Head Seas	**Long**	16 Deg	Maximum	12.89	14.31	8.33	25.72	4.06	1.51
4	7	7.45	11.168	30	150 Off Head Seas	**Long**	8 Deg	Maximum	15.64	1.03	5.89	8.62	2.97	2.58
4	7	7.45	11.168	30	150 Off Head Seas	**Long**	12 Deg	Maximum	12.90	2.25	5.37	9.04	2.74	2.43
4	7	7.45	11.168	30	150 Off Head Seas	**Long**	16 Deg	Maximum	14.21	2.12	6.52	11.42	3.18	2.51
4	7	7.45	11.168	0	Following Seas	**Short**	8 Deg	Maximum	13.18	16.42	6.06	10.62	2.85	4.32
4	7	7.45	11.168	0	Following Seas	**Short**	12 Deg	Maximum	11.21	16.66	4.98	9.52	2.38	4.07
4	7	7.45	11.168	0	Following Seas	**Short**	16 Deg	Maximum	12.78	14.75	6.03	8.03	2.94	3.70
				Heading			**Roll**	Parameter	Surge	Sway	Heave	Roll	Pitch	Yaw
Speed	**Seastate**	**H/13 (m)**	**Tm(sec)**	**deg**	**words**	**Crested**	**Damping**		m	m	m	deg	deg	deg
1	7	7.45	11.168	75	15 off Beam Seas	**Short**	30 Deg	Maximum	14.04	20.11	8.29	26.67	4.07	6.77
1	7	7.45	11.168	75	15 off Beam Seas	**Long**	30 Deg	Maximum	14.03	42.57	12.43	46.19	4.57	4.63
1	7	7.45	11.168	75	15 off Beam Seas	**Long**	30 Deg	Maximum	11.50	26.35	9.44	17.73	4.43	3.10
1	7	7.45	11.168	90	Beam Seas	**Long**	30 Deg	Maximum	11.54	15.76	7.09	26.17	1.59	3.91
1	7	7.45	11.168	90	Beam Seas	**Short**	30 Deg	Maximum	12.55	18.72	7.90	21.83	3.52	5.83
1	7	7.45	11.168	90	Beam Seas	**Short**	30 Deg	Maximum	13.90	22.13	7.58	29.03	3.53	5.31
1	7	7.45	11.168	105	15 off Beam Seas	**Long**	30 Deg	Maximum	12.08	20.40	8.82	19.94	3.86	6.85
1	7	7.45	11.168	105	15 off Beam Seas	**Long**	30 Deg	Maximum	13.03	20.18	8.41	16.85	3.94	7.89

15 Appendix 6: Weight and Center Estimation for Container & Trailer Cargo

The weights of each ISO container and each trailer in the holds was given in the illustration but the centers of gravity for each load item were not stated. Page 10 in the Trim and Stability Booklet contained a curve for the VCG of a trailer based on the weight loaded inside, as shown in Figure 16-1. While the validity of this simple representation for every possible load out and cargo type is doubtful, in the absences of anything better it was used for this investigation.

