ANL/EVS/TM-13/2

# Report on the AMF2 RPH Stabilization Platform: Design and Evaluation

Environmental Science Division

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# Report on the AMF2 RPH Stabilization Platform: Design and Evaluation

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# NOTATION

| | |
|---|---|
| AMF2 | second ARM Mobile Facility |
| ARM | Atmospheric Radiation Measurement |
| deg | degree(s) |
| ft | foot (feet) |
| hr | hour(s) |
| Hz | hertz |
| IMU | inertial measurement unit |
| MAGIC | Marine ARM GCIP Investigation of Clouds |
| min | minute(s) |
| MWACR | marine W-band ARM cloud radar |
| PID | proportional-integral-derivative |
| RPH | roll, pitch, heave |
| RPY | roll, pitch, yaw |
| SEANAV | Seaborne Navigation System |
| sec | second(s) |

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# REPORT ON THE AMF2 RPH STABLIZATION PLATFORM: DESIGN AND EVALUATION

Richard L. Coulter and Timothy J. Martin

## 1 INTRODUCTION

One of the primary objectives of the Atmospheric Radiation Measurement (ARM) Program's second ARM Mobile Facility (AMF2) is to obtain reliable measurements of radiation (solar, surface, and atmospheric), 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. Of the numerous ARM instruments that require a zenith orientation, perhaps the most important are the vertically pointing cloud radars, for which vertical motion is 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 the instruments. The first platform compensated for roll, pitch, and yaw (RPY), as reported previously.[1] Subsequently, a second platform was purchased specifically for operation with the marine W-band ARM cloud radar (MWACR),[2] to compensate for roll, pitch, and heave (RPH). Computer programs originally developed for RPY compensation were modified to communicate with the new RPH platform controller and with an inertial measurements platform that measures true ship motion components (roll, pitch, yaw, surge, sway, and heave). This RPH platform could not be tested dynamically, as the RPY platform had been, because of time constraints requiring deployment aboard the container ship Horizon *Spirit* in September 2012. Hence, the initial motion tests were conducted on the first cruise. Subsequent cruises provided additional test results. The RPH platform, as tested, meets all design and performance criteria established for its use.

This document reports on the results of the RPH platform stabilization efforts and the critical points in moving forward.

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[1] Coulter, R.L., T.J. Martin, and B.W. Orr, 2012, *Report on the AMF2 RPY Stabilization Platform: Design and Evaluation*, ANL/EVS/TM/12-2, Environmental Science Division, Argonne National Laboratory, Argonne, Illinois, August.

[2] See http://www.arm.gov/instruments/mwacr.

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## 2 STABILIZATION SYSTEM DESCRIPTION

Previous experience with RPY compensation led to the choice of the RPY platform manufacturer for the RPH platform, principally because of expense and economy of effort. The RPH controller would be very similar to the RPY controller, and use of the same manufacturer would decrease the time required to develop sufficient control of the RPH platform for deployment within a few months of purchase. However, a hydraulic system was added to the RPH platform because the weight requirements of the payload were greater, and critical elements received less exposure to the ocean environment.

The AMF2 stable platform, built by Sarnicola Systems (Figure 1), 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 compensation is not possible for all of the considerable movement of a ship in the vertical dimension, the third (vertical) degree of freedom is used to maintain the platform at a constant height above its base (and the ship's deck); knowledge of the rate of change of heave measured from the ship's navigation data stream can then be used to compensate for vertical motion of the platform.

**FIGURE 1. The AMF2 RPH stable platform, as originally designed and received.**

The platform's roll and pitch are manipulated by lengthening and shortening the three legs that support the platform. The leg in the foreground in Figure 1 is A; the leg at the left rear is B; and the leg at the right rear is C. The lengths of the legs are under independent hydraulic control by three sensors mounted on the legs, and each leg has 12,000 encoder positions (compared to 118,000 for the electric motors on the RPY platform). When leg B is increased in length and legs A and C are moved equal amounts, the platform tilts in what we have defined as the pitch direction; when legs A and C change in opposite senses with leg B constant, the platform tilts in the roll direction. The dimensions of this particular platform allow for ± 30 deg of pitch and ± 25 deg of roll. However, as for the RPY platform, one cannot reach the extremes of roll and pitch simultaneously.

