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Report on the Second ARM Mobile Facility (AMF2) Stabilization Platform: Control Strategy and Implementation

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ARM CLIMATE RESEARCH FACILITY

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Acronyms and Abbreviations

AMF2	ARM second Mobile Facility
ARM	Atmospheric Radiation Measurement Climate Research Facility
ASR	Atmospheric System Research program
EOM	equation of motion
MFRSR	Multi-Filter Rotating Shadow Band Radiometer
MWR	Microwave Radiometer
RV	research vessel
SeaNav	an electronic system for monitoring ship orientation values for navigation and control
SP	stable platform
TSI	Total Sky Imager

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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 from ocean-going vessels. A pillar of the AMF2 strategy in this effort is the use of a stable platform for those instruments that 1) need to look directly at, or be shaded from, direct sunlight or 2) require a truly vertical orientation. Some ARM instruments that fall into these categories include the Multi-Filter Rotating Shadow Band Radiometer (MFRSR) and the Total Sky Imager (TSI), both of which have a shadow band mechanism, upward-looking radiometry that should be exposed only to the sky, a Microwave Radiometer (MWR) that looks vertically and at specified tilt angles, and vertically pointing radars, for which the vertical component of motion is critically important.

During the design and construction phase of AMF2, an inexpensive stable platform was purchased to perform the stabilization tasks for some of these 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 3-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 and implementation as time permitted.

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

2.0 Brief System Description

The AMF2 Stable Platform (SP) is built by Sarnicola Systems and 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).

Figure 1. The AMF2 Stable Platform as originally designed and received.

The table roll and pitch are manipulated by lengthening and shortening two legs that support the platform (one leg is seen on the lower right of Figure 1; the second is shielded from view to the rear). The lengths of the legs are controlled independently with two electric motors that have 118,000 encoder positions between maximum and minimum extent. When both legs are changed equally, the table tilts in what we have defined as the pitch direction; when the legs change equally in the opposite sense – that is, one leg lengthens and the other shortens – the table tilts in the roll direction. The dimensions of this particular table allow for +/- 25 deg. of pitch and +/- 16 deg. of roll. However, the table 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 +/- 10 deg. This coincides with the design parameters originally specified. When conditions are encountered outside this range, data will be compromised.

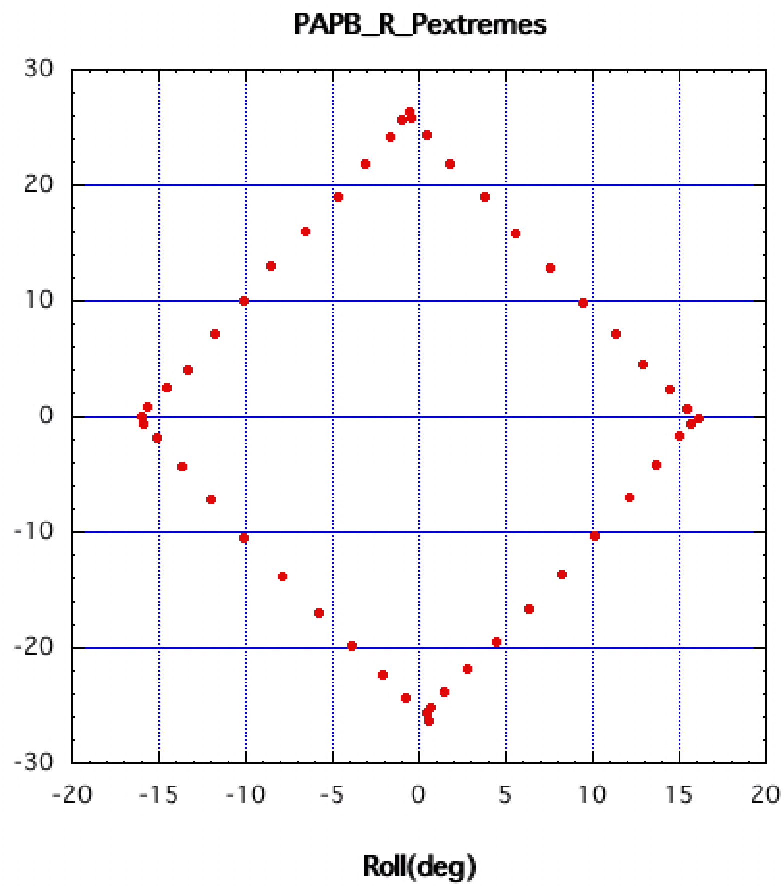

Figure 2. Locations of the maximum and minimum values of roll/pitch that are possible for any given value of pitch/roll. Values were determined by setting encoder positions to their respective max/min values and measuring the table roll and pitch with a tilt sensor mounted on the table.

