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Impulse Propagation using WATTCH

James A. Theriault
Sean Pecknold

Defence R&D Canada – Atlantic

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Author

Approved by

N. Sponagle
Head/US Section

Approved for release by

Kirk. Foster
Head/Document Review Panel

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Abstract

DRDC Atlantic has developed a coherent transmission-loss model that simulates the propagation of acoustic pulses through an ocean environment. Using a set of input eigenrays and an input waveform, the **WATTCH** (Waveform Transmission Through a Channel) model can simulate the signal received as a result of transmitting the waveform through the ocean environment. Multiple output time-series channels represent receivers at given ranges and depths. Assuming the required eigenrays can be generated, **WATTCH** can simulate the effects of complex range-dependant environments.

This document presents the mathematical formulation and set of examples used to develop and verify the model. In addition, a comparison is made between two pulse propagation techniques. The first technique uses **WATTCH** to simulate the arrival of a transmitted waveform. The second technique uses **WATTCH** to simulate the arrival of a band-limited impulse waveform, and convolves the results with the desired transmitted waveform. The comparison shows the techniques yield equivalent results and therefore multiple waveforms may be simulated using the second technique, but only running the **WATTCH** model once.

Résumé

RDDC Atlantique a élaboré un modèle cohérent d'affaiblissement de transmission qui simule la propagation d'impulsions acoustiques dans un environnement océanique. En utilisant en entrée un ensemble de rayons propres et une forme d'onde, le modèle WATTCH (Waveform Transmission Through a Channel, transmission d'une forme d'onde dans un canal) peut générer un ensemble de sérer séries chronologiques. Chaque série chronologique représente les signaux prévus correspondant une distance et une profondeur données. Si les rayons propres requis peuvent łtre générés, WATTCH peut simuler les effets d'environnements complexes.

Le présent document montre la formulation mathématique et un ensemble d'exemples utilisés pour élaborer et vérifier le modèle. En outre, il montre une comparaison entre deux techniques de propagation d'impulsions. La première technique utilise WATTCH pour simuler la réception d'une forme d'onde transmise. La deuxième technique utilise WATTCH pour simuler la réception d'une forme d'impulsion bande limitée, puis elle convolutionne les résultats avec la forme d'onde transmise voulue. La comparaison montre que les techniques donnent des résultats équivalents, de sorte que plusieurs formes d'onde peuvent łtre simulées l'aide de la deuxième technique, mais en nécessitant une seule exécution du modèle WATTCH.

Ceci est le résumé en français.

Executive summary

Background

Underwater acoustic communication requires the robust transfer of information through the water column. Communication systems must convert a sequence of digital signals to a sequence of acoustic symbols that are transmitted through the underwater environment. A receiving system must convert the acoustic signals in order to process and reconstruct the original digital signals.

The underwater acoustic environment impacts on the received signals. Multiple arrivals and signal distortion may cause degradation in the arrived signals. This degradation may result in a loss of ability to reconstruct the original information.

Results

The **WATTCH** model predictions are compared with other methods of estimating the impact of the acoustic environment on a communication system. The **WATTCH** model is then used to produce simulated received signals based on two approaches. The first approach uses **WATTCH** to simulate the received time series based on transmitting a given waveform. The second approach uses **WATTCH** to simulate the received time series based on transmitting a band-limited impulse waveform. The output is convolved with the original waveform to yield a received time series equivalent to the first approach.

Significance

The **WATTCH** model has been delivered for use in signal processing studies. The impact of the environment on underwater acoustic communication systems is of particular interest, but the model can be used to investigate coherent pulse propagation for Anti-Submarine Warfare active sonar studies.

Future work

The **WATTCH** model is to be used to study underwater acoustic communication. Extensions are likely to be undertaken in order to interpret measurements.

James A. Theriault and Sean Pecknold; 2006; Impulse Propagation using **WATTCH**; DRDC Atlantic ECR 2004-248; Defence R & D Canada – Atlantic.

Sommaire

Introduction

Les communications acoustiques sous-marines nécessitent un transfert fiable d'information dans la colonne d'eau. Les systèmes de communication doivent convertir une séquence de signaux numériques en une séquence de symboles acoustiques qui sont transmis dans l'environnement sous-marin. Un système de réception doit effectuer la transduction des signaux acoustiques pour traiter et reconstruire les signaux numériques initiaux.

L'environnement acoustique sous-marin a une incidence sur les signaux reus. Les réceptions multiples et la distorsion des signaux peuvent causer une dégradation des signaux reus, laquelle peut réduire la capacité de reconstruction de l'information initiale.

