From Weather to Wave Response: An End-to-End Process for Bringing Environmental Data to Distributed Simulations

Karl B. Washburn
Naval Research Laboratory, Code 5580
Washington, DC 20375-5337
(202) 767-8023
`washburn@ait.nrl.navy.mil`

Richard Allard
Naval Research Laboratory, Code 7322
Stennis Space Center, MS 39529
(228) 688-4894
`allard@nrlssc.navy.mil`

Paul Maassel
Visitech, Ltd.
Arlington, VA 22201
(703) 624-1829
`maassel@visitech.com`

Keywords:

Natural Environment, Ocean, Surf, Wave Response, Vehicle Dynamics, Semi–Automated Forces, JointSAF, TAOS, DVW, AAAV

ABSTRACT: *As part of the DMSO–sponsored "Representational Resources Integration Experiment" (RRIE), NRL teamed with the Advanced Amphibious Assault Vehicle (AAAV) Technology Center to explore moving real ocean surf data through a Distributed Simulation network to a JointSAF representation of the AAAV which had been made dynamically responsive to ocean surface waves. In a multi–stage process, (1) surf conditions of interest were identified, (2) historical data were searched for matching conditions, (3) a series of surf models provided hindcasts for the identified time and region, (4) the data were served to the JointSAF system, and (5) the wave response of the AAAV model was measured. Providing consistent surf data involved searches of surf buoy data, use of the NORAPS weather forecast model, wave and surf models including WAM, STWAVE, and SURF96, and the Total Atmosphere and Ocean Server Surf Receivers. Consistency was ensured from model to model. The AAAV model had to be modified to make it respond properly to waves, some minor software was built to measure the response, and the newest versions of JointSAF and TAOS were needed to complete the process. Significant challenges were encountered at each step. This paper details these challenges and explains the steps we went through to get "from weather to wave response."*

1 Introduction

The Defense Modeling and Simulation Office (DMSO) sponsors the "Representational Resources Integration Experiments" (RRIE). The theme of the RRIE program was to demonstrate the process of bringing consistent, multi–domain natural environmental data to simulation systems whose models would, in turn, respond consistently to that data.

There were three RRIE projects in 1998: weather and surf forecast support for Global War Game 98 at the Naval War College in Newport, Rhode Island; mobility response of the US Army Grizzly Mine Plow to soil moistures modified by rainfall; and dynamic response of the US Marine Corps' Advanced Amphibious Assault Vehicle (AAAV) to ocean waves generated by winds. In this paper, we detail this third project.

The AAAV Experiment for RRIE had three components:

1. Generation of surf hindcasts using a chain of physics models beginning with weather;
2. Insertion of surf data into a Semi–Automated Forces (SAF) simulation system, whose AAAV representation was modified to properly respond to waves;

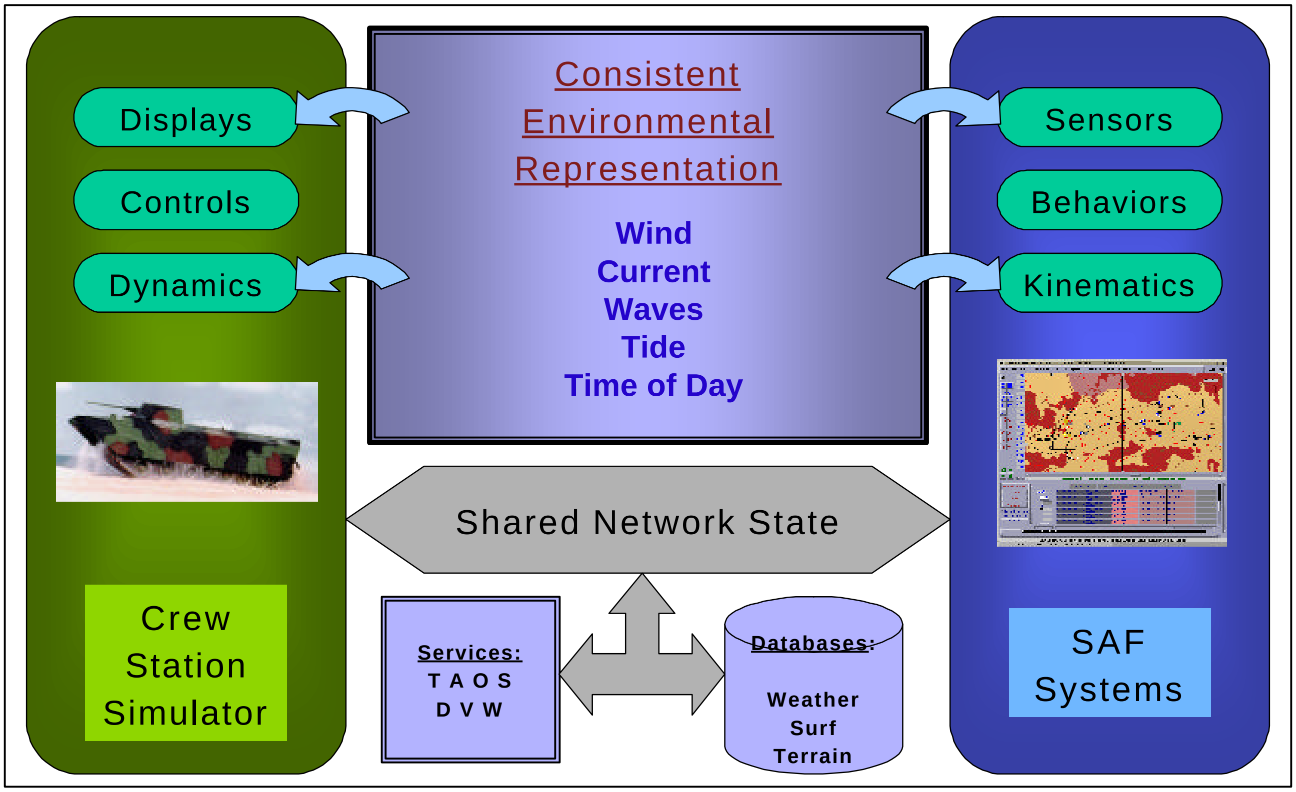

Figure 1. The RRIE AAAV experiment concept for bringing a consistent environment to different simulators.

