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VENUS Ranging Study

Transmission Loss

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Abstract

The underwater acoustic propagation models OASES and PECan are employed to study transmission loss (TL) to the Victoria Experimental Network Under the Sea (VENUS) sensor nodes in the Strait of Georgia as a consequence of Her Majesty's Canadian (HMC) ships operating at the Canadian Forces Maritime Experimental and Test Ranges (CFMETR). Four representative frequencies are studied for a shallow acoustic source, and both hydrophones and bottom-mounted seismometers are considered as receivers at each VENUS node. Bathymetry, measured conductivity, temperature, depth (CTDs), and sediment type are taken into account to study TL as affected by monthly changes in sound velocity profile. It is found that the VENUS node, Delta Dynamics Laboratory (DDL-06), displays the minimum TL at 130 Hz with OASES results indicating horizontal/vertical particle velocity seismic losses of 114/124 dB in February/December, and a PECan result giving pressure loss of 90 dB in January. The VENUS node, East Node (EN), has similar minimal TL values, whereas the Central Node (CN) has higher TL due to a shallow bank off Gabriola Island interfering with line-of-sight acoustic transmissions from CFMETR. It is important to note that the OASES modelling presented in this report, which is mainly used to provide seismic TL, is derived from a range-independent environment. Therefore, the OASES results are inherently less accurate than corresponding PECan results especially in the case of modelling TL to CN where there is significant variability in the bathymetry profile from CFMETR to this node. Three dimensional acoustic propagation with PECan is used to determine the extent that out-of-plane acoustic energy arriving at each node influences TL.

Significance for defence and security

The Canadian Forces Maritime Experimental and Test Ranges (CFMETR) are a frequently used range by both Canadian and American navies and are within 50 km of underwater sensors at nodes of the VENUS array whose acoustic and seismic data are openly available on the Internet. During operations at CFMETR, the Royal Canadian Navy (RCN) implements a Data Diversion Switch (DDS) to intercept data collected from the VENUS array. This study will evaluate the vulnerability of ship signatures operating at CFMETR and will determine standoff ranges to the VENUS nodes. The first step in the vulnerability study requires knowledge of the acoustic and seismic transmission of signals and this paper presents the results of a model study that predicts the minimum expected transmission loss between CFMETR and the VENUS sensor nodes.

Résumé

Nous avons utilisé les modèles de propagation acoustique sous-marine OASES et PECan pour étudier l'affaiblissement de transmission (AT) affectant les nœuds des capteurs du réseau expérimental sous-marin de Victoria (VENUS) dans le détroit de Géorgie, affaiblissement causé par les navires canadiens de Sa Majesté (NCSM) qui manœuvrent au Centre d'expérimentation et d'essais maritimes des Forces canadiennes (CEEMFC). Dans le présent rapport, nous étudions quatre fréquences représentatives d'une source acoustique en eau peu profonde et considérons les hydrophones et les sismomètres installés sur le fond marin comme des récepteurs à chaque noeud VENUS. Nous avons tenu compte de la bathymétrie, de la conductivité, température et profondeur mesurées (CTP) et du type de sédiment pour étudier l'AT d'après les changements mensuels du profil de vitesse du son. Nous avons déterminé que le nœud VENUS du laboratoire sur la dynamique du delta (Delta Dynamics Laboratory, DDL-06) affichait le plus faible AT à 130 Hz ; les résultats produits par OASES indiquaient des affaiblissements sismiques de vitesse acoustique horizontale/verticale de 114-124 dB en février et décembre, tandis que ceux de PECan indiquaient une perte de charge de 90 dB en janvier. Le nœud VENUS Est (East Node ou EN) présentait des valeurs faibles d'AT similaires, alors que le nœud Central (Central Node ou CN) était affecté par un affaiblissement plus prononcé en raison d'un banc en eau peu profonde, près de l'île Gabriola, qui nuit à la visibilité directe des émissions acoustiques en provenance du CEEMFC. Soulignons que la modélisation OASES qui figure au présent rapport et dont le principal objet est de fournir l'AT sismique provient d'un environnement indépendant de la portée. C'est pourquoi l'exactitude des résultats de l'OASES est par définition inférieure à celle des résultats correspondants obtenus par le PECan, en particulier dans le cas de la modélisation de l'AT au CN, laquelle présente une importante variabilité dans le profil de bathymétrie entre le CEEMFC et ledit nœud. Nous avons utilisé la propagation acoustique tridimensionnelle avec le PECan pour déterminer l'étendue de l'incidence sur l'AT de l'énergie acoustique hors plan arrivant à chaque nœud.

Importance pour la défense et la sécurité

Les zones d'essais du Centre d'expérimentation et d'essais maritimes des Forces canadiennes (CEEMFC) sont fréquemment utilisées par la marine canadienne et américaine. Elles se trouvent à moins de 50 km des capteurs sous-marins situés aux nœuds du réseau VENUS dont les données acoustiques et sismiques sont accessibles au public sur Internet. Durant les opérations menées au CEEMFC, la Marine royale canadienne (MRC) utilise un commutateur de détournement des données (CDD) pour intercepter les données acquises par le réseau VENUS. L'étude permettra d'évaluer la vulnérabilité de la signature des navires manœuvrant au CEEMFC et de déterminer les distances de sécurité par rapport aux nœuds VENUS. La première étape de l'étude nécessite la connaissance de la transmission des signaux acoustiques et sismiques. Le présent rapport comporte les résultats d'une étude de modèle permettant de prédire l'AT minimal prévu entre le CEEMFC et les nœuds de capteurs VENUS.

Acknowledgements

The authors would like to thank Kalman Czotter and Mathieu Ouellet at Fisheries and Oceans Canada, and Ulrich Suesser at the Meteorological and Oceanographic Centre at CFB Esquimalt for their assistance in providing environmental data pertaining to the Strait of Georgia.

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1 Introduction

Ocean Networks Canada operates ocean observatories on behalf of a number of universities and organizations led by the University of Victoria. These underwater installations include the Victoria Experimental Network Under the Sea (VENUS) coastal observatories located in Saanich Inlet and the Strait of Georgia, and the North East Pacific Time-series Underwater Networked Experiment (NEPTUNE) observatory off the west coast of Vancouver Island. Each of these observatories consists of a long cable attached to nodes that support a variety of instruments on the seafloor. Collected data are sent through a fibre optic cable to a shore station which is then transferred to the University of Victoria. The VENUS array in the Strait of Georgia (subsequently referred to as the VENUS array) includes hydrophone arrays measuring underwater acoustic pressure covering a wide band of frequencies, 0.1 Hz–100 kHz, and accelerometers measuring seismic activity in the band 1–250 Hz.

The Canadian Forces Maritime Experimental and Test Ranges (CFMETR) provides a deep water acoustic tracking range for torpedo testing, sonobuoy trials, and exercises involving Her Majesty's Canadian (HMC) ships and submarines. As a consequence of the proximity and line-of-sight between CFMETR and the VENUS array the Royal Canadian Navy (RCN) implements a Data Diversion Switch (DDS) to intercept all acoustic and seismic data collected by the VENUS array. Currently, when a data divert is requested through the Regional Joint Operations Centre (RJOC) at Canadian Forces Base (CFB) Esquimalt, the VENUS DDS nullifies all data from 4 Hz–3 kHz while relaying any data outside this band to the VENUS website. The NEPTUNE array implements a more sophisticated DDS, so when a divert from a node is requested the data stream from that node is sent to the Naval Ocean Processing Facility (NOPF) at Whidbey Island and the Acoustic Data Analysis Centre (ADAC) in Halifax for screening by analysts. Sensitive data is withheld and stored at the screening centres, otherwise the data is transferred to the University of Victoria where it is recombined with the rest of the NEPTUNE data.

The objective of this study is to determine standoff ranges for each of the nodes in the VENUS array by taking into account the following: transmission loss in the Strait of Georgia, the local underwater acoustic ambient noise field, typical spectral source levels for HMC vessels, and receiver sensitivities. The focus of this report is solely to quantify transmission loss (TL) from shallow acoustic sources at CFMETR, and to provide conservative estimates of TL (i.e., best acoustic propagation possessing minimum TL) over the course of a year. Since the goal shall be to determine the probability of detection of acoustic sources at CFMETR by the VENUS array then standoff ranges occurring within, or extending beyond, CFMETR indicate a risk of detection by a node of the VENUS array. A similar study for the NEPTUNE array has been conducted [1, 2].

