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Report on the AMF2 RPY Stabilization Platform: Design and Evaluation

Environmental Science Division

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NOTATION

AMF2	second ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
EOM	equation of motion
GHZ	gigahertz
hr	hour(s)
Hz	hertz
RPH	roll, pitch, heave
RPY	roll, pitch, yaw
SEANAV	Seaborne Navigation System
sec	second(s)

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REPORT ON THE AMF2 RPY STABILIZATION PLATFORM: DESIGN AND EVALUATION

Richard L. Coulter, Timothy J. Martin, and Brad W. Orr

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, 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. Consequently, a cornerstone of the AMF2 strategy is the use of a stabilization 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, including vertically pointing radars, for which measurement of cloud vertical motion is of critical importance.

During the design and construction of AMF2, a relatively inexpensive stable platform was purchased to perform the stabilization tasks for some of the instruments. Computer programs were developed to communicate with the platform controller and with an inertial measurements platform that measures true ship motion components (roll, pitch, yaw, surge, sway, and heave). The platform was then tested on a three-day cruise aboard the RV *Connecticut* during June 16-18, 2010, off the East coast of the United States. This initial test period was followed by continued development of the platform control strategy. The performance of the platform during the deployment at sea and subsequent testing is discussed in this report. The platform, as tested, meets all the design and performance criteria established for this test phase.

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2 STABILIZATION SYSTEM DESCRIPTION

During the design of the AMF2, significant effort was invested in researching existing stabilization platforms and methodologies. Few existing systems met the measurement and design requirements necessary to support AMF2 instrumentation. The systems that did were either very expensive or were not physically capable of supporting the weight and size of the AMF2 instrument systems.

In the research process, a company that designs platforms for motion simulation was found. This company's platforms could accommodate the size and weight of AMF2 instruments, but the control software was designed for motion *simulation* versus the motion *compensation* required by AMF2. Discussions with the vendor led to a decision to purchase a custom electromechanical platform capable of maintaining constant vertical orientation (i.e., compensating for measured pitch and roll) on an ocean-going vessel. Additionally, the top of the platform was specially designed so that it could be rotated 360 degrees in order to compensate for heading changes of a ship, thus enabling sun shading or tracking for radiometry measurements. Figure 1 illustrates the platform as it was delivered to Argonne.

The original AMF2 stable platform, 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 yaw (motion about the vertical axis). The designation for this platform is RPY (roll, pitch, yaw).

The platform's roll and pitch are controlled by lengthening and shortening two legs that support the platform. Leg B is seen on the lower right of Figure 1, but Leg A is partially shielded from view to the rear. The lengths of the legs are controlled independently by two electric motors that have 118,000 encoder positions between maximum and minimum extent. When both legs are changed together and equally, the platform tilts in what we have defined as the pitch direction; when the legs change equally in the opposite sense, one leg lengthens and the other shortens, and the platform tilts in the roll direction. The dimensions of this particular platform allow for ± 25 degrees of pitch and ± 16 degrees of roll. However, the extremes of both roll and pitch cannot be attained simultaneously.

Figure 2 illustrates the limits of possible combinations of roll and pitch; all possible combinations within ± 10 degrees are achievable. This coincides with the design parameters originally specified. Figure 2 illustrates the maximum value of pitch/roll that is possible for any given value of roll/pitch. Values in the figure were obtained by placing a tilt sensor on the platform and then moving the control legs through the maximum possible displacements. For vessel motions greater than these values, platform compensation is limited to the maximum possible values. For the vast majority of conditions, these values are rarely exceeded; when they are, conditions are likely to be less than ideal for useful measurements.

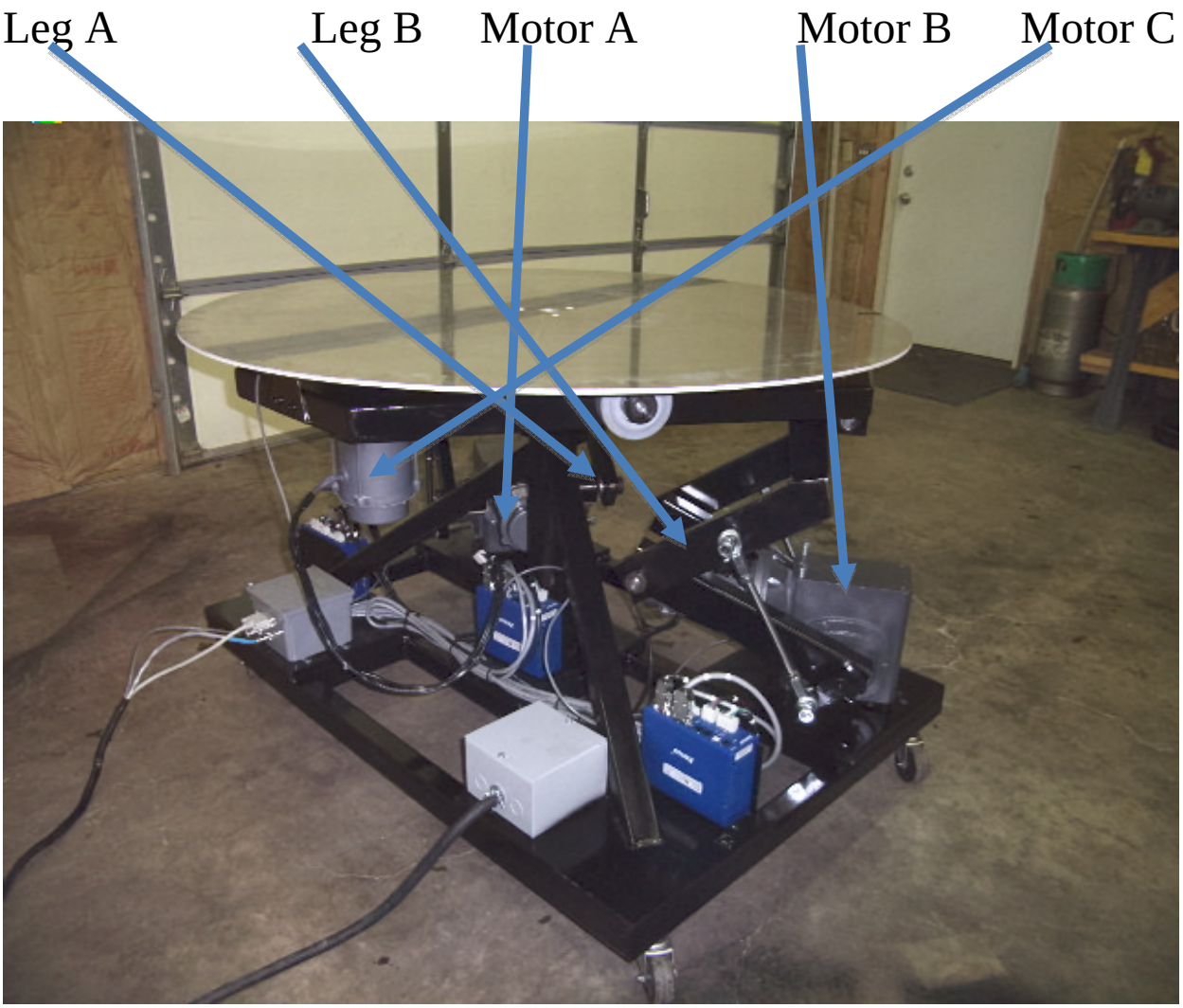

FIGURE 1. The AMF2 stable platform, as originally designed and received. Leg A and Motor A are partially hidden by the support frame. Motor C moves the turntable mounted at the top of the platform. Equipment is then mounted on the turntable.