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

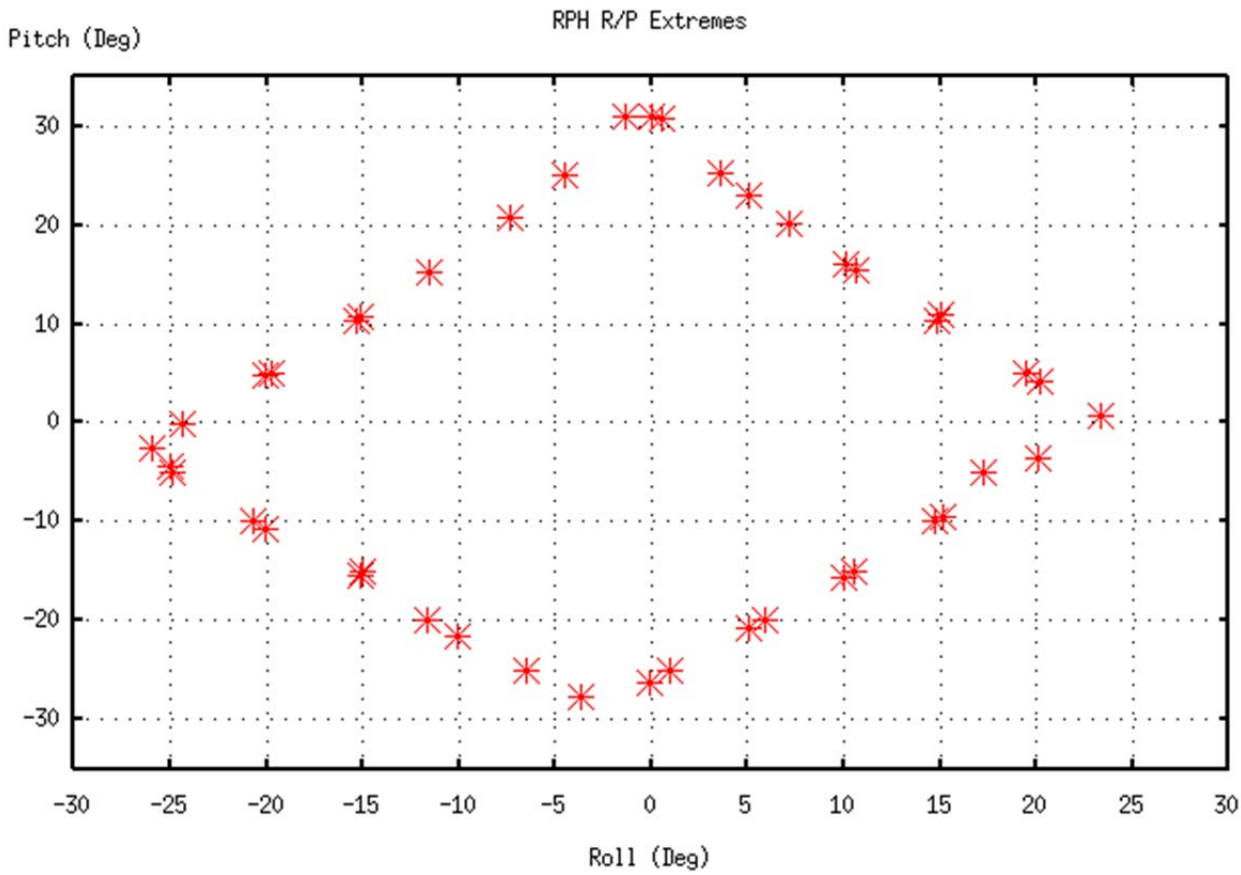


**FIGURE 2. Locations of the maximum and minimum values of roll/pitch that are possible for any given value of pitch/roll. Values were determined by setting encoder positions to their respective maximum/minimum values and measuring the platform roll and pitch with a tilt sensor mounted on the platform.**

The platform 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

$$B_l + (A_l + C_l)/2 = 2D \,. \tag{1}$$

Here $A_l$, $B_l$, and $C_l$ are the encoder counts for legs A, B, and C, respectively, and $D$ is a constant, chosen to be 6,000 to allow for maximum movement of the platform. With this choice, the platform is approximately level when A = B = C = D.

A Galil DMC-21×3 motion controller[3] is used to control the platform. The delivered platform included the Galil controller. Control of the platform 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, so as to maintain the platform in the desired pointing direction. When power is removed from the platform, it is not necessary to reestablish zero for each leg; the leg lengths are uniquely associated with encoder values.

The control of the platform position relies on accurate knowledge of the platform orientation as a function of the platform legs or, in this case, the encoder counts associated with each leg ($A_l$, $B_l$, $C_l$). A table lookup function was developed to provide unique triples of $A_l$, $B_l$, $C_l$ for any pair of roll and pitch values in the range ± 15 deg. This was done by exercising the platform through the complete range of encoder values at increments of 50 encoder counts and measuring the resultant roll and pitch values with a Kearfott SEANAV (Seaborne Navigation System,[4] designed for monitoring ship orientation values) placed at the center of the platform and carefully oriented so that the pitch and roll axes of platform and sensor coincided. After all appropriate encoder values were sampled (roughly a 40-hr operation), the table of values was inverted, so that values of the desired pitch and roll coincided with induces of a two-dimensional array of encoder positions.

[3] See http://www.galilmc.com/products/dmc-21x3.php.
[4] See http://www.kearfott.com/content/view/185/130/.

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# 3 STABILIZATION CONTROL THEORY

Simply sending a command to the platform to move it to a new position on the basis of 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 follows:

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

Here $K_P$, $K_I$, $K_D$ 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 (e.g., for roll, $e_{roll}$) is as follows:

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

Here $roll_m$ 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 platform angles are determined on the basis of the current platform 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 platform to operate independently 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 to a large degree predictable. A predictive algorithm developed for the RPY platform and modified for the RPH platform 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 platform positions. The input to the algorithm is supplied by real-time ship position data provided by the ship disposition data stream. We call the output from the predictive algorithm, used as the primary control of the platform in conjunction with the PID described above, the *enhanced PID*.

Because we did 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.

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# 4 STABILIZATION SYSTEM FIELD TESTING

Final implementation of both the PID and enhanced PID approaches necessarily had to take place aboard the Horizon *Spirit* during its initial voyages for the Marine ARM GPCI[5] Investigation of Clouds (MAGIC) campaign[6] of the AMF2. The Horizon *Spirit* is a 900-ft-long container freighter (Figure 3) traversing between Long Beach, California, and Honolulu, Hawaii, on a two-week schedule (four days out, six days return, two days in each port).

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

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

[5] See https://www.arm.gov/campaigns/amf2012magic.
[6] See http://www.bnl.gov/envsci/arm/magic/.

**FIGURE 4. The RPH (left) and RPY (right) platforms during initial deployment. During this voyage, work with RPH was conducted by using SEANAV ship disposition data, which later were not available.**

Figure 5 shows the first deployment with the MWACR installed, on November 5, 2012, with a tilt sensor mounted in the center of the RPH platform. The tan canvas "skirt" is used to keep large volumes of water from reaching the electronics.

During operation, a navigation system (originally the Kearfott SEANAV, changed to a HYDRINS[7] inertial navigation system in December 2012) is placed at or near the centerline of the ship, in this case in the shipping container behind the RPH platform). This system provides roll, pitch, and yaw (as well as surge, sway, and heave) of the ship at a rate of 50 Hz. This data stream is sub-sampled at a selectable rate and provided to the platform with an appropriate sign change, along with appropriate offset values to compensate for mounting differences to the platform controller. Because the platform cannot adjust instantaneously to the input data stream, some predictive capability is built into the interface between the navigation system and the platform. 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 by using the tilt sensor mounted in the

[7] See http://www.ixsea.com/en/navigation_motion/3/.

middle of the platform. The data from the tilt sensor were supplied to the system operation as in the enhanced 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) creating a feedback loop that continuously attempted to minimize the sensed values of pitch and roll — was implemented extensively during November-December 2012, because the Kearfott SEANAV failed.

**FIGURE 5. The MWACR installed on the RPH platform onboard the Horizon *Spirit*. The Watson tilt sensor can be seen below the MWACR, in the center of the platform.**

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# 5 STABILIZATION PERFORMANCE EVALUATION

Figures 6-10 summarize the performance of the RPH platform during the initial cruise (2A and 2B in Table 1) in September-October 2012. During this period, the effort was directed primarily 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 platform relative to the ship roll. The limitation of the tilt sensor to 0.1-deg resolution during most of this time period places a limit on how close to zero the platform and the analysis can be resolved. Figures 7-10 illustrate average and standard deviation values for ship and platform 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 convenient way to reduce the analysis to a single variable if the actual direction of the tilt is not significant. For example, 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. By the end of the voyage, significant reduction in platform variation from its designated pointing direction had clearly been achieved, with mean and standard deviation values of the tilt on the order of 0.02 and 0.04, respectively. This was, however, while the seas were relatively mild, particularly with the ameliorating effect of a large ship. Thus, the values of the ratio of platform tilt to ship tilt — on the order of 0.03 — give a more realistic prediction of expected performance in all conditions.

