GPU-Accelerated Simulation of Complex Ocean Waves for Maritime Training

Frank Kane
CEO, [Sundog Software LLC](https://sundog-soft.com)

[1]

Figure 1: Real-time Simulated Waves from the Triton Ocean SDK, using the techniques described in this paper.

Abstract

Detailed visual simulation of oceans may be achieved by executing inverse fast Fourier transforms (FFTs) using GPU acceleration, to transform large number of individual waves from the frequency to spatial domain. Well-known models have been developed for visual effects in the entertainment industry, but additional accuracy and flexibility is required for maritime training purposes. This paper describes how algorithms developed for cinematic computer graphics are extended by Sundog Software®'s Triton Ocean SDK™ to incorporate more sophisticated wave models, swell waves, and the integration of external wave models.

The Inverse FFT Trick

At the heart of real-time ocean simulation is the inverse fast Fourier transform, a mathematical tool to convert waves defined by their amplitudes and frequencies into displacements in 3D space over time. The technique begins with a two-dimensional array, where each cell represents a given wavelength and direction. The value of each cell is associated with the Fourier amplitude of that wave. As a simplified example, imagine a 5x5 array:

				a
		X	**b**	
c				

The center of the array, **X**, represents a reference point of the maximum wavelength this array can represent, with no directional motion. The distance from **X** defines the *inverse* of the wavelength of the wave given by a specific cell in the 2D array (specifically, the maximum wavelength this array can represent divided by the wavelength defined by this cell). The direction from **X** corresponds to the direction the wave is travelling. The actual value of each cell corresponds to the amplitude of the wave.

So in this example, **a** corresponds to the Fourier amplitude of the smallest wavelength this array can represent, moving NorthEast. **b** represents a long-wavelength wave moving East, and **c** represents a short-wavelength wave moving SouthWest (the actual directions and wavelengths are a matter of convention, and may be scaled and transformed as desired.)

The Fourier amplitude of a wave a_F is a function of its spatial amplitude a:

$$a_F = \frac{a}{2\sqrt{\pi}}$$

The value stored in each cell is in actuality a complex number, which may further be used to define a phase offset for each wave in addition to its amplitude.

The computation of inverse FFT's may be parallelized, which means they can be executed very quickly on consumer-grade GPU's. Software frameworks, including CUDA, OpenCL, and DirectCompute all include means for GPU acceleration of 2D inverse FFT's, meaning large numbers of ocean waves may be simulated over time at interactive frame rates on GPU's from any commercial manufacturer.

A limitation of this approach is that only a discrete set of wavelengths and directions may be simulated. The specific wavelengths and directions desired in a simulation must be rounded to correspond to a specific cell in the 2D array. But by increasing the number of cells in the array, better resolution may be achieved. Sundog Software's Triton Ocean SDK uses a 256x256 array, which represents wavelengths up to 256 meters. By tiling the spatial transform of this inverse FFT, realistic ocean scenes consisting of the sum of 65,536 discrete waves may be rendered out to the horizon at many hundreds of frames per second on consumer-grade hardware. Real-time height queries on the generated ocean surface may also be used to power buoyancy models to simulate the motion of ships, buoys, and other objects floating on this simulated ocean in a highly realistic manner.

Wave Models

The challenge is how to populate this 2D array of waves in a manner that realistically represents ocean conditions for given sea states for training purposes. The Triton Ocean SDK offers three models to choose from:

- **Tessendorf**. This wave model was described in a paper[2] on how the visual effects in the movie Titanic were achieved, and is the basis for most 3D ocean effects in the world of computer graphics and games. It produces realistic oceans, but was developed for the film industry and not for training. It models only waves from wind traveling over an infinite distance, using the "Phillips" wave spectrum.
- **Pierson-Moskowitz**[3]. Like Tessendorf, this wave model assumes a "fully developed" sea where winds are assumed to travel over an infinite distance. However, it is a more sophisticated model based on wave measurements from accelerometers on actual ships in the North Atlantic. The model represents a fit of the actual wave data they obtained, and so is more appealing for the purpose of maritime training. The Triton Ocean SDK uses proprietary algorithms to implement the Pierson-Moskowitz spectrum as a GPU-accelerated inverse FFT.
- **JONSWAP**. The JONSWAP model[4] extends Pierson-Moskowitz to recognize that in the real world, waves are never "fully developed" and winds actually travel over a finite distance, called the "wind fetch." JONSWAP allows us to model in these "fetch lengths," which may be specified as part of the wind conditions given to the Triton Ocean SDK, for even more realistic waves.

[2] Tessendorf, Jerry. (2001). Simulating Ocean Water. SIG-GRAPH'99 Course Note.

[3] Pierson, Willard J., Jr. and Moskowitz, Lionel A. Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S. A. Kitaigorodskii, *Journal of Geophysical Research*, Vol. **69,** p.5181-5190, 1964.

[4] Hasselmann K., T.P. Barnett, E. Bouws, H. Carlson, D.E. Cartwright, K. Enke, J.A. Ewing, H. Gienapp, D.E. Hasselmann, P. Kruseman, A. Meerburg, P. Mller, D.J. Olbers, K. Richter, W. Sell, and H. Walden. Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)' *Ergnzungsheft zur Deutschen Hydrographischen Zeitschrift Reihe*, A(8) (Nr. 12), p.95, 1973.