3. Simultaneous insertion of surf data into the AAAV Crew Station Simulator[1], a prototype hard and virtual mockup of the crew stations.

Time and budget constraints prevented completion of the third component. This paper focuses on the first two.

2 Background

The Advanced Amphibious Assault Vehicle (AAAV) is the US Marine Corps' next–generation amphibious vehicle. Among many new features and technologies, the most important to our discussion is its high–speed water mode, during which it can skim on plane at over 25 knots. This gives the Marines a new, over the horizon assault capability. As part of the vehicle development, a modeling and simulation program, including virtual prototyping and construction of a virtual Crew Station Simulator (CSS), has been fully integrated from the start.

The RRIE's AAAV experiment was conceived as a means by which external natural environmental data could be collected and distributed to multiple components within the AAAV CSS in a consistent manner. As shown in **Figure 1,** the consistent environmental representation would include atmospheric, oceanographic, and terrain/bathymetric elements. Given databases for these environmental elements, a service would provide updates to the simulations through a shared network.

The AAAV CSS is a higher–fidelity simulation system. It has detailed visual and dynamics models that execute in real time, stimulating four simulated crew stations. The externally–supplied natural environment would directly impact the dynamic modeling of the simulated vehicle as well as the visual "out–the–window" displays; it would indirectly impact the vehicle controls through changes to the vehicle's simulated motion and the participants' reaction to their virtual displays.

The Semi–Automated Forces (SAF) represents a lower–fidelity simulation system. By maintaining simpler, mostly kinematic representations of vehicle entities, a moderate amount of computing power is capable of supporting multiple unit instantiations simultaneously. The externally–supplied natural environment would directly impact the motion of selected, wave–responsive vehicles; it would indirectly impact the vehicles'

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[1] The AAAV Crew Station Simulator is being developed as part of the AAAV Modeling and Simulation Integrated Product Team at General Dynamics Land Systems Inc., Amphibious Vehicles Division, Woodbridge, VA.

behaviors through the modeled sensors and responses to differing degrees of motion.

Benefits would accrue in both directions from a shared, consistent representation of the natural environment. For the CSS, two objectives are met. First, as seen by crew members through their virtual ports, the additional vehicles (supplied over the network by the SAF) would behave in a more realistic manner, reacting to the surf rather than flying over it. This adds realism to the scenario and allows training (or procedure development) by requiring doctrinally sound station keeping. Second, it introduces the process by which operational forecast products can be introduced to the CSS itself. This allows for realistic training and assessment in a variety of actual environmental conditions, and it opens the door in future years to direct linkage of CSS systems to live exercises. (To reiterate, this component of the project was not completed.)

For the SAF system, it completes a chain of intended use for surf data envisioned some time ago but only now becoming realized. In particular, externally–generated, consistent surf hindcasts can be introduced to the SAF systems directly from the network through an environmental server. Vehicles can then respond directly to this external information both dynamically and behaviorally.

The goal for RRIE was to exercise the process from requirements definition, through environmental modeling, to database construction for and data ingestion by the simulation systems. Having ingested the data, the simulations would then be measured to evaluate consistency and quality in the presence of disparate vehicle representational fidelity. The process is represented schematically in **Figure 2**.

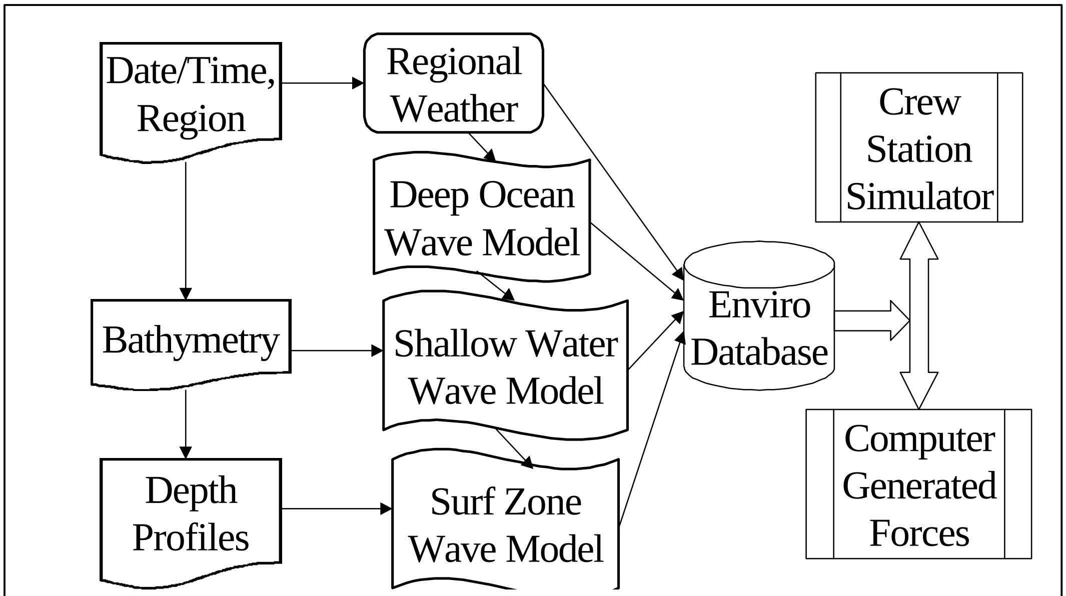

Figure 2. Data flow process, bringing natural environment to AAAV simulators.

