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A parametric study of long-range atmospheric sound propagation using underwater acoustics software

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In the context of a research on the measurement of long-range attenuation of noise from terrestrial sound sources, a parametric study of atmospheric sound propagation channel characteristics as a function of source height, ground characteristics and meteorological conditions is presented in this paper. The study relies on ray-tracing. The Bellhop ray tracing model which is well known in underwater acoustics has been used here. In this paper, the accuracy of Bellhop's predictions in the atmosphere is first addressed by comparison with results from Salomons's ray model and published benchmarks cases by Attenborough *et al.* No significant discrepancy was noticed with respect to these references. The second part of the paper presents a parametric study for source heights ranging from 0.05m to 200m, a grid of receivers at ranges between 200m and 2km from the source and between 2m and 50m height. A homogeneous flat absorbing ground described by a complex reflection factor is assumed. For the atmospheric conditions, a subset of five different classes in the wind and stability classification from ISO-standard 1996(2)2017, was considered. The results are analyzed from the point of view of the receiver and discussed in terms of attenuation, number of arrivals and number of reflections.

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1. INTRODUCTION

The way sound propagates in the atmosphere and underwater has been exciting the curiosity of scientists for centuries.[1–3] But the interest for sound propagation in the atmosphere really increased during the XXth century and especially after the Second World War, due to the growing problem of noise pollution.[4–7] Atmospheric sound propagation is more complicated than geometrical spreading above a rigid flat ground. It deals with spatially and temporally varying media. Sound propagation in the outdoor environment is affected by several factors like topography (including natural and artificial obstacles), different atmospheric conditions (stable or unstable atmosphere, turbulence). These factors lead to a number of frequency-dependent effects (scattering, reflection, refraction, diffraction and medium attenuation). The impact of the atmospheric conditions appears to increase with distance.[2]

Therefore, the knowledge of the atmospheric sound speed profile plays a vital role in outdoor sound propagation modelling. This information can originate from empirical models, from in-situ measurements or from computational flow simulation. To study outdoor sound propagation several numerical methods have been developed like Fast Field Program (FFP),[8] Parabolic Equation (PE),[9] Finite-Difference Time-Domain (FDTD)[10] and Ray-tracing.[11] But the main disadvantage of several of these numerical methods is their high computational cost and their poor scalability with the volume of the simulation domain. As a high-frequency approximation, ray-tracing appears to be one of the less computationally intensive, which makes it convenient for parametric studies. However, at the beginning of our research we could not find any freely available ray-tracing code for atmospheric acoustics that could handle arbitrary sound speed gradients and non-flat terrain.

But the ray-tracing tool named Bellhop[12] is widely used in the underwater acoustics community. It is freely available, it has a good reputation and is being actively maintained. The purpose of our communication is (1) to show that Bellhop can be used in the study of outdoor sound propagation without major modifications and (2) to present preliminary results of the parametric study of long-range atmospheric sound propagation based on simulations with Bellhop. This paper focuses on (1). The preliminary results of the parametric study are available elsewhere[13] .

Our paper is structured as follows. Section 2 introduces Bellhop and describes Atmospheric-Bellhop. Section 3 presents a validation of Atmospheric-Bellhop with respect to benchmark cases.

2. BELLHOP

A. BELLHOP FOR UNDERWATER ACOUSTICS

In 1987, Michael B. Porter designed an highly efficient ray-tracing tool named Bellhop for predicting acoustic pressure field and ray trajectories in 2-D ocean environment for a given sound speed profile $c(z)$ with rigid or absorbing boundaries. Bellhop is available from the ocean acoustics library as part of acoustics toolbox.[14]

Bellhop implements the solution of ray equations[15] to produce a variety of output including eigenrays, ray coordinates, transmission loss or acoustic pressure, travel time and amplitude. Acoustic pressure calculation is based on Gaussian beams[3,16] theory but other approximations can also be used like geometric beams, beams with ray-centered coordinates, beams with Cartesian coordinates, Gaussian ray bundles[17] approximation.

In Bellhop, angle-dependent plane wave reflection factors can be used to specify boundary conditions at the sea bottom and air/water interface.

The original Bellhop software was written in FORTRAN. Bellhop can be compiled for the target operating system via any available FORTRAN compiler and the resulting executable can also be called via Matlab for post-processing and visualization. Matlab scripts are actually part of the current distribution of Bellhop. Versions of Bellhop exist in other programming languages, but the FORTRAN version was used here.

