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Task 4: Environmental Impact Monitoring at WETS

Transmission Loss Modeling Acoustic Model Survey & Implementation of Parabolic Equation Model

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Transmission Loss Modeling

Acoustic Model Survey and Implementation of Parabolic Equation (PE) Model

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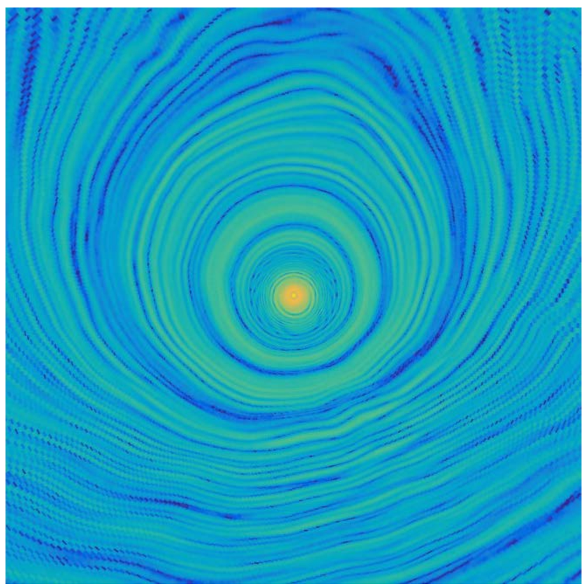

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1 Introduction

This report provides a brief introduction to acoustic modeling and describes efforts to model the acoustic emissions of the NWEI Azura wave energy converter (WEC) at the US Navy Wave Energy Test Site (WETS) in Kaneohe Bay, HI.

Sound produced by the Azura has been measured using drifting hydrophones (A-SWIFTS) and stationary hydrophones (SeaSpiders, SLOW). Measurements made with drifting hydrophones reveal spatial variation in the sound produced by the Azura, but measurement resolution is limited by the accuracy of current GPS units and the finite number of platforms that can be deployed simultaneously. Stationary hydrophones provide information about how WEC sound varies with changes in wave conditions (e.g. significant wave height and period), however the ideal deployment locations for stationary hydrophones are not necessarily obvious *a priori*. Acoustic modeling can supplement both efforts by providing estimates of the acoustic field that can clarify trends in the measured spatial distribution of sound and by identifying locations for future stationary hydrophone deployments that will result in higher signal-to-noise ratios (SNR) at frequencies of interest.

A parabolic equation model (RAMGeo) is implemented to predict transmission loss in the vicinity of the Azura as a function of range, depth, source frequency, and metocean conditions. The model selection process, model parameters, and the model's limitations are presented. Estimates of transmission loss are discussed in the context of current measurement objectives at WETS.

2 Methodology

2.1 Transmission Loss

Transmission loss is a particularly useful quantity that is estimated by an acoustic model and is the primary quantity discussed in this report. Transmission loss (*TL*), as described by the sonar equations (Eq. 1), is the reduction in sound intensity that occurs between the sound source and the receiver. Because of the large dynamic ranges in underwater acoustics, source level (*SL*) and received level (*RL*) are typically presented in logarithmic scale with units of dB re 1 µPa. Therefore, transmission loss is a relative quantity with units of decibels (dB).

$$\boldsymbol{TL = SL - RL} \qquad \textbf{Eq. 1}$$

2.2 Model Selection

Choosing a suitable model depends on the degree of importance of many parameters, including, but not limited to, water depth, bathymetric variation, the composition of the ocean bottom, spatial variations in sound speed, the frequencies of the sound source, and the available computational resources. Table 1 (Farcas et al. 2016) summarizes the applicability of three common acoustic models: BELLHOP (a ray tracing model), KRAKEN (a normal modes model), and RAM (a parabolic equations model).

Table 1: Applicability of common acoustic models as a function of sound frequency, water depth, bathymetric variation, and computational expense (Reproduced from Farcas et al. 2016, "Underwater noise modeling for environmental impact assessment"). Terms are described in the narrative text.