Control of the pointing direction, or yaw, is accomplished using a turntable mounted on the top of the table that is belt-driven by an electric motor. There are 1800,000 encoder counts for a complete rotation, or roughly 1-second accuracy.

A Galil DMC-21X3 motion controller controls the platform. Delivery of the SP included the Galil controller and a software program, named EOM (equation of motion), that takes roll, pitch, and yaw values (provided by an external computer, for example) and calculates the appropriate encoder counts to position the legs and turntable in the desired position. It is also possible to "talk to" the controller directly with a set of commands to adjust the table to any desired position. For example, whenever power is removed from the platform, it is necessary to reestablish zero on each leg. This was originally accomplished using three contact switches that changed state when the legs were in their home positions. This was found to be imprecise, however, so home position is determined visually by the operator when necessary.

Figure 3 shows the platform during its maiden voyage. The MWR and MFRSR are mounted on either end 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 must be implemented.

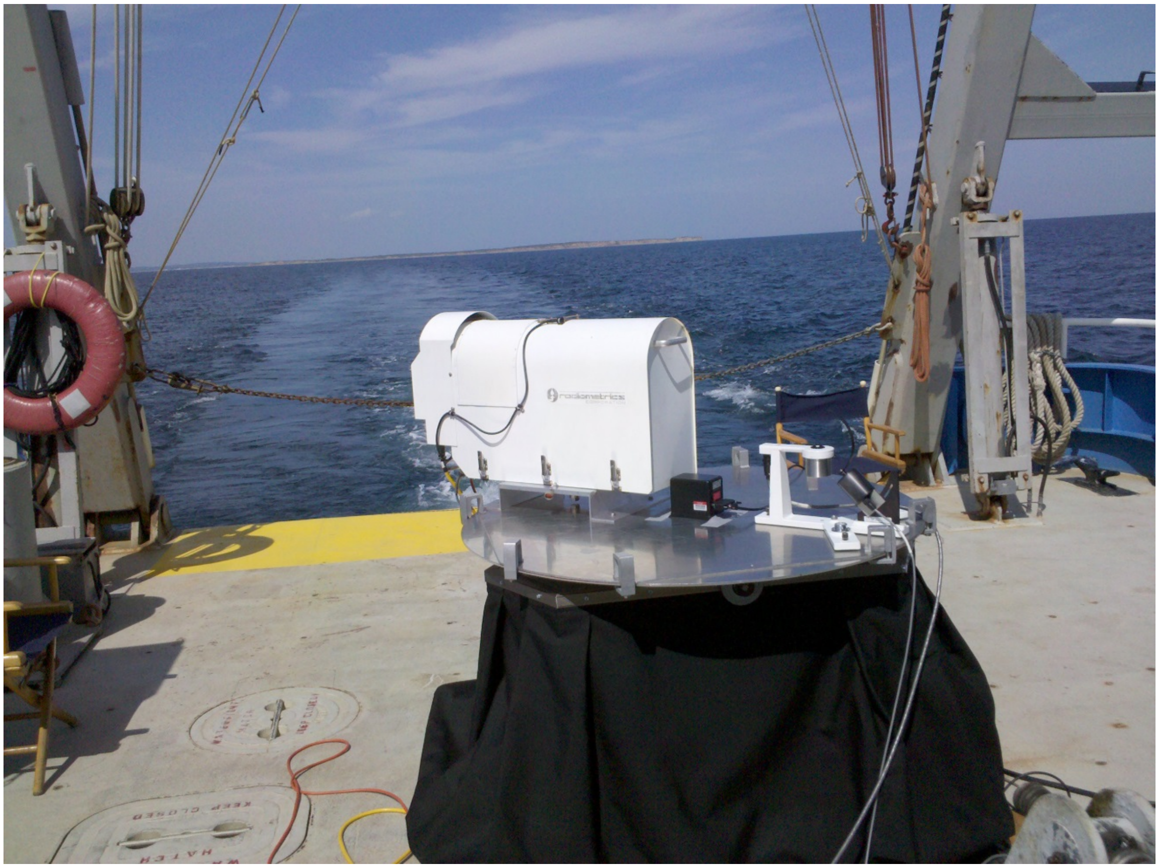

Figure 3. The platform during its initial deployment, pointed at 215 degrees. During this voyage, if the ship were to "come about", the yaw zero would need to be reset. For all maneuvers less than 180 degrees, however, the yaw compensation was very good. The cables to the instruments also had to be managed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