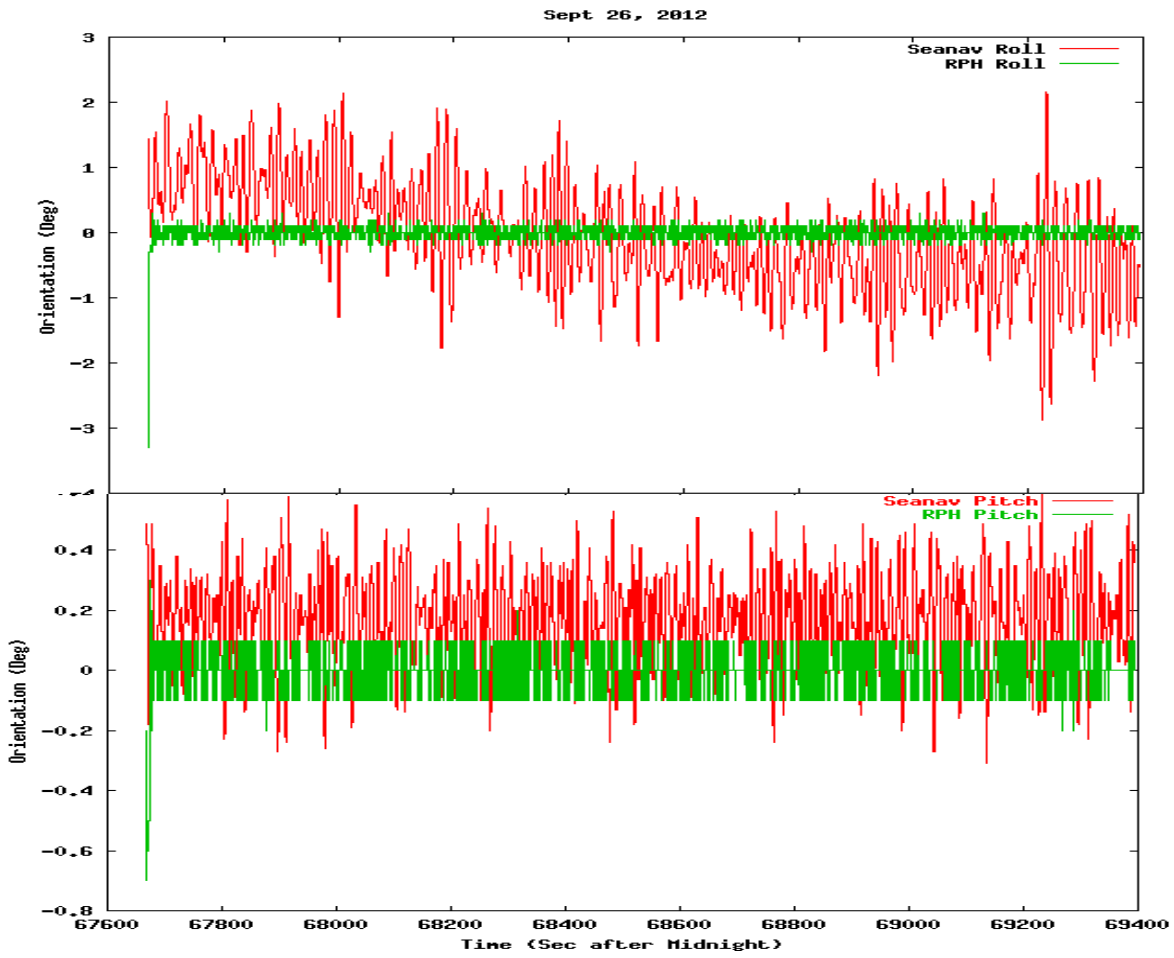


**FIGURE 6. Sample data from September 26, 2012, for roll (top), pitch (middle), and resultant (bottom) values from the ship (red) and the RPH platform (green). The minimum resolution of 0.1 deg from the tilt sensor is clearly evident in the small pitch values.**

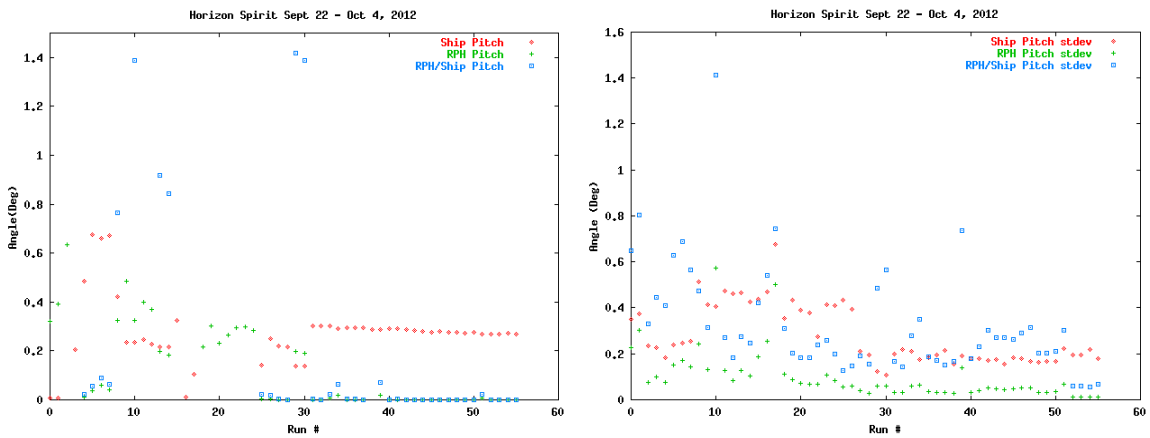


**FIGURE 7. Mean (left) and standard deviation (right) of pitch from the ship (red), RPH platform (green), and ratio of platform to ship (blue), obtained in roughly hour-long periods during the cruise. Values show improvement of the algorithm as control variables were fine-tuned during the voyage.**