Model approach	Example algorithm	Applications							
		Shallow water				Deep water			
		Low frequency		High frequency		Low frequency		High frequency	
		RI	RD	RI	RD	RI	RD	RI	RD
Ray	BELLHOP (Porter and Liu, 1994)								
Normal mode	KRAKEN (Porter, 1992)								
Parabolic equation	RAM (Collins, 1993)								

Each model is evaluated based on its ability to provide accurate and timely results given a subset of model parameters: water depth, source frequency, and bathymetric variation. Black boxes indicate that a model is appropriate for the combination of parameters, grey boxes indicate that the model is either not accurate or is computationally expensive, and white boxes indicate that the model is either too inaccurate or computationally expensive to be viable.

Water depth is described here in relative terms as being either "shallow" or "deep". Shallow water environments typically have near constant sound speed profiles that result in only downward refraction. As a consequence, long range sound propagation in shallow water usually involves frequent reflection from the ocean bottom. Such conditions are probable in regions with depths less than 200 m. Conversely, sound speed profiles in deep water environments cause both downward and upward refraction, allowing sound to propagate over long distances with minimal or no bottom interaction. Regions with depths in excess of 2000 m are traditionally defined as "deep".

Frequency is also described in relative terms as being either "high" or "low", where sounds with wavelengths longer than 1 m are said to be "low" frequency. This distinction provides some direction for model selection. In practice, however, the definitions of "high" and "low" frequency are much more ambiguous.

If sound propagation is likely to be affected by changes in bathymetry, the domain is said to be range dependent (RD). Alternatively, if bathymetric variations may be neglected, the domain is range independent (RI). These terms are used loosely in this context to provide a general assessment of each models strengths and limitations. Using this figure (and supporting literature) as a guide, an appropriate model can be selected.

The 30-meter berth at WETs is a "shallow" water environment with relatively uniform depth in the immediate vicinity of each berth. Within a short distance from a deployed WEC, variations in water depth may be neglected, though depth variation should be included in a model for estimation of sound propagation beyond a few hundred meters from a WEC (particularly in the direction of shore or open ocean). Consequently, a range independent model could be used as short range.

Acoustic measurements of the Azura have shown that most sound is at frequencies below 5 kHz. Though this is not typically considered “high frequency” in the context of ocean acoustics, other WECs deployed at WETS may produce higher frequency sound (i.e., the Fred. Olsen Lifesaver during breaking wave conditions). As such, it is beneficial for future work to develop site models that accurately predict propagation of a wider range of frequencies.

Based on these parameters, a coupled normal mode model or parabolic equation model is well-suited to the frequencies of Azura sound and WETS bathymetry. The RAMGeo parabolic equations model was selected for both its flexibility and ease of its implementation, as well as its ability to support pressure waves in a multi-layered seabed.

2.3 Parabolic Equation (PE) Model Implementation

2.3.1 Acoustic Toolbox and RAMGeo

RAMGeo is available through the Acoustic Toolbox (AT), a free collection of sound propagation codes based on a variety of mathematical methods, including ray theory, normal modes, and parabolic equations. The codes available in the Acoustic Toolbox have many developers, but the toolbox is now available through the Ocean Acoustic Library, which is maintained by the U.S. Office of Naval Research (ONR). AcTUP, a suite of MATLAB scripts written by Alec Duncan at the Centre for Marine Science and Technology, allows codes in the Acoustic Toolbox to be called from a MATLAB GUI. Many of the codes in the Acoustic Toolbox are written in C or FORTRAN. AcTUP provides a convenient method of preparing, running and comparing results of various codes for those unfamiliar with these languages. It is straightforward to prepare MATLAB scripts that will call the underlying models in batches, which is useful for sweeping through model parameters (e.g., a variety of source frequencies or propagation paths). Such scripts have been developed and are available for use by UH in future modeling efforts.