Résultats

Les prévisions du modèle WATTCH sont comparées aux prévisions obtenues avec d'autres méthodes d'estimation de l'incidence de l'environnement acoustique sur un système de communication. Le modèle WATTCH est alors utilisé pour produire deux signaux reus, le premier basé sur l'hypothèse d'une forme d'onde donnée, le deuxième utilisant une forme d'impulsion bande limitée. En convolutionnant les résultats de la prévision obtenue pour une forme d'impulsion avec la forme d'onde donnée, on montre que le résultat est équivalent la transmission simulée de la forme d'onde initiale.

Portée

Le modèle WATTCH a été livré en vue de son utilisation dans les études de traitement des signaux. L'incidence de l'environnement sur les systèmes de communications acoustiques sous-marines présente un intérłt particulier, mais le modèle peut łtre utilisé pour étudier la propagation cohérente d'impulsions aux fins de son application au sonar actif de guerre anti-sous-marine.

Recherches futures

Le modèle WATTCH est destiné à être utilisé pour l'étude des communications acoustiques sous-marines et il sera élargi seulement à la suite d'une interprétation plus approfondie des mesures effectuées dans l'essai en mer.

Ceci est le sommaire en français.

James A. Theriault and Sean Pecknold; 2006; Impulse Propagation using **WATTCH**; DRDC Atlantic ECR 2004-248; R & D pour la défense Canada – Atlantique.

Acknowledgement

The development of a coherent pulse-propagation model, **WATTCH**, was supported by the US Office of Naval Research (ONR) under contract N00014-03-C-0147.

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1 Introduction

Underwater acoustic communication requires the robust transfer of information through the environment. Systems for communication must convert a sequence of digital signals to a sequence of acoustic symbols that are transmitted. A receiving system must convert the acoustic signals in order to process and reconstruct the original digital signals.

The underwater acoustic environment impacts on the received signals. Multiple arrivals and signal distortion may cause degradation in the arrived signals. This degradation may result in a loss of ability to reconstruct the original information.

With support from the US Office of Naval Sonar (ONR), DRDC Atlantic has developed a coherent pulse-propagation model. Though full-wave-equation solutions, such as OASES [1], exist, they are computationally intensive and restricted in the environments they can model. Westwood [2] claimed that a ray-theory based model could contain all of the relevant physics for the problem of interest, and be significantly less computationally demanding.

Starting with a set of input eigenrays and an input waveform, the **WATTCH** (Waveform Transmission Through a Channel) model can simulate the expected time series received at a set of hydrophones. Each time series represents the expected signals corresponding to a given range and depth. Assuming the required eigenrays can be generated, **WATTCH** can simulate the effects of complex range-dependant environments.

This document presents the mathematical formulation and set of examples used to develop and verify the model. For the purposes of this document, the eigenrays are generated by the US Generic Sonar Model (**GSM**) [4]. However, in principle, eigenrays generated from other models such as CASS/GRAB [5] or Bellhop [6] could also be used. The results, based on **GSM**, are compared with time series predicted by Chapman et al. [7] using the benchmark OASES model. A separate document [8] describes the software. Using the benchmark model (OASES) [1] at a 2 km range on a dual 2 GHz Xeon computer (with 2 GB of memory) running Linux, 10.44 hours were required. The same test, using **GSM/WATTCH** required 9 s. These times and the agreement between the benchmark and **WATTCH** model support Westwood's conclusion [2].

In addition, a comparison is made between two pulse propagation techniques. The first technique uses **WATTCH** to simulate the arrival of a transmitted waveform. The second technique uses **WATTCH** to simulate the arrival of a band-limited impulse waveform, then convolve the time series with the desired transmitted waveform.

Using a waveform and environment presented by Chapman et al. [7], together with a 500 Hz to 6500 Hz band-limited impulse waveform, the comparison shows that the techniques yield equivalent results. Therefore multiple waveforms may be simulated using the second technique while only running the **WATTCH** model once. The advantage with the second technique is that the time required for execution of the **WATTCH** model depends on the sampling frequency and length of the modeled waveform. The second technique involves propagating a very short duration waveform, and will generally require significantly less time for any reasonable waveform duration. In the example given, the **WATTCH** model required nine seconds to propagate the band-limited impulse waveform to a distance of 2 km, while a 0.2 second long LFM pulse required 33 seconds of computation. The convolution required approximately 15 s. Therefore, by using the convolution approach, approximately 9 s of computational load are saved for each receiver distance for this waveform, with more time saved for any additional waveform types required. This computational savings is increased with increasing waveform length and sampling rate. Additionally, in the case where the pulse to be propagated is either very long or of very large bandwidth, the WATTCH model can become memory-limited. This problem is eliminated by propagating the impulse function.