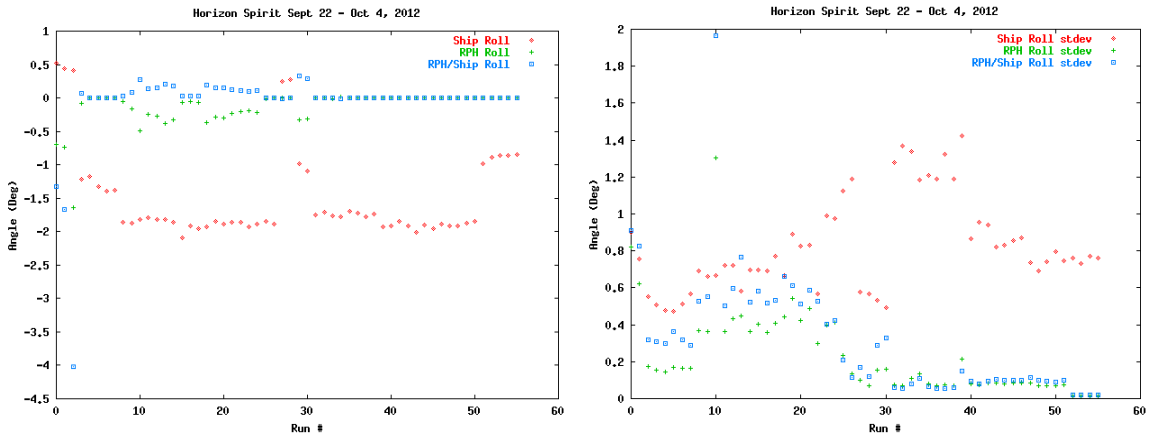


**FIGURE 8. Mean (left) and standard deviation (right) of roll from the ship (red), RPH platform (green), and ratio of platform to ship (blue), obtained in roughly hour-long periods during the cruise. Values show improvement of the algorithm as control variables were fine-tuned during the voyage.**

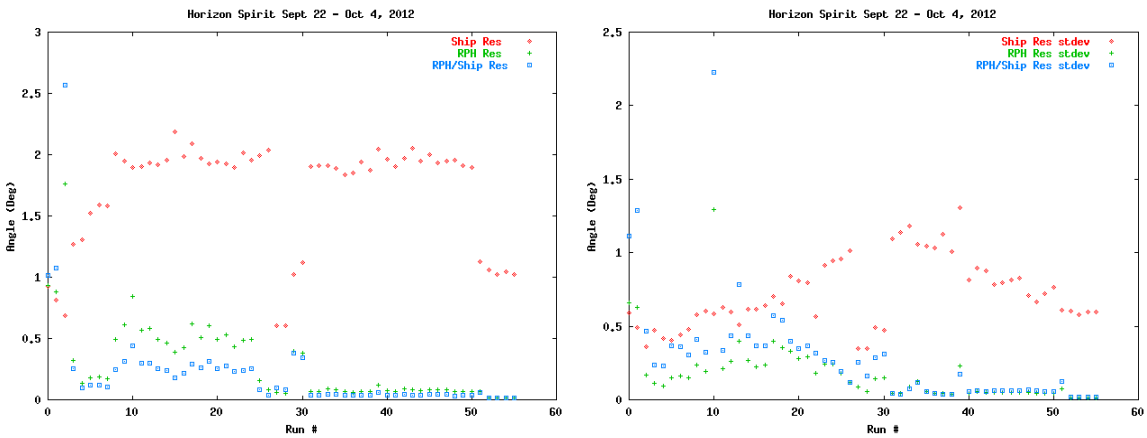


**FIGURE 9. Mean (left) and standard deviation (right) of resultant tilt from the ship (red), RPH platform (green), and ratio of platform to ship (blue), obtained in roughly hour-long periods during the cruise. Values show improvement of the algorithm as control variables were fine-tuned during the voyage.**

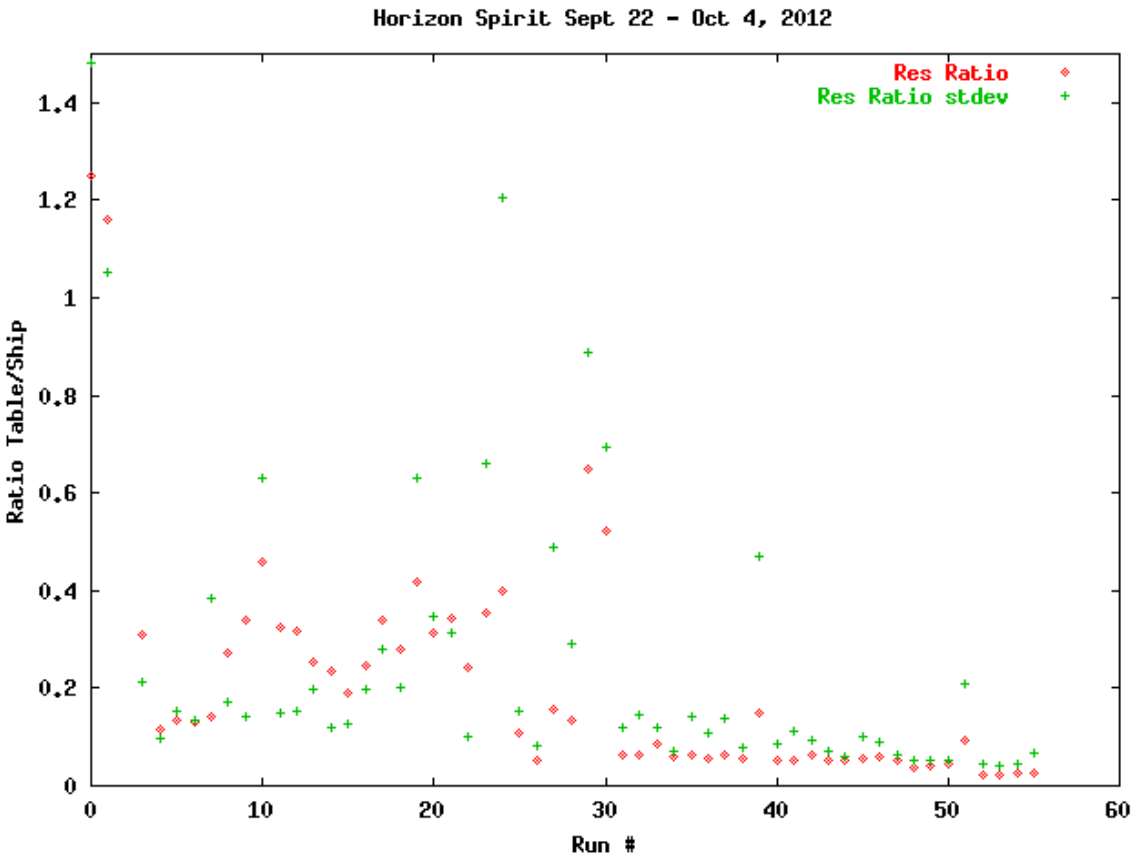


**FIGURE 10. Mean (red) and standard deviation (green) of resultant tilt ratio (platform/ship). Here the ratio is calculated from instantaneous values of ship and platform resultant, rather than the ratio of the means (as in Figures 7-9). Values show improvement as control variables were fine-tuned during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

Unfortunately, we were not able to use the enhanced PID approach for any significant period after the initial voyage, because the Kearfott SEANAV began to fail and was not replaced until December. After the MWACR was installed in early November, the original 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 in Table 1. Cruise 7B is absent, because one of the legs of the platform malfunctioned and could not be repaired until the ship reached port. Overall, conditions did not vary significantly among cruises, although periods of heavier conditions occurred during the earlier portions of the cruises that were north of the trade winds (Figure 11). Most of the larger platform tilt values during cruises 8B and 9B are from times when the enhanced PID routine was used with inappropriate feedback values. During cruise 5A, the platform was pointed at -1 deg (relative to the platform), rather than the usual 0 deg. This is reflected in the tilt values in Figure 11 and subsequent probability distributions.