2.3.2 Bathymetry

Bathymetric measurements of Kaneohe Bay are provided by NOAA. Because the bathymetric data are composed of several measurements made at different times, the resolution of the measurements varies based on position. Linear interpolation is applied to estimate the bathymetry between sampling points, resulting in a regularly spaced grid of water depth estimates in a Cartesian coordinate system. This data set could be replaced by gridded bathymetry products developed by UH. From the bathymetric grid, water depth is estimated as a function of range and bearing angle relative to the location of the Azura at the 30 m berth. For each bearing angle, a range/depth “slice” is read in by RAMGeo and used to calculate transmission loss as a function of range and depth. This is commonly known as a “2D+1” implementation because it results in an estimate of transmission loss in three dimensions (range, depth, and bearing) but does not account for three dimensional effects, such as refraction of sound between adjacent slices. Within a kilometer of a sound source, as is the case in all acoustic measurements and modeling of WETS to date, refraction of sound due to variation in sound speed appears to be negligible and can be neglected with minimal error. Bathymetric refraction, which is caused by changes in water depth, can have a significant effect on sound propagating towards shorelines but is not accounted for in the current model.

2.3.3 *Bottom Properties*

The sediment surrounding the Hawaiian Islands is primarily composed of basalt beneath a layer of sand. The pressure wave attenuation coefficient affects the degree of attenuation that occurs as pressure waves propagate through the bottom layer(s). The p-wave attenuation coefficient varies widely among different basalt samples and is a function of the confining pressure, alteration, porosity, water saturation, and composition of the rock (Wepfer and Christensen 1990, "Compressional Wave Attenuation in Oceanic Basalts"). A measurement of the properties of basalt in the vicinity of the Azura would be necessary to improve the accuracy of bottom loss effects in the model. For now, a p-wave attenuation coefficient of 0.8 was used for sand and a coefficient of 0.1 for basalt (Jensen et al. 2011, "Computational Ocean Acoustics, *Second Edition*"). The thickness of the sand layer is assumed to be 1 m, and the basalt layer is modeled as a semi-infinite half-space.

2.3.4 *Sound Speed*

Sound speed is a function of water depth, salinity, and temperature. Water temperature and salinity can vary with lateral position and depth. Therefore, it would be useful to measure the sound speed profile at a variety of locations if modeling were to be extended over a larger area. The sound speed profile has been measured in proximity to the Azura during all measurements of the device with A-SWIFT drifters. Although it is possible to account for variations in sound speed in the RAMGeo model, this information has not yet been included in the model, though the effects of sound speed variation are expected to be minimal within a kilometer of the Azura based on measurements to date.

2.3.5 *Sea Surface Properties*

The abrupt change in acoustic impedance at the air-water interface causes most underwater sound arriving at the sea surface to be reflected. However, reflected sound can be scattered by an air-water interface that has been disturbed by wind-driven waves. Two mechanisms contribute to this effect. An uneven sea-surface (in contrast to one that is calm and glassy) results in deviation from specular (i.e., mirror-like) reflection, particularly at higher source frequency and lower grazing angle (defined as the angle of incidence relative to the horizontal plane). Bubbles entrained by wave breaking also contribute to scattering and are more dominant than surface roughness at higher grazing angles (i.e., nearer to normal incidence). Empirically derived equations are used to calculate the effect of surface scattering as a function of grazing angle, sound frequency, and wind speed (assuming the sea-state is fully developed as a result of a particular wind speed). For comparison of model results and measured data, the surface roughness coefficient should be set according to the surface wave conditions present when data were acquired, particularly if high frequencies are to be compared accurately. A surface roughness coefficient of 0.1, representing light wind waves without whitecaps, was used in the current model.

2.3.6 *Source Properties*

Measurements with A-SWIFT drifters and SeaSpiders have shown that the Azura emits a series of continuous narrow-band sounds. The approximate bandwidth of Azura sound ranges from about 200 Hz to 1500 Hz, and measurements with rigid-spar A-SWIFTs suggest that Azura sound is emitted relatively uniformly with bearing angle at a depth of 1 m. The RAMGeo model is run for three source frequencies: 100, 500, and 1000 Hz and assumes a monopole source (uniform acoustic emission). These frequencies were chosen to explore how the model's value and limitations change with frequency.

