SpinMoor Participant Study: Revision 1

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Abstract

A highly simplified and standardized vessel and turret mooring system, combined with a simplified wind-squall-inspired transient excitation, is proposed to systematically compare predictions of commercially-available time-domain mooring simulation codes for squall-like transient events. The protocol for the composite dynamical system (vessel, mooring and environment) requires elimination of all simulation-specific "adjustable parameters". We call this simplified mechanical system and excitation the "SpinMoor™". A SpinMoor analysis was carried out using ten independent commercially available time-step simulation codes; each analysis was carried out by the code developer, or by a developer-designated agent. The resulting ten time-history response streams are compared and summarized.

The simplicity of the system and elimination of all user control suggests that, within the limits of floating-point numerical accuracy, all thoroughly vetted and adequately benchmarked time-step simulation products should produce virtually indistinguishable time histories for the SpinMoor; however, this expectation was not realized. Rather, straightforward measures of SpinMoor response comprising mean and maximum turret load and offset estimates, were found to differ by roughly 100% (i.e., a factor of 2) across the 10 participating programs, with estimates bifurcated into two distinct groupings. This discrepancy points to significant flaws underlying the time-step numerical algorithms, or the implementation of the underlying dynamical laws, or both, for a significant subset of the ten participating codes.

Going beyond the highly simplified SpinMoor protocol, it is demonstrated that the surprising bifurcation of outcomes across the available simulation collection extends to a comprehensive and realistic squall environment dataset, comprising many hundreds of thousands of unique simulation runs, using a realistic asymmetrical mooring system, with risers and umbilicals, and range of vessel draft conditions.

Revision 1 Note

Subsequent to the discovery of erroneous zero-frequency added mass values in their SpinMoor submissions, two participants submitted revised results. The report, graphics, and tables herein have been updated using the revised results from the two participants.

1 The SpinMoor Study: Motivation and Historical Perspective

Towards the end of 2015, ExxonMobil Upstream Research Company approached SeaSoft® Systems, a long-time provider of frequency-domain mooring software and technical consultant, to investigate a troubling disparity in design load estimates independently submitted by several of ExxonMobil Production Company [EMPC] established consultancies. These divergent estimates had been prepared for EMPC turret-moored systems whose design conditions were governed by wind-squall events.

SeaSoft's investigation initially focused on a clean-sheet development of a time-domain add-on module to SeaSoft's suite of frequency-domain mooring analysis tools; the add-on module was dubbed SquallSim®.

In early 2016 it became clear that SquallSim estimates of turret-moored vessel response to a typical squall-type transient event were at odds with the response predicted by one commercially available simulation program, 'Simulation Q', which was used in one of the original problematic EMPC-commissioned consultancy reports whose load estimate discrepancies triggered this study.

As investigation of the SquallSim-Simulation Q discrepancies proceeded, a *second* code path within SquallSim was utilized, which across a comprehensive suite of squall-like test cases duplicated with high fidelity the responses predicted by 'Simulation Q'. At that time, these developments and discrepancies were shared, under contractual non-disclosure agreements, with ExxonMobil Upstream Research Company, Shell International Exploration and Production, and Sofec [1].

By mid-2018, after exhaustive time-step algorithm trouble-shooting and testing of alpha and beta software versions with EMPC, SquallSim was used in two comprehensive mooring system studies [2].

By late 2018 the collective evidence, comprising the earlier anecdotal experience of widely differing design loads reported in consultancy analyses for the same system and metocean squall data, in combination with various discrepancies discovered during SquallSim development and deployment, pointed to the need for a controlled and systematic "due diligence" squall response study, to include the consultancy-utilized simulation codes and methodologies of potential importance to EMPC. In response to this imperative, SeaSoft developed a set of highly simplified test scenarios, particularized for squall-type transient events, to be used in further investigations. Two of these scenarios, dubbed the SpinMoor and the SpinTransit™, were proposed for possible use in a comparative analysis study to be carried out using commercial time-domain numerical codes in use by potential ExxonMobil Upstream Integrated Solutions Company [EMUISC] consultancies. Ultimately, in order to limit the size of the present study, the proposed scenario universe was culled to a single candidate: the SpinMoor.

The central objective of the SpinMoor Study was to eliminate all program-specific "adjustable factors", or the use of any other subjective considerations, commonly adopted by mooring analysts and code developers to better align ("benchmark") simulation results with model test data. It is well understood in the hard sciences that, with a handful of adjustable parameters (mostly, in the present instance, vessel and slender body hydrodynamic damping coefficients), a handful of experimental metrics (mean positions, maximum excursions, etc.) can be matched within “experimental uncertainties”. This circumstance has long provided cover for flawed or otherwise problematic underlying simulation methodologies in the offshore industry.

SeaSoft and EMUISC invited a total of 11 independent consultancies, each using different time-domain numerical simulation tools, to participate in the SpinMoor Study. Each participant was to receive in return an anonymized summary of the results from all participants. The Study was joined by 8 of the 11 invitees, and the final SpinMoor results were submitted to SeaSoft for processing in mid-January, 2020.

2 SpinMoor Design Considerations

The worst-case squall scenario for any vessel restrained by a weathervane-capable mooring (e.g., turret, SALM, CALM-buoy-hawser, "Wishbone", etc.), comprises a rapidly building wind event, with wind initially incident from astern quadrants, in otherwise comparatively quiescent conditions. This scenario produces an abrupt change in vessel heading as the vessel spins to face into the mean squall environment. Any realistic squall event is by nature chaotic, so a simpler standardized transient excitation was developed to capture the key ingredients of squall events, while eliminating the chaotic time dependence of wind speed and direction and the associated chaotic blurring of the underlying dynamical methodology and numerical algorithms of participating simulation codes.

3 Vessel Selection

To avoid issues surrounding proprietary vessel design particulars, the vessel selected was the Marin wave-basin facility's standard 200-kdwt tanker. Its particulars are widely available in the open literature, and in Johann Wichers' PhD thesis available online from Marin [3]. Subsequent to Wichers' thesis work, this vessel has been used in numerous studies at the Marin test facility and elsewhere. In particular, it was chosen for the landmark 2000-2002 DeepStar experimental and simulation studies of FPSO, TLP and Spar mooring performance in extreme GOM hurricane and Loop Current environments [4].

4 Mooring System

The SpinMoor mooring was designed to provide near-perfect azimuthal symmetry, and a linear force-offset characteristic of ~ 1.92 tonne/meter for all offset directions, by specifying an array of 24 symmetrically deployed "linear spring" mooring lines. The linear mooring allows the turret centroid displacement from equilibrium to be a perfect proxy (differing only by a factor of 1.92) for the total turret load.

Note: The SpinMoor protocol stiffness of 1.92 t/m is rather low; this was to permit relatively large offsets that are more easily visualized in graphical displays and faux-video snippets.

To eliminate simulation-specific treatments of line-associated dynamics, the selected moorings are massless. To eliminate simulation-specific handling of line damping due to line motions relative to the surrounding fluid, the taut massless moorings are deployed above the waterline, between turret-attached fairleads and above-water anchors.

5 Environment

In order to produce simulation-independent system excitation, the SpinMoor protocol calls for perfectly quiescent background wind, wave, and current conditions. The only non-mooring forces permitted to act on the vessel are [i] a specified constant vessel-fixed applied force, [ii] the potential-flow reactions produced by the surrounding fluid to vessel motions, and [iii] relative-motion hydrodynamic dissipative forces derived from the vessel midships velocity vector applied to protocol-specified OCIMF-style current drag coefficients. Furthermore, the protocol specifies that the OCIMF yaw moment coefficients, the flow-relative yaw-angle dependent Munk Moment, and all yaw-rate-dependent moments, are eliminated (i.e., set to zero).

These protocol restrictions assure uniformity of dissipative effects and simulation-specific yaw moment treatments across participating codes in order to achieve two distinct goals: [a] The elimination of any irreproducible simulation-specific handling of forces and moments and [b] to guarantee that in the steady-state (orbital) portion of the SpinMoor time development, the vessel centerline remains perfectly aligned with the mooring centroid offset vector; any extraneous yaw moments whatsoever would disrupt that perfect alignment. The SpinMoor protocol for this study calls for a 200 tonne vessel-fixed lateral (sway) force applied at the midships station.

The lack of background waves produces, besides dynamical simplicity, one other desirable side effect: elimination of the need for diffraction analysis to determine vessel wave-frequency dynamical properties, including the zero-frequency added-mass matrix. The mass matrix is therefore specified as a part of the SpinMoor protocol, and is taken directly from Wichers' thesis, simplified slightly by imposing fore-aft symmetry on the vessel (by setting the sway-yaw added mass cross-terms {a26, a62} to zero). One participant was unable to accommodate specified zero-frequency added mass values; that participant used added mass estimates that were generated internally to the simulation itself. As might be expected, the internal estimates in that one case were within a few percent of Wichers' (and protocol) values, so these differences did not contribute in a meaningful way to the motion and load estimates for that participant.

6 Initial Condition

The vessel is initially stationary at its quiescent mooring equilibrium, with turret center located at {Rx, Ry} = {0, 0} and a zero yaw angle. The applied vessel-fixed lateral "spin" force is applied impulsively at t = 0.

The SpinMoor protocol as submitted to participants can be found in Appendix I.

7 SpinMoor Description and Qualitative Response

The SpinMoor response to the steady applied lateral midships force probes two important regimes of time-domain analysis codes: a mildly complex transient startup phase, followed eventually by a long-term steady-state vessel rotation about a point fixed in space as the startup transients are damped out hydro-dynamically via square-law damping.

8 The SpinMoor Scenario: Characterization of Results

The characterization of the SpinMoor transient and steady state phases comprises two metrics:

[1] Transient phase: the maximum predicted turret centroid radial offset "Rxy-Max".

[2] Steady State phase: The predicted orbital radius "Rxy-SS" of the turret centroid and speed and period.

Because the mooring force-offset characteristic is azimuthally symmetric and linear, the Rxy offset is a direct proxy for the total turret load, with a constant of proportionality of 1.92 tonne/meter for the SpinMoor protocol of Appendix I.

9 Summary and Discussion

Earlier versions of most widely-utilized commercial mooring analysis codes in use today, including those represented in this Study, have been available for decades; most of these efforts date to the 1980s, some even earlier. During the intervening years, and across the offshore industry, these codes have been benchmarked against, and presumably improved by, hundreds of wave-basin model tests conducted by the most technically capable offshore engineering enterprises, operators and consultancies, under the scrutiny of qualified engineering staff, technically talented experts, and consultants. An important milestone in this ongoing improvement effort was the DeepStar GOM hurricane and Loop Current studies of 2000-2002 [5]. Given the intensity of this scrutiny over so many years, it is natural to assume from the simplicity of the SpinMoor protocol that variability of SpinMoor simulation results across available mooring software products would be negligible; this expectation was in fact reflected in considerable early skepticism amongst prospective SpinMoor Study participants about the usefulness of such an exercise. This skepticism is somewhat at odds with what appears to be a timely and robust interest in the squall response of moored assets worldwide, as witnessed by an ongoing multi-phase Joint Industry Project [6] to investigate and contribute to the state of the art in squall response estimates for moored systems.

Participant results, taken directly from tabular turret centroid motions provided by each participant, are summarized, combined, and plotted in Figures 1 through 3. These results paint a somewhat surprising picture, one that is consistent with EMPC's anecdotal historical experience with wide differences between multiple independent-consultancy analyses. Individualized plots for each participant can be found in Appendix X; the combined summary graphics below are somewhat cluttered, but serve to emphasize visually the peculiar bifurcation of results that is a central outcome of this Study.

Predicted vessel responses are seen to cluster rather tightly into two main groups with a substantial gap in predicted offset and load metrics separating the two. For purposes of discussion we categorize participant results as being either in the "L" group (larger steady-state offset), or the "S" group (smaller steady-state offset):

"L" Group: Participants {1, 4, 6, 8, 9}
"S" Group: Participants {2, 3, 5, 7, 10}

These two participant groupings ("L" and "S") are characterized by maximum offset differences, and steady-state turret orbital radius values, that differ by about a factor of 2 for the fully loaded case and a somewhat smaller factor for the 40% ballasted condition (see Table 1 and Figure 1).

Note that the two available SquallSim branches discussed in the historical notes contribute one result to each {L, S} participant grouping. These two SquallSim branches provide a convenient means of comparison between "average" {L, S} group predictions for more realistic and complex squall and background environments. See Appendices VII, VIII and IX for additional comments and {L, S} group comparisons.

In Figures 1 through 3 {Rx, Ry} are the global turret centroid locations relative to the origin; Rxy, Fxy are the turret centroid radial offset and corresponding net turret force; "Max R" is the reported participant-specific maximum predicted Rxy; "ssR" the steady-state orbital radius (i.e., the asymptotic Rxy value near the end of the time history); {period, speed} refer to the asymptotic orbital period and the corresponding asymptotic sway velocity at midships. Note that in the steady state orbital phase, the square-law hydrodynamic sway force on the vessel should exactly cancel the protocol sway force of 200 tonnes. Therefore one would expect that, with considerable precision, all participants would predict the same steady state midships speed, so any significant differences must represent numerical or dynamical modeling imperfections. Note that in the case of Participant_4's full draft results, the reported steady state period and speed values, which were obtained algorithmically by assuming the last complete 360 degree orbit could be used to determine those quantities, was compromised by the failure of that Participant's result to establish a non-oscillatory steady state over the simulation duration; this circumstance is likely responsible for the evidently "out-of-range" values listed for that Participant.

Table 1. SpinMoor Summary of Results

Participant Program	**Full Draft**						**Ballast Draft**					
	Maximum		***Steady State***				***Maximum***		***Steady State***			
	Rxy m	Fxy tonne	Rxy m	Fxy tonne	Period sec	Speed m/sec	Rxy m	Fxy tonne	Rxy m	Fxy tonne	Period sec	Speed m/sec
Participant_1	87.5	168	69.2	133	1902	0.806	75.4	145	54.3	104	1128	1.277
Participant_2	53.0	102	41.2	79	1678	0.809	54.0	104	38.1	73	1048	1.277
Participant_3	52.9	102	41.2	79	1676	0.810	54.3	104	38.4	74	1049	1.278
Participant_4	81.5	156	70.4	135	2017	0.764	73.2	141	55.4	106	1132	1.278
Participant_5	52.5	101	39.1	75	1665	0.807	54.1	104	37.3	72	1043	1.278
Participant_6	87.9	169	69.2	133	1890	0.811	75.5	145	54.4	104	1127	1.278
Participant_7	57.5	110	42.3	81	1719	0.793	57.4	110	38.9	75	1051	1.277
Participant_8	88.0	169	69.3	133	1890	0.812	75.7	145	54.4	105	1127	1.278
Participant_9	75.6	145	67.4	129	2026	0.751	60.3	116	54.5	105	1127	1.279
Participant_10	46.8	90	39.0	75	1663	0.808	44.8	86	37.2	71	1043	1.277

Figure 1. SpinMoor Maximum and Steady State Response Summary

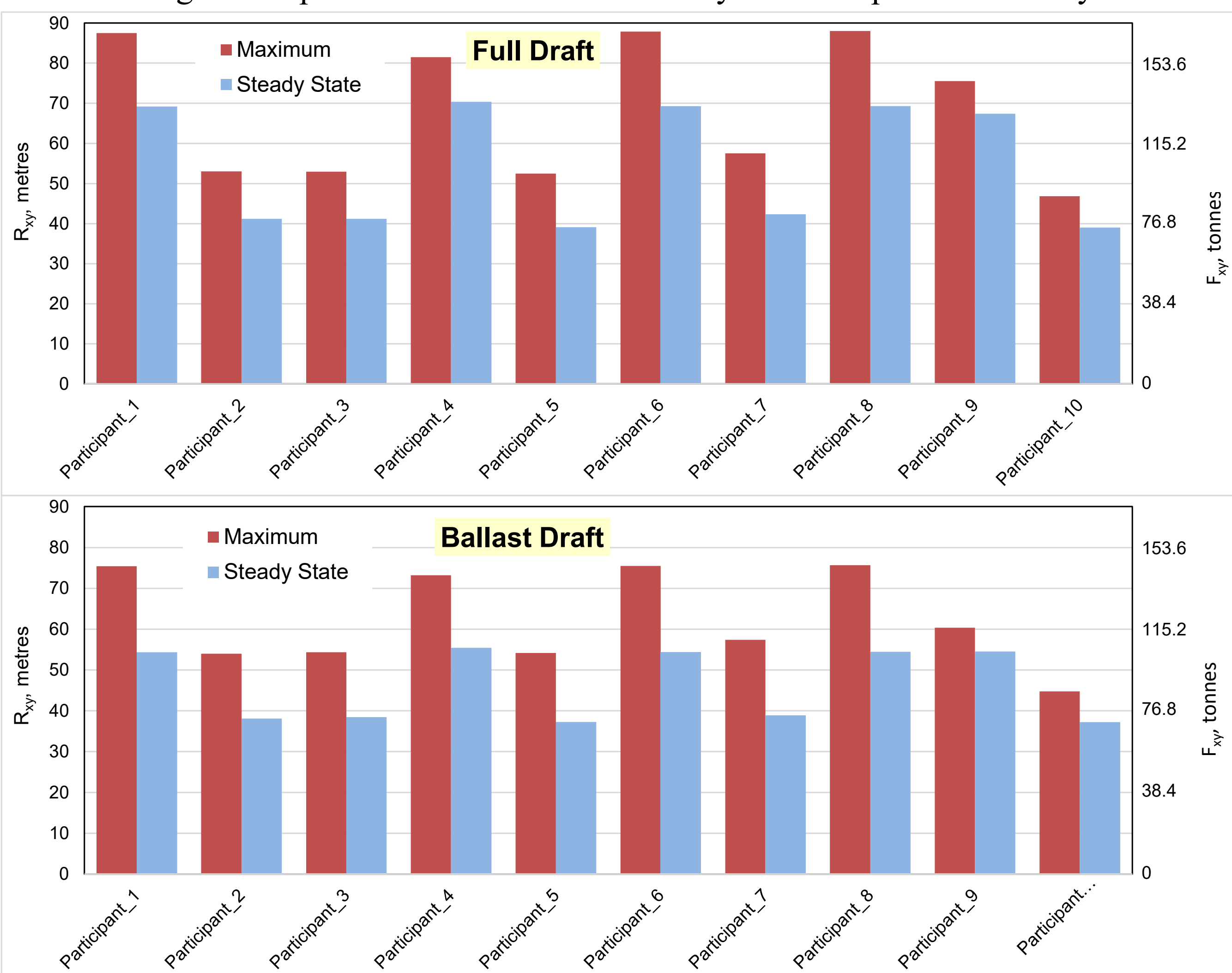


Figure 2. SpinMoor Participant Rx, Ry, and Rxy Comparisons for Full Draft

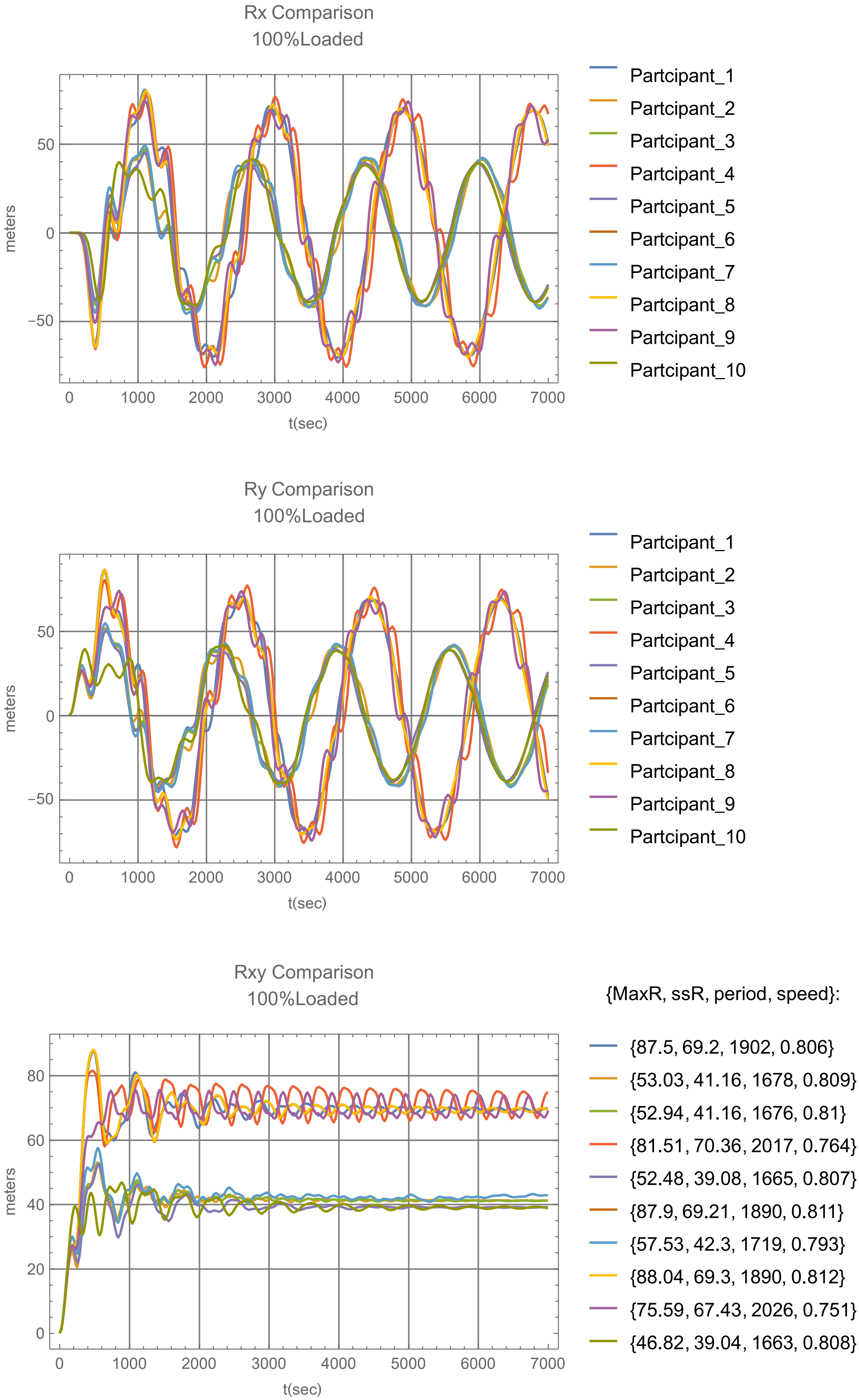
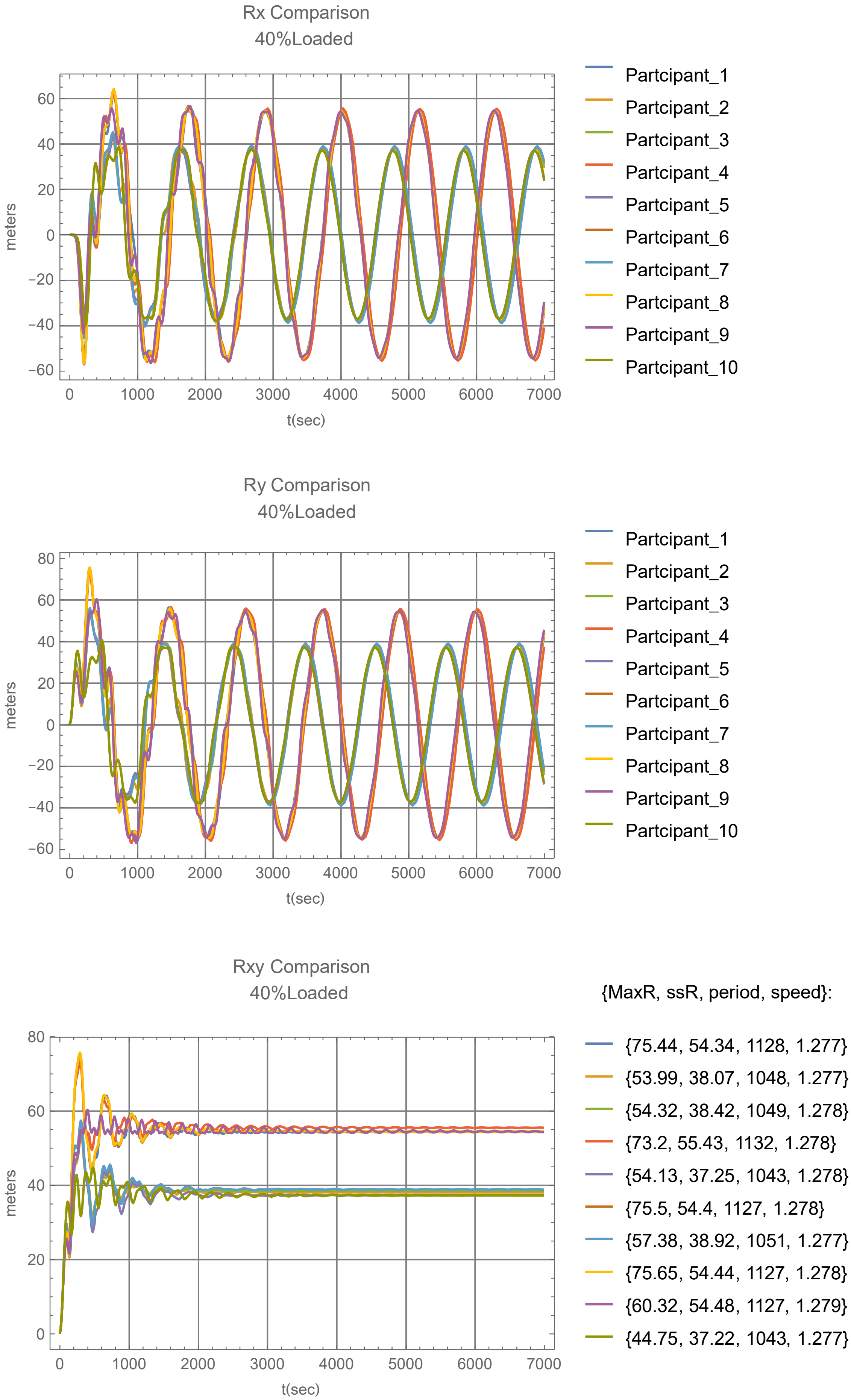


Figure 3. SpinMoor Participant Rx, Ry, and Rxy Comparisons for Ballast Draft



10 The SpinMoor Bifurcation: Design Safety Factor Consequences

Assuming for the sake of argument that the observed "L" over "S" load factor ratio of order 2 extends to more realistic squall scenarios, it must be remarked that variability of that magnitude would be a somewhat sobering development. As a result of presumed steady improvements in simulation and model test capabilities, recent decades have witnessed load safety factors decline steadily from ~ 200% or more in the distant past to something around 25% to 50% today; a difference of 100% between low and high SpinMoor turret load metrics lies well beyond the range of currently applied safety factors. We explore this issue of the impact of more realistic environmental conditions in additional detail in Appendices VII, VIII, and IX.

The SpinMoor load estimate divergence across participant codes raises other interesting questions: What is the consequence of the differing methodologies underlying the bifurcated SpinMoor estimates for *non-squall* environments, such as the "statistically stationary" conditions used in many sea-keeping model tests, as typified by the hurricane and Loop Current environments of the 2001 DeepStar Model Test and follow-on analyses? Other crucial offshore numerical analysis areas include slender-body dynamics, tugboat, thruster and rudder-driven maneuvering analyses, towing analyses, and so on. How are they impacted by this bifurcation?

Additional topics of possible interest that arose during conversations with SpinMoor participants have been collected into a FAQ list (see Appendix II).

Plotted per-participant result summaries for each of the 10 anonymous participants can be found in Appendix X.

11 Conclusions

The raison d'etre for time-domain analyses is a comprehensive treatment of transient events, whose character is manifestly non-stationary and its modeling decidedly non-linear.

Looking beyond a West African-type squall environment, it is reasonable to ask if a similar cross-simulation bifurcation amongst widely-used simulation codes can be demonstrated for similar transient events, such as current-eddy advection, tsunami or tidal flow reversals, hurricane eye passage, and non-environmental transient phenomena, including maneuvering events where the transient is induced via thrusters, rudders, tugboats, and the like. We believe, on the basis of limited comparisons similar to those motivating the SpinMoor Study, that the answer to that question is an unequivocal yes.

Finally, looking still further beyond overtly transient squall-type events, it is difficult to imagine a universe in which the marked bifurcation of outcomes in the SpinMoor Study would *not* impact more common "statistically stationary" environments, such as a North Sea storm event, or the Gulf of Mexico hurricane or Loop Current conditions of the DeepStar experimental and theoretical modeling studies [5]. In the DeepStar studies, most participants felt that large discrepancies found between theory and experiment resulted from substantial and unanticipated wave basin current fluctuations. However, it is now natural to wonder if underlying issues of the kind revealed in the SpinMoor study did not also play a role in the disappointing DeepStar theory-measurement comparisons.

With respect to the possible impact of *user-controllable* damping adjustments on the consultancy-specific differences in design loads that triggered the SpinMoor Study, it is reasonable to ask: Beyond the demonstrated simulation *modeling* issues, inaccessible to the user and on display in the SpinMoor Study, are there *user interventions*, specifically via manipulation of simulation-specific adjustable damping and other dynamical parameters, that are capable of producing simulation differences approaching the factor of ~ 2 found in this study? That scenario is the subject of Appendix V, where it is demonstrated that user adjustment of a *single number*, the maximum sway DOF OCIMF drag coefficient Cy, from 1.0 to 1.9, reduces simulated offsets and loads from the level of the "L" group down to those of the "S" group.

Other adjustable parameters, most notably user-specified yaw-rate-dependent sway and yaw damping coefficients, have similar impacts and can be used to produce a similar level of variability in simulation estimates.

Editorial aside: In our view, the availability and manipulation of user-adjustable parameters in dynamical simulations represents a largely avoidable and potent source of uncertainty in mooring design and analysis. That view is neatly captured in the comment of one SpinMoor Study invitee, a highly qualified Ph.D.-level professional engineering analyst, when addressing the reported SpinMoor group differences between different software products: "I can give this problem to three different highly qualified engineers, each using the *same* simulation program, and get three results differing by amounts comparable to those of this study."

We therefore feel obligated to repeat, for emphasis: Only a small handful of user-adjustable simulation parameters are required to manipulate the output stream of any simulation in order to "tune" its estimates to match any similar-sized handful of design metrics.

Acknowledgements

We wish to acknowledge the time, expertise, and ongoing support of three individuals who provided valuable input and guidance throughout the three-plus year explorations leading ultimately to the SpinMoor Study.

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SpinMoor Participant Study Revision 1.

28 April, 2020

Subsequent to the discovery of erroneous zero-frequency added mass values in their SpinMoor submissions, two participants submitted revised results. The report graphics and tables have been updated using the participant's corrected data.

The participant originally reporting the smallest loads and offsets (participant 9) was one of those with revised data. As a result, participant 10 replaced participant 9 in Appendix VI: "Largest and Smallest Participants Compared".

One interesting consequence of the revised results: each of the "L" and "S" groups now contains exactly half of the contributions.

The corrected results have no material impact on the general conclusions of the SpinMoor study, and aside from incidental and typographic corrections, the report body remains unaltered in this revision, with the above-noted exception of Appendix VI.

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Appendices

I	SpinMoor Protocol
II	SpinMoor FAQ
III	Alternate Testbeds
IV	Mooring Stiffness Considerations
V	Adjustable Parameter Impacts
VI	Largest and Smallest Participants Compared
VII	Squall Analysis Part 1: In Depth Results for Two Cases
VIII	Squall Analysis Part 2: Summary of Intact Results for Maximum Draft and 100 Year Return Period Load Cases
IX	Squall Analysis Part 3: Summary of Intact Results for Three Drafts and 1 to 1,000 Year Return Period Load Cases
X	Per-Participant Graphical Summaries

References

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7. *Evaluation of Low Frequency Damping and Analysis Methods for MODU Moorings*, Kwan C.T. et al, OTC 20164, May 2009.

Appendix I
SpinMoor Protocol Specifics

I. Vessel

- Mass, hydrostatic, and zero-frequency added mass data is in "Marin_200kdwt.xls" (both loaded and ballasted cases).
- Vessel is fore-aft symmetric, with LCG at OCIMF midships.
- Turret centroid: 175 meters forward of midships (20 m forward of bow).
- Turret height above keel: 19 m (.1 m above waterline at full load, 11.44 m above waterline at ballast load).

Note: In the loaded configuration, this tanker has a very small GM; this was dictated by the desire to make the loaded and ballasted cases as similar as possible and to keep the mooring fairleads above water, at the same level as the VKG, to eliminate roll moments from the moor for programs using a full 6 DOF simulation space.

II. Mooring & VKG:

- 24 identical azimuthally symmetric above-water massless linear springs (no lines in the water):
- 3000 meter lines with elastic modulus of 400 metric tonnes;
- 100 MT pretensions, all lines;
- Fairlead locations: 3.5 meters radially from turret centroid;
- Anchor placement: 1 meter above waterline so that mooring lines remain dry at all draft conditions.
- VKG: At fairlead level = 19 m for both loaded and ballasted cases.

Note: Please advise of any complications arising from this "impossible moor", which requires the vessel to be transparent to the lines, allowing lines to "slice through" the vessel during its motion. For example, if your software will not permit this transparency, we can easily work around that using submerged fairleads and anchors, and zero-diameter, neutrally buoyant lines with zero drag coefficient.

III. Environment

No wind, waves or background current.

Sinusoidal lateral OCIMF current coefficients and zero OCIMF CzCur.

CxCur = Cos[theta]
CyCur = Sin[theta]
CzCur = 0 at all angles

Note: the potential-flow "Munk Moment" is ignored for these tests; for software that permits simultaneous Munk Moment and non-zero Cz OCIMF current moment, both moment contributions should be set to zero.

Aside from the linear mooring springs, OCIMF-mediated hydrodynamic drag from relative vessel-fluid motion provides the only interplay with the surroundings.

In particular, no supplemental forces or moments, such as sway-yaw damping contributions beyond the OCIMF CyCur, are to be applied.

Null OCIMF wind coefficients, so no wind loads arise from vessel motions.

CxWnd = CyWnd = CzWnd = 0, all angles.

IV. Initial condition and applied forces at T = 0.

Vessel starts at the quiescent turret centroid equilibrium point, headed North.

At T = 0 a steady 200 MT transverse force is applied at midships, as if by a propeller affixed to the deck, oriented transversely. See "SpinMoor.mov" for a qualitative visual summary.

V. Simulation duration:

The simulation runs until a steady-state circular orbit is achieved. This should occur within 3 hours of prototype time for the proposed mooring, vessel and OCIMF values. There should be at least three complete orbits in the steady state condition before terminating the simulation.

VI. Possible glitches:

Should any unexpected issues arise, please call to discuss workarounds. Two possible numeric issues come to mind:

1. Numeric limit-cycle oscillations that prevent establishment of a steady state. Should that occur (very doubtful), a small linear surge damping may be applied to quench it; this will not impact the final steady-state motion, which is purely orthogonal to the centerline.

2. If massless (or neutrally buoyant) moorings create a computational problem, a numerically negligible line mass/unit length can be used; please call to discuss.

longitudinal direction by means of a light weight trim device connected at its forward and aft perpendicular.

Designation	Symbol	Unit	Magnitude		
			Loaded	Inter-mediate	Ballasted
Loading condition			100%	60%	25%
Draft in per cent of loaded draft			100%	70%	40%
Length between perpendiculars	L	m	310.00	310.00	310.00
Breadth	B	m	47.17	47.17	47.17
Depth	H	m	29.70	29.70	29.70
Draft	T	m	18.90	13.23	7.56
Wetted area	S	m^2	22,804	18,670	13,902
Displacement volume	∇	m^3	234,994	159,698	88,956
Mass	M	tfs^2/m	24,553	16,686	9,295
Centre of buoyancy forward of section 10	$\overline{FB}$	m	6.6	9.04	10.46
Centre of gravity above keel	$\overline{KG}$	m	13.32	11.55	13.32
Metacentric height transverse	$\overline{GM}_t$	m	5.78	8.66	13.94
Metacentric height longitudinal	$\overline{GM}_1$	m	403.83	-	-
Transverse radius of gyration in air	k_{11}	m	14.77	15.02	15.30
Longitudinal radius of gyration in air	k_{22}	m	77.47	77.52	82.15
Yaw radius of gyration in air	k_{66}	m	79.30	83.81	83.90
Wind area of superstructure (aft):					
- lateral area	A_{LS}	m^2	922	922	922
- transverse area	A_{TS}	m^2	853	853	853
Added mass	a_{11}	tfs^2/m	1,594	755	250
ω = 0 rad/s	a_{22}	tfs^2/m	25,092	10,940	5,375
(water depth 82.5 m)	a_{26}	tfs^2	-83,618	-30,400	-16,132
	a_{62}	tfs^2	-83,618	-30,400	-16,132
	a_{66}	$tfms^2$	123,510,000	59,607,700	23,200,000

Table 2.1 Particulars of the tanker

During the tests the surge, heave and pitch motions and the longitudinal mooring forces were measured. The surge and heave motions were measured in the centre of gravity (G) by an optical tracking device. The pitch motion was measured by means of a gyroscope. The sign convention is given in Figure 2.5. The mooring lines were connected to force transducers. All measurements were recorded on magnetic tape to facilitate the data reduction. All data were scaled to prototype values according to Froude's law of similitude.

