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A Novel Interference Suppression Algorithm Based on Analog Circuits Preprocessing

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ABSTRACT: Aiming at two problems of the low radiation efficiency of the transmitted antennas and facing strong interference in extremely-low-frequency (ELF) communication, a new structure of a receiving array is proposed, and the signal preprocessing scheme in the receiver front-end is designed, which can suppress 50 Hz interference and its harmonic components effectively, thereby enhancing the detective ability on the weak desired signal. In order to suppress the interference within signal bandwidth, a novel improved generalized sidelobe cancellation algorithm (IGSCA) is proposed. By combining with the proposed receiving array structure, the problem on the desired signal radiated into the reference antennas has been addressed effectively. In order to test the proposed algorithm's performance, an experimental platform is set up under the laboratory environment, mainly adopting a data acquisition unit named NI 9184. The results show that the proposed algorithm can improve the better signal-to-noise-plus-interference ratio (SINR) to a great extent, and the more the number of reference antennas is, the higher the improved performance is.

1. INTRODUCTION

ELF communication [1] is considered a reliable underwater communication method due to its low attenuation, stable signal propagation in seawater, and strong anti-interference ability. However, the radiation efficiency of the antenna is rather low (about 10^{-5}) [2]. In addition, within signal bandwidth, the received signal also faces strong background noise interference, resulting in extremely low SINR in ELF communication. To address the aforementioned problems, receiver backend typically employs traditional algorithms, including linear filtering (LF) [3], adaptive filtering (AF) algorithm [4, 5], signal subspace decomposition (SSD) [6], beamforming algorithms [7, 8], etc. However, in actual ELF communication, due to the inability to know the direction of the desired signal in advance, the reference antenna inevitably receives the desired signal component. Therefore, traditional algorithms partially cancel out the desired signal component when performing interference suppression, resulting in less SINR significant improvement.

At present, there are related research reports on interference suppression in ELF communication based on our previous research works [9–13]. The proposed algorithm is different from our previous research works. The differences mainly include structure of the receiving array, structure of algorithm, the input signals of blocking module, the desired signal and interference signals arrival directions.

In order to solve the problem of insufficient performance improvement in traditional algorithms, this paper focuses on the generalized sidelobe cancellation (GSC) algorithm widely used in speech signal enhancement [14]. The GSC algorithm relies on the characteristics of main channel signal enhancement, sidelobe channel blocking, and post-processing algorithm, and has better application prospects in interference suppression of ELF communication. However, there are some issues that need to be addressed when this algorithm is applied into ELF communication. Firstly, the performance of the fixed beamforming algorithm (FBA) [7, 8] used in the main channel is limited by the number of main antennas, and FBA requires prior information about the desired signal direction. Secondly, the design of the partitioning algorithm is too simple, resulting in the reference antennas being unable to obtain interference reference information without the desired signal. Again, the adaptive algorithms used in the post-processing scheme often increase the noise floor and cannot guarantee the convergence of each set of data, which means that there may be unstable interference suppression results.

Starting from the actual ELF communication environment, this paper considers the interference suppression problem under harsh conditions, that is, strong interference and the desired signal have the same incident wave direction, both located in the 45 degree direction of the receiving array. In this case, the reference antenna will receive more desired signal component, which has a negative impact on interference suppression. To overcome this difficulty, a signal preprocessing scheme is proposed at the front end of the receiver to filter out 50 Hz interference and its harmonic components. Combined with an improved GSC algorithm, the post-processing algorithm can concentrate on processing strong interference within the signal bandwidth. Some improvements have been made to the original GSC algorithm. Firstly, the main channel adopts the LF algorithm instead of the FBA algorithm to send the enhanced signal to the adaptive blocking algorithm (ABA), improving the algorithm's ability to suppress incoherent noise. Secondly, in

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response to the problem of signal leakage in ELF communication, a receiving array structure with high sensitivity of the main antenna and low sensitivity of the reference antenna is designed to address the weak signal required in ELF communication. This reduces the possibility of the reference antenna receiving the desired signal to a certain extent. Based on the principle of the lowest SINR within the signal bandwidth, an adaptive grouping algorithm is proposed. Basically, it can solve the above-mentioned leakage problem of the desired signal, providing more reference information for estimating the noise and interference of the main channel by eliminating the output signal of the sidelobe channel. Finally, applying the LF algorithm to the post-processing stage of sidelobe cancellation channels, although the performance slightly decreases, the computational efficiency is improved, and the interference suppression results are relatively stable, which is crucial for achieving reliable ELF communication. Through the above improvement scheme, various strong interferences have been effectively suppressed, and SINR improvement within the signal bandwidth has been successfully achieved. The more reference antennas there are, the more obvious the improvement effect is.

