ABSTRACT

Military sea basing operations include mooring ships together offshore and transferring cargo and equipment between them. A newly developed Environmental and Ship Motion Forecasting (ESMF) System will facilitate these operations by providing predictions of ship motions in waves. Coherent forecasts of the ship motions are provided through remote sensing of the ambient waves and using these waves as input to a predictive ship motion simulation. Key technologies developed in support of the ESMF system include: a custom-built wave sensing radar; a least squares inverse wave retrieval algorithm; a ship motion model for performing rapid seakeeping simulations; and a robust peer-to-peer system architecture. The ESMF system was tested extensively in a demonstration aboard the R/V Melville with very good results, often achieving correlations of forecast-to-realized signals of better than 80% over 30 minute intervals.

INTRODUCTION

New military sea basing concepts include plans for mooring ships together offshore in order to transport cargo and equipment between them. These operations become challenging when there is relative motion between the ships operating in ocean waves. The U.S. Office of Naval Research (ONR) has guided the development of an Environmental and Ship Motion Forecasting (ESMF) System focused on predicting these ship motions in waves. The system is required to provide phase-resolved predictions of ship motion for a thirty second prediction window, as well as a five minute “energy” forecast of significant motion events. These short-term predictions can assist in the timing of sea basing operations affected by ship motions.

We are currently developing an ESMF system composed of a custom-designed Doppler radar, wave-retrieval processing, and rapid ship motion simulation. The Advanced Wave Sensing Radar (AWSR) prototype was developed in conjunction with the University of Washington Applied Physics Lab (UW-APL) specifically for wave sensing in support of ship motion prediction, and features vertical polarization, four antennas, and extensive user-configurable settings. The radar data feeds a custom signal processing algorithm which fits ocean wave modes to the Doppler data using a least-squares inversion technique with an over-determined solution to reduce noise. The discrete ocean wave spectrum is fed to a ship motion reduced-order model to predict the future motion of one or more ships in the observed wave field, using a pre-calculated database of wave forcing and impulse responses. An open system architecture provides a peer-to-peer data exchange between system components, enabling minutes of forecast in just a few seconds.

After an initial development phase, the APS-ESMF system was tested extensively aboard the 85m R/V Melville to demonstrate the real-time capability of the system to produce phase-resolved forecasts of ship motion. System performance was monitored through correlations of the forecasted and observed motions. The performance varied with environmental conditions, heading to the waves, and ship response mode. The best performance was generally for heave and pitch in bow
seas, often with correlations in excess of 80% for the approximately 30 minute test legs. The most extreme ship response of the cruise was a roll event swinging greater than 20 degrees that was well predicted by the ESMF system minutes in advance. A system replay function facilitates ongoing refinement of the core processing algorithms using the R/V Melville test data as the system is being prepared for multiple-ship sea base testing.

In this paper we review the enabling technology developed in support of building the prototype ESMF system. After first reviewing the overall problem statement, we break down the technology development in sections covering Wave Sensing Radar, Wave Retrieval Processing, Ship Motion Modeling, and System Integration. We then review the ship motion forecasting performance during at-sea testing of the prototype system.

PROBLEM DEFINITION AND SYSTEM OVERVIEW

In order to perform time-domain phase-resolved ship motion forecasting, a system needs to measure the waves that will interact with the ship during the forecast interval and simulate the ship motions resulting from interaction with these waves. A depiction of the measurement concept is presented in Figure 1. For a forecast interval of up to 5 minutes, and ship speeds of up to 10 knots, the ocean waves which will interact with the ship in the forecast interval are all contained within a 5km radius of the ship location. Thus, a wave sensing system which can measure waves out to 5km is theoretically sufficient to provide the necessary observations for coherent forecasting up to 5 minutes. The selection of X-band radar as the wave sensing technology and the associated wave retrieval processing approach are described in detail in the following sections.

The system’s ship motion simulation component must be able to ingest data from the wave measurement subsystem and predict the response of the ship to the particular wave forcing. The ONR Broad Agency Announcement1 specified the requirement to predict specific wave and ship motions for a 30 minute forecast interval and critical environmental conditions for a 5 minute forecast interval, providing important input for operational decision-making. This requirement is interpreted as a need to provide good phase-resolved ship motion forecasting up to 30 seconds, and identification of larger energy groups and associated motions to 5 minutes. Meeting both of these goals requires an ability to measure the particular wave field and predict the associated ship response. Thus, to provide useful forecasts, the ship motion simulation component must be able to simulate up to 5 minutes of seakeeping response to an input wave field with a calculation time of a few seconds. To ensure that the short-term forecasts are consistent with the initial state, the system must provide data from a ship motion sensor to the seakeeping simulation to be used as an initial condition. We describe the approach used to achieve this in the Ship Motion Modeling section.

While the radar and ship motion sensor are the main driving sensors for the ship motion forecasting, there are other sensors, such as AIS and meteorological sensors, that feed secondary processes such as the UI displays. The ship motion forecasting simulation provides the key raw output of the system, which is a time sequence of the predicted future motions. This output feeds real-time processing that indicates system performance (performance monitoring via cross-correlation of forecasts to ground truth), statistics, and UI displays. An archive component saves all of the system data in a form that can be easily extracted for analysis, replayed for future system testing, or model parameter optimization. Details of the key originating sensors and downstream processing components are described in the following sections.

