Methods of clutter modeling for development testing of hydroacoustic systems

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Abstract. The paper considers an approach to the construction of a clutter model used in software of the technological part of the test bench for simulation and development testing of hydroacoustic systems. Simulation of clutter on antenna arrays is a rather complex independent task important from the point of view of ensuring the correct SNR for the simulated noise sources at the antenna input. The existing methods of clutter simulation are presented and a new approach is proposed that eliminates the existing drawbacks while maintaining high performance.

Introduction

The basis of the surveillance systems used in autonomous underwater vehicles (AUVs) to create a model of the environment is formed by hydroacoustic systems. Such systems are quite expensive to develop and require significant expenditures to test the algorithms and software. Such testing is usually carried out in sea conditions, however, due to close connection of the surveillance systems and AUV control system, organizing this is quite problematic. As a result, using advanced simulation systems can significantly reduce the time and expenses needed to develop the hydroacoustic systems. Such systems, in their turn, contain complex software-algorithmic models that allow adequate reproduction of data generated in the AUV hydroacoustic systems.

To test the entire complex of algorithms and programs of AUV hydroacoustic systems, it is required to construct a software model of antenna arrays, namely, the output data of their receiving channels. Moreover, the simulation of outputs of the receiving channels is the most adequate and imperative, comparing favorably with other approaches to the organization of simulation on bench equipment [1–4]. In such a simulation model, two key tasks can be distinguished: generating the response of antenna array to a local sound source (another AUV, a fishing trawler, a large hydrobiont, etc.) and to a clutter (usually, wind). This work is devoted to the problem of modeling the latter.

1. Coherent clutter model

Consider a clutter model as a set of infinitely distant local sources distributed over a sphere around the AUV antenna array. In this case, for a certain spectral sample $i_{ss}$ (further this index is omitted for convenience) the model for a certain $i_{ss}$-th sensor of the antenna array is written as (after simple transformations of formula (1.2.23) from [5, p. 38]):
\[ S(i_{SR}) = \sqrt{P_{\text{whole}}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} N_{\text{clutter}}(\alpha, \beta) e^{i(\alpha, \beta)} e^{i(\alpha, \beta, j_{SR})} \cos(\beta) d\beta d\alpha, \]  

(1)

where \( \alpha \) and \( \beta \) – relative bearing and elevation angle of a remote local source, \( P_{\text{whole}} \) – clutter power (total over the entire surface of the sphere at the point where the antenna array is located) for the spectral sample \( i_{SS} \) in frequency band \( \Delta f \) (corresponding to the step of spectral samples), \( N_{\text{clutter}}(\alpha, \beta) \) – normalized power of clutter depending on relative bearing and elevation, \( w(\alpha, \beta) \) – implementation of a uniform random number distributed over a range of values \([0,2\pi]\), \( \varphi(i_{SR}) \) – phase shift for the Fraunhofer zone on \( i_{SR} \)-th sensor relative to the phase center of the antenna, and

\[ \varphi(i_{SR}) = -2\pi \frac{f}{c} \left( e(\alpha, \beta), r_{SR}(i_{SR}) \right) + \left( e(\alpha, \beta), r_{\text{phase}} \right), \]  

where \( f = \Delta f \cdot i_{SS} \), \( \Delta f \) – spectral resolution, \( c \) – sonic speed in the area of the antenna array, \( e(\alpha, \beta) \) – ort in direction \( \{\alpha, \beta\} \) to a remote local source, \( r_{SR} \) – antenna array sensor coordinates, \( r_{\text{phase}} \) – coordinates of the phase center of the antenna (chosen arbitrarily and for convenience usually combined with the center of mass of the AUV).

Putting \( r_{\text{phase}} = 0 \), the above expression can be simplified as follows:

\[ \varphi(i_{SR}) = -2\pi \frac{f}{c} \left( e(\alpha, \beta), r_{SR}(i_{SR}) \right). \]

In most cases, we can put \( N_{\text{clutter}}(\alpha) = \text{const} \). For the isotropic clutter used in practice for debugging the software of hydroacoustic systems \( N_{\text{clutter}}(\alpha, \beta) = \text{const} \). However, this will not critically simplify the calculation of (1). Note that the integration of expression (1) is a rather difficult computational process. It is usually implemented as a Monte-Carlo procedure [6] as follows:

\[ S(i_{SR}) = 2\pi^2 \sqrt{\frac{P_{\text{whole}}}{N_{\text{sample}}}} \sum_{i_{\text{sample}}} N_{\text{clutter}}(\alpha, \beta) e^{w(\alpha, \beta)} e^{i(\alpha, \beta, j_{SR})} \cos(\beta), \]

