Waymark Based Underwater Acoustic Channel Model - MATLAB code description

I. INTRODUCTION

THESE notes describe the Matlab code for the Waymark based underwater acoustic propagation model [1][2][3]. Figs. 4 and 5 show a block diagram of the channel model (web version 2). In Fig. 4, an ADC and DAC are shown only to emphasise that the channel model is for signal transmission, the Waymark simulation has $s(nT_s)$ as an input, and $y(nT_s)$ as an output. Fig. 5 shows internal variables in the Matlab code with reference to the model in Fig. 4.

Two example simulations are included in the software. The first example is a simple environment with a flat surface and sea bottom with a constant sound speed profile. The second example is a simulation of the environment described in the SwellEx-96 Shallow water experiment [4], including the bathymetry of the area [5], and a surface wave model.

II. PREREQUISITES

The waymark model uses the Acoustic Toolbox from Heat, Light, and Sound Research, Inc. [6] for the underwater environment modelling. Therefore, this needs to be installed before proceeding further with the Waymark model.

The current version of the channel model was tested using Matlab R2017a, with Windows 10.

III. MAIN CODE LOOP

The function `waymarkModelMain.m` is the main section of code where the calculation and construction of the time varying channel takes place. The signal is optionally downshifted to the baseband, passed through the channel and upshifted back to the passband. The code is designed to process the channel model and signal on a rolling, per waymark basis; this is designed to reduce the memory requirements for very long simulations. It means that the sections of code described in this note are iterated through for each waymark. The function `waymarkModelMain.m` is evoked with parameters from an experiment script `runExperimentLocal.m`, and it is this script that should be executed to start the example simulation.

A. BELLHOP setup

[`staticBellhopSetup.m`]
The initial setup of the environment for BELLHOP is performed by the function [`staticBellhopSetup.m`]. This file contains the default options for the elements of the BELLHOP configuration that do not alter over time.

B. Trajectory generation

[`trajConstVel200.m` (example file)]
In order to calculate the acoustic pressure field, the input to any wave propagation modeller would be the basic environment and the trajectory of the transmitter and/or the receiver within that environment. The trajectory generation specifies the depth, and location in Cartesian coordinates for both the transmitter and receiver. The position is relative to an origin that is referenced to the bathymetry (if it is specified). The position information is generated at every waymark time point along the trajectory. Additional waymarks are added before and after the time interval of interest to accommodate the channel filter and the spline approximation. The trajectory path can be generated analytically or can be interpolated from a table; because of this, each trajectory is defined in it's own user defined function for which the handle is specified for each experiment.

C. Surface generation

[`surfaceGen3DSine.m` (example file)]
For experiments with a dynamic surface wave, the shape of the wave is generated from a user defined function. The total surface wave for the time instant associated with each waymark is generated. BELLHOP reads this information via the .ati file which is updated for each waymark in the surface generation function. The handle for the function is a top level input into `waymarkModelMain.m`.

D. Waymark field generation

[`waymarkFieldGenBellhop.m`]
[`editBellhopEnvFile.m`] This function takes a set of trajectory parameters for each waymark point and modifies the BELLHOP input files [7][8]. BELLHOP is then run and the arrival times and complex valued amplitudes are read in and organised into a structure to be returned to the main code. More details of the setup for the BELLHOP wave propagation modeller can be found in Appendix B.

E. Waymark delays and adjustment

[`waymarkDelayCalc.m`]
The aim of this section of the code is to find the delays between the waymarks for a time varying channel. Although the waymarks are equally spaced in time along the trajectory, because of the variation in the speed of the sound propagation they are generally not equally spaced relative to the signal. The delay estimation is performed from the first waymark to the latest, building up the composite delay of each waymark. The delays are estimated in the frequency domain. The common

propagation delay is removed from the arrival time of all of the waymarks; this common arrival time being the first arrival at the first waymark, τ_{min}. The frequency response $P_m(k)$ at waymark m is given by:

$$P_m(k) = \sum_{n=0}^{N-1} c_n e^{-j2\pi(\tau_n - \tau_{min})f_k} \quad (1)$$

where:

$P_m(k)$: frequency response for waymark index m,

c_n: baseband complex amplitude of the multipath arrival,

τ_n: multipath arrival delay,

τ_{min}: minimun delay for all paths,

n: index for the multipath arrival,

k: index $k = 0, \ldots, K - 1$ for each frequency component in the search or channel frequency range.