2 The WATTCH Model

The **WATTCH** model simulates the effect of transmitting a waveform through an underwater acoustic environment. Figure 1 shows the basic operations required to produce a simulated time series. Starting with a description of the acoustic environment, geometry, and frequency band, a set of eigenrays is generated. The eigenrays represent all of the significantly-contributing acoustic paths connecting the source to a receiver. The source location is assumed to be defined by a depth, z_0, at range zero. For a given receiver depth, z, the range, r can vary by equal increments between a minimum and maximum. The frequency range is assumed to cover the spectrum of the intended waveforms.

The eigenrays can be computed by various acoustic models such as the US Generic Sonar Model (**GSM**) [4], CASS/GRAB [5], or Bellhop [6]. **GSM** is used as the baseline model. However, it was recognized at the outset that the enhanced ability for either GRAB or BellHop to model an environment that changes with range may be required. Investigations of using both GRAB and BellHop have been carried out as separate activities.

Using the set of eigenrays and the waveform (specified in DRDC .dat32 format [9]), **WATTCH** computes the predicted time series. The process starts with computing the Fast Fourier Transform (FFT) of the waveform. This yields the frequency-dependent amplitude and phase representation of the waveform. Conceptually, each of the frequency components then propagates as described by the frequency-dependant eigenrays. The propagated components are then reassembled to yield the predicted waveforms at the defined receivers.

The mathematical formulation starts with the real input waveform, $s(t)$, which can be represented using a discrete Fourier series,

$$s(t) = \sum_{n=0}^{\infty} b_n \cos(2\pi f_n t + \phi_n) \tag{1}$$

where s is defined for time t between 0 and τ_0, the pulse length. The amplitude, b_n, and phase, ϕ_n are the real discrete-Fourier Transform coefficients at the frequencies f_n. The previous equation can be approximated

$$s(t) \approx \sum_{n=0}^{N} s_n(t). \tag{2}$$

f_n is defined to be $n/(NT)$ where N and T are the number of points in the FFT and the sampling period, respectively, and $s_n(t) = \cos(2\pi f_n t + \phi_n)$.

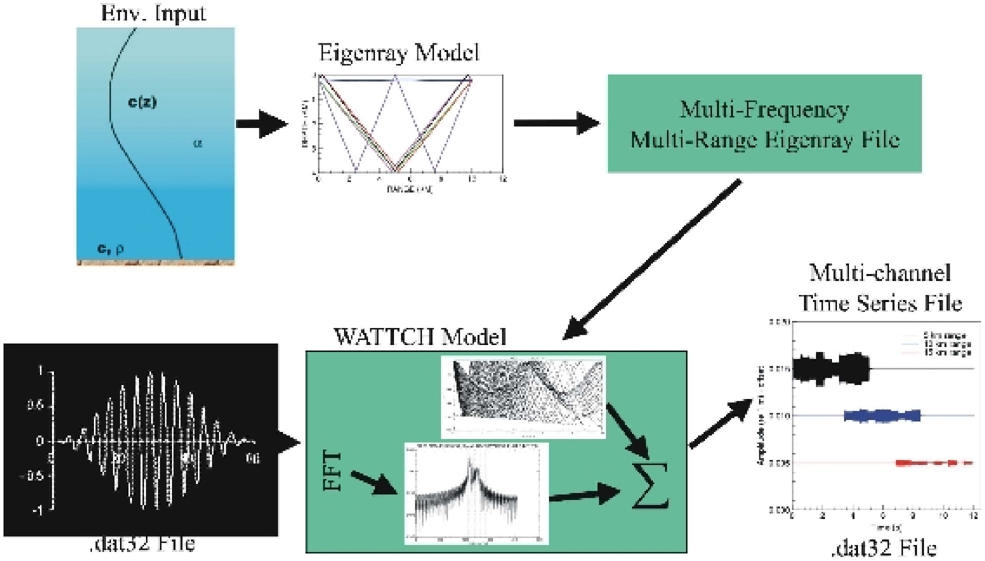

Figure 1: **WATTCH** *model concept*

Consider propagating this waveform through the underwater acoustic medium. Multiple paths connect the source and receiver (see Figure 2). For a given geometry (r, z, z_0 specified), environment, and eigenray tolerance (defining if an eigenray is making a significant contribution), there are M eigenrays. Each eigenray connecting the source and a receiver defines the parameters describing acoustic propagation conditions. Each eigenray is parameterized as a function of frequency, f, by the launch angle, arrival angle, amplitude a_m, phase shift θ_m, and time of flight t_m. For **WATTCH** purposes, the launch and arrival angles are not required. Though both the time of flight, t_m, and the phase shift, θ_m can be assumed to be independent of frequency, only t_m will be assumed to be independent of frequency.