Data copied from Wichers' Thesis pp 38			Loaded	Mid	Ballast
Loading condition		%	100.00	60.00	25.00
Draft in per cent ofloaded draft		%	100.00	70.00	40.00
Length between perpendiculars L	L	m	310.00	310.00	310.00
Breadth B	B	m	47.17	47.17	47.17
Depth H	H	m	29.70	29.70	29.70
Draft T	T	m	18.90	13.23	7.56
Wetted area S	S	m^2	22804.00	18670.00	13902.00
Displacement volume V	V	m^3	234994.00	159698.00	88956.00
Mass M	M	tf*s^2/m	24553.00	16686.00	9295.00
Centre of buoyancy forward FB of section 1	FB	m	6.60	9.04	10.46
Centre of gravity above keel KG	KG	m	13.32	11.55	13.32
Metacentric height transverse GMt	GMt	m	5.78	8.66	13.94
Metacentric height longitudinal GMl	GMl	m	403.83	403.83	403.83
Transverse radius of gyration in air kll	k11	m	14.77	15.02	15.30
Longitudinal radius of gyration in air k22	k22	m	77.47	77.52	82.15
Yaw radius of gyration in air k66	k66	m	79.30	83.81	83.90
Lateral wind area of superstructure (aft)	Ax	m^2	922.00	922.00	922.00
Transverse area of superstructure (aft)	Ay	m^2	853.00	853.00	853.00

Zero frequency added mass matrix (water depth 82.5 m)

Thesis values			Loaded	Mid	Ballast
	a11	tf*s^2/m	1594.0	755.0	250.0
	a22	tf*s^2/m	25092.0	10940.0	5375.0
Fore-aft symmetric vessel	a26	tf*s^2	0.0	0.0	0.0
Fore-aft symmetric vessel	a62	tf*s^2	0.0	0.0	0.0
	a66	tf*s^2*m	123510000.0	59607700.0	23200000.0

Added Masses in Kilograms					
	a11	kg	1.56371E+07	7.40655E+06	2.45250E+06
	a22	kg	2.46153E+08	1.07321E+08	5.27288E+07
Fore-aft symmetric vessel	a26	kg*m	0.00000E+00	0.00000E+00	0.00000E+00
Fore-aft symmetric vessel	a62	kg*m	0.00000E+00	0.00000E+00	0.00000E+00
	a66	kg*m^2	1.21163E+12	5.84752E+11	2.27592E+11
Displaced Mass	Mdisp	kg	2.40865E+08	1.63690E+08	9.11840E+07
Virtual Mass Coefficients	vmc11	dimensionless	1.06492	1.04525	1.02690
	vmc22	dimensionless	2.02195	1.65564	1.57827
	vmc22-vmc11	dimensionless	0.95703	0.61039	0.55137

OCIMF Current Areas

Head-on (Transverse)	Axc	m^2	891.51	624.06	356.61
Beam-on (Lateral)	Ayc	m^2	5859.00	4101.30	2343.60

OCIMF Wind Areas

Head-on (Transverse)	Axw	m^2	1362.44	1629.89	1897.34
Beam-on (Lateral)	Ayw	m^2	4201.00	5958.70	7716.40

Note: Thesis masses (tf*s^2/m) in kilograms = 1000*g*[Thesis Value]; g ~ 9.810

Appendix II

SpinMoor FAQ

Q1: Input stream: What variables are you looking for from the input stream?

A: It would be helpful to have a summary of the input data used in the simulations in case we find anomalies and need to try and track down possible typos or input errors. Screen shots would be fine if text files are not available.

Q2: Output stream: Do you want movies of the vessel motion, similar to the SpinMoor.mov you supplied with the information packet?

No movies, please; the size becomes a problem for email attachments.

Q3: Output stream: What variables are you looking for in the output stream. Do you want plots or tabular data, or both?

A: We need tabular data, preferably tab-delimited if possible, for the turret centroid location {Rx,Ry} and vessel yaw angle at each reported time step in order to prepare comparison plots. The time derivatives of those quantities would be appreciated if that is convenient, but those are not essential. Simple plots, such as those in the "SpinMoorPlots.pdf" file supplied to you as qualitative examples, could be useful for error checking but likewise are not necessary.

Also, fairlead load time histories at 4 fairleads would be useful but not essential; e.g., Fairlead Numbers {1,7,13,19}

Q4: Time step: what time step are you looking for in the simulation analysis?

A: One-half second should be generous and will produce manageable time history file sizes. One second is also ok; nothing is happening very fast in the SpinMoor.

Q5: Diffraction analysis: My program requires input from a diffraction analysis. Where can I find the particulars for Marin "standard" 200 kdwt tanker?

A: Since there are no waves, and since the zero-frequency added mass values are specified, a diffraction analysis is not necessary.

If your program requires one, any vessel with the SpinMoor-specified mass properties, added mass values, moorings, hydrostatics and current areas will give the same time history for the motion and mooring loads. So, use any vessel specification file from your library that you want, provided only that it is adjusted to reproduce exactly all the data in the supplied Marin_200kdwt.xls spreadsheet file, including the zero-frequency added mass values.

That said, if you want to build a panel model for Marin's 200 kdwt standard, I believe the specs are available in Wichers' thesis, which can be found on Marin's website:

https://www.marin.nl/publication/a-simulation-model-for-a-single-point-moored-tanker

----

Q6: Fairlead locations: You have the fairleads positioned 3.5m from the turret centroid; my simulation tools handle rotating turrets somewhat differently. Can I move all fairleads to the turret centroid so they do not move relative to the vessel?

A: Yes, certainly. The decision to displace fairleads from the centroid was a cosmetic choice to make the mooring slightly more realistic.

Q7: OCIMF sway force and yaw moment: Can you confirm that the OCIMF hydrodynamic sway force on the vessel is simply equal to:

sway force = .5*Cd*rho*Length*Draft*|Vcg|^2

where rho is water density, Cd = Sin[90°] = 1, Vcg is the vessel speed at midships [cg] and that the hydrodynamic yaw moment about the CG is at all times zero? That would mean there is no yaw moment or sway force contribution due to the different lateral speed at the bow and stern. That does not seem very realistic.

A: You are absolutely correct on all counts:

[A] The sway force on the vessel is as you have described.
[B] There is no OCIMF hydrodynamic moment about midships since the Cz (yaw) OCIMF coefficient is zero.
[C] A and B are not realistic.

Differential bow-stern lateral speed through the fluid is the principal contributor to "added sway/yaw damping contributions" offered by some vendors in addition to the OCIMF treatment. We want to eliminate possible conflicts in handling of the differential speed to insure all participants are using identical relative-motion hydrodynamic damping equations.

Q8: fore-aft symmetry & waterplane areas: My program requires some values that do not appear in the Marin_200kdwt.xls excel spreadsheet. What should I use for:

1. Longitudinal flotation center, longitudinal center of buoyancy (LCB)
2. Waterplane areas

A:

1. To ensure the fore-aft symmetry we are seeking, all "longitudinal" quantities (LCG, LCB, etc.) should be placed at midships in all cases.
2. The waterplane areas of the Marin 200 kdwt tanker are:

{Loaded, Ballasted} = {13,400, 12,310} m^2

Q9: Lateral ("Propeller") force vertical application point: A deck-mounted "propeller" providing the constant lateral 200 mt force to the SpinMoor produces a small roll moment in my 6 DOF simulation that is causing some roll response. Can I move the vertical application point to somewhere near half draft to minimize or eliminate that roll moment?

A: Yes, please do so. In addition, please see the next FAQ for a comment on added damping to quench motions that might arise in those degrees of freedom.

Q10: GML (and, KML) value confusion: The spreadsheet Marin_200kdwt.xls shows GML the same for both loaded and ballasted. That seems unreasonable. Comments?

A: Right you are; the GML specs given in Johann Wichers' thesis were missing for the Intermediate and Ballasted cases; we therefore used the loaded value for both. Despite this being incorrect, please use the quoted value (403.83 m) for both cases so everyone will use the same numbers. The natural period of pitch will only affect those running 6 DOF codes, and there should be virtually no pitch in our waveless environment.

For 6 DOF codes with stability problems in heave, roll and/or pitch, it might be useful to use a small linear damping to suppress/quench motions that might arise in those degrees of freedom.

Q11: Mooring length, pretension, and elastic modulus: I have some trouble getting a pretension of 100 tonnes using your mooring spec (3000 m line length, elastic modulus of 400 metric tons). Can you confirm those values?

A: The spec should have specified a bit more clearly: "un-stretched line length of 3000m ". Under 100 mt pretension, with that elastic modulus, the actual fairlead-anchor distance is 3750m, not 3000m. Sorry for the confusion.

Q12: Vertical location of the lateral-force application point: I see no mention in your specs of a vertical location for the 200 tonne lateral force application point. I do see mention of "propeller affixed to the deck", so am I to apply the force at deck level? Won't a force applied at that level produce a roll transient from the impulsive force application at T = 0 and a mean roll angle in the steady-state orbital condition?

A: Yes, I see that the force application height specification got overlooked, this yet another victim of 3 DOF thinking; sincere apologies.

To minimize roll moments related to the lateral force application, please apply the force at half-draft level on a vertical line through midships centerline; that will be close enough to both (a) the vertical center of the vessel sway virtual mass (vessel + zero-frequency added mass in sway), and (b) the vertical center of the lateral drag force developed by transverse motion. That application level will minimize both the transient roll response to the step force at startup, and the mean roll angle in the steady state orbital condition.

If you find small oscillations developing in roll, pitch or heave, they can be quenched with a small amount of linear damping in those oscillatory degrees of freedom without impacting the 3-D squall response motions that are the focus of this investigation.

Q13: What is the "theta" variable plotted in "SpinMoorPlots.pdf"? Also, is that the same theta that appears in the OCIMF coefficient specs in "SpinMoor_Specification_Review"? For example,

CxCur = Cos[theta]

A: I use theta generically for angles in a couple of places:

The theta in the "SpinMoorPlots.pdf" example is the global angle from the initial (quiescent) turret centroid to the instantaneous turret centroid as time marches on from t = 0. Theta is the ArcTangent of (Ry/Rx) where {Rx,Ry} are the global instantaneous coordinates of the centroid relative to the initial centroid position, which is the origin of coordinates {Rx,Ry} = {0,0}.

The theta in the OCIMF coefficients, e.g.

Cx = Cos[theta]

is the angle of the current velocity vector relative to the vessel centerline, said current arising from the vessel motion in still water.

Q14: OCIMF surge force. There is some confusion as to how to apply your specified OCIMF coefficients:

Cx[theta] = Cos[theta] (head-on force)
Cy[theta] = Sin[theta] (beam-on force)

The "logical" method used in our office uses the head-on projected area (beam*draft) for the area in the surge force equation. The OCIMF spec calls for the *same* area to be used with both Cx and Cy coefficients: The beam-on projected area (length*draft)

surge force (logical) = .5*Cx*rho*Beam*Draft*|Vcg|^2

surge force (OCIMF) = .5*Cx*rho*Length*Draft*|Vcg|^2

Which of these methods should we use for the SpinMoor with your Cx = Cos[theta]?

A: Please use the "logical" formulation and Cx[theta] = Cos[theta]. The OCIMF formulation will produce unrealistically large drag forces in head-on flows for Cx = 1. That said, in the SpinMoor configuration the flow is almost entirely in the lateral (sway) Cy direction so the two methods will give very nearly the same result in any case.

Q15: Observed non-alignment of steady state vessel and turret offset vector from quiescent turret position:

In the "qualitative behavior" SpinMoor graphic provided at the outset of the study (ref: "SpinMoorPlots.pdf"), you depict a vessel which, in its long-term steady-state orbital motion, aligns with the instantaneous turret offset vector.

My software shows the vessel orbiting about a point fixed in space, but the vessel is not perfectly aligned with the offset vector in steady state. Rather it settles into a noticeable "steady state skew" relative to the offset vector. Am I doing something wrong, or is the original "SpinMoorPlots" graphic in error?

A: Steady state balance of moments acting on the vessel (from hydrodynamic drag and the applied lateral force) requires that the steady state motion of the vessel be aligned with the turret offset vector from its T = 0 origin.

Any "skewed" steady-state vessel orientation arises from vessel moments other than those specified: i.e., the applied transverse force at midships and the OCIMF drag forces. Note that the Yaw [Cz] OCIMF coefficient is required to be zero for the SpinMoor analysis, and all other yaw moments must be eliminated.

Check to see if your software has a default "yaw rate damping" coefficient which is nonzero, and set it to zero to eliminate the extraneous moment, which will produce the behavior you report and otherwise impact the output stream, including the important offset values and net turret loads.

Q16: In your SpinMoor Vendor Comparison summary, you state there is a spread of roughly a factor of 2 between the loads and offsets between competing simulation programs. Since the external environment in the SpinMoor scenario is completely absent (no background wind, waves or current), I am wondering if that factor of 2 might be reduced (or eliminated) once environmental forces beyond the steady midships-lateral SpinMoor-protocol applied force are included in the simulation. Do you have any evidence that such a large spread across simulation products will persist in the face of a realistic environment?

A: The original motivation for the development of the SpinMoor testbed was the wide range in design load estimates produced by a cross-section of available commercial mooring software. Upon analysis of the SpinMoor study results, a follow-on study of design loads was conducted using two simulation products (one from each of the "L" and "S" subgroups in the SpinMoor report) applied to a realistic turret-moored vessel and riser complex, subject to Metocean environmental conditions (wind, waves and current) for a site off of West Africa. The estimated design load spread between SpinMoor study "L" and "S" subgroups, using the metocean conditions, was roughly consistent with the factor of two reported in the (quiescent-background) SpinMoor study. The design metric for these follow-on examinations was the maximum single-line mooring load and maximum Rxy excursion, applied to both load conditions (100% and 40% load). See also Appendices VII, VIII and IX of the SpinMoor Participant Study.

Q17: If one were to attempt to model test the SpinMoor, how would you deal with the gradual "toilet bowl" spin-up of the surrounding fluid?

A: As can be seen from the SpinMoor time histories, the steady-state orbital motion is reasonably well established after ~2 orbits. The vorticity imparted to the test basin fluid will therefore be limited, and is easily estimated, so that test measurements could be corrected to first order in the vorticity injection rate for comparison to the SpinMoor simulation, if necessary.

Q18: The mooring stiffness in the SpinMoor protocol is rather soft compared to actual field moorings. Can you comment on why that is so, and what impact that relatively soft moor has on SpinMoor load metrics (maximum and steady-state turret offsets and loads)?

A: The soft moor was chosen for two reasons: [1] Very stiff moors are problematic numerically because the large stiffness translates to abrupt dynamic loading in transient conditions; softer is better for all numerical time-step tools. [2] The mooring centroid excursions in a soft moor are more easily visualized: in an infinitely stiff moor, there is no visible motion of the mooring centroid. Our somewhat arbitrary choice of ~ 2 tonne/meter was therefore a compromise. Real moorings in the relative shallow-water environments subject to frequent squall events are, as you note, several times stiffer.

Q19: Long-term oscillations in the steady-state SpinMoor regime? I see some participants predict a long-lasting oscillation in the turret centroid Rxy persisting for hours. Can you comment? Is this even physically possible in light of the OCIMF dissipative mechanisms siphoning off energy from surge and sway motions?

A: Yes, it is physically possible. It is analogous in a way to the fish-tailing of a tanker that is hawser-restrained to a pylon in a steady current; in that situation there is plenty of energy in the mean flow to feed fishtail oscillations once they get started, if the oscillations are dynamically consistent with the nonlinear governing equations.

The turret moored FPSO of the SpinMoor possesses three quasi-static degrees of freedom, {Xcg, Ycg, Yaw}, and therefore has three quasi-static normal modes commonly called the surge, high sway-yaw, and low-sway yaw modes (see nearby graphic). Of these, the high sway-yaw mode will usually have the shortest period. These normal mode periods are readily computable for the SpinMoor. For example, the undamped modal periods in the loaded SpinMoor condition are approximately:

{Hi Sway-Yaw, Surge, Lo Sway-Yaw} = {280, 730, 1390} seconds

Further, the long-term oscillation observed in the reported loaded-vessel response of SpinMoor Participant 4 appears to be about 350 seconds. If this were a single degree-of-freedom system, the 280s vs 350s values would represent a system with damping of about 30% of critical. Furthermore, the steady-state strobe images for Participant 4 bear the unmistakable imprint of the high sway-yaw normal mode: We therefore suspect that Participant 4's long term oscillation is an unquenched, persistent, high sway-yaw modal oscillation.

There are similar oscillations observed to a greater or lesser degree in other participant time traces (primarily for the loaded case), although most show a rapid decay of amplitude. Nonetheless, just as for the fish-tail motion of a hawser-restrained tanker in a current, a long-term oscillation in the SpinMoor can persist, fed by the never-ending input energy supplied by the steady transverse forcing agent. When conditions and parameters are just right, this energy source can set up a limit-cycle type oscillation that may or may not damp itself out.

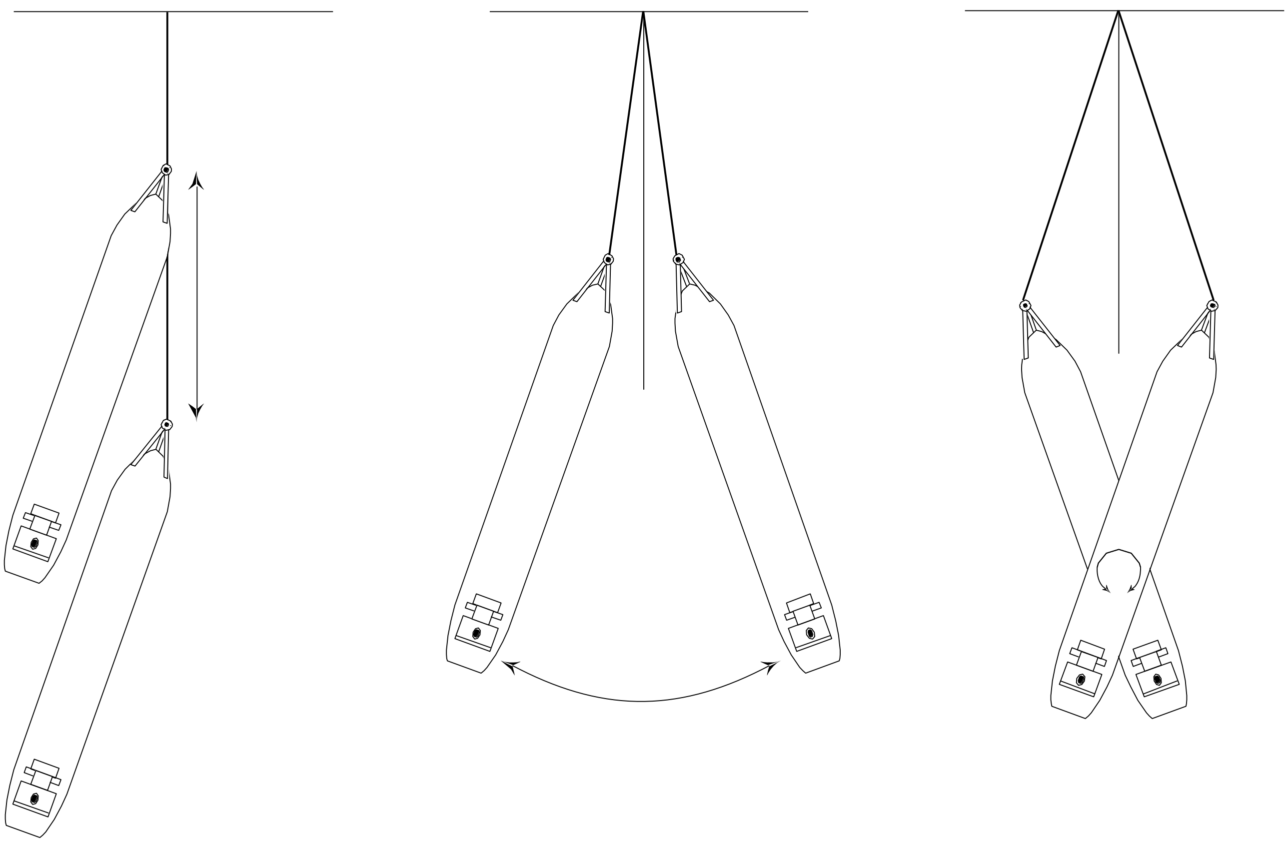
The more interesting question is why all participants do not exhibit nearly identical levels of normal mode damping. That circumstance, like the striking two-group SpinMoor bifurcation, can only be explained by differences in numerical time-step algorithms, or differences in implementation of the governing equations, or some combination.

Q20: I am confused by the units "tf*s^2/m" for added mass used in the SpinMoor Protocol documents. Can you give the added mass in more transparent units, like kilograms?

A: This unfortunate terminology is historical, harking to a time when wave basins used nautical terminology in which a "tonne" was usually understood to be a unit of force (or, in the nautical arena, a "displacement") equal to the weight of 1000 cubic meters of water, or about 9810 Newtons for fresh water. This was an unfortunate circumstance, compounded when dealing with seawater whose density is ~ 2.5% greater than fresh water. Today a "tonne" is understood by most engineers to be a unit of mass equal to 1000 kg, and not as the weight of 1000 cubic meters of fluid.

The added mass units given in Johann Wichers' thesis, which dates to the mid-late 1980s, are "tf*s^2/m". "tf" stands for "tonne force"; that is, the weight of a 1000 kilogram mass. To convert a tf to a mass, you divide by the local gravity constant (~9.81 m/s^2), which division is incorporated in Wichers' numerical values; the thesis audience was alerted to that hidden factor by the units displayed (tf*s^2/m). To convert "tf*s^2/m" to kilograms, Wichers' values must be multiplied by 1000*G ~ 9.81*10^3.

Figure A2-1



Surge Mode **_Low Sway-Yaw Mode_** **_High Sway-Yaw Mode_**

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Appendix III

Alternative Testbeds

A number of test case scenarios besides the SpinMoor were considered for comparative study of squall-capable mooring analysis codes.

An interesting set of highly idealized squall-similar transient environmental conditions were developed and experimented with. These conditions included "step" wind and current excitations, in which the SpinMoor vessel and mooring is subjected to a "step-function" wind or current, incident upon the stern (180° attack angle), or beam-on (90° attack angle) at T=0. These transients were deemed too problematic, with far too much potential for inconsistent handling and reporting in a comprehensive comparison between many software products.

Another attractive and interesting highly simplified case, the SpinTransit™ scenario, was ultimately omitted from the formal study because it was believed many available codes would not be able to accommodate the SpinTransit protocol off the shelf.

The SpinTransit protocol, as the name implies, calls for the analysis of an unmoored vessel, simultaneously spinning and translating in a perfect fluid, with no dissipative mechanisms whatever (i.e., OCIMF surge and sway coefficients {Cx, Cy} are both identically zero). In the SpinTransit scenario, however, the (non-dissipative) Munk Moment is included via a suitably crafted OCIMF-style yaw coefficient {Cz}. Like the SpinMoor, this is a condition of little, if any, direct relevance to real-life problems in the offshore industry, but whose simple dynamics offers a thicket of numerical and methodological cracks and crevices to trip simulation software.

As with the SpinMoor, one would hope that all simulation products in wide use would produce identical SpinTransit responses. And, as with the SpinMoor, one's hopes would not be fulfilled.

At this point, we have verified that four of the simulation codes included in the SpinMoor Study, including SquallSim and "Simulation Q" mentioned in the historical introduction, produce results at odds with one another consistent with the bifurcated group differences found in the SpinMoor study.

Whether or not there will be a SpinTransit comparison study as follow-up to the SpinMoor study remains to be determined.

Appendix IV

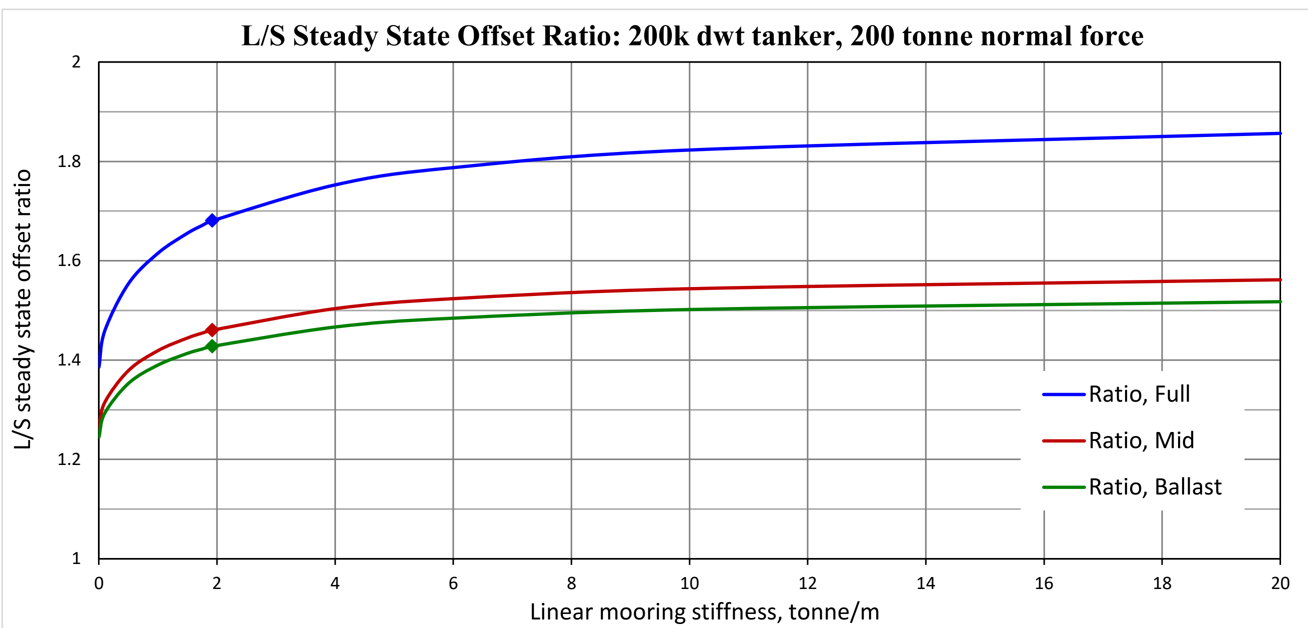
Mooring Stiffness Considerations

The question of mooring stiffness selection on SpinMoor offsets came up in a participant FAQ (See SpinMoor FAQ 18: ”Sensitivity of SpinMoor Conclusions to Mooring Stiffness”, in Appendix II).

We have conducted a preliminary exploration of this issue using SquallSim's two-branched execution model, using the SquallSim “L” branch as proxy for the average L subgroup participant, and its “S” branch as proxy for the average S subgroup participant. Mooring stiffness was varied across two orders of magnitude by suitable adjustment of mooring EA values. Interestingly, and somewhat surprisingly, the steady-state mooring force ratio Rxy[L]/Rxy[S] connecting the two SquallSim execution branches increases steadily with increasing mooring stiffness, the ratio approaching asymptotic values for {loaded, ballasted} conditions of about {1.9, 1.5} in the limit of large stiffness. Reading from the Figure A4-1 below, we see the ratio Rxy[L]/Rxy[S] for the rather soft SpinMoor protocol stiffness (1.92 tonne/meter) is {loaded, ballasted} ~ {1.68, 1.43}. This closely matches an “eyeball average “of the values reported in Figure 1.

Further implications of the SpinMoor bifurcation for real systems subjected to a realistic squall and background environment are presented in Appendices VII, VIII, and IX.

Figure A4-1



Appendix V

Adjustable Parameter Impacts

Sway Damping Adjustments

To illustrate the power, and danger, of user-adjustable parameters to impact broad metrics in a simulation study, we inquire what would be required to pull the offset and load results from the L group of Participants down to the level of the S group. The investigation of this Appendix was triggered by one of the very circumstances that set this SpinMoor study into motion: Wide differences in design loads estimated by two mooring consultants, using different simulation tools that we now know to be from the *same* branch of the SpinMoor bifurcation. Those differences therefore almost certainly arise from differing choices for user-modifiable coefficients, quite likely involving those associated with adjustable vessel yaw and sway-yaw damping coefficients.

We can use the {L, S} branches of SquallSim to determine what change in the maximum Cy (sway) OCIMF coefficient is required to cause predicted motions and loads in the L group to join the S group. To do this, we take the unadulterated SquallSim "S" branch SpinMoor protocol result, for which the OCIMF Cy value is

Cy = Sin[theta],

and compare that with the SquallSim "L" branch result, but replace the protocol Cy value above with an *enhanced* value:

Cy = 1.9*Sin[theta].

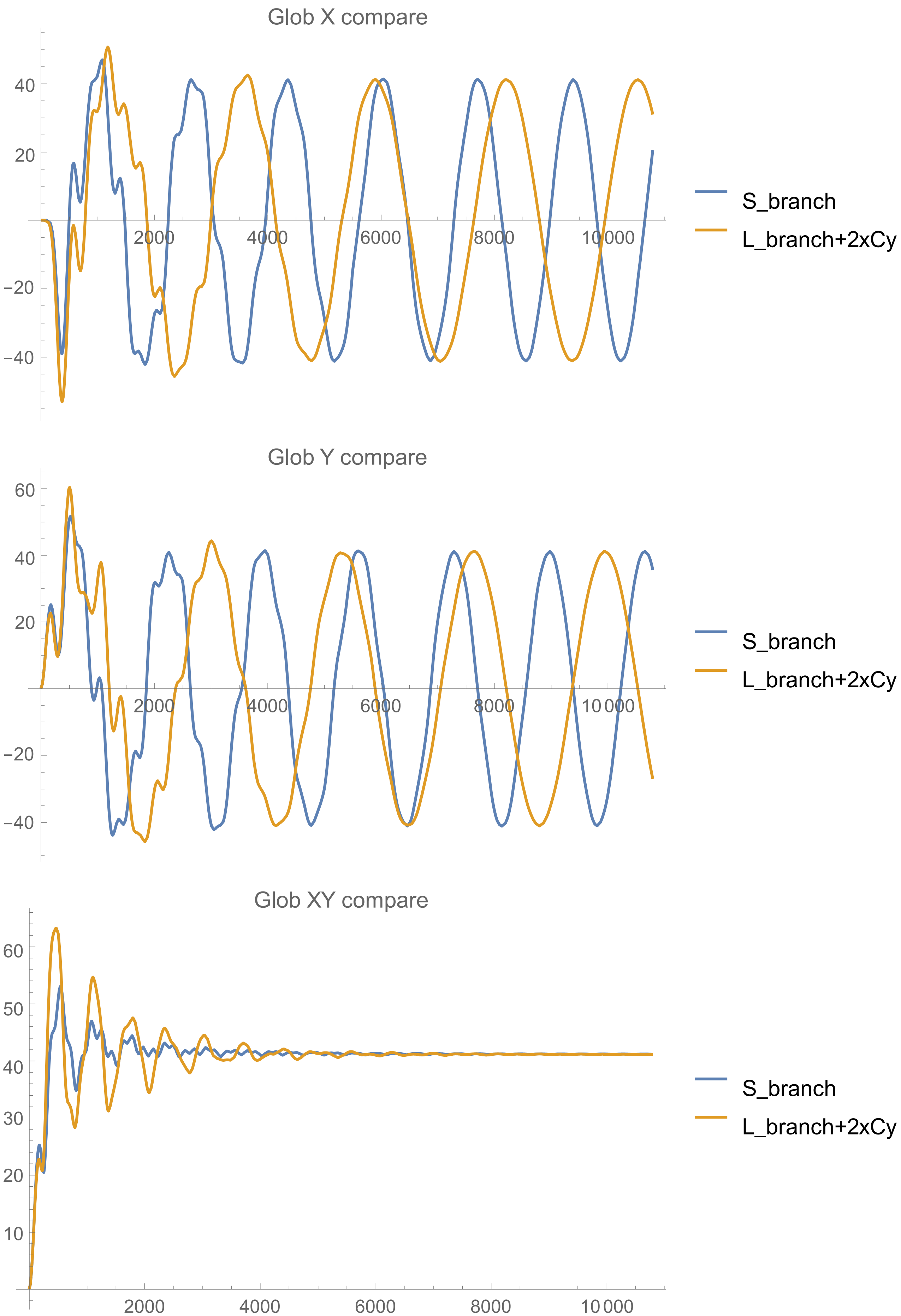
This single Cy adjustment to SquallSim's "L" branch simulation pulls the SpinMoor response down to the level of the unadulterated S branch. This Cy change has other consequences of course (it produces a different orbital period, for example), but the offset metrics align closely, as plotted in Figure A5-1 below.

The "S_branch" curve is the SquallSim SpinMoor-protocol result, while the "L_branch+2xCy" curve uses SquallSim's "L" branch code with the (roughly doubled Cy -> ~ 2xCy) Cy coefficients noted above.

Note that in the SpinMoor scenario of a vessel rotating about a fixed point, the Cy[90°] value can be viewed as a kind of "yaw rate" damping coefficient, since the sway motion is generated by pure yaw about a point. So, it is not hard to see that user adjustment of "yaw rate" and "sway-yaw coupled rate" constants, which adjustments are available in one form or another in most simulation programs (but proscribed for the SpinMoor Study) could have a similar impact.

As an aside, and as a statement of our distaste for user-specified damping factors, SquallSim has no adjustable yaw, or sway-yaw added damping parameters. Rather, there is a (non-adjustable) closed-form yaw-rate add-on to supplement the OCIMF coefficients, which add-on is derived *from* the OCIMF coefficients; however, this yaw rate contribution is either on or off, and not continuously user-adjustable; it is off for results governed by the SpinMoor Protocol, including all results in this appendix. We believe that the vessel information encapsulated in OCIMF-style square-law force and moment coefficients is sufficient to establish a robust yaw-rate damping estimate using a strip-theory-type distribution of hydrodynamic drag forces. User control of these important dynamical quantities should be avoided, or tightly controlled to within very narrow limits.

Figure A5-1


Glob X compare
40
20
-20
-40
2000
4000
6000
8000
10000
S_branch
L_branch+2xCy
Glob Y compare
60
40
20
-20
-40
2000
4000
6000
8000
10000
S_branch
L_branch+2xCy
Glob XY compare
60
50
40
30
20
10
2000
4000
6000
8000
10000
S_branch
L_branch+2xCy

There are other extant examples of the inappropriate use of user-adjustable dissipative coefficients in widely referenced offshore engineering reports.

An important and under-reported example: During the 2001 DeepStar tests [5] the 200 kdwt turret moored tanker, sporting a generous complement of fully modeled mooring and riser lines, was subjected to a complex environment including GOM Loop Current conditions in the Marin model basin. The tests showed a much larger mean vessel offset than most participants predicted. The response to this failing, rather than a thoughtful critique of the horizontal force model used to compute current loads on inclined slender members (mooring lines, risers, etc.), was to suggest that a drag coefficient in the range of 3 to 4 or even more should be used in the Morrison slender-body drag evaluations for the mooring lines and risers. However, a drag coefficient of that magnitude is physically impossible to achieve for a cylindrical member, as can be demonstrated by straightforward application of momentum conservation to the problem of an inclined circular cylinder in a horizontal flow. [7]

Appendix VI

Largest and Smallest Participants Compared

Visualization plots for vessel motions between the participants with smallest (Participant 10) and largest (Participant 8) maximum and steady-state Rxy values can be found below, for both 100% and 40% load cases.

In addition, a video snippet of the fully loaded case, showing a side-by-side comparison of the two solutions, can be found here: Compare_Hi+Lo

When viewing the above video, recall that according to the SpinMoor protocol the instantaneous net turret force is proportional to the offset from the zero point; i.e. the distance from the origin to the turret, which is represented by a small colored dot just forward of the bow. For better visualization of the response the vessels are not to scale.