It is easy to state the intent of this work: make amphibious vehicle models react to a model of real surf *using existing software products*. The execution of that work is a long chain, involving many people of diverse expertise and software products that are developmental and not yet robust. While it is our intent to describe, in detail, the process of getting from "weather to wave response," we also point out where assumptions (about models, data formats, and reusability) nearly derailed us. We learned that bringing environmental data to a simulation is a straigtforward, if time– and resource–consuming, process. However, it is all too easy to underestimate the effort involved in making seemingly simple things happen when *reusing* existing simulation components.

3 From weather to waves: the environmental modeling

3.1 Environmental Data Products

This Section details the environmental data products that were defined, developed, and distributed for the AAAV experiment.

The first step in developing data products was defining the scenario in which they would be used. The region of interest was selected as Camp Pendleton, CA, the primary proving ground for the AAAV prototypes. Two *Littoral Penetration Points* (LPPs, the points at which the vehicles would come ashore during operations) were defined along the coastline.

In addition to geophysically locating the scenario, a time frame had to be selected. We restricted allowable sea surface conditions to those between Sea State 1 and Sea State 3 (Beaufort Sea Scale) and constrained a search of historical data to the recent past. We selected the period from 16 through 18 August, 1998. We then employed models within the Integrated Ocean Program (IOP) to create surf hindcasts of increasing resolution, from deep water through the surf zone and up to the beach itself.

Camp Pendleton has approximately 17 miles of shoreline trending NW from Oceanside to San Mateo Point. Most amphibious training is conducted north of Oceanside at Las Pulgas (Red) Beach, where the 10m depth curve, which delineates the surf zone, is located about 1 km offshore. A directional Waverider measurement buoy operated by the Coastal Data Information Program (CDIP) is deployed 6.4 km offshore of Oceanside at 33° 10.7' N; 117° 28.2' W in water that is 227m deep. It provides time series and directional wave information as a function of wave frequency.

Individual records were evaluated from April through August 1998 to identify times when sea states were either ≤ 1 or $\cong 3$. Planning periods were identified having winds from 0 to 8 knots and waves up to 0.3 m (sea state 1) or winds up to 15 knots and waves up to 1.2 m (sea state 3).

We weren't able to exactly match these criteria, but Summer conditions provided the best opportunity to obtain Sea States which did not exceed 4. The period from 9 through 20 August 1998 provided significant wave heights that ranged from 0.6m to 1.4m with corresponding periods from 6 to 19s. Prevailing wind speeds were found to be 8 knots with directions from the Southwest.

3.2 Models

The Integrated Ocean Program (IOP) used the Regional Wave Action Model (WAM), Steady-State WAVE (STWAVE) model and the Navy Standard Surf Model (NSSM) to produce physically consistent surf hindcasts for the period 16–18 August 1998. Here, we provide overviews of these models. For a more comprehensive discussion of the IOP modeling procedure and techniques **(Allard 1998)**.

3.2.1 WAM

The WAM spectral wave prediction model see **(WAMDI 1988; also Komen et al. 1994)** is the deep-water wave model for this study. WAM describes the sea surface as a two–dimensional (frequency and direction) spectrum of sea surface elevation variance density. WAM computes the variance density in each spectral component. Energy is also propagated laterally, including refraction due to depth variation and proper dispersion.

The Fleet Numerical Meteorological and Oceanography Command and Naval Oceanographic Office (NAV-OCEANO) runs operational global and regional implementations of WAM Cycle 4 **(Wittmann and Farrar 1997)**. We used the Southern California Regional WAM implementation with a resolution of 0.05°. The directional wave spectra at 33.2° N, 117.55° W became the boundary conditions for the STWAVE model.

The Point Mugu Navy Operational Regional Atmospheric Prediction System (NORAPS) surface wind stresses were used as driving forces input to WAM. Point Mugu NORAPS has a horizontal resolution of 0.2° and covers the domain from 29.0–39.0° N, 126.5–114.5° W.

3.2.2 STWAVE

We used the Spectral Transformation Wave (STWAVE) model for nearshore waves for the period 9–22 August 1998 at Camp Pendleton, CA. STWAVE **(Davis 1992)** transforms offshore wave spectra from WAM into the nearshore spectra. A *spectral* wave model was selected because it provides not only the wave height, period, and direction in the nearshore, but also the wave spectra needed to drive the surf model.

To execute STWAVE one needs:

- bathymetry and shoreline data;
- size and resolution of the grid;
- water levels based on tides;
- 2D wave spectrum input on the offshore grid boundary; and
- wind speed and direction.

STWAVE is a finite–difference model: it calculates the wave spectra on a rectangular grid with square grid cells. The optimal grid orientation for STWAVE is with the y–axis aligned along the bathymetry contours and the x–axis aligned normal to those contours. The National Ocean Service supplied bathymetry for the Camp Pendleton region to NRL at a resolution of 100m. The STWAVE grid orientation was aligned with the shoreline and bottom contours. For Camp Pendleton, the grid resolution was 100m.

The main forcing functions for nearshore waves are wave spectra on the offshore boundary of the STWAVE grid. These input spectra are the outputs from time–dependent WAM wave model runs. STWAVE has the same frequency resolution as WAM, but the STWAVE grid orientation and directional resolution differ from the WAM output. Thus, the WAM spectra were translated into the STWAVE orientation using truncation and linear interpolation. Wind speed and direction also drive STWAVE. The wind parameters were supplied from the Point Mugu NORAPS model. As with the WAM data, the wind direction data were rotated into the STWAVE reference frame. Wind speed and direction were taken as constant over the STWAVE model domain. Depth changes due to tides (actual tidal elevations recorded off La Jolla, CA) were included in these simulations.