In this first paper we will present results of modelling TL using the range-independent wavenumber integration model, Ocean Acoustic and Seismic Exploration Synthesis (OASES), and also the range-dependent Canadian Parabolic Equation model (PECan). PECan acoustic modelling incorporates variations in bathymetry and sediment type to determine acoustic TL from CFMETR to each VENUS node. However, OASES does not take into account variations in the environment as a function of range, so the modelling is performed with a constant water depth and a fixed, uniform, sediment type. Therefore, the results from OASES are less accurate than PECan, especially when acoustic energy is propagating over a strongly range-dependent environment such as propagation to the VENUS Central Node where the bathymetry varies significantly, as discussed in Section 2.1. OASES modelling is primarily used to provide seismic TL in terms of horizontal and vertical particle velocities to each VENUS node. Particle accelerations measured by accelerometers are derivatives of particle velocities and have accelerometer TLs proportional to particle velocity TLs through a frequency dependent factor. The aim here shall be to establish overall minimal TL values, or best acoustic propagation under realistic environmental conditions, that results in the most conservative estimate of vessel signature capture.

2 Strait of Georgia environment

2.1 Bathymetry

The VENUS array consists of three nodes located in the south-east region of the Strait of Georgia [3]. Extracting a chart region from [4] allows a plot of these waypoints to be shown in Figure 1 as Central Node (CN), East Node (EN), and Delta Dynamics Laboratory (DDL-06) with quoted water depths at each node of 300 m, 170 m, and 108 m respectively. Each of these nodes evolves as a result of regular maintenance, and the addition or removal of instruments. Consequently, their positions change slightly with time, along with the types of sensors supported. For example, EN and Delta Dynamics Laboratory are currently the only nodes supporting hydrophones, and the Delta Dynamics Laboratory node is presently labelled DDL-07. In this study we assume that each node supports two types of receivers: a hydrophone located 1 m above the seafloor, and a bottom-mounted seismometer. The boundary of the CFMETR 3D range is denoted by waypoints R1–R10, and range centre by RC. HMC vessels operating at CFMETR are modelled as sources located at a depth of 2 m and transiting from a maximum range RMAX along straight trajectories to each node up to a minimum range near the CFMETR boundary between R6 and R7.

Bathymetry for the Strait of Georgia was obtained from the General Bathymetric Chart of the Oceans (GEBCO) using the GEBCO_08 Grid [5] which provides a spatial resolution of 30 arc-second intervals of latitude and longitude. A region defined by a (latitude, longitude) minimum: (48.808333, −124.241667) and maximum:

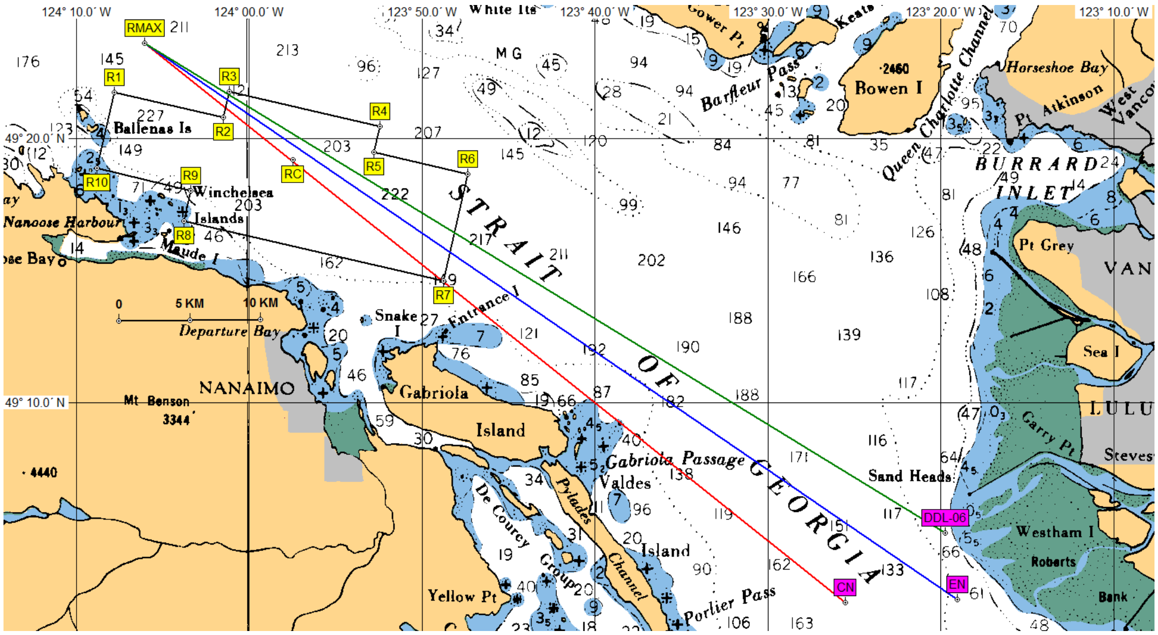


__Figure 1:__ CFMETR boundary R1–R10, range centre RC, and VENUS nodes CN, EN and DDL-06. Depths are shown in fathoms.

(49.633333, −123.025) was selected and interpolated to show contours of constant depth/elevation in Figure 2. The thick black contours represent the interpolated coast line with green to red representing land. The contours showing water depth are spaced 88 m apart whereas the contours showing elevation above sea level are at a spacing of 326 m.

The red straight line tracks from RC to each VENUS node shown in Figure 2 have corresponding bathymetry profiles given in Figure 3. These profiles are used in the two dimensional PECan modelling presented in the next section. The seamount at 30 km range from RC to CN has a significant effect on propagation by attenuating low frequency modes. We have verified for the source–receiver ranges used that the difference between great circle trajectories and the straight line tracks implemented is negligible. Furthermore, the two dimensional Strait of Georgia interpolated bathymetry is employed in a three dimensional PECan model to obtain results illustrating full field acoustic propagation.

2.2 Oceanography

In Figure 2, the yellow symbols mark the approximate locations of 6022 conductivity, temperature, depth (CTD) profiles [6] taken from 1969 to 2009 throughout various times of the year. The monthly means of these CTD profiles were converted to sound velocity profiles (SVPs) using the Mackenzie equation [7], as shown in Figure 4. Mod-

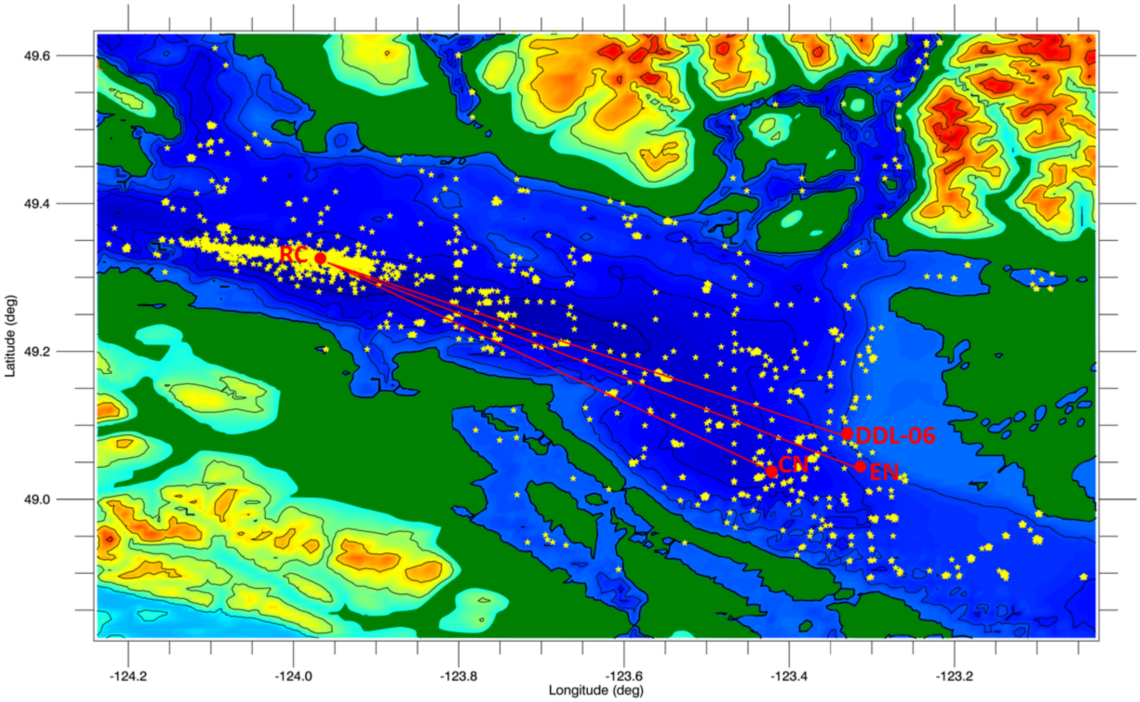


Figure 2: *Bathymetry contours in the region of CFMETR range centre (RC) and VENUS nodes CN, EN, and DDL-06 (in red). Positions of historic conductivity, temperature, depth (CTD) profiles are indicated by the yellow symbols.*