2. SIGNAL MODEL

Magnetic antennas are mainly composed of induction coils and magnetic cores. The selection of magnetic cores is important for the performance of magnetic antennas. The ratio of magnetic core length to diameter is directly proportional to the effective magnetic permeability. When the above ratio remains constant, in order to ensure that the effective magnetic permeability remains constant, the initial magnetic permeability must be greater than a certain value. Therefore, when a magnetic core is chosen, the above factors must be considered. The magnetic core material used in this paper is nanocrystalline alloy, which is a kind of soft material with high magnetic permeability and saturation strength [15]. The material size is 6003030 mm, with a length to diameter ratio of 20. Compared with other metal soft magnetic materials, this material has better performance and lower price.

When producing magnetic antennas, the motor and reducer are combined into a winding machine to achieve automatic winding instead of manual winding. A counter is installed on the winding machine to automatically record the number of turns, improving winding efficiency and accuracy. In order to reduce the distributed capacitance of the magnetic antenna, acrylic partition segmented windings were used. In addition, soak the made magnetic antenna in varnish for a period of time to firmly fix the coil on the magnetic core. The specific design and fabrication process of the magnetic antennas has been described in the literature [9]. The parameters of the final produced magnetic antenna with higher sensitivity are as follows. Winding diameter is 0.2 mm; number of winding turns is 12000; the length of the acrylic is 200 mm; the distance of the each acrylic framework is 40 mm; the number of turns of the coil in each winding slot of the acrylic framework is 3000. The parameters of the final produced magnetic antenna with lower sensitivity are different in terms of number of winding turns and the length of the acrylic, and other parameters are the same. The number of winding turns is 8000, and the length of the acrylic is 100 mm. The sensitivities of $Cm1$ and $Cm2$ are the same, about $115\,\text{fT}/\sqrt{\text{Hz}}$@$135\,\text{Hz}$, and the sensitivities of $Cr1$, $Cr2$, $Cr3$, and $Cr4$ are the same, about $780\,\text{fT}/\sqrt{\text{Hz}}$@$135\,\text{Hz}$.

In order to effectively suppress the 50 Hz interference and its harmonic components, several signal preprocessing schemes are proposed that combine the analog filtering with digital filtering method at the receiver front-end. The weak desired signal at the front-end is amplified under the premise of introducing the less noise. The difference between the filtered signals in the main antennas is narrowed, and the better effect on interference suppression is achieved. This paper proposes three kinds of signal preprocessing schemes, and the digital filtering method in each scheme is the same, adopting 8 Hz bandwidth, 16 Hz bandstop, and 60 dB attenuation factor. The difference in each scheme is the analog filtering method. The first scheme adopts the AD797 chip as preamplifier and 195 Hz low pass filter; the second scheme adopts the same preamplifier as the first scheme and combines 195 Hz low-pass filter with 130 Hz narrow band filter with 10 Hz bandwidth; and the third scheme adopts the same preamplifier as the first scheme and two stage above-mentioned narrow band filters. Different filtering results are shown in Fig. 1.

Through the comparison of experimental results, it is found that the analog filtering method that adopts the AD797 chip as preamplifier and cascades two stage narrow band filters combining with the above-mentioned digital filtering method can achieve the best suppression effect. Therefore, this scheme is adopted as the signal preprocessing scheme of the receiver front-end, and the schematic diagram of parts of the analog filtering in this scheme is shown in Fig. 2.

The structure of the receiving array composed of the magnetic antennas designed in this paper is shown in Fig. 3. The magnetic antennas *Cm*1 and *Cm*2 labeled 1 and 3 are the two main antennas with higher sensitivity, while the other antennas are reference antennas with lower sensitivity. The reference antennas *Cr*1 and *Cr*2 labeled 2 and 4 are orthogonally arranged to the main antennas, and the reference antennas *Cr*3 and *Cr*4 labeled 5 and 6 are respectively placed in 45 degree directions of the main antenna *Cm*1.