Figure A6-1

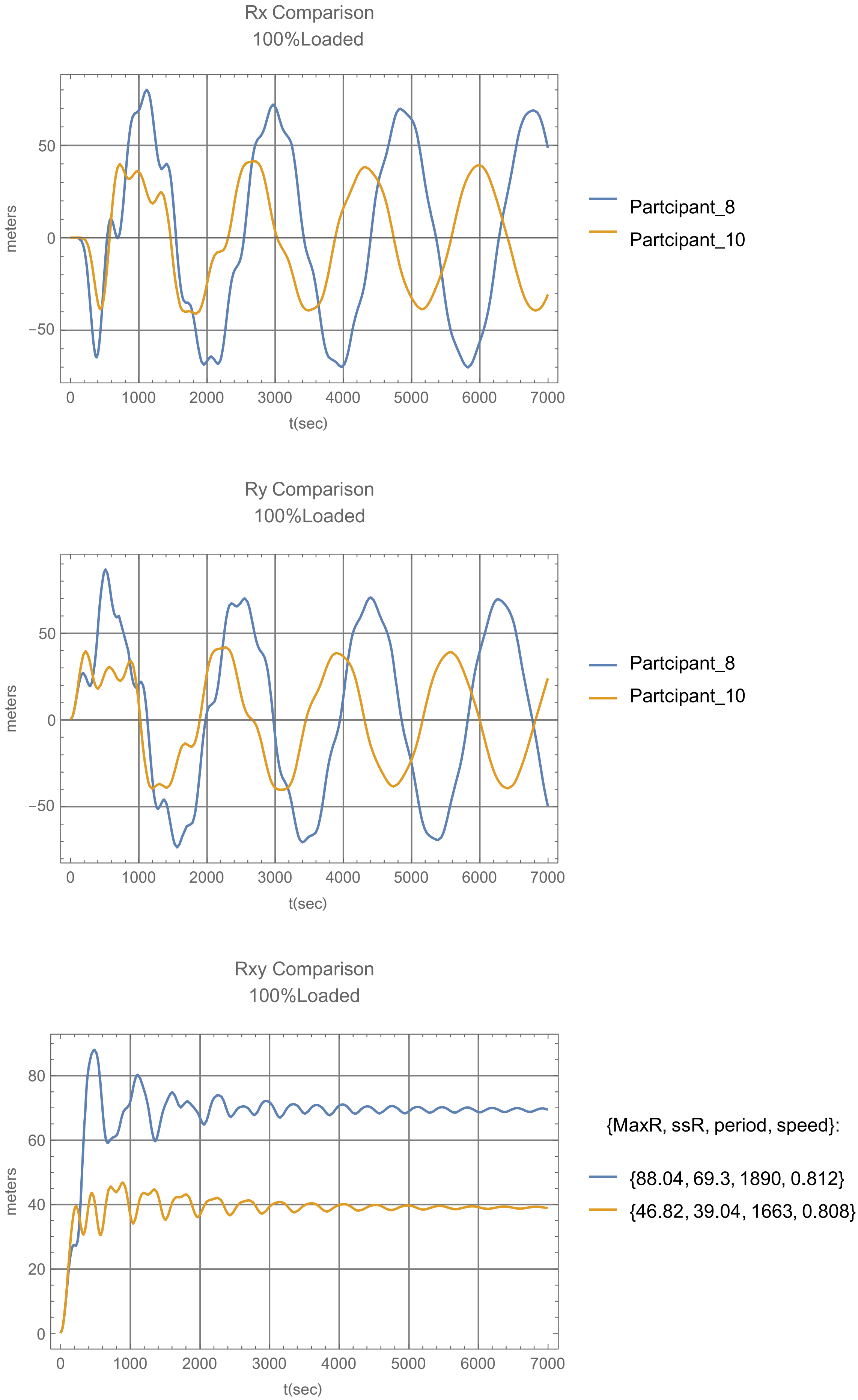
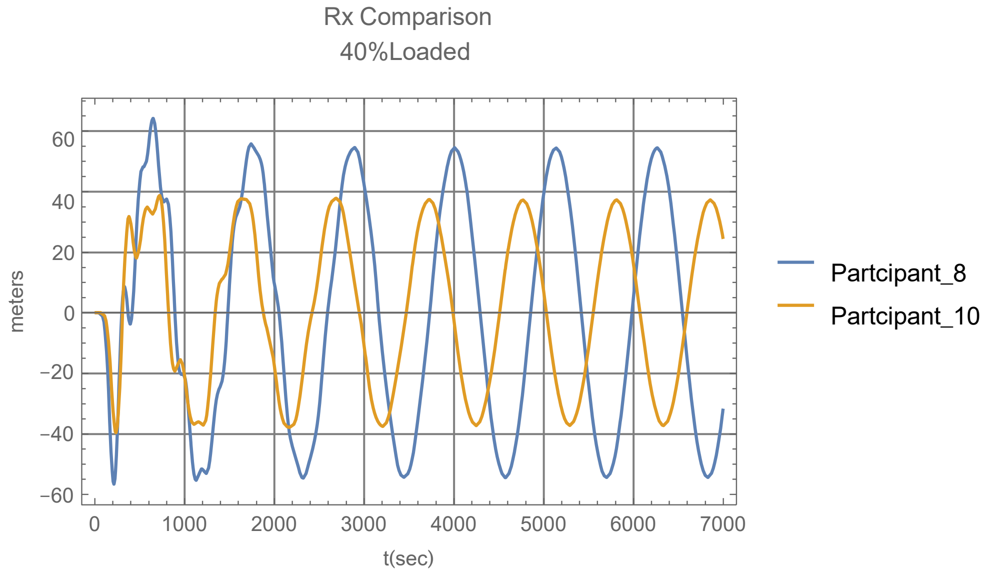
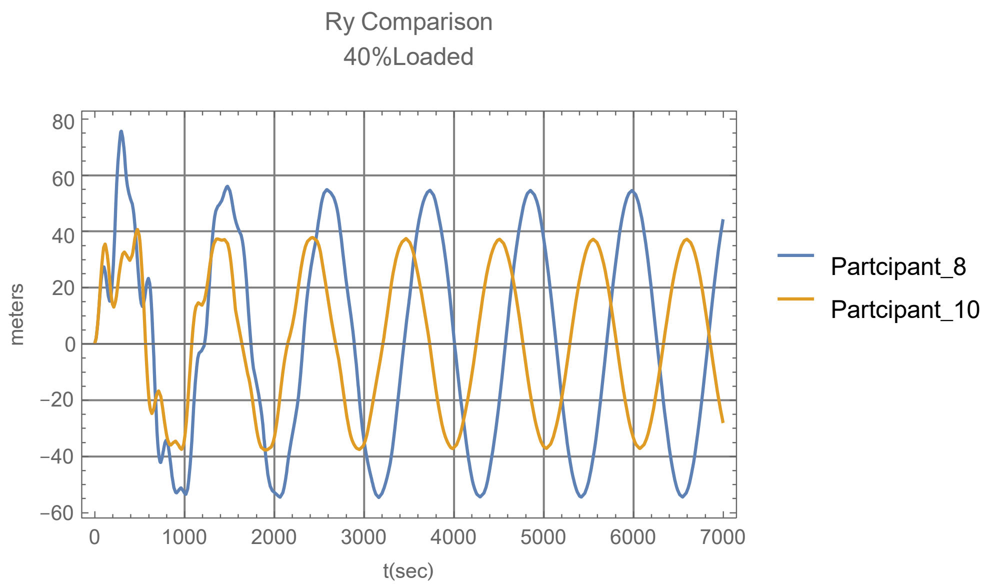
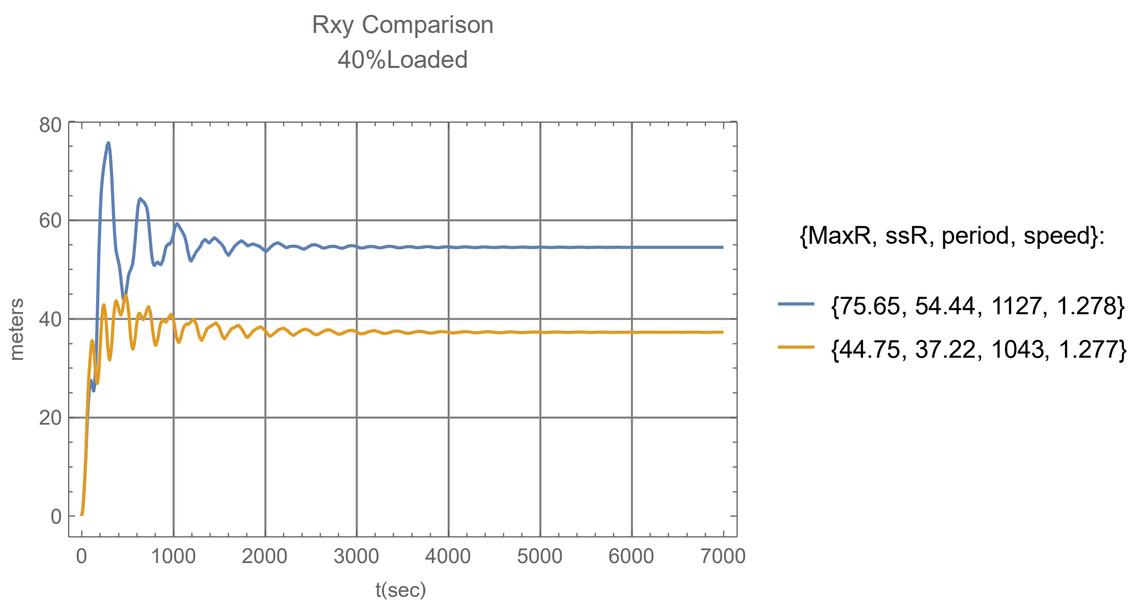

Rx Comparison
100%Loaded
meters
t(sec)
Partcipant_8
Partcipant_10
Ry Comparison
100%Loaded
meters
t(sec)
Partcipant_8
Partcipant_10
Rxy Comparison
100%Loaded
meters
t(sec)
{MaxR, ssR, period, speed}:
{88.04, 69.3, 1890, 0.812}
{46.82, 39.04, 1663, 0.808}

Figure A6-2


Rx Comparison
40%Loaded
meters
t(sec)
60
40
20
0
−20
−40
−60
0
1000
2000
3000
4000
5000
6000
7000
Partcipant_8
Partcipant_10


Ry Comparison
40%Loaded
meters
t(sec)
80
60
40
20
0
−20
−40
−60
0
1000
2000
3000
4000
5000
6000
7000
Partcipant_8
Partcipant_10


Rxy Comparison
40%Loaded
meters
t(sec)
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
7000
{MaxR, ssR, period, speed}:
{75.65, 54.44, 1127, 1.278}
{44.75, 37.22, 1043, 1.277}

Appendix VII

Squall Analysis Part 1: In Depth Results for Two Cases

It is fair to ask whether the surprising factor of order 2 between the “Large” and “Small” SpinMoor participant predictions partially or fully disappears in the face of a realistic wind squall event set against the backdrop of an underlying environment of waves and current. To explore that question, we have selected a pair of more-or-less worst-case scenario simulation runs using 100-year return period squall events. Details of the vessel, mooring, and risers are from a design study for a turret moored installation offshore West Africa [2]. See Appendices VIII and IX for more information on this dataset. This design study included a total of over 1 million independent squall simulations, from which we have selected two 100 year return period cases for the maximum draft condition: one producing the maximum line tension (the “large tension” case, which occurred with squall realization #3), and one producing the maximum turret offset (the “large offset” case, which occurred with squall realization #9). The full presentation document is available here: OSRC2018:

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(A) Analysis and Design for Transient Wind Squall Events

Load Cases

- **Load Cases for Each Return Period (about 20 to 1,000 per return period)**
  - Vessel initial global heading (e.g. spread moor 1, turret moor 36)
  - Squall global directions for each return period, peak wind speed may depend on direction (e.g. spread moor 57, turret moor 29)

  Number of load cases
    - spread moor: 1 vessel heading x 57 squall directions; total = 57 (513 = 57 x 9 squalls,)
    - turret moor: 36 vessel headings x 29 squall directions; total = 1,044 (9,396 = 1,044 x 9 squalls)
- **Realizations/Simulations for Each Load Case (EM uses 9 others may use more or fewer squall time histories)**
  - Squall realizations per load case (e.g. different scaled wind squall time histories; EM total = 9)

Note: Swell and Wind-Sea variability assumed to have an insignificant effect on the peak tensions, i.e. different realizations of wave conditions are not included

Number of Simulations

- **Vessel and Mooring System Conditions (about 10 to 100)**
  - Vessel drafts (e.g. min op, mid, and max op; total = 3)
  - Mooring system configurations(e.g. 1 intact case, 12 one-line broken cases, and 8 two-lines broken cases; total = 21)

  Total number of system conditions: 3 drafts x 21 intact and line broken conditions; total = 63
- **Number of Simulations for Each System Condition**
  - Spread moor: about 57 load cases (1 initial vessel heading x 57 squall directions) x 9 squall realizations = **513** simulations per system condition and return period

    Number of analyses increase by a factor of 9 (= number of squall realizations)
  - Turret moor: about 1,044 load cases (36 initial vessel headings x 29 squall directions) x 9 squall realizations = **9,396** simulations per system condition and return period

    Number of analyses increase by a factor of 324 (= 36 initial vessel headings x 9 squall realizations)
- **Total Number of Simulations Including multiple Return Periods and System Conditions**
  - Spread moor: about 513 simulations per system condition and return period x 63 conditions x 9 return periods = **290,871** simulations
  - Turret moor: about 9,396 simulations per system condition and return period x 30 conditions x 4 return periods = **1,127,520** simulations

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We are not interested in the details of the squall profiles involved; our intent is merely to compare response predictions of the “L” and “S” branches of the SpinMoor participant universe for a ‘typical’ realistic squall scenario. To that end, we again use the two {“L”, “S”} branches of SquallSim to perform the analysis, under the assumption that those branches can be used as proxies to gauge the difference in outcomes between an ‘average’ participant from each group {L, S} of the SpinMoor study. Aside from the SquallSim code branch, there are no user-specifiable parameters influencing this comparison.

Qualitative particulars of the vessel, moor and environmental conditions follow: The vessel is a converted VLCC with an external forward turret, the maximum operating draft, at midships, is approximately 21 m. The moor consists of nine chain/wire/chain mooring lines arranged in three groups with three lines in each group. The water depth varies over the anchor radius with an average depth of about 500 m. There are about 10 risers and umbilicals. The typical non-squall environmental conditions, 50% non-exceedance, consist of a background current of about 0.5 knots at the surface, swell waves with a significant wave height of about 1.5 m, and wind-seas with a significant wave height of about 1.0 m. The 100 year return period squall peak speed depends upon the squall direction. Over all squall directions the maximum wind speed varies between approximately 38 and 70 knots, the wind direction varies during the squall, and the squalls build from astern in each case.

Because the waves were small, so too were the wave-frequency load increments atop the very large quasi-static squall-driven levels; wave-frequency data is therefore not included in the graphics below.

The full study from which the two cases were drawn included 9 squall realizations. Figures A7-1 to A7-4 relate to the "Large Tension" simulation case. Figure A7-1 gives a birds-eye overview and comparison of the predicted {L, S}-branch turret tracks for all 9 (color-coded) squalls, each track arising from the same initial vessel heading and squall direction at the time of maximum wind speed. Figure A7-2 is a snapshot, at the time of maximum wind speed, from a video graphic of the simulation results (see links below). Figure A7-3 is an overlay comparison of the two turret centroid tracks predicted by SquallSim and Figure A7-4 of the predicted quasi-static line tensions in each line, together with an overlay of the squall speed time history.

Similarly, Figures A7-5 to A7-8 relate to the "Large Offset" simulation case.

Focusing on the quasi-static motions and loads, and the L-vs-S branch differences, we see that there is sufficient energy in the squall-induced vessel whiplash to produce a difference in extreme Rxy between the L and S branches of order 50%. Extreme line loads in the L branch are of order 100% larger than the S branch. Since the net turret load in this 3-leg grouped mooring arises from contributions by 3 tightly grouped mooring legs, the net turret load can also be estimated to be of order 100% larger for the L branch simulation than for the S branch. This estimate is consistent with an independent static offset analysis at the simulation-estimated extreme {L, S} turret offsets.

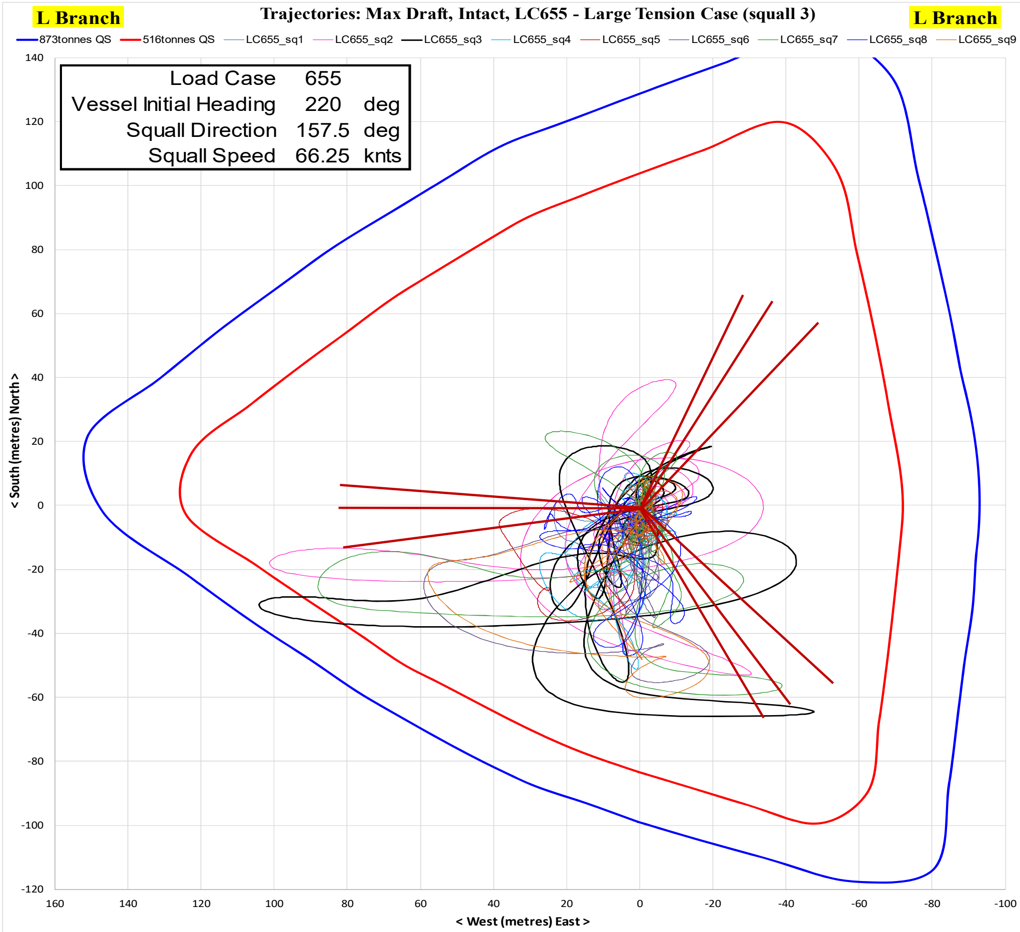
So, in this instance at least, the SpinMoor factor of order 2 in maximum offsets and total turret loads survives as a reasonable characterization of the offsets and loads experienced in this conventional catenary moor subject to two realistic design squall scenarios. This outcome can be understood, at least in part, from consideration of the approximately fixed (i.e., mooring system independent) injection of a given amount of squall-sourced vessel energy that must eventually be absorbed by the moorings, and ultimately dissipated into the environment, so it comes as no surprise that the maximum turret loads and offsets, seen as proxy for system energy injected by the squall, depends primarily on the intensity of the squall and the initial condition of the vessel at squall onset.

Links to videos displaying the two-vessel side-by-side behavior of the L and S simulations for maximum tension and offset cases can be found here: CompareTension_L+S and CompareOffset_L+S.

Links to single-vessel videos of the L and S simulation runs used for the comparison videos above for the Large Tension case can be found here: L_Tension and S_Tension.

When viewing the above videos, recall that for the SpinMoor protocol the instantaneous net turret force is proportional to the offset from the zero point; i.e. the distance from the origin to the turret. In this example, in view of the highly nonlinear catenary moor, the net turret force is governed by the catenary-elastic behavior. So, the last meter of a total offset produces a much greater turret force increment than the previous (next-to-last) meter of offset.

Figure A7-1 Large Tension Case – Turret Trajectories



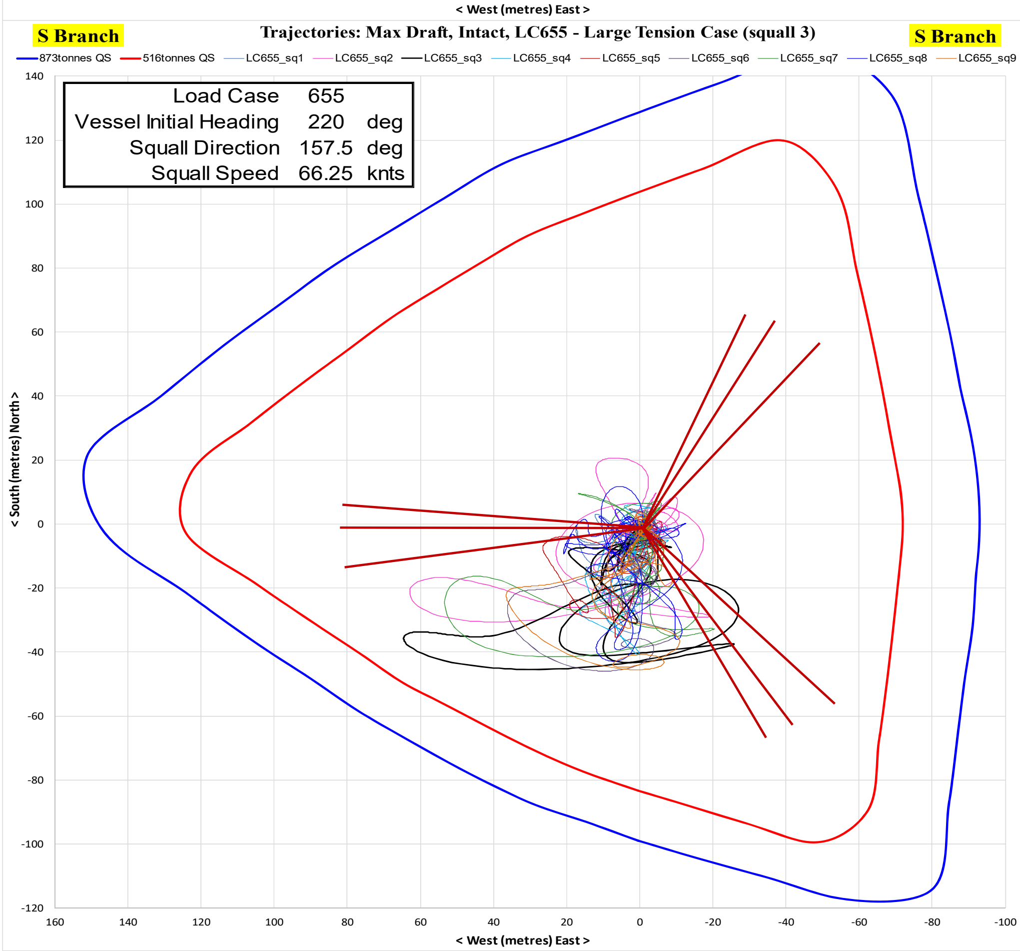
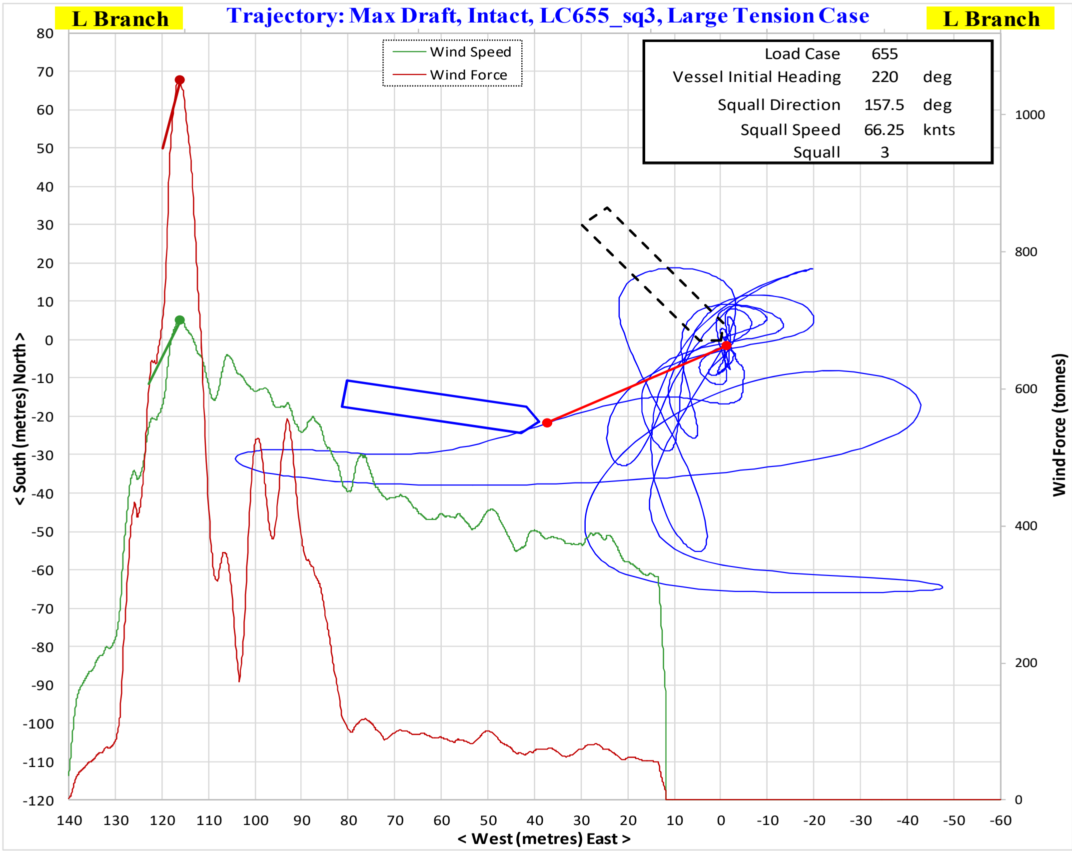


Figure A7-2. Large Tension Case – Time History Snapshot

Time = 479 sec X = -21.8 m Y = 37.4 m Yaw = -99.9 deg
Vw = 66.3 knts Vw.dir = 157.5 deg Force = 1050 tonne Frc.dir 167.8 deg



Time = 479 sec X = -26.3 m Y = 21.2 m Yaw = -99.1 deg
Vw = 66.3 knts Vw.dir = 157.5 deg Force = 1048 tonne Frc.dir 168.3 deg

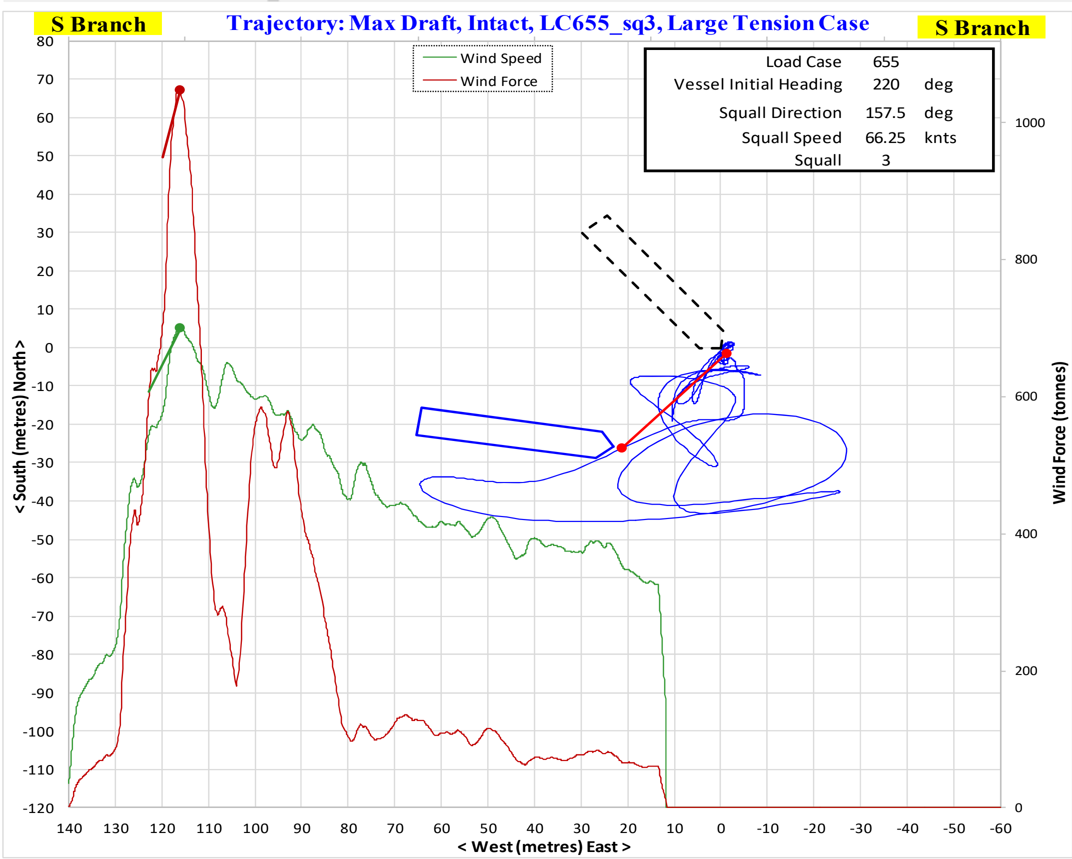


Figure A7-3. Large Tension Case – Compare Turret Trajectories

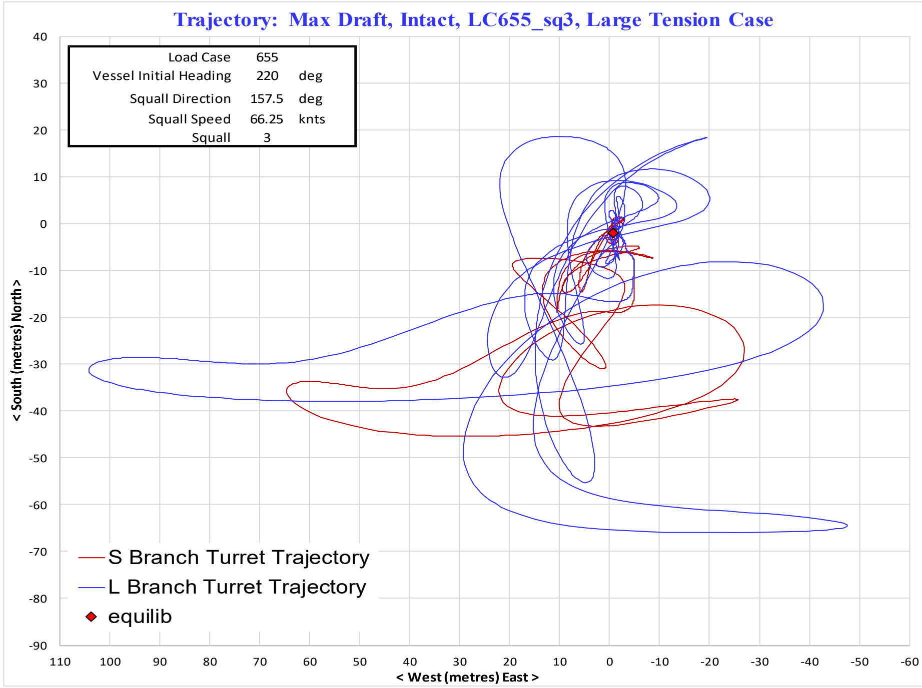


Figure A7-4. Large Tension Case – Compare Line Tensions

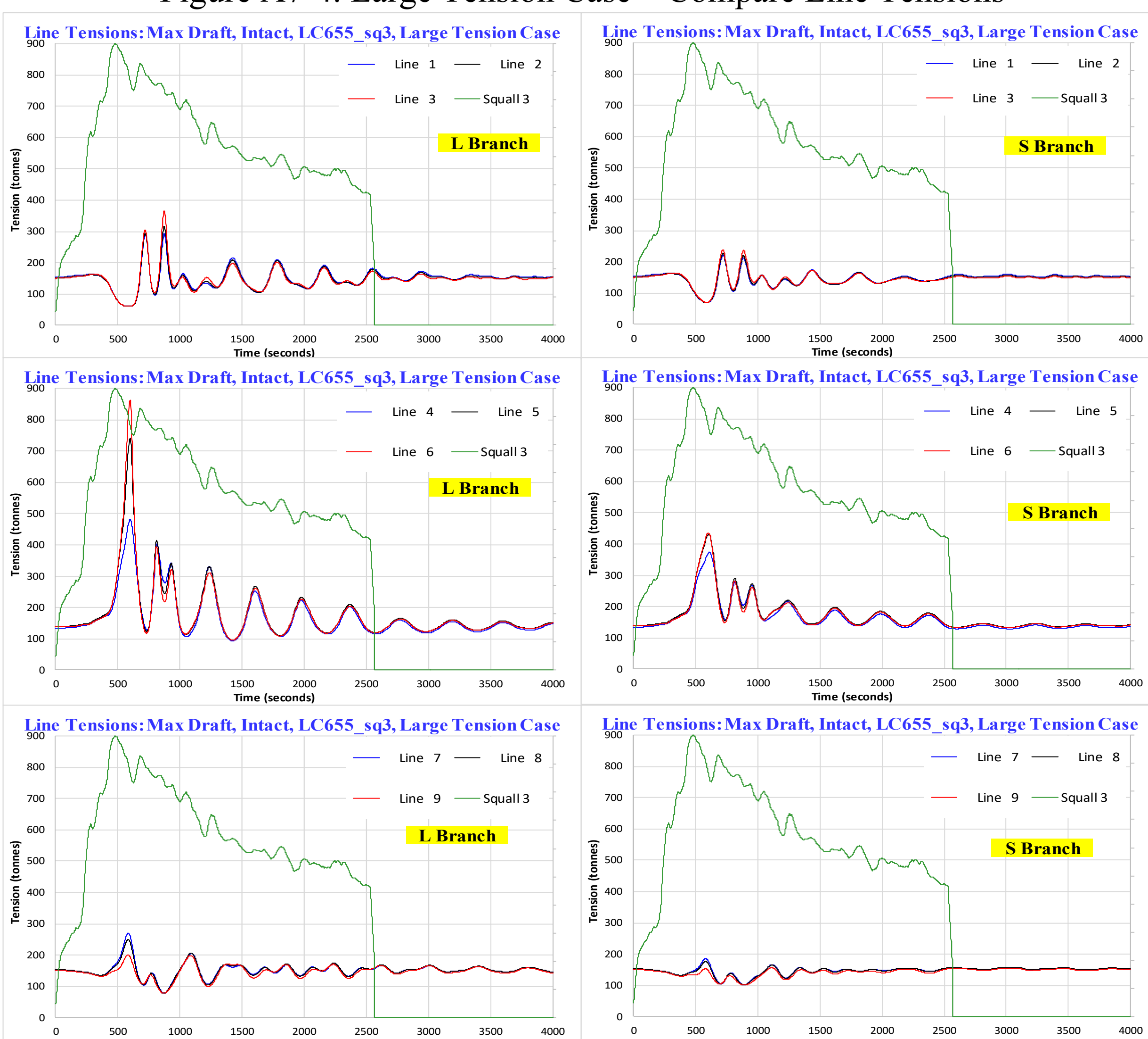
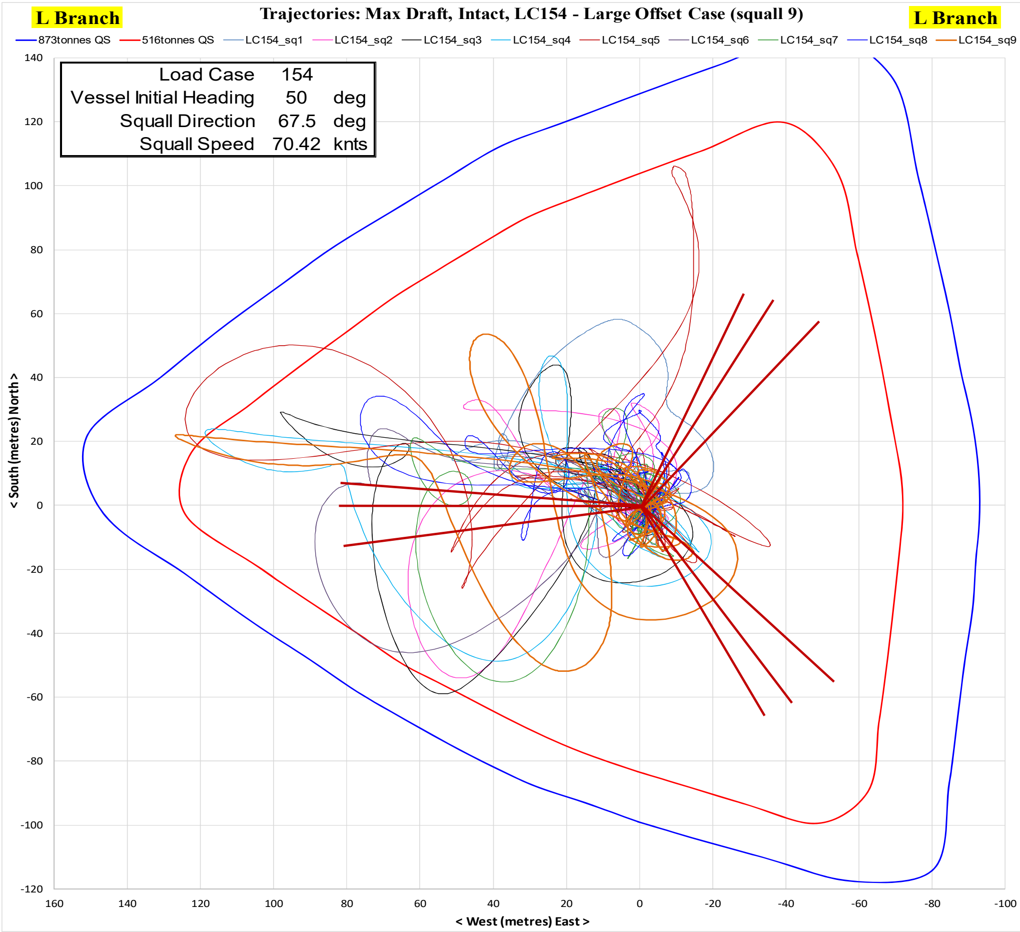