As described in [3] the delay shift is found by shifting the impulse response in time (or multiplying in the frequency domain) and looking for the best correlation. More formally, from [3]:

$$\Delta = \arg \max_{\Theta} J(\Theta) \quad (2)$$

where:

$$J(\Theta) = \left| \sum_{k=0}^{K-1} p_m(\omega_k) p_{m-1}^*(\omega_k) e^{j\omega_k \Theta} \right|^2 \quad (3)$$

where:

Θ: the shift in time,

p_m: frequency response for waymark index m.

This process estimates the delay between waymarks, these delays are accumulated, the sum representing the composite delay from the first waymark.

Fig. 1 shows an example of a waymark impulse response. The response is long enough to encompass all of the multipath components; this is dependent upon the environment that is being modelled.
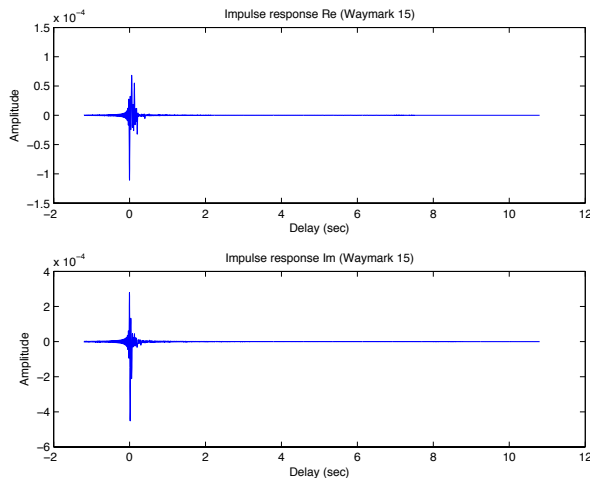

Fig. 1. A plot showing an example of a generated impulse response.

F. Shifting the input signal to the baseband

[waymarkModelMain.m]

If baseband processing is enabled, in this section of code the input signal is converted to an analytic signal and decimated. The downshift in the frequency domain is achieved by multiplying the input signal samples by $e^{-j2\pi f_c t}$, therefore:

$$s_e(nT_s) = s(nT_s)e^{-j2\pi f_c nT_s} \quad (4)$$

where:

n: sample index,

$s_e(nT_s)$: frequency-shifted signal,

$s(nT_s)$: input signal,

f_c: carrier frequency,

T_s: sample period.

This signal is then passed through a low pass filter to remove all but the frequencies centred around zero. For this a raised-cosine filter is used where the filter impulse response is given by:

$$r(nT_s) = \mathrm{sinc}(f_0 nT_s)\frac{\cos(\pi f_0 \alpha nT_s)}{1 - (2f_0 \alpha nT_s)^2} \quad (5)$$

where:

f_0: a cut-off frequency of interest,

α: roll-off factor.

Fig. 2, shows the spectrum of the original signal, the downshifted signal and the filtered and decimated signal. It is this processed signal that is the input to the channel model.
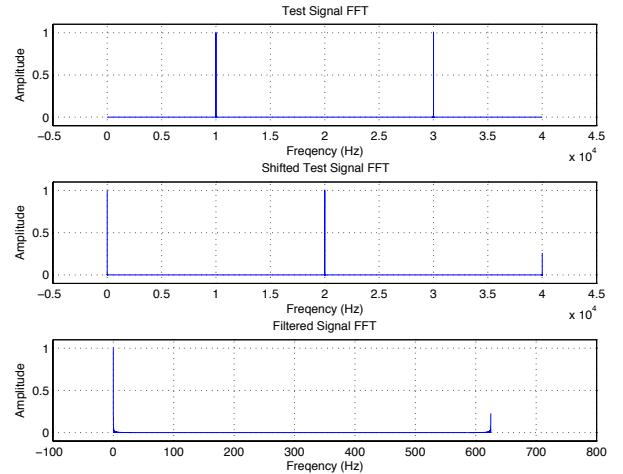

Fig. 2. A plot showing the spectrum of the input signal (f_s = 40kHz), the downshifted signal spectrum (f_s = 40kHz) and spectrum of the filtered and decimated signal (f_d = 625Hz)

If baseband processing is not enabled then the signal is passed unaffected to the next stage and the decimation factor is set to 1, i.e. no decimation.