WAVE SENSING RADAR

A survey of available wave sensing technologies suggests the superiority of X-band radar for practical application of wave sensing in the ESMF system. A field of point sensors (buoys) could theoretically provide wave sensing in the required measurement region indicated in Figure 1. However, it is not currently practical to consider deploying, maintaining, and communicating with such a large field of sensors to obtain all wave phase information over square-kilometers of the ocean surface. A remote sensing approach with the hardware residing on board the ship housing the ESMF system is a more feasible path. Wave measuring LIDAR has been used for such remote sensing18, but is limited in range to tens of meters, far short of the kilometers needed for the present application.

The mechanism of microwave Bragg scattering from ocean surface roughness for measurement of Doppler velocities on the ocean surface has long been established14. Continuing research13 has established and overcome some of the key challenges in exploiting this mechanism for measurement of ocean wave orbital velocities from a shipboard X-band
microwave radar. Such studies have demonstrated that radar provides a capable technology for performing the wave field remote sensing. Relying on the UW-APL’s vast experience in developing this technology, we set about designing an application-specific X-band radar that could meet the ESMF wave sensing requirements. This Advanced Wave Sensing Radar (AWSR) was to meet the following goals:

- Accurate Doppler sensing to 5 km, enabling a 5 minute wave forecasting capability in all environmental and ship speed scenarios of interest.
- Azimuthal scanning interval of less than 3 seconds providing sufficient sampling criteria for wave fields whose content is largely for periods > 6 sec.
- Azimuthal resolution of ~ 2.5 deg and range resolution of ~ 7.5m, metrics derived from modeling studies as a trade between sampling requirements and system bandwidth/antenna size.
- Operation from a large moving ship able to accommodate height-above-waterline of >30m, installation of ~500kg of equipment, and supply of ~2kW of power

The AWSR achieves these goals by drawing on many of the design features of UW-APL’s previous ship-board CORAR system\(^1\). These features include:

- VV-Polarization: Substantially improved scattering performance compared to standard marine radar HH-polarization.
- Coherent Doppler Radar: Stable oscillator and 3kW amplifier permit high-fidelity measurement of the Doppler shift, which is linearly related to the wave orbital velocity. (In contrast, radars that are limited to only backscatter power require a nonlinear Modulation Transfer Function that needs to be continuously calibrated for environmental conditions.)
- Four-Antenna Switching Network: Use of four antennas allows for a slower rotation rate while maintaining the required repetition rate. This permits longer dwell times, providing an improved Doppler measurement.
- Custom Elliptical Antenna Design: The antennas were designed to provide 10 degree vertical beamwidth and 2.5 degree horizontal beamwidth. The narrow horizontal beamwidth is important to maintain good azimuthal resolution of wave measurement at longer ranges.

The AWSR was implemented in two components, a Deck Top Unit (DTU) and Mast Top Unit (MTU), as shown in Figure 2. These are designed to be separable or stacked. The DTU contains all of the large electronics and computing resources, sending out the RF signal via wave guide to the MTU. The MTU consists of a fixed and rotating portion, with a rotator housing an RF slip-ring, above which is the antenna switching network. A commercial trailer with erectable tower was purchased and customized to provide a mobile AWSR unit for testing. This allowed for preliminary testing of the radar looking at ocean waves from the Scripps Pier, La Jolla, CA, as shown in Figure 3. These tests provided a checkout for the AWSR function, and allowed us to feed and test our wave retrieval processing, checking against wave buoys.

![Figure 2 - Deck Top Unit (left) and Mast Top Unit (right).](image1)

![Figure 3 - AWSR testing at the Scripps Pier, La Jolla, CA.](image2)

**WAVE RETRIEVAL PROCESSING**

The AWSR is designed to measure the Doppler shift due to wave orbital velocity over a grid cell of the ocean surface. For the AWSR, cell size is 5m in range and 2.5 degrees in azimuth. The measured Doppler shift is from the radial component of the wave orbital velocities. In order to provide an accurate measure of the wave surface elevation field, a processing algorithm must be implemented to translate radial orbital velocity measurements to a surface elevation field. Previous studies have examined candidate approaches\(^11\) using FFTs of the observation data. One of the main difficulties is in incorporating the fact that the Doppler radar is observing only radial velocities. We lay out here a wave retrieval approach that uses an exact expression of this directivity.
The wave retrieval algorithms are formulated under the assumption that wave fields can be forecasted throughout a specified spatio-temporal forecast region by calculating an initial wave field condition throughout a suitable region-of-influence, a concept that has been previously studied. Strictly speaking, and in the most general case, ocean surface waves propagate in a nonlinear manner (i.e. each spectral component does not propagate independently of each other component). However over the time-scales, spatial scales and sea states of interest for the coherent forecasting problem, ocean surface waves are well represented by linear propagation.