Considering the m^{th} eigenray, let $a_{m,n}(r,z,z_0)$ and $\theta_{m,n}(r,z,z_0)$ represent the amplitude and phase shift at the f_n^{th} frequency. Hence, each of the sinusoidal components s_n needs to be shifted by $\theta_{m,n}(r,z,z_0)$ resulting in the received time series from the pulse component, $s_n(r,z,z_0)$, along the m^{th} eigenray to be given by

$$u_{m,n}(t,r,z,z_0) \;=\; \begin{cases} a_{m,n}(r,z,z_0)b_n \;\times & \\ (\cos(2\pi f_n t + \phi_n + \theta_{m,n}(r,z,z_0)), & if\ t \in [t_m, t_m + \tau_0] \\ & \\ 0 & Otherwise. \end{cases} \qquad (3)$$

Hence, the simulated time series, u, that includes contributions from all of the eigen-

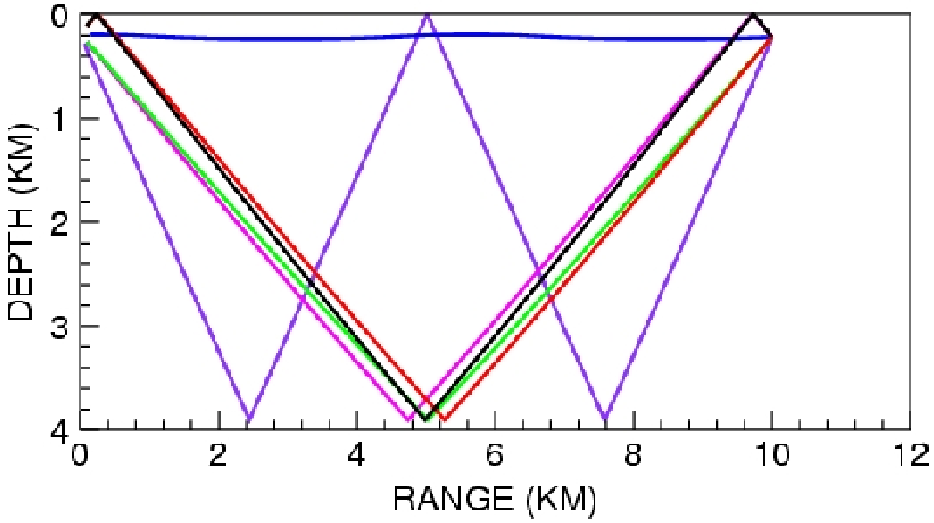

Figure 2: *Example multi-path ray diagram*

rays and frequency components is given by

$$u(t,r,z,z_0) = \sum_{m=1}^{M(r,z,z_0)} \sum_{n=0}^{N} u_{m,n}(t,r,z,z_0) \tag{4}$$

The **WATTCH** model uses this formulation to simulate the time series at a given receiver. After choosing source and receiver depths, and specifying a set of ranges, **WATTCH** will produce a time series associated with each range. The current version of **WATTCH** adjusts the time scale by subtracting the minimum $t_m(r,z,z_0)$ for a given range from the associated time series. By shifting the time-series, in time, the arrival information is preserved while requiring significantly less computer memory and disk space. The software is described by Calnan [8].

3 WATTCH Verification

3.1 Constant Sound Speed Environment

Section 2 describes the **WATTCH** mathematical formulation. Calnan [8] implemented the described model in the IDL language. Chapman et al [7] presented the development and comparison of a set of benchmark models. Starting with OASES [1] as a benchmark, Reference [7] compared it with the Mathematica-based **KosmicRay** model. Being a full-wave model, OASES is a theoretically exact, analytic solution of the wave equation, and is thus taken as the benchmark "truth."

Figure 3 shows the results presented as Figure 15 in Reference [7]. The two channels shown in the figure represent the simulated arrivals of a 500 to 6500 Hz bandlimited function at a range of 2 km. The pulse length is 0.01 s. The broadband waveform is represented by

$$s(t) = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} \cos(2\pi\beta t)\, d\beta \tag{5}$$

where f_1 and f_2 represent the low and high frequency covered by the bandwidth.The environment has a 120 m depth, with the source and receiver at 100 m. The sound speed is 1450 m/s. A Raleigh phase shift [3] and reflection coefficient is assumed for the seabed reflection. The bottom density is 1.9 g/cm^3 and the bottom sound speed is 1650 m/s. The two models show reasonably good agreement (for example, see the circled sections considered in detail in Reference citechapman).