G. Channel Model

[waymarkModelMain.m]

This section of code creates the channel impulse response at the decimated sampling rate. This is done using a spline approximation between the waymark impulse responses. Based on the estimated waymark delays, the total delay to the signal is calculated for each decimated sample point. These delays
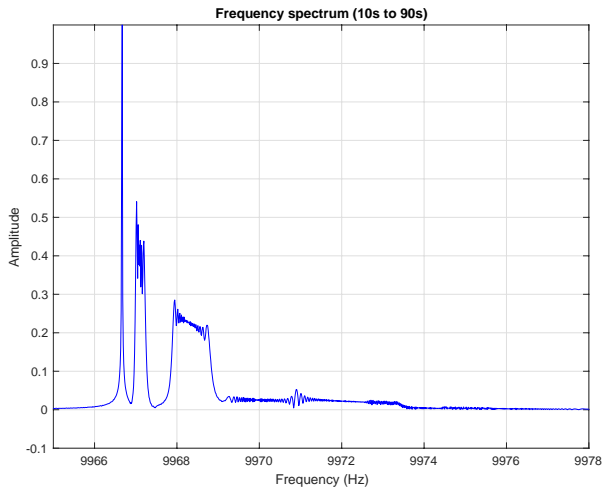
Fig. 3. A plot showing the spectrum of the signal over an example experiment (the transitions at the beginning and end of the signal have been removed).

are then used to interpolate a correctly timed signal for every sample point allowing it to be convolved with the generated channel impulse response to produce an output sample.

H. Shifting the output signal to the passband

[waymarkModelMain.m]
If baseband processing is enabled, The output signal from the channel model is upsampled back to the original sampling frequency using a raised-cosine low pass filter with the same parameters as the one used in the downsampling. Thus the baseband signal is restored at the original sampling rate.

The signal is shifted back to the passband by multiplying each sample by $e^{j2\pi f_c t}$, however the time t for each sample nT_s takes into account τ_n:

$$y(nT_s) = \Re\left\{ y_e(nT_s)e^{j2\pi f_c(nT_s - \tau_n)} \right\} \tag{6}$$

where:
n: sample index,
$y(nT_s)$: output signal,
$y_e(nT_s)$: low frequency equivalent signal,
f_c: carrier frequency,
T_s: sample period,
τ_n: estimated additional delay,
$\Re\{\cdot\}$: real part.

For the final output wav file the initial delay is restored by zero padding the beginning of the file with the appropriate number of samples.

IV. EXAMPLE SIMULATION

[runExperimentLocal.m]
A 10kHz signal of duration 10s is passed through the channel whist the range between the transmitter and receiver is increasing by 5m/s; giving a theoretical Doppler shift of 33.33Hz. The transmitter and receiver were both at a depth of 100m and the initial range between them is 1000m. The environment was 200m deep, with the speed of sound at 1500m/s over the whole depth. The bottom is a flat ridged

plane. Fig. 3 shows the spectrum of the received signal. The direct path can be seen with the multipath components having an altered Doppler shift due to the angle of incident of the reflections.

The main experiment setup parameters are as follows: Setup the path to the Acoustic Toolbox [6] and include the sub-folders in the current directory. This path needs to be appropriate for the operating system.
```
path(path,genpath('~/Documents/MATLAB/at'));
path(path,genpath('./'));
```

Specify the input waveform filename.
```
SRC_DATA.waveformName = 'cw_10kHz_100s';
SRC_DATA.waveformExt = 'wav';
```

Add some extra information about the input waveform. The fCarrier parameter is the frequency shift to move the signal to the baseband, fSample and bandwidth define the amount the signal may be decimated.
```
SRC_DATA.fCarrier = 10e3;
SRC_DATA.fSample = 40e3;
SRC_DATA.bandwidth = 2*156.25;
```

The matlab function that is used to describe the relative position of the transmitter and receiver as a function of time.
```
TRAJECTORY_FUNCTION = @trajConstVel200;
```

The name of the file that is used to setup the environment parameters for the BELLHOP underwater propagation simulator [7].
```
ENVIRONMENT_FILE_NAME = 'iso200';
```

The roll off factor for the low-pass filter:
```
MISC.ROLL_OFF = 0.1;
```

The control to enable baseband processing:
```
MISC.BASEBAND_PROC = false;
```

The control to change the behaviour of the model if a full-duplex experiment is being performed:
```
MISC.FULLDUPLEX_PROC = false;
``` If this is set to true then the signal delay interpolation is disabled.