Figure A7-5. Large Offset Case – Turret Trajectories



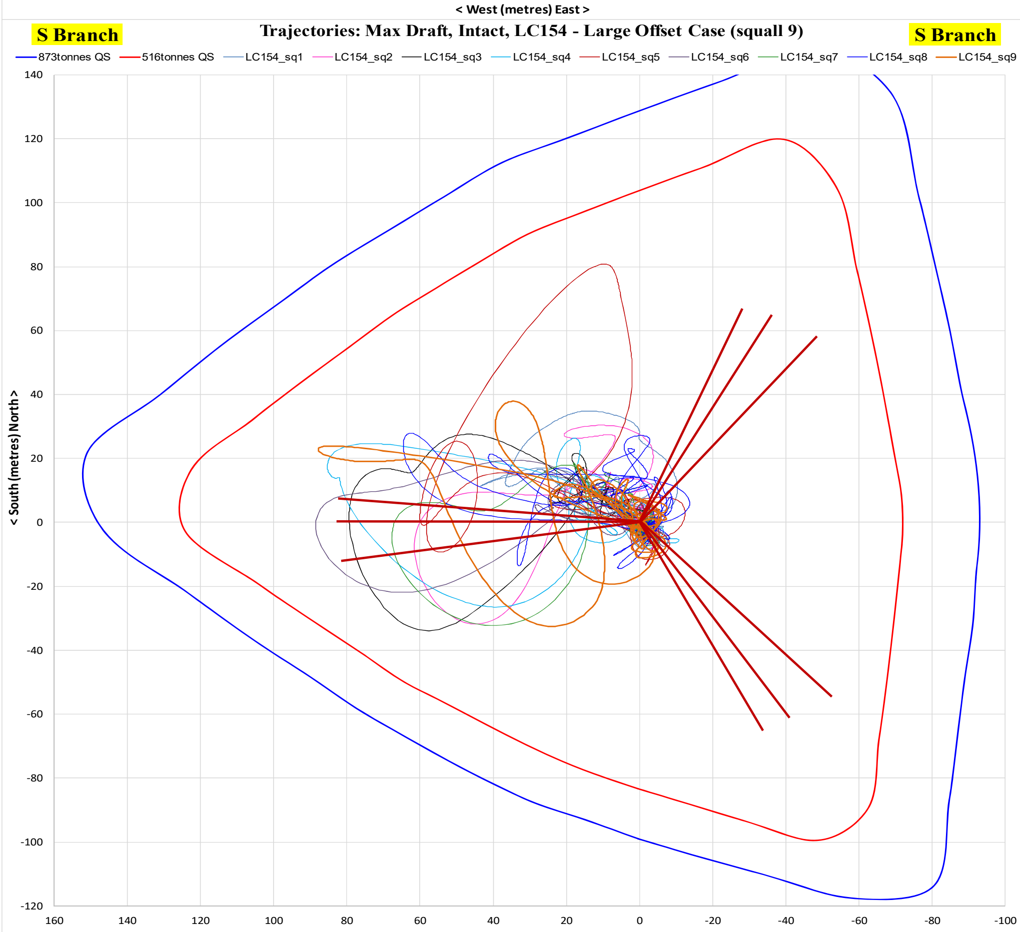
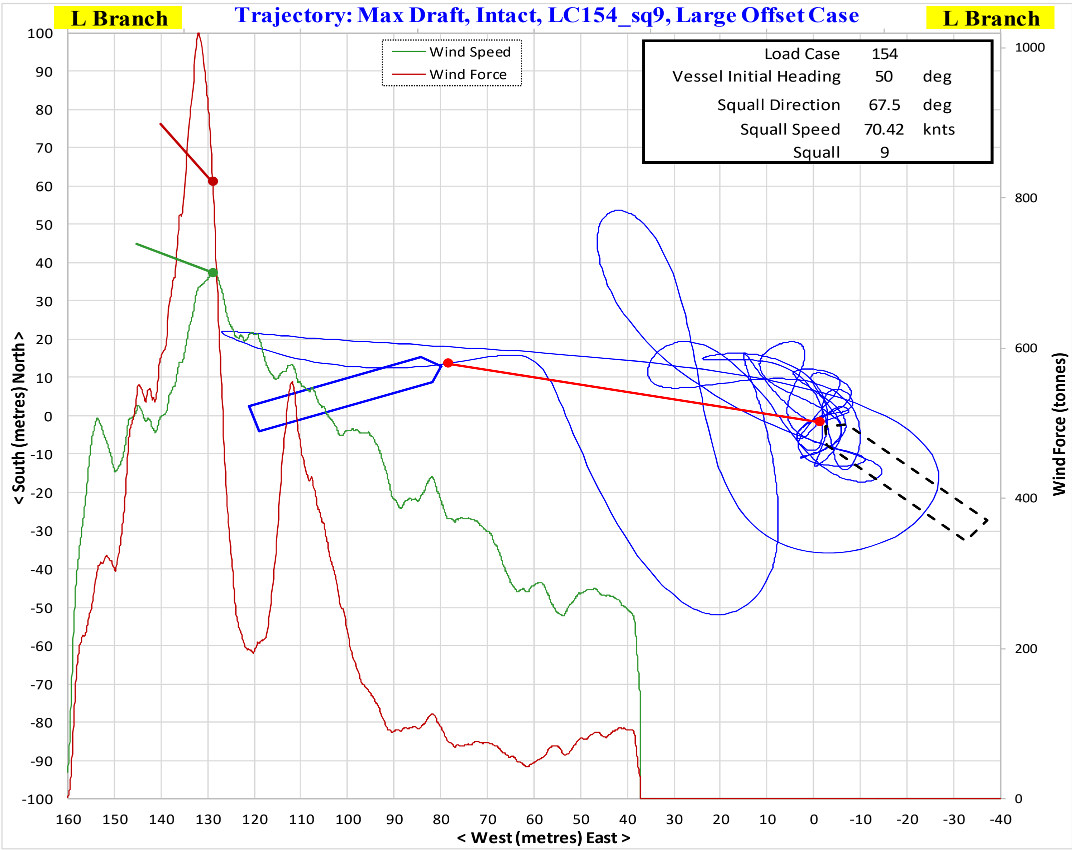


Figure A7-6. Large Offset Case – Time History Snapshot

Time =	623	sec	X =	13.6	m	Y =	78.3	m	Yaw =	-70.9	deg
Vw =	70.4	knts	Vw.dir =	67.5	deg	Force =	821	tonne	Frc.dir	39.0	deg



Time =	623	sec	X =	18.1	m	Y =	63.4	m	Yaw =	-74.7	deg
Vw =	70.4	knts	Vw.dir =	67.5	deg	Force =	760	tonne	Frc.dir	37.8	deg

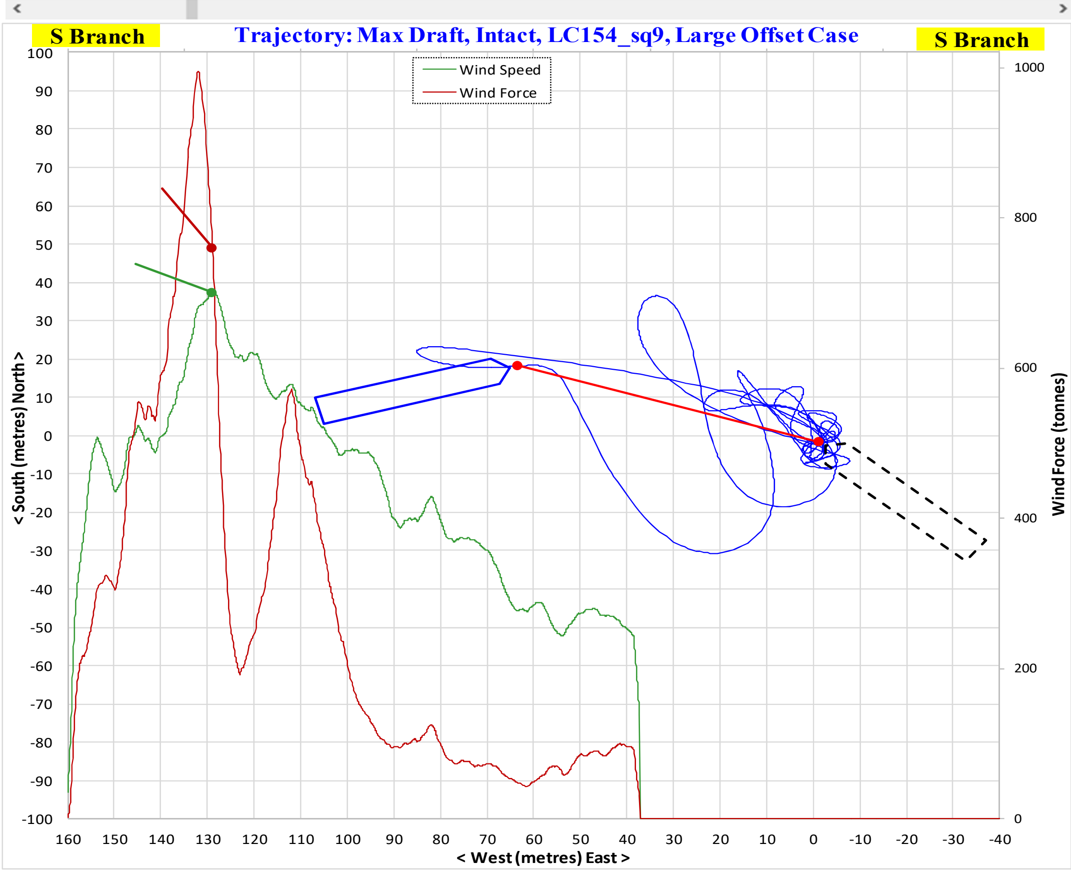


Figure A7-7. Large Offset Case – Compare Turret Trajectories

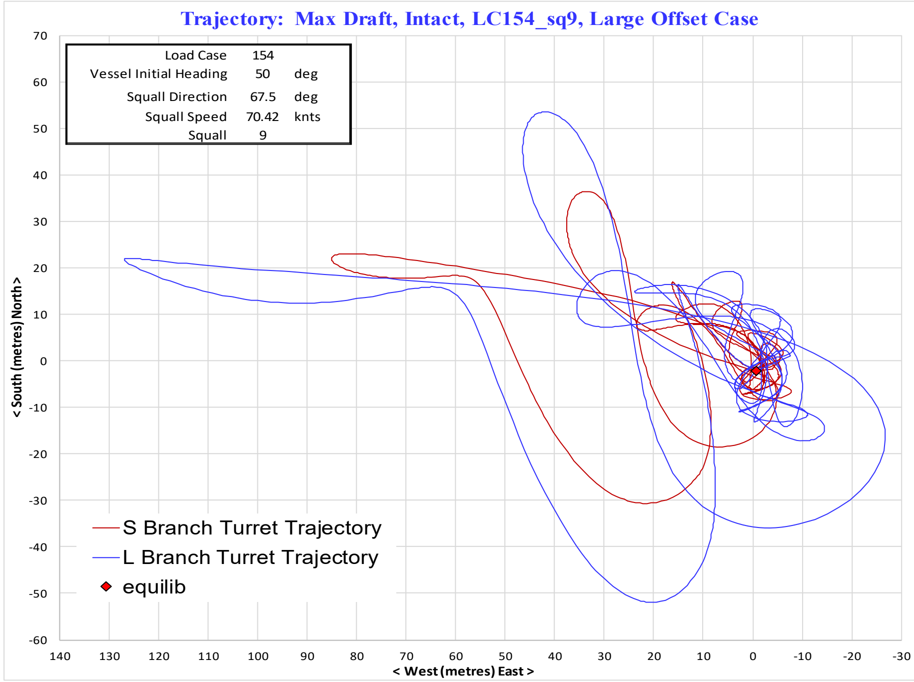
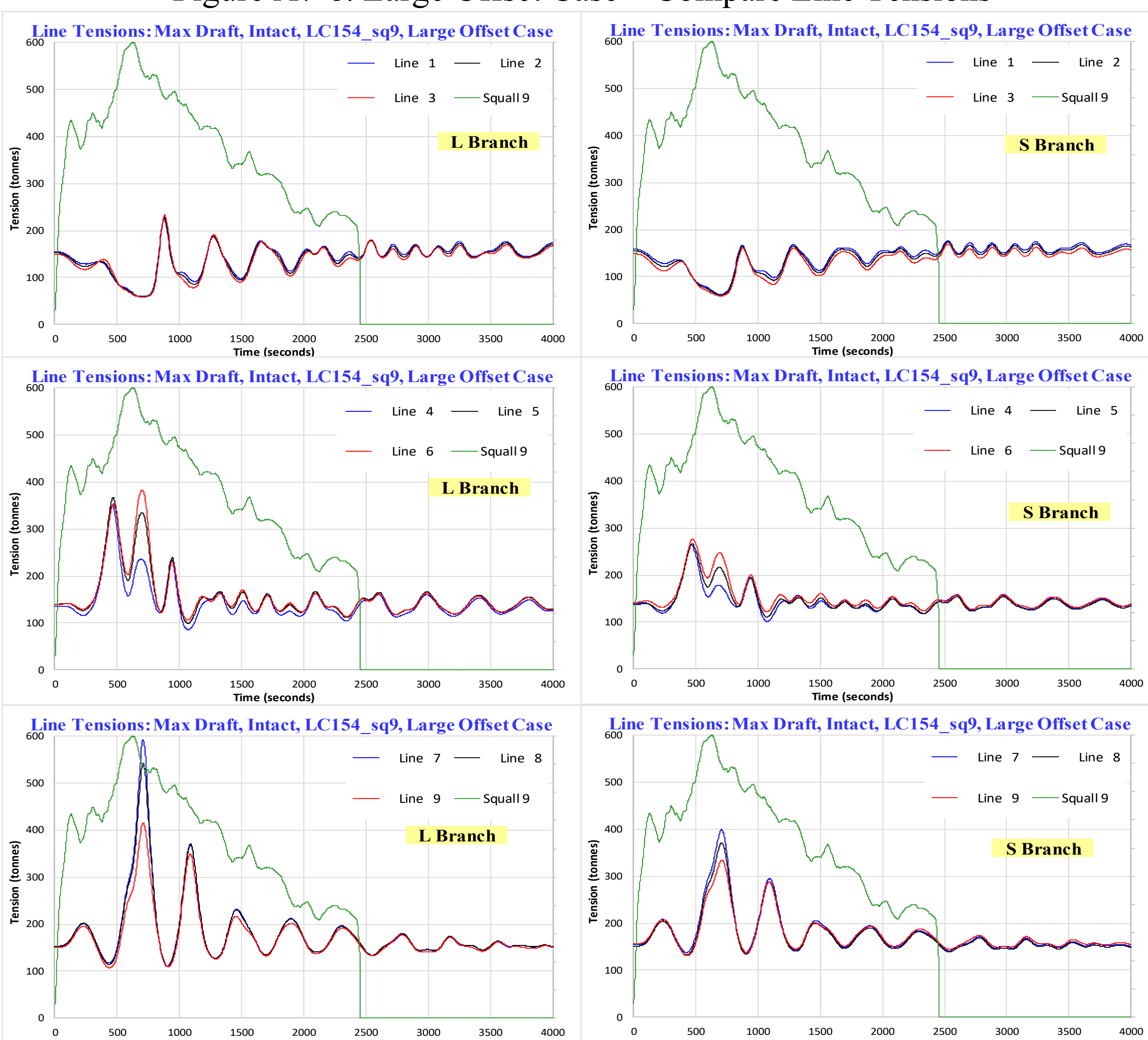


Figure A7-8. Large Offset Case – Compare Line Tensions



Appendix VIII

Squall Analysis Part 2: Summary of Intact Results for Maximum Draft and 100 Year Return Period Load Cases

This Appendix is devoted to the consequence of the SpinMoor "L" branch versus "S" branch bifurcation for a generic comprehensive design study for maximum draft and 100 year return period squalls across a universe of 9 squall profiles, each squall profile applied to ~ 1,000 cases {36 initial vessel headings x 29 squall approach directions} for a total of ~ 10,000 independent simulation runs. This universe of simulations was run twice: Once for each of SquallSim's "L" and "S" branches, which are again assumed to represent a suitable proxy for the average behavior of SpinMoor participant programs in each branch. Documentation of the analysis methodology behind the plots below can be found here: OSCR2018.

The two SquallSim branches use default SquallSim handling in all respects, including the important "added sway-yaw" damping properties. Those default damping properties derive directly from the OCIMF coefficients and have no user-adjustable components. As a result, there are no adjustable parameters in these simulation runs aside from the "L" or "S" branch designation.

The plots in Figures A8-1 to A8-4 below represent two different representations of the data for each of the "S" and "L" participant groupings; the "L" branch results follow those of the "S" branch in the plot ordering.

The scatter plots in Figures A8-1 and A8-3 comprise the ~ 10,000 estimated maximum line loads and maximum turret Rxy values. The "LF Tension" values comprise the low-frequency, quasi-static, component of the total line tension; the "NetMax" tension includes the wave-frequency [WF] contribution atop the LF baseline. Because the waves are modest, and approximately uncorrelated with the LF motions, WF tension contributions decline in relative significance with increasing LF tension, becoming, in effect, "noise" at the extreme tension events.

The second set of plot pairs in Figures A8-2 and A8-4 comprises contour maps of maximum offset and characteristic design tension as a function of initial vessel heading and squall direction, and demonstrates the complex topology of these design parameters in a circumstance where both initial vessel heading and squall directionality are varied independently, each extending to nearly 360 degrees.

From Figures A8-1 and A8-3 below, we see the ratio of the extreme "L" branch single line load to the extreme "S" branch load in the 10,000 simulation ensemble was (863/500) ~ 1.73. As in Appendix VII, we can infer, from a static offset analysis, that this 1.73 {L, S} branch single line load ratio will translate to a net turret load ratio of something around 2.0. Further, thanks to the exhaustive coverage of the dataset, we can state with confidence that the "worst case" squall events of Appendix VII have many "near neighbors". That is, the Appendix VII "worst case" events are not simply extreme outliers.

Figure A8-1

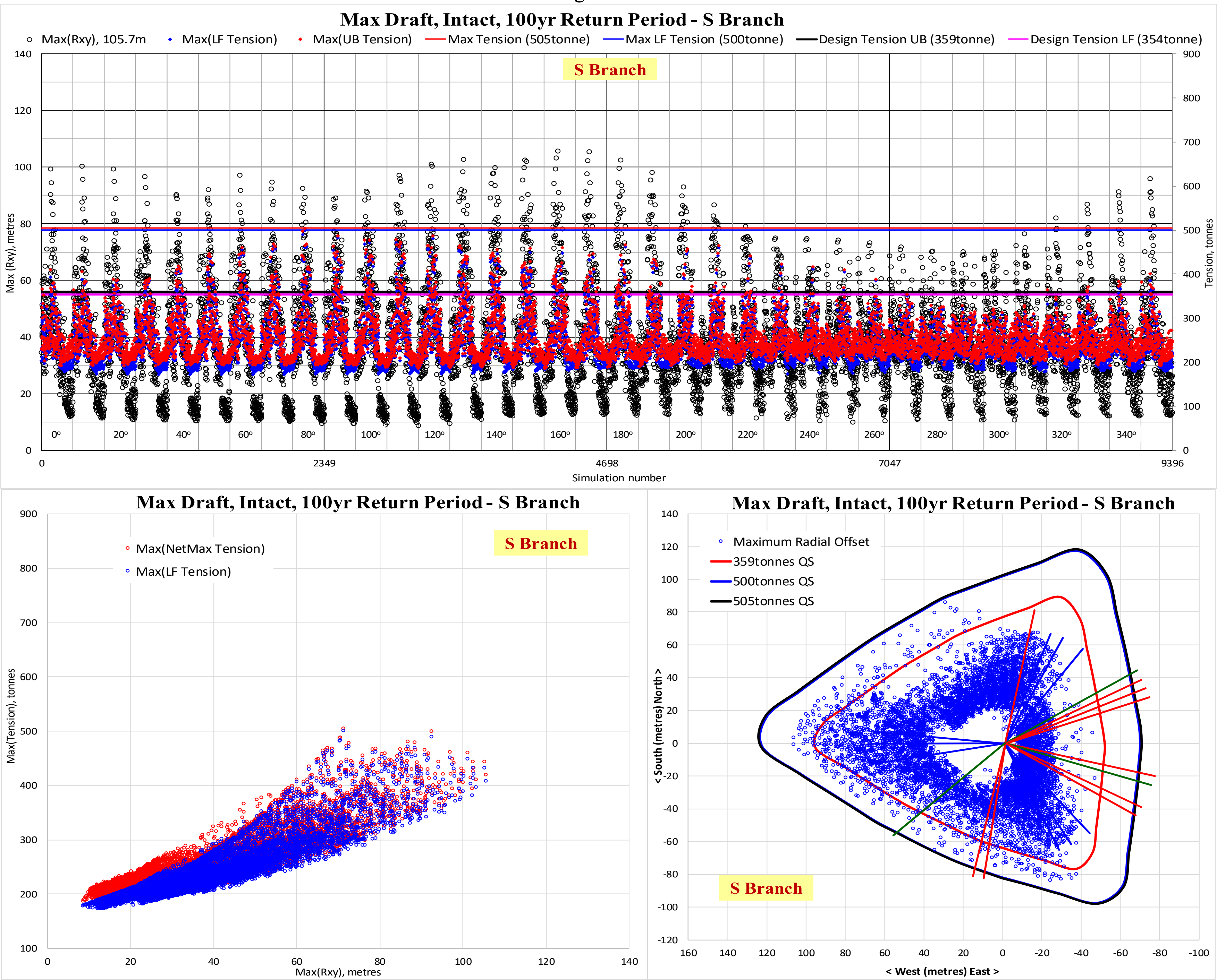
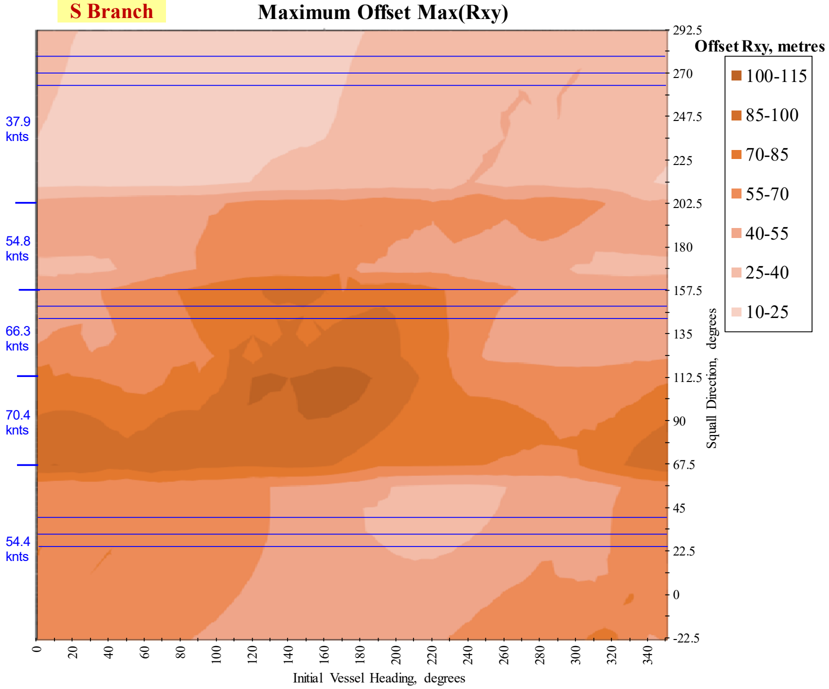

Max Draft, Intact, 100yr Return Period - S Branch
Max(Rxy), 105.7m
Max(LF Tension)
Max(UB Tension)
Max Tension (505tonne)
Max LF Tension (500tonne)
Design Tension UB (359tonne)
Design Tension LF (354tonne)
S Branch
Max (Rxy), metres
Tension, tonnes
Simulation number
0
2349
4698
7047
9396
0º
20º
40º
60º
80º
100º
120º
140º
160º
180º
200º
220º
240º
260º
280º
300º
320º
340º
Max Draft, Intact, 100yr Return Period - S Branch
Max(NetMax Tension)
Max(LF Tension)
S Branch
Max(Tension), tonnes
Max(Rxy), metres
Max Draft, Intact, 100yr Return Period - S Branch
Maximum Radial Offset
359tonnes QS
500tonnes QS
505tonnes QS
S Branch
< South (metres) North >
< West (metres) East >

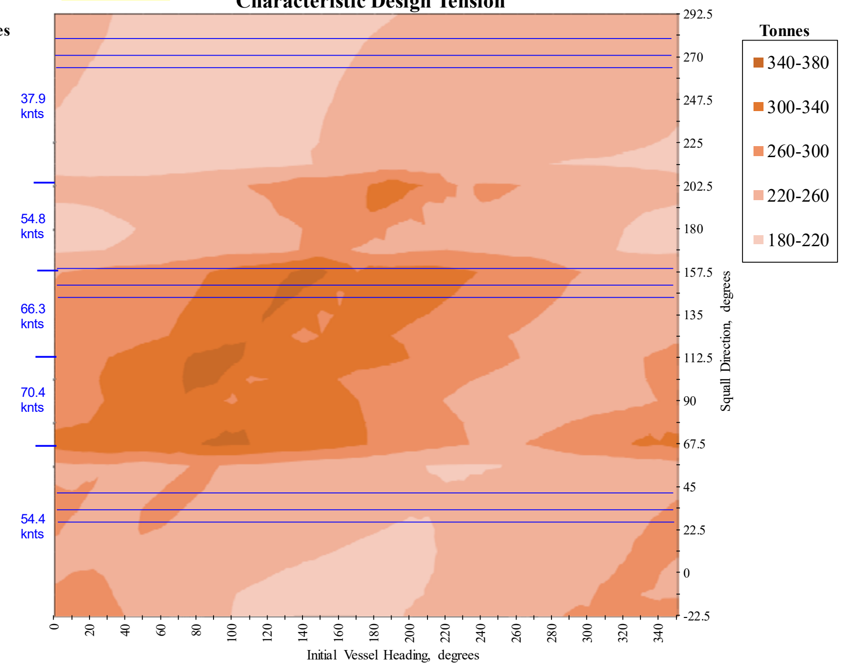
Figure A8-2

Max Draft, Intact, 100yr Return Period - S Branch

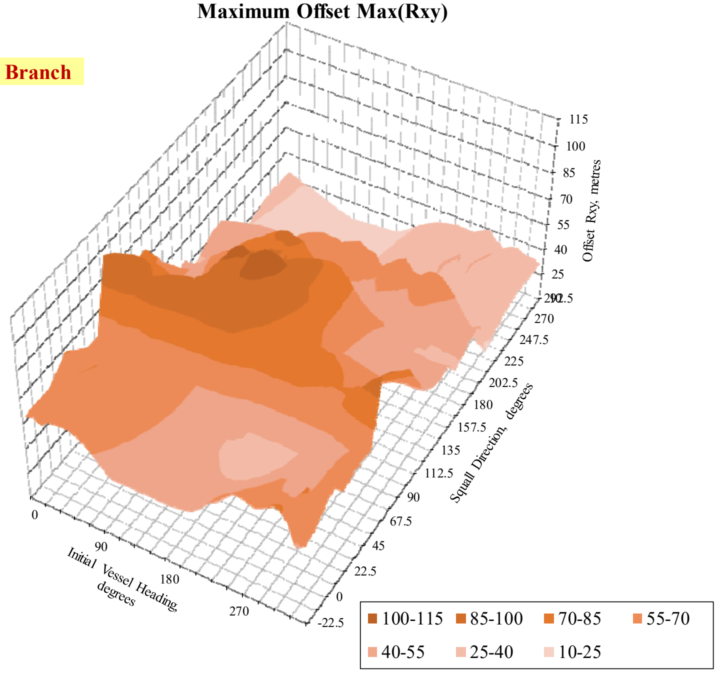
Maximum Offset Max(Rxy)



Characteristic Design Tension



Maximum Offset Max(Rxy)



Characteristic Design Tension

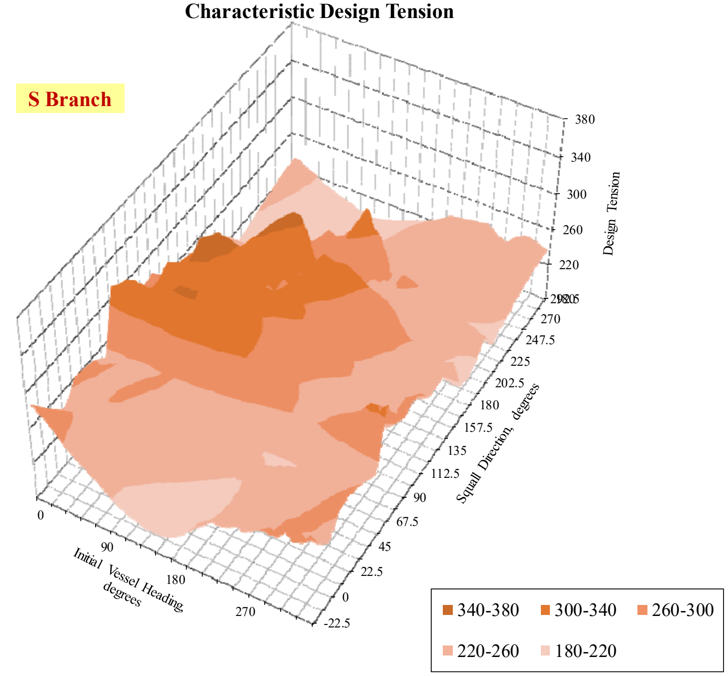


Figure A8-3

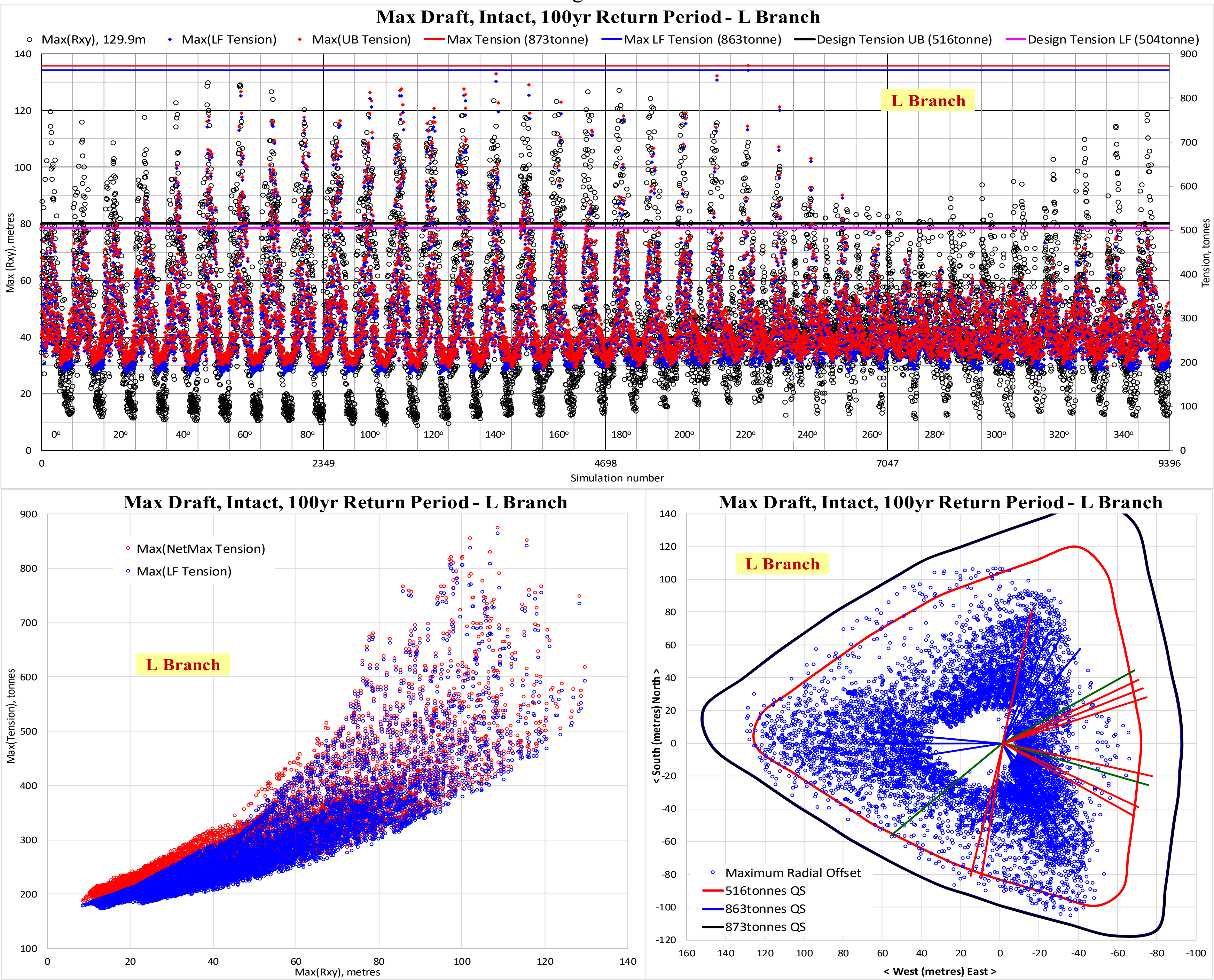
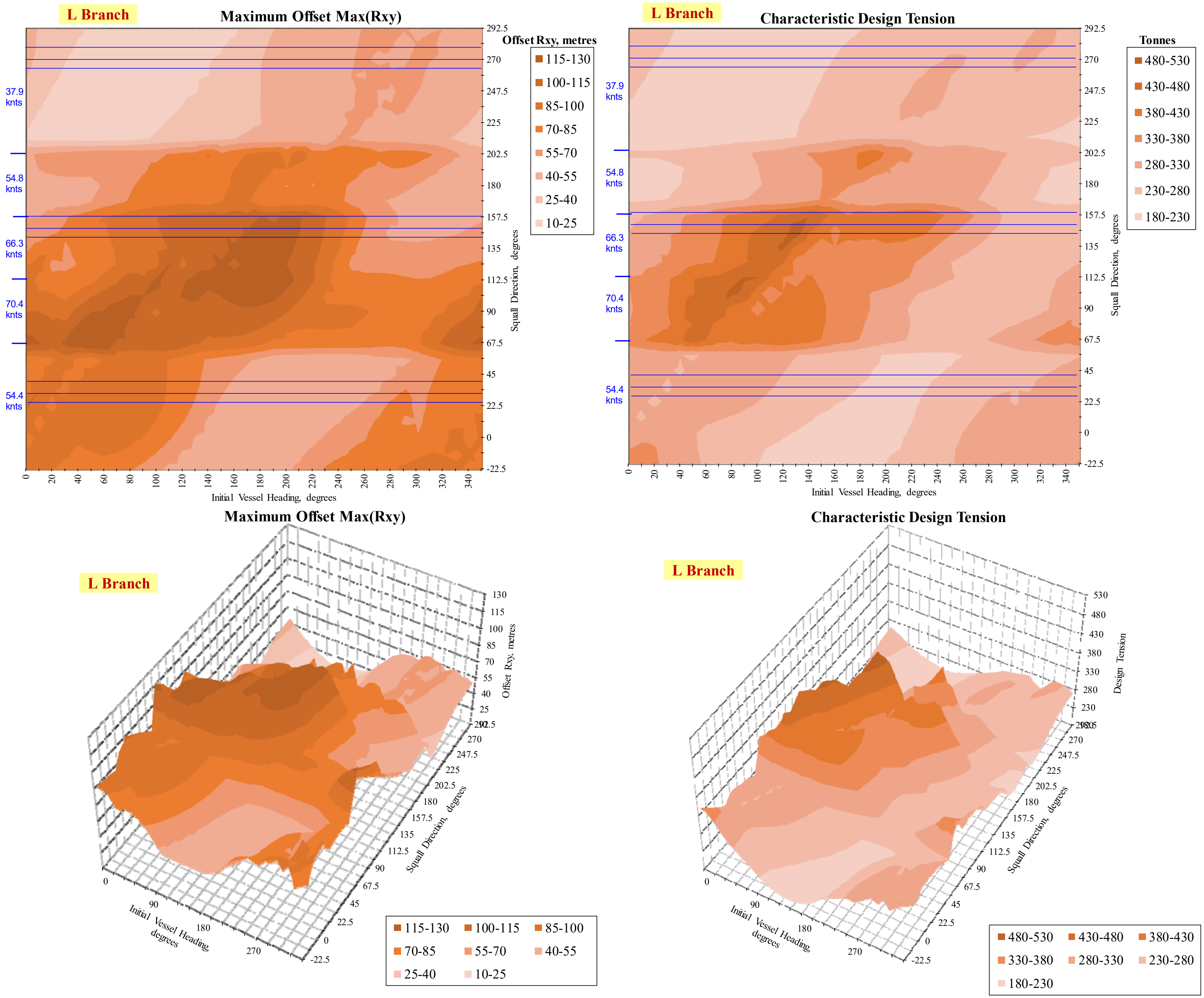

Max Draft, Intact, 100yr Return Period - L Branch
Max(Rxy), 129.9m
Max(LF Tension)
Max(UB Tension)
Max Tension (873tonne)
Max LF Tension (863tonne)
Design Tension UB (516tonne)
Design Tension LF (504tonne)
L Branch
Max (Rxy), metres
Tension, tonnes
Simulation number
0 2349 4698 7047 9396
0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260° 280° 300° 320° 340°
Max Draft, Intact, 100yr Return Period - L Branch
Max(NetMax Tension)
Max(LF Tension)
L Branch
Max(Tension), tonnes
Max(Rxy), metres
Max Draft, Intact, 100yr Return Period - L Branch
L Branch
Maximum Radial Offset
516tonnes QS
863tonnes QS
873tonnes QS
< South (metres) North >
< West (metres) East >

Figure A8-4

Max Draft, Intact, 100yr Return Period - L Branch



Appendix IX

Squall Analysis Part 3: Summary of Intact Results for Three Drafts and 1 to 1,000 Year Return Period Load Cases

It is commonly believed that the analysis and testing of squall scenarios for weather-vane capable moorings need only include the lightest ballast draft condition, regardless of environmental intensity (quantified in this instance by the maximum squall speed and "acceleration", or speed ramp up rate, of the squall speed versus time profile). The logic for this intuition is compelling: small draft results in higher mooring pretensions (and associated increased mooring force fluctuations), and the greatest wind areas, both longitudinal and lateral, producing greater wind forces and greater energy transfer from the squall to the vessel, which energy must ultimately be absorbed by the moorings.