Control of the pointing direction, or yaw, is accomplished by using a turntable mounted on the top of the platform. The turntable is moved by a belt drive run by a third electric motor (Motor C in Figure 1). A complete rotation encompasses 1,800,000 encoder counts, which yields roughly 0.6-second accuracy.

A Galil DMC-21X3 motion controller is used to control the platform. The delivered RPY platform included the Galil controller and a software program, named EOM (equation of motion), that takes roll, pitch, and yaw values (provided by an external measurement system such as the Kearfott SEANAV [Seaborne Navigation System] chosen for use by AMF2) and calculates the appropriate encoder counts necessary to position the legs and turntable to the desired position. It is also possible for the user, with a set of commands, to direct the controller to position the platform as desired.

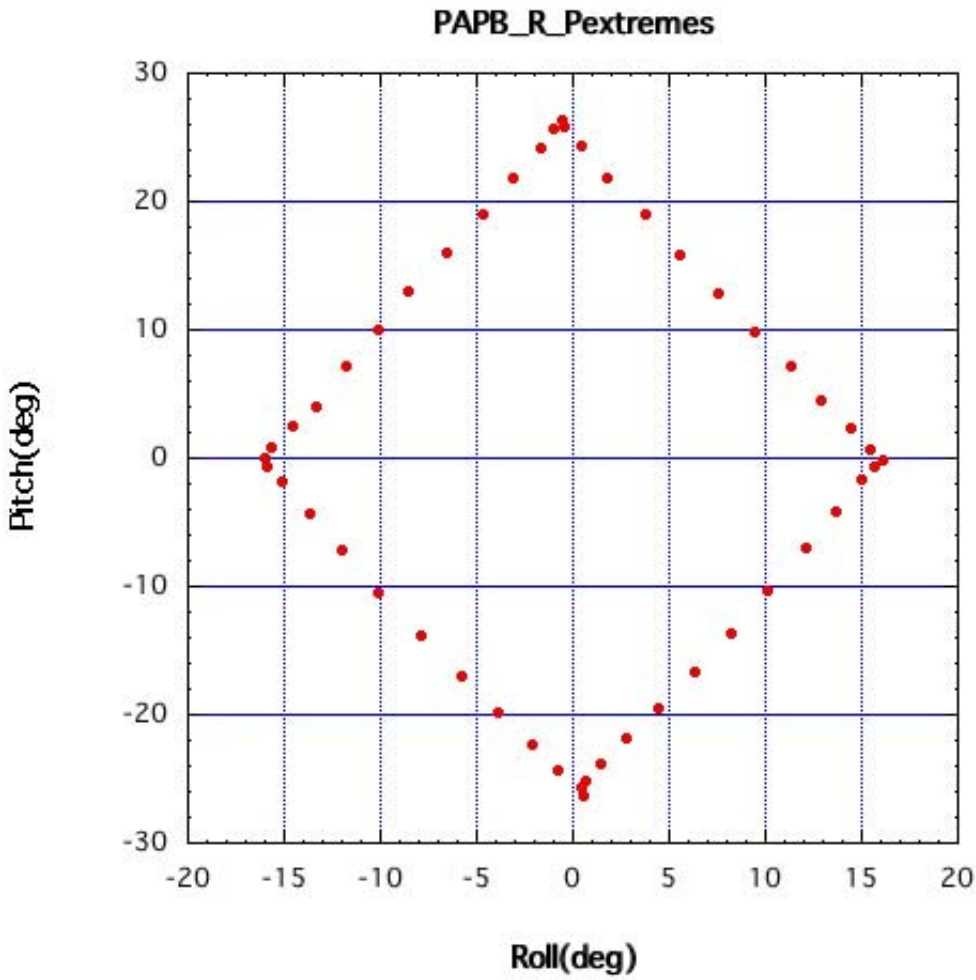

FIGURE 2. Locations of the maximum and minimum values of roll/pitch that are possible for any given value of pitch/roll. Values were determined by setting encoder positions to their respective maximum/minimum values and measuring the platform roll and pitch with a tilt sensor mounted on the platform.

The motor control for each leg is not absolute, because the control is of a rotary nature. Once the maximum or minimum is exceeded, the motors continue to rotate beyond the maximum/minimum values but with a sign reversal. Thus, absolute control is lost once the maximum/minimum has been exceeded.

In addition, whenever power is removed from the platform, the assumed encoder value for each leg is zero upon reapplication of power. In this case it is necessary to reestablish a useful zero for each leg. This was originally accomplished by using three contact switches that changed state when the legs were in their “home” (or shortest leg) position. This was found to be imprecise, however, because at the “home” position, the change of leg length per encoder count is at its minimum for the given leg and platform geometry. Thus, when using the provided

contact switches to establish the "home" position, one can easily have a variation of several hundreds of encoder counts with essentially no change in platform pitch/roll.

For this reason, a procedure was developed in which the "home" position is determined near the middle of the possible leg extension values, where the change in roll/pitch per encoder count is at a maximum. This is achieved by measuring precisely the height of the platform above the A and B legs and requiring that they be equal. Then the encoder zero value is set to zero. With this scenario, the motor encoder counts can be ± 59,000, and the level position is nearly (but not exactly) at zero encoder counts on both legs.

3 STABILIZAZTION CONTROL THEORY

Wave motions over the ocean are principally a superposition of waves of various wavelengths and amplitudes. As such, they are largely well behaved. Simply sending a command to the platform to move it to a new position based on measured ship motion data will never suffice, however, because compensation is never instantaneous; mechanical and computational delays must be taken into account. For example, the average delay between command and position achievement for this platform is about 0.24 sec for normal sea states.

In an attempt to smooth the motion of the stabilization platform, a predictive algorithm was developed that provides an estimate of where the platform will need to be several samples in advance. The predicted position is obtained from a polynomial of first and second derivatives calculated from the previous three platform positions, as well as an error estimate derived from the difference between predicted and true required positions. This predicted position is adjusted relative to what the actual position should be, on the basis of real-time ship position data. Moving the platform into the predicted position should, in most cases, locate the platform closer to the desired real-time position and provide for more accurate platform operation. Testing and evaluation of this method was pursued throughout the entire development and field testing phases.

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

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4 STABILIZATION SYSTEM FIELD TESTING

Figure 3 shows the platform during its maiden voyage on the RV *Connecticut*. This test cruise was in the eastern Atlantic off the coast of Massachusetts, near Woods Hole Oceanographic Institution, in June 2010. In the photograph, the AMF2 microwave radiometer and multi-filter rotating shadowband radiometer are mounted on opposite edges of the platform, and a tilt sensor is mounted in the center. The black canvas "skirt" was used to keep large volumes of water from encroaching on the electronics. For longer deployments, a more robust arrangement of water protection is needed.