**Wave Motions**

In a regular wave field, a single monochromatic component, or “mode”, is present – propagating with a fixed wave period, wavelength, and propagation direction. Temporarily assuming no mean surface current, the vertical displacement of a surface wave in a regular wave field can be represented as:

\[ \eta(x, t) = \text{Re}(A \exp(i[k_x x + k_y y - \omega t])) \]

where
- \( A \) is the “modal” (or “Fourier”) amplitude, which is a complex number characterizing the magnitude and phase (at the origin) of the monochromatic wave component.
- \( k_x \) and \( k_y \) are the wavenumbers of the wave component in the x and y directions
- \( \omega \) is the temporal frequency as measured in a ground-fixed (not moving with respect to the ground/Earth) coordinate system.

The wave period \( T \), measured in a ground-fixed coordinate system, is \( T = 2 \pi/\omega \).

Here, \( k_x, k_y \) and \( \omega \) define the wavenumber-frequency “triplet” which, for low amplitude surface waves in deep water, follows the deep-water linear dispersion relationship for surface waves:

\[ \omega = \sqrt{g k}, \text{ where } g = \text{gravitational acceleration} \]

and \( k = \sqrt{k_x^2 + k_y^2} \).

The wavenumber can also be represented in terms of the wave’s propagation angle:

\[ k_x = k \sin \beta, \quad k_y = k \cos \beta \]

where \( \beta \) is the angle of the direction that the wave is propagating to and is defined clockwise from the positive y-axis.

A more compact vector notation can be adopted. Let \( \hat{i} \) and \( \hat{j} \) be unit vectors in x and y directions respectively, so that

\[ \mathbf{x} = x \hat{i} + y \hat{j} \]

And now redefine the propagation wavenumber vector as

\[ \mathbf{k} = k_x \hat{i} + k_y \hat{j} \]

We can define a unit vector in the direction of propagation as

\[ \mathbf{e}_k = \frac{\mathbf{k}}{|\mathbf{k}|} = \sin \beta \hat{i} + \cos \beta \hat{j} \]

An open-ocean surface will have a continuum of waves present. Throughout a limited spatio-temporal region around the origin we can represent the surface elevation as a discrete (Fourier) summation of wave components:

\[ \eta(x, t) = \text{Re} \left( \sum_{n=1}^{N} A_n \exp(i(x \cdot \mathbf{k}_n - \omega_n t)) \right) \]

or, in terms of propagation direction

\[ \eta(x, t) = \text{Re} \left( \sum_{n=1}^{N} A_n \exp(i(k_n x \cdot \mathbf{e}_{kn} - \omega_n t)) \right) \]

The horizontal wave particle velocity in linear theory can likewise be written as the linear superposition

\[ \mathbf{v}_p(x, t) = \text{Re} \left( \sum_{n=1}^{N} A_n \omega_n \exp(i(x \cdot \mathbf{k}_n - \omega_n t)) \mathbf{e}_{kn} \right) \]

**Doppler Radar Measurement of Wave Motion**

To extract the radial velocity from the radar backscatter signal, we employ the method of spectral moments. Although this process is standard in pulse-Doppler radar, it is worthwhile to work through the analysis in order to reveal several key system design features and physical limitations of the process.

Assume that a sequence of \( N \) transmissions have been made and the baseband receiver data organized into a 1xN vector of (complex) data for each range cell. The radial velocity appears as a sinusoidal periodicity in the complex signal. To find this periodic component, the Fourier Transform is taken:

\[ \tilde{p}(f_m, R) = \sum_{n=1}^{N} p(t_n, R) \exp(i2\pi f_m t_n) \]

The first moment reveals the peak frequency, which can be shown to be the Doppler shift that results from the relative motion of the patch:

\[ f_D(R) = \frac{\sum_{m=1}^{N} f \| \tilde{p}(f_m, R) \|^2}{\| \tilde{p}(0, R) \|^2} \]

We refer to this as the “moment generator”. The fundamental Doppler resolution of the moment generator is:

\[ \Delta f_D = \frac{1}{N \Delta T} \]

Where \( N \) is the total number of transmissions and \( \Delta T \) is the time between transmissions – and the product is the dwell time of the line scan. Clearly, Doppler resolution improves as the dwell time increases.

The aliasing frequency of the Fourier Transform is:

\[ f_{D, \text{max}} = \frac{1}{2 \Delta T} \]

which limits the maximum target measurement velocity, the sum of the wave orbital velocity and the velocity of the ship observing the waves.

**Radar Observation Model**

We now consider the remote sensor observation (or “forward”) model, which can later be inverted to solve for a
collection of modal components used to represent a wave field within a specified spatio-temporal region.

The Doppler shift of an interrogating radio signal scattered off a moving target is:

\[
f_D = 2 \frac{f_c}{c} v_{\text{target}}
\]

where \(f_c/c\) is the ratio of the transmission frequency to the speed of light, and with \(v_{\text{target}}\) being defined as the target’s radial speed towards the RF projector/receiver. When \(v_{\text{target}} > 0\) (the “closing” target case), the Doppler shift is positive.

