DOE/SC-ARM-TR-166

Report on the Second ARM Mobile Facility (AMF2) Roll, Pitch, and Heave (RPH) Stabilization Platform: Design and Evaluation

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Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

AMF2	ARM second Mobile Facility
ARM	Atmospheric Radiation Measurement Climate Research Facility
IMU	inertial measurement unit
MAGIC	Marine ARM GPCI Investigation of Clouds
MWACR	Marine W-band Cloud Radar
PID	proportional integral derivative
RPH	roll, pitch, and heave
RPY	roll, pitch, and yaw
SeaNav	an electronic system for monitoring ship orientation values for navigation and control
SP	stable platform

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1.0 Introduction

One of the primary objectives of the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Climate Research Facility's second Mobile Facility (AMF2) is to obtain reliable measurements of solar, surface, and atmospheric radiation, as well as cloud and atmospheric properties, from ocean-going vessels. To ensure that these climatic measurements are representative and accurate, many AMF2 instrument systems are designed to collect data in a zenith orientation. A pillar of the AMF2 strategy in this effort is the use of a stable platform. The purpose of the platform is to 1) mitigate vessel motion for instruments that require a truly vertical orientation and keep them pointed in the zenith direction, and 2) allow for accurate positioning for viewing or shading of the sensors from direct sunlight. Numerous ARM instruments fall into these categories, but perhaps the most important are the vertically pointing cloud radars, for which vertical motions are a critical parameter.

During the design and construction phase of AMF2, an inexpensive stable platform was purchased to perform the stabilization tasks for some of these instruments. The first table compensated for roll, pitch, and yaw (RPY) and was reported upon in a previous technical report (Kafle and Coulter, 2012). Subsequently, a second table was purchased specifically for operation with the Marine W-band cloud radar (MWACR). Computer programs originally developed for RPY were modified to communicate with the new platform controller and with an inertial measurements platform that measures true ship motion components (roll, pitch, yaw, surge, sway, and heave). This platform could not be tested dynamically for RPY because of time constraints requiring its deployment aboard the container ship *Horizon Spirit* in September 2013. Hence the initial motion tests were conducted on the initial cruise. Subsequent cruises provided additional test results. The platform, as tested, meets all the design and performance criteria established for its use.

This is a report of the results of those efforts and the critical points in moving forward.

2.0 Stabilization System Description

Previous experience with RPY led us to choose the same manufacturer for a roll, pitch, and heave (RPH) unit, principally because of expense and economy of effort. The controller for RPH would be very similar to that used for RPY, which would decrease the time required to develop sufficient control of the platform to enable it to be deployed within a few months of purchase. We decided, however, to use a hydraulic system because of the increased weight requirements of the payload and less exposure of critical elements to the ocean environment.

The AMF2 stable platform (SP), built by Sarnicola Systems, is designed to have three degrees of freedom, roll (motion about the longitudinal, or x, axis), pitch (motion about the transverse, or y, axis), and heave (motion in the vertical axis). Because ships move considerably more in the vertical dimension than it is possible to compensate, the third (vertical) degree of freedom is used to maintain the table at a constant height above its base (and the ship's deck). Knowledge of the rate of change of heave measured from the ship navigation data stream can then be used to compensate for vertical motion of the platform.

Figure 1. The AMF RPH Stable Platform as originally designed and received.

The table roll and pitch are manipulated by lengthening and shortening three legs that support the platform (the leg in the foreground is A; the leg at the left rear is B; the leg at the right rear is C). The length of the legs is controlled independently and hydraulically, with three sensors mounted on the legs; there are 12,000 encoder positions for each leg (compared to 118,000 for the electric motors on RPY). When leg B is increased with legs A and C moved equal amounts, the table tilts in what we have defined as the pitch direction; when legs A and C change in opposite senses with leg B constant, the table tilts in the roll direction. The dimensions of this particular table allow for ± 30° of pitch and ± 25° of roll. However, similar to RPY, one cannot reach the extremes of roll and pitch simultaneously.

Figure 2 shows that all possible combinations of roll and pitch are only possible for values within ± 15°. This coincides with the design parameters originally specified. When conditions are encountered outside this range, data will be compromised, but it is unlikely that data from other instruments will be viable in this case.

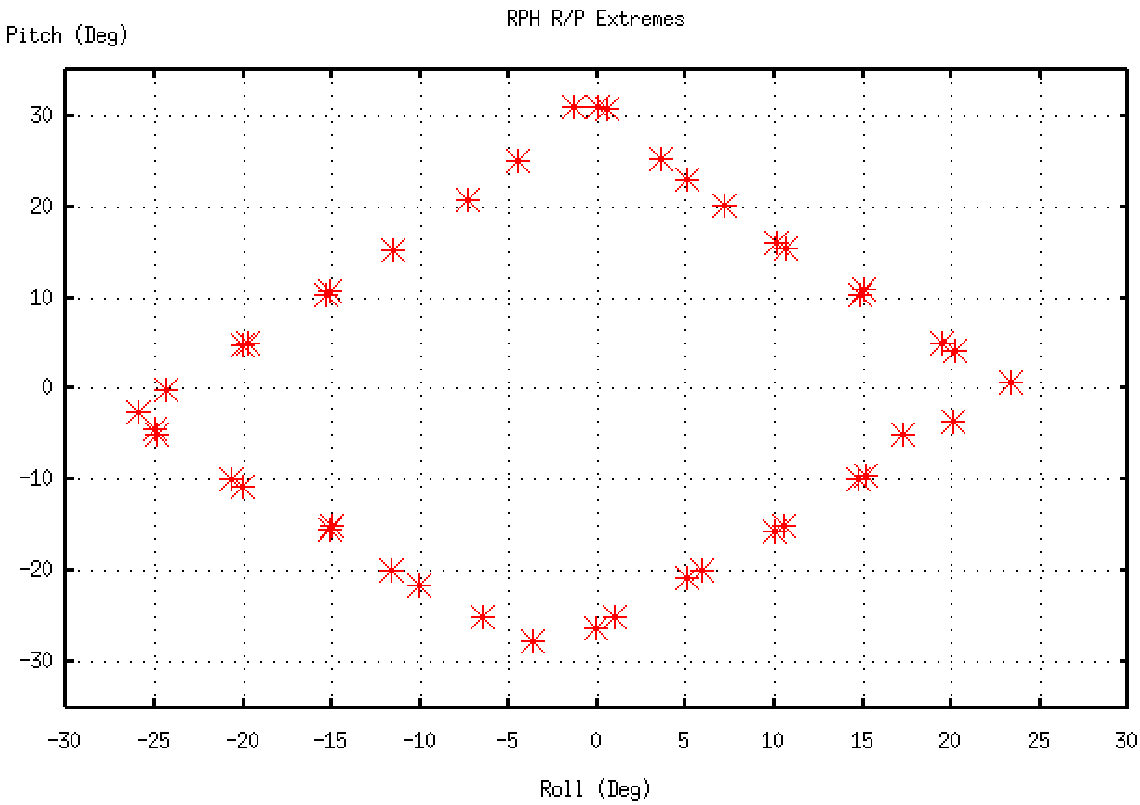


Figure 2. Possible locations of the maximum and minimum roll/pitch values, according to any value, are mapped above. Values were determined by setting encoder positions to their respective max/min values and measuring the table roll and pitch with a tilt sensor mounted on the table.

The table is maintained at a constant height relative to its base by requiring that legs A and C decrease/ increase by the same amount that leg B increases/decreases. This can be expressed mathematically as

$$Bl + (Al+Cl)/2 = 2D \quad (1)$$

where Al, Bl, and Cl are the encoder counts for legs A, B, and C respectively and D is a constant, chosen to be 6000, so as to allow for maximum movement of the table. With this choice, the table is approximately level when A = B = C = D.

A Galil DMC-21X3 motion controller is used to control the platform. Delivery of the SP included the Galil controller. Control of the table is accomplished through another computer that issues commands to the Galil controller. The set of possible commands is extensive; however, the dominant commands used are those to send position, speed, and acceleration commands to each leg to maintain the table in the desired pointing direction. Whenever power is removed from the platform, it is not necessary to reestablish zero on each leg; the leg lengths are uniquely associated with encoder values.

The control of the table position relies on an accurate knowledge of the table orientation as a function of the table legs or, in this case, the encoder counts associated with each leg (Al, Bl, Cl). A table lookup function was developed to provide unique triples of Al, Bl, Cl for selected pairs of roll and pitch values between ±15°. This was done by exercising the table through the complete range of encoder values at 50 encoder count increments and measuring the resultant roll and pitch values with the SeaNav system (designated for monitoring ship orientation values) placed at the center of the table and carefully oriented so the pitch and roll axes of table and sensor coincided. After all appropriate encoder positions were sampled (roughly a 40-hour operation), the table of values was inverted such that values of desired pitch and roll coincided with indices of a 2D of encoder positions.

3.0 Stabilization Control Theory

Simply sending a command to the platform to move it to a new position based on measured ship motion data will never suffice, because compensation is never instantaneous: mechanical and computational delays must be taken into account. The proportional integral derivative (PID) controller is a feedback loop controller that can be applied to this problem. A correction term, c(t), is determined from an error function, e(t) as

$$c(t) = K_P e(t) \int_0^t e(t')dt' + K_D \frac{d}{dt} e(t) \tag{2}$$

where K_P, K_I, and K_D are feedback constants for the proportional, integral, and differential terms of the error function, determined by the situation. In this case, correction terms for both roll and pitch are necessary. The error term is supplied by a tilt sensor mounted on the platform, supplying roll and pitch as a function of time; then the error function, that is, for roll, e_{roll} is

$$e_{roll}(t) = roll_m(t) - roll_d \tag{3}$$

where $roll_m$ is the tilt sensor measurement and $roll_d$ is the desired roll. The expression for pitch is similar. This approach is used essentially to drive the error functions toward zero. Given a value for c(t), the new table angles are determined based on the current table position supplied by the controller and the table lookup function. This approach does not require any knowledge of the actual ship roll and pitch and allows the table to operate independent of external measurements.

The PID approach, while attractive and useful, assumes no knowledge of the system being controlled. Wave motions over the ocean are principally a superposition of waves of various wavelengths and amplitudes. As such, they are largely well behaved and predictable. A predictive algorithm was developed for RPY and modified for RPH that provides an estimate of where the platform needs to be several samples in advance. The predicted position is obtained from a polynomial of first and second derivatives calculated from previous platform positions and an error estimate derived from predicted and actual table positions. The input to the algorithm is supplied by real-time ship position data provided by the ship disposition data stream. Output from the predictive algorithm, used as the primary control of the table and used in conjunction with the PID described above, we call the modified PID.

Because we do not have regular access to shipboard deployment, much of the control software development was accomplished by controlling the platform with a known time series of roll/pitch values (obtained from past shipboard measurements) and measuring the platform position. Comparisons between the “desired” and “measured” positions were then used to evaluate the control strategy.

4.0 Stabilization System Field Testing

Final implementation of both the PID and modified PID approaches necessarily had to take place aboard the *Horizon Magic* during its initial voyages during the Marine ARM GPCI Investigation of Clouds (MAGIC) campaign of the AMF2. The *Horizon Magic* is a 900-foot long container freighter (Figure 3) traversing between Long Beach, California and Hawaii on a two-week schedule (4 days out, 6 days return, 2 days in each port).

Figure 3. *Horizon Spirit* under way carrying approximately 1,000 seatainers. The bridge is forward beneath the mast. A flat open area behind the bridge is the location of AMF2 sensors.

Figure 4 shows the RPH platform (and RPY) during its maiden voyage aboard the *Horizon Spirit*. The white box below the platform is a weather-resistant container for the Galil controller and inputs from the ship navigation system and local tilt sensor mounted on the table.

Figure 4. The RPH (left) and RPY (right) platforms during initial deployment. During this voyage, work with RPH was using SeaNav ship disposition data, which later was not available.

Figure 5 shows the first deployment with the MWACR installed (November 5, 2012) and a tilt sensor mounted in the center. The tan canvas "skirt" is used to keep large volumes of water from encroaching on the electronics. During operation, the system operates as follows. A Seaborne Navigation System (originally Kearfott SeaNav, changed to Hydrins in December 2012) is placed at, or near, the centerline of the ship—in this case, in the seatainer behind the RPH. This system provides roll, pitch, and yaw (as well as surge, sway, and heave) of the ship at a 50 Hz rate. This datastream is sub-sampled at a selectable rate and provided to the table with an appropriate sign change, along with appropriate offset values to compensate for mounting differences to the control program that then communicates with the controller. Because it is not possible for the table to adjust instantaneously to the input datastream, some predictive capability is built in to the interface between the SeaNav and the SP. During the voyage aboard the *Horizon Spirit*, a sample rate of 17 Hz was used. The ability of the platform to maintain level was monitored using the tilt sensor mounted in the middle of the platform. The data from the tilt sensor was supplied to the system operation as in the modified PID procedure outlined above. One of the principal quantities of interest from the MWACR is vertical velocity. The MWACR measures local vertical motion; hence, lever arm corrections are not necessary.

The alternate method of operating, with only the values sensed with the tilt sensor (or equivalent) to create a feedback loop that continuously attempts to minimize the sensed values of pitch and roll, was implemented extensively during November–December because the Kearfott SeaNav failed.

Figure 5. MWACR installed on RPH on board *Horizon Spirit*. Watson tilt sensor can be seen below MWACR, in center of table.

