IPAS : Interactive Phenomenological Animation of the Sea

Marc Parenthoën  Thomas Jourdan  Jacques Tisseau
Laboratoire d’Ingenierie Informatique (LI2), Centre Européen de Réalité Virtuelle (CERV)
Technopole Brest Iroise - Parvis Blaise Pascal, CS 73862, F-29238 Brest cedex 3, FRANCE

ABSTRACT
No current real-time animation model of the sea simultaneously holds account of a heterogeneous water plane up to 10 km² with the local effects of breakings, winds, currents and shallow waters on wave groups, and this on all the wavelength scales, phenomena however essential so that maritime simulation could have meaning for sailors and remains physically believable for the eyes of oceanographers.

We propose a new approach for the real-time simulation of the sea: instead of numerically solving Navier-Stokes equations on a grid of points, we use oceanographical results both from theory and experiments for modeling autonomous entities, interacting in a multi agent system without any predefined grid. Our model IPAS (Interactive Phenomenological Animation of the Sea) includes entities such as wave groups, active and passive breakings, local winds, shallow waters and currents. Some of the whole set of interactions are modeled.

KEY WORDS : wave field animation; phenomenological simulation; multi agent system; wave groups; breakings; interactions.

INTRODUCTION
The interactive animation of the sea in real time constitutes a strategic stake in many application related to various sea trades. Indeed, more and more often, specialists in navigation, shipbuilding, offshore, maritime safety, nautical competition,... have recourse to simulation and virtual reality.

Sailors use specific vocabulary to describe the sea as a heterogeneous water plane on which they observe localized phenomena (figure 1). These phenomena are modeled by oceanographers, who view the sea as a complex system where many models are superimposed (figure 2). A model for interactive animation of the sea, on the one hand should propose the mediation of a maritime language for the interactive specification of a heterogeneous water plane, and on the other hand should respect oceanographical laws as well as possible, while knowing virtual reality constraints.

However, no current real-time interactive animation model of the sea surface (Gonzato and Saëc, 2000; Thon et al., 2000; Jensen and Gollas, 2001; Premoze and Ashikhmin, 2001; Tessendorf, 2001; Hinsinger et al., 2002; Cieutat et al., 2003; Loviscach, 2003) simultaneously holds account of a heterogeneous water plane up to 10 km² with the local effects of breakings, winds, currents and shallow waters on wave groups, and this for all the wavelength scales, phenomena however essential so that maritime simulation could have meaning for the sailors and remains physically believable for the eyes of oceanographers.

<table>
<thead>
<tr>
<th>phenomenon</th>
<th>oceanographical modeling</th>
<th>parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>wave group</td>
<td>Wave group with a finite extent (Longuet-Higgins, 1957; Sawinney, 1962; Longuet-Higgins, 1986). They propagate along rays (Komen and Hasselmann, 1994). Wavelet analysis using Morlet 2D (Arrascada et al., 1995; Chapron et al., 1995; Donelan and Drennan, 1996).</td>
<td>Age, spectrum, main number of waves, mean wave-vector, mean group, wave vector, extent.</td>
</tr>
<tr>
<td>wave-wind interaction</td>
<td>Action transfers from group to breaking and dissipation of short waves by turbulence (Longuet-Higgins, 1969; Whitham, 1974). Growth of crest length (Banner and Tian, 1998), increasing number of waves and wave length (Donelan and Yuan, 1994).</td>
<td>Particle/crest speed, foam-layer thickness, frequency down-shifting.</td>
</tr>
<tr>
<td>group-depth interaction</td>
<td>Conservation of wave crests and energy. Dispersive action and enlargement of groups (Willsbrand, 1975; WAMDI-groups, 1988).</td>
<td>Depth map, group wave-numbers and frequencies, wave local amplitudes and phases.</td>
</tr>
</tbody>
</table>

This table summarizes the way in which the principal phenomena used by the sailors are modeled in physical oceanography.

Fig. 1. Sea state sailors’ vocabulary

This table summarizes the main maritime terms for water plane description.

Each term corresponds to the designation of a phenomenon taking part in the choices of the strategies of trajectories according to the ship used. A simulator of sea, to be usable by sailors, must represent dynamically, in real time and in an interactive way, the whole of the phenomena described by this specific vocabulary.

Fig. 2. Physical modeling of sea state phenomena
We propose a new approach for the real time simulation of the sea: instead of directly solving Navier-Stokes equations based on a grid of points, we use oceanographical results both from theory and experiments for modeling autonomous entities which interact in a multi agent system, without the need for a grid. This article emphasizes the oceanographical aspects of our model and does not concern the physical believability of a language to specify a heterogeneous water plane, or graphical representation, or computing solutions about the O(n²) complexity of interactions underlying any multi agent system, where n is the number of interacting agents.

In the next section, we expose the principle of autonomy which guides our approach and give main characteristics of our model IPAS (Interactive Phenomenological Animation of the Sea). Then we follow by specifying the wave group and breaking agents and their interactions with each other and other agents. Finally, we conclude about this multi agent approach for the phenomenological animation of the sea and give some perspectives.