During operation, the system operates as follows. A Kearfott Seaborne Navigation System (SeaNav) is placed at or near the centerline of the ship. 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 platform 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 *RV Connecticut*, a sample rate of 10 Hz was used. The ability of the platform to maintain level was monitored using the tilt sensor mounted in the middle of the platform. An alternate method of operating would be to use the values sensed with the tilt sensor (or equivalent) and create a feedback loop that continuously attempted to minimize the sensed values of pitch and roll. This would eliminate the need for carefully evaluating orientation offsets between the SeaNav and SP (except for yaw).

3.0 Performance Evaluation

During the period before initial deployment of the SP to the *RV Connecticut*, we developed procedures and programs to interface between the SeaNav and the Galil controller, bearing in mind that the time delay between the two should be as short as possible. We discovered that the EOM provided by the manufacturer was not as accurate as hoped; however, due to time limitations, we used this implementation during the *RV Connecticut* cruise to establish proof of principle and to acquire much-needed experience in operating a system of this type.

Figure 4 is a five-minute snapshot of the measured roll by the SeaNav and the tilt sensor mounted on the platform taken during moderate conditions. It is apparent that there is an offset of about 0.5 deg. between the two measurement systems; this is of little concern. It is also evident that the motion compensation reduces roll effects by about five or so. The standard deviation of the roll or pitch is one method to express the magnitude of the motion about the mean. The standard deviation of table roll for 10 hours of operation on June 18 was 0.497 deg. while SeaNav standard deviation was 1.86 deg. over the same period.

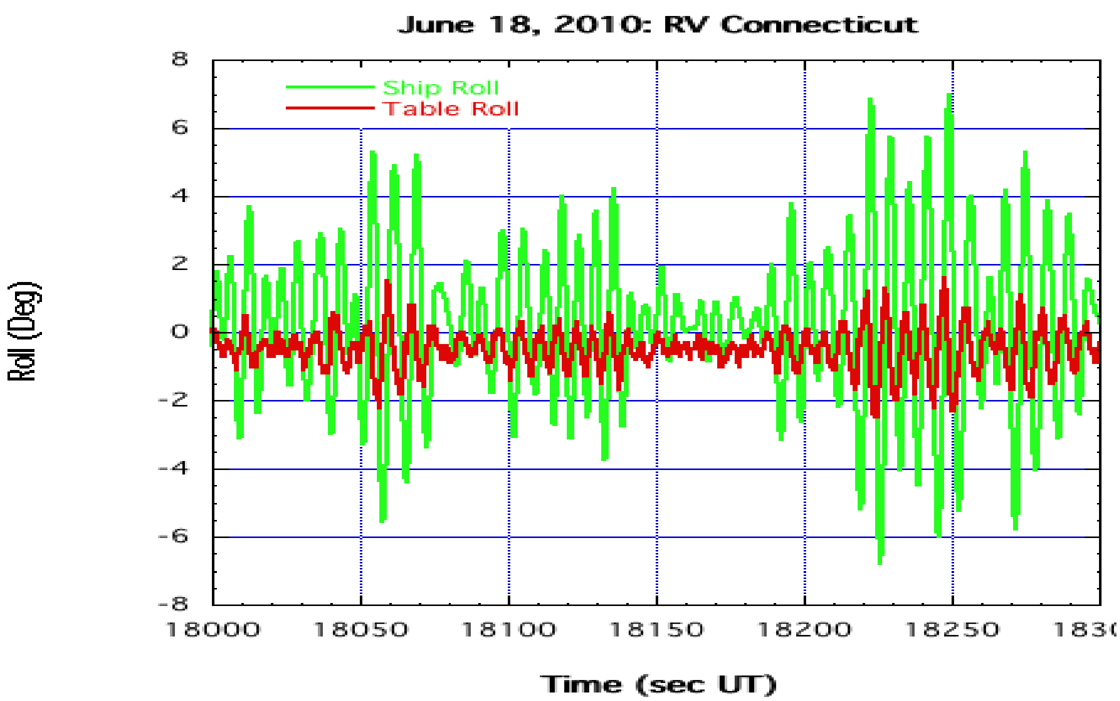

Figure 4. An example of roll of the ship (green) and simultaneous roll of the platform in moderate conditions on June 18, 2011.