elling of acoustic propagation was carried out on a monthly basis and assumed that a monthly mean SVP holds throughout the Strait of Georgia, therefore at depths where the mean SVP does not exist it was extrapolated by assuming that salinity and temperature remain constant as depth increases beyond the deepest known value. This assumption simplifies the Mackenzie equation to give an almost linear dependence of extrapolated sound speed c_j in terms of depth D_j as follows

$$c_j \doteq c_i + 1.63 \times 10^{-2}(D_j - D_i) + 1.657 \times 10^{-7}(D_j^2 - D_i^2), \quad D_j > D_i \qquad (1)$$

where c_i is the last known sound speed value at depth D_i. During the winter months from November–March the SVP's are upward refracting while in the remaining months of the year a sound channel axis develops in the range 30–70 m depth.

2.3 Bottom properties

A surficial sediment thickness of 20 m [8] above a limestone basement was used in the propagation modelling. A range-dependent sediment distribution was used for the PECan modelling. The distribution varied along each straight track between RMAX and the VENUS nodes as shown in Figure 5 - this map is a region from a larger chart found in [9]. The mud found near each node differs in the percentages of (sand,

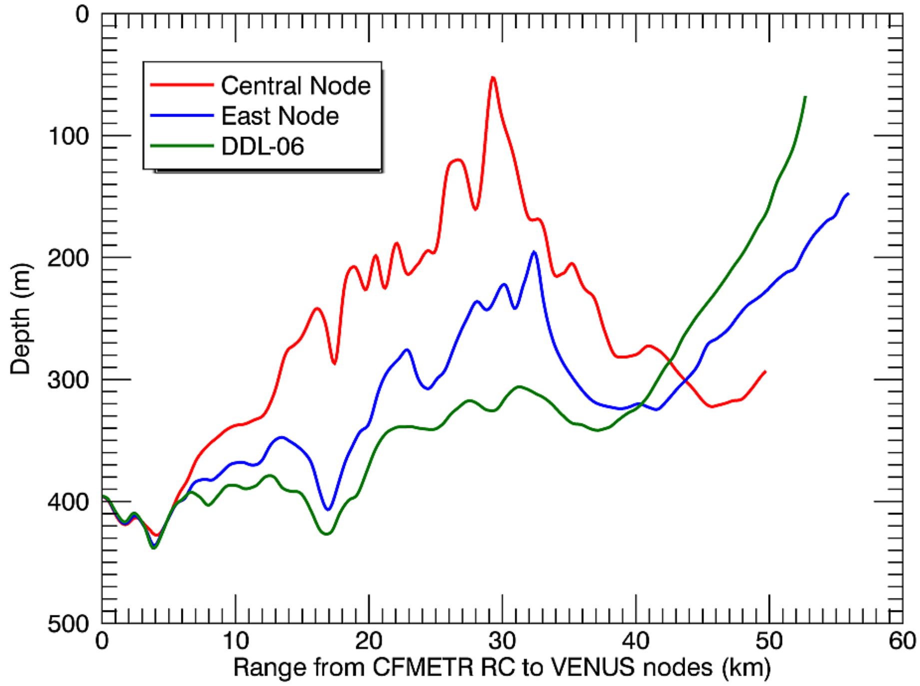


Figure 3: *Bathymetry profile from RC to VENUS nodes CN, EN, and DDL-06.*

silt, clay) [10] as follows CN: $(0, 80, 20)$, EN: $(30, 60, 10)$, DDL-06: (50,40,10) percent, respectively. Using a bulk grain size M_z expressed in $\phi = -\log_2 d$ units, where d is the grain size diameter in mm, these percentages lead to nominal values of M_z at CN of 6.6 (fine silt, clayey silt), at EN of 4.95 (coarse silt) and at DDL-06 of 4.05 (clayey sand).

The density ratio ρ_b/ρ_w, compressional sound speed ratio c_p/c_w, and compressional attenuation[1], α_p, of sediments can be computed [11] as a function of bulk grain size M_z for $-1 \leq M_z \leq 9$. Assuming seawater has a density $\rho_w = 1000\,\mathrm{kg/m^3}$ and a compressional sound speed $c_w = 1500\,\mathrm{m/s}$, Table 1 gives the geoacoustic properties of the surficial sediments used in the PECan modelling. For the OASES modelling, which is range-independent, a uniform sediment type matching the one found at each node was used. Any rock in Figure 5 was assumed to be part of the exposed basement and hence taken to be limestone with the same parameters as those found in [12], except the compressional and shear sound speed for sedimentary rock were taken from [13], as these values were in better agreement with [14]. The shear sound speed in Table 1 was obtained from [15] by taking a sediment depth of 10–20 m which gives a very rough approximate ratio of compressional to shear sound speed of 10. Values for the shear attenuation were taken from [12], and when necessary a simple weighted mean based on percentage compositions was used to compute a combined value for the shear attenuation.

[1] Computed as α_2/f with units of decibels per meter per kilohertz.

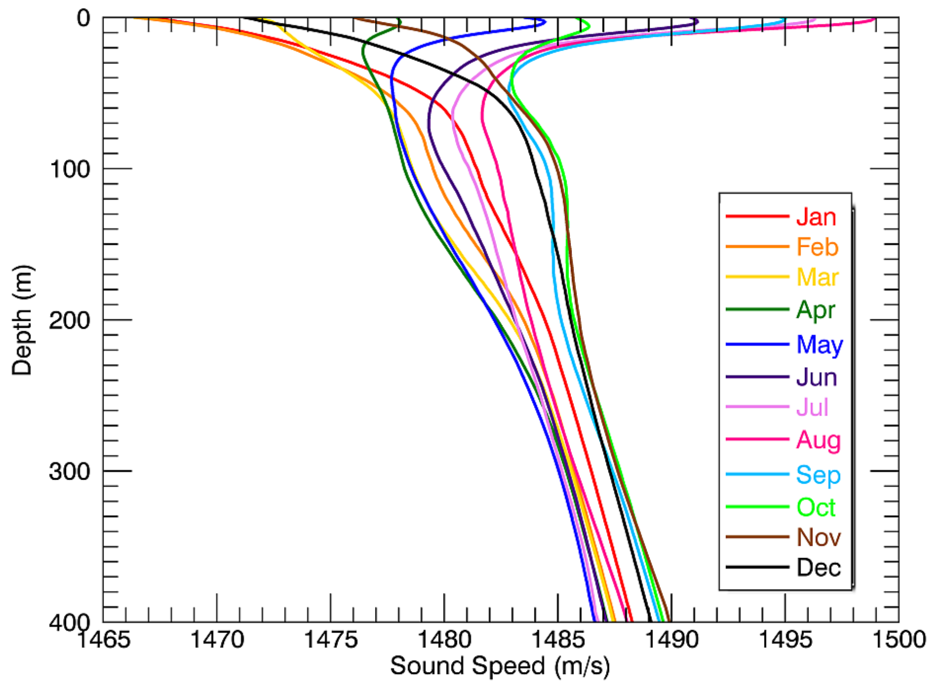


Figure 4: *Monthly mean SVPs in the Strait of Georgia.*

3 Numerical modelling of transmission loss

Two underwater acoustic propagation models were employed to determine transmission loss, namely OASES and PECan. OASES is a wavenumber integration model used for modelling seismo-acoustic propagation, for pressure and particle velocity, in horizontally stratified waveguides. PECan is a parabolic equation model for underwater acoustic propagation, with a number of options for the parabolic equation algorithms. As implemented in this paper, it uses a two dimensional split-step Padé approximation for computing propagation in range, with a self-starting initial field and an energy conservation scaling approximation. The specific algorithm used in PECan allows the number of terms in the Padé series expansion to be selected. Two terms, used in this case, gives a wide-angle (±55° from horizontal) capability [12]. The three dimensional coupling was calculated using a Crank-Nicolson finite-difference approximation to solve a low-order Padé approximation of the azimuthal operator. PECan is not a fully elastic PE model, it uses a complex density, or equivalent fluid approximation, to represent the effects of shear waves.