AUTONOMY REDUCES MODELING COMPLEXITY

Modeling complex system (Waldrop, 1992) like a heterogeneous water plane, with asynchronous information about the state of its different parts, might be observed by the principle of autonomy (Varela, 1979). By applying this principle to sea state modeling, we obtain a multi agent system named IPAS where each agent is considered as an autonomous entity (Brooks, 1991) interacting with its environment via interaction mediators.

Principle of Autonomy

The model autonomisation by need relates to the instantaneous holding account of changes in environment, by the organizations as by the mechanisms (Tisseau and Harrouet, 2003). The physical modeling of mechanisms generally goes through the resolution of differential equation systems: as is the case for the sea with the Navier-Stokes equations (Chen et al., 1999; Grilli et al., 2001). This requirement causes the knowledge of boundary conditions (Lakos, 1999) which force the movement but, in reality, these conditions continuously change, and their causes could be known or not (interactions, disturbances, environment modifications). The model must thus be able to perceive these changes to adapt its behavior during its execution. This is all the more true when a human is in the loop because, via his avatar, he can cause initially unforeseeable modifications. For example, how to predict the trajectory followed by such or such sailing ship controlled by a human operator on the virtual water plane? The autonomisation by need of a model contributes to reinforce the feeling of reality.

The sea surface model retained consists of a whole of autonomous reactive entities interacting in a Multi Agent System (MAS) (Ferber, 1997). An agent is an autonomous reactive entity, having sensorimotor capacities, and communication with the environment (Ferber, 1995). These agents are located in the environment where they evolve/move according to their behavioral model which defines their capacities of perception, action and decision according to internal characteristics and interactions with the environment. We use oceanographical results both from theory and experiments on modeling interacting agents. Like any modeling, the MAS approach simplifies the studied phenomenon. But, by distributing control on the level of each agent, it allows to mainly respect its complexity, while authorizing a diversity of the components, a diversity of the structures and a diversity of the interactions brought into play.

IPAS: a Multi Agent System

Our model IPAS (Interactive Phenomenological Animation of the Sea) includes primitive physical agents such as wave groups, active and passive breakings, synoptic and local winds, bathymetry and currents. Other agents assume the physical believability of the virtual environment and their modeling is inspired by the oceanographical description of entities responsible for sea states (figure 2). Other agents realize the mediation of maritime language, for friendly interactive water plane specification (figure 1); these high level agents are for example: swell, wind-sea or rogue wave for the friendly interactive water plane specification (figure 1); these high level agents assume the physical believability of the environment and their modeling is inspired by the oceanographical description of entities responsible for sea states (figure 2). Other agents realize the mediation of maritime language, for friendly interactive water plane specification (figure 1); these high level agents assume the physical believability of the virtual environment and their modeling is inspired by the oceanographical description of entities responsible for sea states (figure 2).

Physical agents are situated at the surface of the environment and can perceive properties of the environment via interaction mediators. An interaction mediator is any position z₀ on the water plane (altitude and current) associated with specific attributes.

Every cycle, each agent records its interaction mediators where it needs information according to its behavior and can act on its environment by updating some attributes of mediators situated in its neighborhood, depending on its abilities. For example, wind, current and bathymetry agents are able to update respectively wind speed vector \( \vec{W}_{alt.10m} \), current \( \vec{V} \), depth \( p \) and depth gradient \( \nabla_p \) of a mediator at any position z₀ of the water plane. To date, physical agent models in IPAS are declined in an oceanographical model for wave groups and breakings, and a descriptive model for winds, currents and bathymetry. Some of the whole of interactions are modeled in IPAS (figure 3): action towards wave groups from other groups, breakings, winds, bathymetry and currents, and action toward breakings from wave groups, waves and currents.

<table>
<thead>
<tr>
<th>Group</th>
<th>Breaking</th>
<th>Winds</th>
<th>Current</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>action</td>
<td>wave,</td>
<td>creation</td>
<td>wave,</td>
<td>energy</td>
</tr>
<tr>
<td>energy</td>
<td>action, transport</td>
<td>wave,</td>
<td>energy</td>
<td></td>
</tr>
</tbody>
</table>

Winds Current Depth
These agents are modeled by a descriptive way.

In a multi agent system, the modeling of an interaction between agent A and agent B, unlike the physical notion of interaction, needs to specify both directions (Ferber and Miller, 1998): what does A do to B (action) and what does B do to A (reaction). The upper table, where "x type agents act on y type agents" should be read, presents interactions modeled in IPAS. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

Thus, by distributing the sea state complexity at the level of quite simple autonomous entities interacting in a multi agent system, our model for the animation of the sea offers physical believability for the animation up to 50'000 particles, anywhere on a heterogeneous 10 km² water plane at 10 fps, with a normal PC.

The next two sections describe physical agents in IPAS and their interactions between each other and other agents.

PHYSICAL AGENTS

IPAS is peopled by two types of agent, whose modeling is inspired from oceanographical work: wave group agent and breaking agent. This section details the characteristics of these two agents.