The best variables for ongoing quantitation of the platform response are the standard deviations of roll, pitch, and (to some degree) tilt. Figure 12 compares 15-min calculations of roll and pitch standard deviation for both ship and platform. In general, platform roll and pitch standard deviations are lower by more than an order of magnitude than ship values. Probability distributions of tilt (Figure 13) reflect this as well; again note the additional distribution of platform values around 1 deg on leg 5A. The two-dimensional probability distributions (Figure 14) illustrate that the ship is usually tilted somewhat to port and forward. The platform, on the other hand, has an even distribution of small tilt angles.

The cumulative probability distributions in Figure 15 show that, overall, more than 90% of platform tilt values are within 0.15 deg of level, and more than 99% are within 0.5 deg. This is encouraging, because systematic use of the enhanced PID approach is expected to improve performance further.

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

Table 2 gives a statistical summary, by cruise, of the platform performance.

**TABLE 1. Times and directions of cruises.**

| Cruise | Beginning Date and Time | | Ending Date and Time | | 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 | 11/03/12 | 19:00 | 11/08/12 | 14:00 | SW |
| 5B | 11/09/12 | 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 |

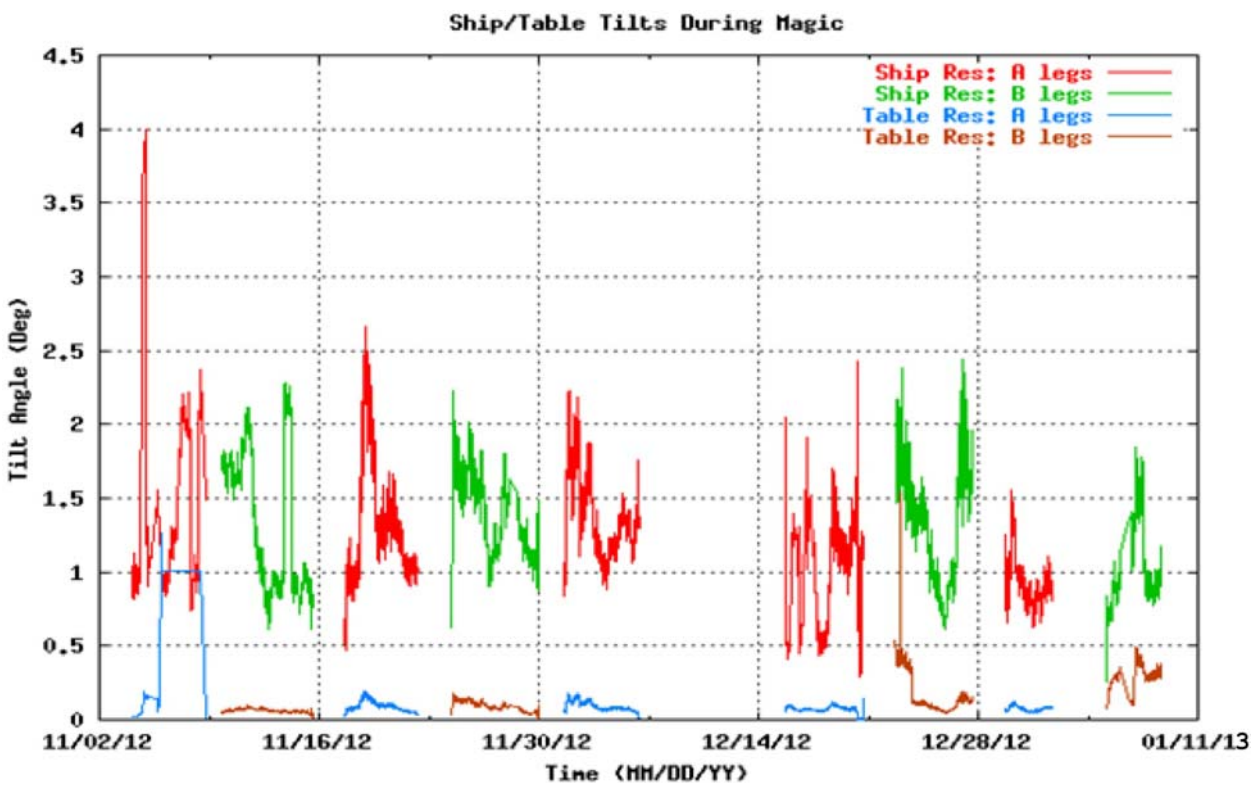


**FIGURE 11. Synopsis of mean tilt values for ship and platform during MAGIC, averaged over 15-min intervals and separated by cruise number and direction.**