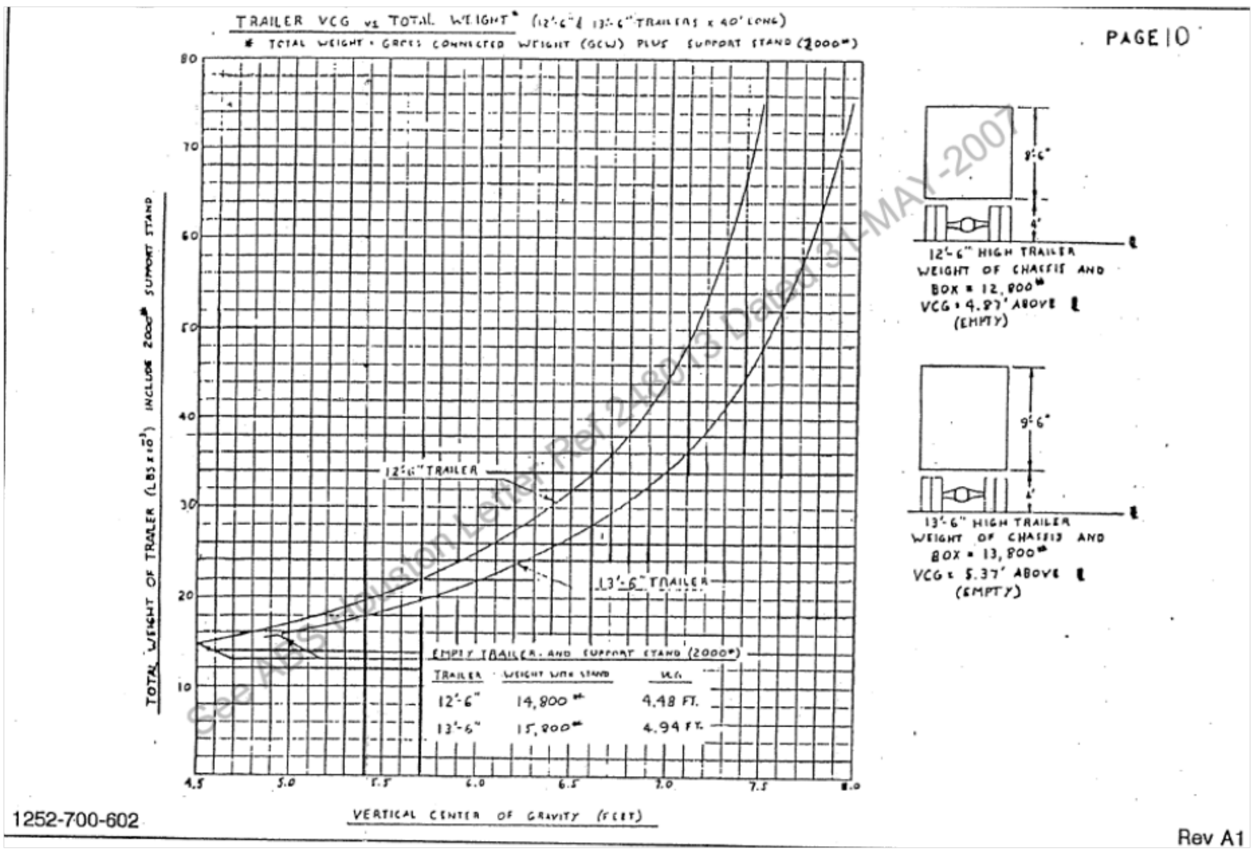


Figure 15-1: Trailer VCG Based On Weight Loaded And Trailer Size

In order to easily apply this to the trailers and containers loaded, it was convenient to digitize this into Excel and use a simple curve fit that could then be used to quickly and easily calculate the approximate VCG for the 500 or so weight items. These curves are shown in Figures 16-2 and 16-3.

Truck+ Stand+	Trailer	Trailer
Cargo	8'-6"	9'-6"
Weight	box	box
10^3 pounds	Heigth	Heigth
	VCG (ft)	VCG (ft)
12.8	4.87	
13.8		
14.8	4.48	
15.8	4.80	4.94
18	5.15	5.40
20	5.47	5.75
22	5.70	6.02
24	5.82	6.26
26	6.08	6.43
28	6.23	6.60
30	6.37	6.74
32	6.51	6.88
34	6.60	6.98
36	6.70	7.09
38	6.78	7.18
40	6.86	7.26
42	6.92	7.33
44	6.98	7.38
46	7.04	7.45
48	7.09	7.50
50	7.13	7.55
52	7.18	7.60
54	7.21	7.64
56	7.26	7.68
58	7.28	7.72
60	7.32	7.75
62	7.35	7.78
64	7.37	7.82
66	7.40	7.85
68	7.42	7.87
70	7.45	7.90
72	7.47	7.92
74	7.48	7.95
76	7.50	7.98