We express the nth Doppler observation with reference to the local coordinate system assumed as:

\[
f_{D,n} = 2 \frac{f_c}{c} v_{\text{rad}}(x_n, t_n, \theta_{\text{look},n})
\]

Because the radar is mounted on the moving ship, the relative particle velocity seen from the radar at the location of the nth measurement is:

\[
v_{p,\text{rel},n} = v_p(x_n, t_n) - v_s,n
\]

With \(v_{s,n}\) being the ship’s velocity vector (over ground).

Using the expression for \(v_{p,\text{rel},n}\), the Doppler shift \(f_{D,n}\) can be expressed as:

\[
f_{D,n} = -2 \frac{f_c}{c} \left( (v_p(x_n, t_n) - v_s,n) \cdot e_{\text{look},n} \right)
\]

Recall the modal series representation of the particle velocity:

\[
v_p(x_n, t) = \Re \left( \sum_{m=1}^{M} A_m \omega_m \exp(i(x_n \cdot k_m - \omega_m t)) e_{k,m} + u_c \right)
\]

Which can be substituted into the previous equation for Doppler:

\[
f_{D,n} = -2 \frac{f_c}{c} \left( \Re \left( \sum_{m=1}^{M} A_m \omega_m \exp(i(x_n \cdot k_m - \omega_m t)) e_{k,m} + u_c - v_{s,n} \right) \cdot e_{\text{look},n} \right)
\]

Now defining the “D Function” as:

\[
D_{n,m} = -2 \frac{f_c}{c} e_{k,m} \cdot e_{\text{look},n} = -2 \frac{f_c}{c} \cos(\beta_m - \theta_{\text{look},n})
\]

We can write:

\[
f_{D,n} = \Re \left( \sum_{m=1}^{M} D_{n,m} A_m \exp(i(x_n \cdot k_m - \omega_m t)) \right) + (u_c - v_{s,n}) \cdot e_{\text{look},n}
\]

The above equation is referred to as our observation model.

The \((u_c - v_{s,n}) \cdot e_{\text{look},n}\) term in the above expression results from the ship moving relative to the ocean surface. It is a constant in the sense that it does not depend on \(x\) or \(t\). Therefore a high-pass spatial filter can be applied to the radar observation to eliminate that term leaving only the spatio-temporal varying term:

\[
f_n = \Re \left( \sum_{m=1}^{M} D_{n,m} A_m \exp(i(x_n \cdot k_m - \omega_m t)) \right)
\]

**Least Squares Inversion Process**

Given the derived observation model relating Doppler observations to a set of modal wave amplitudes, we now seek a means for solving for the unknown wave amplitudes. This is done by accumulating a large number of radar observations, as taken cell-by-cell over multiple line scans, and organizing each of the Doppler observations into a long column vector a measurement vector. We then nominate a local spatio-temporal reference (i.e., \(LAT_0, LON_0, T_0\)) along with a set of modal components (each with a unique frequency-propagation angle pair) to solve for. In doing so, we can write the observation model for each element of the measurement vector as a dot product

\[
f_{D,n} = \Re \left( \sum_{m=1}^{M} A_m \exp(i(x_n \cdot k_m - \omega_m t_n)) \right)
\]

With \(P_{nm}\) resulting from the observation model:

\[
P_{nm} = \Re \left( \sum_{m=1}^{M} A_m \exp(i(x_n \cdot k_m - \omega_m t_n)) \right)
\]

Which now allows us to write the observation model for the entire measurement vector in matrix form:

\[
\begin{bmatrix}
  f_{D,1} \\
  f_{D,2} \\
  \vdots \\
  f_{D,N}
\end{bmatrix} = \Re \left( \begin{bmatrix}
  P_{1,1} & P_{1,2} & \cdots & P_{1,M} \\
  P_{2,1} & P_{2,2} & \cdots & P_{2,M} \\
  \vdots & \vdots & \ddots & \vdots \\
  P_{N,1} & P_{N,2} & \cdots & P_{N,M}
\end{bmatrix} \begin{bmatrix}
  A_1 \\
  A_2 \\
  \vdots \\
  A_M
\end{bmatrix} \right)
\]

Or, more concisely:

\[
f_D = PA
\]

The matrix \(P\) is referred to as the propagator matrix. Assuming that the above relation is overdetermined, meaning that there are more measurements than there are unknown wave amplitudes, we can use the least squares method to solve for the unknown wave amplitude vector \(A\):

\[
A = (P^T P)^{-1} P^T f_D
\]

Given a set of modal amplitudes and knowledge of the frequency/propagation angle pair of each mode, we can then calculate the wave height at a specified location at a specified time (both prior to and after \(T_0\)) using the following wave synthesizer equation:

\[
\eta(x, y, t) = \Re \left( \sum_{n=1}^{N} A_n \exp(i(k_{x,n} x + k_{y,n} y - \omega_m t)) \right)
\]

In this way, solving for the set of modal wave amplitudes essentially provides the initial conditions needed to launch a wave field forecast which covers a desired forecast region over a desired forecast interval. Note that the initial condition is not formed by a single snapshot in time – it is in fact determined through an extended observation of the wave field over space and past time.