5.0 Stabilization Performance Evaluation

Figures 6 through 10 summarize the performance during the initial cruise (2AB in Table 1). During this period the effort was primarily directed toward improving the enhanced PID approach by changing model parameters and varying the PID coefficients. Figure 6 is a sample of the instantaneous performance of the table relative to the ship roll. The tilt sensor was limited to 0.1° resolution during most of this period, which places a limit on how close to zero the table and the analysis are able to resolve. Figures 7–10 illustrate average and standard deviations of ship and table roll, pitch, and resultant tilt values, where

$$res \approx \left(roll^2 + pitch^2\right)^{1/2}. \tag{4}$$

The resultant tilt values are a handy way to reduce the analysis to a single variable if the actual direction of the tilt is not significant. Note, for example, that the tilt values for the ship are almost never zero because of the nature of wave motion. The time periods were defined by different combinations of controlling parameter values and by improvements and corrections in the operation of the algorithms. Clearly by the end of the voyage, significant reduction in table variation from its designated pointing direction had been achieved, with mean and standard deviation values of the tilt on the order of 0.02 and 0.04, respectively. One should keep in mind that the seas were relatively mild, particularly with the ameliorating effect of a large ship. Thus the values of the ratio of table to ship tilts on the order of 0.03 give a more realistic view of expected performance in all conditions.

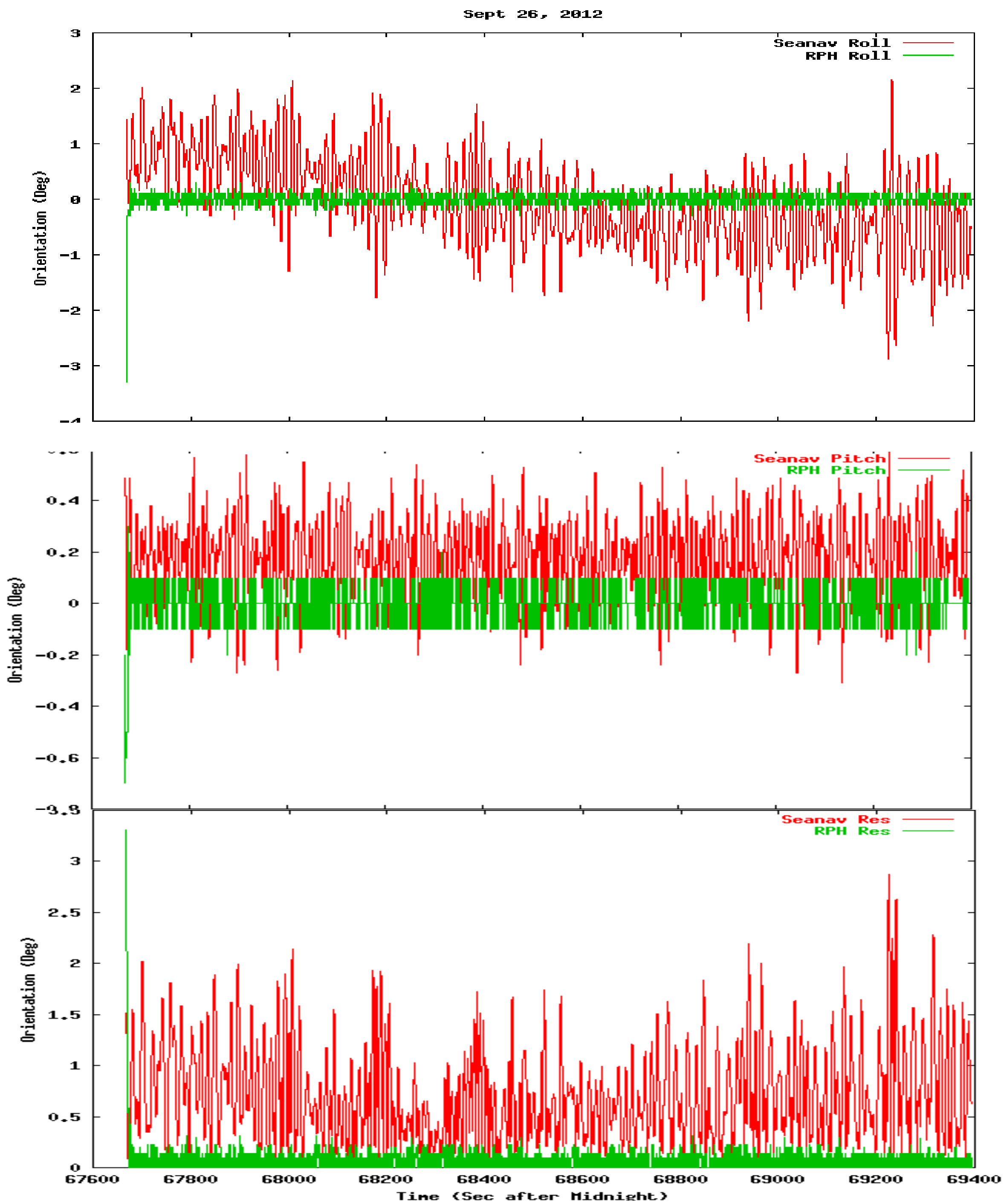


Figure 6. Sample data from September 26, 2012. Roll (top), pitch (middle), and resultant (bottom) values from ship (red) and table (green). Note that the minimum resolution of 0.1° from the tilt sensor is clearly evident in pitch values because they are small.

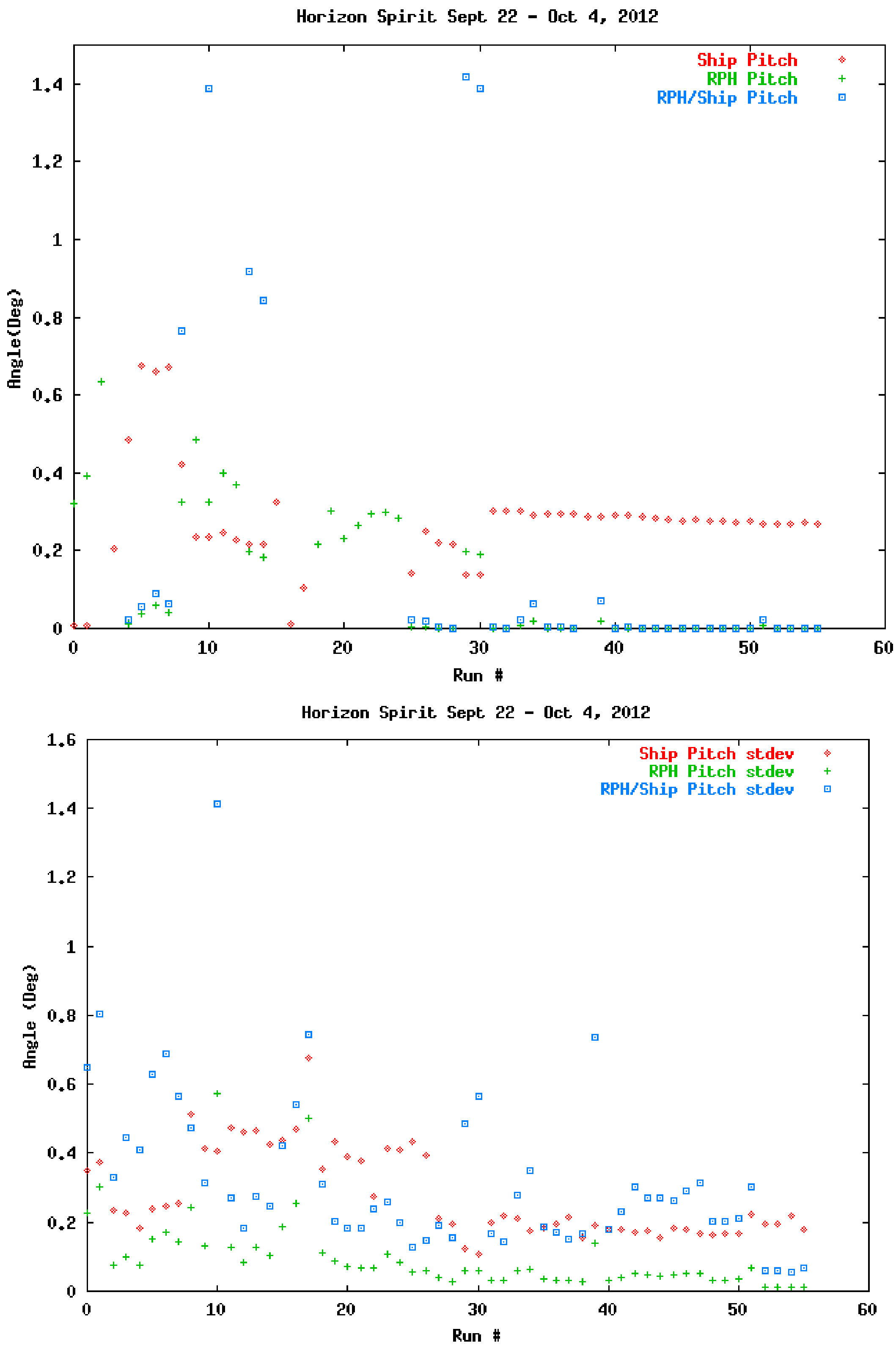


Figure 7. Mean (left) and standard deviation (right) of pitch from ship (red), RPH table (green), and ratio of table to ship (blue). Values obtained from roughly hour-long periods during cruise. Values show improvement of algorithm as control variables are fine-tuned during voyage.

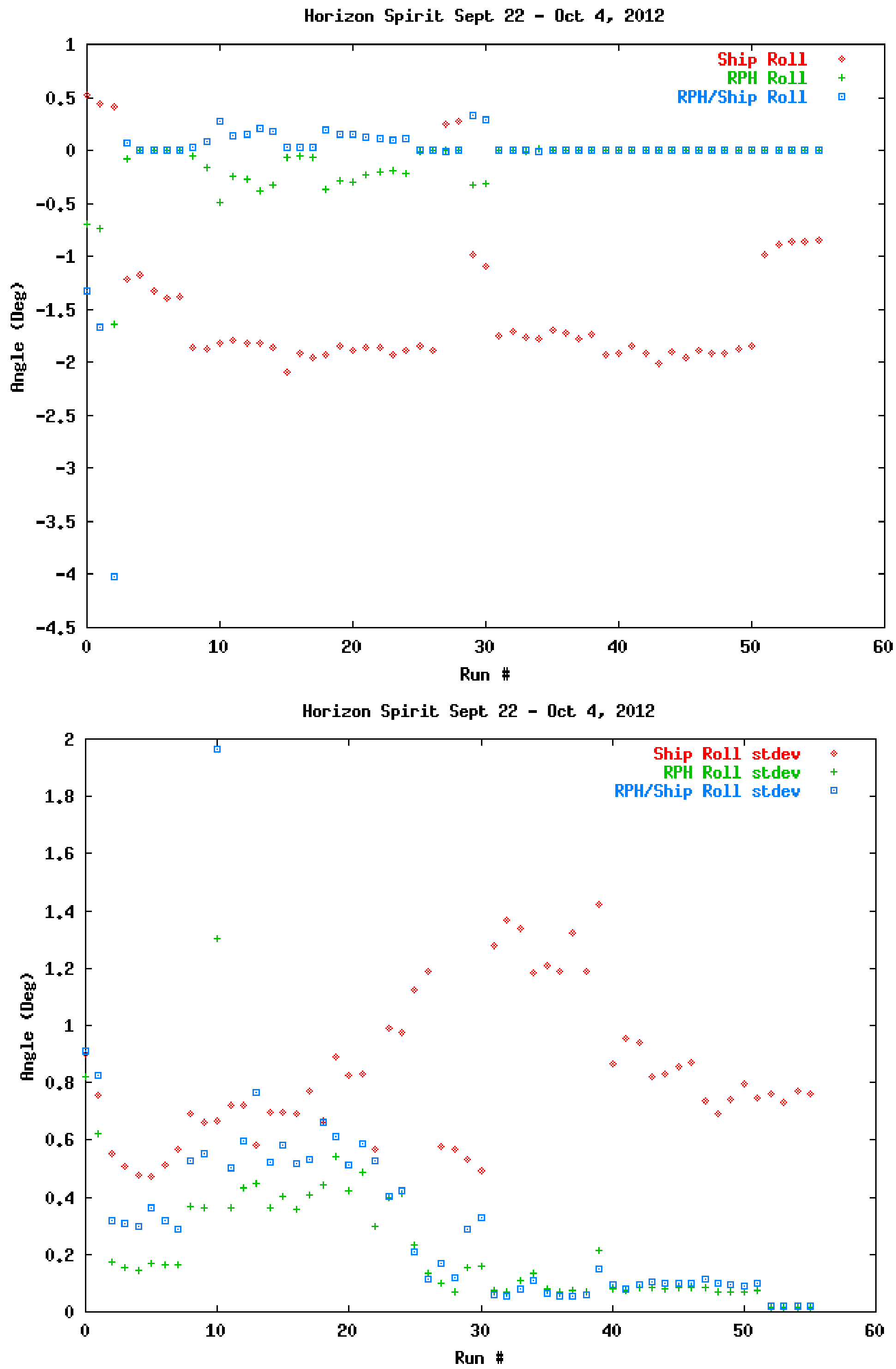
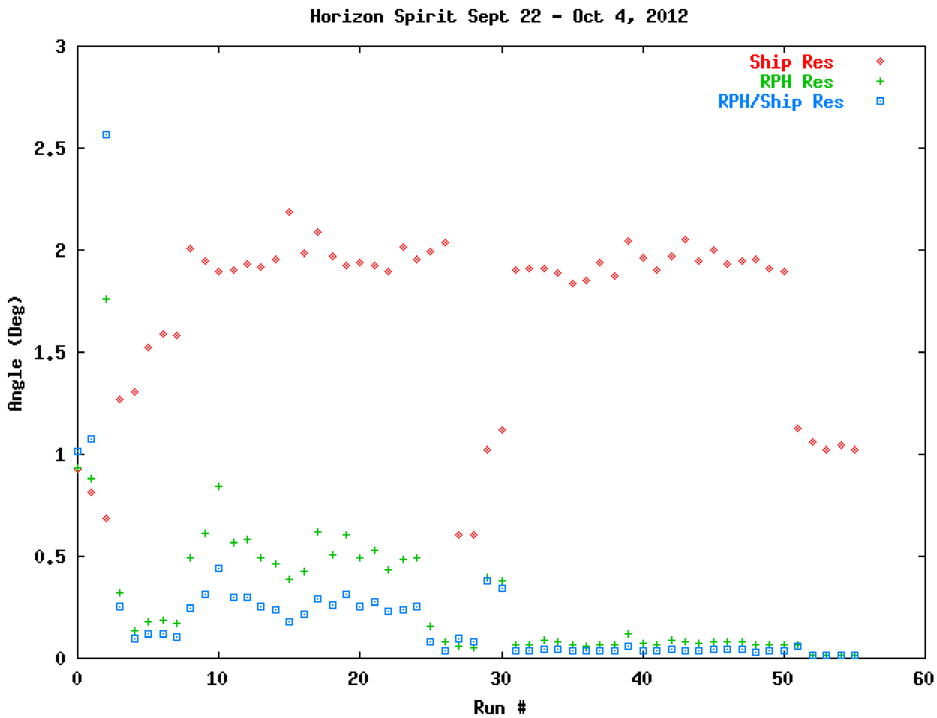


Figure 8. Mean (left) and standard deviation (right) of roll from ship (red), RPH table (green), and ratio of table to ship (blue). Values obtained from roughly hour-long periods during cruise. Values show improvement of algorithm as control variables are fine-tuned during voyage.