We wish to test the "ballast draft governs mooring design" notion for realistic squalls across the two branches of the SpinMoor Study. Once again, we use SquallSim's "L" and "S" branches, again assumed to be reasonable proxies for the average behavior of SpinMoor participant programs in each {L, S} branch. We also again call upon the environmental dataset technology outlined in OSRC2018 as our source of data.

The simplest set of meaningful metrics for this sub-study are, as usual, the maximum predicted offsets and characteristic design line loads across the dataset of ~ 10,000 cases per draft and per return period. In this case, we wish to expand the investigation to span 3 orders of magnitude in the return periods (to {1, 10, 100, and 1,000} years), and investigate the dependence of the maximum load metric upon the squall intensity variable in addition to the draft.

Note: The "Max Rxy" offset metric is of marginal value for this particular highly asymmetric triangular mooring layout; this layout possesses three "soft" directions that will always collect the maximum offset events, which events will therefore correlate poorly with maximum line load events which comprise our central focus. More information regarding the shape of the offset envelope can be found in Appendices VII and VIII.

The results are summarized in the top tables of Figures A9-1 and A9-2; the first is for the "S" SpinMoor group, the second for the "L" group.

The first qualitative observation is surprising and counter-intuitive, like the SpinMoor grouping itself. Using the maximum Top Chain loads across the dataset as our "load" metric we see, for the "S" branch of the SpinMoor groups, Figure A9-1, a *weak* but steady progression in Top Chain maximum load with decreasing draft, in line with the intuitive argument of the first paragraph above. That weak progression somewhat mysteriously breaks down between 100 and 1,000 year return periods. The metrics for turret *offset* using this "S" branch analysis, across all return periods, are very similar for maximum and mid drafts, and somewhat smaller for the minimum draft.

In contrast to the "S" branch behavior, the "L" branch, Figure A9-2, of the SpinMoor group shows, for the longer return periods (100 and 1,000 years) exactly the reverse: Markedly relatively *decreasing* maximum tensions with decreasing draft. The milder environments in branch "L" (1 and 10 year return periods) are somewhat mixed; this presumably arises from the competing influence of increasing pretensions (associated with shallower drafts), and the underlying dynamical "L" branch tendency of *smaller* loads for lesser drafts. That competition arises as follows: For weak environments, the increase in mooring pretension with decreasing draft overcomes the underlying dynamical trend of reduced load variability with decreasing draft; in the more extreme 100 and 1000 year environments, pretension increases, which are independent of environment, become overwhelmed by the dynamical decrease in load variability with decreasing draft. Even more interesting, the Max Rxy metric in the "L" branch is in lock step with the maximum load metric's draft dependence, decreasing with decreasing draft. This trend contrasts with the behavior of the Max Rxy metric for the "S" branch, which is rather indifferent to vessel draft.

Figure A9-1

Max Draft, Intact: 1 to 1,000yr Return Periods - S Branch

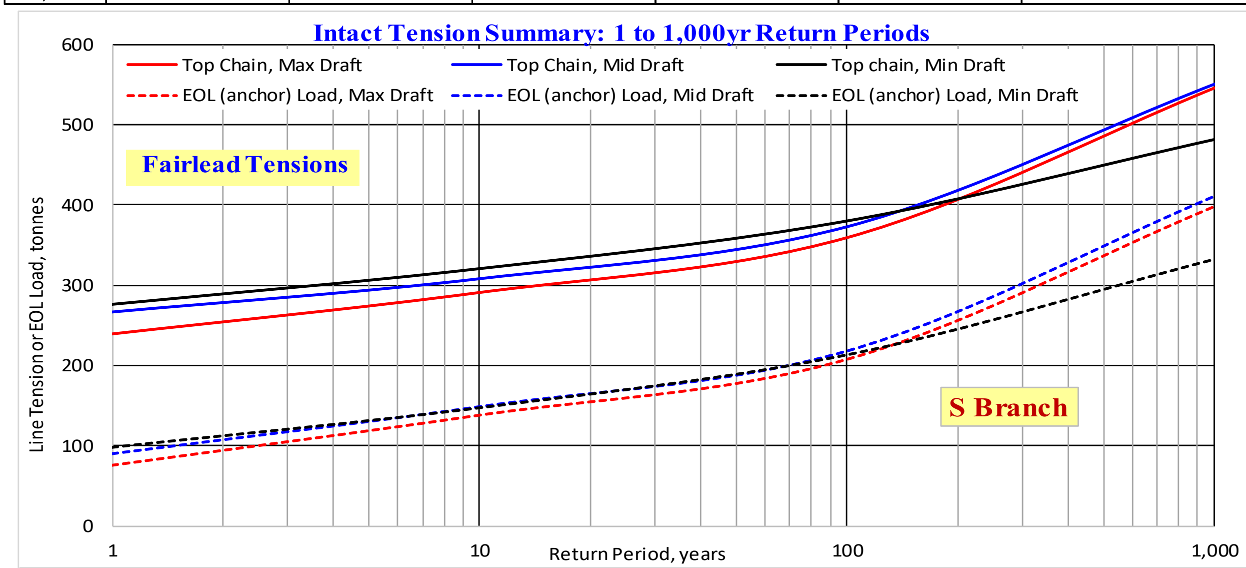
Return Period	Max. Turret Offset		Maximum Line Tensions						Maximum EOL (anchor) Load		Minimum Grounded Length	
	Tension Contour	Max all Rxy	Top Chain		SS-wire		Bottom Chain					
years	m	m	tonne	location	tonne	location	tonne	location	tonne	location	m	location
1	57	53	239	Line 8	211	Line 3	196	Line 3	75	Line 5	281	Line 6
10	76	79	290	Line 5	265	Line 5	251	Line 5	138	Line 5	209	Line 6
100	95	106	359	Line 5	334	Line 5	320	Line 5	208	Line 5	122	Line 6
1,000	131	131	545	Line 4	521	Line 4	507	Line 4	399	Line 4	0	Line 4 & 1 others

Mid Draft, Intact: 1 to 1,000yr Return Periods - S Branch

Return Period	Max. Turret Offset		Maximum Line Tensions						Maximum EOL (anchor) Load		Minimum Grounded Length	
	Tension Contour	Max all Rxy	Top Chain		SS-wire		Bottom Chain					
years	m	m	tonne	location	tonne	location	tonne	location	tonne	location	m	location
1	61	54	266	Line 3	239	Line 3	224	Line 3	90	Line 5	248	Line 6
10	75	79	308	Line 8	281	Line 5	267	Line 5	149	Line 5	184	Line 6
100	93	105	373	Line 5	347	Line 5	334	Line 5	218	Line 5	99	Line 6
1,000	127	128	551	Line 4	528	Line 4	515	Line 4	411	Line 4	0	Line 4 & 2 others

Min Draft, Intact: 1 to 1,000yr Return Periods - S Branch

Return Period	Max. Turret Offset		Maximum Line Tensions						Maximum EOL (anchor) Load		Minimum Grounded Length	
	Tension Contour	Max all Rxy	Top Chain		SS-wire		Bottom Chain					
years	m	m	tonne	location	tonne	location	tonne	location	tonne	location	m	location
1	60	50	276	Line 3	250	Line 3	235	Line 3	97	Line 5	236	Line 6
10	74	75	321	Line 8	293	Line 8	278	Line 8	147	Line 5	175	Line 6
100	91	98	380	Line 7	354	Line 7	339	Line 7	213	Line 4	98	Line 6
1,000	121	121	481	Line 4	457	Line 4	443	Line 4	333	Line 4	0	Line 4 & 2 others



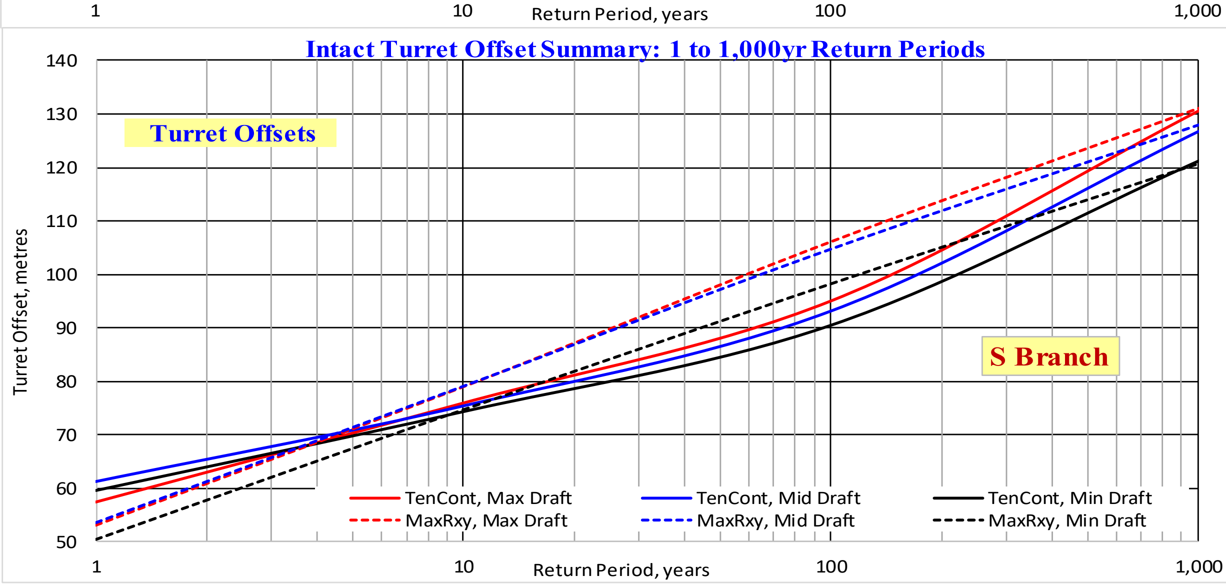


Figure A9-2

Max Draft, Intact: 1 to 1,000yr Return Periods - L Branch

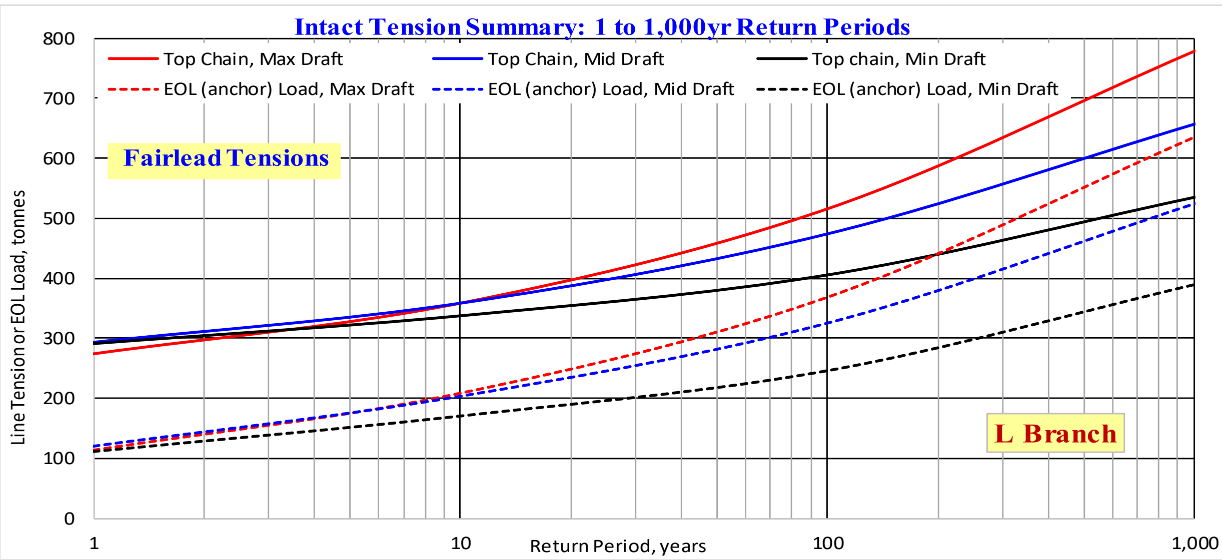
Return Period	Max. Turret Offset		Maximum Line Tensions						Maximum EOL (anchor) Load		Minimum Grounded Length	
	Tension Contour	Max all Rxy	Top Chain		SS-wire		Bottom Chain					
years	m	m	tonne	location	tonne	location	tonne	location	tonne	location	m	location
1	71	74	275	Line 1	249	Line 1	234	Line 1	114	Line 5	238	Line 6
10	95	102	359	Line 4	334	Line 4	320	Line 4	209	Line 4	124	Line 4
100	126	130	516	Line 4	491	Line 4	478	Line 4	369	Line 4	0	Line 4 & 2 others
1,000	151	158	778	Line 6	754	Line 6	742	Line 6	636	Line 6	0	Line 4 & 5 others

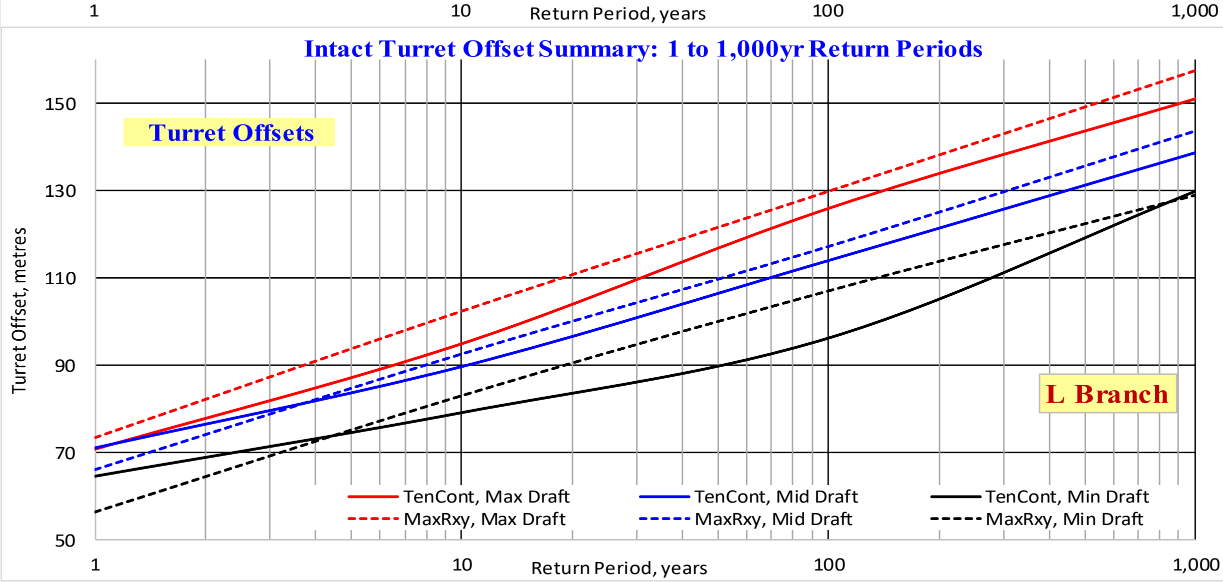
Mid Draft, Intact: 1 to 1,000yr Return Periods - L Branch

Return Period	Max. Turret Offset		Maximum Line Tensions						Maximum EOL (anchor) Load		Minimum Grounded Length	
	Tension Contour	Max all Rxy	Top Chain		SS-wire		Bottom Chain					
years	m	m	tonne	location	tonne	location	tonne	location	tonne	location	m	location
1	71	66	294	Line 1	267	Line 1	253	Line 3	120	Line 5	216	Line 6
10	90	93	359	Line 5	334	Line 5	320	Line 5	204	Line 5	121	Line 5
100	114	117	475	Line 5	450	Line 5	437	Line 5	326	Line 5	0	Line 4 & 2 others
1,000	139	144	657	Line 4	635	Line 4	623	Line 4	525	Line 4	0	Line 4 & 5 others

Min Draft, Intact: 1 to 1,000yr Return Periods - L Branch

Return Period	Max. Turret Offset		Maximum Line Tensions						Maximum EOL (anchor) Load		Minimum Grounded Length	
	Tension Contour	Max all Rxy	Top Chain		SS-wire		Bottom Chain					
years	m	m	tonne	location	tonne	location	tonne	location	tonne	location	m	location
1	65	56	291	Line 3	264	Line 3	250	Line 3	112	Line 5	220	Line 6
10	79	83	337	Line 8	310	Line 8	295	Line 8	171	Line 5	151	Line 6
100	96	107	405	Line 8	379	Line 8	365	Line 8	247	Line 4	62	Line 6
1,000	130	129	535	Line 4	511	Line 4	498	Line 4	390	Line 4	0	Line 4 & 2 others





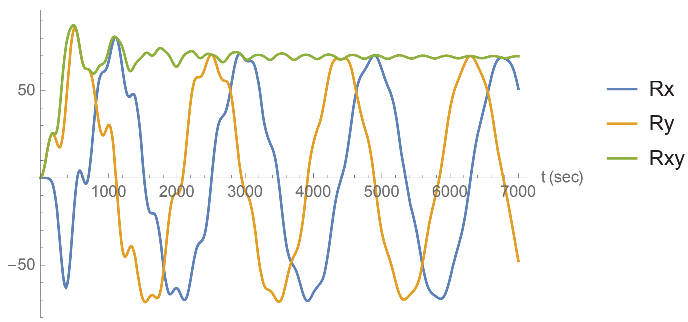
Appendix X

Per-Participant Graphical Summaries

Visualizations of the vessel motions for each of the ten Participants are provided on the following pages.

Results for both 100% and 40% loaded cases are included.

Partcipant_1
100% Loaded



Partcipant_1
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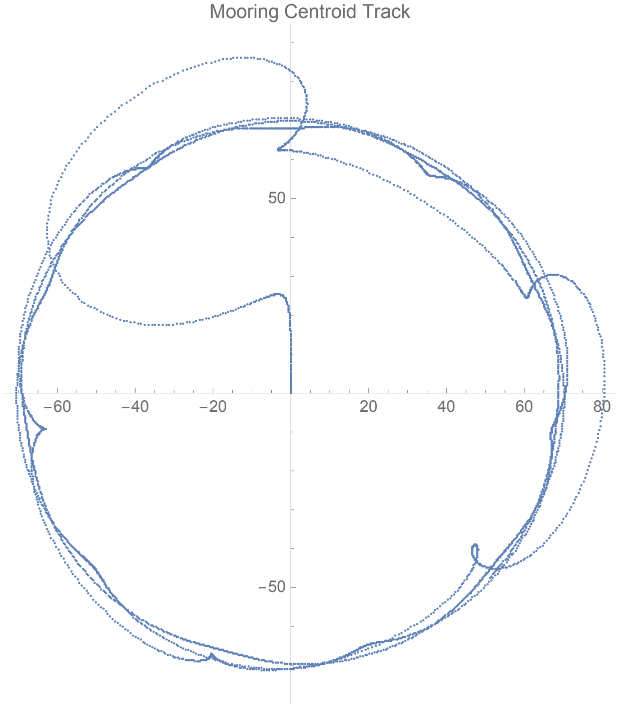
Mooring Centroid Track



Partcipant_1
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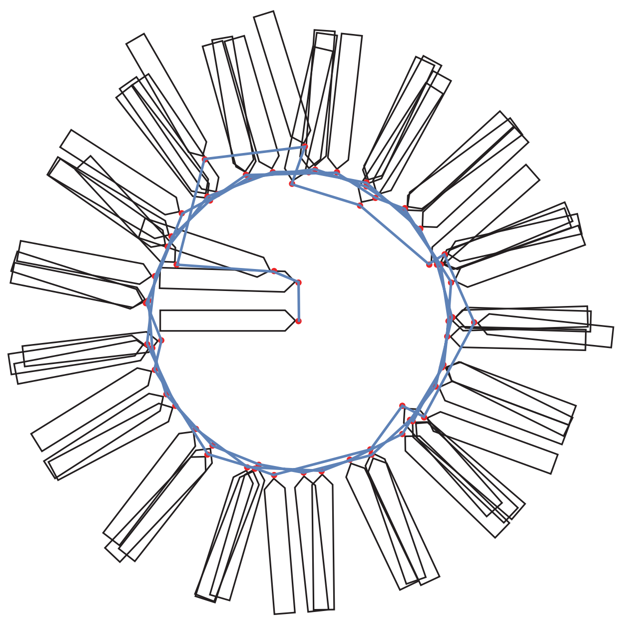
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



Partcipant_1
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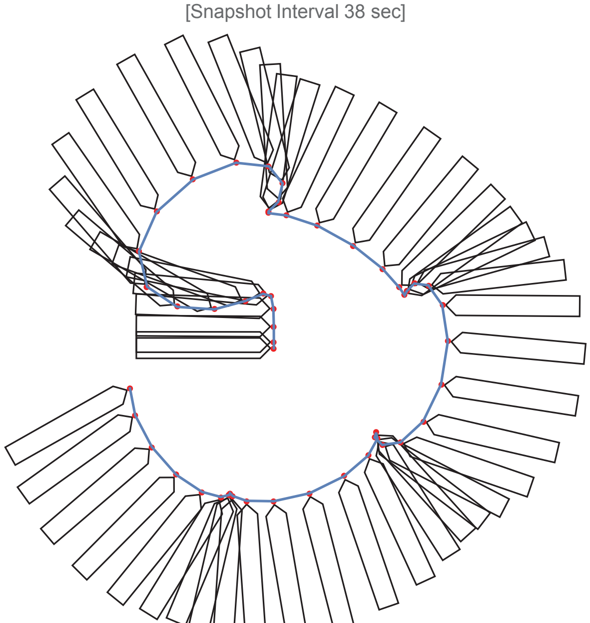
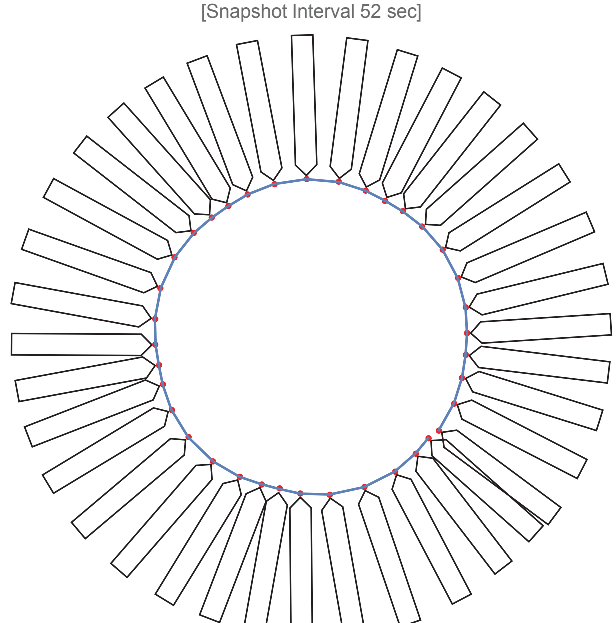
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



Partcipant_1
100% Loaded
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]



Partcipant_2
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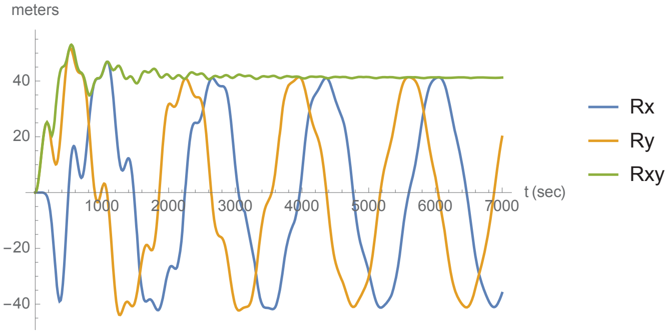

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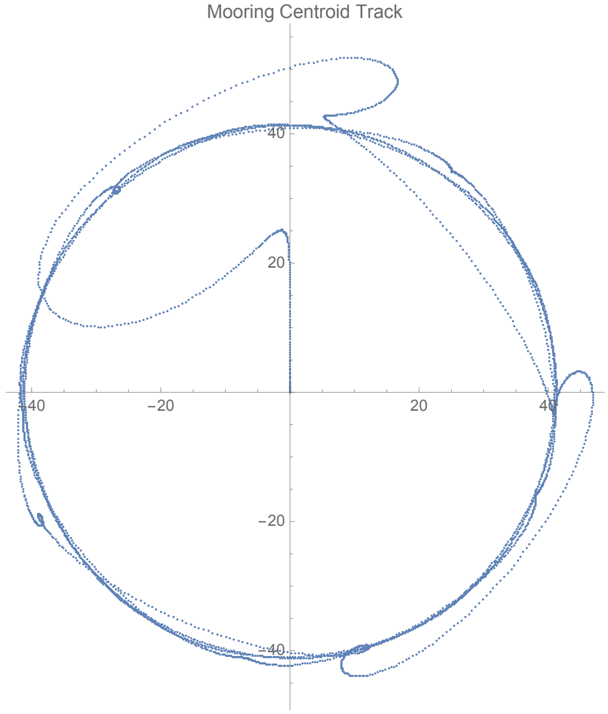
Mooring Centroid Track



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Full Duration Vessel Strobe Images
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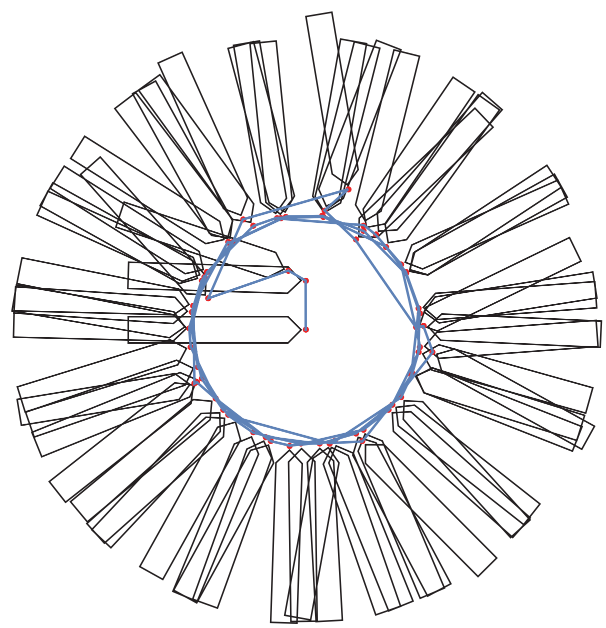
[Snapshot Interval 111 sec]



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Startup Vessel Strobe Images
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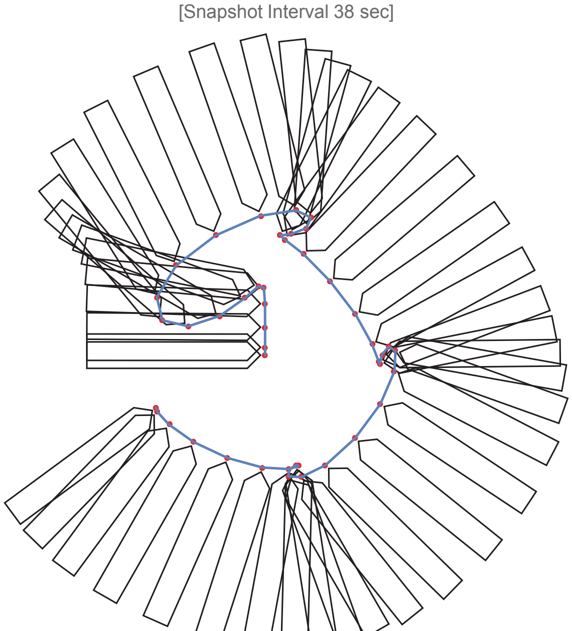

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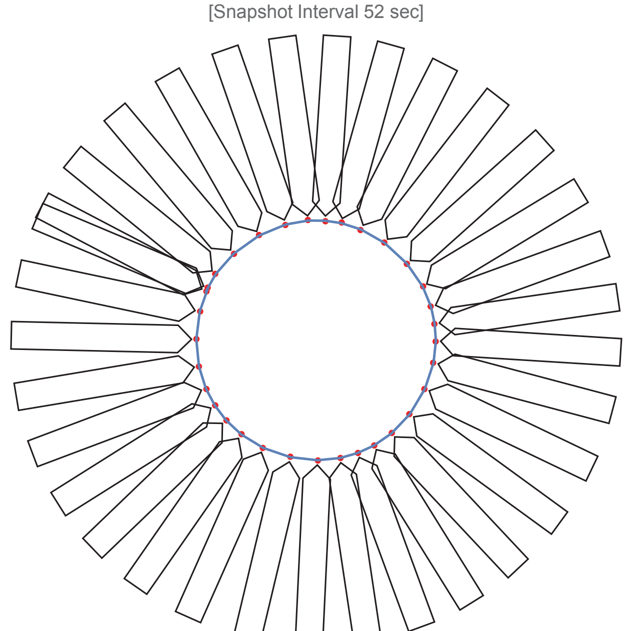
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]



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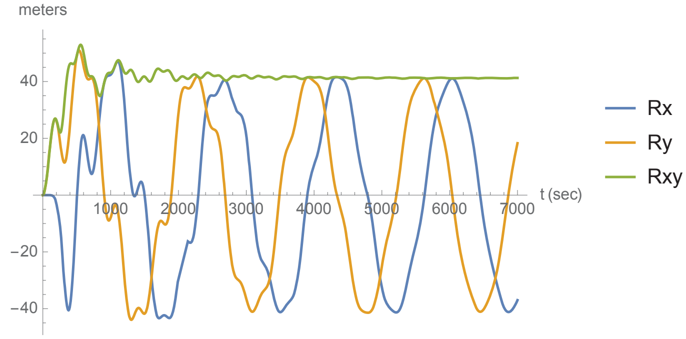

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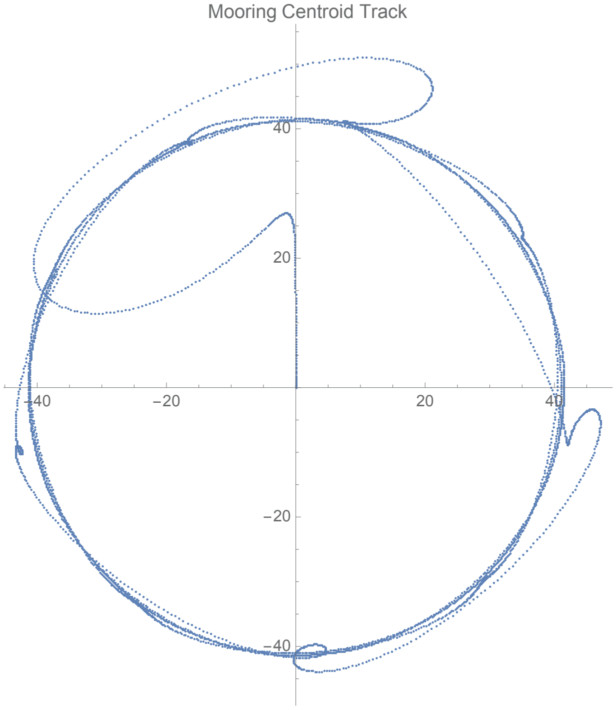
Mooring Centroid Track



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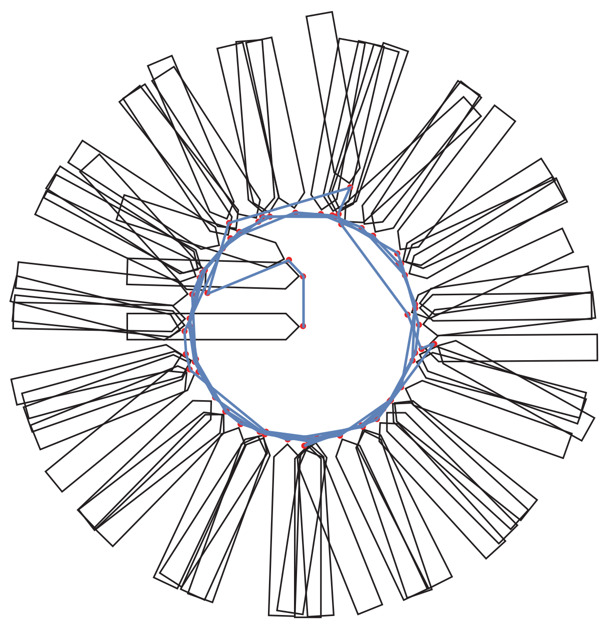
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