Figure 5 shows the distribution of values for roll and pitch as measured by SeaNav and the table-mounted tilt sensor.

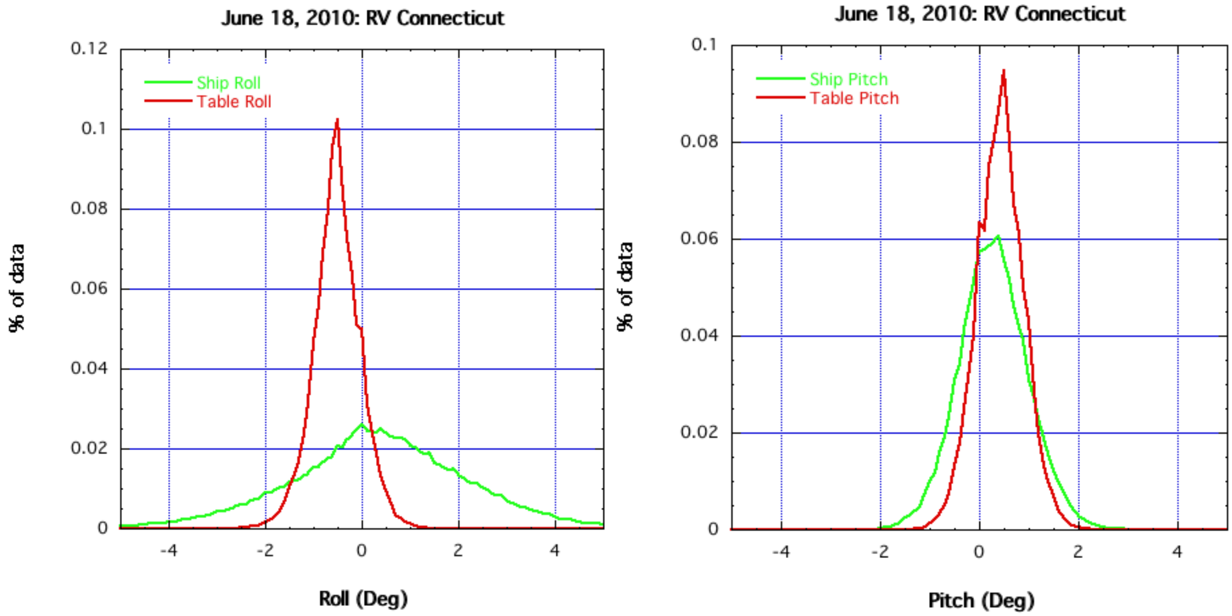

Figure 5. Distribution of values for roll (left) and pitch (right) for ship (green) and table (red) on June 18, 2010.

Clearly the response of the table to pitch control was much poorer than to roll control. On the other hand, the variation of the ship motion along the pitch axis was considerably smaller than along the roll axis. Note that the spread of the roll and pitch values of the table are quite similar. It is possible that this amount of spread in the distribution was indicative of the amount of noise in the procedure at that time (Table 1).

Subsequent analysis of table response to input data and elimination of programming errors has improved things considerably. The EOM program approach was eliminated in favor of controlling the table directly through the Galil controller using primitive commands to control leg lengths. A table lookup function was created by cycling the table through its full range of motion and measuring the true roll and pitch angles. This table 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 table position. The actual table position was measured simultaneously with the tilt sensor mounted as in Figure 3. With the input wave form regulated to 10 Hz, we determined from a time-lagged correlation that the table was approximately one sample (0.1 sec) delayed (data not shown). This delay was then compensated by a predictive routine that operated on the input data before feeding it to the platform. Figure 6 and Figure 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 there is a considerable improvement in both roll and pitch differences. Note that the scales used in the plots accentuate the pitch differences, which still have a standard deviation of less than 0.25 deg. 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 SP is considerably improved with this new approach. However, we note that the pitch response is still poorer than the roll response.