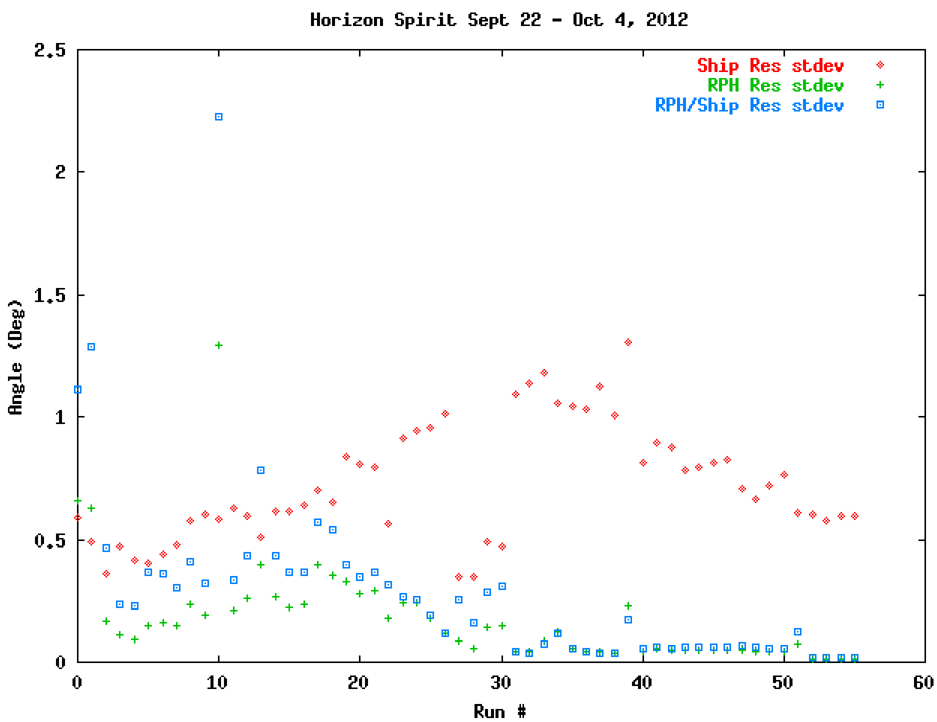


Figure 9. Mean (left) and standard deviation (right) of resultant tilt from ship (red), RPH table (green), and ratio of table to ship (blue). Values obtained from roughly hour-long periods during cruise. Values show improvement of algorithm as control variables are fine-tuned during voyage.

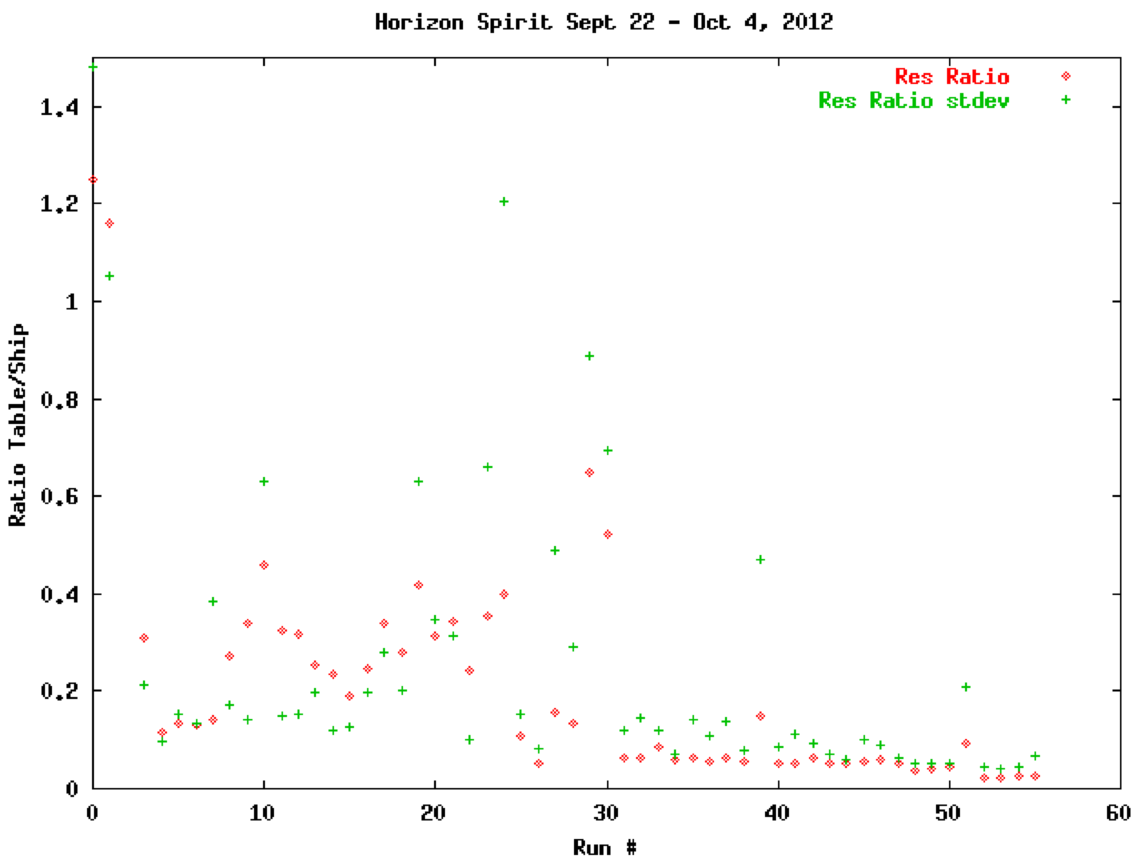


Figure 10. Mean (red) and standard deviation (green) of resultant tilt ratio (table/ship). Here, the ratio is calculated from instantaneous values of ship and table resultant rather than the ratio of the means in Figures 7–9. Values show improvement as control variables are fine-tuned during voyage.

Unfortunately, we were not able to use the enhanced PID approach for any significant period following this voyage because the Kearfott SeaNav began to fail and was not replaced until December. After the MWACR was installed in early November, the straight PID approach was used for all of November and most of December. Results from these cruises are summarized in Figures 11–12. Dates for the cruises are given in Table 1. Note that cruise number 7B is not present because one of the legs of the table malfunctioned and could not be repaired until reaching port. Overall conditions did not vary significantly among cruises, although there were periods of heavier conditions during the earlier portion of the travel that were north of the trade winds (Figure 11). It should be noted that most of the larger table tilt values during 8B and 9B are times when the enhanced PID routine was used with inappropriate feedback values. It is important to note that during 5A, the table was “told” to point at −1° (relative to the table), rather than the usual 0. This is reflected in the tilt values in Figure 11 and subsequent probability distributions.

The best variables for quantifying the table response in an ongoing way are the standard deviations of roll, pitch, and to some degree, tilt. Figure 12 compares 15-minute calculations of roll and pitch standard deviation for both ship and table. In general, table roll and pitch standard deviations are more than an order of magnitude less than ship values. Probability distributions of tilt (Figure 13) reflect this as well; again, note the additional distribution of table values around 1° on leg 5A. The 2D probability distributions (Figure 14) illustrate the fact that the ship usually is somewhat tilted to port and the combination of roll and pitch is such that the largest and most often encountered ship tilts are to port and forward. The table, on the other hand, has an even distribution of small tilt angles.

The cumulative probability distributions shown in Figure 15 indicate that, overall, more than 90% of table tilt values are within 0.1° of level and more than 99% are within 0.5°. This is encouraging because it is anticipated that systematic use of the enhanced PID approach will improve this performance.

We emphasize that these performance values depend entirely on the local tilt sensor being used. As will be discussed later, there is some question about the absolute accuracy of that instrument. However, that in no way affects the representative capability of the table. If a different local measure of error is available, the table should respond equally well to that input.

Finally, Table 1 gives a statistical summary, by cruise, of the table performance.

Table 1. Times and directions of cruise numbers.

Number	Begin Date	End Date	Direction
2A	09/22/12 23:00	09/27/12 05:00	SW
2B	09/28/12 11:00	10/04/12 13:00	NE
5A	11/3/12 19:00	11/8/12 14:00	SW
5B	11/9/12 18:00	11/15/12 14:00	NE
6A	11/17/12 14:00	11/22/12 06:00	SW
6B	11/24/12 12:00	11/30/12 01:00	NE
7A	12/01/12 15:00	12/06/12 09:00	SW
8A	12/15/12 14:00	12/20/12 14:00	SW
8B	12/22/12 10:00	12/27/12 23:00	NE
9A	12/29/12 13:00	01/03/13 06:00	SW
9B	01/05/13 08:00	01/08/13 15:00	NE

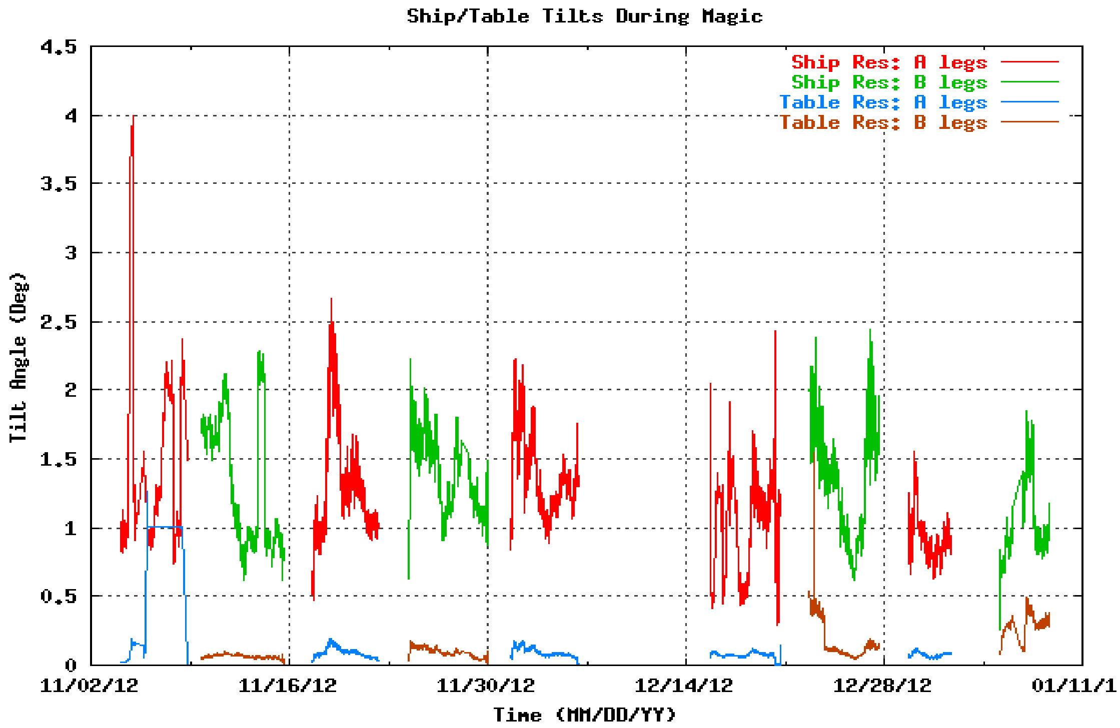


Figure 11. Synopsis of mean tilt values for ship and table. Values are averaged over 15 minutes and separated by cruise number and direction.