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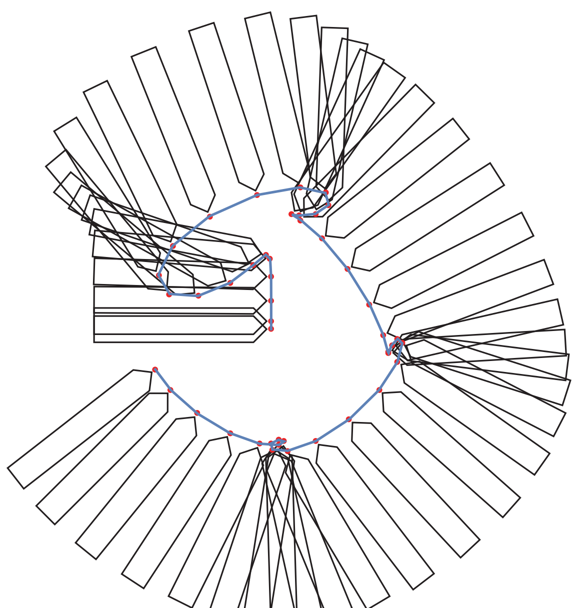
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



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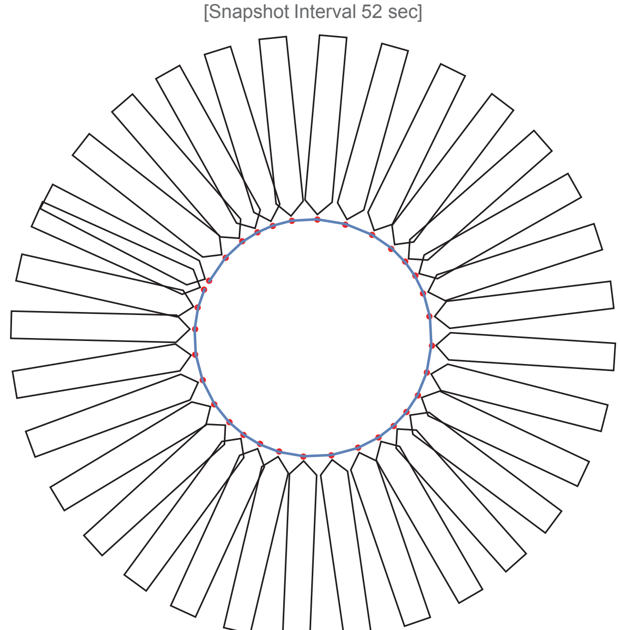
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]



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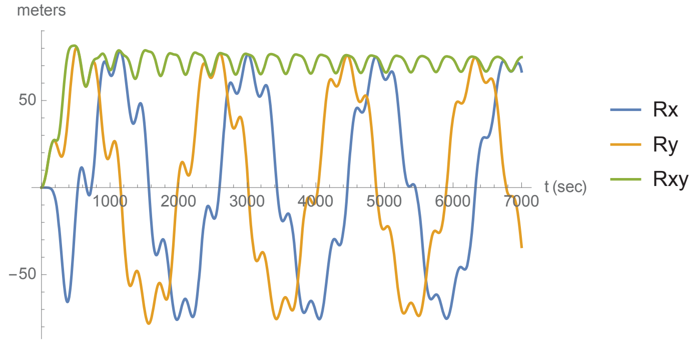

Partcipant_4
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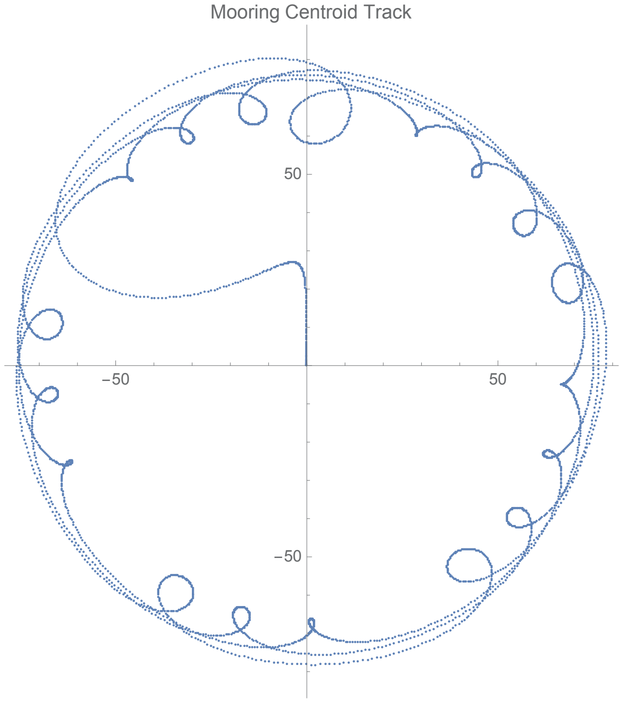
Mooring Centroid Track



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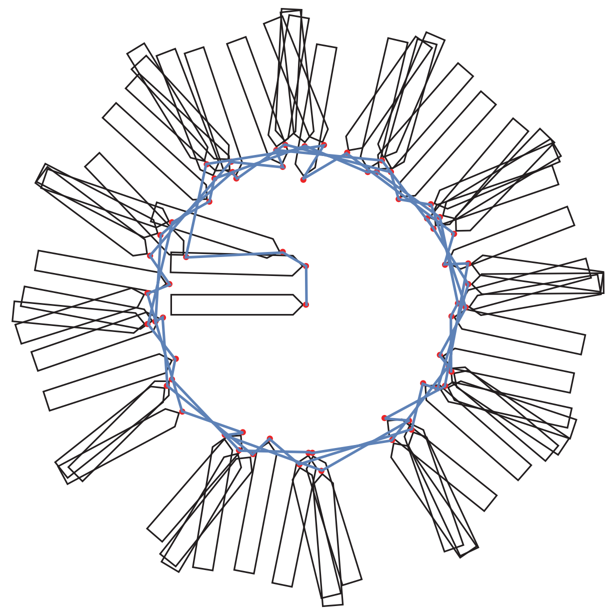
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



Partcipant_4
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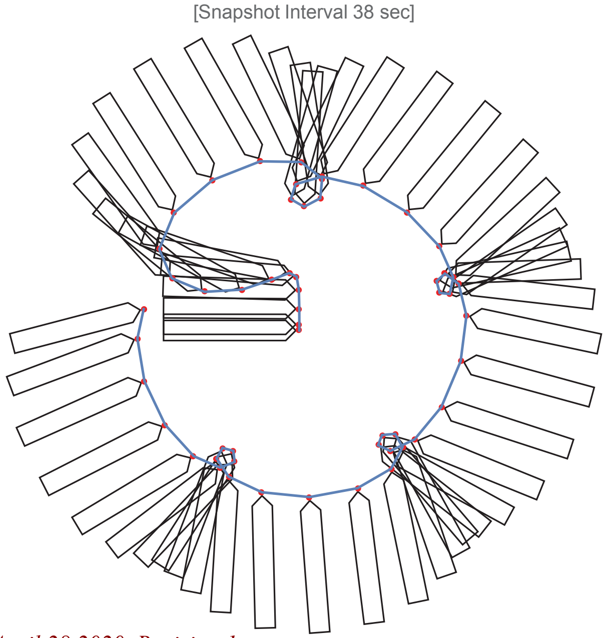
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



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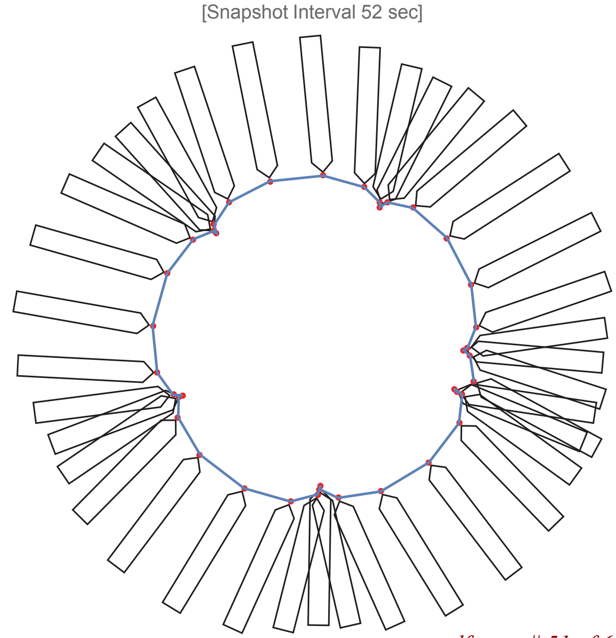
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]



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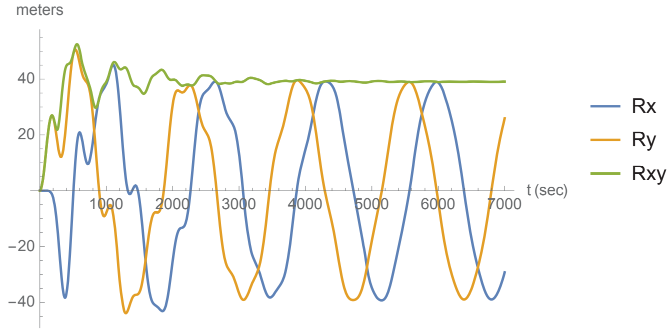

Partcipant_5
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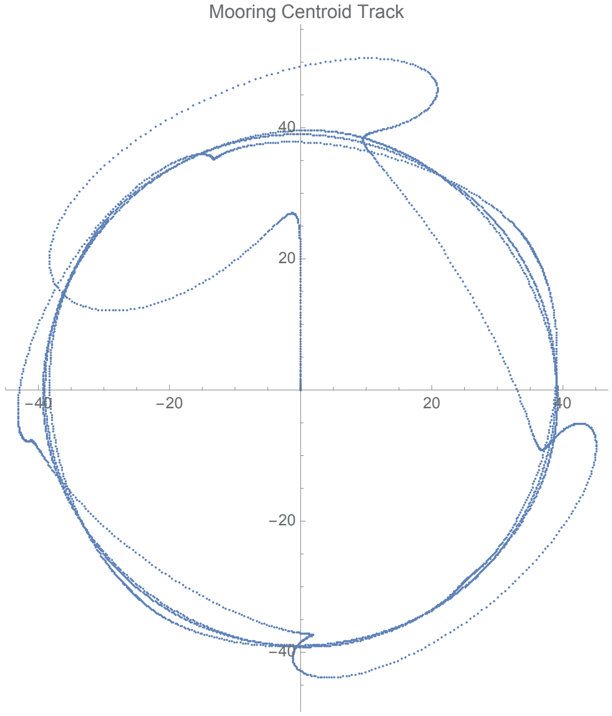
Mooring Centroid Track



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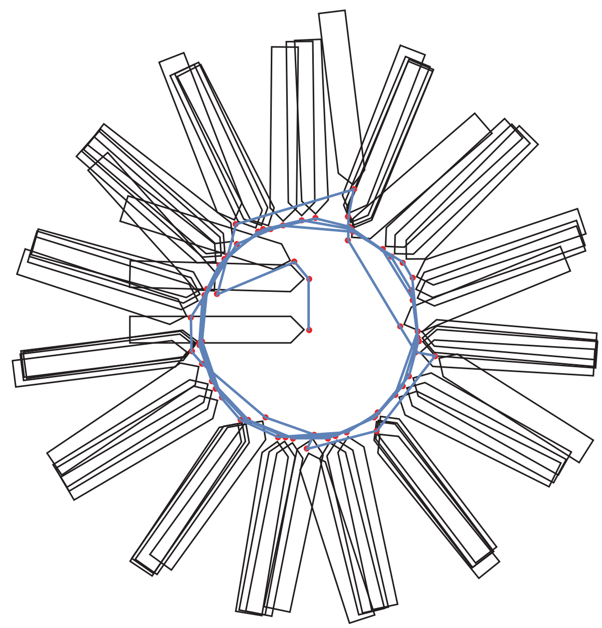
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



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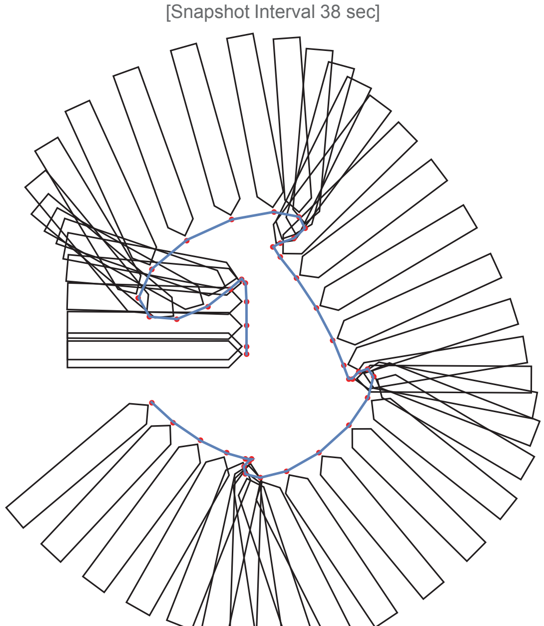
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



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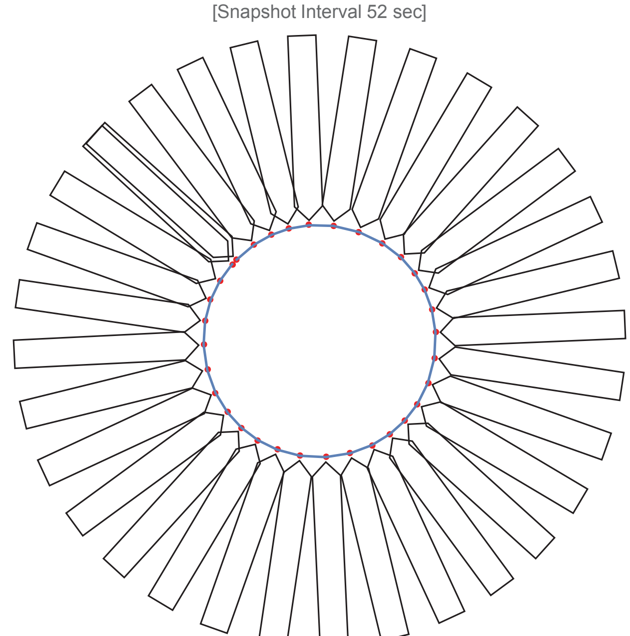
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]



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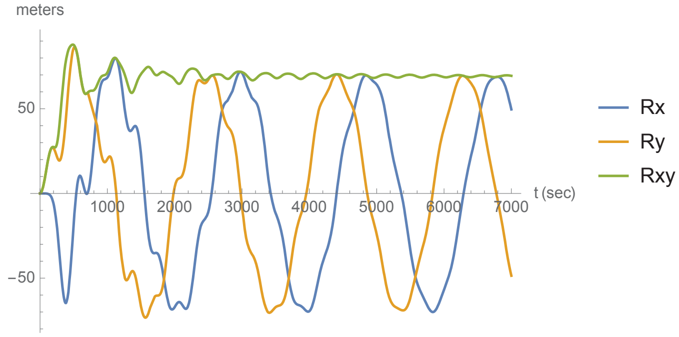

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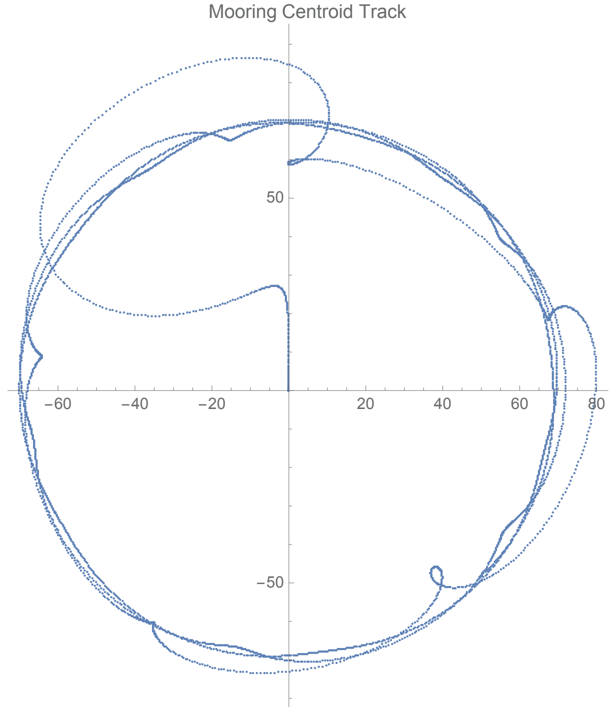
Mooring Centroid Track



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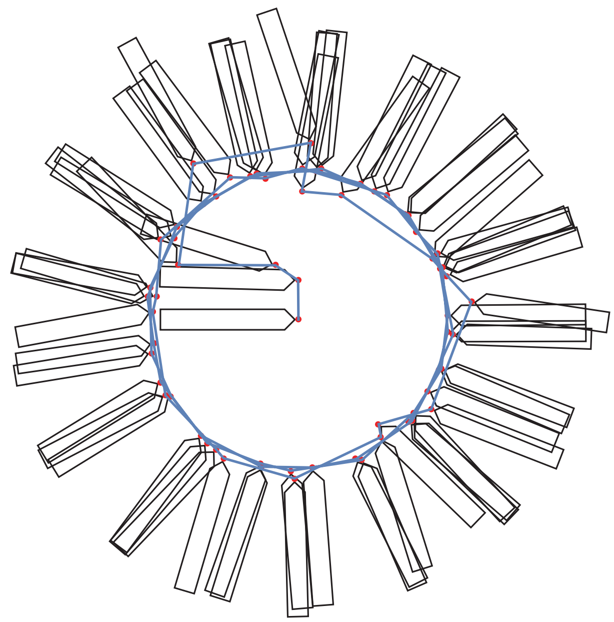
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



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[Relative Vessel Scale 1/5
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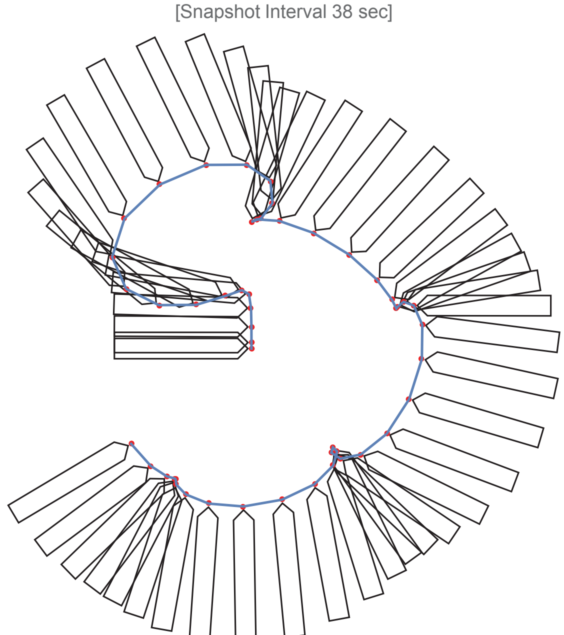

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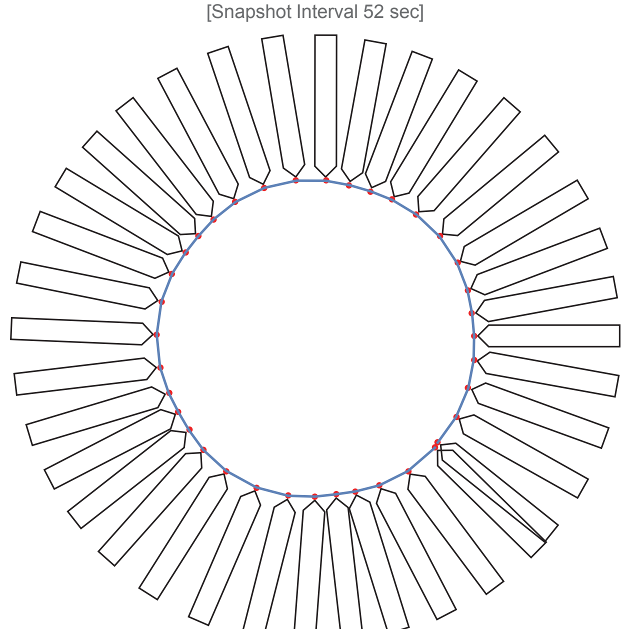
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]



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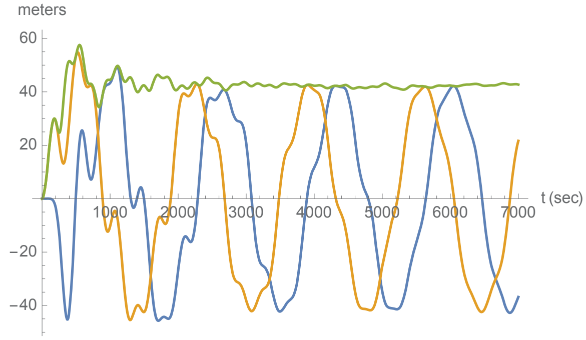

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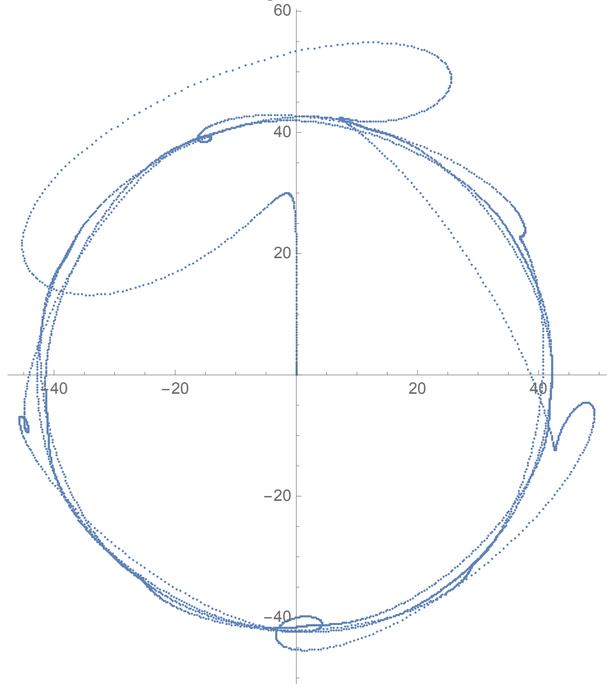
Mooring Centroid Track



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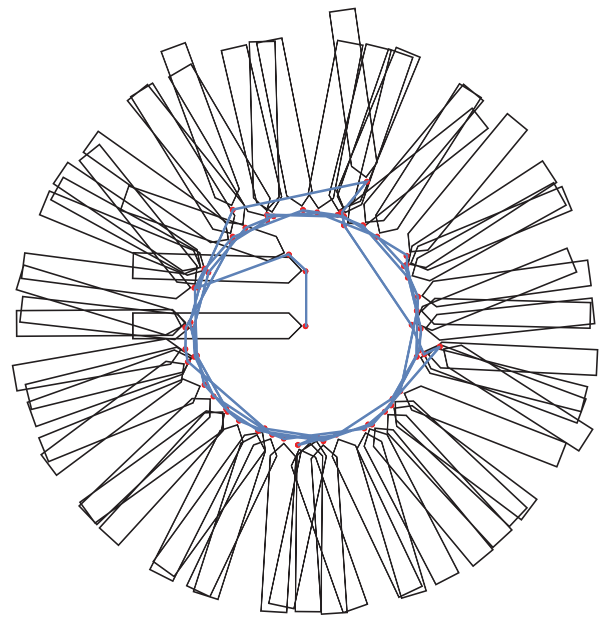
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



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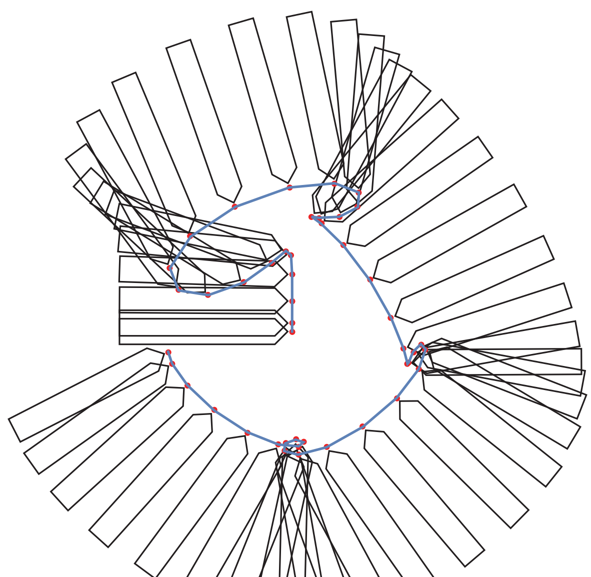
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



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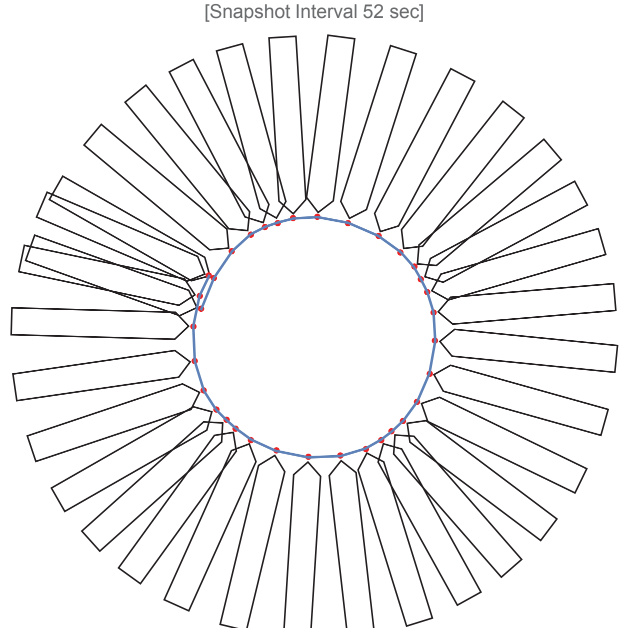
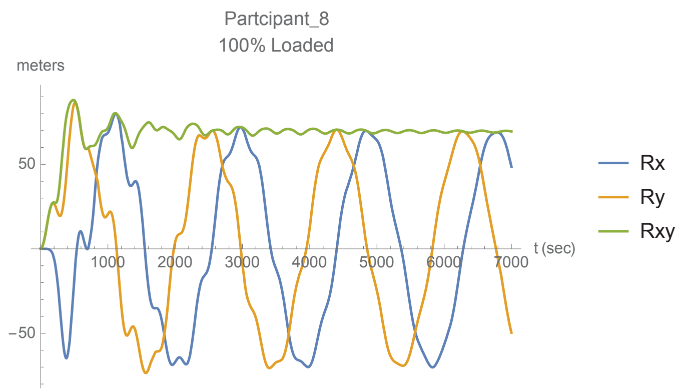
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]




Partcipant_8
100% Loaded
meters
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t (sec)
Rx
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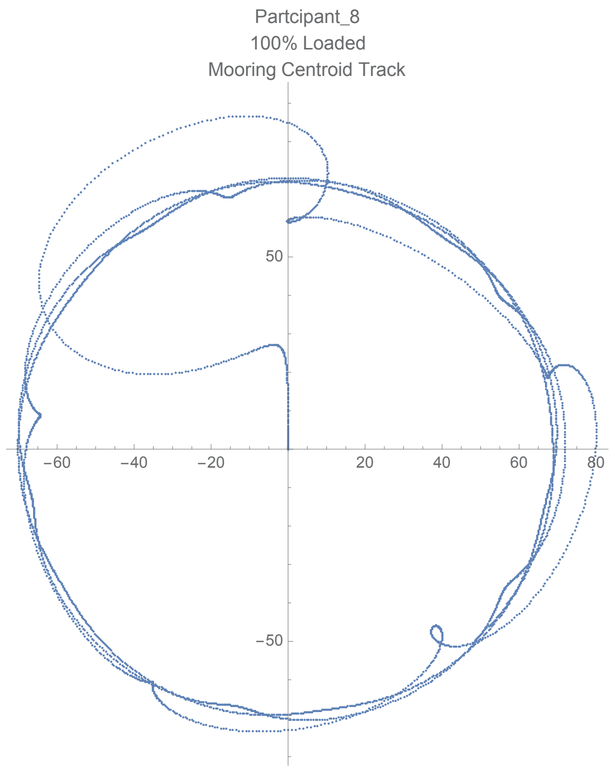
Partcipant_8
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Mooring Centroid Track
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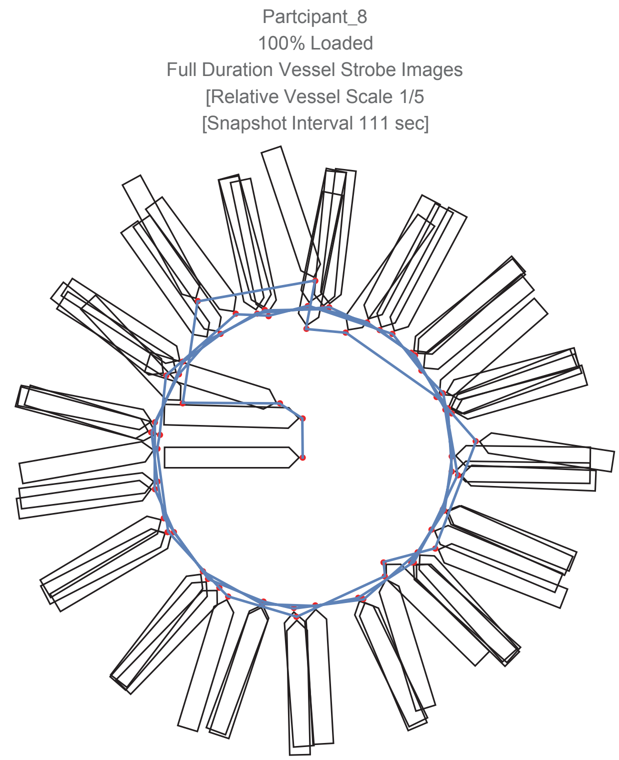
80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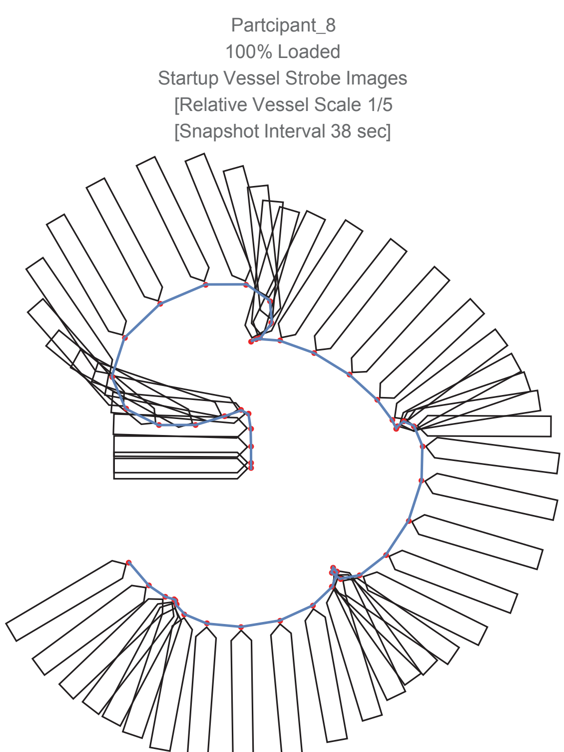
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]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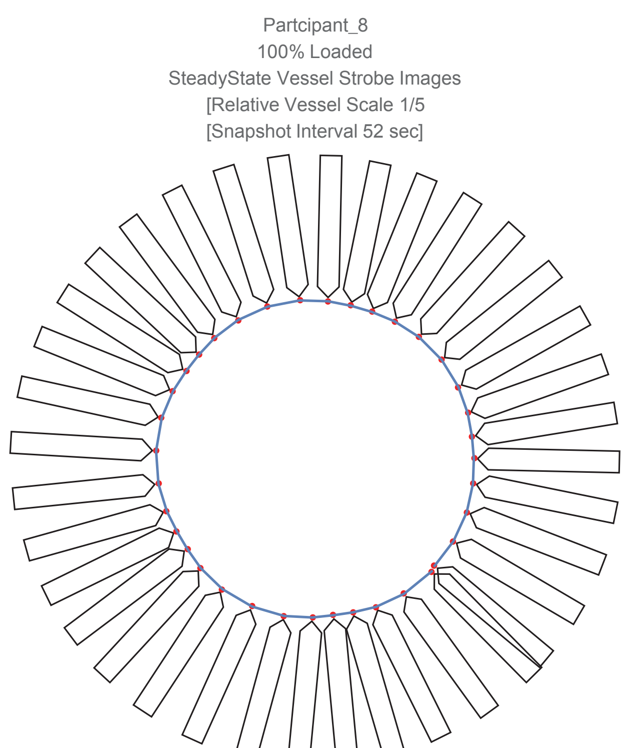
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]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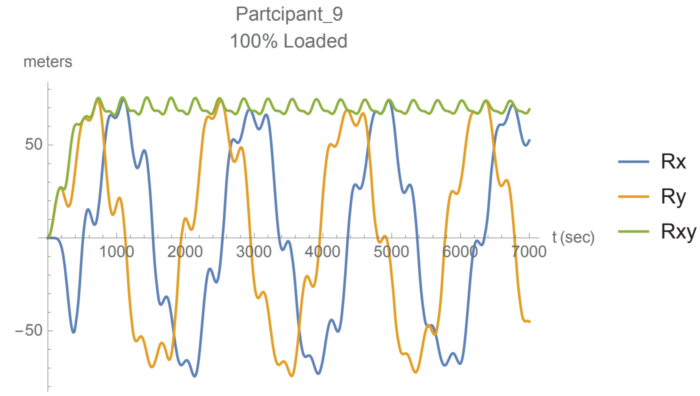
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]


Partcipant_9
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meters
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Rx
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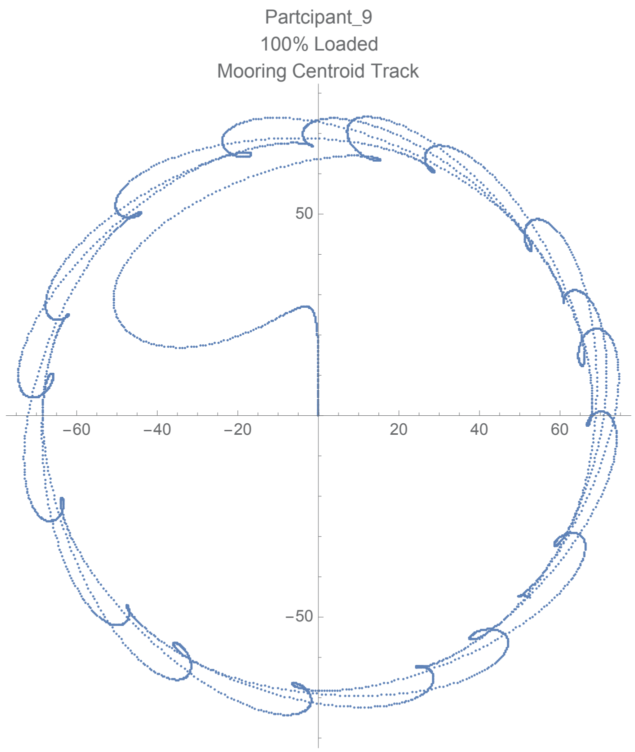
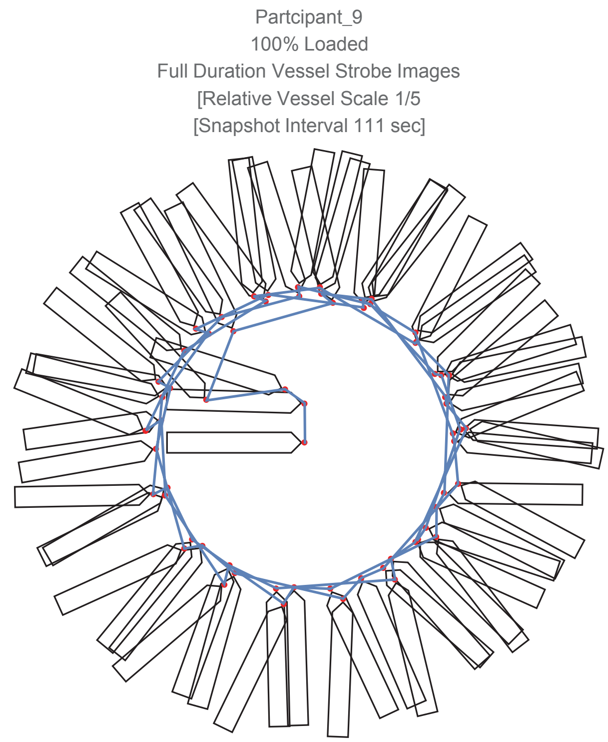
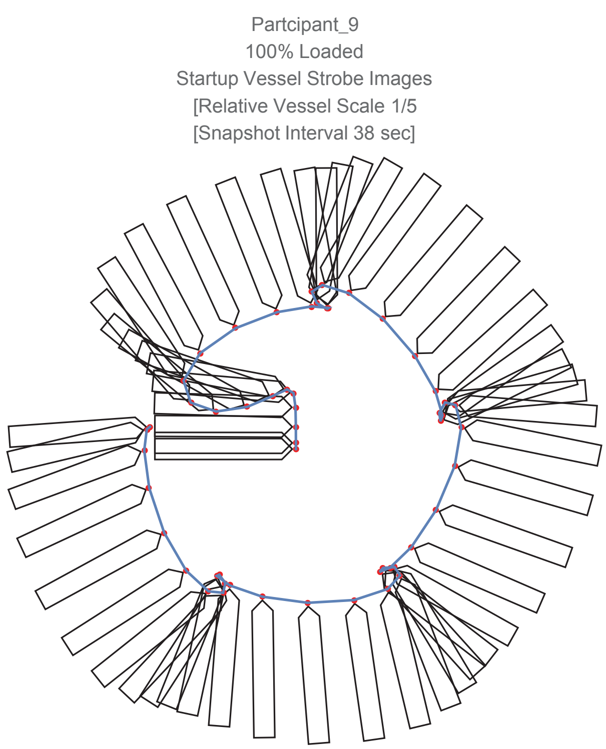