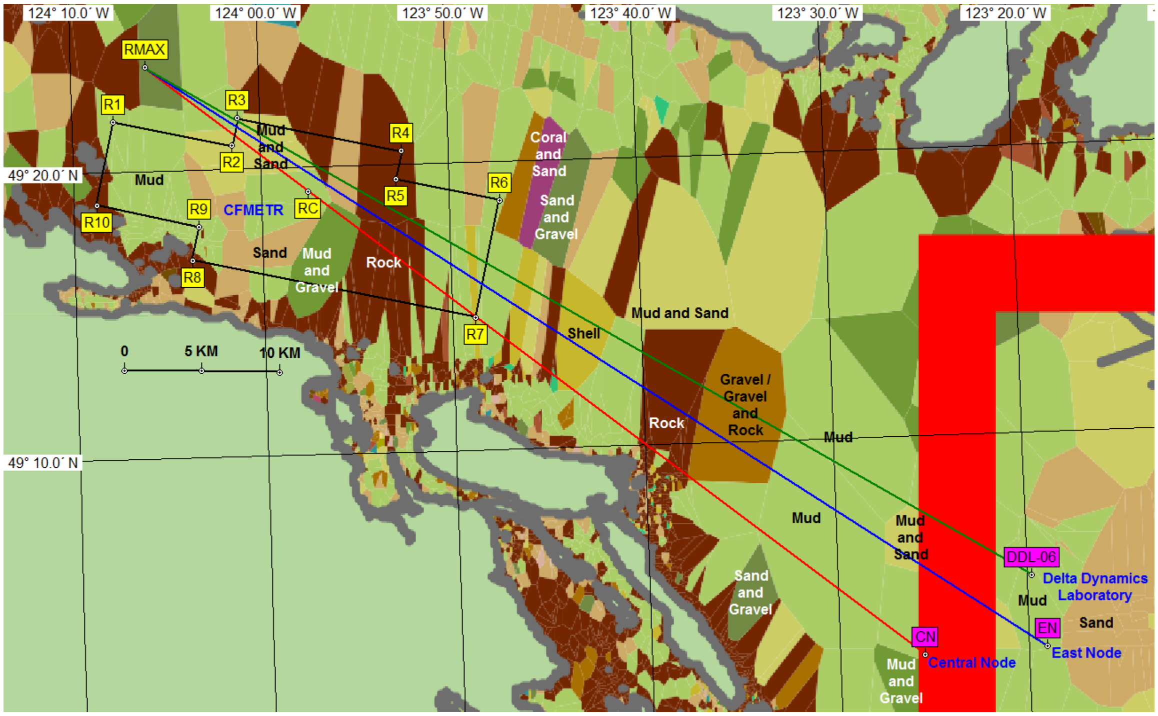


Figure 5: *Surficial sediment distribution found in the Strait of Georgia. RMAX marks the maximum extent to each VENUS node connected by straight tracks (red, blue, green) used in the PECan modelling.*

Table 1: *Geoacoustic properties of sediments found in the Strait of Georgia.*

Sediment Name	ρ_b/ρ_w –	c_p/c_w –	c_s (m/s)	α_p (dB/λ_p)	α_s (dB/λ_s)
Fine Silt, Clayey Silt (CN)	1.148	0.986	$c_p/10$	0.155	1.4
Coarse Silt (EN)	1.172	1.002	$c_p/10$	0.708	1.75
Clayey Sand (DDL-06)	1.220	1.035	$c_p/10$	1.080	1.95
Mud	1.146	0.982	$c_p/10$	0.089	1.0
Mud and Sand	1.339	1.080	$c_p/10$	0.857	2.0
Sand	1.845	1.178	$c_p/10$	0.739	2.5
Shell	2.231	1.250	$c_p/10$	0.702	2.0
Sand and Gravel	2.492	1.337	$c_p/10$	0.683	1.5
Gravel and Rock	2.4	1.900	$c_p/10$	0.4	0.5
Rock (Limestone)	2.4	2.333	1750	0.1	0.2

HMC vessels operating at CFMETR were modelled as an acoustic source, 2 m deep, following a straight track from RMAX towards each VENUS node up to the CFMETR boundary between waypoints R6 and R7, see Figure 5. More precisely, as the ship travels from RMAX to each node the transmission loss displays a sequence of troughs and peaks[2] - the minimum, maximum, and mean transmission loss to each node was evaluated and plotted using the entire straight track segments from RMAX to the CFMETR boundary (R6–R7) corresponding to the range intervals given in Table 2. The mean SVP for each month was used. The models were run for representative frequencies of 10, 50, 90, and 130 Hz.

Table 2: *Range intervals over which minimum, maximum, and mean transmission loss was computed.*

Node	Range (km)	
	Minimum	Maximum
CN	36.2	62.6
EN	42.5	69.1
DDL-06	39.5	66.1

Note, the vertical bars plotted in Figures 6–9 are *not* error bars for transmission loss, but are minimum and maximum transmission loss values over the range intervals given in Table 2 for each node. A dot between the minimum and maximum values denotes the associated mean transmission loss value.

3.1 OASES results

The OASES acoustic model implemented here comprises a range-independent propagation model, therefore for each node we assumed a constant water depth equal to the depth at that node, in particular TL to CN, EN, and DDL-06 will be modelled using water depths of 300, 170, and 108 m respectively. In addition, a 20 m uniform sediment layer using the appropriate sediment type for the respective nodes, as shown in Table 1, was assumed for each node model run. Notice, both compressional and shear attenuation in the sediment increase in the order CN, EN, and DDL-06. For all three nodes a limestone basement (or half-space) was assumed.

The coherent TL expected from a vessel operating within the range intervals from the nodes, as given in Table 2, was computed for each frequency. The minimum, maximum, and mean TL to a hydrophone 1 m from the seafloor at each node location is

[2] In the PECan modelling, reciprocity was used to interchange source and receiver geometry thereby allowing a fixed source to be located at each VENUS node along with a shallow, range-dependent, receiver. Reciprocity was not used in the OASES modelling since it implements a range-independent environment where the source is at a depth of 2 m and receivers are located at each VENUS node.

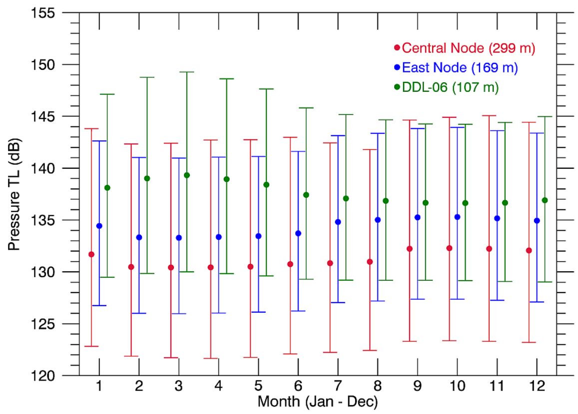
shown in Figure 6. Evidently, there is approximately a 20 dB higher transmission loss at 10 Hz, shown in Figure 6a, than for the higher frequencies. This is expected since at such a low frequency more acoustic energy penetrates and is absorbed into the muddy sediment, and at these long receive ranges (36–69 km) any reflected energy from the basement is lost due to boundary interactions. Furthermore at 10 Hz, DDL-06 generally has more loss than EN, which has more loss than CN. This is accounted for, in part, by the sediment attenuation decreasing in this order and more importantly by the water depth increasing in this order resulting in decreased interaction with the bottom.