(2)

where \( N_{\text{sample}} > N_{SR} \), \( N_{SR} \) – number of sensors in the antenna. Moreover, for high-quality integration, the number of integration points is usually chosen to be much larger than the number of sensors in the antenna array. Usually, \( N_{\text{sample}} \geq 3 \ldots 5N_{SR} \). Moreover, in (2) \( \alpha \) and \( \beta \) are implementations of random uniformly distributed numbers in ranges \([0,2\pi]\) and \([-\pi/2, \pi/2]\) for every \( i_{\text{sample}} \). If in (2) the uniform distribution for \( \beta \) is replaced with the distribution of density \( \cos(\beta) \), then (2) can be simplified by slightly reducing the sample size \( N_{\text{sample}} \):

\[ S(i_{SR}) = 2\pi^2 \sqrt{\frac{P_{\text{whole}}}{N_{\text{sample}}}} \sum_{i_{\text{sample}}} N_{\text{clutter}}(\alpha, \beta) e^{w(\alpha, \beta)} e^{i(\alpha, \beta, j_{SR})} \cos(\beta). \]

(3)

Nevertheless, despite all the simplifications, even in version (3), the computational complexity of the above procedure turns out to be quite high. As a result, various simplified models are used as an alternative, the most widespread among which is the model of incoherent clutter, which is an accurate model (1) for the case of a frequency corresponding to the spatial Nyquist frequency of an equidistant linear antenna.

2. Incoherent clutter model

The incoherent model of clutter is described by the expression:

\[ S(i_{SR}, i_{SS}) = \text{invred} \left( P_{\text{red}, \text{dB}} + k_{\text{clutter, slope, dB}} \log_2 \left( \frac{i_{SS} \Delta f}{f_{\text{red}}} \right) \right) e^{i(\alpha, \beta, j_{SR})}, \]

(4)
where \( P_{\text{red}, \text{dB}} \) – reduced clutter level in dB at a distance of 1 m from a source in a 1 Hz band at a frequency of 1 kHz, \( k_{\text{clutter, slope, dB}} \) – the slope of the clutter spectrum in dB/oct., \( f_{\text{red}} \) – reference frequency (1 kHz), \( \text{invred}(\bullet) \) – conversion of level in dB (in 1 Hz bandwidth) to level in Pa.

Model (4) is characterized by the fact that for a number of antenna arrays it coincides with model (2) at a certain frequency. For an equidistant linear antenna array, this frequency is \( f = \frac{2d}{c} \), where \( d \) – distance between adjacent sensors. The clutter correlation properties at lower frequencies are usually neglected because power ratios are used to construct indicator SNR (sufficient statistics) in the algorithms of modern hydroacoustic systems.

Model (4) has very low computational performance requirements compared to (2). However, this model is not devoid of significant disadvantages associated with the violation of coherence, especially in the low frequency region.

For dependency option \( S^2(i_{ss}) = \text{const} \), there are no significant problems with model (4); however, the vast majority of clutter types are characterized by \( S^2(i_{ss}) \neq \text{const} \). So for wind noise, this value will be \( \frac{S^2(i_{ss})}{S^2(2i_{ss})} = k_{\text{clutter, slope}} = -6 \text{dB/oct} \).

Without considering the problem of generating colored flicker noise (in our case, brown), we will further focus on correct modeling of the clutter power spectral density. At the same time, there are a lot of studies on the synthesis of shaping filters of such noises, for example [5].

In turn, for the real clutter in model (2) for the directional characteristic (DC) [6], the slope changes by the order of \(-6 \text{ dB/oct}\) (proportional to the drop in the concentration coefficient). At the same time, for model (4), due to noncorrelation of data from the sensors at any frequencies, the slope of the clutter in the channels will correspond to the slope at the antenna sensors. This property of the model will lead to the distortion of SNR as one of the main parameters of the detection paths in hydroacoustic systems and will result in incorrect testing of standard algorithms and software.

This effect can be compensated using the heuristic approach described below.

### 3. Incoherent corrected clutter model

Having set one constraint on the applicability of model (4), it is possible to avoid an incorrect SNR in spatial channels due to incorrect clutter power in them. In model (4), the clutter power in DCs at low frequencies is underestimated, since for model (2) and real conditions it will grow in proportion to the drop in the antenna concentration coefficient due to coherence.

Consider the power of the clutter spectrum in the DC:

\[
P_{\text{sc}}(f) \propto \frac{k_{\text{conc}}(f_\perp)}{f^2 k_{\text{conc}}(f)} ,
\]

where \( P_{\text{sc}}(f) \) – clutter power in DC at frequency \( f \), \( k_{\text{conc}} \) – antenna concentration coefficient in the direction of the considered DC, \( f_\perp \) – frequency at which models (2) and (4) are closest to each other.