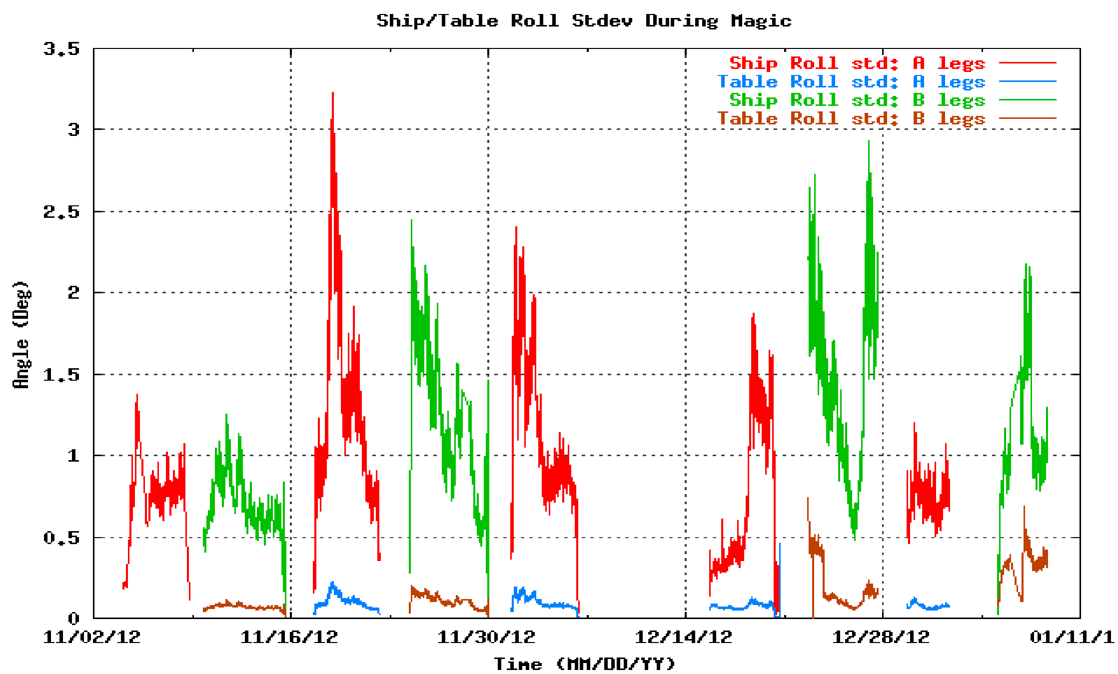


Figure 12. 5-minute calculations of roll and pitch standard deviation for both ship and table.

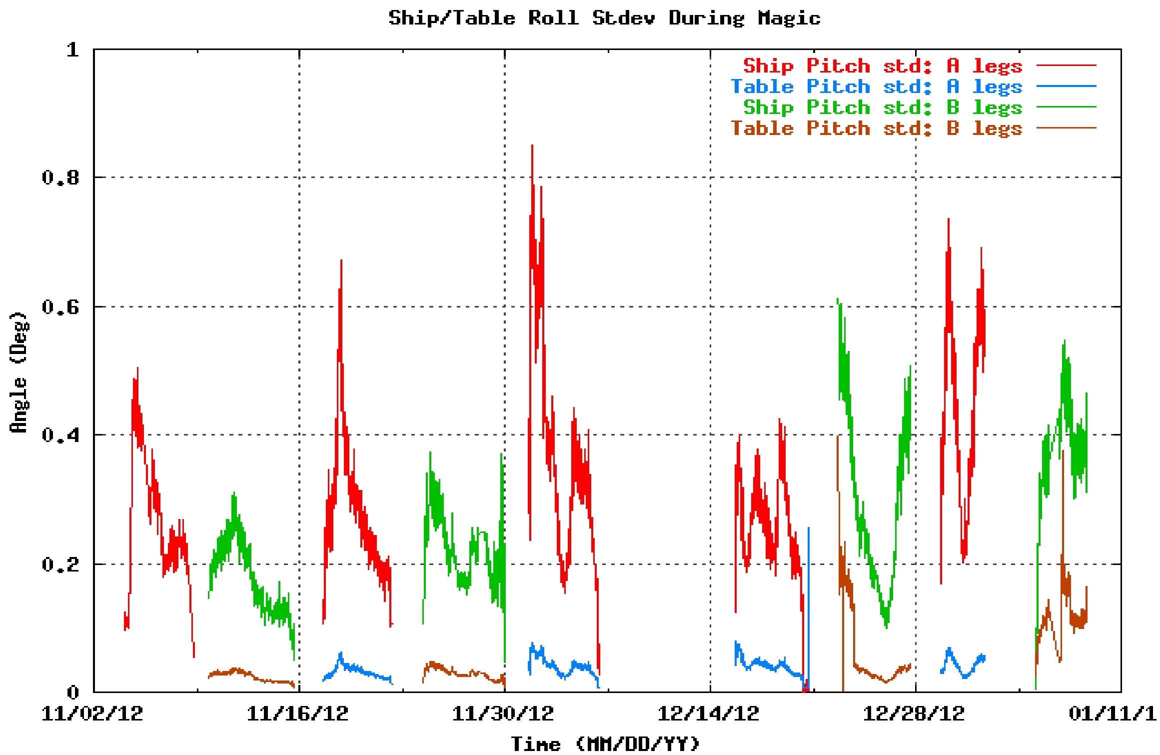
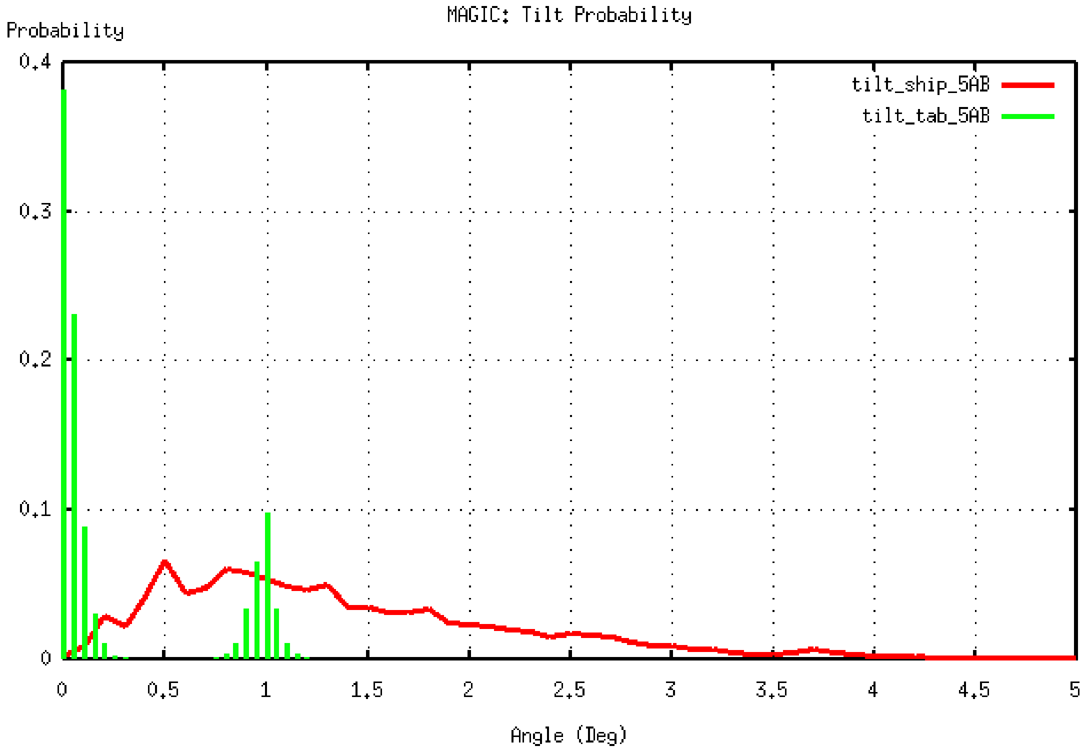
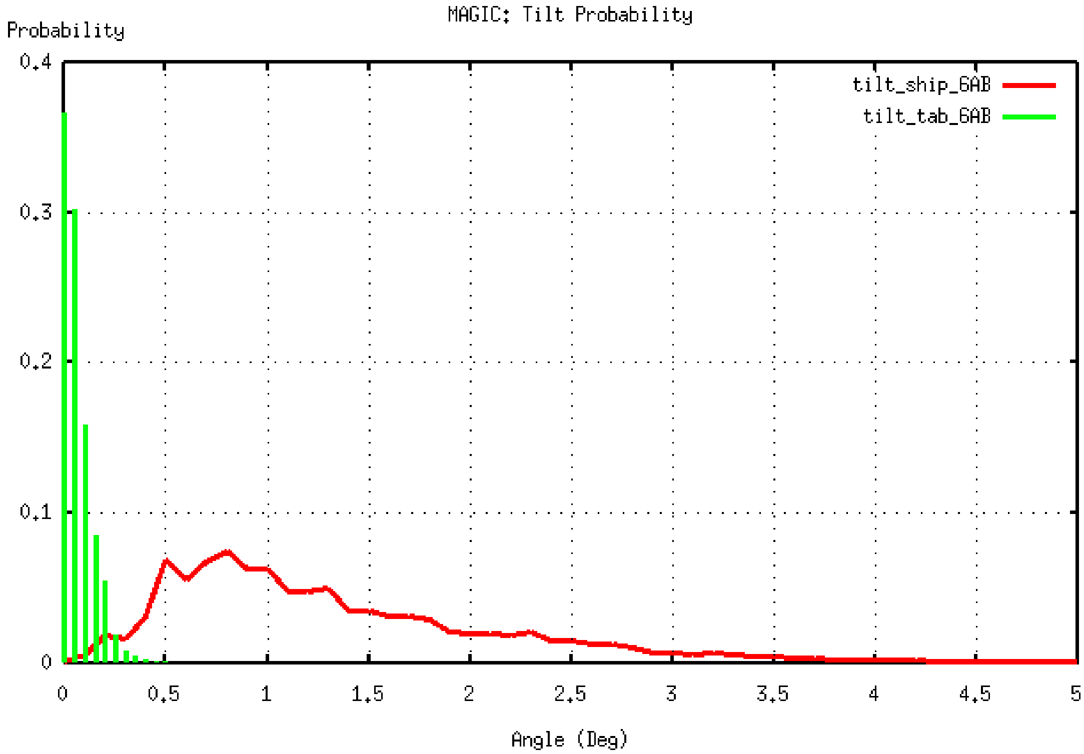
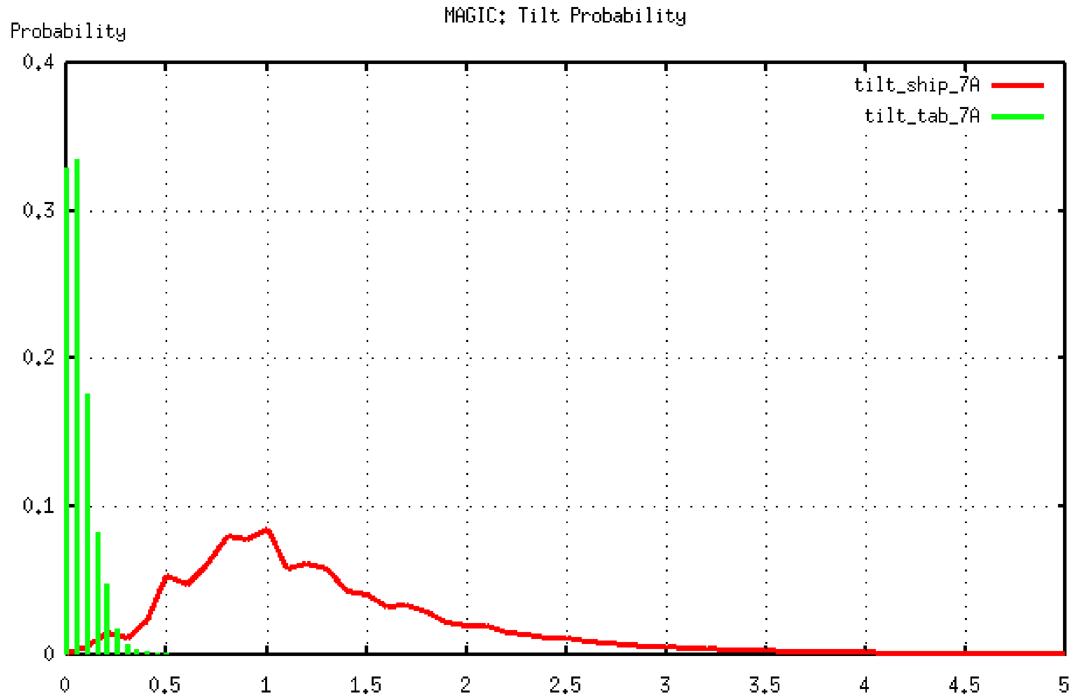
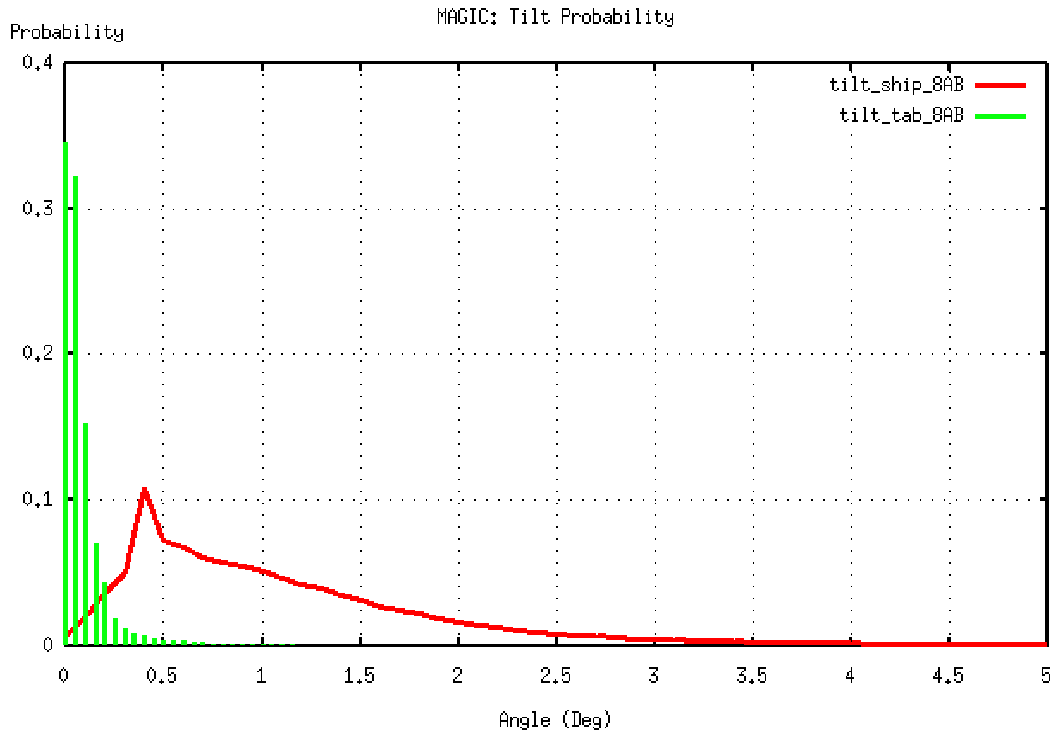


Figure 13. Synopsis of roll (above) and pitch (below) standard deviations during MAGIC. Values are derived from 15-minute samples sampled at 20 Hz and are separated by cruise number and direction.