For RRIE/AAAV, STWAVE was run at 3-hour increments for the period 8 August 1998 18:00 GMT to 21 August 1998 15:00 GMT, a total of 104 model runs. Output includes the wave height in meters, the peak period in seconds, and the mean direction in degrees relative to the STWAVE grid, for all gridpoints, as well as the wave spectra (m^2/Hz/rad) at two locations:

Site 1: 33° 13’ 36.3” N 117° 24’ 47.5” W: Depth = 10.2 m, STWAVE cell (100,17)
Site 2: 33° 15’ 29.6” N 117° 26’ 20.8” W: Depth = 10.0 m, STWAVE cell (109,59)

3.2.3 Navy Standard Surf Model

The Navy Standard Surf Model (NSSM) **(Earle, 1989)** is used extensively by the US Navy for applications including estimation of climatological surf conditions at selected beaches for development of the AAAV **(McDermid et al. 1997)**. The NSSM is composed of two main modules, a wave refraction model and the surf model itself, SURF96. The most recent version of the surf model, SURF96 incorporates several theoretical and numerical improvements **(Hsu et al. 1997)**.

The surf model requires four main inputs: wave spectra, winds, tides, and beach profile. Wave input has a significant impact on surf model output. STWAVE provided directional wave spectra for these model runs. Again, Point Mugu NORAPS provided wind stresses. Tidal data for La Jolla, CA was used. The water elevations correspond to each model run time, effectively raising or lowering the entire column of water in the beach profile.

SURF96 calculates waves along a one–dimensional traverse, perpendicular to the beach. The beach orientation angle of this "line of approach" is important and must be specified. A beach profile containing appropriate bathymetry along the traverse is needed. The model uses these depths as it steps in toward the shore. For this effort two beach profiles were used for the two littoral penetration points:

1. a profile based on an NRL Survey conducted at Camp Pendleton in June 1997 and
2. an equilibrium profile based on "fine sand". (These computed profiles are especially useful when existing profiles are missing data, or as substitutes for beaches that are not surveyed prior to landing.)

The Camp Pendleton model runs began on 16 August at 00:00GMT and proceeded at three-hourly steps for 17 timesteps through 18 August at 00:00GMT. Outputs at each step of the surf model include water depth, breaker height, percent breaking waves, wavelength, and current. Overall breaker period, angle, and type are also output, along with the Modified Surf Index (MSI).

3.3 Model/Data Comparisons

We verified model outputs from WAM and STWAVE for the locations closest to the CDIP Oceanside buoy for the period 15–19 August 1998.

Overall, STWAVE shows improvement over the wave heights and directions compared to WAM. The differences between model data and observations can be attributed in part to several factors:

1. There have been local changes in bathymetry since data was collected in June 1997;
2. The LPP’s used in this study were located on the southern portion of the STWAVE grid: accuracy is increased when the LPP's are located near the center of STWAVE's grid.
3. Wind forcing plays a major role in WAM and, consequently, STWAVE. If the winds are not modeled accurately, this will introduce error into WAM and STWAVE. We did not examine the accuracy of the NORAPS wind products, but they have proven very reliable in operational use.

4 On the simulation side: Creating a wave–responsive SAF representation of the AAAV

This Section describes the work done to create a wave–responsive AAAV model within the Joint Semi–Automated Forces (JointSAF) simulation system. [JointSAF is based on a core set of ModSAF libraries, but with many architectural and behavioral extensions intended for use by the STOW ACTD.]

The original AAAV SAF representation model and software were prepared by L. K. Finman (**Finman 1997**). That work included:

1. Creating a new hull library capable of arbitrating transitions between different hull types; and

2. Creating a new component model for the AAAV water planing flaps and the transition period during their deployment/retraction.

The AAAV work was originally incorporated into Marine Corps Synthetic Forces (MCSF) v2.1. This older version of the USMC–specific SAF system had none of the Synthetic Theater of War (STOW) –developed natural environment capabilities. Thus it was not suitable for these experiments. The vehicle is included in later releases of the environment–capable STOW SAF system, now known as JointSAF, under the MCSAF entity set. However, versions of JointSAF officially released for use in the STOW–98 Event (September 18–22, 1998) did not allow instantiation of the AAAV. The RRIE Program was fortunate to receive a later beta–release of JointSAF v3.0. In that version, the AAAV representation could be instantiated and operated successfully.

In separate development, the Dynamic Virtual Worlds project, of the STOW Synthetic Environments (SE) Initiative, had developed a Wave Response Model for sea–borne vehicles. This model created a data–driven interface allowing vehicles to be "nominated" for wave response dynamic capability. It provided a simple, first order model for any vehicle whose bulk parameters were known. Response Amplitude Operators (RAOs) for roll, pitch, and heave can be inserted if they are available.

4.1 AAAV Dynamics Modeling

The AAAV representation in the Semi–Automated Forces system is detailed in (**Finman, 1997**). In order to allow for an amphibious hull, while not being saddled with creating an entirely new set of libraries for all possible variations, the designer chose to create a "hull arbitration module". This module allowed the SAF to choose between water and land operating modes. In addition, a new type of deployable component, the "flap", was created, to account for the bow and transom flaps used by the AAAV to attain high–speed planing mode over water. Because the flaps have no impact on vehicle dynamics *within the SAF representation*, they will not be discussed further.

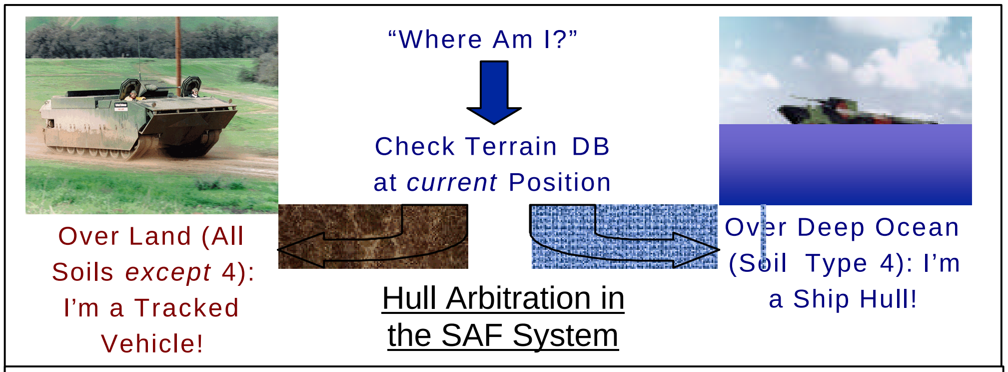

Figure 3. Schematic of hull arbitration as performed by `libvariabledynamics`.