The extraction region and the spectral solution space define which observations to use in forming the measurement vector and the modal components to solve for. The optimal
extraction region and spectral solution space require the following:

- The forecast interval \( T_f \) relative to \( T_o \)
- The forecast region relative to \( LAT_f/LON_f \)
- The 2D power spectrum of the wave field and an accurate estimate of the local mean surface current
- The course and speed that the ship will follow from \( T_o \) to \( T_f \)

With this information, the \textit{extraction region} and the \textit{spectral solution space} can be selected to allow the inversion process to provide a set of wave mode complex amplitudes that can be fed to the ship motion model for motion prediction over the forecast interval.

**SHIP MOTION MODELING**

Ship motion forecasts are the primary output of the ESMF system, and these are provided by a ship motion prediction model. Using the phase-resolved wave field provided by the AWSR and wave retrieval processing, the prediction model must make a deterministic forecast of the ship motions up to several minutes into the future. In seeking an appropriate ship motion prediction model, we consider the following key requirements:

- Accurate prediction of 6 degree-of-freedom (6DOF) ship motions
- Computational efficiency to allow several minutes of motion forecast in ~1 second calculation
- Ingestion of phase-resolved discrete directional surface wave spectrum as system disturbance
- Ingestion of measured ship motions as initial state information
- Ability to include nonlinear external force models
- Easy extension to the multi-body problem

In this section, we describe the formulation, implementation, and testing of a Reduced Order Model (ROM) for ship motion forecasting, developed for the ESMF program to meet the above requirements. While the formulation could be applied to any ship or collection of ships, we were initially focused on the R/V Melville, the 279ft research boat used for ESMF demonstration. The team from the U.S. Naval Surface Warfare Center Carderock Division (NSWCCD) developed and tested a scale model of the R/V Melville, providing a validation data set to be used in ship motion model development and validation.

The ROM is a lumped parameter time-domain model for the ship system as forced by ambient ocean surface waves. There is one equation solved for each degree-of-freedom in the form of Cummins’ (1962)²

\[
m_i \ddot{x}_i + \sum_{j=1}^{N \text{DOF}} a_{ij} \dot{x}_j + \sum_{j=1}^{N \text{DOF}} b_{ij} \dot{x}_j + \sum_{j=1}^{N \text{DOF}} c_{ij} x_j = \sum_{j=1}^{N \text{DOF}} h_j (t - \tau_i) \left[ \dot{\tilde{y}}_j(t, \omega) \right] + \sum_{\omega} \sum_{\beta} \tilde{D}_{ij}(\omega, \beta, U) \varepsilon(\omega, \beta) + \sum_{\beta} F_{i\beta}
\]

This expression describes the response of the \( i^{th} \) mode of motion for a system of \( N \) vessels, each with up to 6DOF. The dynamic responses, \( x_i \), are about a steady state coordinate system translating at the forward speed \( U \), which can be zero. For initial ESMF testing and demonstration, we were primarily focused on the single-ship case where \( N=1 \). We have the following definitions:

- \( m_i \) is the body inertia for mode \( i \)
- \( a_{ij} \) is the high frequency limit added inertia for mode \( i \) due to a unit body acceleration in the mode \( j \) direction
- \( b_{ij} \) is the linear damping coefficient
- \( c_{ij} \) is the hydrostatic restoring for mode \( i \) associated with a unit displacement in mode \( j \)
- \( h_j \) is the impulse response function (IRF) yielding the load in mode \( i \) due to the history of motion in mode \( j \), capturing radiation damping and frequency-dependent added mass
- \( \tilde{D}_{ij}(\omega, \beta, U) \) is the complex (magnitude and phase) force Response Amplitude Operator (RAO) describing the modal force in the \( i^{th} \) direction due to a single wave component with frequency \( \omega \) and heading angle \( \beta \)
- \( \varepsilon(\omega, \beta) \) is the complex amplitude of a wave component; a collection of these make up a discrete wave spectrum
- \( F_{i\beta} \) are other external forcing to mode \( i \), arbitrarily defined (linear or nonlinear) to represent effects or systems not otherwise captured by the equation

The formulation is well-suited to the ESMF application in that it is time domain, allowing for use of the initial condition and inclusion of nonlinear models; it solves a small number of equations, making it very fast; and it is scalable to the multi-body problem. MARIN’s workhorse aNySIM code uses a similar Cummins approach, finding utility in the simple, efficient, and robust formulation.

The coefficients and functions that make up the governing equation are obtainable through simulation or model testing. We utilize the AEGIR ship seakeeping simulation tool to obtain these values, and allow for fine tuning with model test or full-scale ship data. AEGIR is a time-domain seakeeping code that uses an advanced, high-order boundary-element method to solve the three-dimensional, potential-flow, free surface wave problem. It has been used extensively to simulate the response of a variety of mono-hull and multi-hull vessels operating alone or in close proximity to one another.