MAGIC: Tilt Probability
Probability
0.4
0.3
0.2
0.1
0
tilt_ship_5AB
tilt_tab_5AB
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Angle (Deg)


MAGIC: Tilt Probability
Probability
0.4
0.3
0.2
0.1
0
tilt_ship_6AB
tilt_tab_6AB
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Angle (Deg)


MAGIC: Tilt Probability
Probability
tilt_ship_7A
tilt_tab_7A
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


MAGIC: Tilt Probability
Probability
tilt_ship_8AB
tilt_tab_8AB
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Angle (Deg)

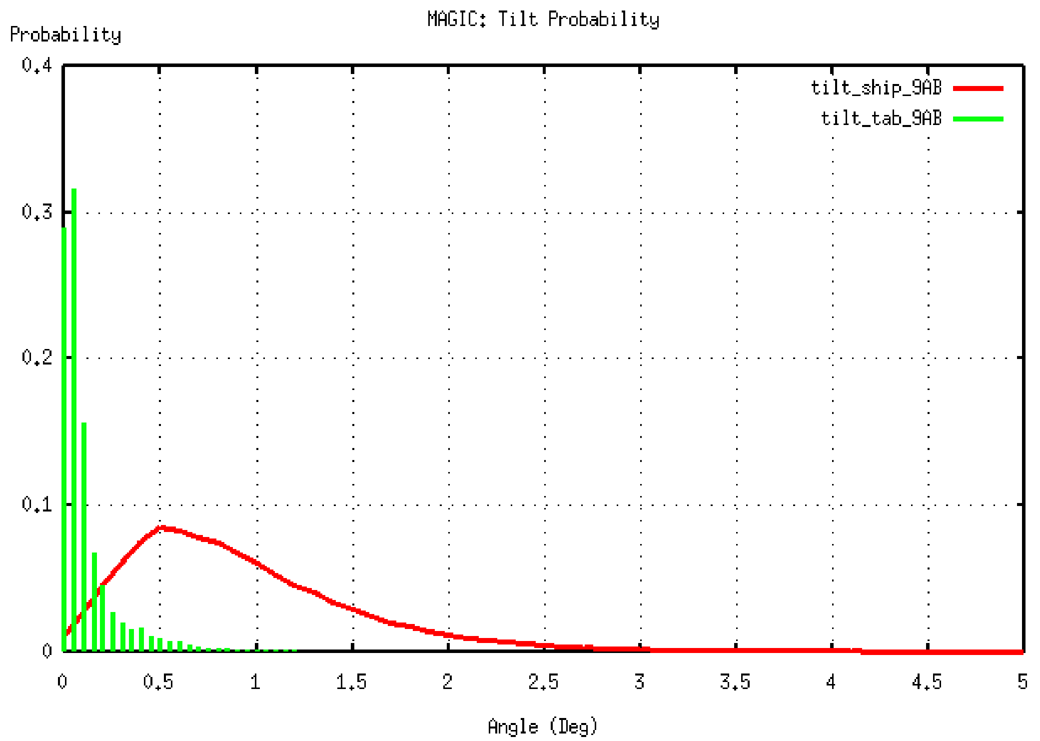
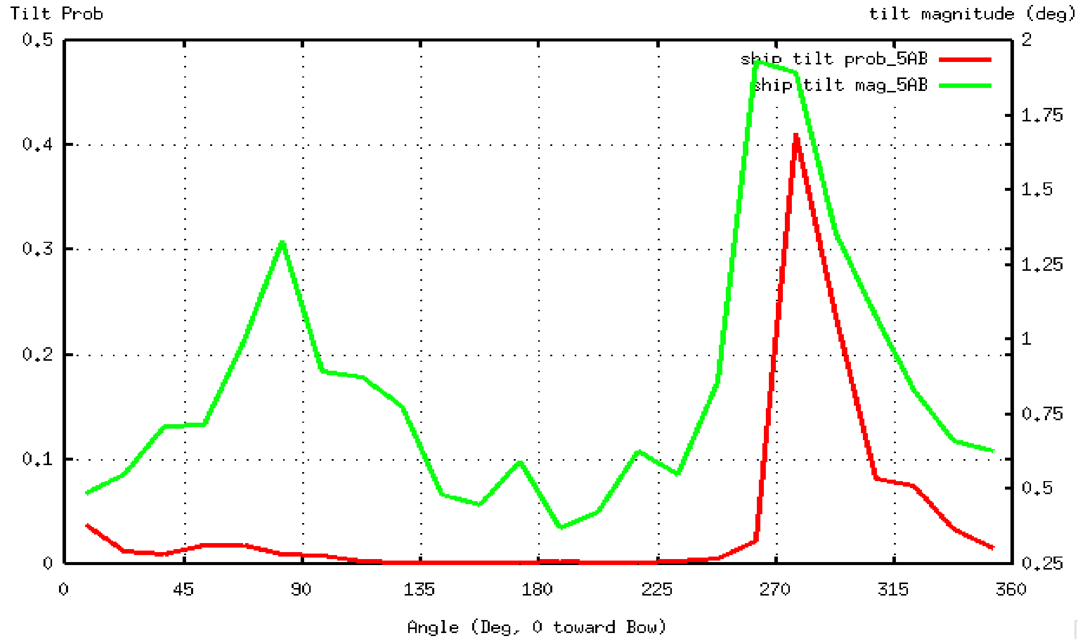
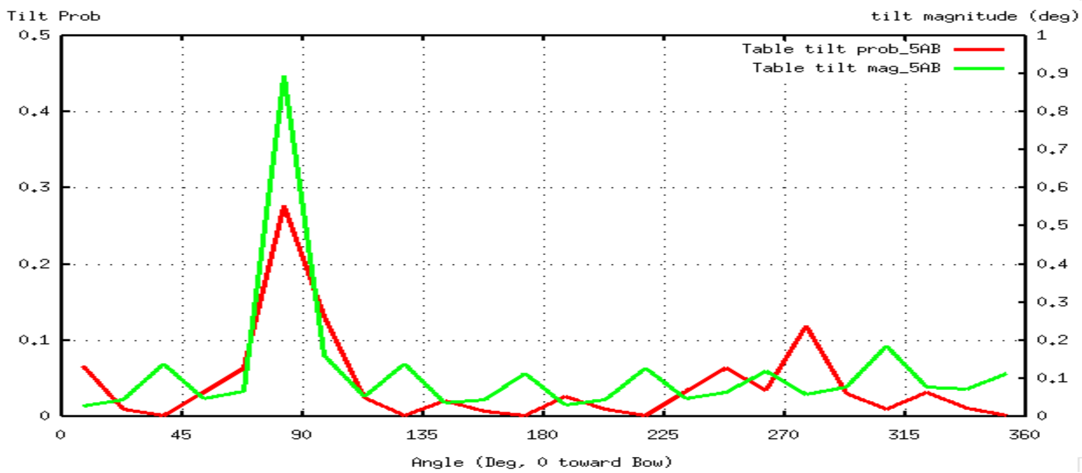
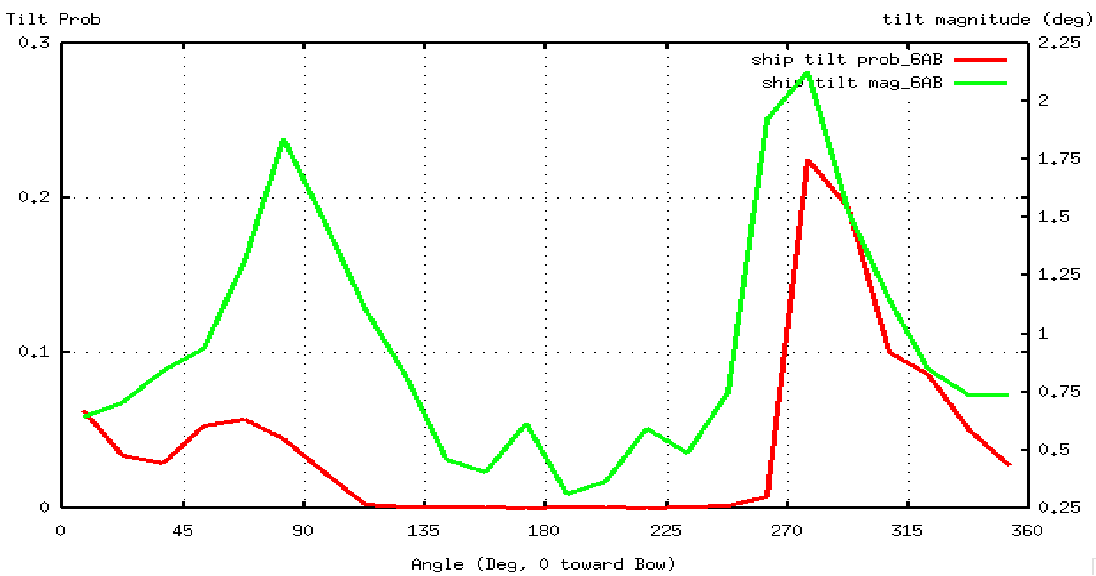
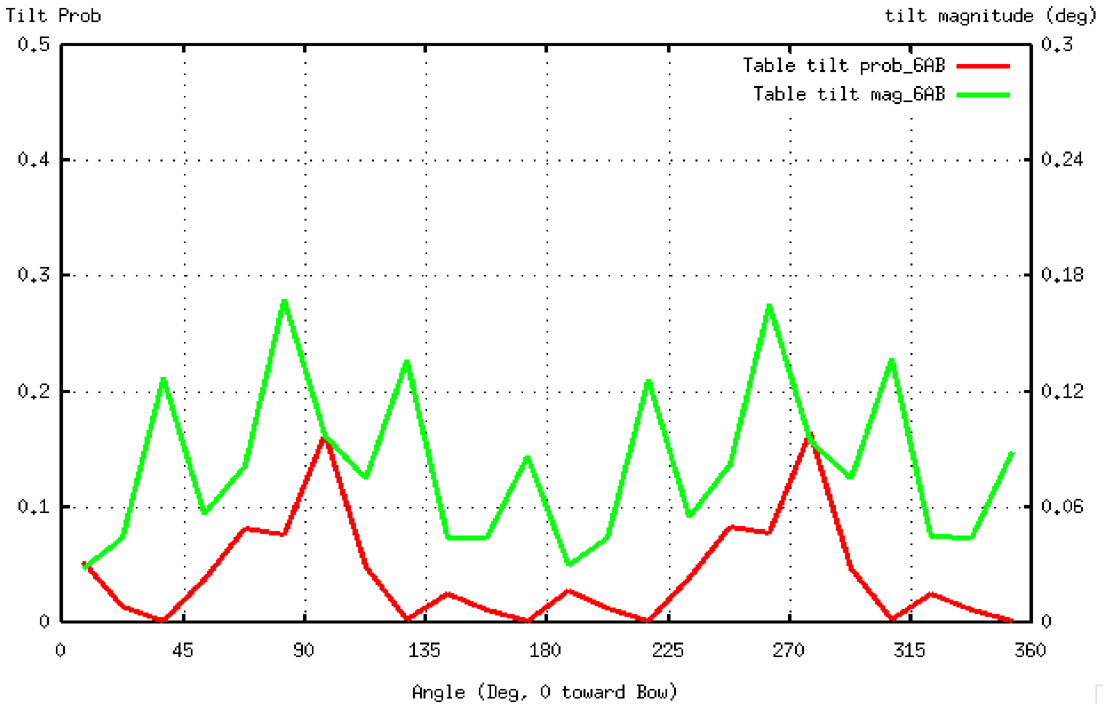