During operation, the RPY system operates with the SEANAV placed at or near the centerline of the ship. Software compensates for any differences between the alignment of the SEANAV and the platform, so long as the differences are known. Lever arm corrections are not

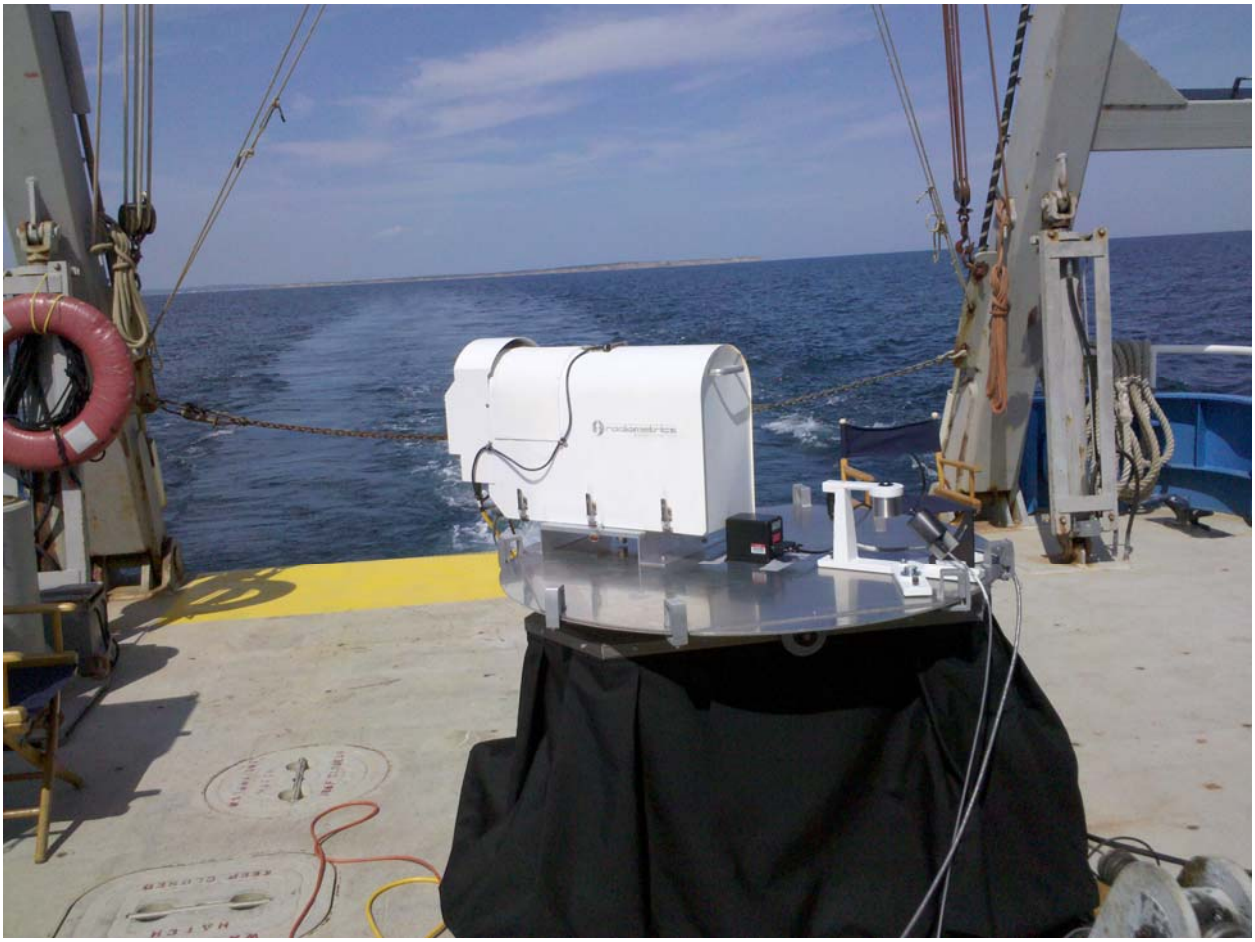

FIGURE 3. The RPY platform during its initial deployment, pointed at 215 degrees. During this voyage, if the ship were to "come about," the yaw zero position would need to be reset. For all maneuvers less than 180 degrees, however, the yaw compensation was very good. In addition, the cables to the instruments had to be managed manually during ship course reversal.

normally necessary with the instruments mounted on this platform; however, if any instruments measuring wind (or other) velocities are mounted on a stable platform, the distance and elevation difference between SEANAV and the platform are critical, as are surge, sway, and heave and their derivatives.

The SEANAV system provides roll, pitch, and yaw (as well as surge, sway, and heave) of the ship at a 50-Hz rate. 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 it is not possible for the platform to adjust instantaneously to the input data stream, a predictive capability is built into the interface between the SEANAV and the RPY. During the voyage aboard the RV *Connecticut*, a sample rate of 10 Hz was used. The ability of the platform to maintain level was monitored by using a tilt sensor mounted in the middle of the platform.

An alternate method of operating is to use the values sensed by the tilt sensor (or equivalent) to create a feedback loop that continuously attempts to minimize the sensed values of pitch and roll by moving the platform. This method, which would eliminate the need for carefully evaluating orientation offsets between the SEANAV and RPY (except for yaw), will be evaluated in the future. This approach, while very attractive, is difficult to evaluate in dry-lab conditions. We have developed the necessary software to implement this approach and have performed rudimentary simulations for testing the system under dry-lab conditions. However, testing in any meaningful way will necessarily take place during sea deployments.

5 STABILIZATION PERFORMANCE EVALUATION

During the period before initial deployment of the RPY to the RV *Connecticut*, procedures and programs were developed to interface between the SEANAV and the Galil controller, keeping in mind that the time delay between the two should be as short as possible. Unfortunately, the EOM provided by the manufacturer was discovered to be less accurate than anticipated. However, because of time limitations, this implementation had to be used during the RV *Connecticut* cruise to establish proof of principle and to acquire much needed experience in this type of system operation.

Figure 4 is a five-minute snapshot of the ship roll measured by the SEANAV (green) and the tilt sensor mounted on the platform (red), taken during a period of moderate sea conditions. An offset of about 0.5 degrees that is apparent between the two measurement systems is of little concern. Also evident is that the motion compensation reduces roll effects by approximately a factor of five. The standard deviation of the roll or pitch can be used to express the magnitude of the motion about the mean. The standard deviation of platform roll for 10 hr of operation on June 18, 2010, was 0.497 degrees, while the SEANAV standard deviation was 1.86 degrees over the same period.

Figure 5 shows the distribution of values for roll and pitch as measured by the SEANAV and the platform-mounted tilt sensor. Clearly, the response of the platform was much poorer to

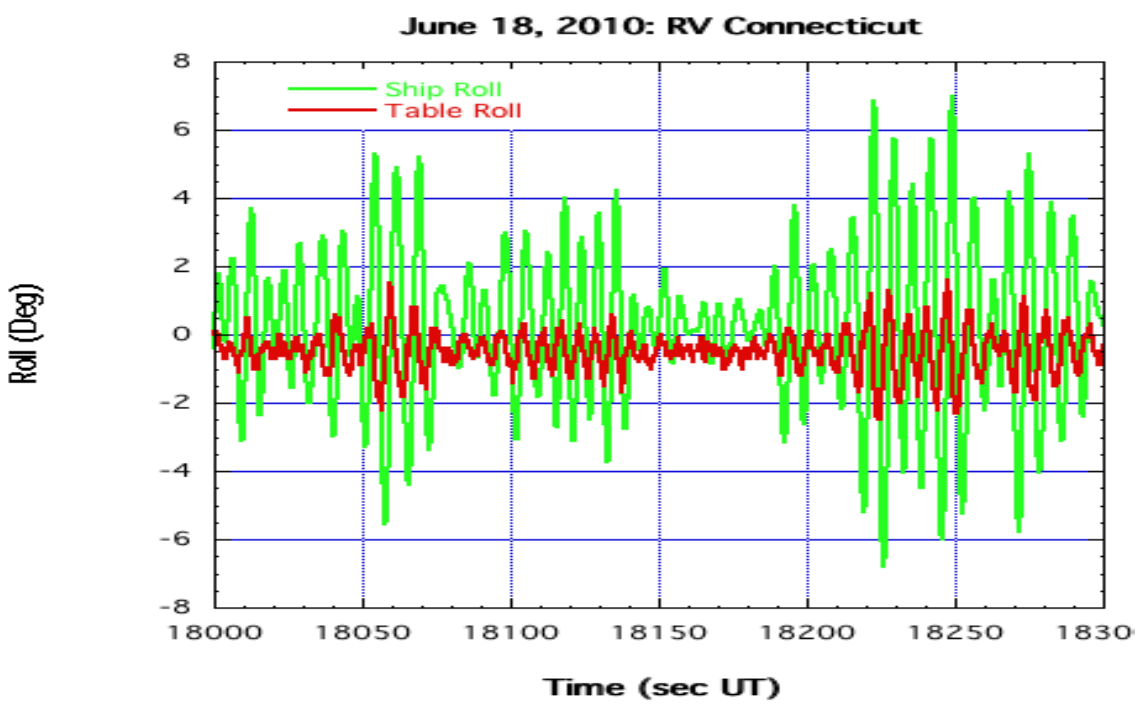

FIGURE 4. An example of roll of the ship (green) and the simultaneous roll of the platform (red) in moderate sea conditions on June 18, 2010.