Wave Group Agent

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.

The wave group agent is our main primitive for the phenomenological simulation of the sea. It includes physical notions like finite depth, wave action, breaking action. Their nature is specified: by wave we mean the modification of wave group parameters, by action an energy transfer mechanism from groups and winds to breakings or from groups, breakings and current to groups implying the modification of wave frequency and amplitude for groups, or an energy transfer mechanism from passive breaking to active breaking for turbulence accumulation, by energy an energy transfer without frequency modification, by transport any phenomenon of position modification other than wave group propagation, and by creation the x type agent ability to generate y type agents.
The behavior of a wave group is characterized by a wave train which controls it, by disturbances in phase and amplitude attached to crests and by competences on interaction mediators. We will see in the next section how it modifies its behavioral parameters according to interaction with other agents.

**Wave Train**

We do not consider the 2D Morlet’s wavelet as a mathematical tool, but as a reification of the physical wave group notion, whose envelope moves at the group speed and whose phase progresses at the phase speed (figure 5).

A wave train is such that $K = 2\pi$, the wavelength is $1\ m$. Its envelope $\Gamma$ is in dash line. The wave train has 5 waves in dash-dot lines (1 to 5). Their crests, in solid lines (1' to 5') have all the same horizontal profile $\psi_{\text{crest}}$. This profile is generated here by a fractional Brownian motion with a Holder exponent $0.9$.

![Fig. 6. Wave crest horizontal profile](image)

Such a profile is used to compute the phase $\chi$, by translating the reference position $x_0$ along the wave-vector $\vec{k}$ with the algebraic distance defined by $\psi_{\text{crest}}(x)$, $v$ being the distance from $x_0$ to the line passing by $\vec{x}$ with direction $\vec{k}$:

$$\forall x_0 \in \Gamma, \chi(x_0,t) = \vec{k} \cdot (\vec{x}_0 - \psi_{\text{crest}}(v)) - \vec{K} + \chi_0$$

with $v = (x_0 - \vec{x}) \cdot \vec{k}$.

$$\chi_0 = \begin{cases} \pi & \text{if } x_0 \in \Gamma \text{ (a),} \\ 0 & \text{if } x_0 \not\in \Gamma \end{cases}$$

$$\vec{x}_0 = \begin{cases} \vec{x} & \text{if } x_0 \in \Gamma \\ \vec{x} + k \vec{z} & \text{if } x_0 \not\in \Gamma \end{cases}$$

where $\vec{z}$ pointing to zenith and $||\vec{z}|| = 1$.

Such a wave train mainly characterizes the influence zone and the crest positions of the wave group attached to it. This influence zone bringing mean wave parameters, propagates on the water plane at the group speed. Added to this, we use local phase and amplitude disturbances attached to crests.

**Phase and Amplitude Disturbances**

To be attached to crest, both phase and amplitude local disturbances are functions of $x_0(t)$ (equation (8)). They are used to specify local effects such as those of winds, breakings, currents and bathymetry on a group, but also unknown previous history aspects of a group.

- **Amplitude Disturbance $\delta H$:** In the envelope equation (5) of a wave train, the local height $H(t)$ is the sum of two terms: a global one $H$ and a local disturbance attached to the crests $\delta H(x_0(t))$:

$$H(\vec{u},t) = H + \delta H(\chi(x_0(t)))$$

where $\delta H < H$, so that $H(\vec{u},t)$ is always positive. $\delta H$ is linearly interpolated between control points situated at the crests of the waves. Each crest brings a set of control points defining a spline $\delta H(x)$. Each time a new wave enters the wave train, a random set of random positive values in $[0,H]$ for control points is associated to this new crest. Then, $\delta H$ evolves through time, depending on group interactions with other agents.

- **Phase Disturbance $\phi$:** Phase disturbance can be viewed as the notion of instantaneous phase (Meyers et al., 1993). It is a modulation of the phase $\chi$ depending on relative position to crests and troughs. This modulation models crests advance, trough delay, the local shape of waves and the speed of particles. Each position at a crest (resp. trough) is associated with $\phi_{\text{max}}$, $0 < \phi_{\text{max}} \leq \pi/3$ (resp. $\phi_{\text{min}}$, $-\pi/3 < \phi_{\text{min}} \leq 0$). The interpolation between crest and trough follows a power function whose exponent $\rho > 1$ depends on the front ($\rho_{\text{front}}$) or back ($\rho_{\text{back}}$) of the crest.