This environment was modeled by **GSM** and used for input in the **WATTCH** model. Alternatively, **KosmicRay** is used to generate the eigenray input. Figure 4 shows the comparison between the **WATTCH** model with the **GSM** and **KosmicRay** eigenrays. The results based on the **KosmicRay** input agree with those generated in Reference [7], but the results based on the **GSM** input show noticeable discrepancy. The **GSM**-based eigenrays have different travel times than those generated by **KosmicRay**, which result in some of the paths adding out of phase rather than in phase.

This may be a limitation of **GSM**'s capabilities in calculating eigenrays for isovelocity profiles. However, it is also the case that even slight changes in environment may yield significant changes in eigenray travel times, phases and amplitudes. If the waveform is sensitive to these changes, the output time series may be altered significantly as well. In the isovelocity case, the difference in eigenray arrival times calculated by **GSM** is sufficient to cause these changes.

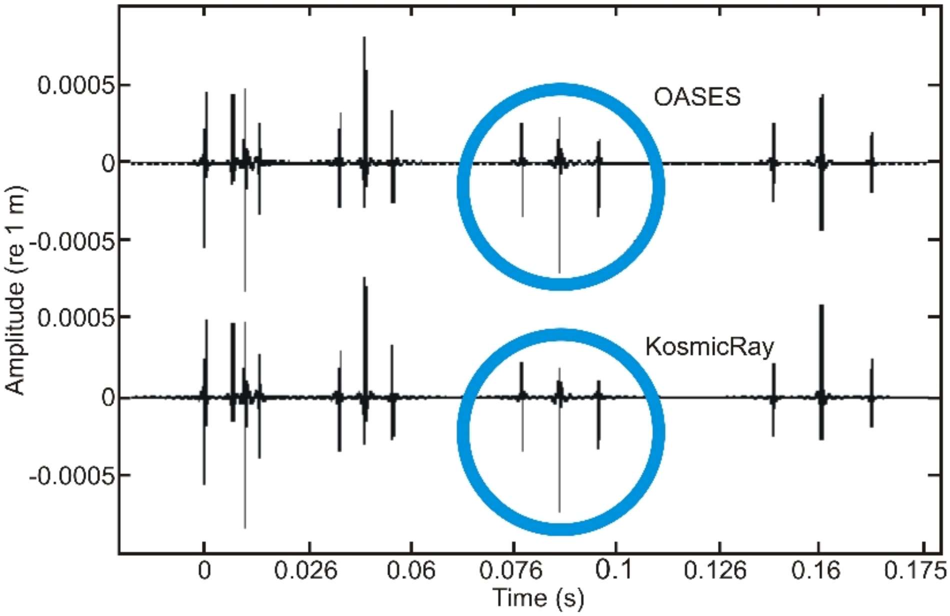

Figure 3: *Comparison of time series generated by* **OASES** *and* **KosmicRay** *for a band-limited impulse function at 2 km distance in a shallow isovelocity ocean environment.*

Figure 5 shows the outputs assuming the same waveform and environment used above, with the exception that in one case, the surface sound speed has been changed to 1453.25 m/s (negative linear sound speed gradient). In the second case the bottom sound speed has been changed to 1453.25 m/s (positive linear sound speed gradient).

In these cases, only the first part of the first group of arrivals shows a noticeable difference between the two examples, and both show a greater degree of similarity towards the isovelocity output of **KosmicRay** than to the isovelocity output of **GSM** for most of the arrival groups. This is consistent with previous experience with **GSM**. Isovelocity profiles often cause difficulty for **GSM**.

3.2 Bilinear Sound Speed Profile Environment

One of the advantages of using **GSM** rather than **KosmicRay** as the source of eigenrays is that it is not restricted to isovelocity environments. An example of this is a bilinear profile, with a negative sound speed gradient near the surface which changes to a positive gradient for deeper depths.