In general, the mean TL values for 90 and 130 Hz, given in Figures 6c and 6d, show a seasonal dependence by having a higher transmission loss (as much as 15 dB) during the summer months. This is a consequence of the warming of the upper surface layer during the summer, resulting in the development of a sound axis between 30–70 m depths. Ducting of acoustic energy in this channel is more efficient at the higher frequencies than low. Because of this, at the higher frequencies during the summer months more of the acoustic energy is trapped in the duct, hence less acoustic energy reaches the near-bottom hydrophone, see Figure 6d. Another general trend is the reduced influence of the different bottom types as the frequency is increased which is illustrated by the means of DDL-06 displaying a steady decrease in TL from Figures 6a to 6d along with a corresponding smaller variance among the means of CN, EN, and DDL-06 on a monthly basis. The spread from minimum to maximum TL arises from multipath interference over the ranges considered, we usually observe in Figure 6 that the spread, or difference between the troughs and peaks of transmission loss, is proportional to the water depth.

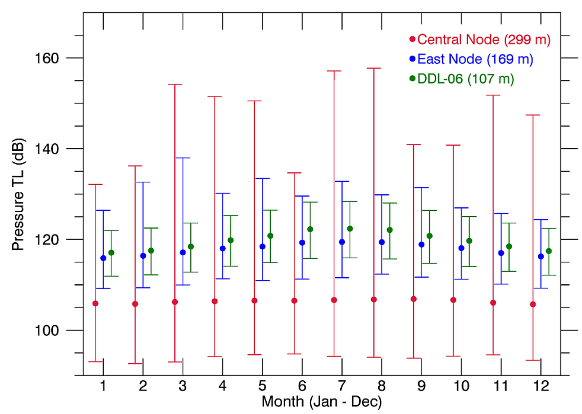
From the OASES model runs shown in Figure 6, we find that the minimum TL, or equivalently the most strongly propagated signals are given in Table 3. Generally, the winter months of December, January, and February all have very similar minimal TL values at each node.

Table 3: *The most strongly propagated signals received by a hydrophone 1 m from the seafloor from OASES runs.*

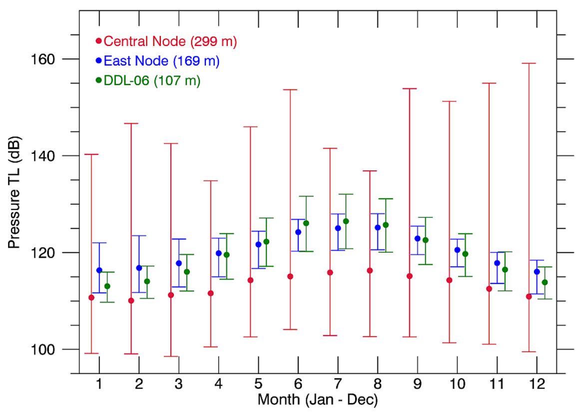
Node	Month	Frequency (Hz)	Minimum TL (dB)
CN	February	50	93
EN	January	50	109
DDL-06	February	130	108



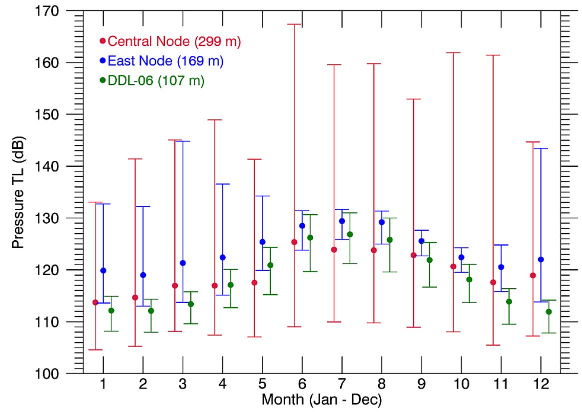
***(a)** 10 Hz*



***(b)** 50 Hz*



***(c)** 90 Hz*



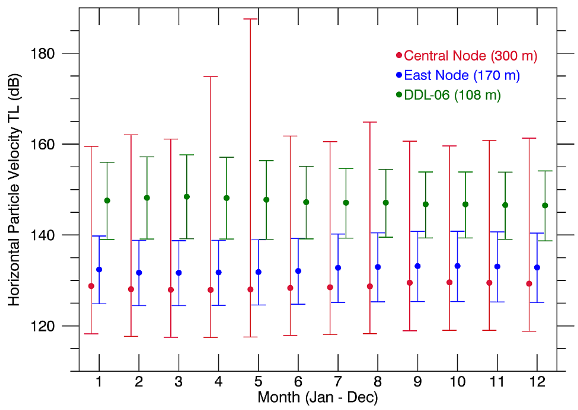
***(d)** 130 Hz*

***Figure 6:** OASES acoustic TL showing minimum, maximum, and mean for each month and VENUS node.*

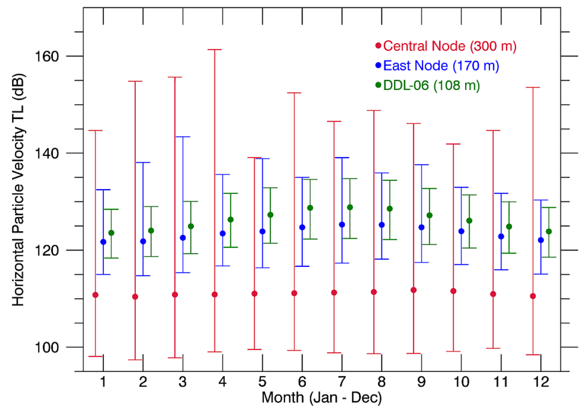
Using the same acoustic source described above we consider propagation to bottom mounted seismometers located at each node. Minimum, maximum, and mean TL for horizontal and vertical particle velocities are shown in Figures 7 and 8 respectively. Horizontal particle velocity TL displays many similar characteristics found in the pressure TL described above with an exception, namely at 10 Hz DDL-06 has approximately 10 dB of additional loss with respect to pressure whereas the other nodes and frequencies generally have only 5 dB of additional loss. This is likely a result of the attenuation properties of the muddy sediments in Table 1.

From Figure 7 the horizontal particle velocity experiences minimum TL, or the received signal is strongest to each node, as given in Table 4. Again, the other winter months have similar minimal TL values.

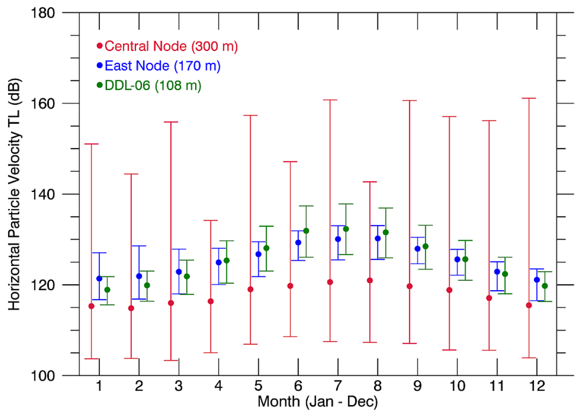
Vertical particle velocity TL is shown in Figure 8. At 10 Hz EN and DDL-06 have similar TL as was found for horizontal particle velocity. However, as the frequency is



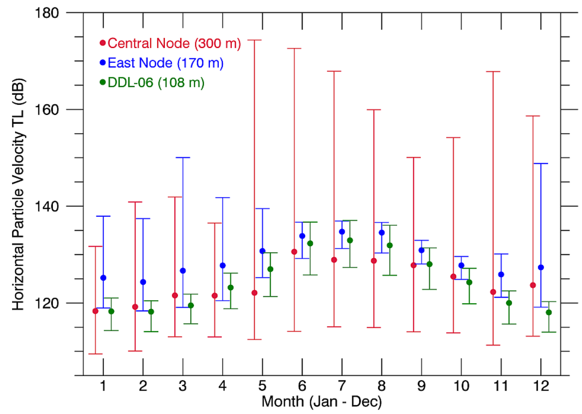
(a) *10 Hz*



(b) *50 Hz*



(c) *90 Hz*



(d) *130 Hz*

Figure 7: *OASES horizontal particle velocity TL showing minimum, maximum, and mean obtained from bottom mounted seismometers at each of the VENUS nodes.*

increased the vertical particle velocity loss increases more quickly for these nodes, so at 130 Hz there is an additional 15 dB of loss in the vertical as opposed to the horizontal particle velocity. Furthermore, CN at 10 Hz has a minimum to maximum spread in TL that is smallest for vertical particle velocity with a spread of approximately 10 dB, whereas the TL spread for horizontal particle velocity is 40 dB and for pressure 20 dB. Another difference for CN is that the mean TL values for 50, 90, and 130 Hz have 13–19 dB of additional loss in the vertical versus the horizontal, except at 10 Hz where this trend reverses with 7 dB more loss in the horizontal.