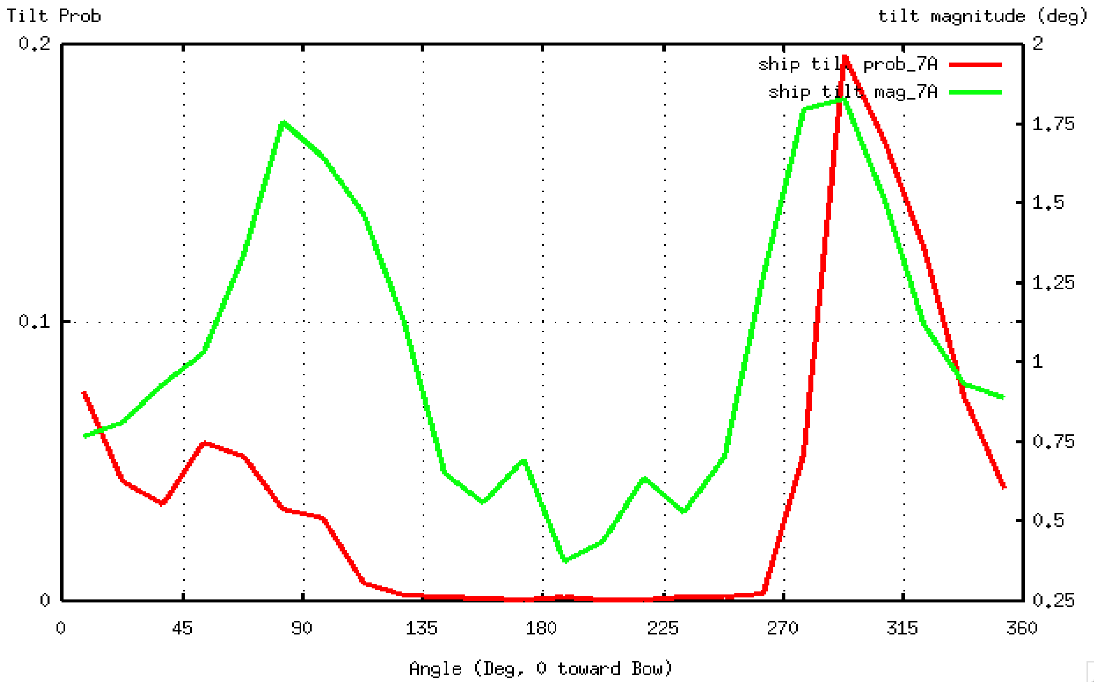
Figure 14. Probability distributions of ship (red) and table (green) tilt angles for ship cruises 5-9. Westward (A) and eastward (B) legs were combined in these plots. Data are sampled at 4 Hz.

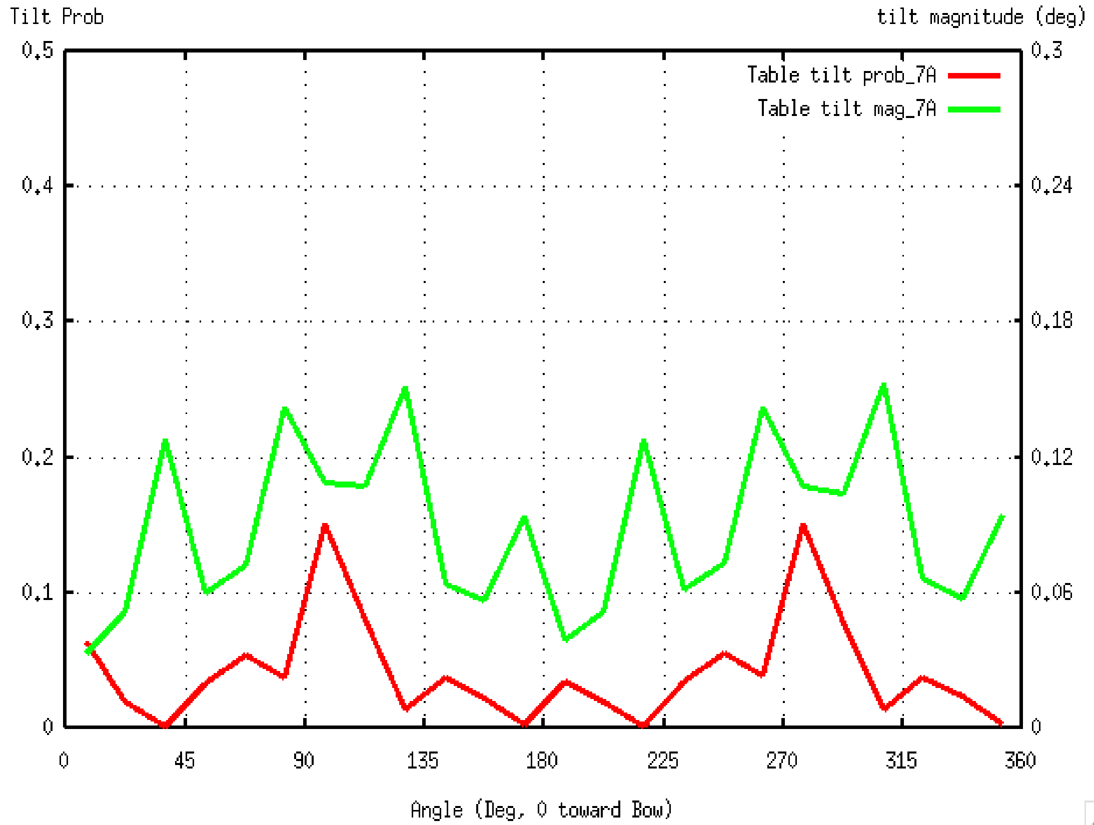

Tilt Prob
tilt magnitude (deg)
ship tilt prob_5AB
ship tilt mag_5AB
0.5
0.4
0.3
0.2
0.1
0
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
45
90
135
180
225
270
315
360
Angle (Deg, 0 toward Bow)

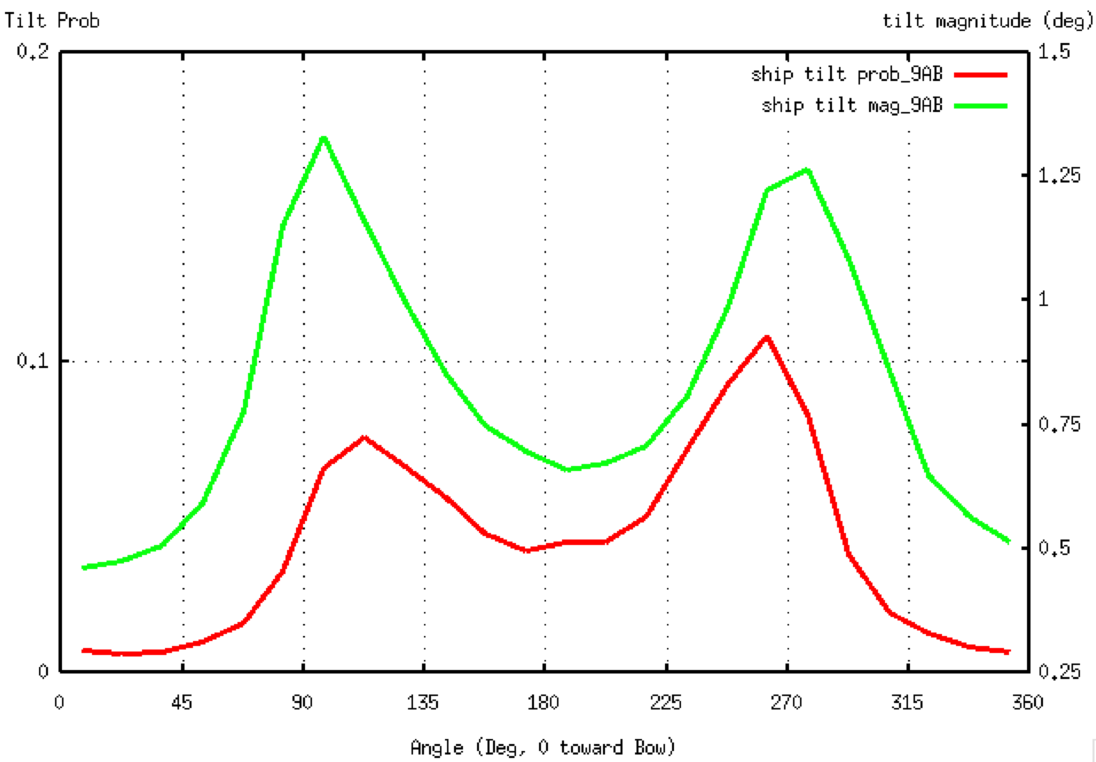

Tilt Prob
tilt magnitude (deg)
Table tilt prob_5AB
Table tilt mag_5AB
0.5
0.4
0.3
0.2
0.1
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
45
90
135
180
225
270
315
360
Angle (Deg, 0 toward Bow)

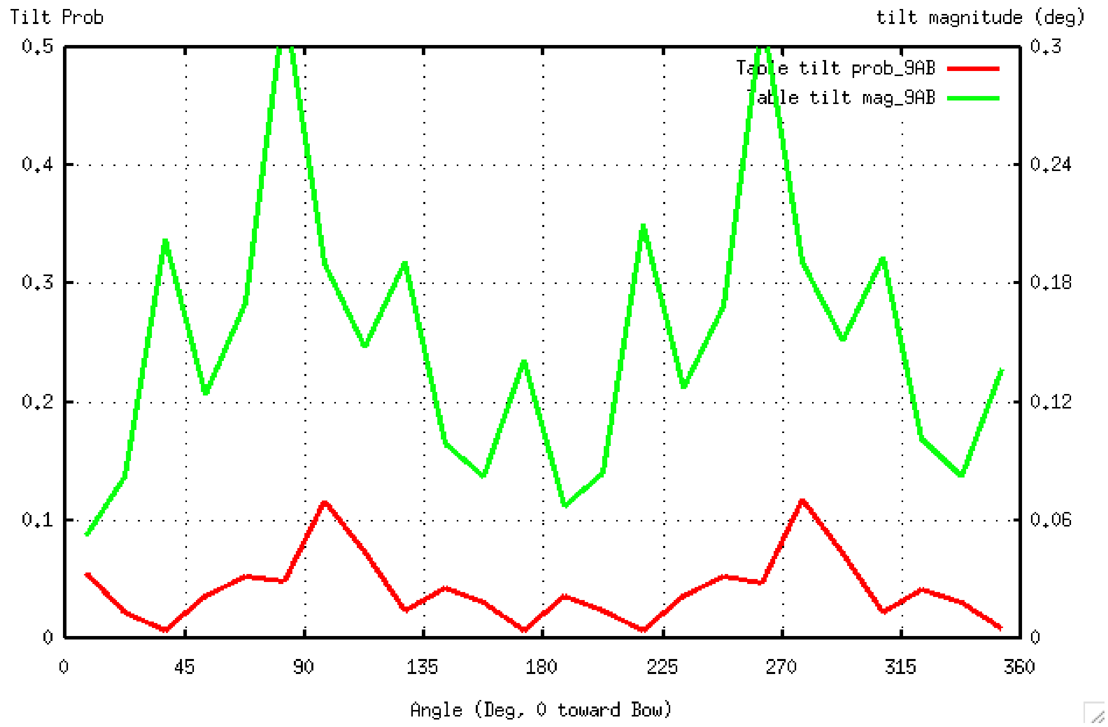

Tilt Prob
tilt magnitude (deg)
ship tilt prob_6AB
ship tilt mag_6AB
0.3
0.2
0.1
0
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
45
90
135
180
225
270
315
360
Angle (Deg, 0 toward Bow)

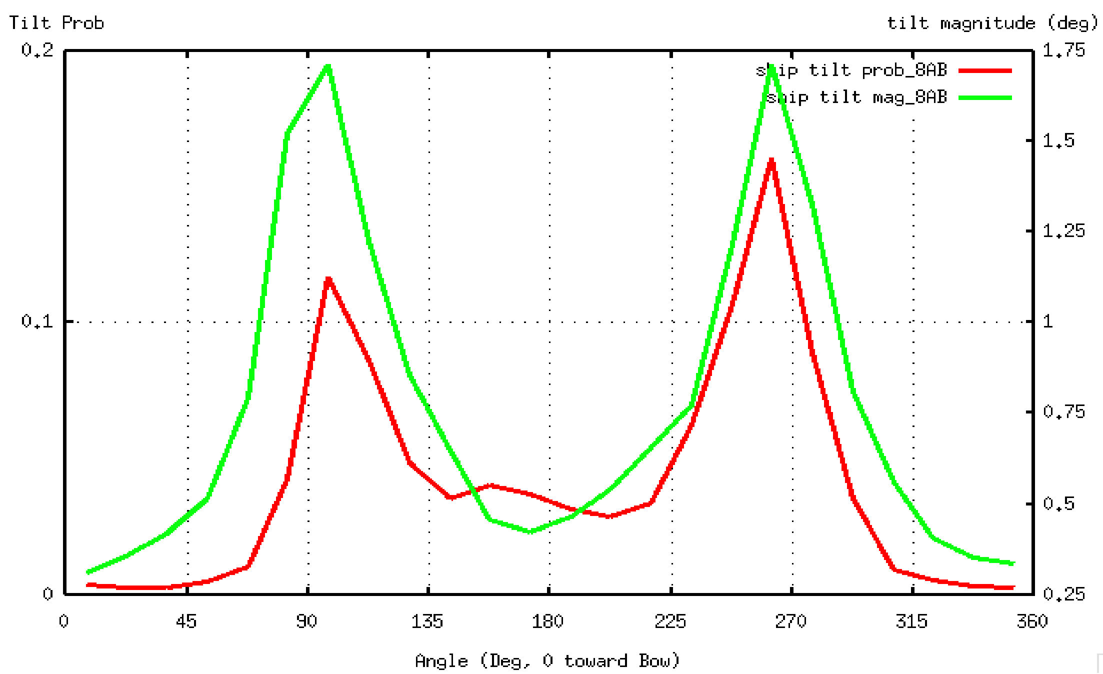

Tilt Prob
tilt magnitude (deg)
Table tilt prob_6AB
Table tilt mag_6AB
0.5
0.4
0.3
0.2
0.1
0
0.3
0.24
0.18
0.12
0.06
0
0
45
90
135
180
225
270
315
360
Angle (Deg, 0 toward Bow)