When animating particles in a Gerstner way (next sub-subsection), the value of exponents modifies wave shape and particle speed. We choose $\rho_{\text{back}} \in [1,3]$ and $\rho_{\text{front}} \in [1,9]$. The effect of the exponents is illustrated by the figure 7: bigger $\rho_{\text{back}}$ increases amount of water in the back; bigger $\rho_{\text{front}}$ increases vertical acceleration and horizontal speed in the front, and shapes the wave until the beginning of a plunging breaking shape. More precisely, interpolation between crests $n,n+1$ and trough $n+1/2$ follows equation:

$$\begin{aligned}
\phi(\chi) &= (\phi_{\text{max}} - \phi_{\text{min}}) \left( \frac{\chi - \phi_{\text{min}}}{\phi_{\text{max}} - \phi_{\text{min}}} \right) + \phi_{\text{min}} \\
&= (\phi_{\text{max}} - \phi_{\text{min}}) \left( \frac{\chi - \phi_{\text{min}}}{\phi_{\text{max}} - \phi_{\text{min}}} \right) + \phi_{\text{min}}
\end{aligned}$$

Here, a wave train is such that $K = 2\pi$, the wavelength is $1\ m$. Its envelope $\Gamma$ is in dash line. The wave train has 5 waves in dash-dot lines (1 to 5). Their crests, in solid lines (1' to 5') have all the same horizontal profile $\psi_{\text{crest}}$. This profile is generated here by a fractional Brownian motion with a Holder exponent $0.9$.

$\chi_{\text{crest}}(x) = \frac{\chi_{\text{crest}}(x) + \phi_{\text{max}} \mod(2\pi)}{2\pi}$

$\chi_{\text{front}} = \phi_{\text{min}} \mod(2\pi)$

$\chi_{\text{back}} = \phi_{\text{max}} \mod(2\pi)$

$\phi(\chi) = (\phi_{\text{max}} - \phi_{\text{min}}) \left( \frac{\chi - \phi_{\text{min}}}{\phi_{\text{max}} - \phi_{\text{min}}} \right) + \phi_{\text{min}}$

$$\begin{aligned}
\phi(\chi) &= (\phi_{\text{max}} - \phi_{\text{min}}) \left( \frac{\chi - \phi_{\text{min}}}{\phi_{\text{max}} - \phi_{\text{min}}} \right) + \phi_{\text{min}}
\end{aligned}$$

The choice of exponents $\rho > 1$ assumes that $\phi$ is differentiable in

Paper No. 2004-JSC-386
Parentéhoën

Page: 3 of 8

### Competences on Interaction Mediators

If an interaction mediator situated in the environment at \( x_0 \) is influenced by a group \( (\bar{x}_0 \in \Gamma) \), such groups add their contributions to four attributes of this mediator. These attributes are called: dynamic position \( \Delta x^+ \), particle speed \( \bar{s} \), normal \( \bar{n} \) and influencing group list \( C \). These competences are inspired from the Gerstner model, imagining water particles as moving around circular orbits in function of their phase. For a single infinite group without disturbance in the Gerstner model of sea without any currents or shallow water, \( \Delta x^+ \) corresponds to particle position relatively to its rest position \( x_0 \), \( \bar{s} \) is particle speed, \( \bar{n} \) is the normal of sea surface and \( C \) contains the name of this group. We assume that when some group agents influence the same mediator, each contribution is added linearly to \( \Delta x^+ \), \( \bar{s} \) and \( \bar{n} \).

For a given group \( (\bar{K}, \alpha, x_0, H, \bar{H}) \), its competences \( \Delta x^+, \bar{s}^+ \) and \( \bar{n}^+ \) on an interaction mediator at \( x_0 \) follow equations:

\[
\Delta x^+ = a \cdot \left( e^{i \chi^+(x_0,t)} \right) \quad (\text{\text{eq. (13)}})
\]

\[
\bar{s}^+ = -a \Omega \cdot \left[ 1 - \frac{4}{5} \phi (\chi(x_0,t)) \right] \cdot \left( e^{i \chi^+(x_0,t)} \right) \quad (\text{\text{eq. (14)}})
\]

\[
\bar{n}^+ = \ii \left[ 1 - a \bar{K} \left( 1 - \frac{\phi (\chi(x_0,t))}{\phi (\chi(x_0,t))} \right) \cdot (\chi(x_0,t)) \right] / (\ii K, \bar{r})\quad (\text{\text{eq. (15)}})
\]

where \( a = (x_0 - \bar{x}, t) \) is the local wave amplitude with its disturbance as defined by equations (5) and (9), \( \chi \) the phase respecting equation (8), \( \chi^\alpha \) the local modified phase defined in equation (12), \( \phi \) the modified phase derive [equation (11)] and \( z \) the normed vector pointing to zenith. Notation \( |\mathcal{A}|(\bar{r}, r, \theta) \) represents, in the complex plane associated to \( (\bar{r}, \bar{r}) \), the vector \( \bar{u} \) whose complex affix is \( \bar{A} \in \mathcal{C} ; \bar{A} = (\mathcal{A}) \bar{u} + 3(\mathcal{A}) \bar{A} \). Notation \( \mathcal{A} \subset \mathcal{C} \).

- Dynamic position [equation (13)] is the application of Gerstner model using disturbed phase for wave containing vertical \( \bar{s} \) and wave-vector \( \bar{r} \), and makes an angle of \( \pi/2 \) in the complex plane \( (\bar{s}, \bar{r}) \) with the vector of affix \( 1 + a \bar{K} e^{i \chi^+(x_0,t)} / \Omega \) whose complex affix is \( \bar{A} = (\bar{A}) \bar{u} + 3(\mathcal{A}) \bar{A} \).