Several input files are required to run Bellhop. In the simplest case, only a so-called environment file (.env) is needed. It provides information about the topography, sound speed profile and bottom description and also which type of output is required by the user. The structure of the general environment file is shown bellow and a sample underwater ray profile is shown in Figure 1.

```
TITLE
Frequency (in Hz)
nmedia (dummy integer < 20)
OPTIONS1                                                   |  Ocean's surface condition
SURFACE-LINE                                              _|_ Surface block
nmesh sigmas z(nssp)                                       |
z(1) cp(1) /                                               |
z(2) cp(2) /                                               |  Sound speed (w.r.t depth)
.      .                                                   |  block
.      .                                                   |
.      .                                                   |
z(nssp) cp(nssp) /                                        _|_
OPTIONS2                                                   |  Ocean' Bottom condition
BOTTOM-LINE                                               _|_ Bottom block
nsources (number of sources)                               |
source-depth(1) source-depth(nsources) / (in m)            |
nrd (number of receivers x depth)                          | Topography
receiver-depth(1) receiver-depth(nrd) / (in m)             | block
nrr (number of receivers x range)                          |
receiver-range(1) receiver-range(nrr) / (in km)           _|_
OPTIONS3                                                   | Output Type
nbeams (number of launching angles)                        | Output
theta(1) theta(nbeams) (launching angles in degrees)       | block
ray-step zmax rmax                                        _|_
```

Structure of the general environment file.

B. ATMOSPHERIC-BELLHOP

To customize Bellhop for atmospheric ray-tracing we needed to take the followings steps:

- Assume "surface block" as the **boundary condition on the ground** and "bottom block" as the **boundary condition at the maximum altitude considered in the simulation**.
- Provide the sound speed profile as a function of height.
- Provide the angle and frequency-dependent reflection factors corresponding to a suitable ground impedance model and include this information by providing another input file specifying the ground reflection factor (with .trc extension).
- A real atmosphere can be regarded as being vertically infinite therefore, the sound waves travel to a point where their amplitude reaches zero. However, the computation in Bellhop assumes that vertical

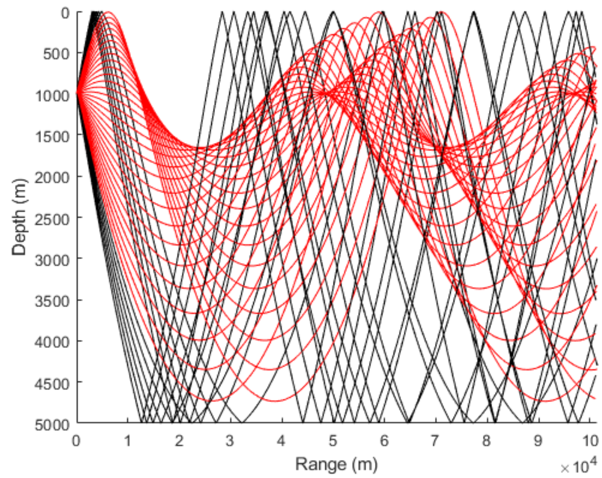


Figure 1: Sample underwater ray profile produced by Bellhop with reflections from the bottom and the sea surface.

the extension of the fluid domain is finite. In order to avoid unphysical reflections from the upper limit of the fluid domain, the boundary condition at the upper limit is defined by a *reflection factor* $= 0$ (perfectly absorbing boundary). This information is provided in another input file called bottom reflection coefficient (with .brc extension) in the original Bellhop terminology. In Atmospheric-Bellhop, this file will contain the reflection factor at the maximum altitude considered in the simulation.

There is no need to change Bellhop's FORTRAN code. The Matlab post-processing routines provided with Bellhop for visualisation purposes need however to be modified to take into account the different coordinate system.

By default, Bellhop does not include attenuation due to the fluid medium. In our case atmospheric attenuation can be added by post-processing after the calculation of transmission loss.

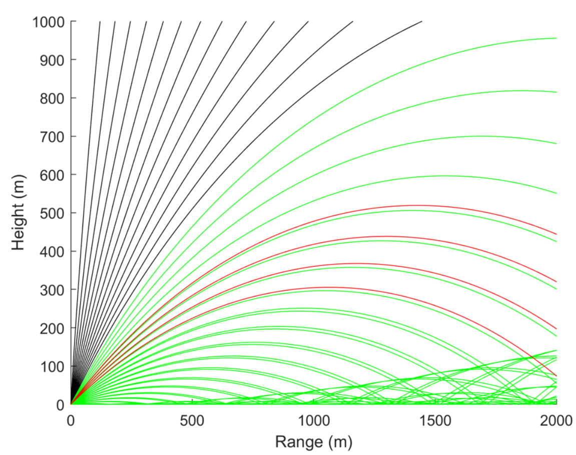


Figure 2: Sample atmospheric ray profile produced by Atmospheric-Bellhop.