3 Results

3.1 Transmission Loss in the Vertical Plane

Transmission losses estimated by the RAMGeo model as a function of range, depth, and frequency (100, 500, and 1000 Hz) are presented in Figure 1. The approximate water depth is indicated by the overlaid black line, and the estimated position of a previously deployed SeaSpider (March – June 2015) is indicated by a white triangle.

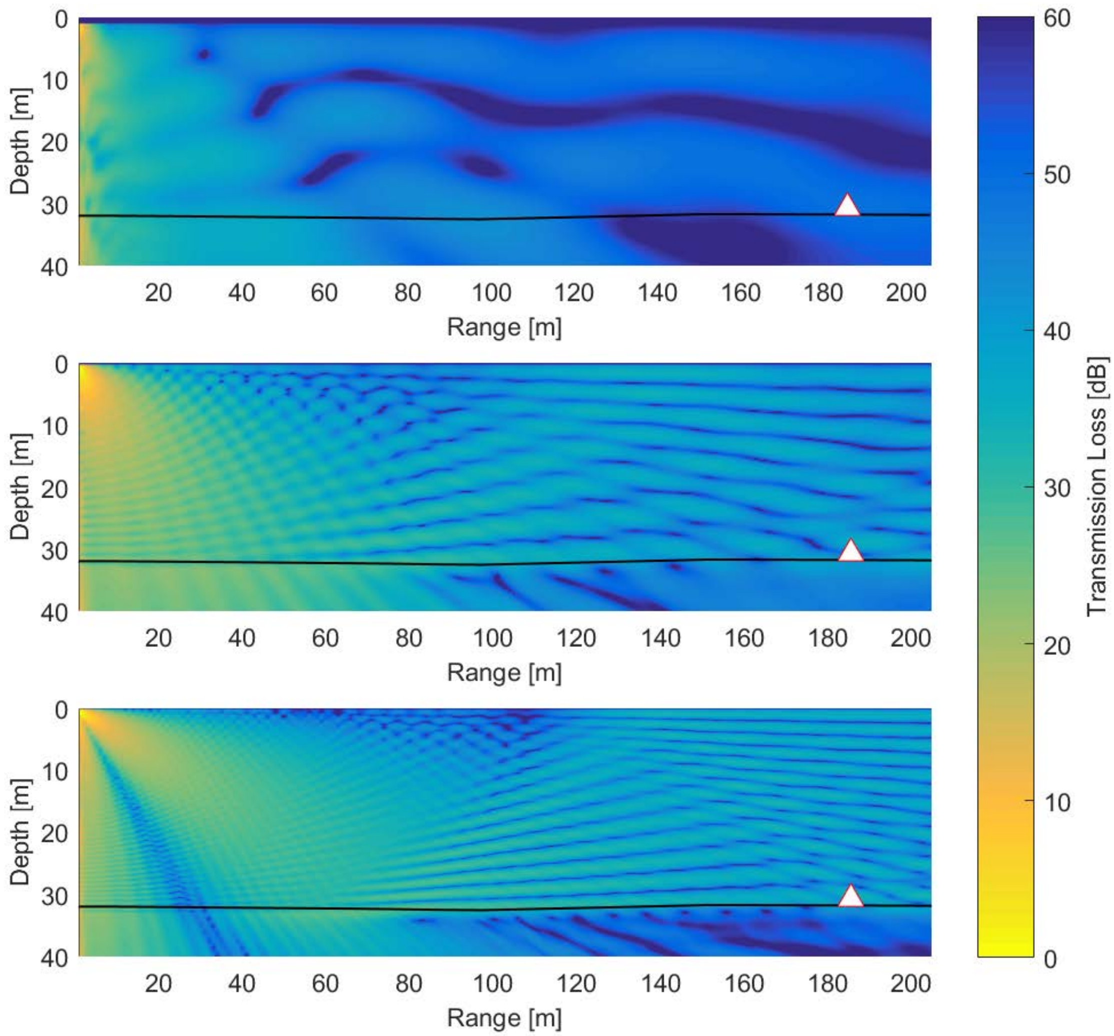

Figure 1: Modeled transmission loss as a function of range, depth, and frequency. Source frequency = 100 Hz (top), 500 Hz (middle), 1000 Hz (bottom). The ocean bottom is indicated by the overlaid black line and the position of the UW SeaSpider (March – June 2015) is indicated by the white triangle. Frequency = 100 Hz (top), 500 Hz (middle), 1000 Hz (bottom).