Tilt Prob
tilt magnitude (deg)
ship tilt prob_7A
ship tilt mag_7A
0.2
0.1
0
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
45
90
135
180
225
270
315
360
Angle (Deg, 0 toward Bow)


Tilt Prob
tilt magnitude (deg)
Table tilt prob_7A
Table tilt mag_7A
0.5
0.4
0.3
0.2
0.1
0
0.3
0.24
0.18
0.12
0.06
0
0
45
90
135
180
225
270
315
360
Angle (Deg, 0 toward Bow)


Tilt Prob
tilt magnitude (deg)
ship tilt prob_9AB
ship tilt mag_9AB
0.2
0.1
0
1.5
1.25
1
0.75
0.5
0.25
0
45
90
135
180
225
270
315
360
Angle (Deg, 0 toward Bow)


Tilt Prob
tilt magnitude (deg)
0.5
0.4
0.3
0.2
0.1
0
0.3
0.24
0.18
0.12
0.06
0
0
45
90
135
180
225
270
315
360
Table tilt prob_9AB
Table tilt mag_9AB
Angle (Deg, 0 toward Bow)


Tilt Prob
tilt magnitude (deg)
0.2
0.1
0
1.75
1.5
1.25
1
0.75
0.5
0.25
0
45
90
135
180
225
270
315
360
ship tilt prob_8AB
ship tilt mag_8AB
Angle (Deg, 0 toward Bow)

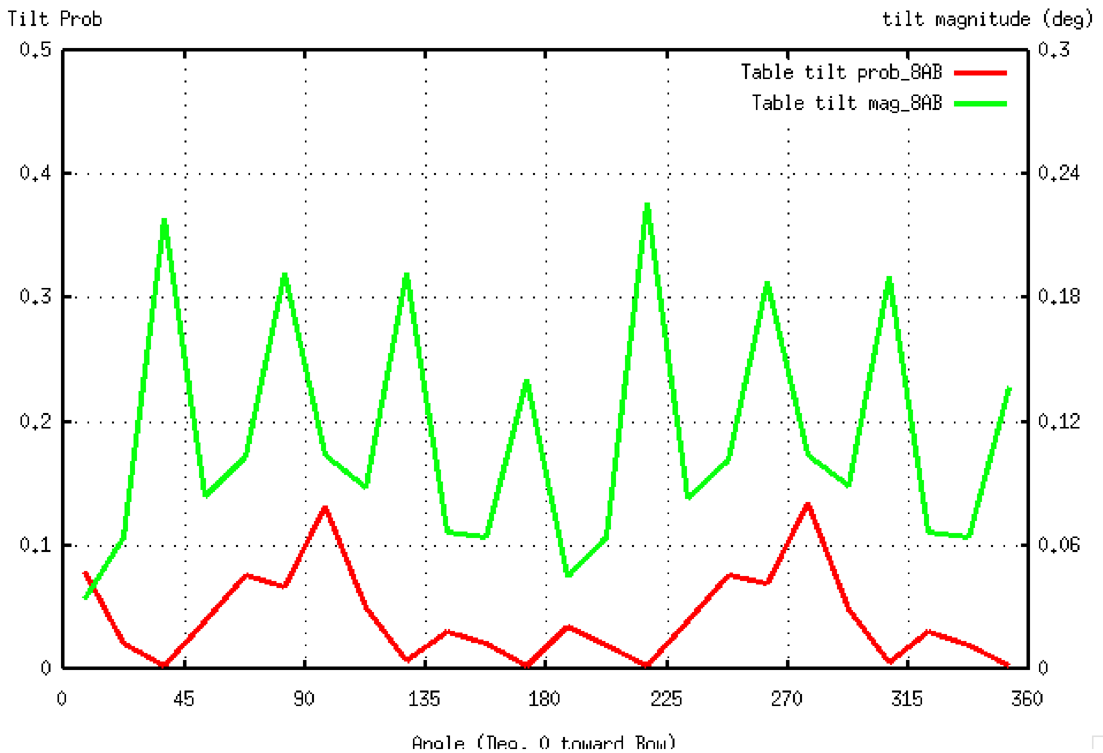
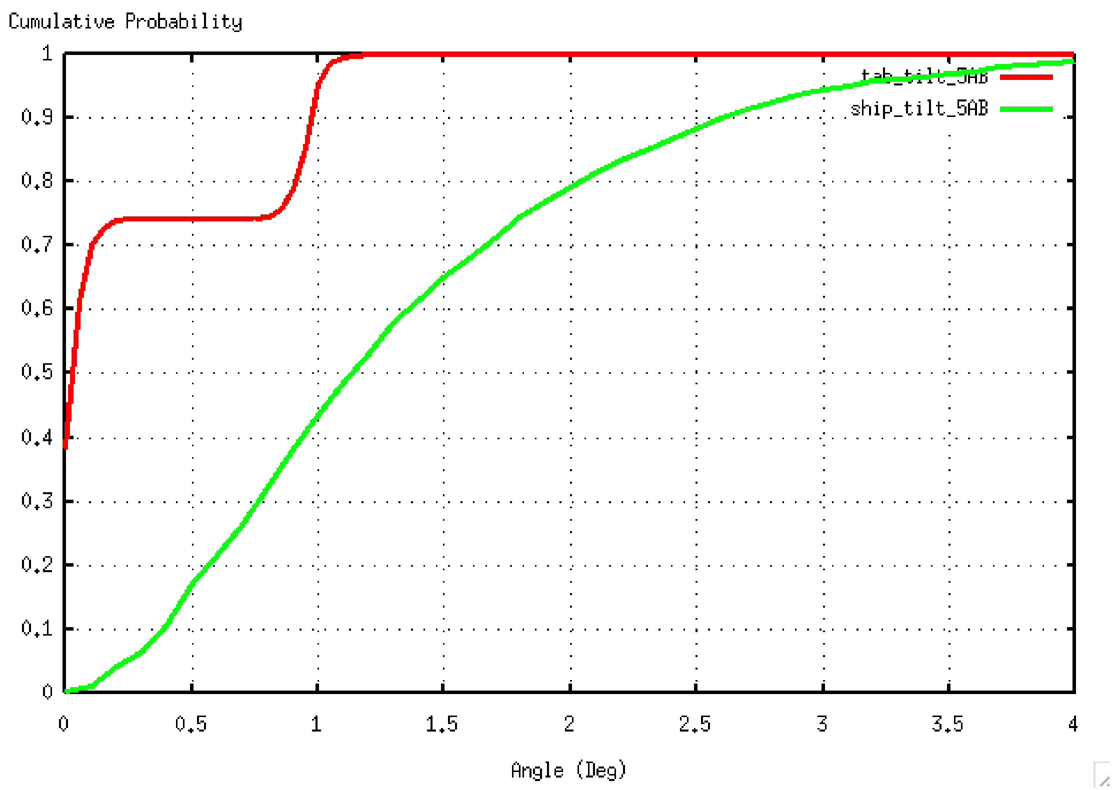
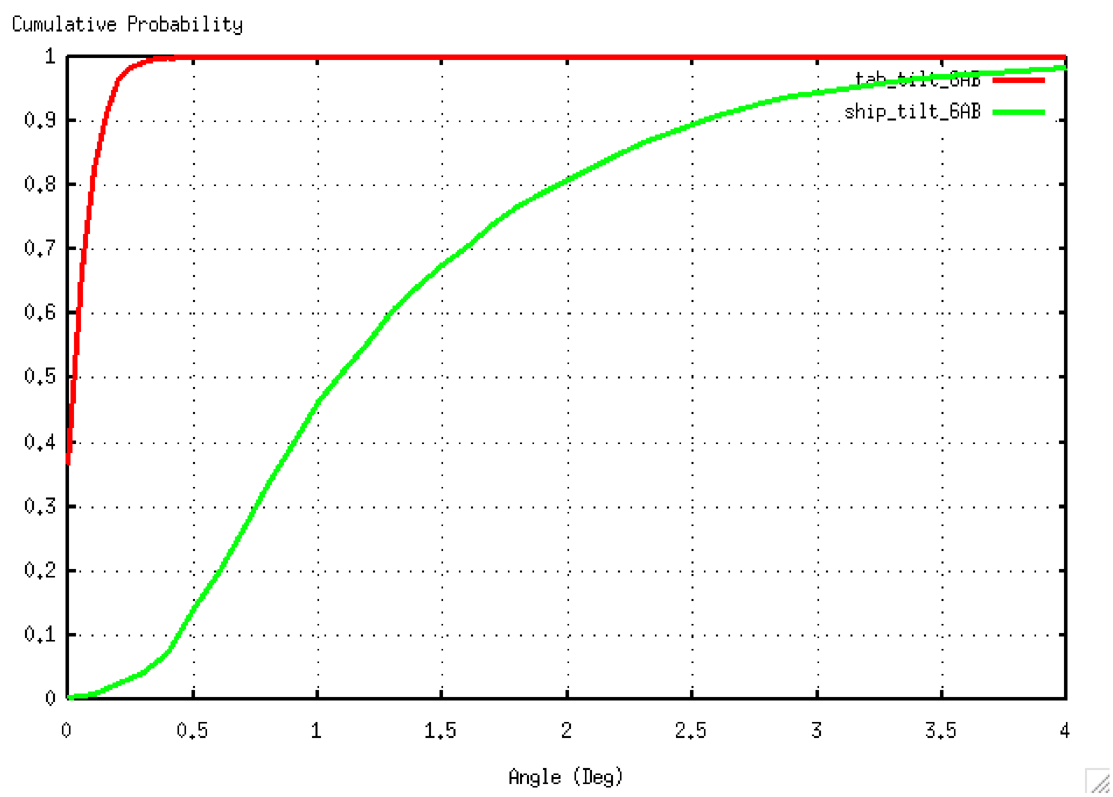
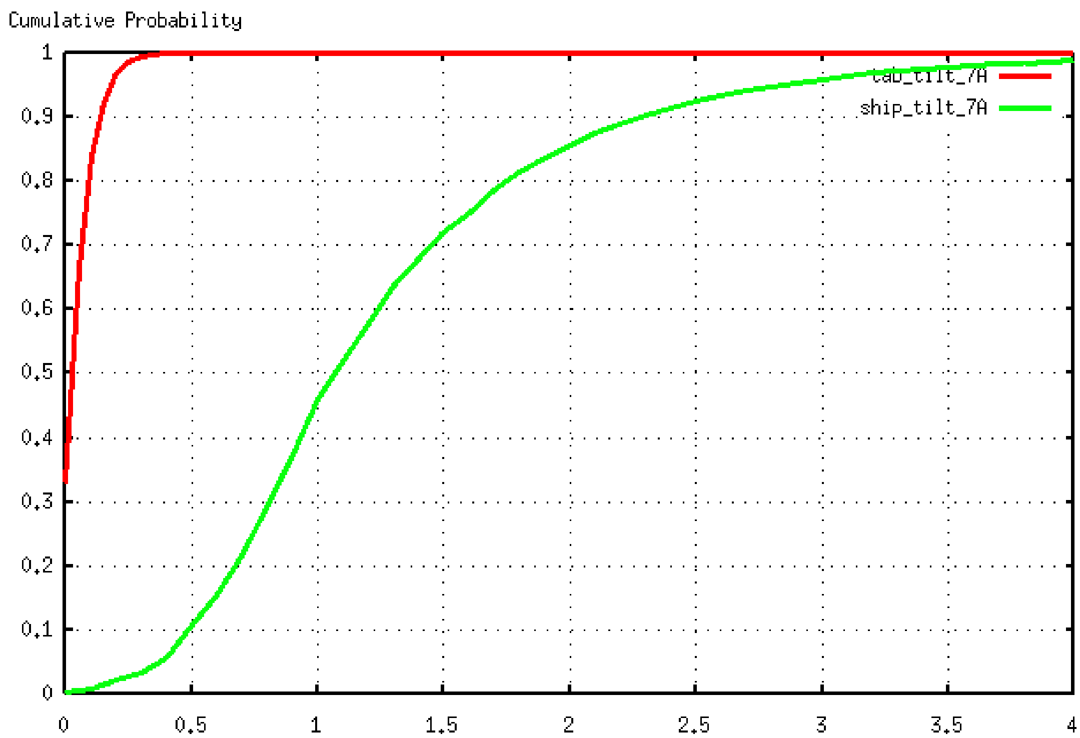
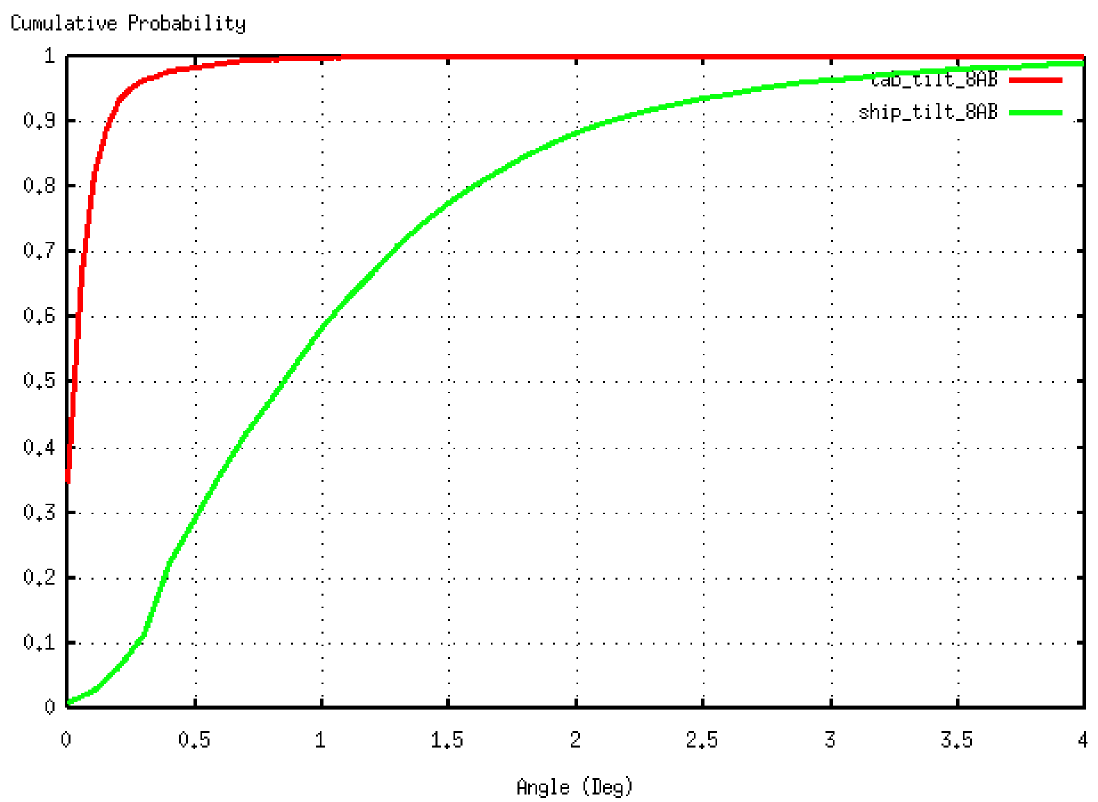


Figure 15. Two-dimensional probability distributions of tilt for ship (left) and table (right).