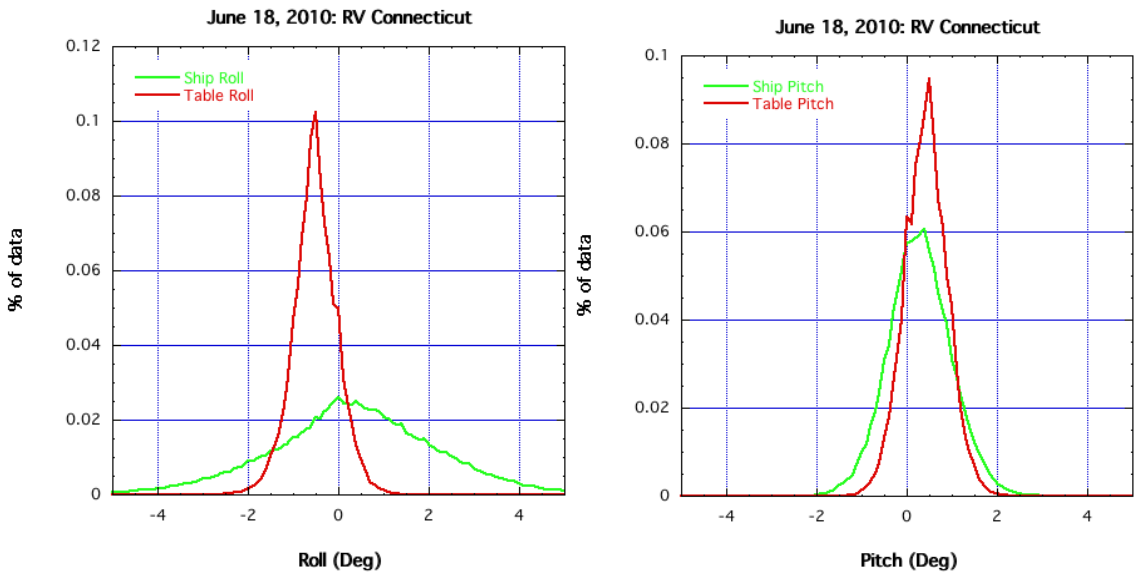

FIGURE 5. Distribution of values of roll (left) and pitch (right) for the ship (green) and the platform (red) on June 18, 2010.

pitch control than to roll control. On the other hand, the variation of the ship motion was considerably smaller along the pitch axis than along the roll axis. The spreads of the roll and pitch values of the platform are quite similar. This amount of spread in the distribution could be indicative of the amount of noise in the procedure at that time (Table 1).

Subsequent analysis of the platform's response to input data and elimination of programming errors has resulted in considerable improvement. The EOM program approach was eliminated in favor of controlling the platform directly through the Galil controller, with primitive commands to control leg lengths. A table lookup function was created by cycling the platform through its full range of motion and measuring the platform roll and pitch angles with a

TABLE 1. Measures of variability for representative wave forms.

	Standard Deviation	
Wave Form	Roll	Pitch
SEANAV	1.86	0.69
Stable platform	0.50	0.48
SP_wave form in	3.14	1.14
SP_difference	0.12	0.22
SP_SEANAV_manual	2.85	0.71
SP_manual	0.62	0.26

platform-mounted tilt sensor. This lookup function is then used to determine the appropriate leg lengths for any given roll-pitch combination.

This new approach was tested by using a time series of roll and pitch values from a previous data set to control the platform position. The actual platform position was measured simultaneously with the tilt sensor mounted as in Figure 3. With the input wave form regulated to 10 Hz, a time-lagged correlation demonstrated that the platform was delayed by approximately two samples (0.2 sec; data not shown). A predictive routine that operated on the input data before feeding it to the platform was then used to compensate for the delay. Figures 6 and 7 illustrate that the two time series are practically indistinguishable, except for a small offset. However, the value of interest in this approach is the difference between the two time series, because the platform, when in operation, is driven by the negative of the measured ship roll or pitch. Clearly, both roll and pitch differences show considerable improvement compared to those from the RV *Connecticut* voyage (Figure 4). Note that the scales used in the plots accentuate the pitch differences, whose standard deviation is still less than 0.25 degrees. Note also from Table 1 that the input wave form is more than two times the magnitude of the conditions encountered aboard the RV *Connecticut*.

The distributions of values in Figure 8 echo the observations above, that the performance of the stable platform is considerably improved with this new approach. However, the pitch response is still poorer than the roll response.

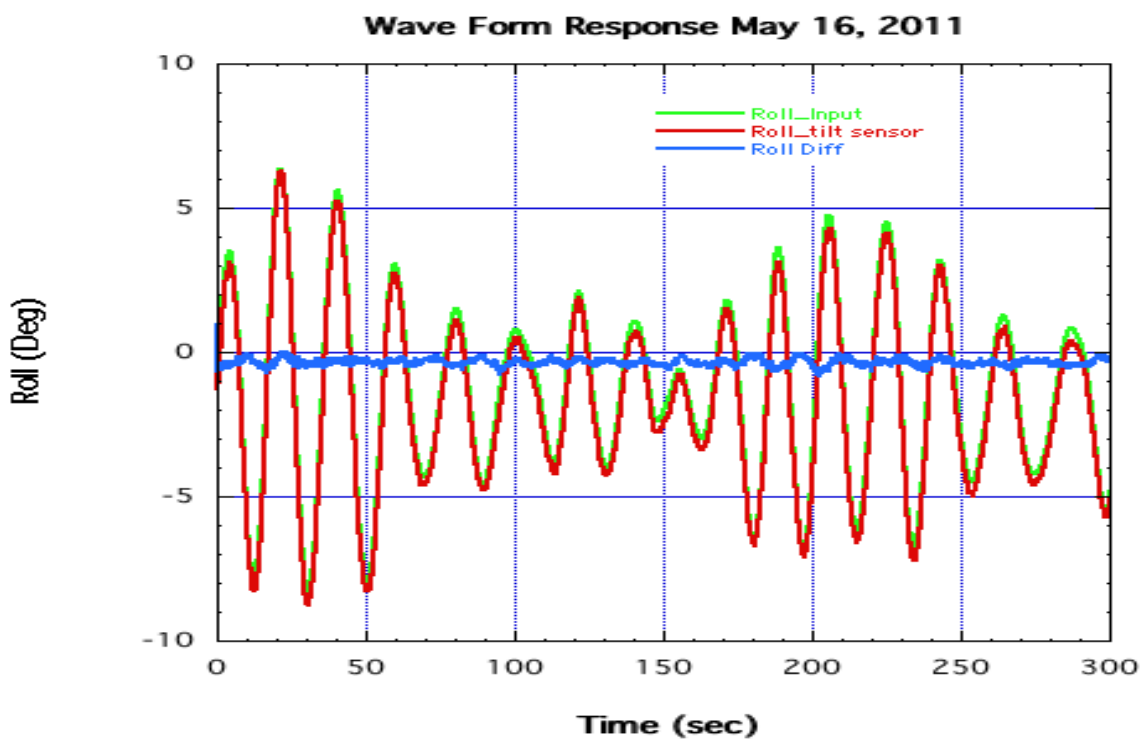

FIGURE 6. Comparison of input wave form (red) and measured platform position (green) for roll. The blue line is the difference.