Among the more striking features are the alternating regions of high and low transmission loss, which are caused by the interference of sound traveling along different paths from the source. In general, sound at any point in the field is composed of many superimposed sound waves. The phase of each wave depends on the initial phase of the sound source and the distance traveled from the source, such that the direct path (i.e., the shortest path, which travels directly from the source to a given position) and any reflected paths (e.g. reflections from water surface or ocean bottom) can add constructively or destructively as a function of position.

A particular instance of destructive interference occurs at the air-water interface. Here, sound waves are reflected from the water surface with a 180° phase shift, resulting in destructive interference with waves arriving at the surface. The effect diminishes with increasing distance from the air-water interface and is further modulated by both grazing angle and surface scattering. For low frequency sources, such as the 100 Hz source modeled in Figure 1, the effect is noticeable up to several meters away from the interface, with transmission loss exceeding 60 dB.

The proximity of the sound source to the air-water interface results in a directivity pattern similar to a dipole source located at the water surface. This directivity results in a "beam pattern", seen here as a cone shaped region of lower transmission loss extending downward and outward from the sound source. At 1000 Hz, the beam pattern contains a central beam and a side lobe separated by a region of relatively high transmission loss that intersects the seabed at a range of approximately 30 m.

3.2 Transmission Loss in Horizontal Plane

It is valuable to examine transmission loss patterns as a function of lateral position at constant depth. The losses from a 500 Hz source for a receiver depth of 30 m are compiled for 360 range-depth slices and linear interpolation is applied to estimate transmission loss on a Cartesian grid, as shown in Figure 2. The site bathymetry is shown in Figure 3. Bathymetric variation is a significant factor in received levels near the ocean bottom.

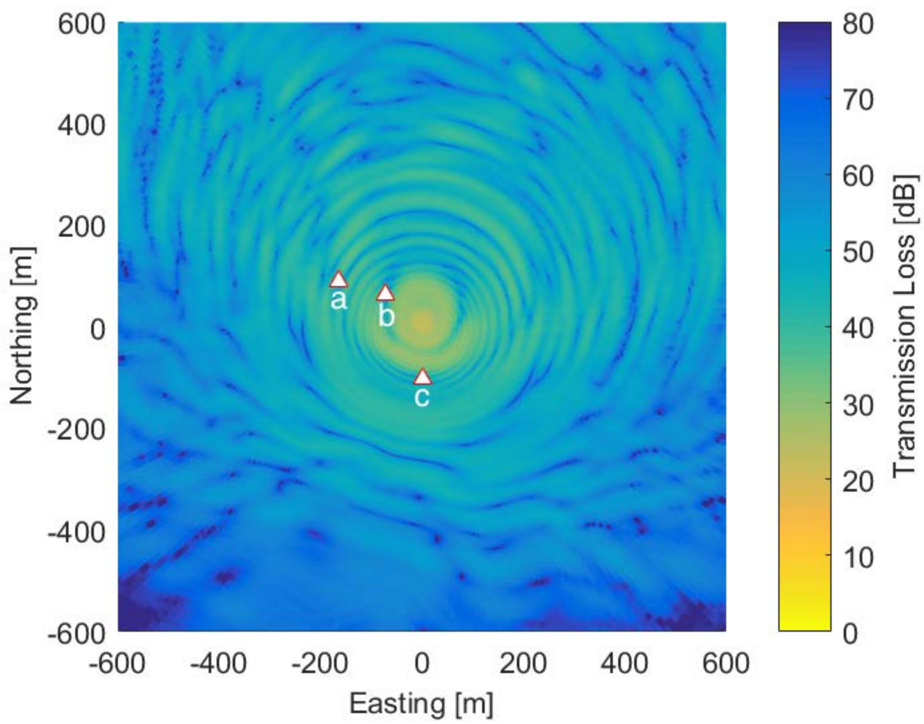

Figure 2: Transmission loss at a depth of 30 m from a 500 Hz source centered on the Azura position. Previous SeaSpider deployments are indicated by white triangles (a: Sea Spider, March – June 2015, b: Sea Spider, January – March 2016, c: Sea Spider, July – October 2015).