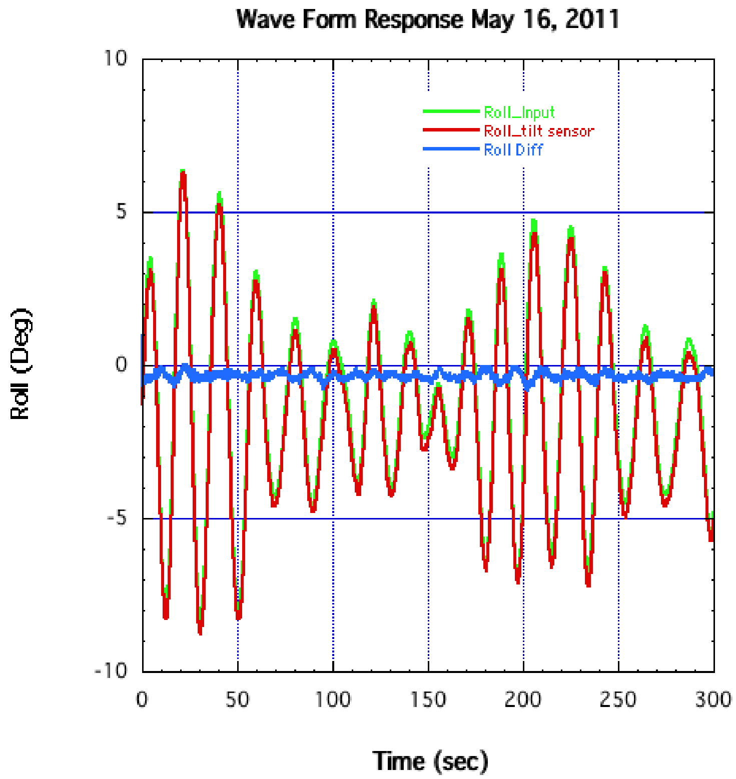

Figure 6. Comparison of input waveform (red) and measured table position (green) roll. The blue line is the difference.

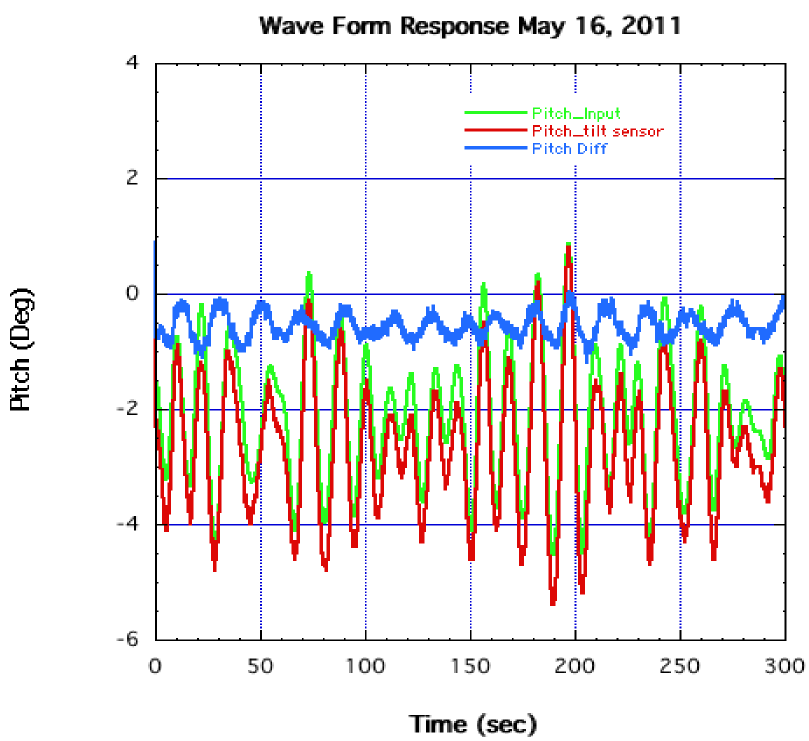

Figure 7. Comparison of input waveform (red) and measured table position (green) pitch. The blue line is the difference.