In the case of model (4), expression (5) will be represented as:

\[
P_{\text{sc}}(f) \propto \frac{1}{f^2} .
\]

Thus, to compensate for it, a correction factor of the following form should be introduced:
\[ k_{\text{clutter slope corr dB}} = 10 \log_{10} \left( \frac{k_{\text{conc}} \left(f_{\frac{c}{2}}\right)}{k_{\text{conc}} \left(0.5f_{\frac{c}{2}}\right)} \right) = \text{const}, \] (7)

where \( f_{\frac{c}{2}} = \frac{c}{2 \langle d_{\text{SR, near}} \rangle} \), \( \langle d_{\text{SR, near}} \rangle \) — average distance between the nearest sensors in the antenna array. Then model (4), taking into account the power balance at frequency \( f_{\frac{c}{2}} \) (equality of models (2) and (4) in DC), will be rewritten as:

\[
\begin{align*}
S(i_{\text{SR}}, i_{\text{SS}}) &= \cdots \\
\cdots &= \text{invred} \left( P_{\text{red dB}} + k_{\text{clutter slope dB}} \right) \log_{10} \left( \frac{i_{\text{SS}} \Delta f}{f_{\text{red}} + P_{\text{corr dB}}} \right) e^{\mu \left(i_{\text{SS}} - i_{\text{SS}} \right)}, \quad (8)
\end{align*}
\]

where \( P_{\text{corr dB}} = P_{\text{red dB}} - k_{\text{clutter slope corr dB}} \log_{10} \left( \frac{i_{\text{SS}}}{f_{\text{red}}} \right) \), \( k_{\text{clutter slope corr dB}} \) — correction factor in dB/oct.

To determine the correction factor, consider the approximate expressions for the concentration coefficient of antenna arrays (along the normal to the antenna surface) of the most common forms for:

- planar antenna of arbitrary configuration:
  \[ K_{CC} = \frac{4 \cdot \pi \cdot S}{c^2} \cdot f_{kHz}^2 \]
- cylindrical antenna:
  \[ K_{CC} = \frac{4 \cdot \pi \cdot 0.866 \cdot D \cdot H}{c^2} \cdot f_{kHz}^2 \]
- circular antenna:
  \[ K_{CC} = \frac{\pi^2 \cdot D^2}{c^2} \cdot f_{kHz}^2 \]
- square antenna:
  \[ K_{CC} = \frac{4 \cdot \pi \cdot D^2}{c^2} \cdot f_{kHz} \]
- linear antenna:
  \[ K_{CC} = \frac{2 \cdot L}{c} \cdot f_{kHz} \]

where \( S, D, H \) and \( L \) — respectively area, diameter, height, or length of the antenna (antenna array), \( f_{kHz} \) — frequency for which the concentration coefficient is calculated, expressed in kHz.

Figure 1 shows the plots of the concentration coefficient vs frequency for the above antennas. Figure 1a shows the dependences in linear, and 1b in logarithmic scales.

Moreover, from the formulas and graphs given, it is easy to see that for planar and equivalent antennas \( k_{\text{clutter slope corr}} = -6 \text{dB/oct} \), and for linear \( k_{\text{clutter slope corr}} = -3 \text{dB/oct} \).

Figure 2 shows the waterfall sweeps of the indicator SNR for model (4) a) and for model (8) b), where the effect of correcting the power spectral density of clutter at low frequencies is clearly visible.

Note that when the clutter level is corrected throughout the frequency range (Figure 3), a parasitic traverse correlation occurs (Figure 4), which is caused by the nonlinear Gibbs effect during processing in standard algorithms due to the large dynamic range of the power spectrum.
Fig. 1. Concentration coefficient vs frequency.

Fig. 2. Waterfall sweeps of the indicator SNR (from top to bottom - frequency increase).

Fig. 3. Power density spectrum of clutter.
To reduce the influence of this effect, the level of the clutter spectrum at low frequencies is reduced, especially outside the operating frequency range of the antenna array sensors (Figure 5). This approach helps to largely reduce the traverse correlation (Figure 6).

Fig. 4. Vertical and waterfall sweeps of the traverse correlation of the clutter.

Fig. 5. Power density spectrum of the clutter.

Fig. 6. Vertical and waterfall sweeps of the traverse correlation of the clutter.
4. Conclusions
Summarizing the above, we can highlight the areas of applicability (and the corresponding restrictions) for each of the presented models. For convenience, the restrictions are given in Table 1 below. The task of clutter estimation and monitoring in the sensors of the antenna array and in the DC, respectively, is denoted by EMC. In addition to the indicated drawbacks, in models with incoherent clutter, the condition of the horizontal anisotropy of the signal is violated, but this point is of little importance in the development of hydroacoustic systems.

Table 1. Restrictions of clutter models.

|                      | Coherent clutter | Incoherent clutter | Corrected clutter | Incoherent clutter |
|----------------------|------------------|--------------------|-------------------|--------------------|
| EMC (antenna sensors)| +                | +                  | -                 |                    |
| EMC (DC)             | +                | -                  | +                 |                    |
| SNR                  | +                | -                  | +                 |                    |
| Horizontal anisotropy| +                | -                  | -                 |                    |
| Calculation speed    | -                | +                  | +                 |                    |

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