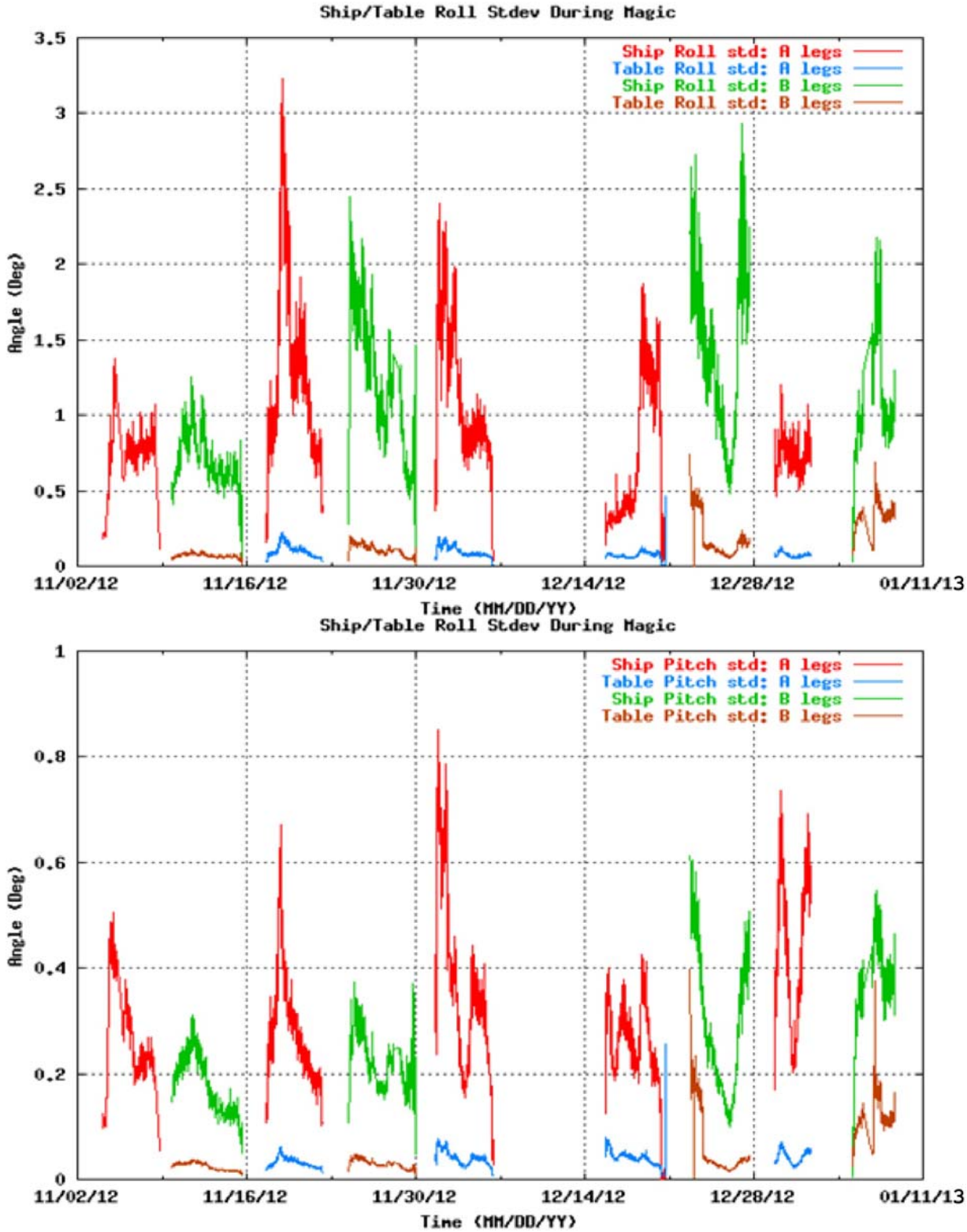


**FIGURE 12. Synopsis of roll (above) and pitch (below) standard deviations during MAGIC. Values derived from 15-min intervals, sampled at 20 Hz, are separated by cruise number and direction.**

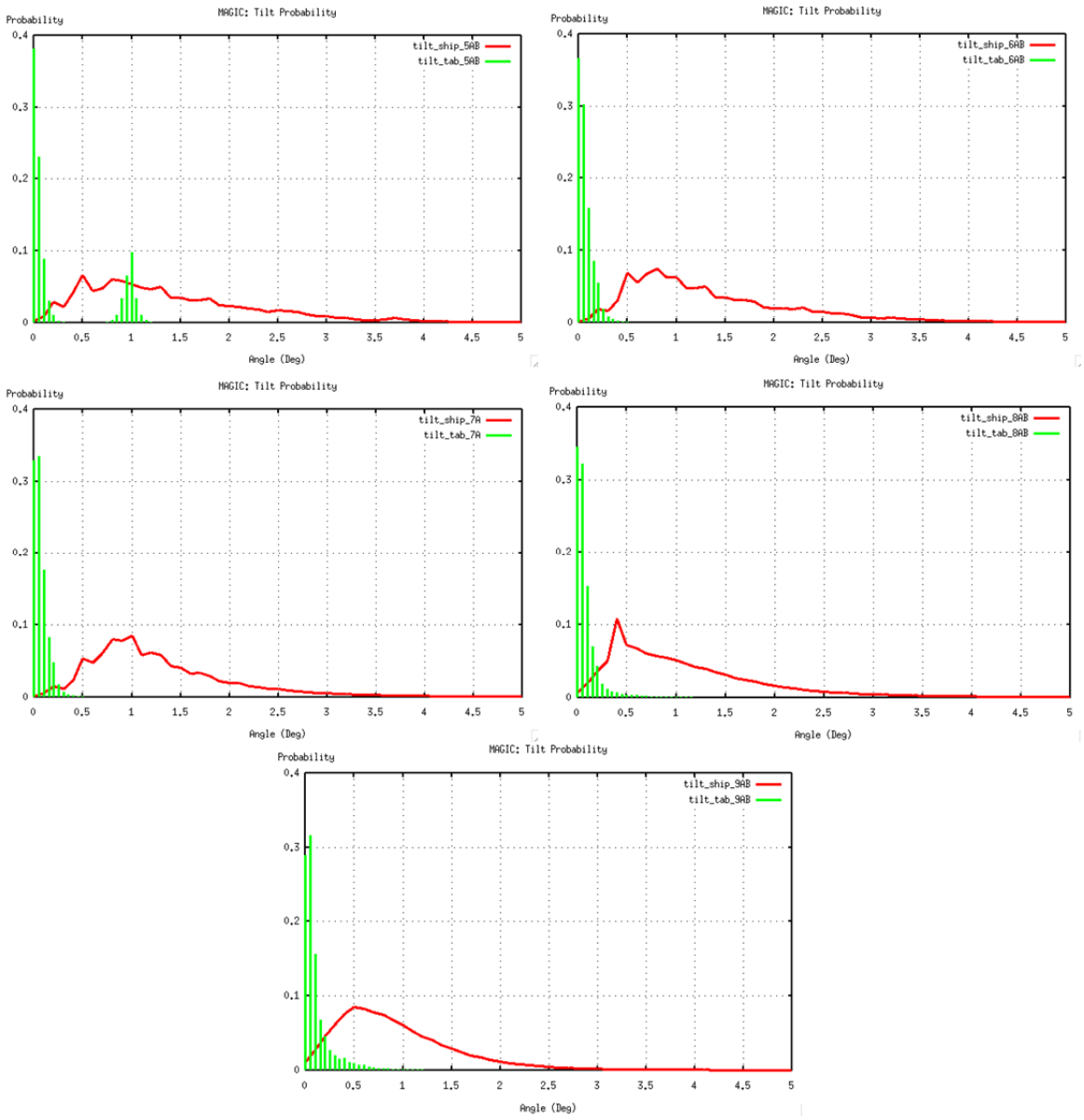


**FIGURE 13. Probability distributions of ship (red) and platform (green) tilt angles for cruises 5-9. Westward (A) and eastward (B) legs were combined in the plots. Data were sampled at 4 Hz.**