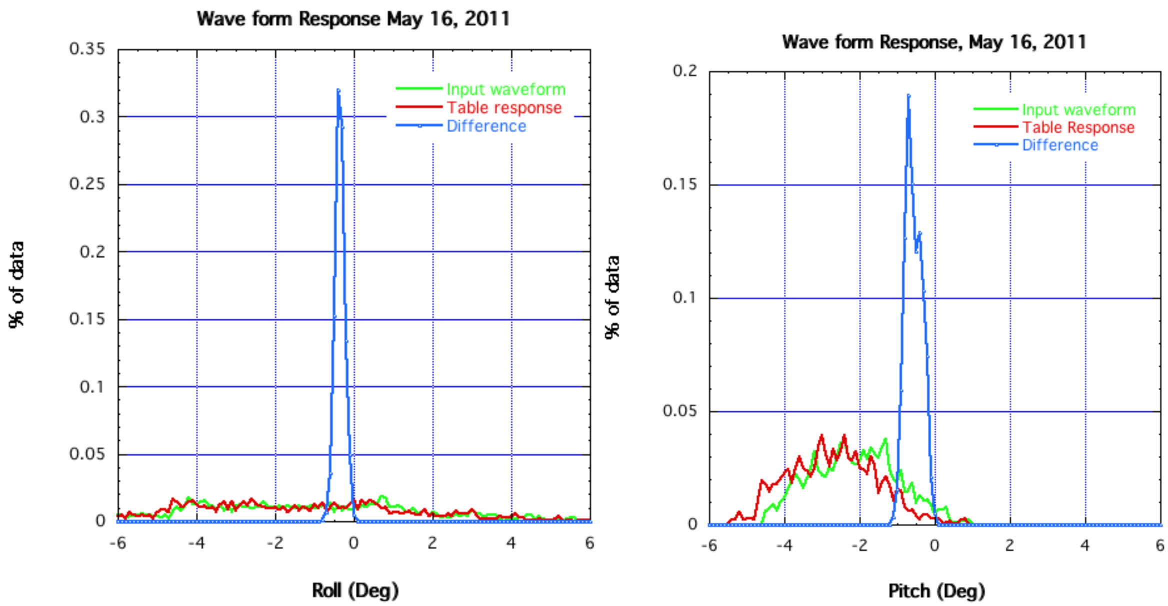

Figure 8. Distribution of input (red) and table (green) roll (left) and pitch (right) values for an input datastream extracted from a shipboard datastream. The blue lines, representative of the table position, when in operation, are the difference.

Table 1. Roll standard deviation and pitch standard deviation.

	Roll Std. Dev.	Pitch Std. Dev.
SeaNav	1.86	0.69
SP	0.50	0.48
WAVEFORM IN	3.14	1.14
SP DIFFERENCE	0.12	0.22
SeaNav_MANUAL	2.85	0.71
SP_MANUAL	0.62	0.26

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 table attempted to compensate. Figure 9 and Figure 10 show the result of this test. The table motion is comparable to that in Figure 6 and Figure 7. The motion imparted to the table in this fashion is in no way smoothly varying in a sinusoidal fashion and has a much more random action superimposed upon it. This makes the predictive routine much less accurate and results in the occasional relatively large excursions reflected in the standard deviations (Table 1).