The hull abitrator is contained in the SAF library `libvariabledynamics`. This module is loaded at run time whenever an amphibious vehicle is instantiated in the SAF. As far as the SAF engine is concerned, this arbitrator *is* the vehicle, and each update of its state is performed through this module. The arbitrator module in turn nominates one of the hull update functions as defined in the vehicle's definition file. For the AAAV, these functions are `ship_tick.c` from the `libshiphull` library for deep water motion, and `trk_tick.c` from the `libtracked` library for shallow water and land motion. Key features of the SAF representation of amphibious vehicles are described below.

Soil Type is the determining factor in choosing one hull or the other. On each update (a call from the SAF engine), `libvariabledynamics` queries the Compact Terrain Database (CTDB), with the vehicle's current coordinates. The CTDB returns the *soil type identifier*, a four–bit enumeration of soil types originally defined as part of the DIS standard (IEEE Std. 1278.1). Of these types, the arbitrator pays attention to only three:

Soil Type 4: Deep water, defined as depths exceeding three meters;
Soil Type 5: Shallow water, defined as depths less than or equal to three meters; and
Soil Types 0–3, 7–15: All other soils, all of which are landforms.

If the CTDB shows that the soil is deep water, the arbitrator uses the ship hull type to update the vehicle's motion. If the vehicle is currently in tracked vehicle mode, the arbitrator initiates a timed transition to ship mode, deploying the flaps. If the soil is shallow water *or* landform, the arbitrator uses the tracked hull to update the vehicle's motion. If the vehicle is currently in ship hull mode, the arbitrator initiates a timed transition to tracked mode, retracting the flaps. During transitions, vehicle motion is updated in tracked mode, regardless of the goal hull type. This principle is shown in **Figure 3**.

Shallow water transit is handled by the tracked hull library. This model choice was made in 1994 when the Amphibious Assault Vehicle (AAV/P7) was included in the original ModSAF system (version 1.5). It was not altered in the development of the AAAV model. Within the tracked vehicle update code (`trk_tick.c`), there is yet another query of the CTDB, and if the vehicle is located over any type of water (soil types 4 and 5), motion is updated apropos a displacement water hull. The difference for the AAAV is the time of transition to and from tracked mode, and the deployment/retraction of the bow and transom flaps.

Deep water *ship hull* mode does not properly model planing. The AAAV becomes a *planing hull* when its flaps are deployed and it is brought to full power in the water. In this configuration, the vehicle rises up out of the water and skims across the water. Its dynamics in this configuration are entirely different from those of a typical *displacement hull*, in which buoyancy is maintained by static displacement of water volume. The `libshiphull` code does *not* account for planing dynamics.

4.2 The JointSAF Wave Response Model

The Dynamic Virtual Worlds (DVW) project was part of the STOW Synthetic Environments initiative. DVW created fifteen different models for various environmental effects within what is now the JointSAF system (**Schaffer, 1997**).

One of these environmental effects models is the Wave Response Model. The model, located in `libwaveresp`, consists of additional code inserted into both `libshiphull` for water–borne vehicles and `libtracked` for amphibious vehicles. This code is executed (in either `ship_tick.c` or `trk_tick.c` as appropriate) to modify the position of a wave responsive vehicle as a function of the local wave state and the vehicle's response parameters.

The Wave Response model provides two levels of detail in modeling vehicle motion. In default mode, the bulk parameters of the vehicle, including length, width, height, and mass, are used to create a constant density "brick", whose center of gravity is taken as its geometric center. The model then updates vehicle orientation as a function of the previous orientation, the time since the last update, and the local sea surface condition. **Figure 4** schematically represents this model. Although this first order model is capable of updating all six degrees of freedom (roll, pitch, yaw, surge, sway, and heave), only three (roll, pitch, and heave) are updated. This obviates having to report back changed position coordinates (from changes in surge and sway) and a new heading (from changes in yaw) for the center of mass of the vehicle.

The next level of detail uses Response Amplitude Operators (RAOs) for roll, pitch, and heave. These RAOs, which must be supplied by the user in the `wvr_sea_veh.rdr` description of the vehicle, include the resonant (radial) frequency of response and the damping factor for each allowed degree of freedom. These factors are then used along with the frequency spectra of local wave conditions to more completely characterize the vehicle's motion on each update.

The RAO model was not used in the experiments reported here for the AAAV. The vehicle itself is very similar to the "brick" envisioned in the first order model, and its center of gravity is just below the geometric center. In addition, there was no need for the finer level of detail since comparisons with the Crew Station Simulator model were not completed for this project.

4.3 AAAV Wave Response

The AAAV was made wave responsive by adding an entry to `wvr_sea_veh.rdr` in `libwaveresp`. Values for the AAAV size and mass were taken from its entry in the `physdb.rdr` file, and verified against data from DRPM AAA. The RAOs are commented out and go unused by the model.