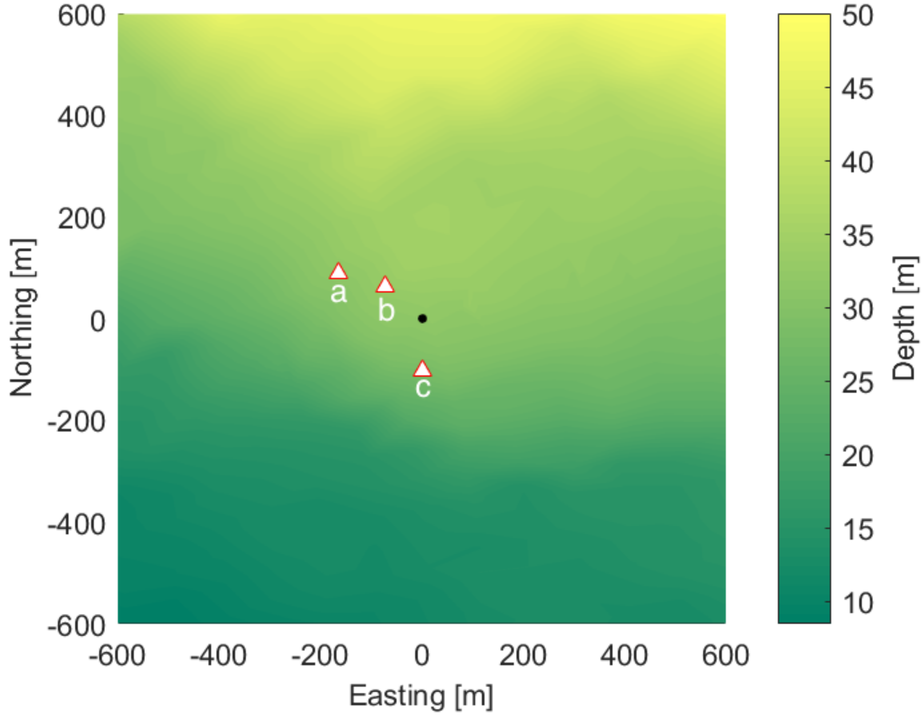

Figure 3: Bathymetry of WETS 30 m berth. Black dot indicates approximate Azura deployment location. Previous SeaSpider deployments are indicated by white triangles (a: Sea Spider, March – June 2015, b: Sea Spider, January – March 2016, c: Sea Spider, July – October 2015).

In Figure 2, the plane of analysis intersects both the water column and the sediment layers where the water depth is less than 30 m. Transmission losses in the sediment layer are generally higher than in the water column, which explains the high losses more than 300 m south of the source.

At a receiver depth of 1 m, the measurement depth of the rigid-spar A-SWIFT, bathymetric variation plays a smaller role within a range of 200 meters from the source. In this region, the transmission loss pattern is nearly axially symmetric. The alternating bands of high and low transmission loss are still apparent, though there is also a clear trend of increasing transmission loss with increasing range in all directions. This is to be expected and is supported by A-SWIFT measurements of the device. Also of note, the modestly higher sound intensities to the fore of the Azura are not present in the simulation, suggesting that sound production by the Azura does have some directionality.