The control to select the way that acoustic field is generated for each waymark:
```
MISC.FIELD_GEN_MODE = 'timeVary';
``` The option 'timeVary' runs BELLHOP at each waymark

Specific command to control BELLHOP and override the defaults specified in [staticBellhopSetup.m]:
```
ENV_PARAMS.Bdry.Bot.Opt = 'R ';
```
Setup for the number of simulated beams in elevation and azimuth:
```
ENV_PARAMS.Beam.Nbeams = 19;
ENV_PARAMS.Beam.alpha = [0 360];
ENV_PARAMS.Beam.Nbearings = 9;
ENV_PARAMS.Beam.beta = [0 360];
```

Always direct a beam bearing line towards the receiver: `ENV_PARAMS.Beam.rxTrack = 'true';` If this is 'true' then the receiver angle (theta) is added to the azimuth angles. This means that there is always a beam plane pointing at the receiver.:

The total simulation time (s). If the simulation time is longer than the input waveform then a zero amplitude signal is input after the waveform has ended.
`SIMULATION_TIME = 120;`

The interval between waymarks (s).
`T_WAYMARK = 0.0512;`

Setup the surface generation parameters; `range`, distance of the surface to generate (m); `numRangePts`, the number of sample points over the surface distance; `SURFACE_FUNCTION`, the matlab function that is used to generate the surface heights as a function distance (range).
`SURFACE_PARAM.numRangePts = 512;`
`SURFACE_FUNCTION = @surfaceGenFlat;`

Specify a experiment number and name; this is useful for batch processing as the results will be put into a folder with this name.
`EXPERIMENT_NUM = 1;`

`EXPERIMENT_NAME = ['exp', num2str(EXPERIMENT_NUM), 'Waymark200Flat'];`

REFERENCES

[1] L. Liao, B. Henson, and Y. Zakharov, "Grid waymark baseband underwater acoustic transmission model," in *Underwater Acoustics Conference and Exhibition*, 2017, pp. 343–350.

[2] B. Henson, J. Li, Y. V. Zakharov, and C. Liu, "Waymark baseband underwater acoustic propagation model," in *Underwater Communications and Networking (UComms), 2014*. IEEE, 2014, pp. 1–5.

[3] C. Liu, Y. V. Zakharov, and T. Chen, "Doubly Selective Underwater Acoustic Channel Model for a Moving Transmitter/Receiver," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 3, pp. 938–950, 2012.

[4] (2003, Accessed 9, August, 2018) The SWellEx-96 Experiment website. [Online]. Available: http://swellex96.ucsd.edu/

[5] (2012, Accessed 3, August, 2018) National Geophysical Data Center. U.S. Coastal Relief Model - Southern California vers. 2. National Geophysical Data Center, NOAA. doi:10.7289/V5V985ZM. [Online]. Available: https://www.ngdc.noaa.gov/mgg/coastal/

[6] (2010, Accessed 3, December, 2016) Heat, Light & Sound Research, Inc. website. [Online]. Available: http://oalib.hlsresearch.com/Modes/AcousticsToolbox/

[7] M. B. Porter, "The bellhop manual and user's guide: Preliminary draft," *Heat, Light, and Sound Research, Inc., La Jolla, CA, USA, Tech. Rep*, 2011.

[8] O. C. Rodriguez, "General description of the BELLHOP ray tracing program," *Physics Department Signal Processing Laboratory Faculty of Sciences and the University of the Algarve Tecnologia (Galician), Version*, vol. 1, 2008.