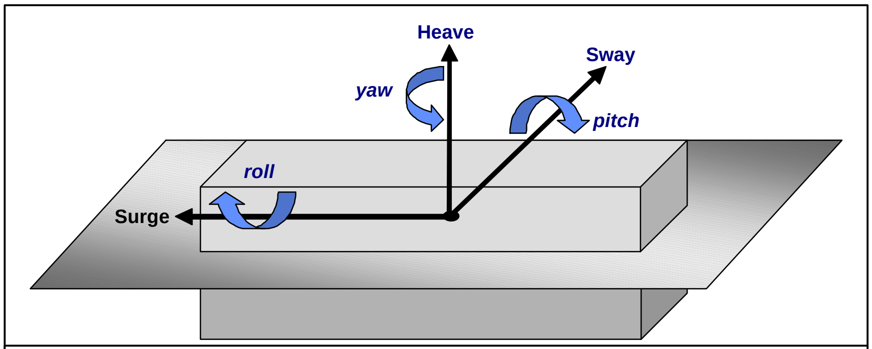

Figure 4. Schematic of the first order "Brick" model of wave response.

4.3.1 Modifying the Variable Dynamics Code

The AAAV SAF entity's wave resonse behavior was evaluated after having been enabled by inclusion into `wvr_sea_veh.rdr`. Upon instantiation of a AAAV in the SAF, we noted that for any wave height greater than zero (as controlled through the SAF Ocean Editor), the AAAV continuously toggled between *ship hull* and

	Significant Wave Height (m)	*Primary Wave Period (s)*	*Wave Direction (°True N)*	*Vehicle Speed (m/s)*	*Vehicle Heading (°True N)*	*Expected Encounter Period (s)*	*Measured Encounter Period (s)*
Trial 1	0.5	3.55	180	10	90	3.55	3.55
Trial 2	0.5	3.55	180	10	0	4.43	4.44
Trial 3	0.5	3.55	135	10	0	12.95	12.60
Trial 4	0.5	3.55	135	10	270	12.95	12.90
Trial 5	0.5	3.55	135	4	180	2.35	2.41

Table 1. Results of applying parametric wave trains to the responsive AAAV.

tracked hull, regardless of assigned task frame or water depth. This state toggling did not allow the vehicle to reach reasonable speeds or conduct maneuvers. We relate the following tale not because of it's particulars, but because it is indicative of the work needed to reuse existing models.

As stated above, the AAAV evaluates its hull state continuously by checking its position on the terrain database. From the position, a lookup is performed to determine the soil type there. The determination of soil type is performed through function `get_soil` in module `vardyn_tick.c` in library `libvariabledynamics`.

When `get_soil` calls the CTDB API, it passes all three coordinates of the vehicle's current position. However, the wave response model requires that the bottom centerline of the vehicle rest below the water surface (zero elevation). Because of this, the *altitude* of the vehicle is constantly offset by its negative displacement; a negative altitude was being reported to the CTDB interface. Having no provision for negative values of that argument, the CTDB returned a nonsensical soil value. `vardyn_tick.c` masks bits in the returned soil value to set the *Deep Water / Anything Else* switch; all unusable values were thrown into the *Anything Else* category. At that moment, the vehicle, even if in *Deep Water*, would be transitioned to a tracked vehicle.

When wave response is enabled, the vehicle can heave enough to bring the keel above the zero altitude (not out of the water, just riding up on a swell). At that moment, a call to `get_soil` would return the correct soil type for *Deep Water*, and the vehicle would begin transitioning back to a ship. The cycle repeated endlessly.

A simple fix would have been to set the *waterline* value to zero or slightly more than zero. However, any virtual stealth viewer would then draw the vehicle as resting on or just above the water's surface, defeating one of the key objectives of the experiment. Thus, it was preferred to make a correction to the code within `get_soil`. Because

	Encounter Direction	*Motion Characteristics*
Trial 1	Abeam	All roll, no pitch. Heave precedes +roll by 90°
Trial 2	Head Sea	All pitch, minimal roll. Heave trails +pitch by 90°
Trial 3	Quarter Following Stbd	Roll and pitch equal, in phase. Heave trails by 90°
Trial 4	Quarter Following Port	Roll and pitch equal, out of phase. Heave trails +pitch, precedes +roll by 90°
Trial 5	Quarter Ahead Port	Pitch > roll, ~160° phase. Heave trails +pitch, precedes +roll by ~90°

Table 2. Observed AAAV wave response behaviors.

that code does not return, modify, or act upon the vehicle position information, we chose to modify the altitude locally (by forcing it to be greater than or equal to zero) only for the call for the soil type from the CTDB interface. This simple code modification allowed the wave response model to continue functioning without a harmful effect on the variable dynamics model. The AAAV ceased its state toggling and behaved as programmed for all soil types and task frames.

4.3.2 Testing Wave Response using the Ocean Editor

With the AAAV behaving properly and responding to wave inputs, the actual response to synthetic waves was evaluated. Using the Ocean Editor within the SAF, various wave heights and primary wave directions were set, and the vehicle was tasked to move linearly across or along them. The results are summarized in **Table 1**. Additionally, **Table 2** lists behaviors for different wave parameters and headings.

The JointSAF environmental sea wave model (developed under DVW and implemented in `libenvsea`) is reported to be a Pierson–Moskowitz model of sinusoidal wave trains. This model for deep ocean waves links amplitude and period directly. The SAF code links the wave frequency to the significant wave height via the relation:

$$\omega_{\max} = \left[\frac{(0.8 c_2)^{\frac{1}{2}}}{h_{\mathrm{w}}} \right]^{\frac{1}{2}},$$

where $\omega_{\max}$ is the (radian) frequency of the primary wave, h_{w} is the significant wave height, and c_2 is a constant equal to 0.32 times the acceleration due to gravity (9.8 m/s^2). Computing the wave period as 2π divided by the frequency, JointSAF links all significant wave heights (as entered into the Ocean Editor) to the primary wave period according to

$$T_{\mathrm{w}} = \frac{2\pi}{\omega_{\max}} = 5.018\sqrt{h_{\mathrm{w}}}\ .$$

Thus, a significant wave height of 0.5m is always assigned a period of 3.55 seconds within the JointSAF Ocean Editor.