The general environment file (.env) and reflection coefficient files (i.e. .brc and .trc) for Atmospheric-Bellhop are shown below. Bottom and top reflection factors files are required in addition to the environment file for atmospheric ray-tracing.

```
TITLE
Frequency (in Hz)
nmedia (dummy integer < 20)
OPTIONS1                                                |  Ground boundary condition
SURFACE-LINE                                           _|_ Ground block
nmesh sigmas z(nssp)                                    |
z(1) cp(1) /                                            |
z(2) cp(2) /                                            |  Sound speed (w.r.t height)
.      .                                                |  block
.      .                                                |
.      .                                                |
z(nssp) cp(nssp) /                                     _|_
OPTIONS2                                                |  Top boundary condition
BOTTOM-LINE                                            _|_ Top Block
nsources (number of sources)                            |
source-depth(1) source-depth(nsources) / (in m)         |
nrd (number of receivers x depth)                       | Topography
receiver-depth(1) receiver-depth(nrd) / (in m)          | block
nrr (number of receivers x range)                       |
receiver-range(1) receiver-range(nrr) / (in km)        _|_
OPTIONS3                                                | Output Type
nbeams (number of launching angles)                     | Output
theta(1) theta(nbeams) (launching angles in degrees)    | block
ray-step zmax rmax                                     _|_
```

Structure of the Atmospheric-Bellhop environment file.

```
ntheta
theta(1)       rmag(1)       rphase(1)       | Description:
theta(2)       rmag(2)       rphase(2)       | ntheta: Number of angles.
 .                                           | theta:  Angle.
 .                                           | rmag:   Magnitude of reflection coeff.
 .                                           | rphase: Phase // // // // // (degree).
theta(ntheta)  rmag(ntheta)  rphase(ntheta)  |
```

Structure of top and bottom reflection coefficient files.

3. ATMOSPHERIC-BELLHOP: VALIDATION

In order to check the accuracy of Atmospheric-Bellhop, Atmospheric-Bellhop's predictions of ray-trajectories and attenuation in an outdoor environment have been compared with results from Salomons's[1] ray model, for a logarithmic sound speed profile and with the benchmark cases defined by Attenborough *et al.*[18] , for a linear sound speed profile. Four different cases are chosen to present in this paper. The parameters of the test cases are shown in Table 1.

A. SALOMONS'S RAY MODEL

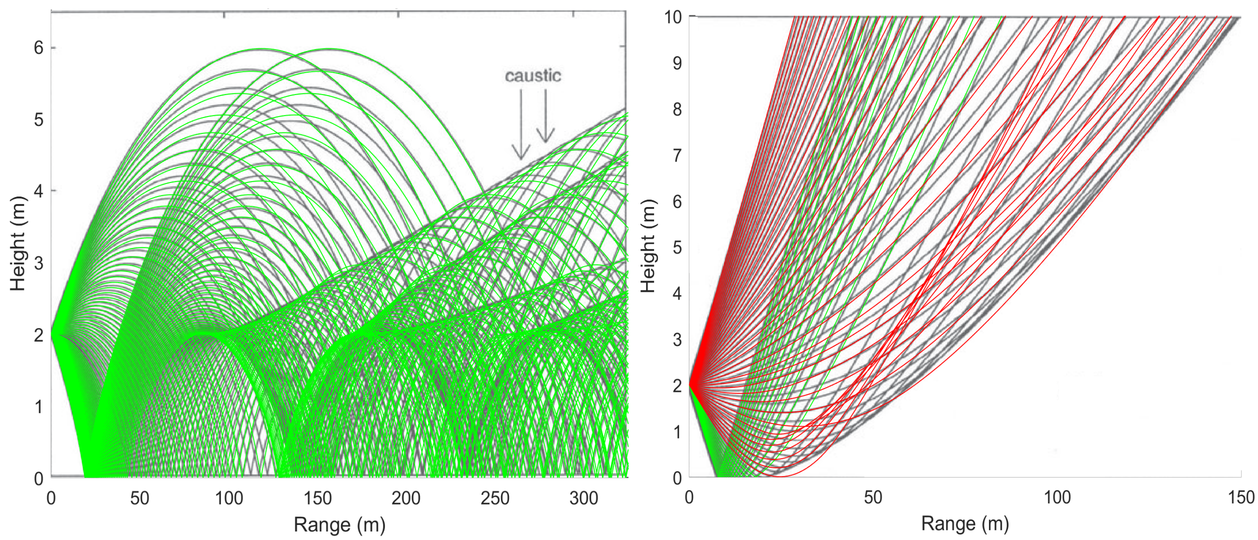
Figure 3 shows the output ray profile from the Salomons's ray model[1] and that from Atmospheric-Bellhop. The between the two models in both downwind and upwind conditions is good.