- Normal [equation (15)] results from weak \( \partial \bar{A}(\bar{r}, r, \theta) / \partial \theta \) hypothesis: the normal \( \bar{n}^+ \) due to a single group is then in the plane containing vertical \( \bar{s} \) and wave-vector \( \bar{r} \), and makes an angle of \( \pi/2 \) in the complex plane \( (\bar{s}, \bar{r}) \).

When more than one group influences this mediator, we can not just vectorially add each 3D normals \( \bar{n}^+ \). We have to respect the following equation resulting from linear considerations:

\[
\forall \bar{r} \in [1, N], \bar{n}^+ \cdot \bar{n}^+ = 0 \quad (i.e.: \text{there is no horizontal normal}),
\]

\[
\bar{n}^+ = \frac{1}{N} \left[ \begin{array}{cccc}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{array} \right] \quad (\text{\text{eq. (16)}})
\]

else, \( \bar{n}^+ = \mathcal{A} \) is the mean horizontal normal.

These group agent abilities are illustrated by figures 7, 9 and 10.
Thus, we have shown the wave group agent used in IPAS. A group is controlled by a wave train carrying mean properties of the group and transporting the envelope. Amplitude and phase disturbances give control at the level of each wave and their parameters modify local wave shape. Particle animation relies on the application of a Gerstner inspired model. Each group influencing an interaction mediator can update dynamic position, particle speed, surface normal and can add its name to the list of groups having a crest near this mediator.

### Breaking Agent

Oceanographers view two phenomena in breaking: one, active breaking following the propagation of breaking fronts and the other, passive breaking explaining foam and turbulence relaxation. Breaking agents are responsible for the representation of both these phenomena. A breaking agent is a set of particles gathered in representatives by neighbourhood. Each representative deals with an area element for simplifying calculi. A representative has one or two particles including one known as principal. Particles are associated to three specific states: active, passive or unknown. These states correspond respectively to belonging to active front, relaxing foam and turbulences or waiting for more information to decide its role in breaking.

We first describe how active breaking fronts are propagating by recording interaction mediators. Then we specify the foam and turbulence relaxation.

#### Active Breaking

Active breaking modelling needs to take into account breaking activity and front propagation. The breaking agent decides its activity in function of the information given by recorded mediators positioned at the active or unknown particles of representatives. The front propagation results from an exploration of the neighborhood of active particles, by creating unknown particles. Let’s specify activity and propagation calculus.

- **Breaking activity.** The breaking agent estimates its activity rate \( \beta \) for a particle potentially belonging to the front, as defined by the following (Reul and Chapron, 2004) inspired equations if there is at least one crest close to this mediator, i.e. \( C \neq \emptyset \):

\[
\forall j \in C, \quad \tilde{C}_j = \left(1 - \alpha(W, \tilde{C}_j)\right) \cdot \tilde{C}_j + \alpha(W, \tilde{C}_j) \cdot (\tilde{C}_j - \tilde{c}_j) \tag{17}
\]

with \( \alpha(W, \tilde{C}_j) = \begin{cases} 0, & \text{if } \forall j \in C, \tilde{s} \cdot \tilde{C}_j \leq c_j^2 \\ \delta \left(\sum_{j \in C, c_j \geq c_j^2} (\tilde{c}_j \cdot \tilde{C}_j - c_j^2) \lambda_j\right), & \text{otherwise,} \end{cases} \]

\[
\beta = 9.9 \times 10^{-2} \lambda^{1/2} \tag{19}
\]

where \( W \) is wind speed, \( \tilde{s} \) particle speed, \( \tilde{n} \) surface normal, \( C \) the indices of groups having a crest near this mediator, and for a group \( j \): \( \tilde{c}_j \) its phase speed, \( c_j \) its group speed and \( \lambda_j \) its wavelength. The function \( \alpha(W, \tilde{C}_j) \) taking values in \([0, 1]\) reflects the risk of air separation close to the crest, supporting an early surge (Liu et al., 1995). The speed \( c_j \) (equation (17)) is then between group speed \( c_j = 1 \) and phase speed \( c_j = 0 \). The wavelength \( \lambda \) (equation (18)) could be imagined as an activity weighted average wavelengths of the groups transferring activity to this breaking (Duncan, 1981). The activity rate \( \beta \) (equation (19)) corresponds to foam thickness increasing rate but also to the growth of breaking intensity (Melville and Matusov, 2002).

If no group has a crest close to this mediator (\( C = \emptyset \)) or if activity rate \( \beta \) given by equation (19) is null, the particle changes to passive breaking mode if it was active or is destroyed if it was unknown. If activity rate \( \beta \) is not null and if the particle was unknown, it changes to active state and destroys the possible second particle, keeping the foam thickness if the destroyed particle was passive; then becomes the principal particle of the representative.