Based on the loss values to each node given in Figure 8, the vertical particle velocity having minimum TL, or propagating the best is given in Table 5 with similar values for the other winter months.

Table 4: *Horizontal particle velocity signals with minimum TL received by bottom mounted seismometers.*

Node	Month	Frequency (Hz)	Minimum TL (dB)
CN	February	50	97
EN	February	50	115
DDL-06	February	130	114

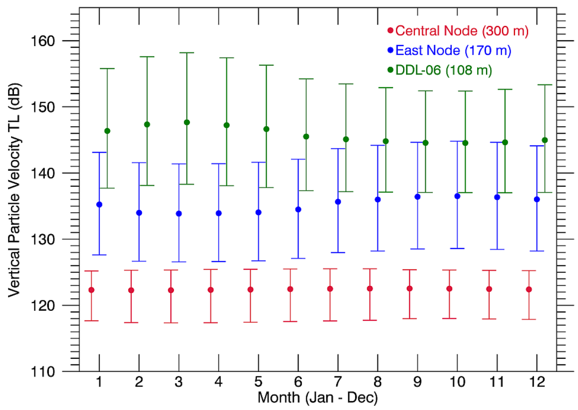
Table 5: *Vertical particle velocity signals with minimum TL received by bottom mounted seismometers.*

Node	Month	Frequency (Hz)	Minimum TL (dB)
CN	February	50	111
EN	January	50	124
DDL-06	December	130	124

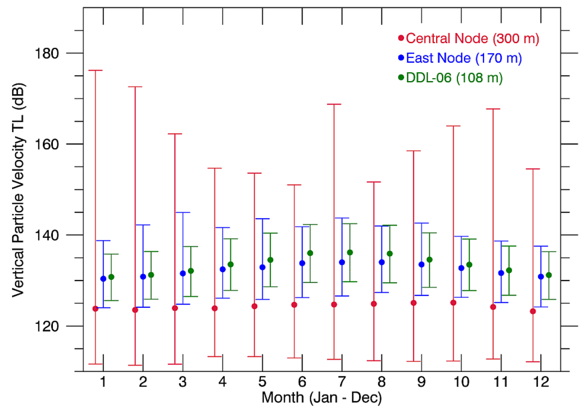
3.2 PECan results

We wish to examine how variations in bathymetry and sediment type will impact our modelled acoustic propagation. To do so, a range-dependent PECan propagation model was employed to determine acoustic TL to each of the VENUS nodes. As a first approach to determining the acoustic TL, propagation predictions will be made using the one dimensional bathymetry profiles in Figure 3, derived from straight line tracks, between RMAX and each of the nodes CN, EN, and DDL-06. The sediment layer was assumed to have a constant thickness of 20 m but with varying sediment type, dependent on range, in accordance with the distribution of sediments along each track given in Figure 5. The geoacoustic parameters used in the PECan model for the sediments encountered are given in Table 1, and as in the previous section a limestone basement is assumed along with any surface sediment marked rock in Figure 5.

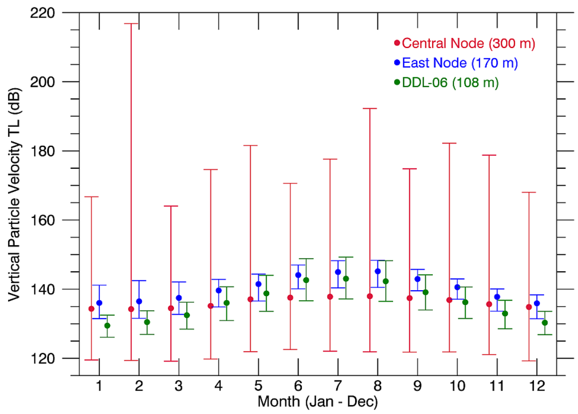
Considering again the frequencies 10, 50, 90, and 130 Hz we show in Figure 9 the minimum, maximum, and mean TL to a hydrophone 1 m from the seafloor at each node. As a result of the extended shallow water depths off the coast of Gabriola Island there is an apparent ‘seamount’ in the bathymetry profiles of CN and EN at a range of 30 km from RC, see Figure 3. The sediment in the region of the ‘seamount’ corresponds to the rock, gravel, and gravel and rock shown in Figure 5 intersecting each track off Gabriola Island. The influence of the ‘seamount’ on acoustic propagation is most significant for the path to the CN node, much more so than for EN and DDL-06, where the depths increase from 50 m to 200 m and 300 m