In this example, the pulse used is the same as in the isovelocity case, a 0.01 s

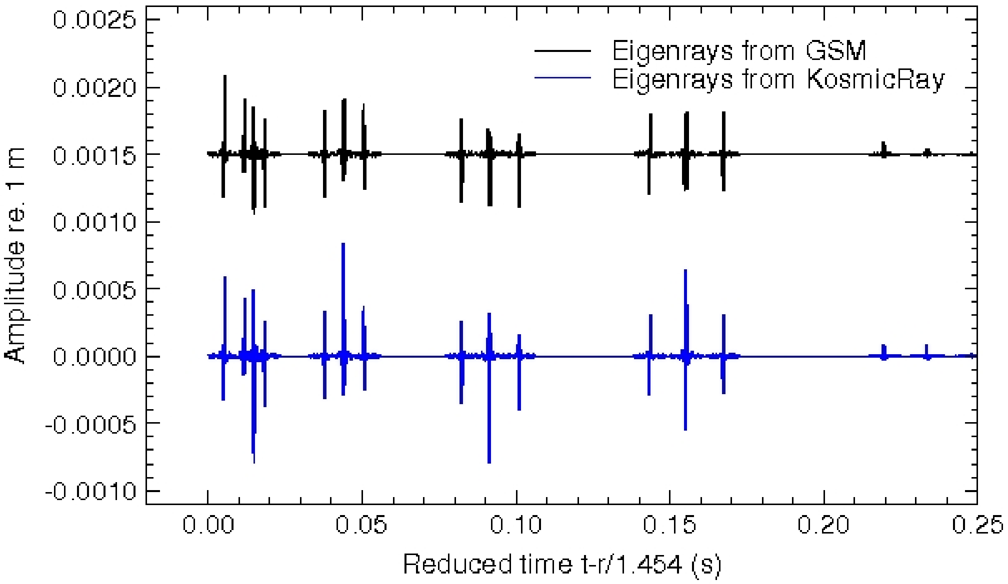

***Figure 4:** Comparison of time series generated by* **WATTCH** *based on eigenrays from* **GSM** *and* **KosmicRay** *for band-limited impulse function at 2 km distance in a shallow isovelocity ocean environment.*

band-limited (500 - 6500 Hz) impulse function. The water depth is 120 m, with source and receiver depths of 100 m. The sound speed is bilinear, with surface speed of 1480 m/s. This changes linearly to 1442 m/s at 60 m then increases linearly to 1447 m/s at the seabed. An isovelocity model such as **KosmicRay** cannot address this problem. The bottom density is 1.9 g/cm^3 and the bottom sound speed is 1650 m/s. A Rayleigh phase shift [3] and bottom reflection coefficient is used.

Figure 6 shows the **OASES** and **WATTCH** results. The two models show generally good agreement in this case.

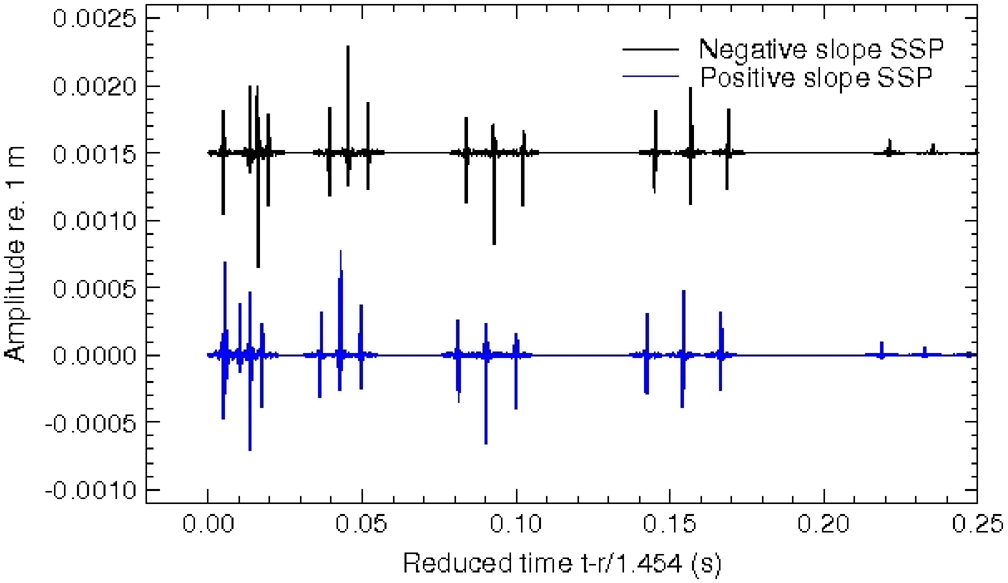

Figure 5: *Comparison of time series generated by* **WATTCH** *based on eigenrays from* **GSM** *for band-limited impulse function at a 2 km distance in a shallow ocean environment, with slightly differing linear-gradient sound speed profiles.*