The "encounter period" is the time between encountering crests of the primary waves when a vehicle is moving relative to them. It is expressed as a function of the wave period T_{w}, the vehicle velocity V, the wave celerity (phase velocity) V_{w}, and encounter angle (as measured from the wave train's heading) μ as

$$T_{\mathrm{e}} = \frac{T_{\mathrm{w}}}{\left(1 - \frac{V}{V_{\mathrm{w}}} \cos \mu \right)},$$

where the celerity is simply the ratio of the wavelength to its period ($V_{\mathrm{w}}= L_{\mathrm{w}}/\ T_{\mathrm{w}}$), and for deep water waves, wavelength can be approximated as

$$L_{\mathrm{w}} = \frac{g\, T_{\mathrm{w}}^2}{2\pi},$$

where g is the acceleration due to gravity. If the ratio of vehicle speed to wave celerity is greater than one, the encounter period can be negative, indicating that the vehicle is overtaking waves even in following seas. When that ratio, in product with the cosine of the encounter angle, is exactly one, the denominator goes to zero, and the encounter period becomes infinite, indicating that the vehicle is maintaining its position at one point on the wave train.

5 Putting it together: from data through TAOS to the SAF

Finally, we describe the process of bringing the data described in Section **3** to the distributed simulation system for the AAAV.

5.1 Representation of Surf Data Products

The database server for this experiment is the Total Atmosphere Ocean Server (TAOS) (**TAOS, 1998** and **Whitney, 1998**). Another of the three products developed for the STOW Synthetic Environment initiative, this system ingests several different data products for the ocean volume, ocean surface, atmosphere, and near space environments. It synthesizes a volumetric and temporal database, overlaying multiple sources whose temporal frames overlap. Once a database is built, TAOS can publish records from it, according to variables selected by the operator, on a time base configurable by the operator.

For sea surface data, TAOS publishes in the "Net Sea" format, which was defined for the JointSAF system. This format does not allow for gridded data (similar parameters simultaneously updated on a grid basis over the surface). Instead, it divides all water surfaces into two categories: Deep Water (all depths greater than 3 meters) and Shallow Water (all depths less than or equal to 3 meters). Thus, any data published to Net Sea by TAOS updates uniformly over the entirety of Deep (or Shallow) Water as defined within the terrain database loaded at run time by the JointSAF system.

In order to accept Net Sea publications, each SAF instantiation must be initialized with the command line argument, `-allow_env`. When a Net Sea publication is received from an external source (like TAOS), the JointSAF system which was nominated as the ocean master (with the command line argument, `-envseasim`) will relinquish that authority to TAOS. Authority is automatically restored to the ocean master SAF if the Ocean Editor parameters are changed and applied.

5.1.1 Passing Surf Data Through TAOS and into JointSAF

Getting sea surface data through the TAOS system (v1.1) proved to be a challenge. Careful reading of the TAOS User's Guide, Section 4.3.1.2, revealed that all Wave/Surf Regime Receivers had been "…tailored for a set of special…runs made by the MEL [Master Environmental Library] project in support of STOW–97." These runs were specific to a scenario in the Persian Gulf.

More to the point, the data had to be in BUFR, a format common to the meteorological community but unheard of in the oceanographic community. Taking the various outputs from the surf models and forcing them into the BUFR format proved a difficult task, and it had never been repeated. In particular, no subsequent data made available through the MEL database has been formatted in this manner. Thus, none of the data products described in Section 3 was originally made available in this special format.

5.1.2 Reformatting the Data

Subsequent to learning of the BUFR format requirement, a small amount of the SURF96 data already provided to the RRIE was converted over to that format using the software developed for STOW–97. Upon receipt of the reformatted data, it was tested with TAOS and found to be readable. A (tiny) database, consisting of all surf parameters for a single point in space (Latitude 33.258ºN, Longitude 117.439ºW) and time (18 August 1998 18:00 UTC) off Camp Pendleton, was created and successfully published to the network via TAOS.

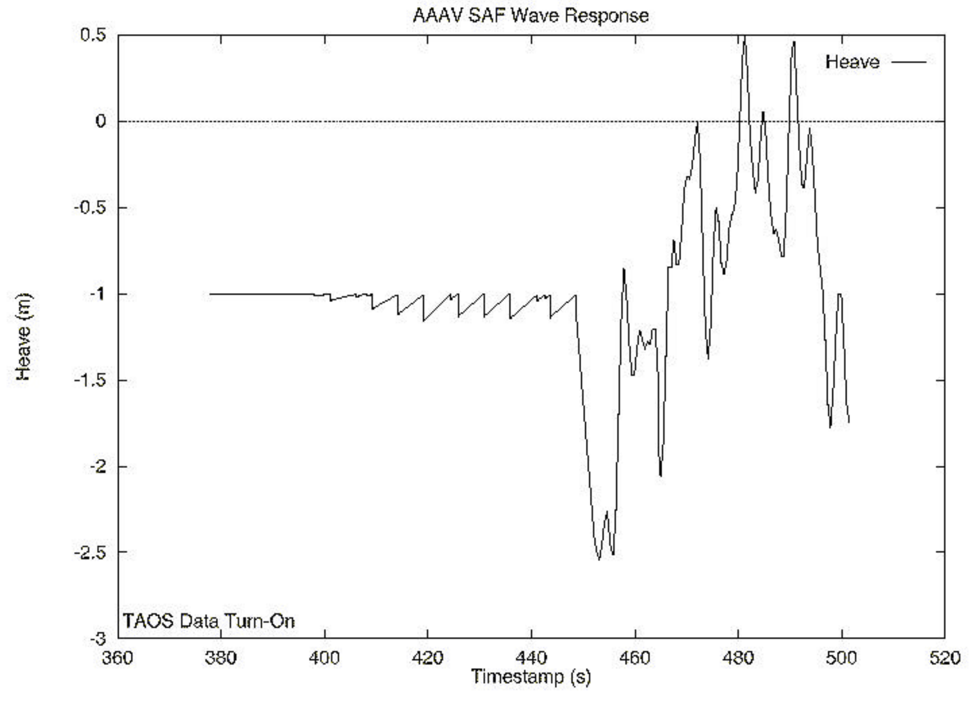

Figure 5. Heave response of AAAV to SURF96 data arriving at timestamp 452.