Assume that the received signal of one of the antennas in the receiving array is $y_i(k)$ $(i = 1, 2, \ldots, 6)$, which can be expressed as

$$y_i\left(k\right) = P_i\left(\alpha_i\right) x\left(k\right) + P_i\left(\theta_i\right) v\left(k\right) + n_i\left(k\right) \tag{1}$$

Among them, i is the label of the antenna; k is the index of the sampled data; $P_i(\cdot)$ is the projection operator; α_i is the angle between the desired signal and the ith antenna of the receiving array; θ_i is the angle between strong interference and the ith antenna of the receiving array; $x(k)$ is the desired signal; $v(k)$ is the strong interference within the signal bandwidth range; and $n_i(k)$ is the background noise.

Since the signal preprocessing scheme in the receiver front-end has filtered the 50 Hz interference and its harmonic components, those parts of interferences are ignored in above equation, and the post-end algorithm of the receiver can concentrate on suppressing the strong interference $v(k)$.

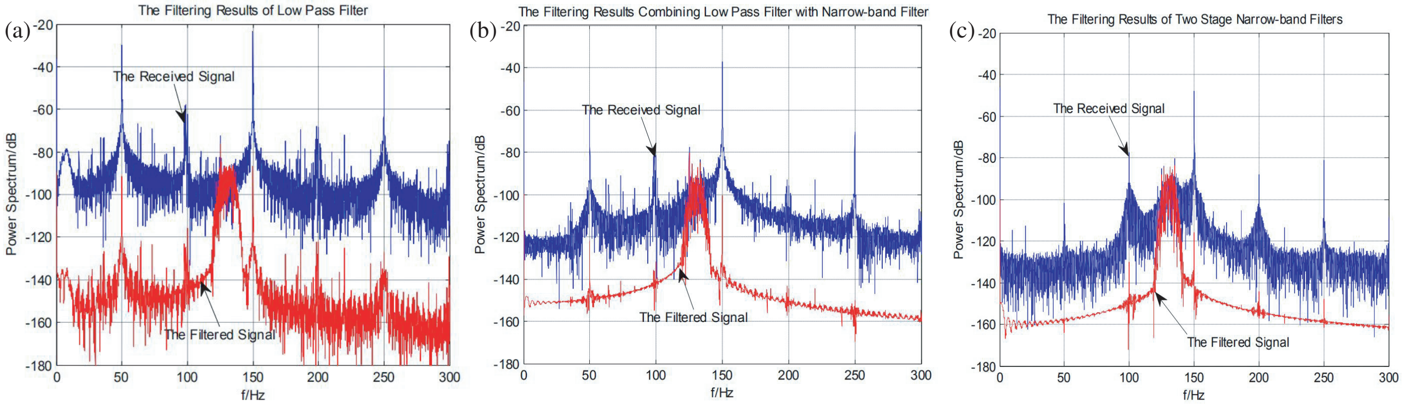

FIGURE 1. The filtering results of different signal preprocessing schemes. (a) The result of first scheme. (b) The result of second scheme. (c) The result of three scheme.