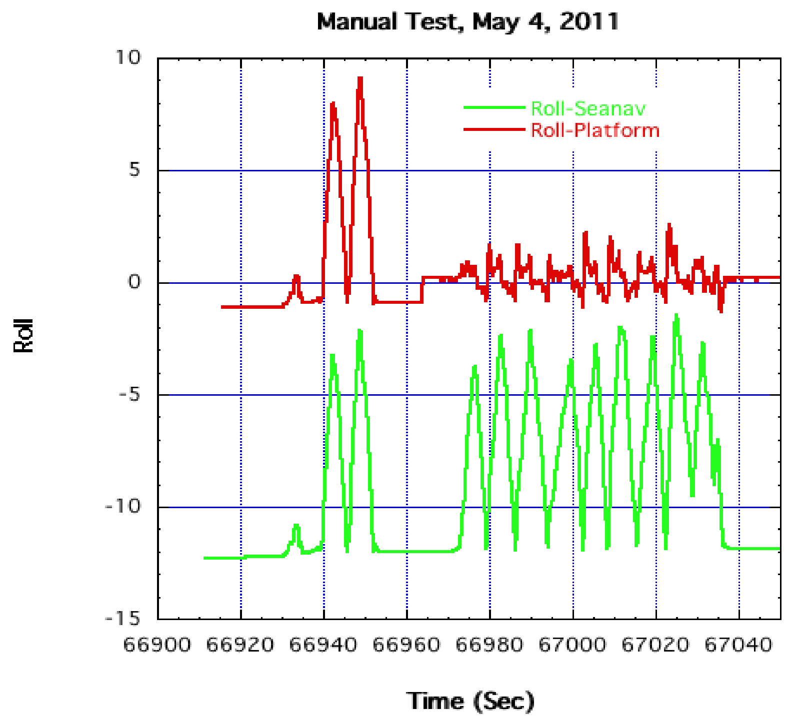

Figure 9. Roll measured from the SeaNav mounted to the base of the table (red) and from the tilt sensor on the platform itself. The two peaks before 6690 sec are before the compensation program begins operation (~66965 sec).

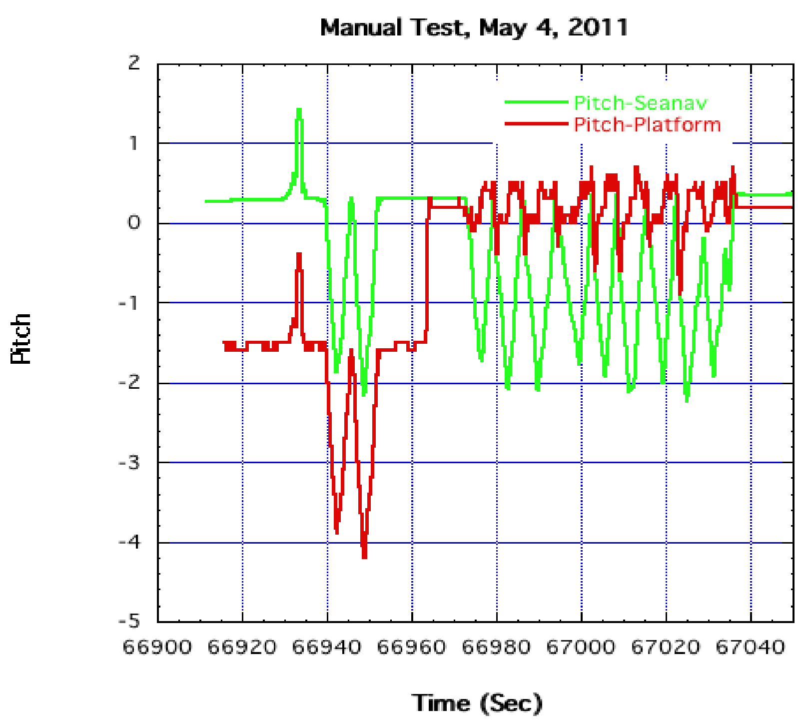

Figure 10. Pitch measured from the SeaNav mounted to the base of the table (red) and from the tilt sensor on the platform itself. The two peaks before 66960 sec are before the compensation program begins operation. (~6695 sec).

4.0 Conclusions and Recommendations

We have made considerable progress in understanding and using the AMF2 Stable Platform. It is reasonable to conclude that with the present system we can expect to maintain the platform within 0.5 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 System Research (ASR) program. It is not known if this degree of control is sufficient for cloud vertical velocity measurements.

The present platform is not large enough to support both radar and radiometric instruments. A second platform is necessary to accomplish this. We note that yaw control is not necessary with a vertically pointing cloud radar. We also conclude that any new platform of this design should be hydraulically controlled. The present, electric control exposes electronics to salt-air contamination.

We have discussed here only the control issues regarding the platform. Significant effort is still required to make the SP seaworthy for long periods. Figure 1 and Figure 3 show that it is largely unprotected from sea water intrusion. The following list recommends steps in proceeding forward.

1. Consolidate the programmatic control of the platform to maximize table response time while minimizing vibration of the platform. This likely would also include moving more of the operations to the Galil controller.
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.
3. Determine if the present platform is adequate, in both payload and pointing control, for handling a vertically pointing W-band cloud radar. This can be determined with the present platform, but a second platform is likely to be necessary in the long run. This would almost certainly require another test at sea.
4. Consolidate the current arrangement of electronics and controllers that resides beneath the platform so as to minimize exposure to the elements and unnecessary cable confusion.
5. Devise a means of controlling cables from the instruments mounted on the platform so that ship maneuvers do not snarl the cables. This could entail routing the cables through the center of the table.
6. Modify the exterior of the table to minimize seawater intrusion.

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