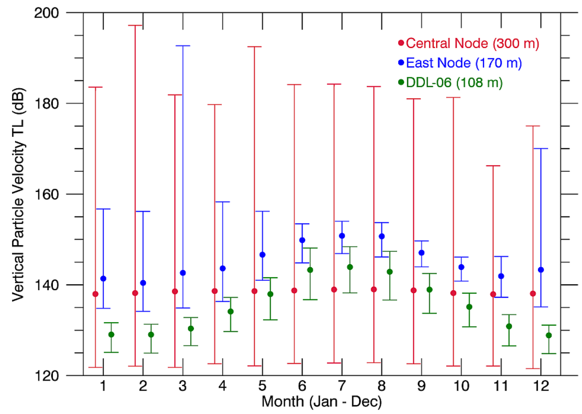
***(a)** 10 Hz*



***(b)** 50 Hz*



***(c)** 90 Hz*



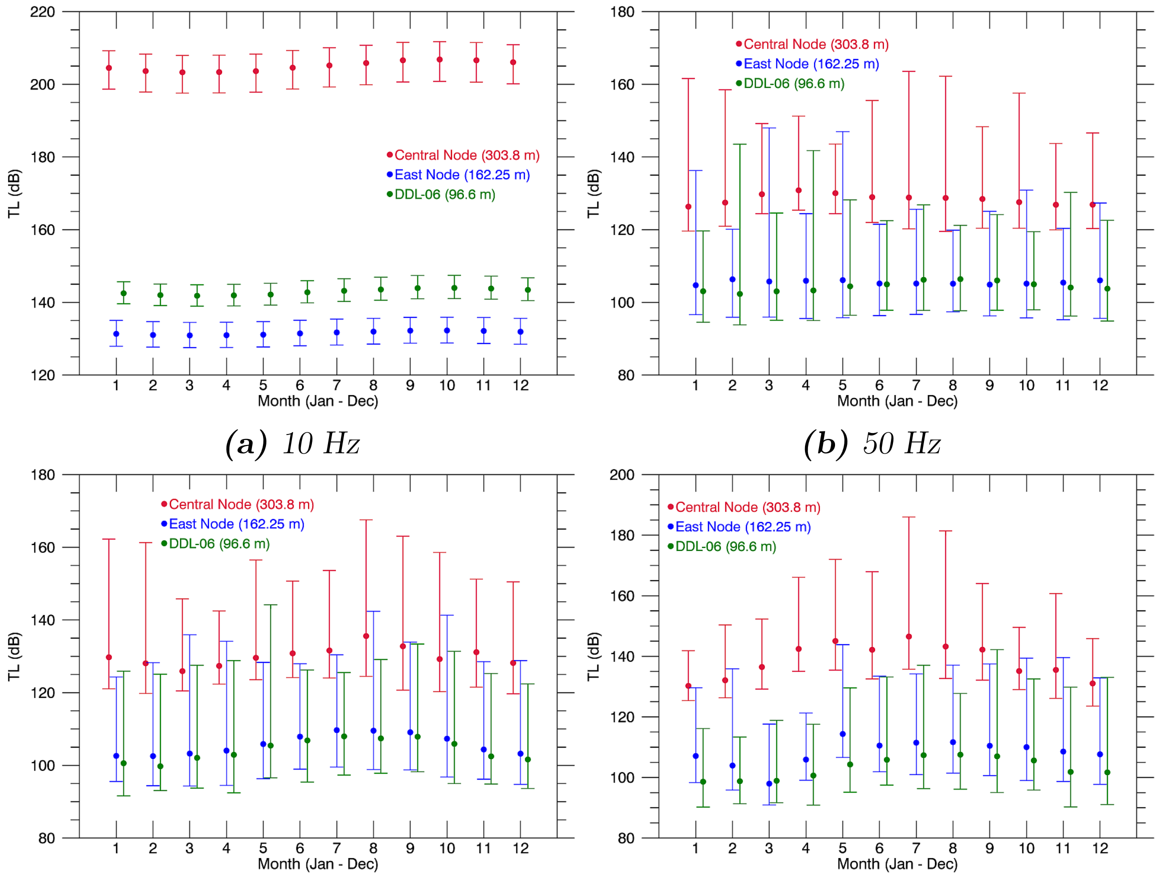
***(d)** 130 Hz*

***Figure 8:** OASES TL for vertical particle velocity showing minimum, maximum and mean.*

respectively at 30 km. Figure 9a illustrates the increased loss the 'seamount' causes to the CN node for the long wavelength 10 Hz signal, resulting in an acoustic TL of 205 dB throughout the year. This effect of mode-stripping, where the wavelength of the acoustic signal is greater than the water depth, results in approximately 70 dB higher loss than for other frequencies to this node. Also at 10 Hz, EN and DDL-06 have higher TL by 25 and 40 dB, respectively, than at the other frequencies; as observed in Section 3.1 the water depth for EN and DDL-06 is acoustically thin at 10 Hz resulting in a greater interaction, hence loss, of the low frequency signal with the bottom. The increased loss caused by the 'seamount' at CN is also noticeable, albeit less, at the higher frequencies of 50, 90, and 130 Hz resulting in approximately 25 to 35 dB additional loss at CN versus EN or DDL-06 as is shown in Figures 9b to 9d.

For the same reasons described in Section 3.1 on the OASES results, the effect of the summer duct in the SVP becomes more apparent at the higher frequencies (90 and

130 Hz) where the acoustic energy is efficiently trapped in the duct, see Figure 9d, resulting in an increased TL for the months of July and August.



(a) *10 Hz* ***(b)*** *50 Hz*

(c) *90 Hz* ***(d)*** *130 Hz*

Figure 9: *PECan acoustic TL showing minimum, maximum, and mean for each month and VENUS node.*

From the output of the PECan modelling given in Figure 9 we find that overall minimum TL, or the strongest acoustic signals received at each node, are given in Table 6. Interestingly, the 50 Hz wavelength is sufficiently small to be somewhat trapped by the summer SVP duct thereby allowing more acoustic energy to get past the CN ‘seamount’ to the hydrophone, thus minimizing TL in August.

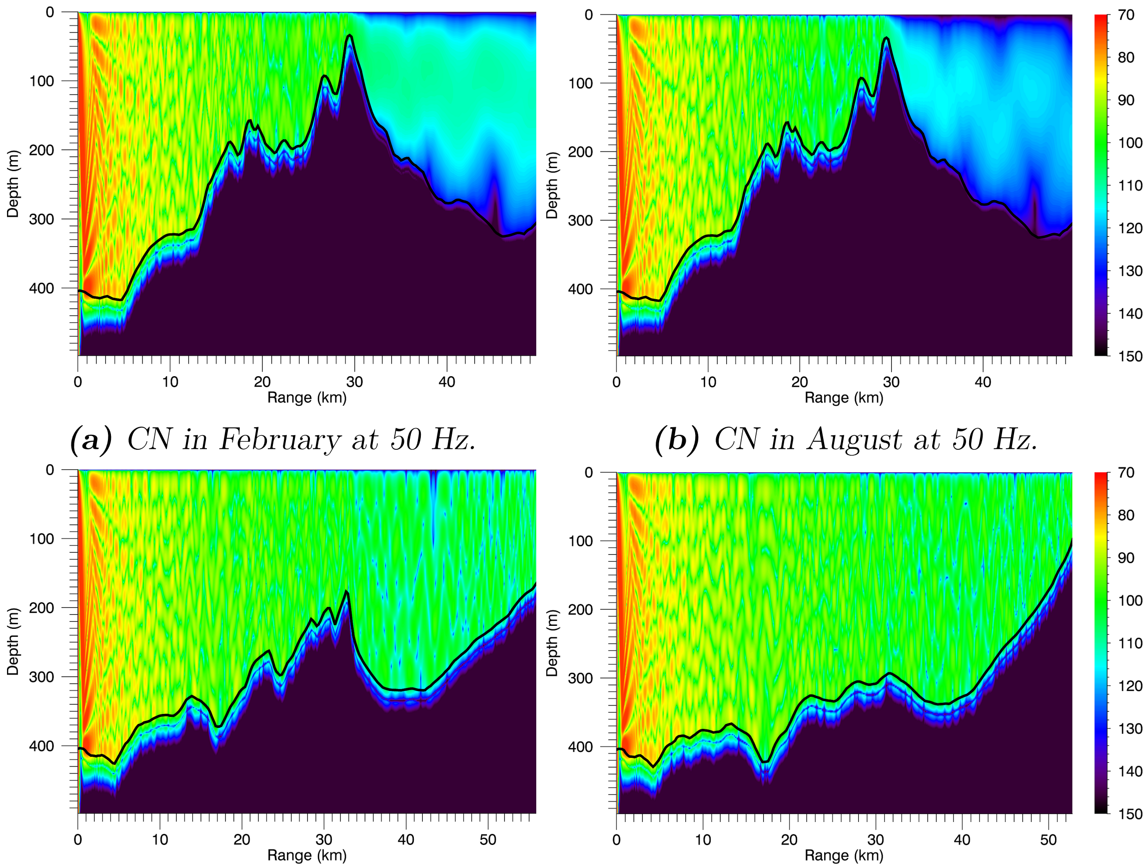
Using the PECan propagation model we show, in Figure 10, two dimensional depth versus range TL plots for a source 2 m deep at RC, located at zero range on the plots, to distances corresponding to each of the VENUS nodes. Figures 10a and 10b illustrate two ways in which the acoustic energy at 50 Hz is transmitted over the seamount to CN. The regions of reduced TL past the seamount, in Figure 10a, are caused by the upward refracting SVP, and in Figure 10b are caused by the inefficient

Table 6: *PECan minimum TL received by a hydrophone 1 m from the seafloor.*

Node	Month	Frequency (Hz)	Minimum TL (dB)
CN	January, August	50	120
	February	90	
EN	March	130	91
DDL-06	January	130	90

trapping and leaking of acoustic energy out of the SVP duct. By comparing Figures 10c and 10d the effect of a more pronounced seamount at 30 km range for EN can be seen where there is generally a higher TL than DDL-06 at ranges greater than 30 km.

The PECan modelling considered to this point has been restricted to two dimensional propagation of acoustic energy, with respect to range and depth. Although this takes into account the varying bathymetry and sediment from source to receiver it neglects three dimensional propagation effects that will impact TL through out-of-plane diffraction and scattering by bathymetric features. For example, the apparent seamount discussed above is actually a cross section of a shallow bank off Gabriola Island that is almost non-existent for the bathymetry profile of DDL-06 (see Figure 3). Taking into account the full bathymetry for the Strait of Georgia, as in Figure 2, a three dimensional PECan propagation model is run using a 50 Hz source at RC with a depth of 2 m and the SVP of February. Furthermore, we simplify the specification of the two dimensional sediment distribution throughout the Strait of Georgia by first requiring that it be equivalent to the varying sediment profile obtained from RMAX to CN, as in Figure 5, then assuming this sediment distribution does not change along transverse directions. For any points beyond RMAX and CN it is assumed that the same bottom type at these points is simply extended. Figure 11 shows the TL obtained from a horizontal slice at a depth of 80 m illustrating the distortion of acoustic energy by the bathymetry. By allowing energy to arrive at the VENUS nodes from these out of plane directions we find that the three dimensional PECan model runs show a 10 dB reduction in TL (110 dB) at CN and no change in the TL at EN and DDL-06 with respect to the two dimensional PECan modelling.