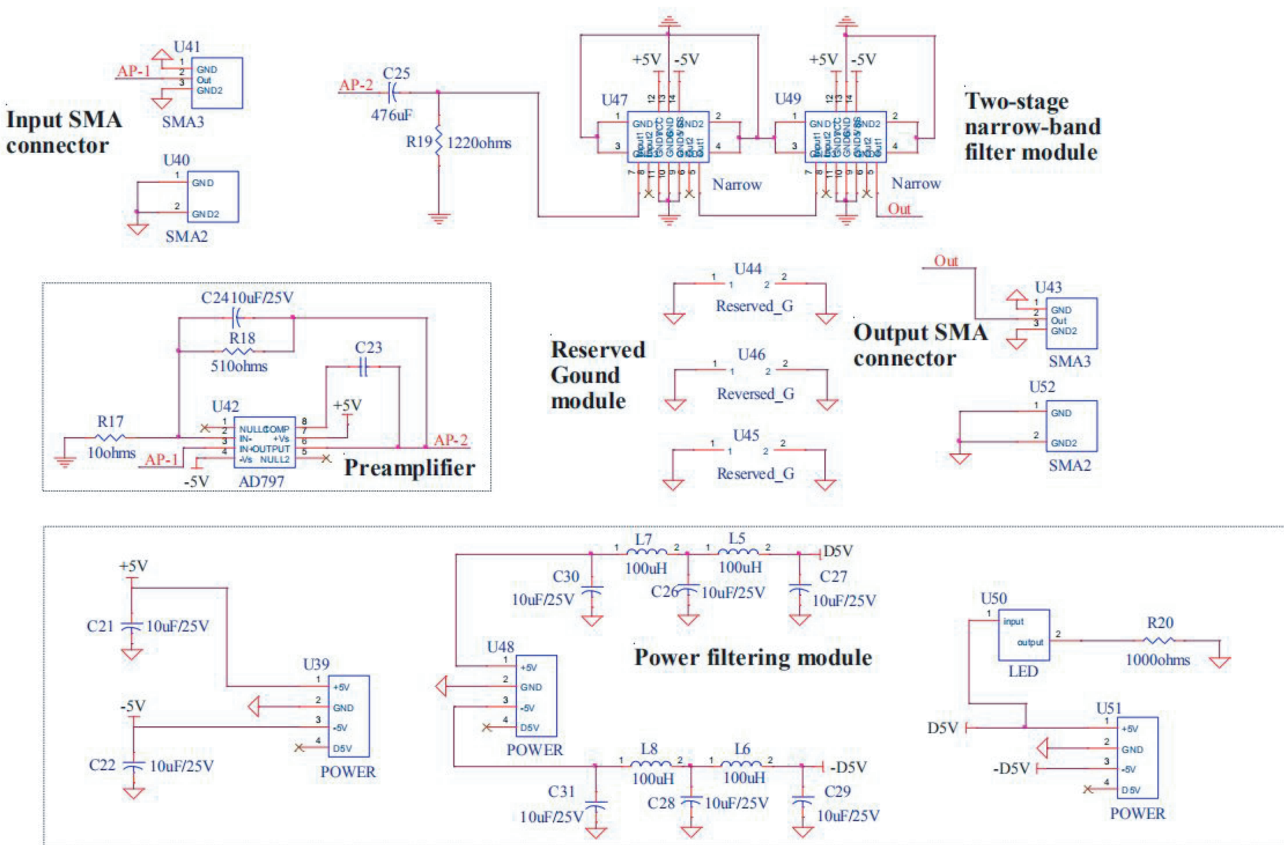

FIGURE 2. The schematic diagram of the part of the analog filtering in this scheme.

3. IMPROVED GENERALIZED SIDELOBE CANCELLATION ALGORITHM

The GSC algorithm belongs to an unconstrained time-domain adaptive beamforming method proposed by Griffith and Jim in 1982 [14]. An improved generalized sidelobe cancellation algorithm (IGSCA) is proposed to address the above issues, and its schematic diagram is shown in Fig. 4. IGSCA consists of LF algorithm, ABA algorithm, and a selection module for receiving signals from two main antennas. This selection module is based on the principle of superior SINR and mainly improves SINR performance by enhancing the desired signal of the main antenna and reducing the leakage of the desired signal in the reference antennas.

From Fig. 3, it can be seen that there are two main antennas and four reference antennas in the receiving array. The algorithm proposed in this paper firstly selects the received signal with the higher SINR from the signals received by the two main antennas as the main signal. Due to the limited production level of magnetic antennas and analog filtering circuits, it is difficult