The breaking agent can update the breaking activity aspects of interaction mediators. Any mediator situated inside the area of a representative possessing an active particle has its activity attribute set to true and the different group contributions \( x_j t \).

### INTERACTIONS

In IPAS, physical agents interact via interaction mediators, respecting oceanographical laws associated to maritime phenomena and summarized in figure 2. We detail in this section interactions presented in figure 3. We first view interactions towards breaking agents, then interactions towards wave group agents.
Interactions Towards Breaking Agent

Breaking are propagating in an autonomous way in interaction with groups and winds on recorded mediators, as specified by the equations (17), (18) and (19) characterizing the quantity of action provided to a breaking agent by groups and winds. We specify here some of the other interactions defined in the table of figure 3; they are related to their creation and their transport. The breaking birth is not spontaneous: it is decided by groups. The current transports the particles of the representatives.

Creation by Groups

At each agent life cycle, a group creates new breaking in two manners: either according to the Stokes’ limiting criterion (Longuet-Higgins, 1969) according to its parameters, or on a slope criterion (Bonmarin, 1989) according to normals provided by the mediators recorded by the group.

- **Stokes’ criterion.** A group can create spontaneously a breaking if its local steepness is too high. The Stokes’ criterion at group center obeys the following equation (considering this group alone):

\[
(H + \delta H_{\text{max}})\Omega^2 \geq g
\]

where \( H + \delta H_{\text{max}} \) is the wave height maximum of the group at moment \( t \), without the Gaussian lens. If this criterion is checked, a position \( \vec{x}_0 \) at a crest of the rear part of the group is drawn by chance to the local steepness \( \delta H_{\text{local}} \) higher than 6% (Rapp and Melville, 1990), a breaking agent is generated with one representative containing a unique unknown particle: the interaction mediator positioned in \( \vec{x}_0 + \Delta \cdot \vec{c} \), for anticipating crest movement until the next cycle.

- **Slope criterion.** When a group reads the attributes of its recorded mediators, it checks the slope using the surface normal \( \vec{n} \). We decide to define the slope criterion by the equation:

\[
\vec{n} \cdot \vec{z} < 0.97 \approx \cos(14^\circ)
\]

where \( \vec{z} \) is the unitary vector pointing to zenith. This criterion assumes slopes greater than 14°, according to experimental observations (Bonmarin, 1989; Rapp and Melville, 1990). If the slope criterion is checked for a given mediator, the group agent creates a breaking agent with one representative containing a unique unknown particle: this mediator with the same position. Indeed, when the slope criterion is checked, there is greater chance to be on the front part of the wave than on its back part.

Whatever the criterion checked, such a generated breaking agent will then evolve autonomously according to its own behavior, in particular, its manner of becoming indeed active or not.

Transport by Currents

The representatives are positioned by co-ordinates in a reference mark related to the ground; the current effect is then onto particles belonging to representatives. Each representative records an interaction mediator situated at its main particle position. This mediator gives the local current value \( \vec{U} \). The particles of a representative are then represented by \( \Delta \cdot \vec{c} \). If such a translation puts a particle outside the representative area, a new representative is added and deals with this particle. If the breaking agent has already a representative at this position, this particle may become one of the particles of this representative. In this last case, the choice for main and second particle depends on the states of particles in competition: active, passive or unknown. When there is only one active particle, its becomes the main one. When there are two active particles, only one is kept: the one with the higher activity; the other is destroyed.

Interactions Towards Wave Group Agent

The effects on the waves of phenomena related on winds, breakings, currents and depth are of capital importance for sailors. It is thus advisable to represent them as correctly as possible, respecting real time constraints. We start by quickly presenting the effects of bathymetry and current, then we will describe action transfers with winds, breakings and other groups. In HAB, these effects are superimposed. All these interactions depend on the attribute values of five recorded mediators \( LFRB \) and \( C \), \( L_{\text{left}} F_{\text{front}} R_{\text{right}} B_{\text{back}} \) being a rhombus included inside the group envelope \( \Gamma \), with \( C \) as center. The position of these mediators structure relative to the group center \( X \) evolve randomly at each life cycle of the group agent.

Interactions with Bathymetry and Currents

The general idea is to modify the mean characteristics of the wave train controlling a group, by respecting usual oceanographical modeling of wave-depth and wind-current interactions: crestedness, period, crest steepness, divergence or convergence of depth gradients and currents viewed by the group while respecting action conservation, the crest profile and the local distribution of phase and amplitude disturbances; in particular, shallow water increases local trough delays until phase disturbance has reached the minimum \(-\pi/3\) and increases local amplitude, while deep water does the opposite; for currents, a current opposite to group propagation (resp. having the same direction) increases (resp. decreases) phase disturbance exponents.