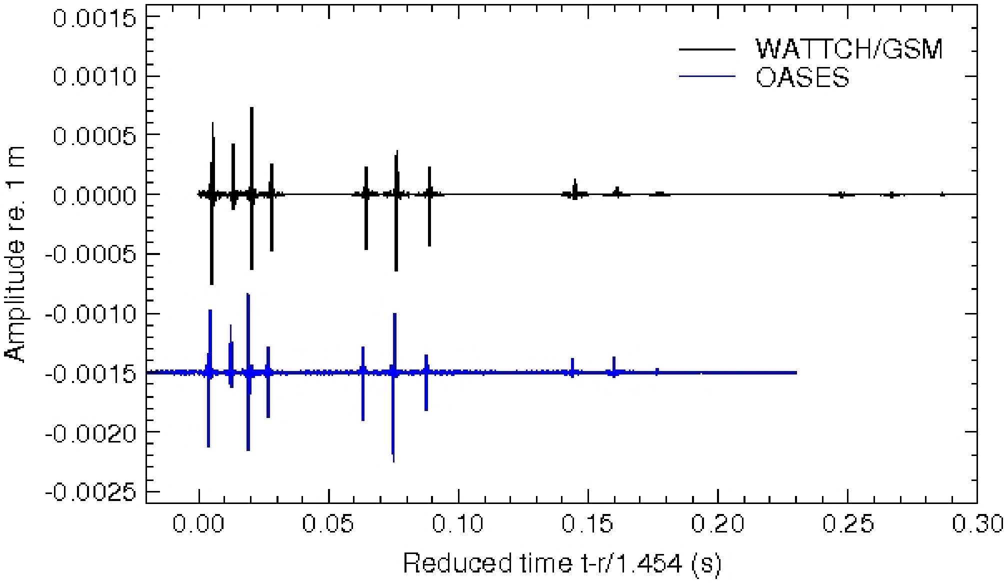

Figure 6: *Comparison of time series generated by* **WATTCH** *and* **OASES** *for for a band-limited impulse function at a 1 km distance in a shallow bilinear-profiled ocean environment.*

4 Broadband pulse convolution

Section 3 verified the operation of the **WATTCH** model. It is capable of producing a simulated time series that can be used in studying the coherence limits of an environment. In order to save computational resources and to reduce the effort for the modeler, an alternative to computing the time series from a given waveform is considered.

Computing the received time series based on a given waveform may be accomplished by convolving a transfer function with the original waveform. The transfer function may be generated by simulating the propagation of a band-limited impulse function. Using this approach requires only one execution of the **WATTCH** model for a given environment and set of geometries. The impact of the environment on a set of waveforms may be studied without repeatedly executing the model. This results in significant time savings.

This section shows the equivalence of the two approaches. Care must be taken when calculating the final convolution, as some software packages may not compute a convolution as expected.

Figures 7 shows a comparison between the direct computation through **WATTCH** of a propagated LFM and the same LFM convolved with the **WATTCH**-computed band-limited impulse function described above. The environment is the bilinear shallow ocean described in Section 3.2. The Hanning-windowed LFM has duration 0.2 s, with a centre frequency of 3000 Hz and a bandwidth of 400 Hz.

Figure 8 shows the power spectra for the waveform at 2 km using both approaches. As expected, the power spectrum for the time series generated by convolving the LFM with the band-limited impulse function shows significantly less power in the frequency bands outside of the 500 to 6500 Hz band of the band-limited impulse function and shows good agreement within the bandwidth. Hence, the convolution approach works well for waveforms having the majority of its energy in the same band as the "impulse waveform." Conversely, for waveforms with significant energy outside of the "impulse waveform," the approach would introduce significant biases.