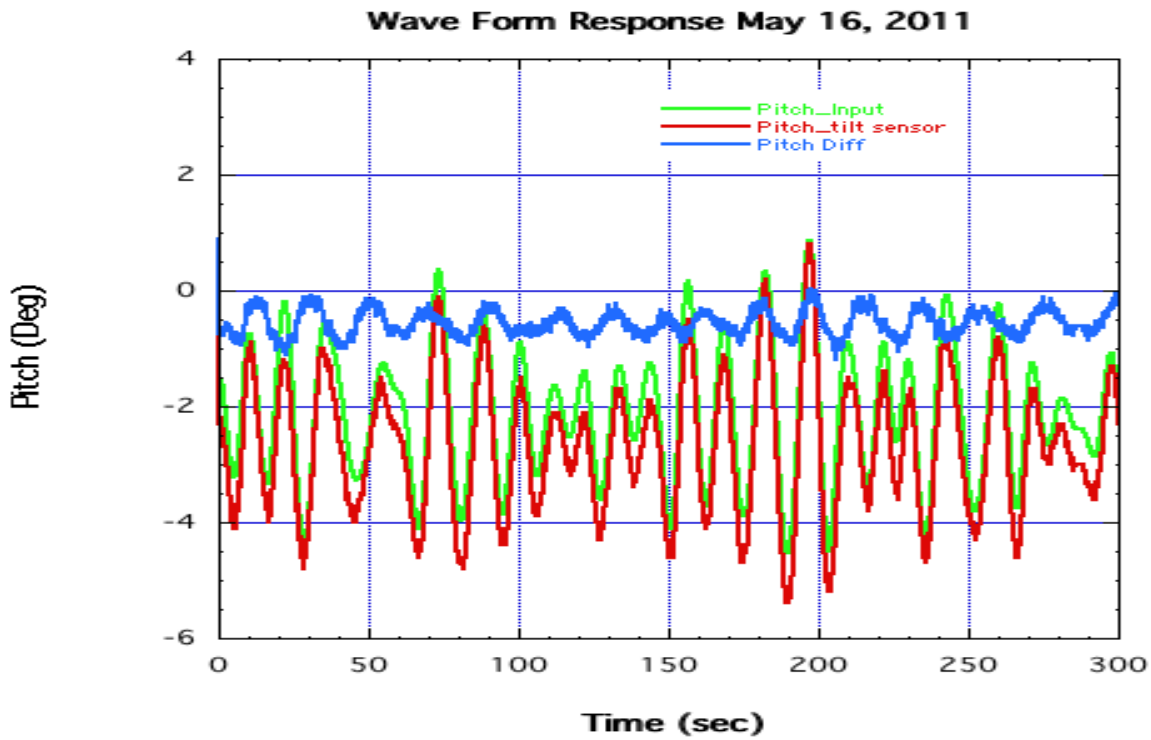

FIGURE 7. Comparison of input wave form (red) and measured platform position (green) for pitch. The blue line is the difference.

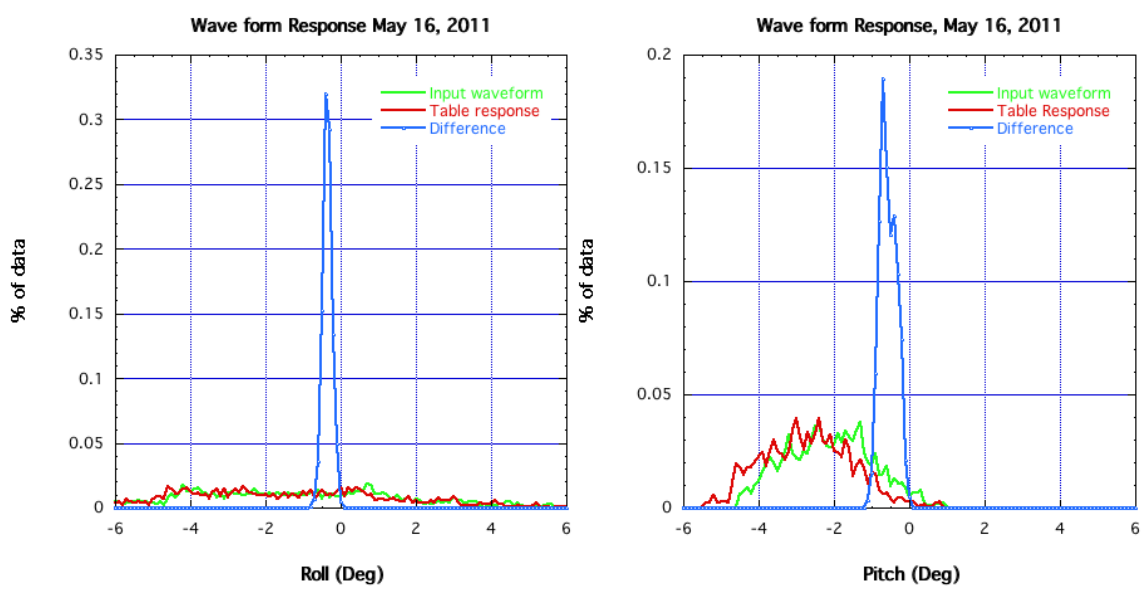

FIGURE 8. Probability distribution of input (red) and platform (green) roll (left) and pitch (right) values for an input data stream extracted from a shipboard data stream. The blue lines, representative of the platform position when in operation, are the differences. Note that an offset from zero is less problematic than the width of the difference distribution, because software can compensate for the former.

Finally, in an attempt to simulate ocean conditions without going to sea, the platform was placed on two dunnage bags filled with sufficient air to elevate the platform off the ground. The entire platform, with the SEANAV mounted to the base, was then manipulated back and forth to simulate ocean wave motion while the platform attempted to compensate. Figures 9 and 10 show the results of this test. The platform motion is comparable to that in Figures 6 and 7. The motion imparted to the platform in this configuration is subject to much random action and is in no way smoothly varying in a sinusoidal fashion. This makes the predictive routine much less accurate and results in occasional relatively large excursions that are reflected in the standard deviations (Table 1).