The added inertia and hydrostatic restoring terms are calculated by AEGIR from a CAD/NURBS representation of the ship geometry and input mass specifications. The IRF and Force RAO functions are calculated with AEGIR through a discretized range of speeds, and wave frequencies and directions, yielding a database which characterizes the hydrodynamic forcing to the ship through all relevant operating conditions. Particular values of these forcing functions are obtained through interpolation of values from the database. The approach uses the assumptions of linear seakeeping theory, where the hydrodynamic forcing can be decomposed into the incident wave, diffraction and radiation forces and these
The coefficients of the governing equation that are calculated with AEGIR provide a linear potential-flow reduced-order model for ship seakeeping. This provides a very good model for predicting the ship response in the heave and pitch modes, as they are dominated by potential-flow effects. However, viscous effects not captured in AEGIR play a significant role in the dynamics in roll, surge, sway, and yaw responses. To obtain an accurate 6DOF ROM, we needed to implement appropriate external models for these other important effects, with particular focus on the roll response. As many of these are approximate models derived from the ship geometry, tuning of the associated coefficients with model test data and/or full scale results may be required to fully capture the properties of a particular ship. With the addition of some functional forms associated with these viscous forces, we obtain an extended form of the general ROM equation as

\[ m \ddot{x}_j + \sum_{i=1}^{N} \alpha_{ij} \dot{x}_i + \sum_{i=1}^{N} \beta_{ij} \dot{x}_i + \sum_{i=1}^{N} \gamma_{ij} x_i + \sum_{i=1}^{N} \delta_{ij} U^2 x_i = \sum_{j=1}^{N} \int_{-\infty}^{\infty} h_j(t - \tau, U) \dot{x}_i(t) d\tau + \sum_{\omega=1}^{\Omega} \tilde{D}(\omega, \beta, U) e^{j\omega t} \dot{y}(\alpha, \beta) + \sum_{k=1}^{K} F_k. \]

This new general form allows quadratic damping, linear-speed-dependent damping, and quadratic-speed-dependent restoring. Note that, instead of forming the equations with equivalent-linear coefficients, our time-domain application allows direct inclusion of the nonlinear form. This offers an advantage over a frequency-domain approach which would require use of ever-changing equivalent-linear coefficients.

The new terms associated with viscous forcing in the roll, surge, sway, and yaw modes are associated with appendages, bilge keels, hull circulation, and propulsor effects. The functional form and initial evaluation of the associated coefficients were determined by drawing upon previous analytical and experimental studies. Primary among these were the works of Schmitke\(^9\), Himeno\(^1\), and McTaggart\(^3\), as well as the ITTC Recommended Procedures for Numerical Estimation of Roll Damping\(^7\). The associated coefficients for these external models were determined for the R/V Melville through representation of the ship geometry, and tuned through analysis of the model test data. While not represented in the scale model tested at NSWCCD, the full-scale R/V Melville incorporates an anti-roll tank system which significantly affects the ship dynamics. This anti-roll tank system was represented by coupling an established lumped-parameter model\(^3,19\) into the ship motion ROM. A ship model optimization tool using Partial Swarm Optimization\(^17\) was incorporated into the system to allow for tuning of the ship model coefficients as experimental full-scale data are obtained. Further description and validation of the ship motion ROM are provided in a companion paper by Milewski et al\(^9\).

**SYSTEM INTEGRATION**

In order implement a successful ESMF system, an architecture must be established that can move the sensor and processed data through the core computational components to the final product of a user interface displaying the wave and ship motion forecasts. During the development of the ESMF system, an open-standards software architecture was designed and developed to satisfy the system requirements while remaining generic and easily extensible. The product of that effort was the Gravity Software Framework. Gravity is an open standards library and tool suite designed to provide a dynamic, asynchronous communication channel between components that is optimized for high throughput and low latency. It supports multiple languages (e.g. C, C++, C#, Java, Fortran, MATLAB) and works on Windows and Linux. Throughout development of the ESMF system Gravity demonstrated immense value by simplifying the development, integration, and testing of new and maturing system components. The architecture was robust and reliable throughout the at-sea system demonstration.

The development of the Gravity architecture began with a trade study to assess the current state of open-source architectures against the ESMF system requirements. The trade study was confined to open-source architectures in order to avoid any proprietary restrictions in the ESMF system. Several architectures were investigated, including OpenDDS, OpenSplice, and RTI’s Connext DDS. The study included Service-Oriented and Data-Centric architectures. The trade study concluded that there were no architecture options available that satisfied the ESMF system requirements. However, the study did identify two open-source technologies that fell short of being complete architectures but could provide significant foundational pieces for the ESMF architecture:

- Google Protocol Buffers (Protobufs): Protocol Buffers are Google’s open-source, language-neutral, platform-neutral, extensible mechanism for serializing structured data. While Gravity supports completely arbitrary data it has built-in support for Protobufs which provide an easy to use mechanism for encoded data in an efficient, extensible, self-describing format. Protobufs help avoid common data interchange pitfalls such as data ordering errors, errors caused by architecture differences between sender & receiver, and changes in data content as system components evolve.

- 0MQ: An open-source networking library providing a network layer built on TCP/IP that abstracts many of the details of working directly with sockets and provides simplified implementations of various transport protocols, including publish-subscribe and request-response.