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APPENDIX A
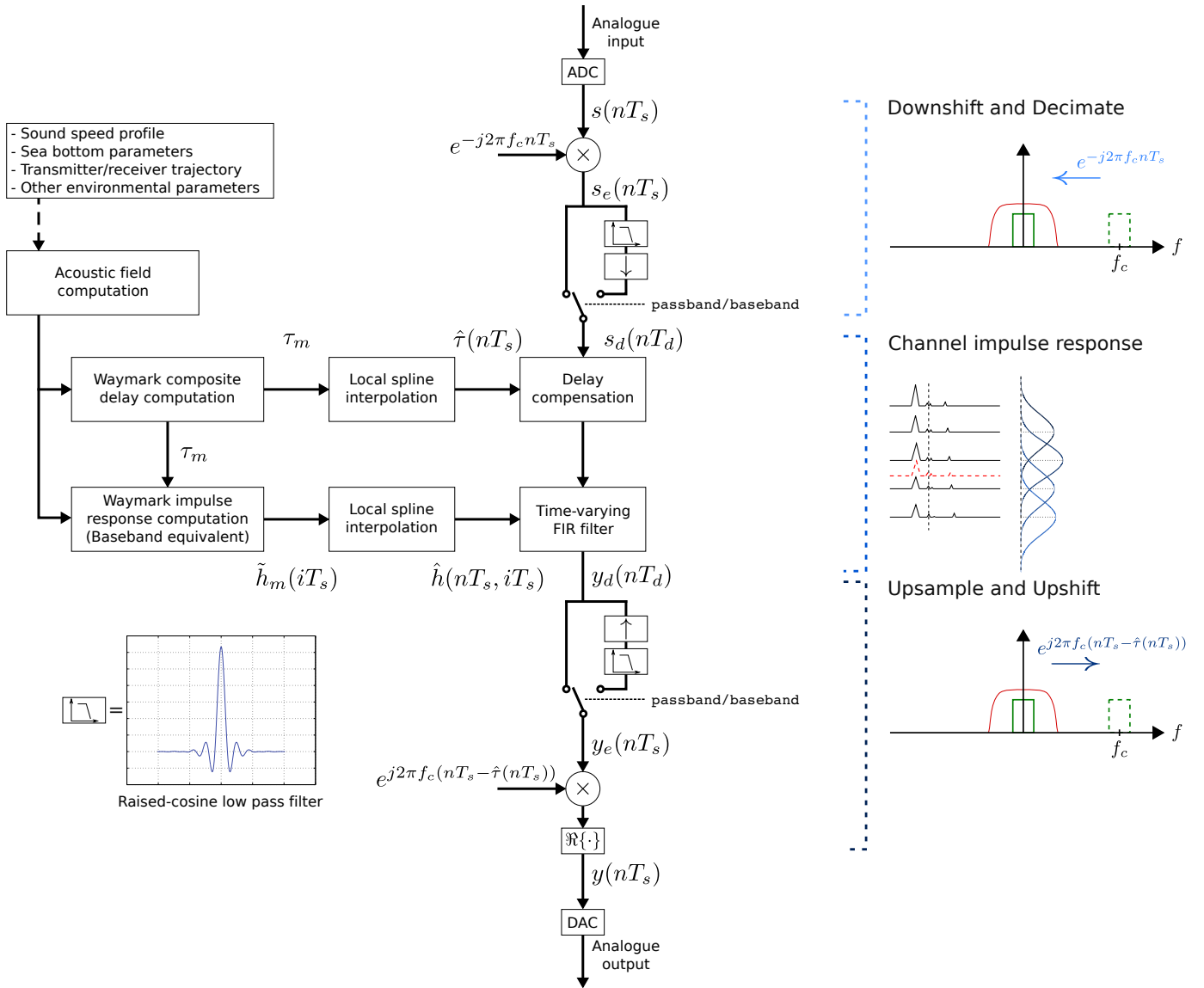UNDERWATER ACOUSTIC UNDERWATER CHANNEL SIMULATOR