Action From Wind

Our modeling is based on (Sverdrup and Munk, 1947)’s measurements (figure 11). Winds can create new groups randomly on the water plane. The characteristics of these new groups are those of the minimal one minute old group. Once they are one minute old, these groups evolve autonomously. Winds also increase wave train height, crest advance or phase disturbance exponents, depending on wave train position in the Sverdrup and Munk’s diagram relative to its age and average wind speed (figure 11). Wind speed reference is the projection of the wind vector \( \vec{W} \) onto the group wave-vector \( \vec{k} \):

\[
\vec{v} = \vec{W} \cdot \frac{k}{k}/k
\]

For such wind speed \( \vec{v} \), when \( \vec{W} > 2.5 \text{ m s}^{-1} \) (else there is no interaction), the diagram gives a significant height \( H_{\text{max}} \) and a significant pulsation \( \Omega_{\text{min}} = 2\pi/P_{\text{max}} \) in function of group age \( a \). We distinguish two cases: \( \Omega > \Omega_{\text{min}} \) or \( \Omega < \Omega_{\text{min}} \): If \( \Omega > \Omega_{\text{min}} \), group height \( H \) is increased by \( \Delta H \), calculated proportionally with cycle duration \( \Delta t \) and max(\( H_{\text{max}} - H(0) \)). We also add to phase disturbance parameters \( \delta\Omega_{\text{front}}, \delta\Omega_{\text{back}} \) local extra advances on each crest and extra exponents \( \delta\Omega_{\text{front}}, \delta\Omega_{\text{back}} \). These modifications of phase disturbances are calculated proportionally with \( P_{\text{wave}}(\vec{W}) - 2\pi/\Omega \), where \( P_{\text{wave}}(\vec{W}) \) is the maximum period reachable by waves stressed by a wind blowing at speed \( \vec{W} \), while respecting constraints:

- \( 0 < \delta\Omega_{\text{front}} + \delta\Omega_{\text{back}} \leq \pi/3 \)
- \( 1 < \delta\Omega_{\text{front}} + \delta\Omega_{\text{back}} < 9 \)
- \( 0 < \delta\Omega_{\text{front}} + \delta\Omega_{\text{back}} \leq 3 \)

- \( \Omega \leq \Omega_{\text{min}} \), possible height increase \( \Delta H \) is computed proportionally with \( \Delta t \) and \( H_{\text{max}} \), e\( -3(\Omega/\Omega_{\text{min}} - 1) \) when \( \gamma \) defines Gaussian repartition of long wave heights around significative waves, while respecting \( \Delta H \geq 0 \).

Fig. 11. Significant heights and periods of wind sea waves

Thus, a group receives from wind an increase of action translated in terms of height increase and phase disturbance modifications. When a group is far from balance with wind, its height all the more grows and phase disturbance modifications all the more increase breaking probability.
Action From Breakings and Other Groups

In spite of the complexity of physical phenomena brought into play for the genesis and the evolution of sea states (Miles, 1957), be it by breaking cinematic mechanisms (Banner and Phillips, 1974) or by resonant coupling (Hasselmann, 1962; Benney and Saffman, 1966), all the explanation of the progressive lengthening of waves (Donelan and Yuan, 1994; Drennan and Donelan, 1996) and the organization of groups (Banner and Tian, 1998) according to the age of the wind sea (Janssen, 1994), in agreement with the sea or by resonant coupling (Hasselmann, 1962; Benney and Saffman, 1962).

We deal in this work with active and passive breakings. Both of them propose lengthening and organization of waves. We propose a simple merge mechanism. The lengthening of waves will be modeled by interaction between groups and breakings. We deal with two types of interaction: from a breaking towards groups, the first is associated with active breaking and the second with passive breaking; both of them propose lengthening and organization of groups.

- **Group merge.** When a group i reads the C attributes of its five recorded mediators, it computes the intersection of these five lists. If it is not empty, for each group j belonging to this intersection, if $k_i \approx k_j$, then group i and j are merged into a new group k progressively replacing both groups i and j, in $N_i + N_j$ periods duration: during the same time, groups i and j decrease their heights, while group k increases its height. The merge respects action conservation, crest positions and envelope extent as best as possible.

- **Active breaking and groups.** When a breaking agent is active, it records interaction mediators at the position of active particles, with activity attribute set to true and the list of groups L [equation (20)] having as a key for this breaking: $x c_j < c_j$. When a group updates such an interaction mediator $n$, it checks if it is one of the groups $j \in \mathcal{L}_n$. If so, it modifies its parameters taking into account its action transfer to this breaking and progressively to other groups. This modification process depends on the position of the crest $p$ to which belongs this particle $n$, relative to the center of the group $j$, according to whether $p$ is located in the front or back part of the group. If the breaking crest $p$ is in the front part, $p$ progressively loses its local positive random phase and amplitude disturbances, at a speed proportional to its activity rate: $\tau_i = \tau(c_j - c_j)$. If the breaking crest $p$ is in the back part, $p$ progressively decreases its mean height $H'$ and mean wave number $K'$. The $H'$ decrease speed $\tau_{H'} < 0$ and the $K'$ decrease speed $\tau_{K'} < 0$, for the whole crests $p \in$ group, respect equations:

$$\tau_{H_{jp}} = -\frac{N(c_j)}{N_{}\text{particles}_p} \sum_{c_j} \left( H_{jp}^{np} - H_j^{n} \right), \quad \tau_{H_{jp}} = \sum_{p \in \text{group}} \tau_{H_{jp}}$$

$$\tau_{K_{jp}} = \frac{2}{N_{r} H_j} \frac{C_{ij}}{c_j} \text{mean} \left( r_{i}^{j} / c_{j} \right), \quad \tau_{K_{jp}} = \sum_{p \in \text{group}} \tau_{K_{jp}}$$

where $c_j$ is phase speed, $H_j^{n}$ the height of the wave at particle $n$ at the position of the breaking activity, $H_{jp}^{np}$ the maximum height of this wave when it will reach the middle of the group, $N$ the number of waves in the group, $\Lambda [m^{-1}]$ the distribution of the average length of breaking fronts per unit area per unit speed interval (Phillips, 1985), empirically modeled by: $\Lambda(c) = 3.3 \times 10^{-4} \left( W / 10 \right)^{0.8}$. (Melville and Matusov, 2002), and $\tau_{H_j}$ an inner coefficient of the group regularly updated to follow slow Sverdrup and Munk’s measurements, by increasing (resp. decreasing) it if group wavelength is too small (resp. large) compared to the significant wavelength of such a group (figure 11). Equation (26) comes from the dispersion relation $\omega^2 = gK$ and phase speed definition $v_{ph} = gK / \omega$. For the complex case, $K'$ is brought closer to particle speed $s$ ruling formula being parameterized in a separation constant $c$. Applying equation (25) decreases group height $H'$. If that leads to $H' \approx 0$, breaking is so intensive, that this group is destroyed. Applying then equation (26) modifies indirectly group length $L'$ and corresponds to a certain amount of action. Group height $H'$ is then corrected by action conservation. This action could also be separated for each active particle $n$ and for each active group $j \in \mathcal{L}_n$. For a given particle $n$, all of its active groups are concerned with a certain amount of action, but the group $i$ with the smallest $K$ influencing this mediator (even if $i \in \mathcal{L}_n$) receives the total of this action in the form of a wavelength increase, then updates its mean height $H'$ to respect action conservation, $H'$ possibly has been already updated by equation (25) and indirectly (26).

- **Passive breaking.** When a group reads its mediators $LFRB$ and $C$, attributes concerning passive breakings give foam and turbulence thickness and whose passive breakings are under it. It can then estimate passive breakings average foam and turbulence thickness $\delta$. Two types of modification occur: the first is addressed to the local phase and amplitude disturbances by decreasing their random part at a speed proportional with local thickness $\delta_{LFRB}$ or $C$; for modeling the absorption of high frequency wave parameters, breaking activity, transport, refraction and creation. For modeling the absorption of high frequency wave, the ratio $\delta_{LFRB}$ or $C$ can then estimate passive breakings average thickness $\delta$ times the quotient of breaking area $S$ by group area $L \times l$, for modeling width group increase (Banner and Tian, 1998). Then, for a given group, when $s > 5L$, its number of waves $N$ is incremented following a process of one period duration. New length $L_{n+1}$ is given by equation (3) and new width $\delta_{n+1}$ is $\delta N$ times $N/(N + 1)$. These modifications are such that the total action of the group is conserved. The matrix $A$ characterizing the group envelope is modified progressively during this period from its current value to its target value $A_{n+1}$ given by equation (4).

Thus, an active or passive breaking takes a certain quantity of action to groups and modifies their wavelengths and widths with the profit of sub-harmonics, while taking as a starting point experimental and theoretical work.

**CONCLUSION & FORWARDS**

We have proposed a multi agent approach for the real time simulation of the sea, while respecting as best as possible oceanographical knowledge. Our model IPAS includes agents in interaction such as wave groups, active and passive breakings, local winds, shallow waters and currents. We have modeled action towards wave groups from breakings, winds, shallow waters and currents, and action toward breakings from wave groups, winds and currents. These interactions are computed in term of action or energy transfer, wave parameters, breaking activity, transport, refraction and creation. IPAS can compute water particle movement at any position on a $10 \times 10$ water plane, up to fifty thousands particles in real time ($> 10$ fps$^3$). Thus, IPAS can help those who have recourse to simulation and virtual reality.

A lot of work has to be done for the oceanographical validation of IPAS, using usual tools for sea states analysis. The simulation method is very flexible, and to some extent, it seems that adequate tuning might bring the results close to any theoretical model or actual measurements at sea, without a great amount of dedicated tuning. An extension of the model to the underwater phenomena could be of great interest, as well as the addition of the not yet modeled interactions.

IPAS may be the first prototype of rising generation models for real time animation of the sea; they will have to be able to manage this complexity related to the diversity of the phenomena (wave groups, active breakings, foam, winds, currents, shallow waters...), on the diversity of the interactions between these entities, and on the diversity of the mechanical, visual and sound effects associated.

**REFERENCES**


Some video samples generated by IPAS are available in .mp4 format on our website http://www.ensi.in.t.fr/~parenthoen/recherche/filmsmer/index.html