Partcipant_9
100% Loaded
Mooring Centroid Track
50
−50
−60
−40
−20
20
40
60


Partcipant_9
100% Loaded
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]


Partcipant_9
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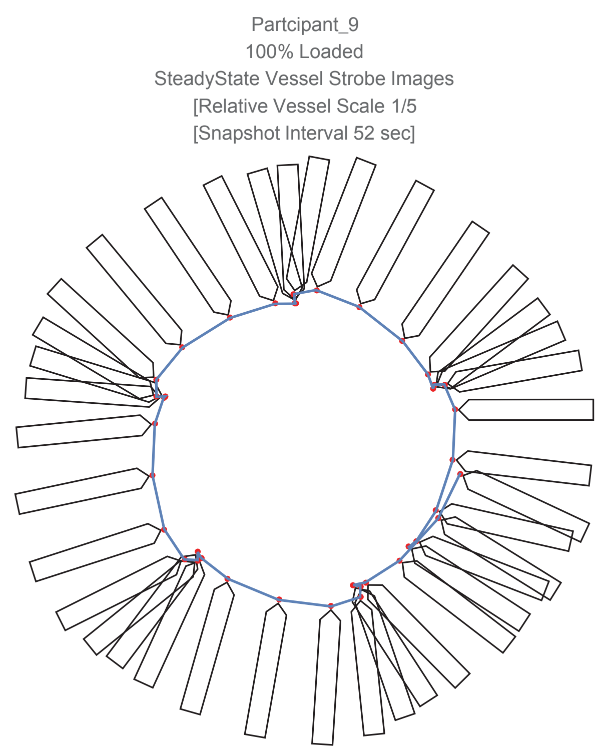
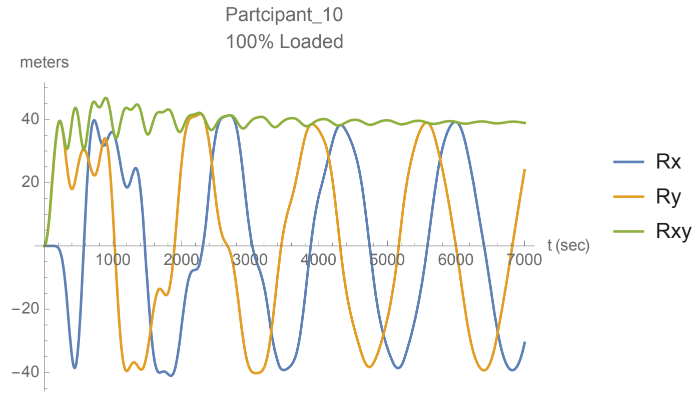
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]


Partcipant_9
100% Loaded
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]


Partcipant_10
100% Loaded
meters
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−20
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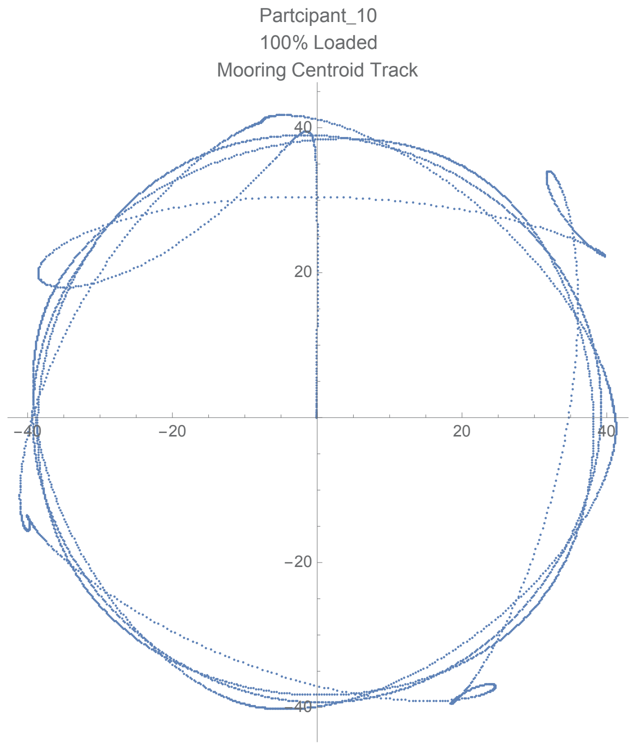
t (sec)
Rx
Ry
Rxy


Partcipant_10
100% Loaded
Mooring Centroid Track
40
20
−40
−20
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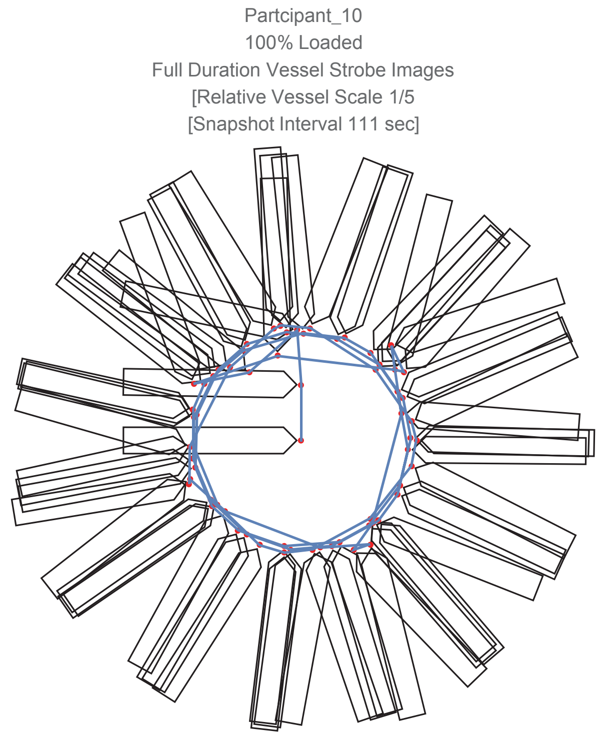
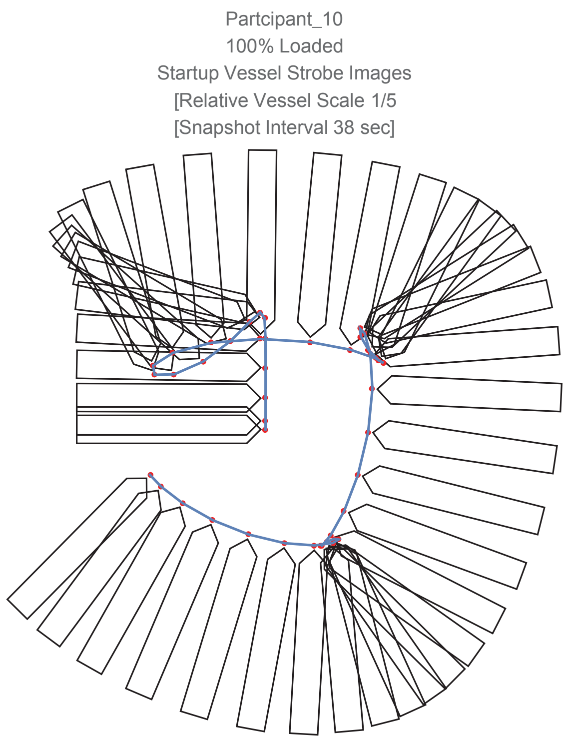
40
−20
−40


Partcipant_10
100% Loaded
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]


Partcipant_10
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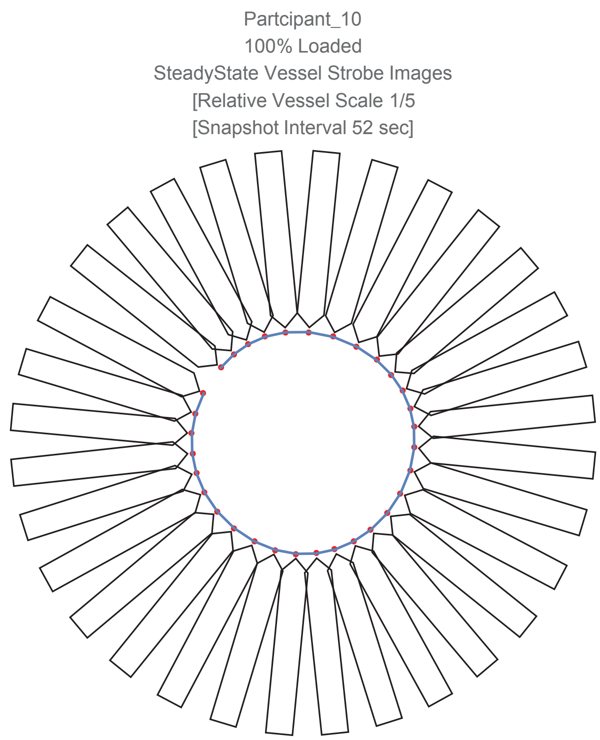
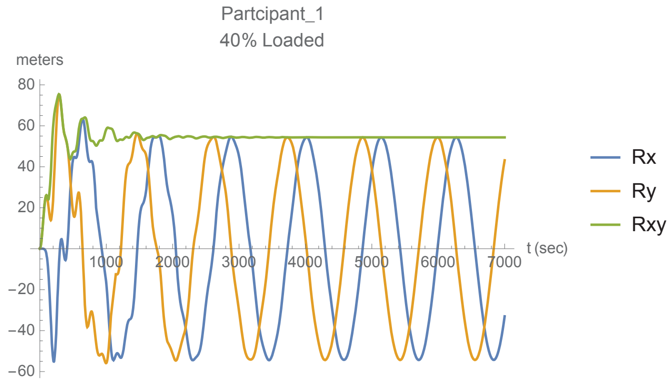
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]


Partcipant_10
100% Loaded
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 52 sec]


Partcipant_1
40% Loaded
meters
80
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t (sec)
Rx
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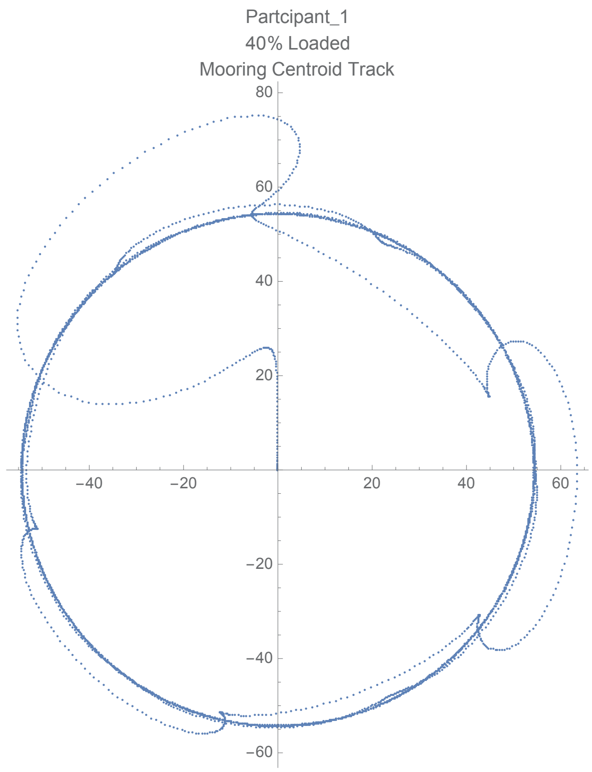
Partcipant_1
40% Loaded
Mooring Centroid Track
80
60
40
20
−20
−40
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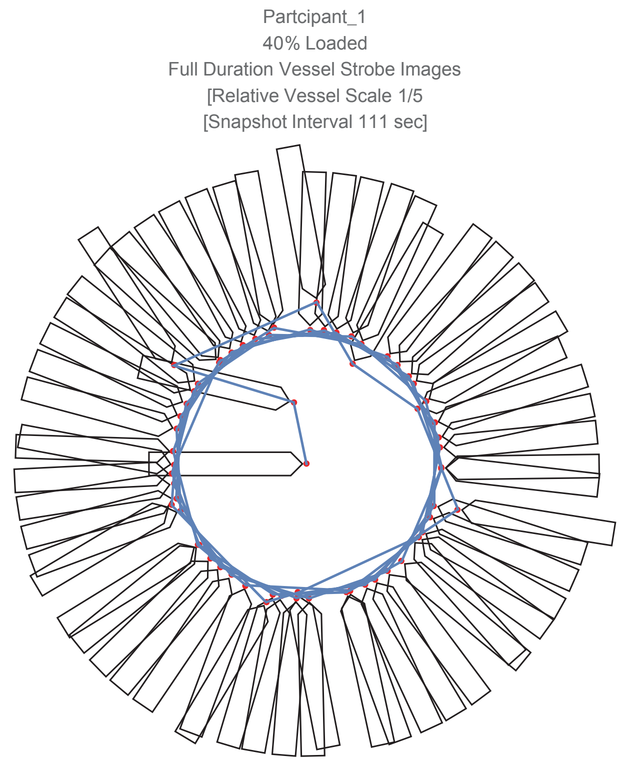
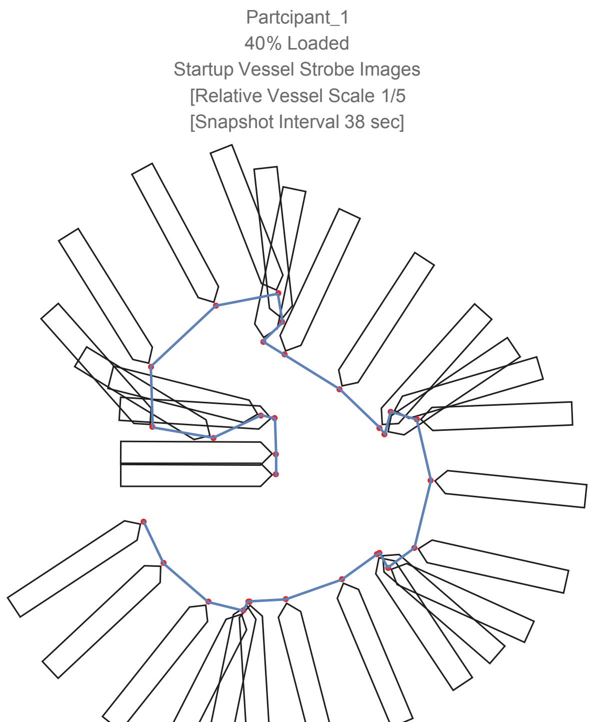
−40
−20
20
40
60


Partcipant_1
40% Loaded
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]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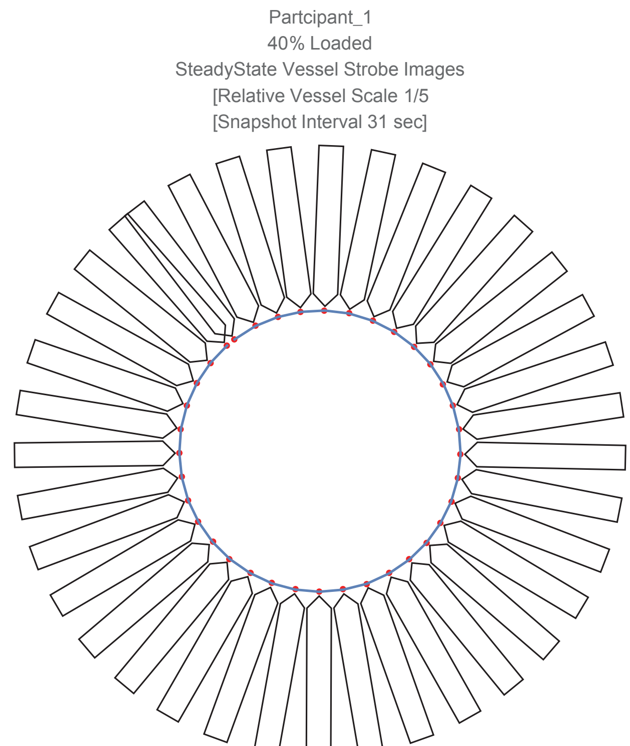
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]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SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 31 sec]

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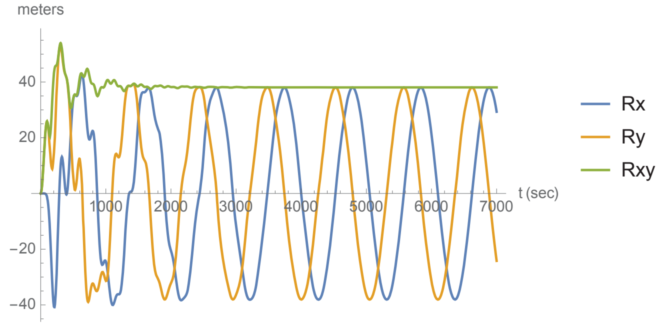

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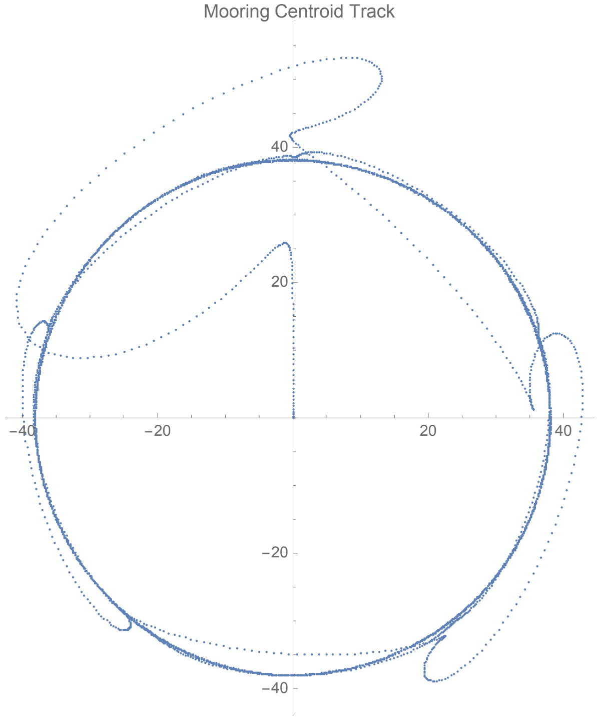
Mooring Centroid Track



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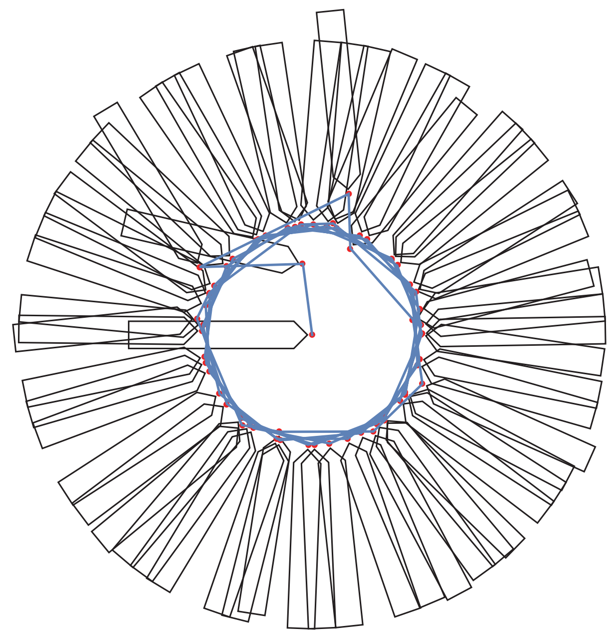
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



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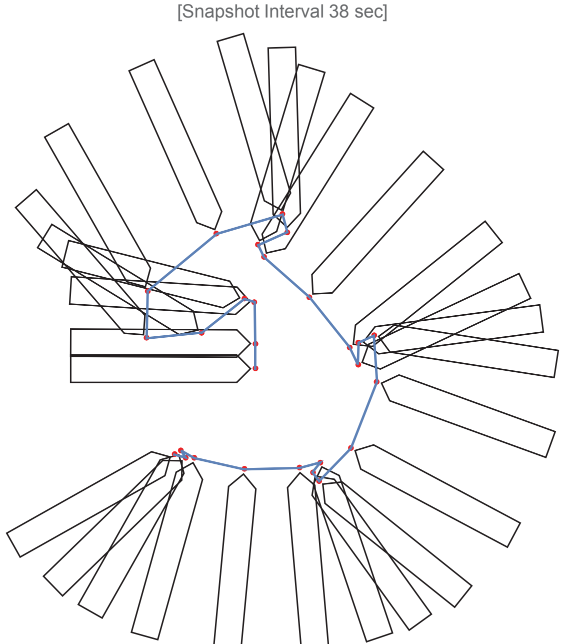

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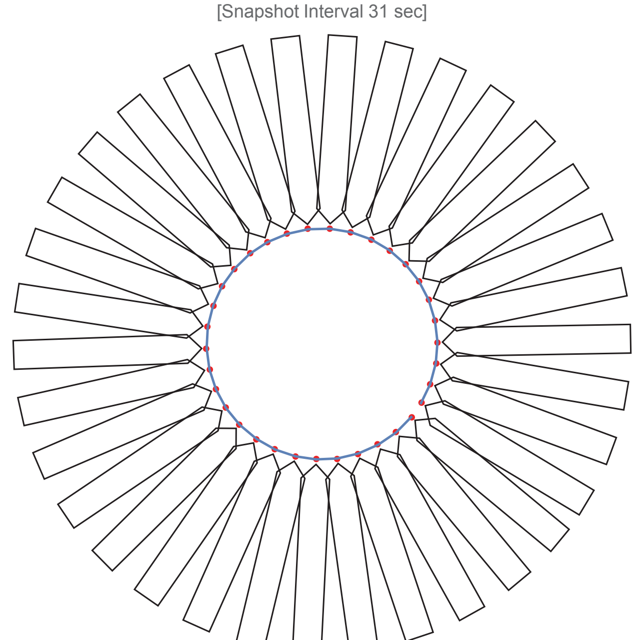
[Relative Vessel Scale 1/5
[Snapshot Interval 31 sec]



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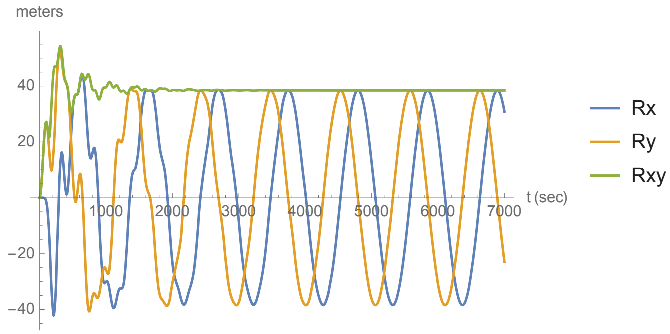

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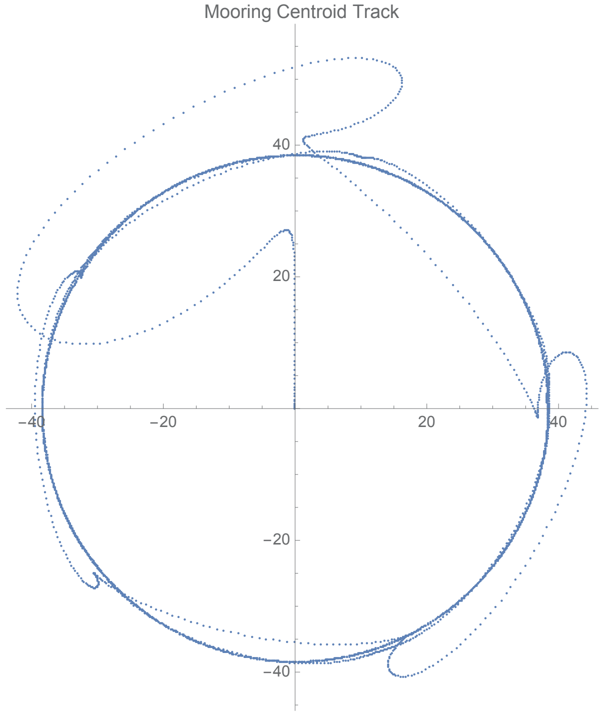
Mooring Centroid Track



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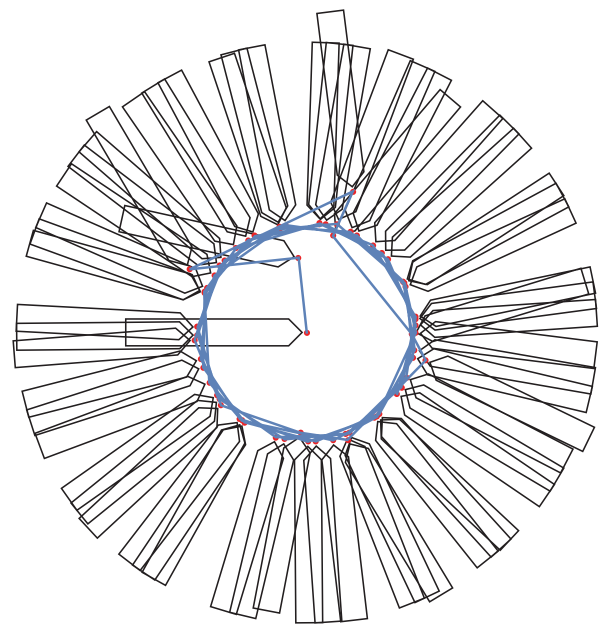
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



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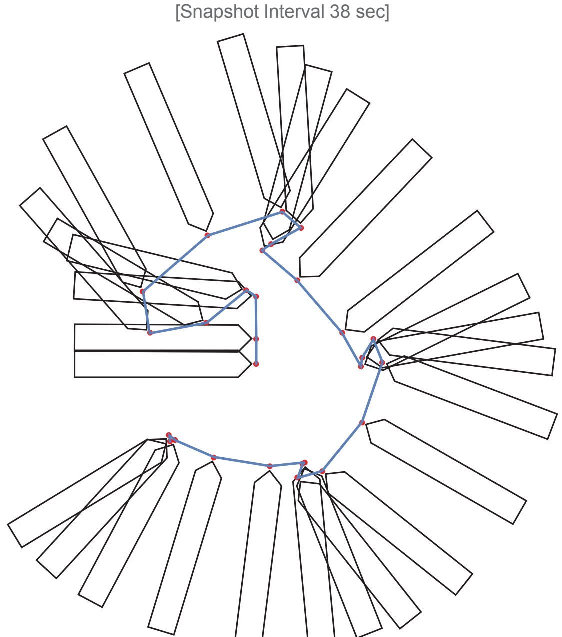
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



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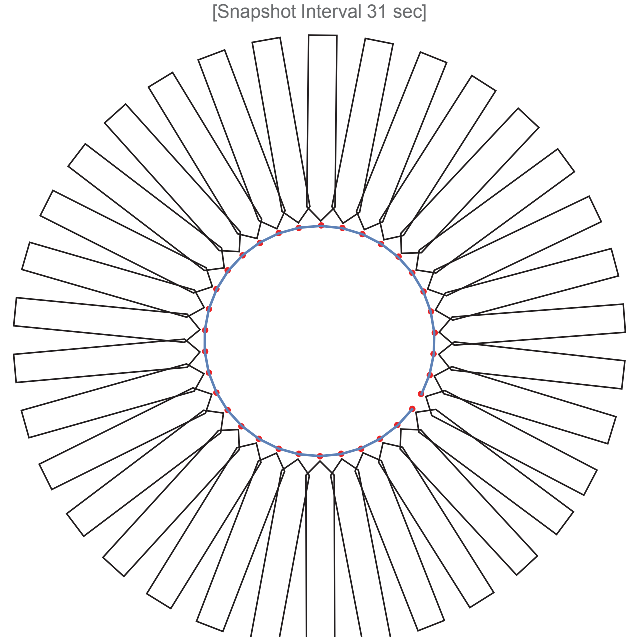

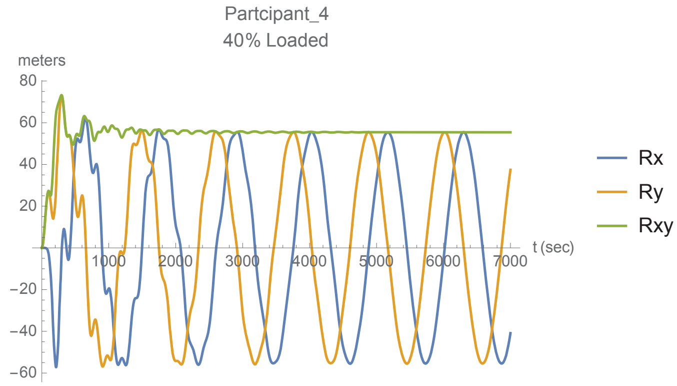
Partcipant_4
40% Loaded
meters
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t (sec)
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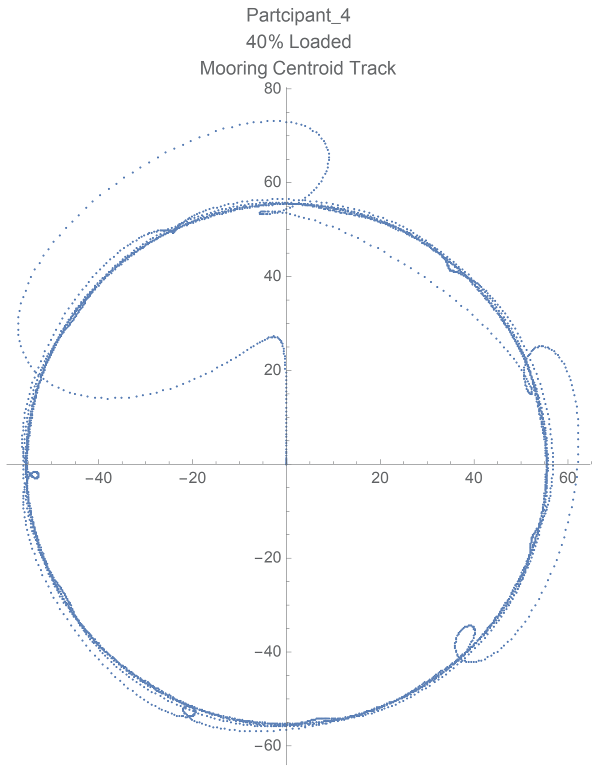
Partcipant_4
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Mooring Centroid Track
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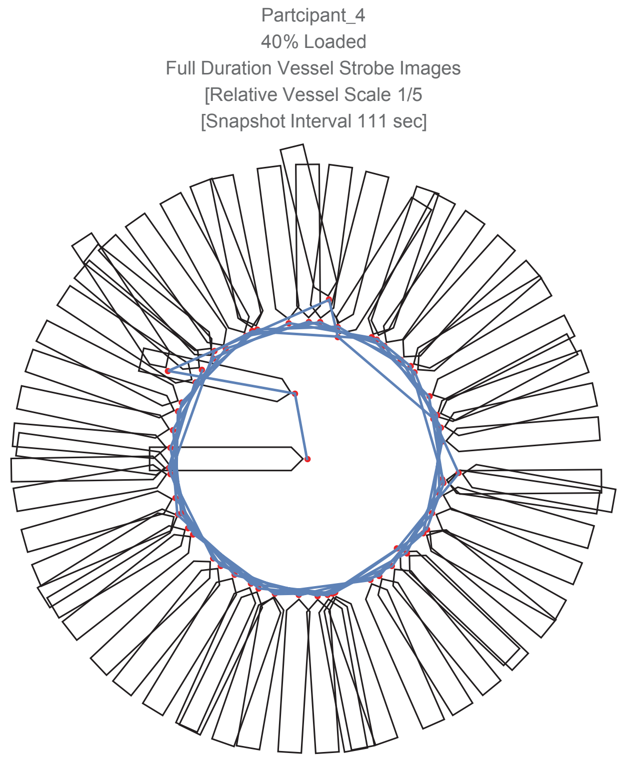
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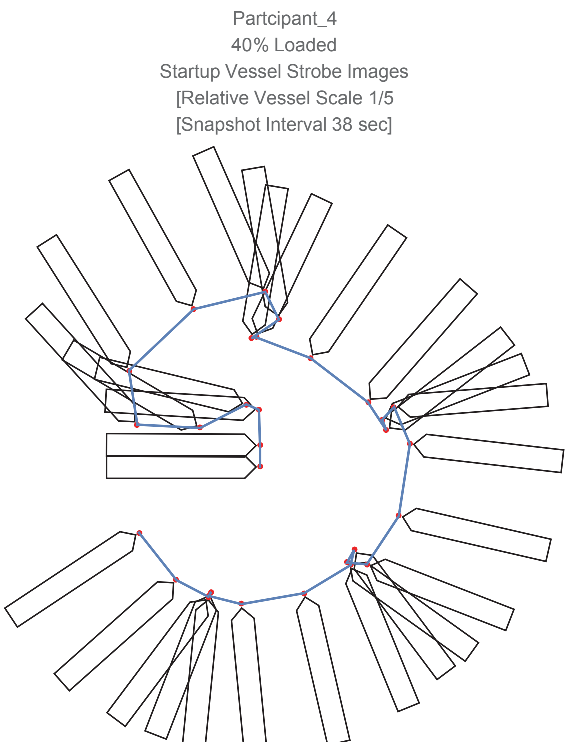
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]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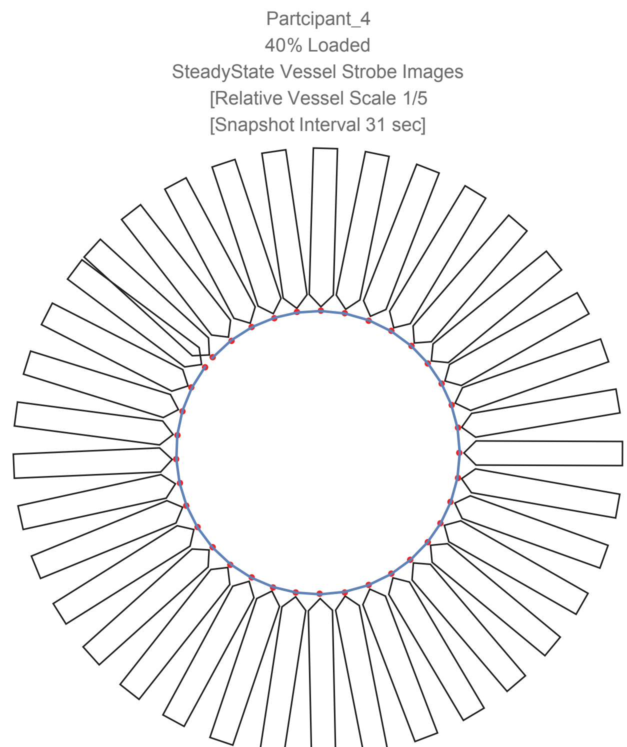
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]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SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 31 sec]