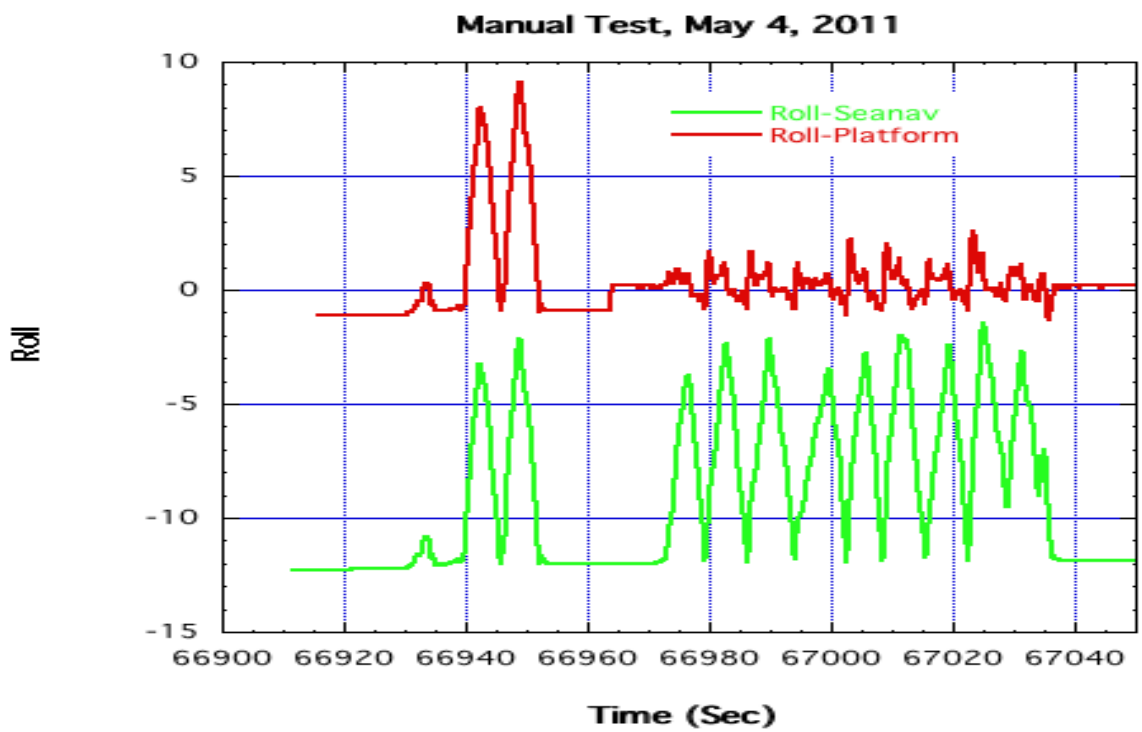

FIGURE 9. Roll measured from the SEANAV mounted to the base of the platform (red) and from the tilt sensor on the platform itself. The two peaks before 66,960 sec were recorded before the compensation program began operation (~66,965 sec).

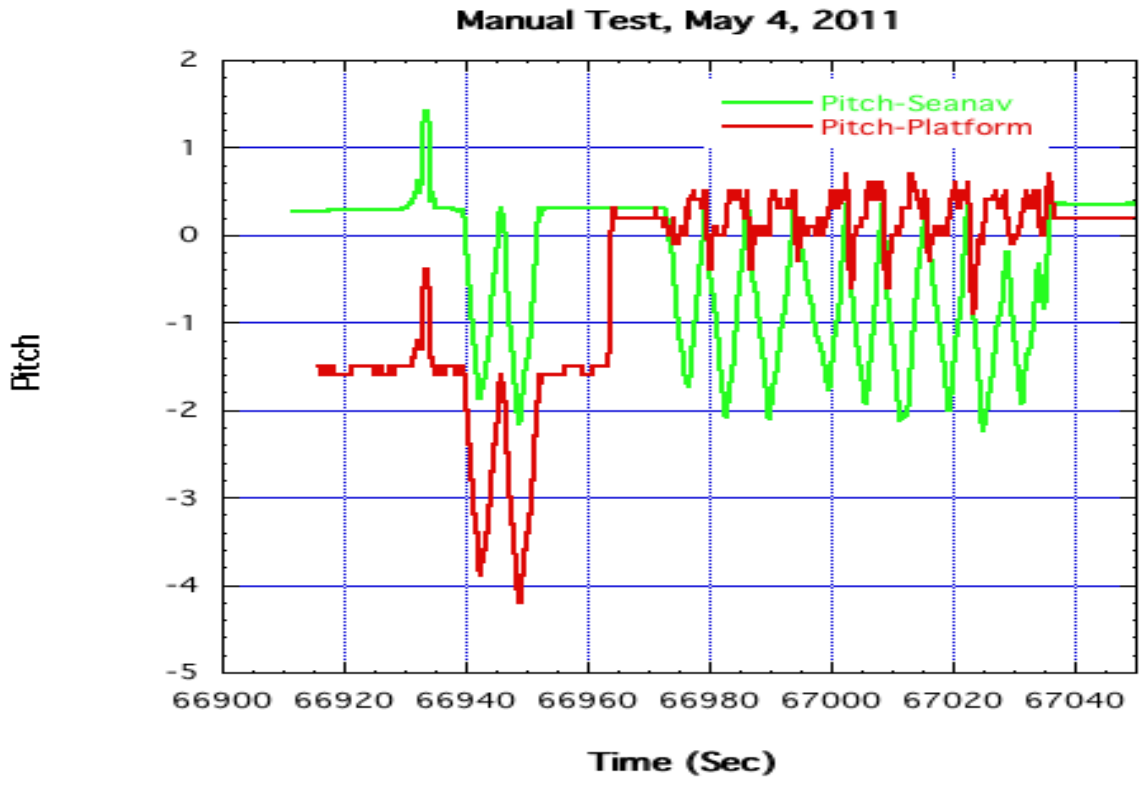

FIGURE 10. Pitch measured from the SEANAV mounted to the base of the platform (red) and from the tilt sensor on the platform itself (green). The two peaks before 66,960 sec were recorded before the compensation program began operation (~66,965 sec).

6 PREDICTIVE ROUTINE EVALUATION

The predictive routine used to drive the platform was evaluated by using a high-seas and a low-seas time series of roll and pitch obtained aboard the RV *Ron Brown*.

As noted previously, this routine uses first and second derivatives of the roll and pitch time series, an error estimate derived from predicted and known input values (Table 2), and the number of points ahead of the present time to predict, *Pa*. The value of *Pa* will depend on the sampling rate used and may be thought of as the time delay between a command and the platform's execution of the command. Figure 11 illustrates the method for determining the appropriate value of *Pa*. Clearly, the correlation between the two series is very good, and the peak is found at a delay of *Pa* = 3, or about 0.21 sec. The differing rates of degradation of the correlation reflect the different primary periods controlling the roll and pitch variables in the data; this is largely a result of the course of the ship relative to the ocean wave motion.

TABLE 2. High-sea state and low-sea state statistics for evaluation of the predictive routine, derived from data obtained aboard the RV *Ron Brown*.

	Roll (deg)				Pitch (deg)			
Sea State	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
Low	-8.289	6.359	-1.448	3.018	-4.534	0.868	-2.127	1.147
High	-8.788	3.306	-2.583	2.502	-10.92	11.08	-1.663	3.336

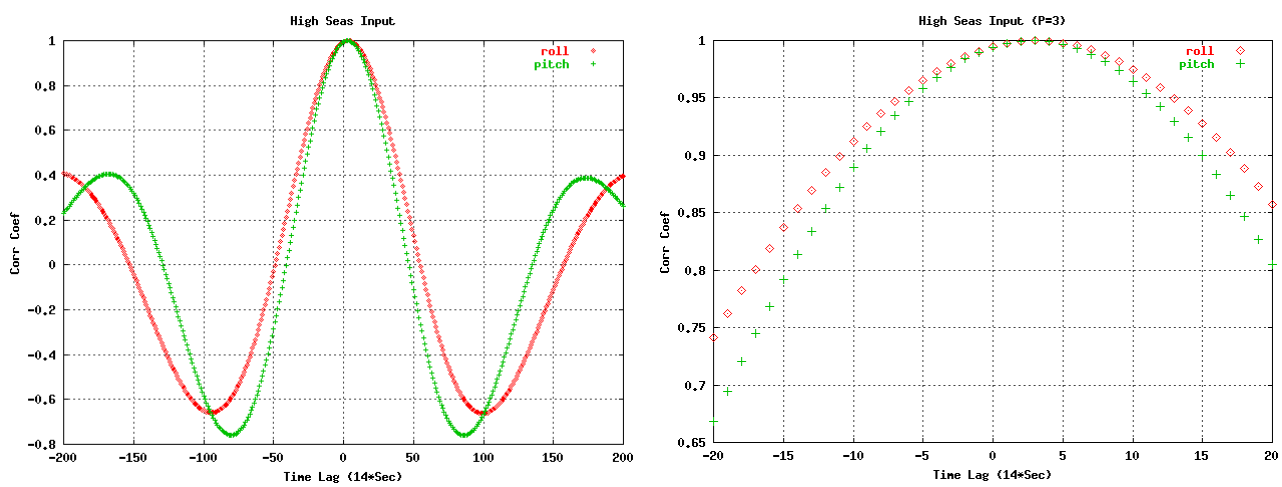

FIGURE 11. Example of time-lagged correlation between input and measured roll and pitch. The abscissa is determined by the effective input time series sample rate (14 Hz) and the number of points in the lag.