Fig. 4. A block diagram of the underwater acoustic simulator as a development on the system presented in [2].
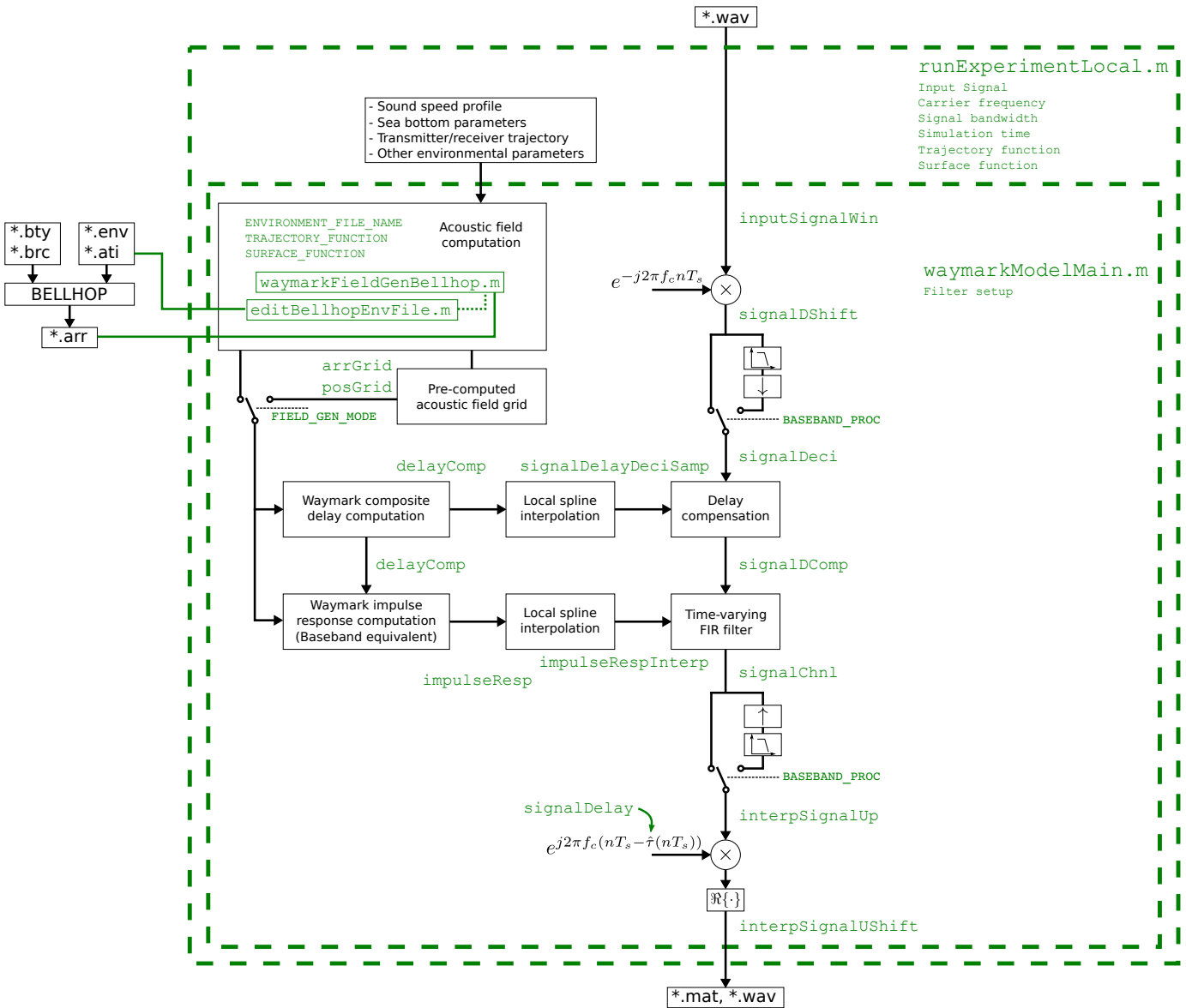
Fig. 5.   A block diagram of the underwater acoustic simulator detailing the key variables and the main division in the code.

APPENDIX B
BELLHOP SETUP

The underwater propagation modeller BELLHOP [7] is part of the Acoustic Toolbox created by HLS Research [6]. Listing 1 shows the environment file for the SwellEx-96 Shallow water experiment [4], the full speed of sound table has been truncated to shorten the listing but it shows the options for BELLHOP and the Speed of Sound Profile (SSP) for the water column. The BELLHOP program is unable to model the sub-bottom profile directly, however it is able to process a set of tabulated complex bottom reflection coefficients. This is not as accurate as a it would be with a full-wave model, however, it does

improve the treatment of a layered bottom [7]. The tabulated reflection coefficients are produced by creating an environment file with the sub-bottom profile only, then from the Acoustic Toolbox the BOUNCE program is run with the file as an input. This creates a bottom reflection coefficient file that can then be used as an input the the BELLHOP modeller. Listing 2 shows the option and the SSP for the sub-bottom sediment layers. A brief description of BOUNCE can be found in the report for the KRAKEN normal mode program [9]. The option 'F' on line 17 of Listing 1 indicates that the bottom reflection coefficient should be read from a file. More detail about the options set may be found in the BELLHOP descriptions [7] and [8].