Partcipant_5
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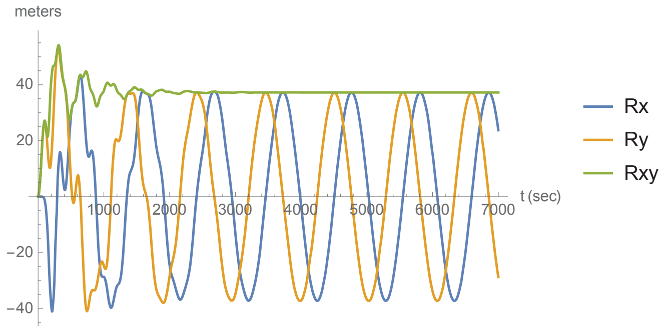

Partcipant_5
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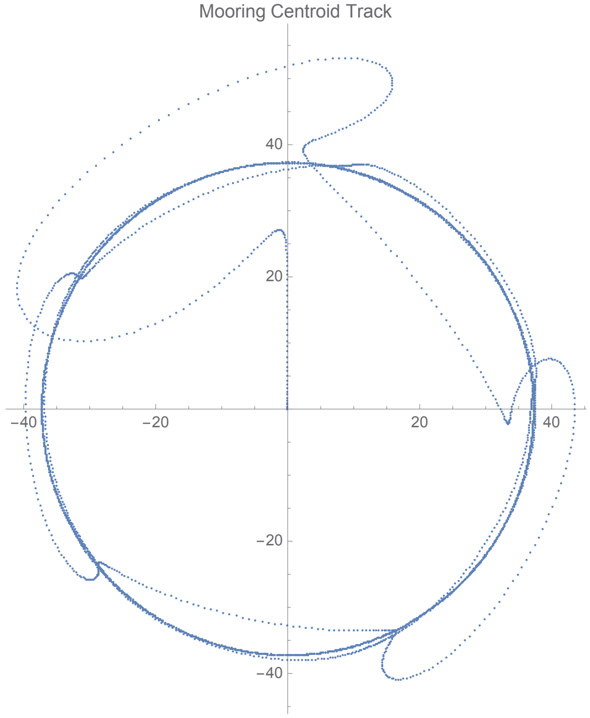
Mooring Centroid Track



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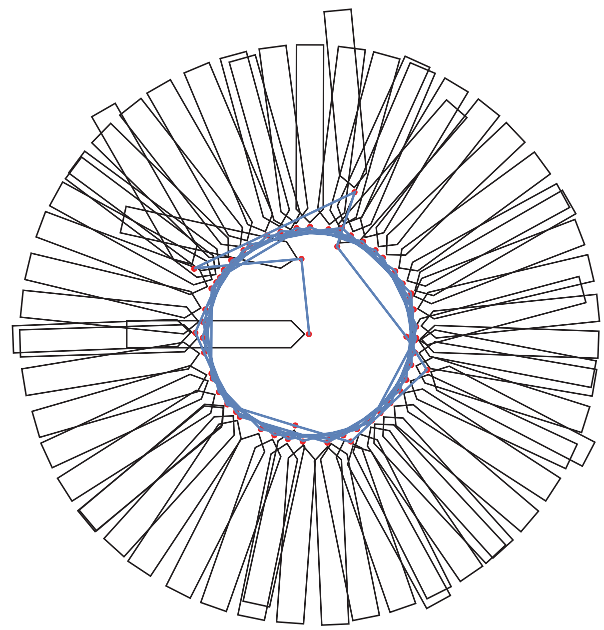
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



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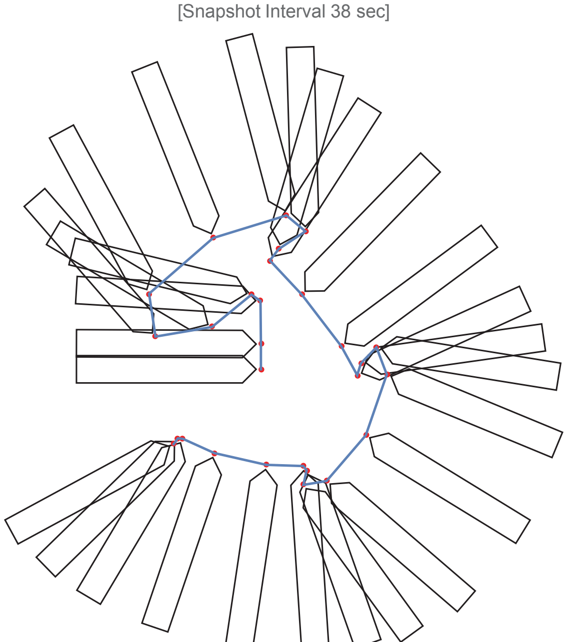
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



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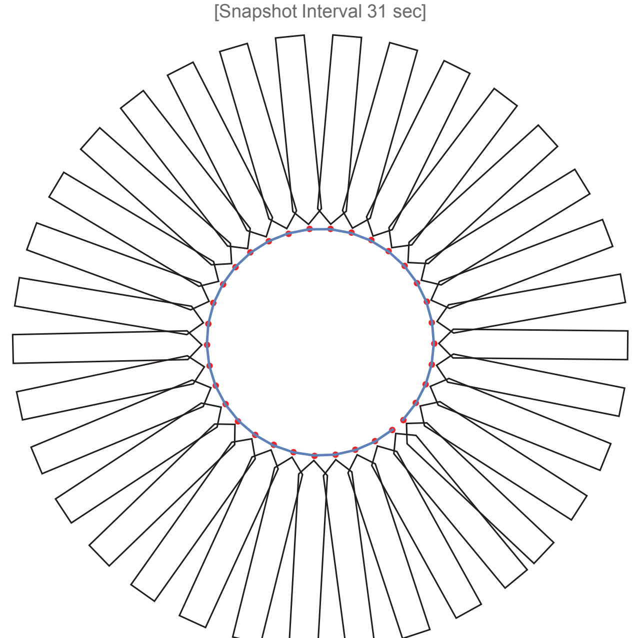

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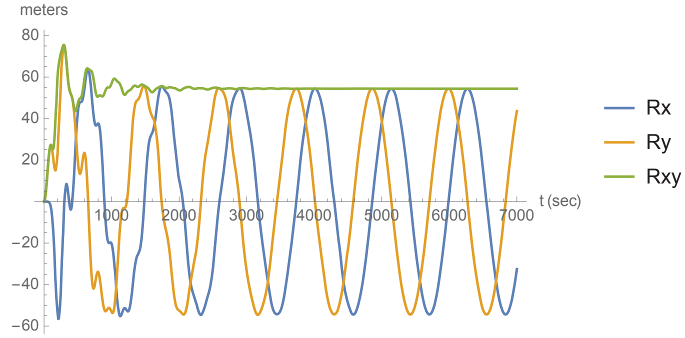

Partcipant_6
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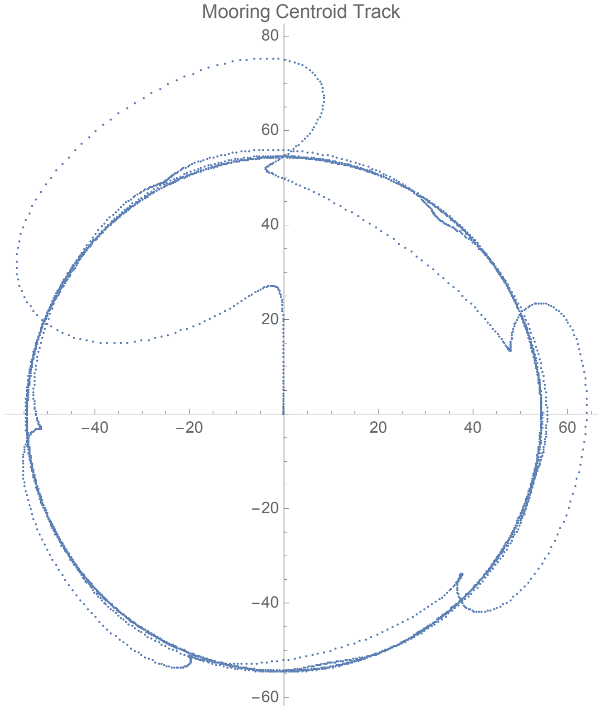
Mooring Centroid Track



Partcipant_6
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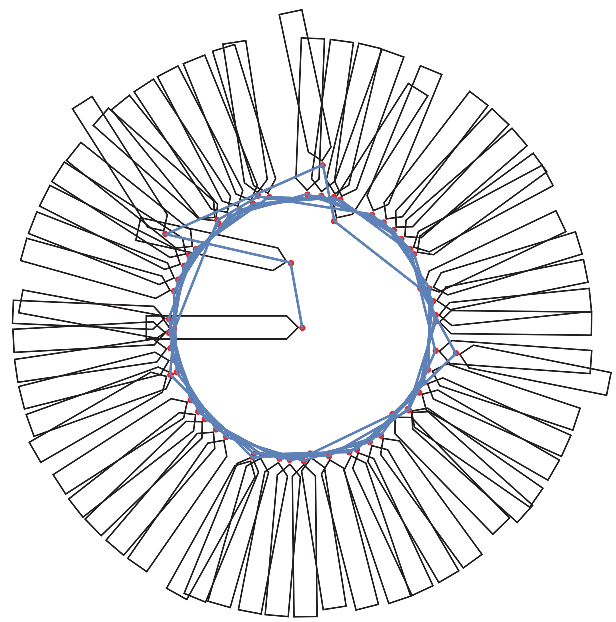
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



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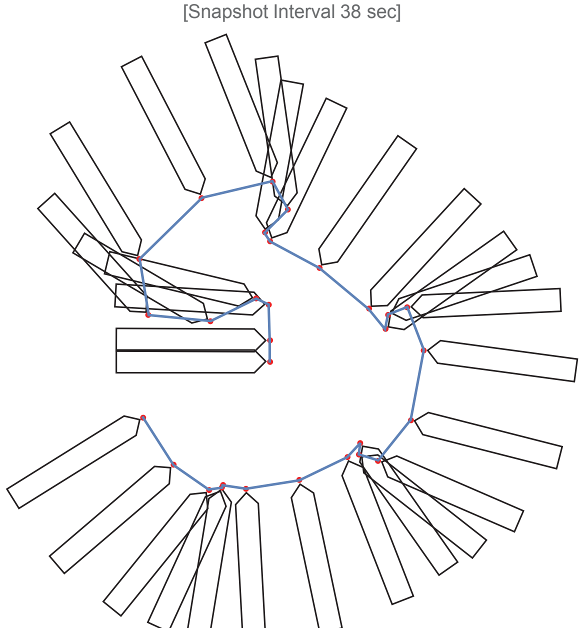
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



Partcipant_6
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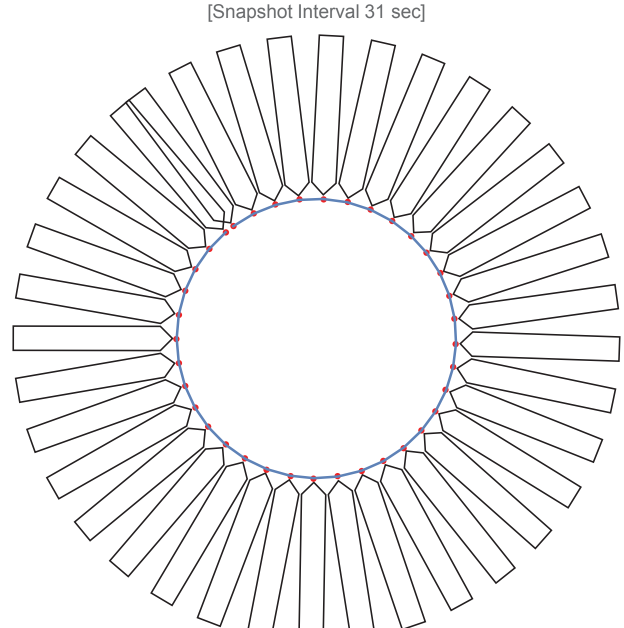
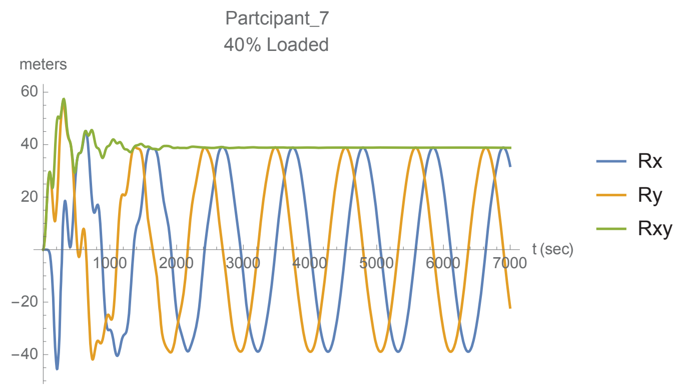
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 31 sec]




Partcipant_7
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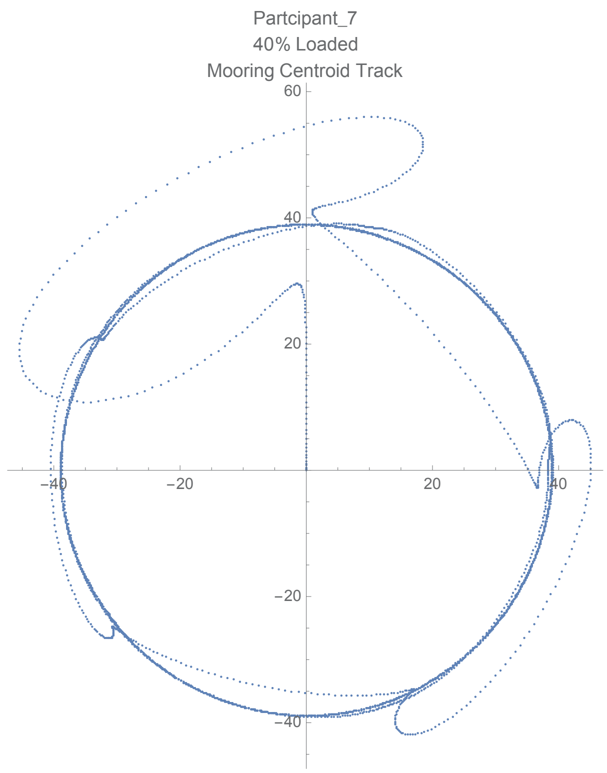
Partcipant_7
40% Loaded
Mooring Centroid Track
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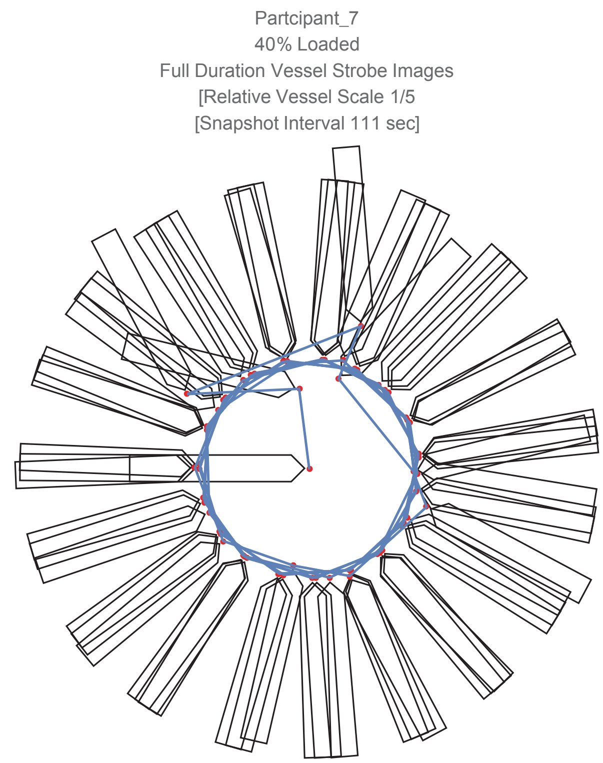
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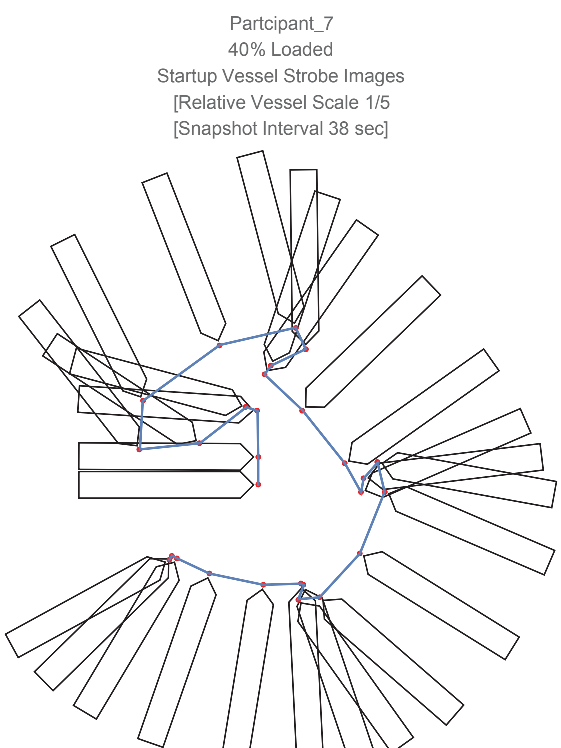
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]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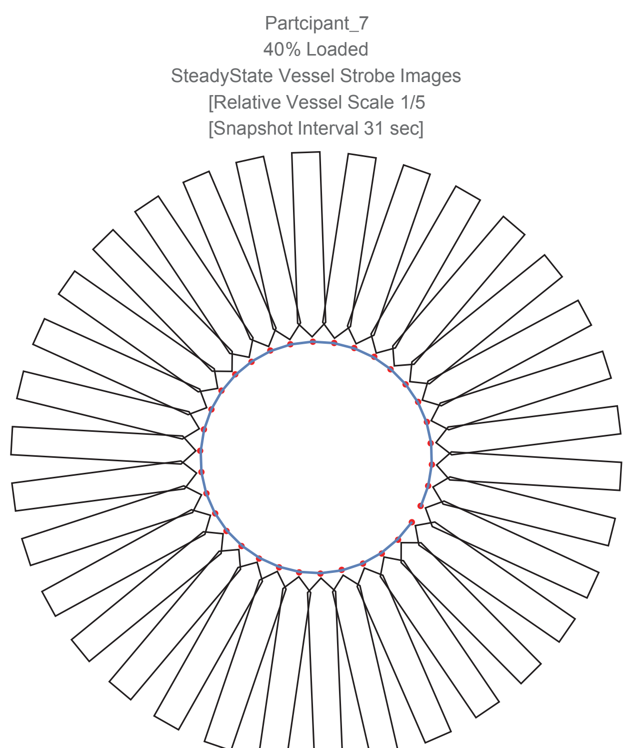
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]


Partcipant_7
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SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 31 sec]

Partcipant_8
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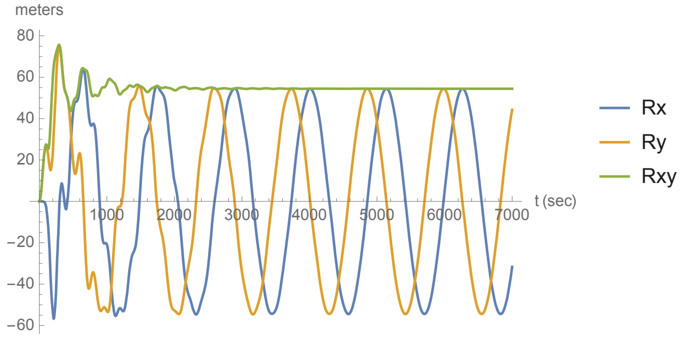

Partcipant_8
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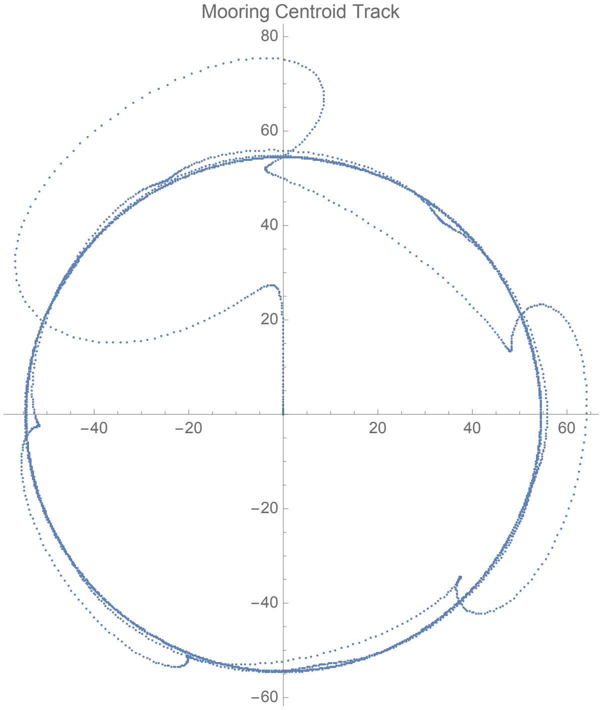
Mooring Centroid Track



Partcipant_8
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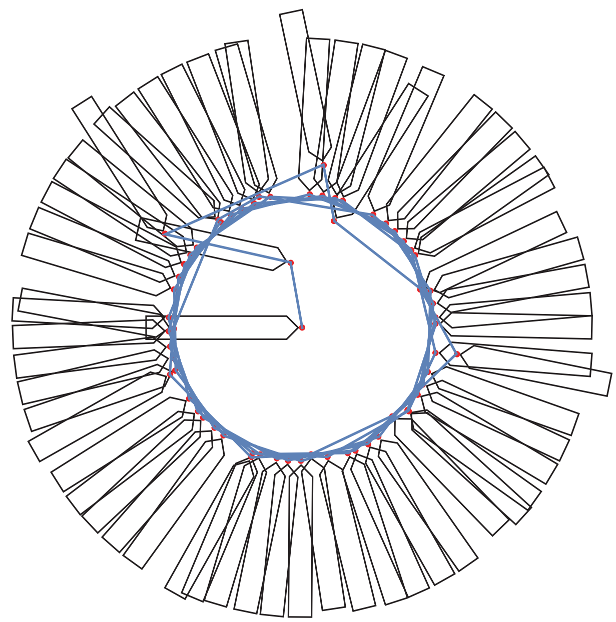
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



Partcipant_8
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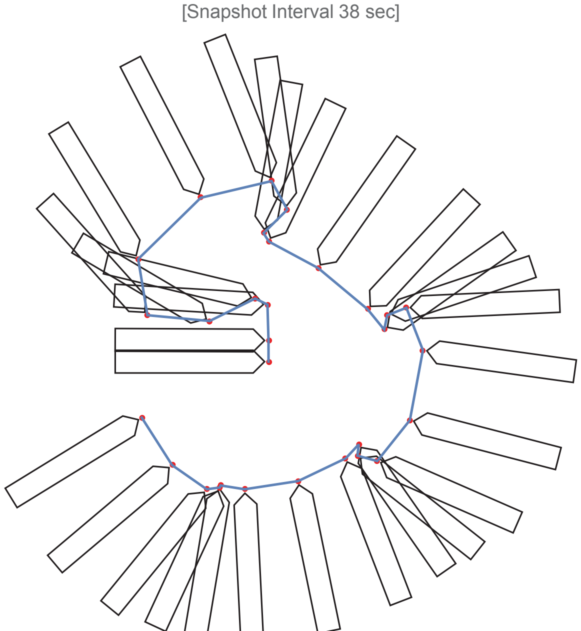
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



Partcipant_8
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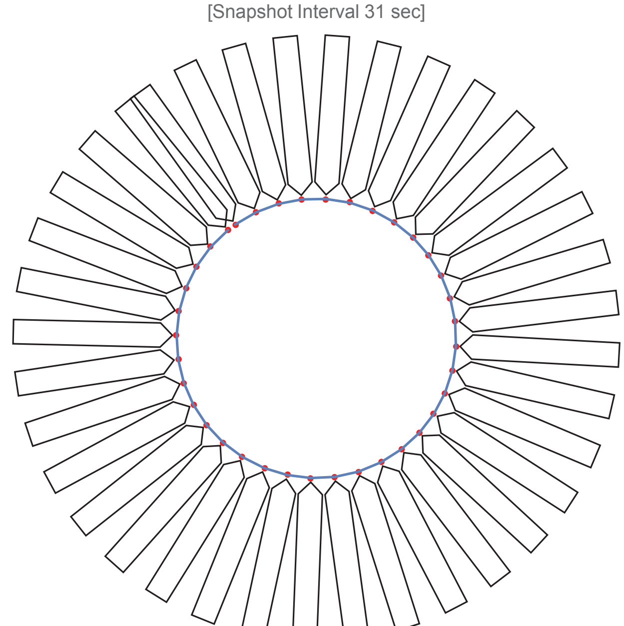
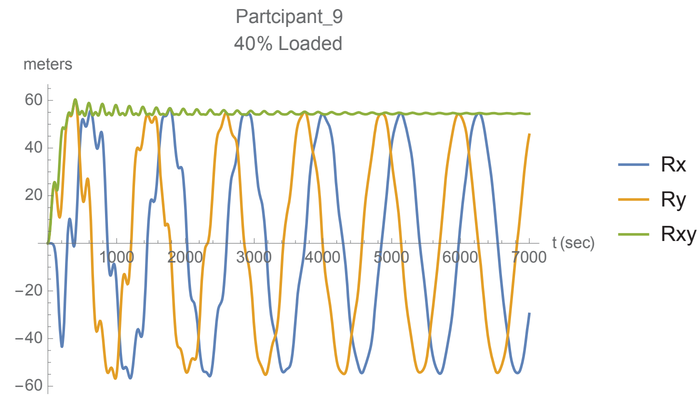
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 31 sec]




Partcipant_9
40% Loaded
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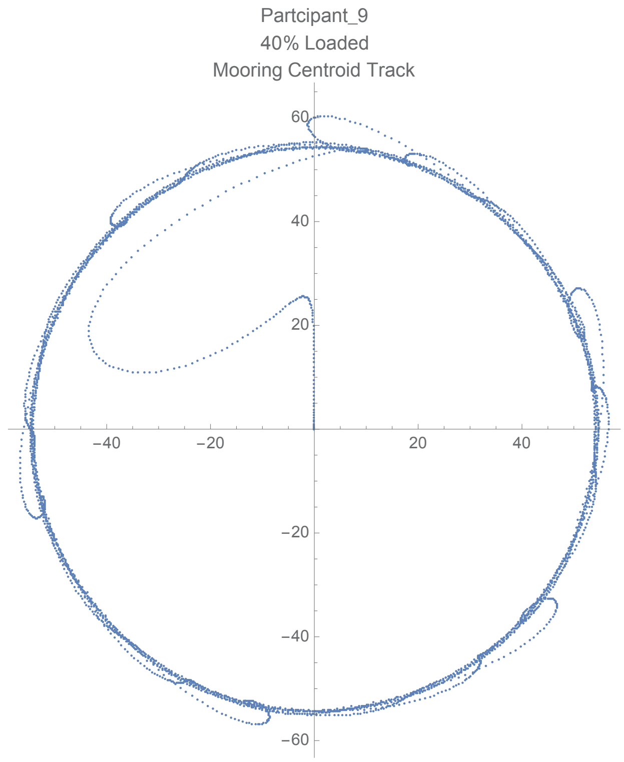
Partcipant_9
40% Loaded
Mooring Centroid Track
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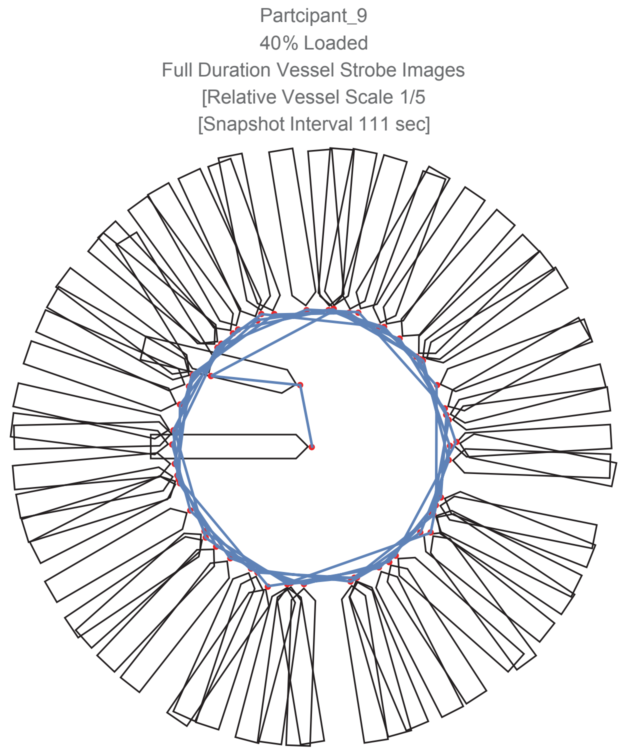
Partcipant_9
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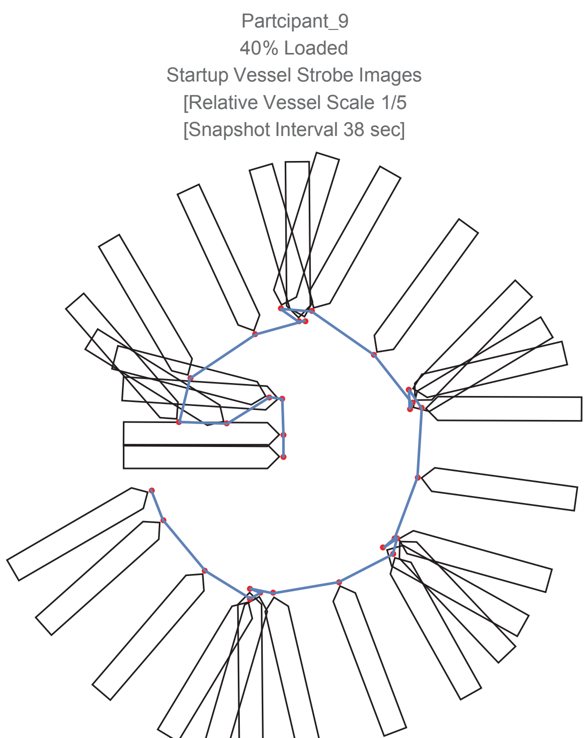
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]


Partcipant_9
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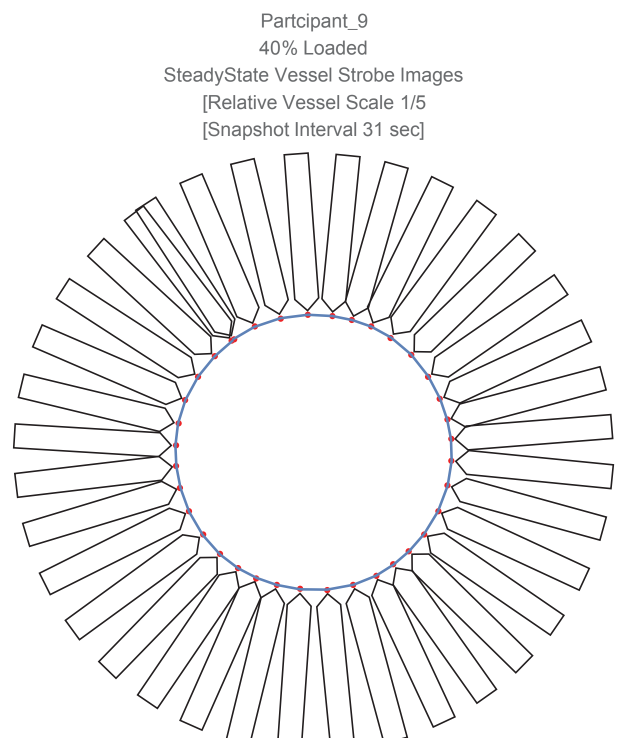
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]


Partcipant_9
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SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 31 sec]

Partcipant_10
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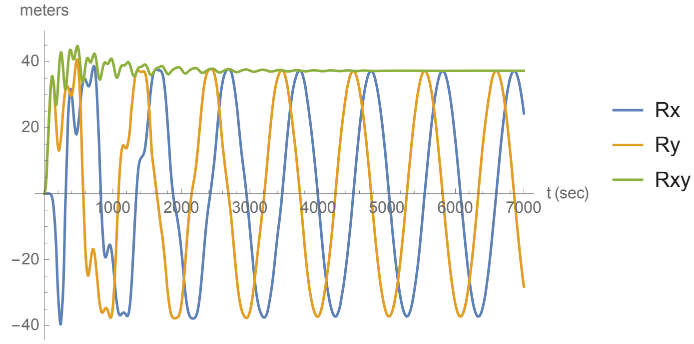

Partcipant_10
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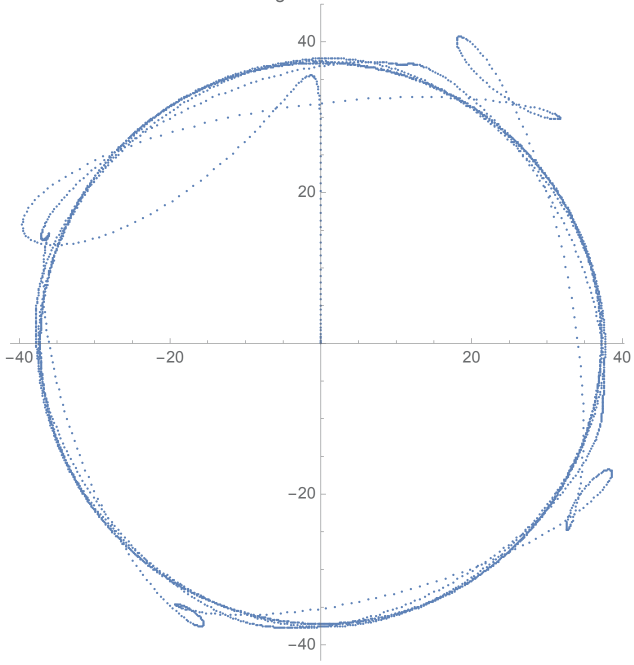
Mooring Centroid Track



Partcipant_10
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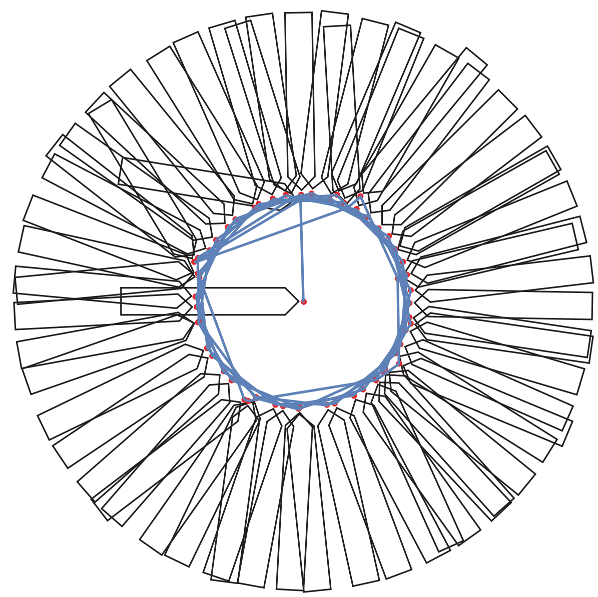
Full Duration Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 111 sec]



Partcipant_10
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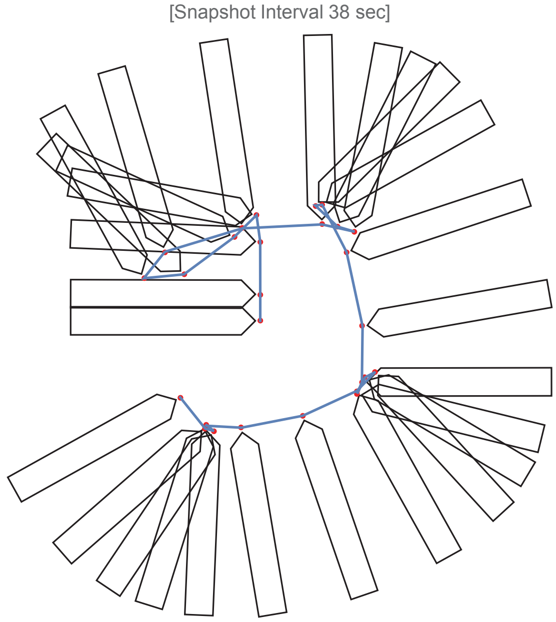
Startup Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 38 sec]



Partcipant_10
40% Loaded
SteadyState Vessel Strobe Images
[Relative Vessel Scale 1/5
[Snapshot Interval 31 sec]