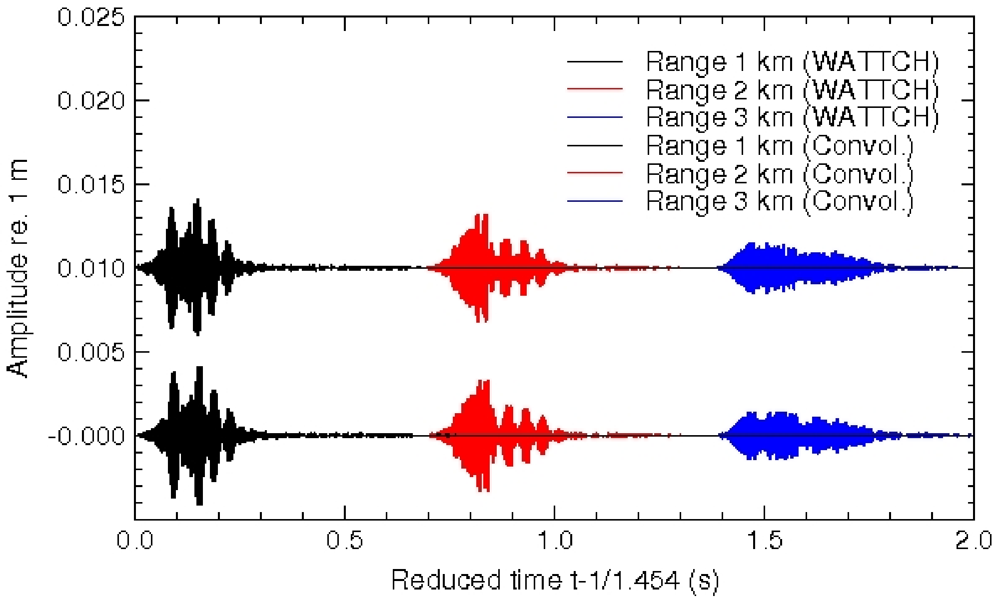

Figure 7: *Time series generated by* **WATTCH** *for an LFM (shallow bilinear-profile ocean environment) (upper trace) and by convolving the LFM with* **WATTCH** *output (lower trace) based on a band-limited impulse waveform at different ranges.*

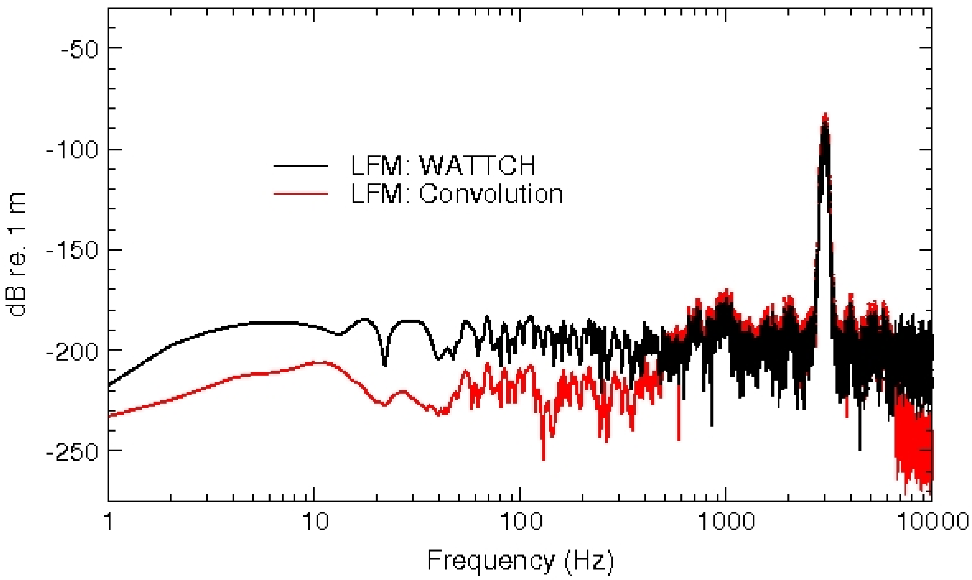

Figure 8: *Power spectrum comparison for the 2 km outputs for Figure 7.*

5 Summary

Underwater acoustic communication requires the robust transfer of information through the water column. Communication systems must convert a sequence of digital signals to a sequence of acoustic symbols that are transmitted through the underwater environment. A receiving system must convert the acoustic signals in order to process and reconstruct the original digital signals.

The underwater acoustic environment impacts on the received signals. Multiple arrivals and signal distortion may cause degradation in the arrived signals. This degradation may result in a loss of ability to reconstruct the original information.

The **WATTCH** model predicts the received time series based on eigenray input, geometry, and waveforms. This document presents the formulation, verification, and an alternative approach to directly computing the resulting time series.

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DRDC Atlantic has developed a coherent transmission-loss model that simulates the propagation of acoustic pulses through an ocean environment. Using a set of input eigenrays and an input waveform, the **WATTCH** (Waveform Transmission Through a Channel) model can simulate the signal received as a result of transmitting the waveform through the ocean environment. Multiple output time-series channels represent receivers at given ranges and depths. Assuming the required eigenrays can be generated, **WATTCH** can simulate the effects of complex range-dependant environments.

This document presents the mathematical formulation and set of examples used to develop and verify the model. In addition, a comparison is made between two pulse propagation techniques. The first technique uses **WATTCH** to simulate the arrival of a transmitted waveform. The second technique uses **WATTCH** to simulate the arrival of a band-limited impulse waveform, and convolves the results with the desired transmitted waveform. The comparison shows the techniques yield equivalent results and therefore multiple waveforms may be simulated using the second technique, but only running the **WATTCH** model once.

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Underwater Acoustic
Transmission Loss
Coherence
Pulse Propagation

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