For these data at least (an admittedly small sample), *Pa* was found not to be dependent on sea state (Table 3). For large deviations, *Pa* would probably increase somewhat because of the increased distance for platform movement between positions.

TABLE 3. Summary of statistics for varying *Pa* and sea state.

Number of Points Ahead	Sea State	Roll (deg)		Pitch (deg)	
		Mean	Std Dev	Mean	Std Dev
0	Low	0.093	0.275	0.047	0.196
0	High	0.100	0.272	0.020	0.437
3	Low	0.104	0.073	0.051	0.116
3	High	0.103	0.115	0.022	0.125
4	Low	0.090	0.125	0.038	0.124
4	High	0.095	0.125	0.023	0.176
5	Low	0.076	0.210	0.044	0.152
5	High	0.094	0.164	0.016	0.284

After *Pa* was determined, the "best" values of the fraction of first and second derivatives and fraction of error were determined by performing multiple comparisons of input with measured roll and pitch. These results are summarized in Table 4. In both high-sea and low-sea conditions, the best agreement was found with a first-derivative fraction of 0.9 and a small error estimate correction. The reasons for this are as follows:

- There is a certain amount of inaccuracy in the platform motions; that is, the platform does not always return exactly to the same position for a given motor encoder position.

- The accuracy of the tilt sensor used here is only 0.1 degree, which limits the accuracy for small angular deviations.

Figures 12, 13, and 14 show examples of the low and high roll/pitch time series. Standard deviations of differences within 0.1 degree appear to be realizable with the current routines. Although it is small, some correlation remains between the measured difference and the input time series. Note that the precision of the tilt sensor (0.1 degree) contributes substantially to the measured variance. Figure 15 shows an example of time-lagged correlation for roll/pitch in high-sea and low-sea states.

TABLE 4. Summary of error statistics between input and measured roll.[a]

Sea State	Derivative Multiplier	Error Norm[b]	Err_{pred} (deg) Mean	Err_{pred} (deg) Std Dev
High	1.0	5	0.0019	0.117
High	1.0	10	0.0017	0.080
High	1.0	15	0.0013	0.073
High	0.9	5	0.0017	0.111
High	0.9	10	0.0016	0.077
High	0.9	15	0.0014	0.072
High	0.8	5	0.0016	0.108
High	0.8	10	0.0014	0.080
High	0.8	15	0.0013	0.077
Low	1.0	5	0.0015	0.032
Low	1.0	10	0.0013	0.027
Low	1.0	15	0.0010	0.026
Low	0.9	5	0.0014	0.039
Low	0.9	10	0.0011	0.037
Low	0.9	15	0.0009	0.037
Low	0.8	5	0.0011	0.056
Low	0.8	10	0.0010	0.058
Low	0.8	15	0.0009	0.059

[a] The second-derivative fraction was found to be best at a value of 0. The standard deviation of the difference between input and measured roll is used as the best estimate of performance.

[b] Large values correspond to small fractions of error used in the routine.

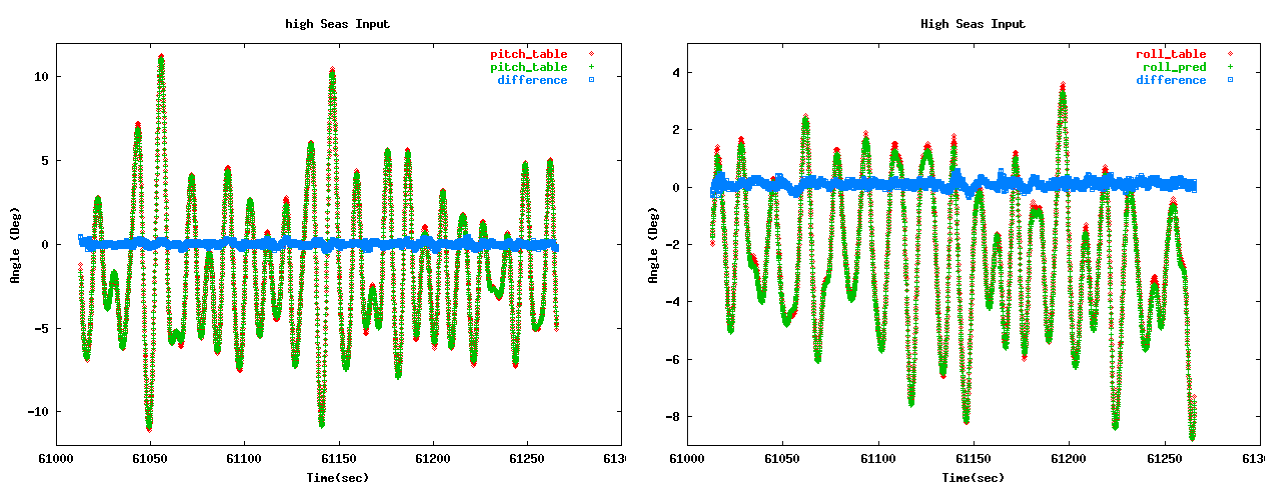

FIGURE 12. Roll and pitch high-seas time series sample with predicted time series.

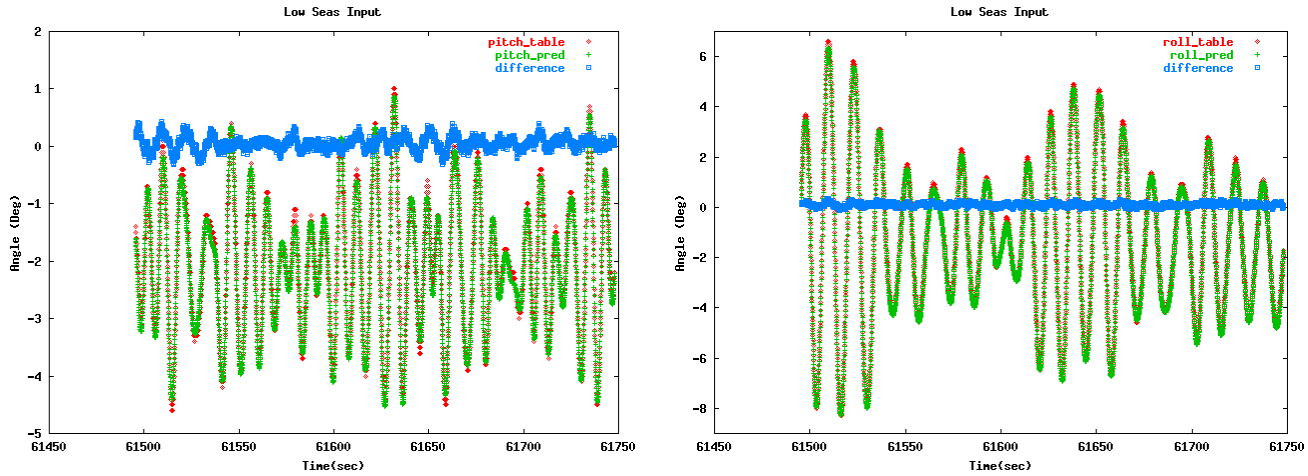

FIGURE 13. Roll and pitch low-seas time series sample with predicted time series.