Integrating Swell Waves

While the above models can produce realistic wave spectra for wind-driven waves, maritime training applications often wish to also specify longer-wavelength swell waves in addition to wind waves. The Douglas Sea Scale[5] can be used to specify wind and swell wave conditions independently, as opposed to the Beaufort scale[6] that is only defined by wind conditions. Triton allows sea states to be specified using either scale.

Integrating specific swell waves of a given wavelength, amplitude, direction, and phase is simply a matter of adding them into the inverse FFT input created by the wave models above. Triton offers a `Triton::Environment::AddSwell` API to convert a desired individual swell wave to specific values in a specific cell of our inverse FFT input array. In this way, large numbers of algorithmically-generated wind waves may be combined with user-specified swell waves for a desired training scenario.

Integrating External Wave Models

In some applications, an existing wave model is desired to be retained, while using the Triton Ocean SDK to create accompanying real-time visualization of the wave model.

Often, these external models focus on longer-wavelength waves, and ignore the smaller, "capillary" waves rippling on the ocean surface. These low-amplitude, high-frequency waves have no appreciable impact on the simulated motion of ships, but they are necessary for visually convincing water. To blend the two, one may start with waves generated by one of Triton's built-in models in order to achieve a realistic full spectrum of waves, and then use Triton's `AddSwell` API to inject the longer-wavelength waves defined by the external model. The external model's waves must be rounded in a manner identical to how they are discretized into Triton's FFT input cells to ensure perfect correlation.

External models often define waves by their frequency, while Triton's FFT expects waves to be defined by wavelength. A wavelength L is related to a frequency ω as:

$$\omega = \sqrt{g \times \frac{2\pi}{L}}$$

Where g is the gravitational constant, 9.81 m/s^2

Another approach is to explicitly hand Triton a pre-computed inverse FFT array to use, in place of Triton's own wave models. The `Triton::Ocean::OverrideFFTInputArray` API is offered for this purpose.

Simulating Other Water Disturbances

Wind and swells are only two forces that affect the simulated ocean surface. The [Triton Ocean SDK](#) also allows the user to model water displacements resulting from:

- Ship wakes
- Rotor wash

---

[5] https://en.wikipedia.org/wiki/Douglas_sea_scale
[6] https://en.wikipedia.org/wiki/Beaufort_scale

- Impacts
- Interaction with coastlines and shallow water
- Leeward dampening
- Tidal wakes

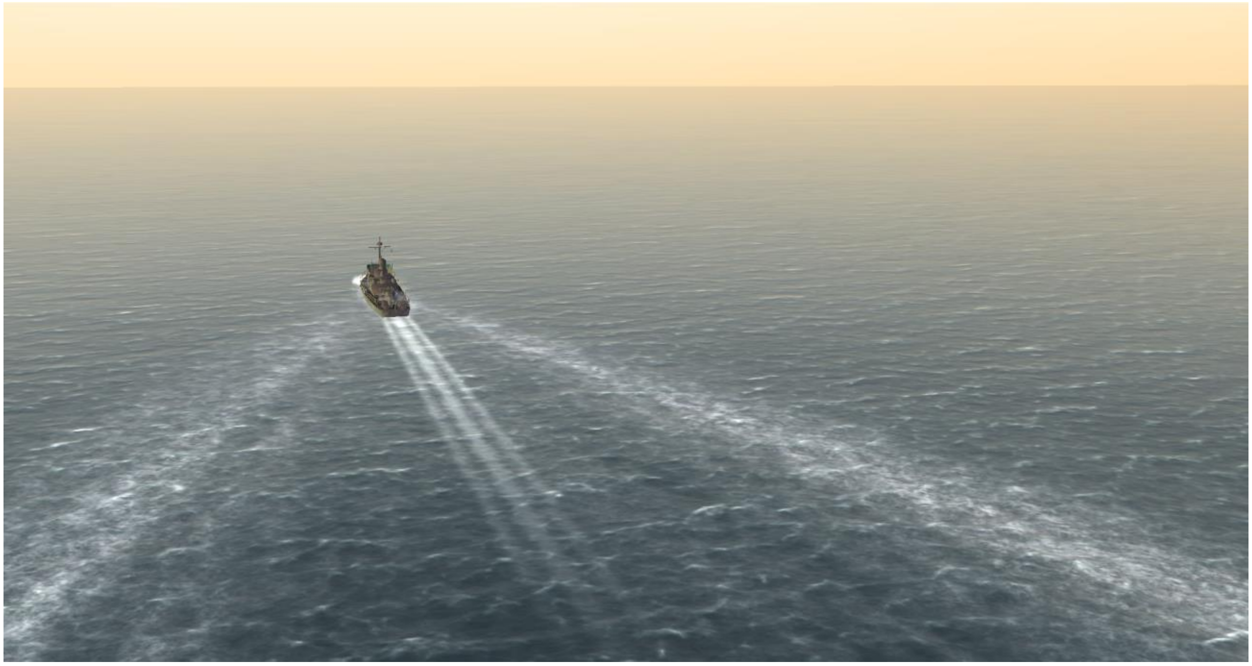

Figure 2: Ship wakes added into simulated wind waves in the Triton Ocean SDK.

Learning More

We invite the reader to visit our website at https://sundog-soft.com/ to learn more about the Triton Ocean SDK, as well as our SilverLining Sky, 3D Cloud, and Weather SDK. Freely downloadable evaluation SDK's, comprehensive documentation, and licensing information is available at our site. The author welcomes your inquiries at fkane@sundog-soft.com.