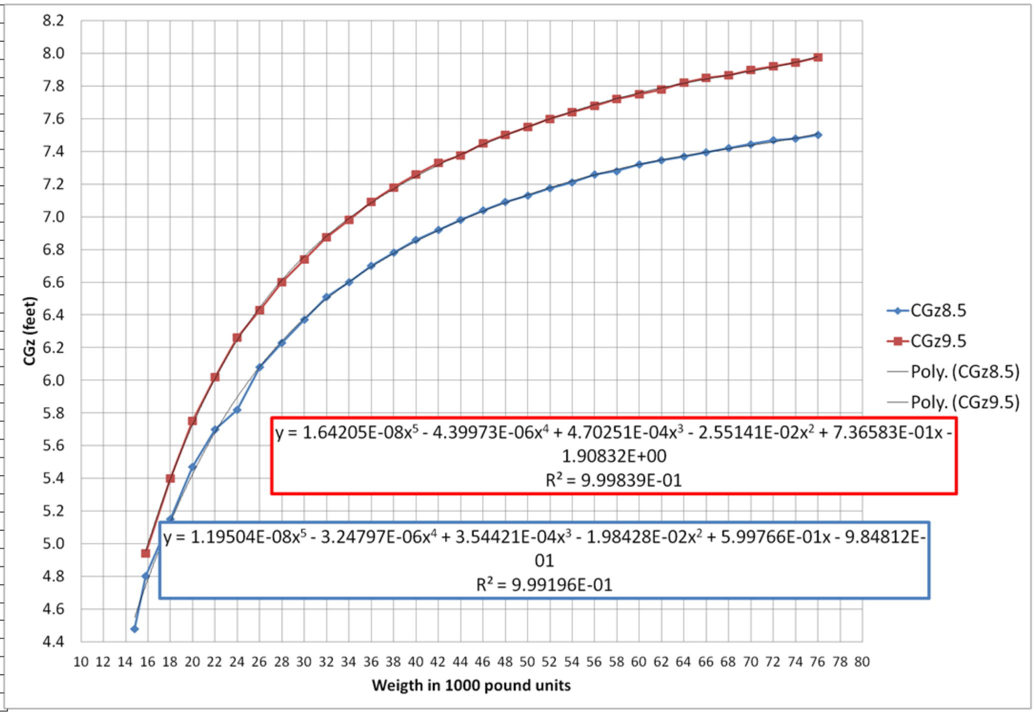


Figure 15-2: VCG Curve Fits for Trailers with Chassis and Stands

	ISO-Box	ISO-Box
	8'-6"	9'-6"
	box	box
	Heigth	Heigth
	VCG (ft)	VCG (ft)
Weight	CGz8.5	CGz9.5
15.8	0.80	0.94
18	1.15	1.40
20	1.47	1.75
22	1.70	2.02
24	1.82	2.26
26	2.08	2.43
28	2.23	2.60
30	2.37	2.74
32	2.51	2.88
34	2.60	2.98
36	2.70	3.09
38	2.78	3.18
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72	3.47	3.92
74	3.48	3.95
76	3.50	3.98

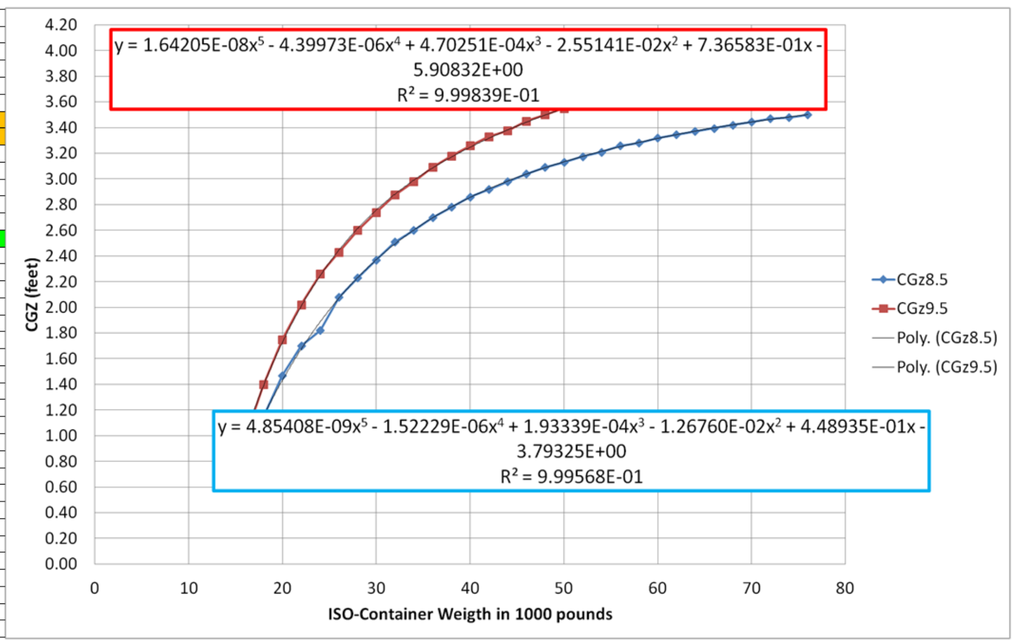

Figure 15-3: VCG Curve Fit for ISO Containers

The axes in Figures 16-2 and 16-3 have been changed to facilitate the Excel plotting commands and curve fits. The ISO container VCG curves were not explicitly stated in Figure 16-1. These were arrived at by subtracting the weights and centers of a typical chassis and stand from the data feeing Figure 16-2 and then recalculating the centers with the ISO container lowered to the height of a twist lock fitting above the deck.

These curve fits were promulgated through the weights spreadsheet to produce the VCG for the containers and the trailers.

In the absence of anything else to work from, the longitudinal and transverse weight centers of the cargo items were assumed to be at the center of the geometry.

The Center of Buoyancy (CB) of each container was assumed to be at the center of the geometric volume in all cases.