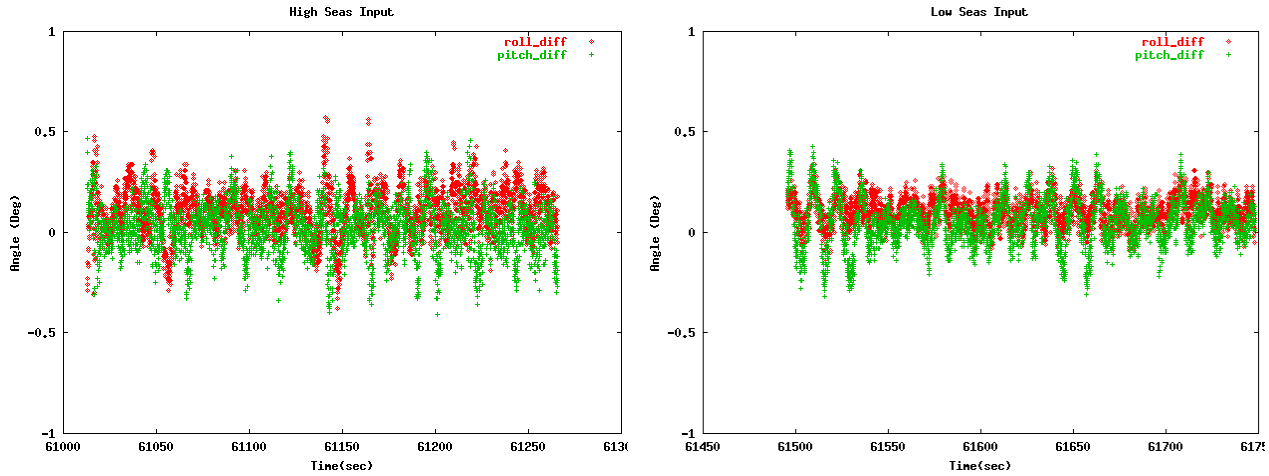

FIGURE 14. Roll and pitch high-seas and low-seas differences (input minus predicted) for roll and pitch.

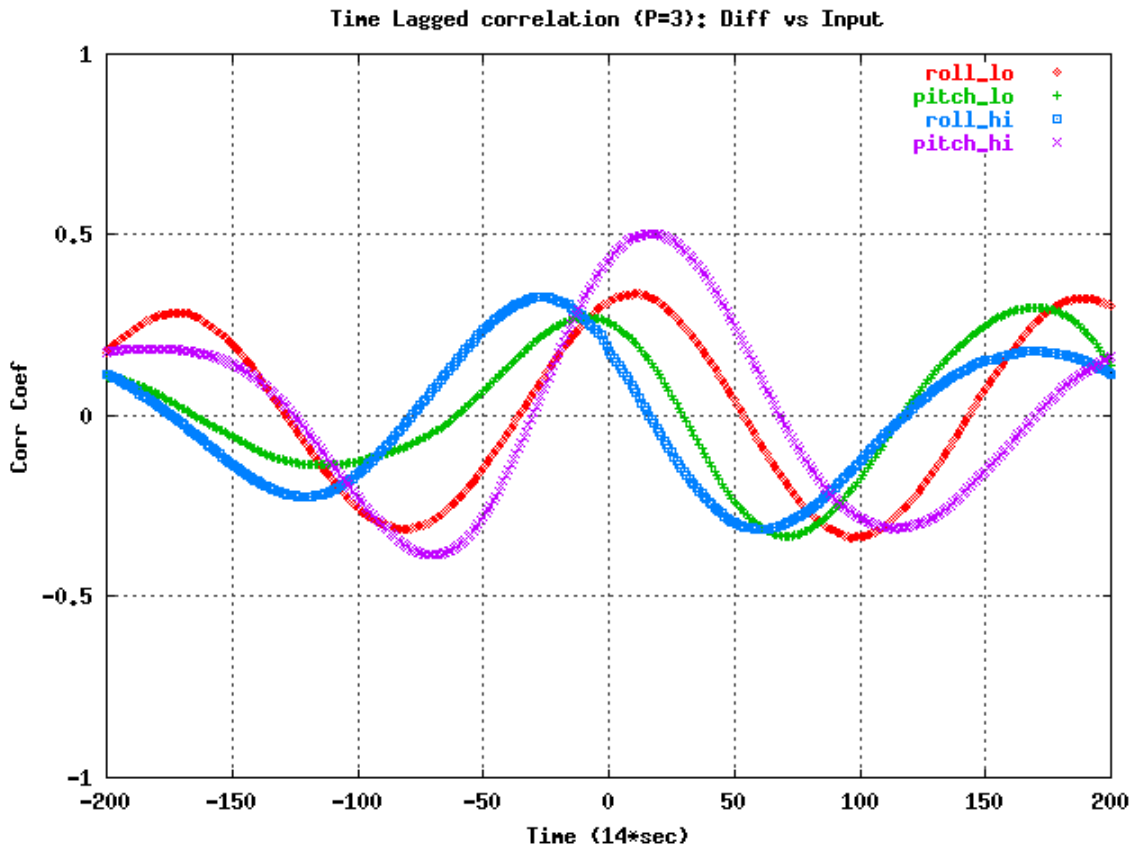

FIGURE 15. Time-lagged correlation for roll/pitch for high-sea and low-sea states.

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7 CONCLUSIONS

We have made considerable progress in understanding and using the AMF2 RPY stable platform. It is reasonable to conclude that with this system we can expect to maintain the platform within 0.3 degrees 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 ARM Program.

A second platform — roll, pitch, heave (RPH) — was procured to be used for stabilization of the marine W-band (95 GHz) ARM cloud radar. Yaw control is not necessary for this platform, but vertical motion control is still required. The new RPH platform design is also hydraulic rather than electromechanically controlled. The software commands for controlling this system are identical to those of the previous system, but there are nuances in the way they are applied. These differences are somewhat smaller than those with the RPY.

Making the RPY and RPH seaworthy for long periods of time will require additional effort. Figures 1 and 3 show that RPY is largely unprotected from seawater intrusion. The following steps are recommended in proceeding forward:

1. Consolidate the programmatic control of the platform to minimize platform response time while minimizing vibration of the platform. We intend to implement an additional feedback from a platform-mounted tilt sensor that will effectively determine roll/pitch offsets and can be manipulated in real time. Thus, we will have two shared memory applications — one from absolute measurements through the SEANAV and the second from relative measurements from a tilt sensor mounted on the platform itself.

2. Finish and test development of the “local” control scenario, whereby a feedback loop from a platform-mounted sensor is used to minimize pitch/roll variations. This will also operate through shared memory, though SEANAV input will not be required.

3. Consolidate the current arrangement of electronics and controllers that reside beneath the platforms to minimize exposure to the elements and unnecessary cable confusion.

4. Devise a means of controlling cables from the instruments mounted on the RPY platform, so that ship maneuvers do not cause the cables to become snarled. This could entail routing the cables through the center of the platform.

5. Modify the exterior of the platform to minimize seawater intrusion.

6. Develop a reliable means for allowing a crane to lift the platform into position aboard ship.

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