B. ATTENBOROUGH *et al.*

The results for another benchmark case of downward refracting atmosphere[18] is shown in Figure 4. This atmosphere will lead to more reflections on the ground and more possibility for constructive and destructive interference. In Figure 4a, the results match very well until the horizontal distance reaches 3000m. At

Test case	Sound speed profile	Atmosphere	Ground
Salomons's	Logarithmic	Upward refraction; $b = -1m/s$	Rigid
	Logarithmic	Downward refraction; $b = 1m/s$	Rigid
$f = 500Hz$; $z_0 = 0.1m$; $S_H = 2m$; $R_H = 2m$; $Range = 300m$ & $150m$			
Attenborough's	Linear	Downward refraction; $a = 0.1s^{-1}$	Absorbing
$f = 10Hz$		$Range = 10km$	$Z_g = 38.79 + 38.41$
$f = 100Hz$		$Range = 200m$	$Z_g = 12.81 + 11.62i$
$z_0 = 0.1m$; $S_H = 5m$; $R_H = 1m$			

Table 1: Acoustic and environment parameters for test cases in a refracting atmosphere.



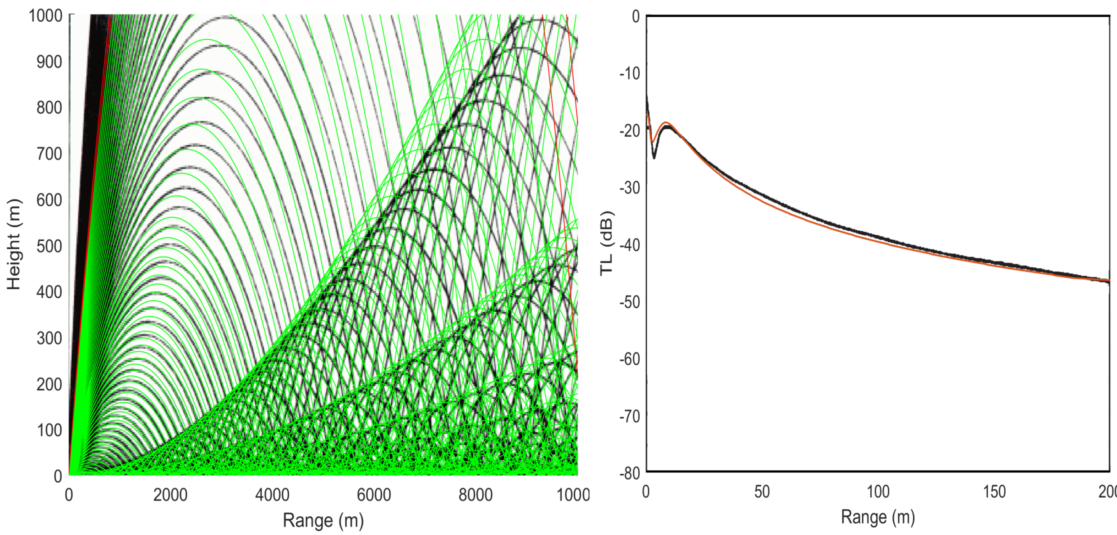
(a) Downward refracting atmosphere. ***(b) Upward refracting atmosphere.***

Figure 3: Comparison with Salomons's ray model[1] . In black: the reference, in color overlay: the output from Atmospheric-Bellhop.

longer ranges the ray pattern shows a much more complicated structure due to the larger number of ground reflections. There are visible differences in the predicted rays but they occur at distances that are not relevant for our purposes. Figure 4b presents the attenuation as a function of range. Atmospheric-Bellhop follows the reference quite closely.

4. CONCLUSION

In relation to a parametric study of long-range attenuation of noise from terrestrial sound sources we investigated the possibility to use the freely available and actively maintained underwater ray-tracing Bellhop software for atmospheric sound prediction. Bellhop appears to be quite usable in the atmosphere too.



(a) Ray Profile for $f = 10$ Hz. *(b) Attenuation for $f = 100$ Hz.*

Figure 4: Comparison between Atmospheric-Bellhop and reference results[18]. In black: the reference, in color overlay: the output from Atmospheric-Bellhop.

There is no need to change the FORTRAN code, but we had to adapt the Matlab code for post-processing and visualizing the results. Only minor changes to the input files are necessary. A comparison of Atmospheric-Bellhop's predictions to 3 published benchmark cases did not reveal any major discrepancy.

The preliminary results of the parametric study[13] illustrate that (a) a shadow zone can be found in stable downward refracting cases when source height is high ($\geq 50m$); (b) In the parameter range considered, the number of ground reflections for 1^{st} arrival at each receiver position is constant in downward refracting conditions but it increases in range with increasing source height in upward refracting scenario; (c) In downward refracting atmosphere, the number of arrivals at each receiver position decreases with increasing height but increases in upward refracting atmosphere with increasing height. But it is observed the number of arrivals in both conditions are overestimated and this warrants further investigation.

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