The final determination upon completion of the trade study was that the unique requirements of the ESMF system necessitated the development of a new architecture and that the risk and development time to create this architecture could be minimized by incorporating Google Protocol Buffers and 0MQ.

Gravity was designed from the outset to ensure that it met the key architectural requirements of the ESMF system: open standards; high-performance; scalability; modularity; language and operating system flexibility; and ease of use. The Gravity
framework is a library providing a dynamic, robust, high-performance communication layer built on top of 0MQ and Google Protocol Buffers. Application modules interact with the library through a simple API and a set of services that provide valuable capabilities and features for complex systems, including a Directory Service, Distribution Configuration Service, a Logging Service, Archival & Replay Services, and a Metrics Service.

Another key design aspect of Gravity is its Peer-to-Peer architecture. Unlike many communication architectures, Gravity does not require a centralized “broker” component to manage the transfer of data between system components. Gravity automatically configures a peer-to-peer relationship between data producers and consumers. This provides a more efficient, more reliable, highly scalable solution that is easier to configure and manage.

Gravity provides application modules with two options for communications with other components, Publish-Subscribe and Request-Response:

- Publish-Subscribe: A messaging pattern in which senders of data (i.e. publishers) advertise their data, allowing other components (i.e. subscribers) to subscribe to their data feed. Publishers and subscribers function without knowledge of the other. This pattern provides scalability and supports a dynamic network topology.
- Request-Response: A messaging pattern in which a requesting component requests specific data from a provider component. The provider then returns a response to the requesting component. It is a simple but powering communication protocol that supports a direct communication between two components.

The development methodology for Gravity followed the standard spiral lifecycle model. The key aspect of this model is the iterative nature of the development process. It allows the development team to start with smaller rapid prototyping, and then move iteratively through requirements, design, development, and test/evaluate cycles. This process allowed for timely delivery of infrastructure capabilities, early identification of defects, and quick execution of fixes and new capabilities.

**TESTING AND PERFORMANCE**

Testing of the ESMF system consisted of component testing in laboratory and field environments, simulated system testing, and full system field testing. The tiered approach to testing ensured that the system components and integrated system would be ready for the final system demonstration in September, 2013 aboard the R/V Melville.

Preliminary lab testing of the AWSR was followed by testing of the wave measurement process performed at the Scripps Pier, La Jolla, CA. This testing, as depicted in Figure 3, included the use of wave buoys as ground truth sensors for wave measurement. A sample of the associated data is presented in Figure 4. The figure shows a retrieved wave field from the AWSR pier test data, in a measurement area similar to that used in a ship board installation. A time history plot shows comparison of the retrieved wave field elevation to the ground truth measured by a wave buoy. The pier testing was a valuable step in tuning the wave measurement process in advance of system testing.

The other key sensor that feeds the ESMF system is the ship motion sensor. We purchased and incorporated an off-the-shelf motion sensor, the OXTS-2502. The sensor incorporates an IMU and dual-antenna GPS that is able to provide absolute heading information to better than 0.5 degree accuracy using real-time-kinematic processing. The dual-GPS heading sensor was a necessity for the present system, which requires accurate heading information at low speeds to register radar data. The sensor was tested with a land-based test rig, using a string potentiometer to provide ground truth sensing. These tests confirmed the manufacturer’s specification for motion and heading measurement. The tests also enabled testing and tuning of the system interface for the ship motion sensor, which provided integration and filtering to deliver motion data in the format required for downstream ESMF system components.

Preliminary testing of the system components also included extensive exercising of the system computational core in lab-based simulation. The tests included stimulation of the system with synthetic sensor data being fed at the actual system data rates, including asynchronous function of the system components. All of the computational components demonstrated their ability to meet the run-speed requirements, completing the computational chain of wave retrieval and ship motion forecasting in a few seconds.
Testing of the system aboard the R/V Melville marked a full installation of the prototype system, with all system sensors, computational components, and user interfaces integrated into a real-time ship motion forecasting system. The demonstration was a full-scale, single ship exercise conducted on board the R/V Melville, a 85m research vessel operated by the Scripps Institute of Oceanography (SIO), from 6 – 18 September 2013. The operational area for the demonstration was the eastern Pacific Ocean, west of San Clemente Island, California and as far north as San Miguel Island near Pt. Conception. The exercise allowed the ESMF team to demonstrate system functionality, measure the systems’ ability to meet their objectives, and collect full-scale data to support follow-on design efforts. A U.S. government team from NSWCDD directed the test, providing ground truth sensing, and collecting real-time delivered forecast data from the system developers. The real-time data collection permitted a clear evaluation of the ESMF forecasting performance.