**FIGURE 14. Two-dimensional probability distributions of tilt for the ship (left) and the platform (right).**

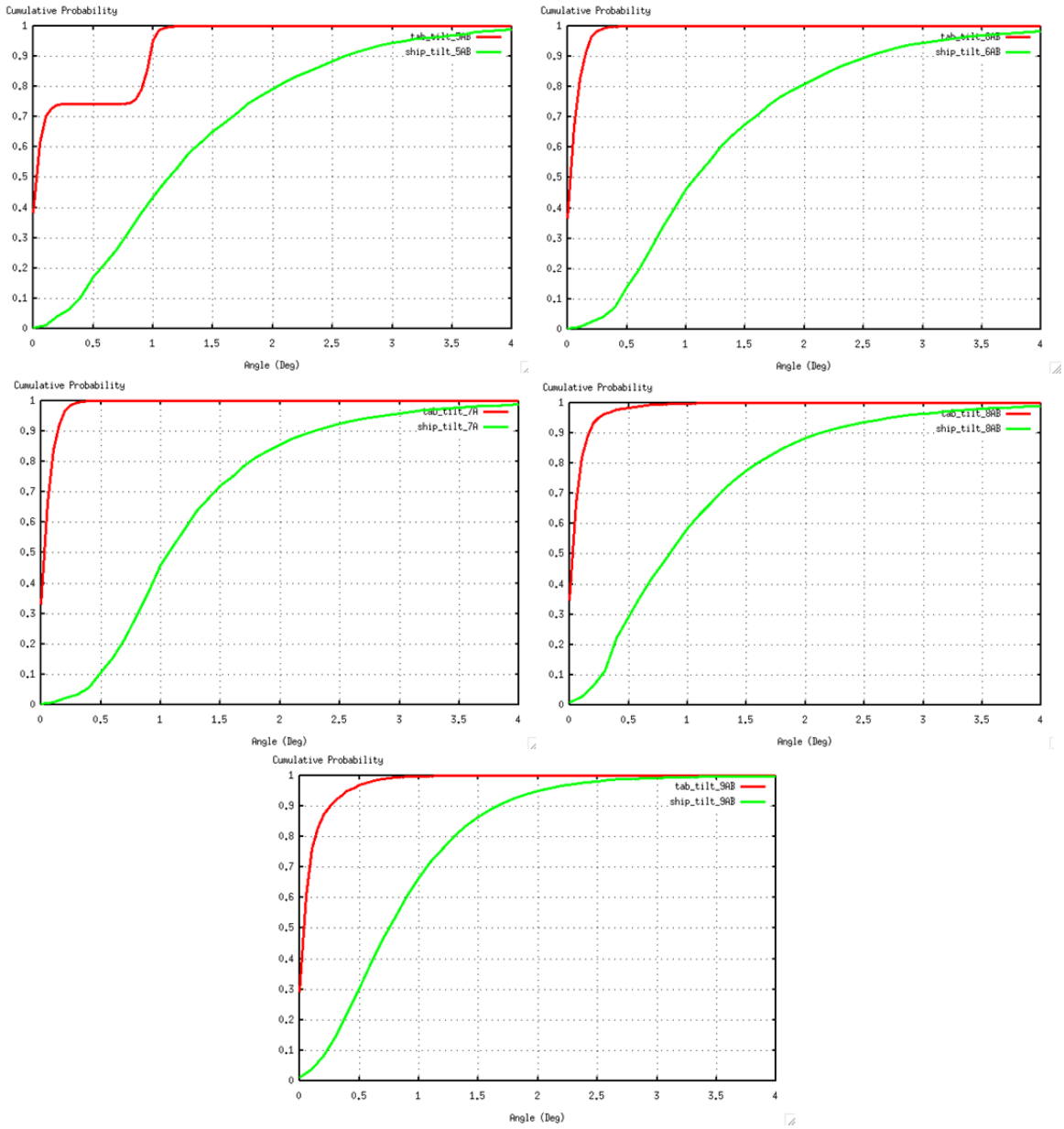


**FIGURE 15. Cumulative probability distributions of tilt of the ship (green) and the platform (red) for five cruises.**

**TABLE 2. Statistics from MAGIC cruises 5-9.**

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

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# 6 CONCLUSIONS AND RECOMMENDATIONS

We have made considerable progress in understanding and using the AMF2 RPH stable platform. With the present system, we can reasonably expect to maintain the platform within 0.1 deg of level more than 90% of the time in moderate conditions. This should certainly suffice for almost all of the radiometry measurements presently made in the U.S. Department of Energy's Atmospheric Science Research program. Whether this degree of control is sufficient for cloud vertical velocity measurements is unknown, however. In placing the MWACR on the platform, two offset values were apparently insufficiently resolved: (1) the alignment between the MWACR inertial measurement unit (IMU) and the radar antenna and (2) the alignment between the MWACR IMU and the platform tilt sensor. We have no control over the first of these. However, we clearly found differences between the static position of the MWACR and our tilt sensor, on the order of -0.9 deg in roll (tilt sensor minus IMU) and 0.6 deg in pitch, from estimates taken during installation. That is why the capability of pointing at any angle was incorporated into the RPH platform 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 platform correction. Figure 16 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 platform was not running, although the data stream was still available from both the IMU and a second Watson tilt sensor being used to monitor ship motion data while the Kearfott SEANAV was being replaced. During the period of these data, the platform was not operating. The offset results from the offsets mentioned above, as well as from the fact that when the platform is at rest, it is not parallel to the deck of the ship. More important are the evident periods when the Watson (green) sensor detects ship motion that is not evident in the IMU (red), for example at 70,455 and 70,470 sec. Because the Watson-type sensor is used to control the platform, the platform control will compensate for these additional motions.

Which sensor is closer to reality remains uncertain, though we can answer that question tentatively by observing Figure 17. 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 platform 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 sensor, on the other hand, again shows slightly different periodicity at times (8,115 sec) and consistently appears to overshoot the maxima and minima observed by the HYDRINS and MWACR IMU.

These observations indicate, therefore, that the Watson tilt sensor is inadequate for the precise timing and measurement accuracy required for MWACR measurements with the RPH platform. The fault is not with the platform, but with the sensor used for the error function in the PID.