5.1.3 Results: Running the AAAV through SURF96 data

The data described above were sent from a TAOS database over the network to which JointSAF/MCSAF v3.0 was connected in DIS mode. The SAF was configured (through the Uniform Weather Editor) to a few minutes before 18 August 1998 18:00 UTC; the Ocean Editor was used to set zero wave height and current in both Deep and Shallow Water. A single wave–responsive AAAV was instantiated, and the simulation clock was allowed to elapse until it had transitioned from tracked vehicle to ship hull. At that time, it was given a *USMC Move* task frame, ordering it to head due East through deep water at a maximum speed of 10m/s, and the *On Order* was released for that vehicle.

Once the AAAV was underway and accelerating from 0 to 10 m/s, the TAOS data was released from the TAOS GUI. At 18:00 simulation time, the single Net Sea datum was received by the SAF. The MCSAF gave up ocean master control, and the sea surface parameters were updated. Upon receipt of these data, the SAF overrode the Primary Wave Mean Period, setting it to 5.68s as determined from its own internal model.

The vehicle immediately began responding to the new wave input. The large wave height, coming all at once, caused a severe transient response in the motion of the vehicle. However, the underlying wave component was visible, and the transient began dying out within about 10 seconds. The heave response curve is shown in **Figure 5**. (The sawtooth "noise" prior to the arrival is due to dead reckoning error introduced by the measurement software; once the vehicle began responding to waves, entity state PDU's came much more frequently, and that software no longer had to dead reckon the position.)

This constituted the first known instance in which an end–to–end capability has been demonstrated: from definition of desired sea conditions, through identification and hindcasting of real conditions, delivery of that data, distribution of it through a DIS network, reception of it by a DIS simulation, and response to it in real time by a simulated vehicle.

6 Summary

Throughout the RRIE program, the focus was on determining an end to end process by which simulators could define their environmental needs, environmnetal modelers could satisfy those needs with consistent, multi–domain models, the data they provided could be ingested and served to a simulation system, and entities within that system could respond appropriately to the dynamic environment. Getting from one end to the other required the efforts of a large number of people whose widely varying expertise had to be co-ordinated and synchronized.

We believe we have successfully achieved this objective in the AAAV project. However, we learned that any simulation pro-ject manager that hopes to use available envi-ronmental pro-ducts, while *re-using* existing simulation sys-tems, must be prepared to focus considerable resources on that effort. Early planning and coordination are critical but very difficult: the many parties do not often speak the same language. Full disclosure of capabilities, and full documentation, are required of the simulation software components in order to use them productively. The lack of these particulars cost us both time and money.

Each year, rapid and consistent inclusion of the natural environment into simulations gets closer. But we're not there yet. It is still a labor intensive, detail–oriented process.

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8 Acknowledgements

The authors gratefully acknowledge the program support of the DMSO Modeling and Simulation Executive Agents (MSEAs), especially Mr. G. McWilliams (Air and Space Natural Environment). We acknowledge the cooperation of DRPM AAA M&S IPT lead Mr. R. Hepler, and the GDLS M&S Lead, Mr. M. Routson, whose strong vision and system support got this work underway. Many thanks to Maj. R. Nichols (USMC Res.) of Neptune Sciences for searching the buoy data and providing much needed surf expertise, to Mr. S. Kukolich for discussing his wave response model, and to Mr. J. Huntley and Mr. S. Haes at Army TEC for helping us get TAOS up and running. Finally, our deep gratitude to Ms. L. K. Finman, without whose superb work on the AAAV entity model we would never have gotten our feet wet.

Author Biographies

KARL B. WASHBURN is a Research Physicist with the Advanced Information Technology Branch of the Naval Research Laboratory. Mr. Washburn has been working in distributed simulation systems for Naval systems since 1995. Prior to that, he spent ten years researching Structural Acoustics at NRL. He holds a B.S. in Applied Physics from Case Western Reserve University and an M.S. in Acoustics from The Pennsylvania State University.

RICHARD ALLARD is an Oceanographer with the Ocean Dynamics and Prediction Branch of the Naval Research Laboratory. Mr. Allard is the project lead for the Integrated Ocean Program and has worked closely with the Master Environmental Library since its inception in 1994. Mr. Allard's research in coupled wave/surf modeling was successfully demonstrated at two JTFEX experiments in 1997, and during the NATO Exercise Strong Resolve in March 1998. His collaboration with the Modeling & Simulation community includes participation in the STOW-97 Exercise and the Global '98 Wargame with the Navy War College. Mr. Allard holds a B.S. in Meteorology from the University of Lowell and an M.S. in Atmospheric Science from Texas Tech University.

PAUL MAASSEL is Vice President of VisiTech, Ltd., Arlington, VA. Mr. Maassel provides Systems Engineering support to the Naval Research Laboratory on programs such as the RRIE and Joint Countermine Operational Simulation (JCOS). Mr. Maassel has been active in the simulation community since 1988, including work with SAF, Naval natural environment representations and embedded training. Prior to joining VisiTech, Mr. Maassel provided Systems Engineering support to DARPA on the STOW program and prior to that was a civil servant at NAWCAD's Manned Flight Simulator. Mr. Maassel holds a B.S. in Electrical Engineering from Valparaiso University and a M.S. in Systems Management from the University of Southern California.