To evaluate the performance of the forecasts, we adopt the normalized cross correlation coefficient as the primary metric to compare the forecasted motion to the realized motion. We focus on the 30 second phase-resolved forecast, and on the performance of the real-time system data. In short, we compare the predictions that were streamed out 30 seconds in advance to what actually happened by correlating the two signals. A correlation value of +1.0 means that the two signals are the same, a value of 0.0 means they are uncorrelated, and a value -1.0 means that the signals are similar, but 180 degrees out of phase. Both zero and peak lag coefficients are calculated. The zero-lag cross correlation is a rigid metric, requiring a very close match in the signal phases as well as amplitudes and frequencies, to achieve a high value. The peak lag cross correlation coefficient provides an indicator of how well two signals compare while permitting timing offsets. We allow for a maximum delay of +/-3 seconds in the peak lag cross correlations presented. Depending on the particular application of the ESMF system, a lag may or may not be important. At this point, however, the peak-lag cross correlation coefficient provides an estimate of the upper bound on system performance during the test.

A series of “star-leg” patterns were performed from 10 – 17 September 2013, each at a fixed course and speed for a duration of 20-30 minutes. Speed ranges of 4 to 8 knots were used. In Figure 5 - Figure 7 we plot the cross correlation of the 30 second forecast to the ground truth for heave, roll, and pitch, for bow seas conditions over the duration of the ESMF system test. Bearing in mind that a truly uncorrelated forecast would have correlations equally likely negative and positive, it is clear that the forecasts are positively correlated. This indicates that the end-to-end process of wave measurement to ship motion forecasting was indeed working.

The red bars in the correlation plots which indicate zero-lag correlation are clearly lower than the blue bars, indicating some phase error in the forecast. Post-processing analysis of the data did indicate some of the sources of these errors, along with associated system corrections, allowing improved performance from the real-time forecast data that are plotted here.

The roll forecasting performance was generally worse than heave and pitch. This was expected, as roll response is very sensitive to external model coefficients that are only approximately known a priori. The improvement in roll forecasting that can be seen mid-way through the test is due in part to coefficient optimization performed with the aforementioned ship model optimization tool.

![Heave correlation plot](image1)

**Figure 5 – Cross correlation performance for 30 second heave forecasts for bow seas legs from 10-17 September 2013. Red is zero-lag correlation and blue is peak correlation.**

![Roll correlation plot](image2)

**Figure 6 - Cross correlation performance for 30 second roll forecasts for bow seas legs from 10-17 September 2013. Red is zero-lag correlation and blue is peak correlation.**
One of the goals of the ESMF system is to predict large events. On the final day of testing we were presented with such an event, manifesting as a 12 degrees of roll with nearly 2 meters of heave. This roll prediction was well captured by the 30 second forecast, as depicted in Figure 8.

The radar-measured wave field for the large event is plotted in Figure 9. The plot shows the ship coming out of a deep trough near the end of the large roll event. The wave trace indicates a peak-to-peak wave of 4-5 meters. The forecast of this large wave is notable in that the ability to prepare for such disruptive events should be a key outcome of a successful ESMF system.

The performance of the ESMF system during the prototype demonstration was by no means perfect. However, the predicted motions over the range of speeds, wave conditions, and wave directions correlated at 0.68 for pitch and 0.62 for heave (peak correlations in +/-3sec lag window). These values indicate very promising performance of this technology.

SUMMARY AND CONCLUSIONS

The development of a successful ESMF system requires a successful merging of technologies into an integrated real-time system. We set about to merge the best components to perform ocean wave field measurement and associated ship motion prediction. In doing so, we developed a purpose-built Advanced Wave Sensing Radar to achieve the best possible performance in measuring Doppler shift due to wave orbital velocities. A novel wave retrieval algorithm was developed and implemented, using a least-squares inversion approach to incorporate the Doppler measurement directivity and utilize the

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Figure 7 - Cross correlation performance for 30 second pitch forecasts for bow seas legs from 10-17 September 2013. Red is zero-lag correlation and blue is peak correlation.

Figure 8: Pitch, roll and heave 30-second predictions (blue) and ground truth (red) for the large wave event of 17 September 2013.

Figure 9: Measured wave field associated with the large wave event of 17 September 2013.
overdetermined system to improve measurement quality. An accurate reduced-order model for ship motion simulation was incorporated to achieve the fast calculation times required for a real-time forecasting system. To manage the copious and asynchronous flow of data through the system, the robust Gravity system architecture was developed, also enabling rapid integration of system components.

With the prototype system developed and integrated, it was taken to sea for a system demonstration. The correlations realized between the forecasted and observed motions clearly indicate that the system performed the function of:

- Wave measurement and wave field reconstruction
- Ship motion forecasting through linear evolution of the measured wave field and associated seakeeping simulation
- Real-time ship motion forecasting with significant correlation to the later realized ground truth motions

The system performance reported here is for the motion predictions made in situ during the September 2013 ESMF demonstration. Analysis of the test data has highlighted a number of system improvements that have since been implemented. These improvements provide substantially better forecasting performance of the system, which will be realized in future system testing and demonstration. Exactly what defines sufficient forecasting performance will be somewhat application specific. It has been demonstrated, however, that ship board remote sensing wave measurement and associated ship motion forecasting is possible. Continuing improvement of the system performance, and its practical application will be the next steps.

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REFERENCES

1. Environmental and Ship Motion Forecasting (EMSF), ONR BAA Announcement # 10-019.