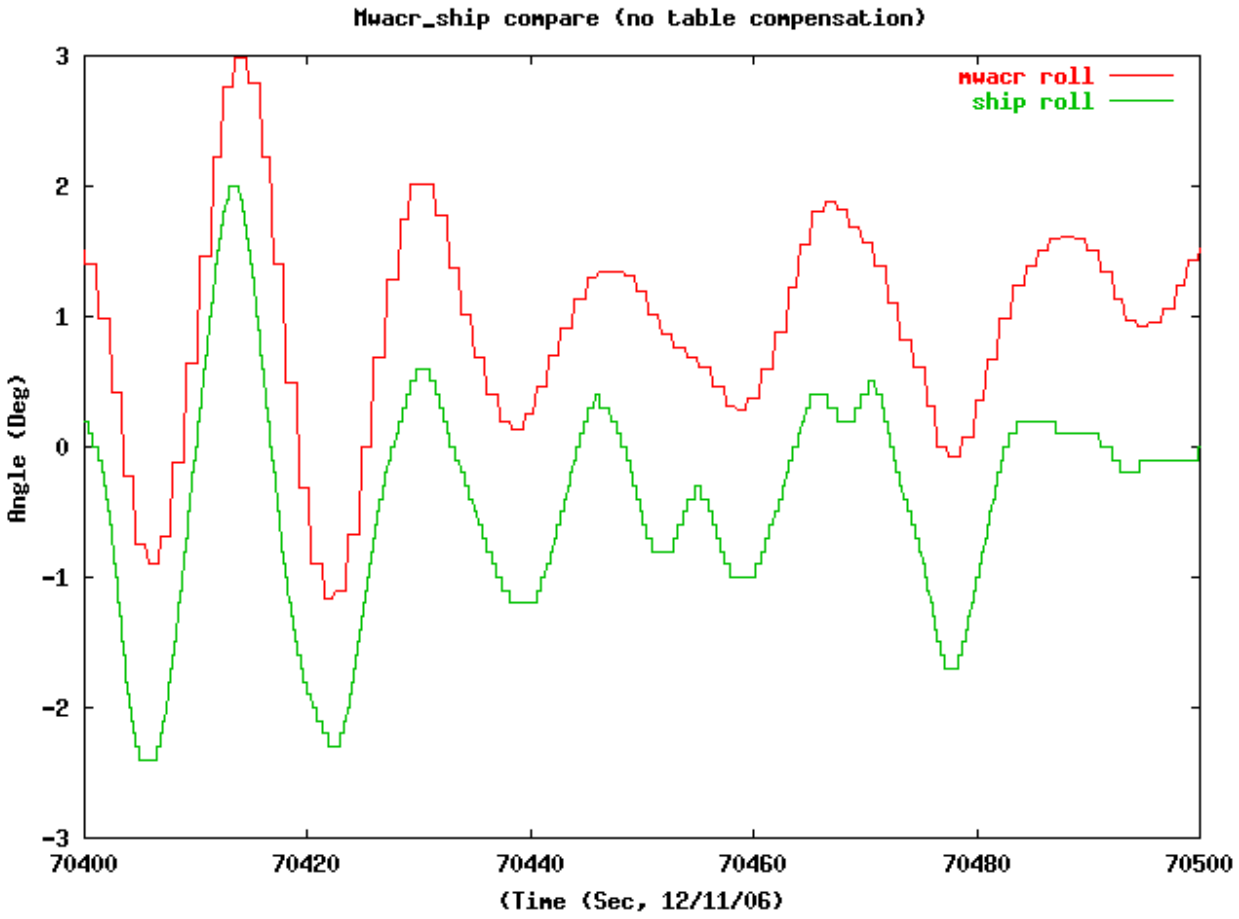


**FIGURE 16. Time series of roll measured by the Watson tilt sensor (green) and the MWACR IMU (red) during a period when the RPH platform was not operating. The offset is arbitrary, because the platform rest position was not parallel to the ship deck.**

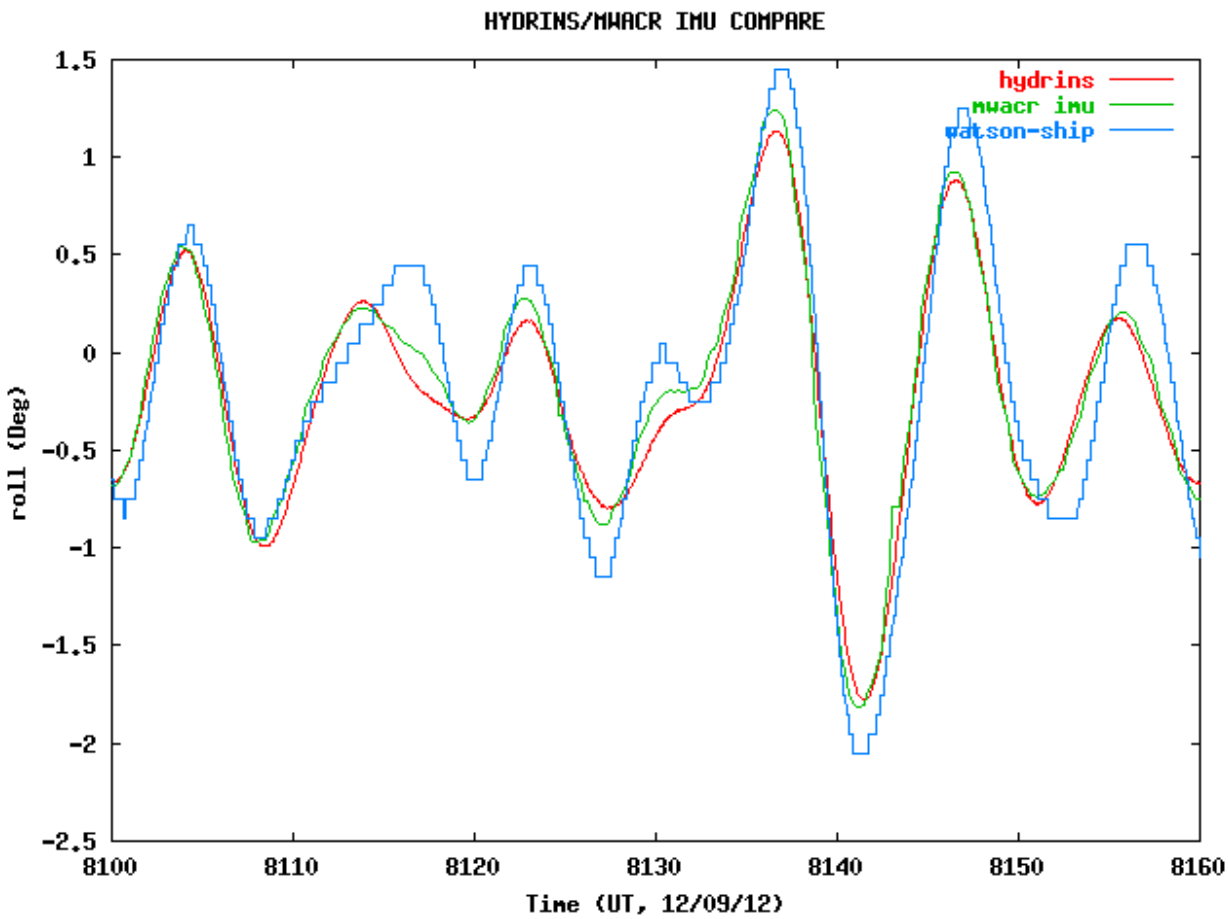


**FIGURE 17. Time series of roll measured by the Watson tilt sensor (blue), the MWACR IMU (green), and the HYDRINS (red) during a period when the RPH platform was not operating.**

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

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