Cumulative Probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
Angle (Deg)
ship_tilt_5AB


Cumulative Probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
Angle (Deg)
ship_tilt_6AB


Cumulative Probability
cab_tilt_7A
ship_tilt_7A
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4


Cumulative Probability
cab_tilt_8AB
ship_tilt_8AB
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
Angle (Deg)

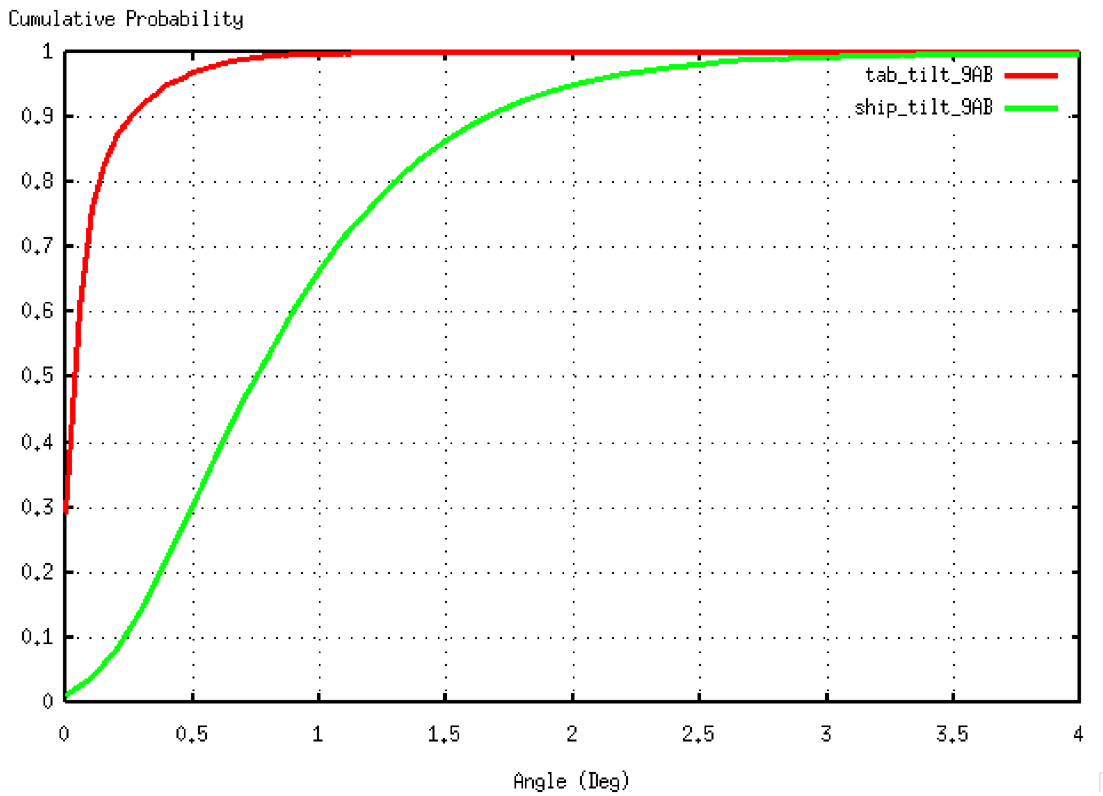


Figure 16. Cumulative probability distributions of tilt of ship (green) and table (red) for five cruises.

Table 2. Statistics from MAGIC cruise 5–9.

Cruise	Roll	Roll Std	Roll Ratio	Pitch	Pitch Std	Pitch Ratio
5A	-0.72	0.060	0.085	0.05	0.032	0.130
5B	0.00	0.069	0.101	0	0.024	0.137
6A	0.00	0.101	0.082	0	0.031	0.116
6B	0.00	0.106	0.087	0	0.029	0.131
7A	0.00	0.098	0.088	0	0.041	0.117
8A	0.00	0.070	0.134	0	0.039	0.255
8B	0.00	0.118	0.093	0	0.029	0.126
9A	0.00	0.075	0.101	0	0.042	0.097
9B	0.00	0.121	0.091	0	0.052	0.125

6.0 Conclusions and Recommendations

We have made considerable progress in understanding and using the AMF2 RPH stable platform. It is reasonable to conclude that with the present system we can expect to maintain the platform within 0.1° of level more than 90% of the time in moderate conditions. This should certainly suffice for almost all the radiometry measurements presently made in the ARM Climate Research Facility. It is not known if this degree of control is sufficient for cloud vertical velocity measurements. In placing the MWACR on the table, apparently two offset values were insufficiently resolved: 1) the alignment between the MWACR IMU and the radar antenna, and 2) the alignment between the MWACR IMU and the table tilt sensor. We have no control over number 1. However, it was clear that there were differences between the static position of the MWACR and our tilt sensor, on the order of −0.9° in roll (tilt sensor–IMU) and 0.6° in pitch from estimates taken during installation. That is why the capability of pointing at any angle was incorporated into the RPH software. The actual value of this difference still needs to be resolved.

A larger, unresolved problem remains in the dynamic response of the Watson tilt sensor that has been used for table correction. Figure 17 shows a short time series that compares the real-time output from the IMU and the Watson tilt sensor during a period when the RPH table was not running, although data was still available from both the IMU and a second Watson tilt sensor that was being used to monitor ship motion data while the Kearfott SeaNav was being replaced. During the period of this data, the table was not operating. The offset results from the offsets mentioned above and from the fact that when the table is at rest, it is not parallel to the deck of the ship. More important are the evident periods when the Watson (green) sensor "sees" ship motion that is not evident in the IMU (red): for example, at 70455 and 70470 seconds. Because the Watson-type sensor is used to control the table, these additional motions will be compensated in the table control.

The question as to which sensor is closer to reality remains, of course. We can answer that question, at least tentatively, by observing Figure 18. This time series, again of the roll component of motion, was taken when the new Hydrins ship navigation system was installed and operating. Here again, the table was not running, and the Hydrins data are included. In this case, the offsets have been removed from the data to allow precise comparison. The Hydrins and MWACR IMU agree with one another quite closely (with a few minor differences), particularly in the periodicity and location of maxima. The Watson, on the other hand, again shows slightly different periodicity at times (8115 s) and consistently appears to overshoot the maxima and minima observed by the Hydrins and MWACR IMU.

It appears evident, therefore, that the Watson tilt sensor may be inadequate for the precise timing and measurement accuracy required for MWACR measurements using the RPH table. This fault is not with the table, but with the sensor used for the error function in the PID.

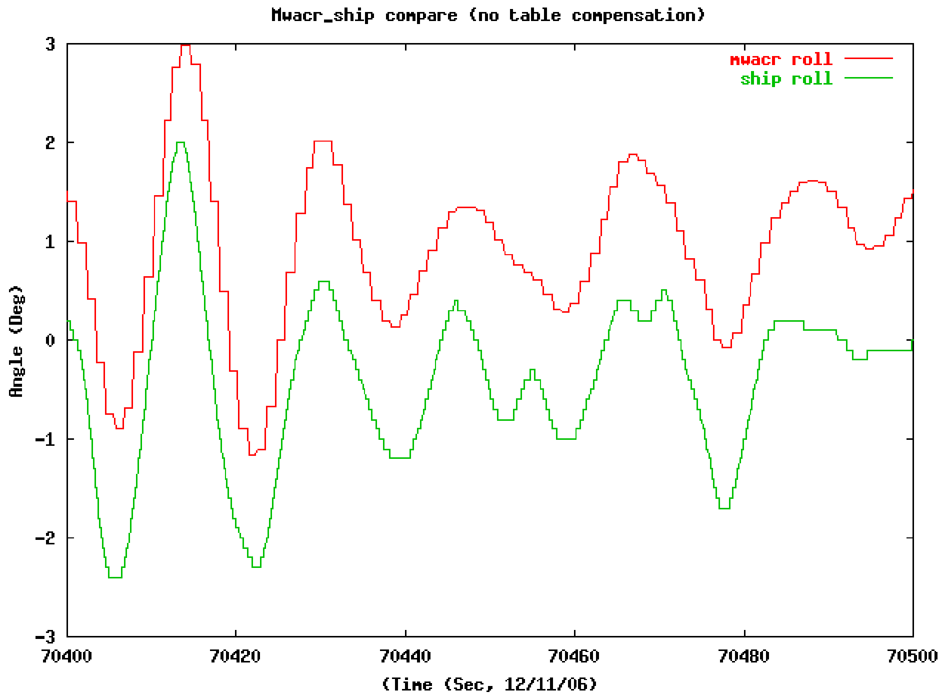


Figure 17. Time series of roll measured by Watson tilt sensor (green) and MWACR IMU (red) during a period when table was not operating. The offset is arbitrary because the table rest position is not parallel to the ship's deck.

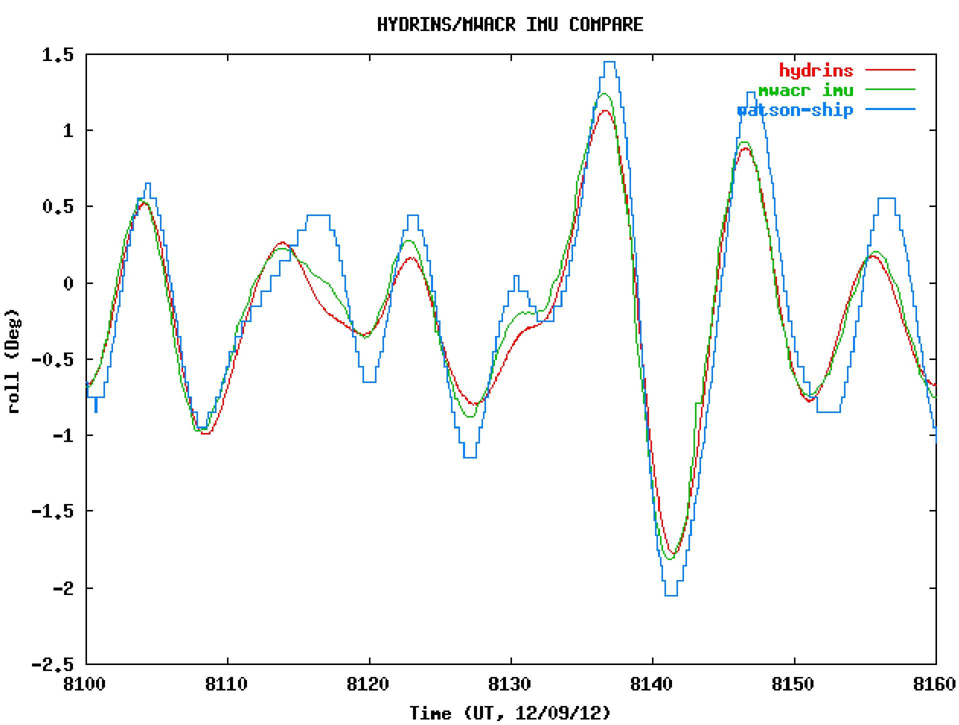


Figure 18. Time series of roll measured by Watson tilt sensor (blue), MWACR IMU (green), and Hydrins (red) during a period when the table was not operating.

The solution to this problem is simply to use the data from the MWACR IMU to control the RPH rather than the Watson tilt sensor. This will eliminate at least one of the alignment problems mentioned above (between table and MWACR). After all, it is the instrument on the table that needs to be level, not necessarily the table itself. This solution is being implemented in the continued deployment plans by making the IMU values available in real-time to the RPH control.

7.0 References

Kafle, DN, and RLCoulter. 2012. “Micropulse lidar-derived aerosol optical depth climatology at ARM sites worldwide.” *Journal of Geophysical Research: Atmospheres* 118: 7293-7308, doi:10.1002/jgrd.50536.

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