(a) CN in February at 50 Hz. *(b) CN in August at 50 Hz.*

(c) EN in August at 50 Hz. *(d) DDL-06 in August 50 Hz.*

Figure 10: *PECan transmission loss from a 2 m deep source at RC to the VENUS nodes.*

4 Conclusion

The OASES and PECan acoustic propagation models have been used to model TL in the Strait of Georgia for 2 m deep sources representing ships operating at CFMETR and receivers located at the VENUS nodes. Our goal was to obtain a worst case scenario, that is, to determine minimal TL values under realistic environmental conditions for representative signals, namely 10, 50, 90, and 130 Hz. To increase fidelity of the models we have included bathymetry for the Strait of Georgia, used mean monthly SVPs obtained from numerous historical CTDs, and incorporated the varying distribution of sediment type when possible.

OASES is a range-independent seismo-acoustic propagation model that provides seismic TL by estimating horizontal/vertical particle velocity. Bottom mounted seismic sensors were considered at each of the VENUS nodes and it was found that minimum horizontal particle velocity TL was attained at CN. However, since we expect the

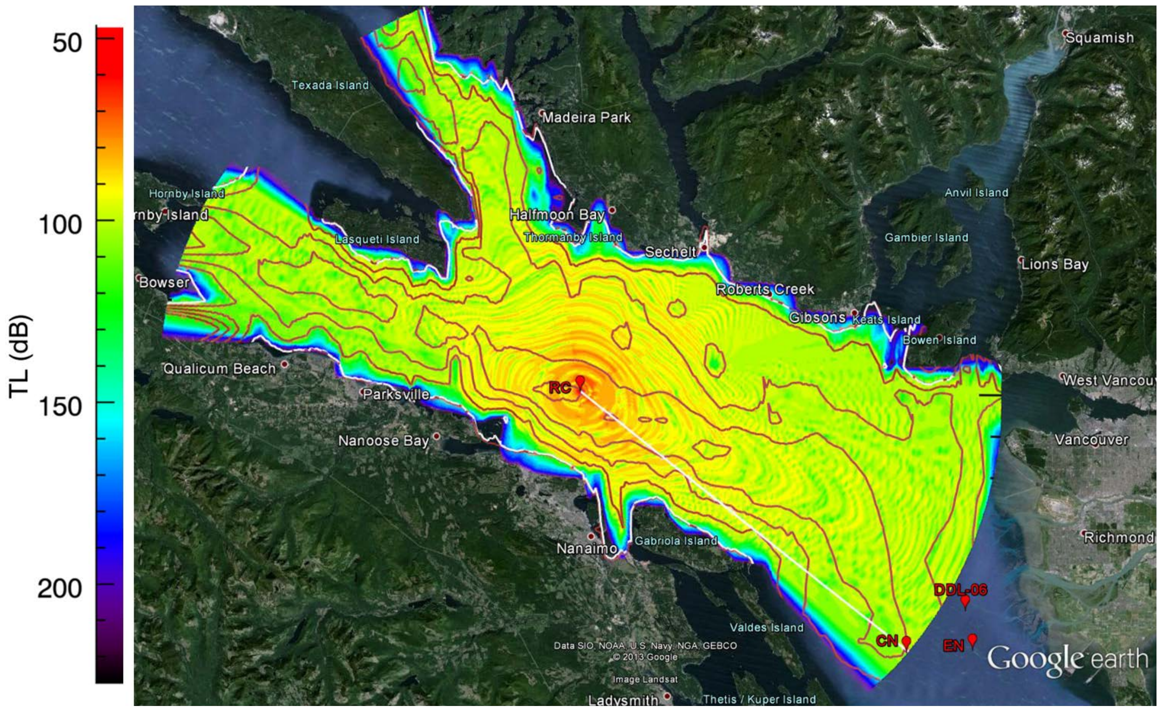


Figure 11: *Transmission loss at a depth of 80 m for a three dimensional PECan model run using a 50 Hz source, 2 m deep, at RC.*

dominant form of coupling of acoustic energy to the bottom mounted seismometer is through the neighbouring water column in the vicinity of the sensor then, based on our PECan modelling, it is anticipated that the seamount would have a significant impact increasing horizontal/vertical particle velocity TL at CN, and less so for EN and DDL-06. Therefore we find that DDL-06 has minimal horizontal particle velocity TL of 114 dB at 130 Hz in February, and a vertical particle velocity TL approximately 10 dB higher. EN had similar horizontal/vertical particle velocity TL values, but for 50 Hz rather than 130 Hz. The winter months of December, January, and February all display minimal seismic losses. It is worth reiterating that since OASES is a range-independent model then its accuracy in estimating TL will be significantly reduced in strong range dependent environments, such as propagation to CN. A modification of PECan to include geophones thereby extending the modelling to seismic cases may be possible but has not been investigated.

Two dimensional pressure TL was modelled using OASES and PECan by considering hydrophones, 1 m from the seafloor, at the VENUS nodes. OASES modelling assumed a constant water depth with a uniform sediment layer and basement whereas the PECan model included the varying bathymetry and sediment. When the seamount to CN is included, the PECan minimum TL at CN increased by 27 dB above the OASES estimate resulting in CN generally showing the largest losses over the other nodes at all frequencies and months considered. The minimum pressure TL was found to occur at DDL-06 for 130 Hz in January with 90 dB of loss from PECan, and a similar minimal TL value for EN in March. In comparison, the OASES minimum pressure TL was 18 dB higher for DDL-06 and EN than the corresponding PECan results.

Including three dimensional propagation effects indicates a negligible change in TL at DDL-6 and EN, whereas CN had a 10 dB improvement in transmission, which was still higher TL than other nodes. Another factor influencing TL is the depth of the source. By increasing source depth from 2 m to 5 m both OASES and PECan give an overall shift in TL by approximately -8 dB while generally preserving many of the other transmission features discussed in previous sections. In other words, the 5 m source depth improves transmission by 8 dB over all months.

A TL experiment was conducted in the summer of 2014 using a number of acoustic sources at CFMETR. Signals were transmitted at various frequencies and depths, and the corresponding signals were received at the VENUS nodes. The collected experimental data will be analyzed and compared to the theoretical model results presented in this report. Furthermore, in the winter of 2014 the same TL experiment will be performed at CFMETR which will show the effect of a winter sound velocity profile on acoustic propagation. Future work in the modelling of TL from CFMETR to the VENUS array will focus on higher frequencies relevant to active sonar.

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The underwater acoustic propagation models OASES and PECan are employed to study transmission loss (TL) to the Victoria Experimental Network Under the Sea (VENUS) sensor nodes in the Strait of Georgia as a consequence of Her Majesty's Canadian (HMC) ships operating at the Canadian Forces Maritime Experimental and Test Ranges (CFMETR). Four representative frequencies are studied for a shallow acoustic source, and both hydrophones and bottom-mounted seismometers are considered as receivers at each VENUS node. Bathymetry, measured conductivity, temperature, depth (CTDs), and sediment type are taken into account to study TL as affected by monthly changes in sound velocity profile. It is found that the VENUS node, Delta Dynamics Laboratory (DDL-06), displays the minimum TL at 130 Hz with OASES results indicating horizontal/vertical particle velocity seismic losses of 114/124 dB in February/December, and a PECan result giving pressure loss of 90 dB in January. The VENUS node, East Node (EN), has similar minimal TL values, whereas the Central Node (CN) has higher TL due to a shallow bank off Gabriola Island interfering with line-of-sight acoustic transmissions from CFMETR. It is important to note that the OASES modelling presented in this report, which is mainly used to provide seismic TL, is derived from a range-independent environment. Therefore, the OASES results are inherently less accurate than corresponding PECan results especially in the case of modelling TL to CN where there is significant variability in the bathymetry profile from CFMETR to this node. Three dimensional acoustic propagation with PECan is used to determine the extent that out-of-plane acoustic energy arriving at each node influences TL.

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