Listing 1.   SWellEx experiment setup file example

```
1 'exp1_SWellExS5_surfaceGen3DSine_trajSWellExS5_pass'      ! Title
2 225.00 ! Frequency (Hz)
3 1                        ! NMedia
4 'NVM ~ ' ! Top Option
5 1 0.00 220.00    ! N sigma depth
6 -10.00 1521.95   0.00      0   0.000000   0.00 /        ! z c cs rho
7 -5.00  1522.07   0.00      0   0.000000   0.00 /        ! z c cs rho
8 0.00   1521.95   0.00      0   0.000000   0.00 /        ! z c cs rho
9 5.00   1521.38   0.00      0   0.000000   0.00 /        ! z c cs rho
10 10.00   1518.71   0.00      0   0.000000   0.00 /        ! z c cs rho
11 ...
12 Truncated table for example listing
13 ...
14 205.00 1488.26   0.00      0   0.000000   0.00 /        ! z c cs rho
15 210.00 1488.25   0.00      0   0.000000   0.00 /        ! z c cs rho
16 215.00 1488.26   0.00      0   0.000000   0.00 /        ! z c cs rho
17 220.00 1488.30   0.00      0   0.000000   0.00 /        ! z c cs rho
18 'F~'   0.00               ! Bottom Option, sigma
19         1               ! Nsx number of source coordinates in x
20 -0.996858            / ! x coordinate of source (km)
21         1               ! Nsx number of source coordinates in y
22 -8.132058            / ! y coordinate of source (km)
23         1               ! Nsd number of source depths
24 54.000000            / ! depth of source (m)
25         1               ! Nrd number of receiver depths
26 200.990000           / ! depth of receiver (m)
27         1               ! Nrr number of receiver ranges
28 8.192929             / ! ranges of receivers (km)
29         1               ! Nrb number of receiver bearings
30 83.011337            / ! ranges of bearings (degrees)
31 'AG RR3'           ! Run Type
32        19           ! Nbeams
33 0.000000 360.000000 /   ! alpha1, alpha2 (degrees) elevation angles
34        9           ! Nbearings
35 83.011337 443.011337/    ! beta1, beta2 (degrees) bearing angle fan
36 0.000000 2.081417 9.426032 1128.245403   ! deltas (m) Box.x (km) Box.y (km) Box.z (m)
```

Listing 2.   SWellEx experiment setup file example with the sub-bottom reflection coefficients specified

```
1 'SwellEx Environment  Bach2geo output for Range =   0.'
2 10000.000       | Frequency
3 2               | Number of Layers
4 'NVW'           | SS interp. option, Upper half opt, atten
5 0 0.0  19       | 2nd layer (sediment)
6 0    1549.99487 0.0   1.73236012   0.322001904 0.0 /
7 1    1549.99487 0.0   1.73236012   0.322001904 0.0 /
8 2    1570.45447 0.0   1.73336411   0.290452182 0.0 /
9 3    1575.71143 0.0   1.73436713   0.285457075 0.0 /
10 4    1579.02234 0.0   1.73536932   0.282913357 0.0 /
11 5    1581.53076 0.0   1.73637068   0.2812877   0.0 /
12 6    1583.59741 0.0   1.73737097   0.280136436 0.0 /
13 7    1585.38354 0.0   1.73837054   0.279272139 0.0 /
14 8    1586.97559 0.0   1.73936915   0.278598756 0.0 /
15 9    1588.42542 0.0   1.74036694   0.278060824 0.0 /
16 10   1589.76611 0.0   1.74136376   0.277623594 0.0 /
17 11   1591.02087 0.0   1.74235976   0.277263939 0.0 /
18 12   1592.20581 0.0   1.7433548    0.276965588 0.0 /
19 13   1593.33289 0.0   1.744349     0.276716828 0.0 /
20 14   1594.41162 0.0   1.74534225   0.276508957 0.0 /
21 15   1595.44897 0.0   1.74633467   0.276335329 0.0 /
22 16   1596.45068 0.0   1.74732614   0.276190668 0.0 /
23 17   1597.42126 0.0   1.74831676   0.276070833 0.0 /
24 18   1598.36438 0.0   1.74930656   0.275972456 0.0 /
25 19   1599.28333 0.0   1.7502954    0.275892854 0.0 /
26 0 0.0  819                     | 3rd layer (mudstone)
27 19 1881 0.0   2.05999994   0.0599999987 0.0 /
28 819 3245 0.0   2.05999994   0.0599999987 0.0 /
29 'A' 0.0                        | Bottom halfspace option, RMS Rough
30 819 5200.0   0.0 2.66 0.02 0. | Halfspace acoutic properties
31 1400.0 1.0E9                   | Lower and upper phase speed cutoff
32 10.0                          | Maximum range
```