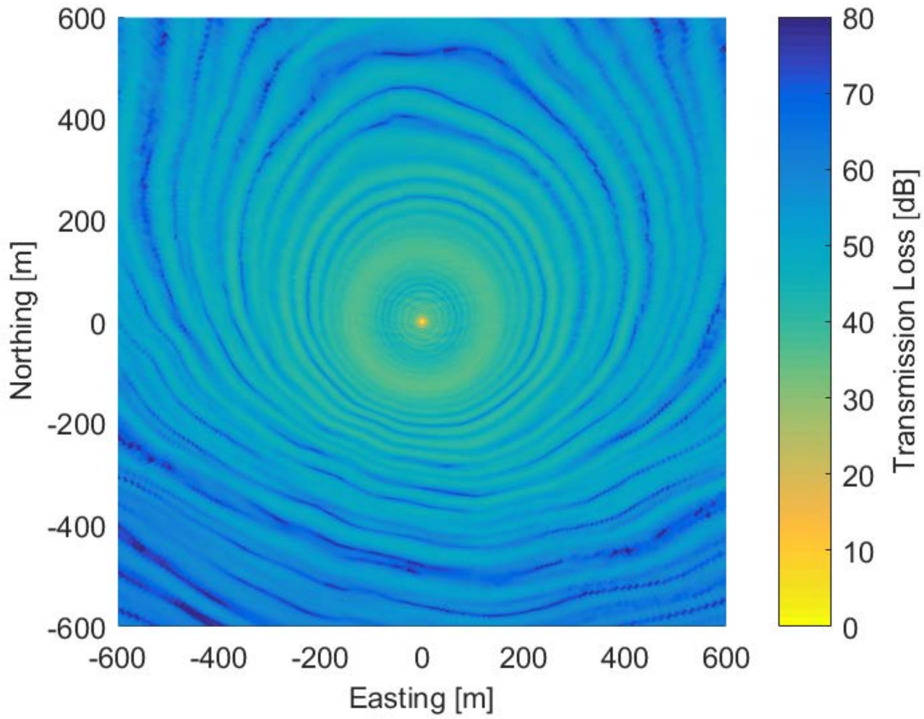

Figure 4: Transmission loss at a depth of 1 m from a 500 Hz source centered on the Azura position.

4 Conclusions and Discussion

The initial simulations suggest rich spatial variability in transmission loss around the Azura. Repeating these simulations for other berths and devices would likely reveal similarly rich patterns. In addition to refining simulations, further efforts will be required to validate their accuracy. For example, validated models could be used to select locations for future Sea Spider deployment locations that result in minimal transmission loss in frequency bands of interest to maximize signal-to-noise ratios. The more complex interference patterns apparent in high-frequency data (such as alternating regions of high and low transmission loss) will be difficult to "map" experimentally since, *in situ*, as in the model, they are a function of many time varying parameters. However, at low frequencies, the regions of constructive and destructive interference may be broad enough to directly compare between modeled and measured data, particularly as refinements to the A-SWIFT push the flow-noise and self-noise floors lower. At higher frequencies, interpretation of A-SWIFT and Sea Spider data should use volumetrically smoothed model output since the location of the receivers will have uncertainties associated with GPS accuracy and line angle. Future versions of the A-SWIFT that utilize RTK GPS may allow more precise comparison of measured and modeled spatial patterns. In the interim, a next step would be to validate simulations using a group of A-SWIFT drifters with hydrophones at multiple depths relative to a controllable source (e.g., icTalk), also at known depth and position. This would improve confidence in model output to predict transmission losses between a WEC and receiver (i.e., Sea Spider or A-SWIFT).

The current RAMGeo model approximates the sound source as a monopole, which emits sound uniformly in all directions from a single point. It is thought that vibrations created by the Azura's internal machinery causes sound to be emitted from the surface of its submerged hull. If this is the case, some directionality in the emitted sound that is apparent in A-SWIFT measurements would likely result from the hull geometry. Replacing the single point representation of Azura sound with a multi-point representation could further improve model accuracy, but would increase complexity.

Field measurement of the Azura's source directivity as a function of elevation angle will capture both the directivity effects introduced by the device's design and the effects resulting from the proximity of the source to the air-water interface. It may be possible to separate the contributions of these effects through comparison of modeled and measured data, though, as previously discussed, the low frequencies where these effects are most pronounced are also the hardest to measure. Further understanding may help to guide the development and application of international standards for the acoustic characterization of wave energy converters.

5 Acknowledgement

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