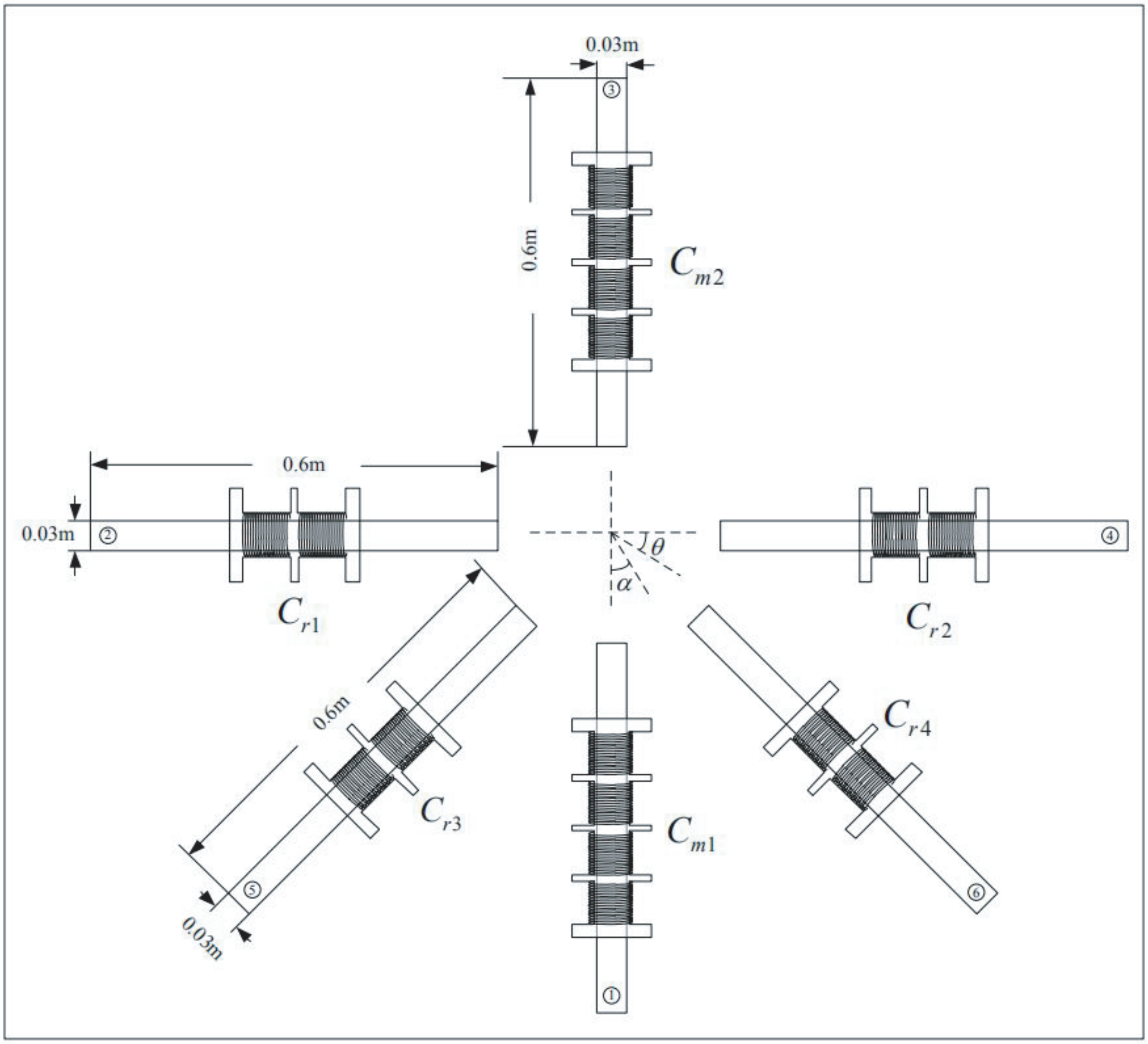

FIGURE 3. The structure of the proposed receiving array.

to ensure that the signals received by each antenna are completely consistent. In order to avoid false performance gain, this paper selects the signal with better SINR between the two received signals obtained from two main antennas as the main signal of IGSCA. This paper assumes that the signal received by the magnetic antenna labeled 1 is the main signal.

The main function of ABA is to eliminate the desired signal component received by the reference antennas, providing reference information for interference estimation and signal enhancement of the main channel in the absence of the desired signal. From the ABA module in the upper part of Fig. 4, it can be seen that the blocking reference signal $y_{bi}(k)$ $(i = 3, 4, 5, 6)$ can be described as

$$y_{bi}\left(k\right) = \begin{cases} \min\limits_{\tau_i} SINR\left(y_1\left(k\right) - \tilde{y}_i\left(k+\tau_i\right), f_c\right) \\ s.t. \qquad \tau_i \in [a:b] \end{cases} \tag{2}$$

wherein, f_c indicates the frequency of the desired signal; τ_i $(i = 3, 4, 5, 6)$ respectively indicate the range of delay time for each reference antenna; a and b respectively indicate the upper and lower limits of delay time; the calculation process of the ABA is as follows. Firstly, the root mean square (RMS) values of the main signal $y_1(k)$ and four reference signals $y_i(k)$ $(i = 3, 4, 5, 6)$ are separately calculated, and the RMS values of four reference signals $y_i(k)$ $(i = 3, 4, 5, 6)$ are adjusted according to the RMS value of the main signal $y_1(k)$, so that the amplitude of the desired signal component in each reference signal is substantially the same as the amplitude of that in the main signal. Then, the reference signals of the adjusted amplitude $\widetilde{y}_i(k)$ $(i = 3, 4, 5, 6)$ are respectively aligned with the main signal by setting some delay units. Finally, the subtracted signals are respectively obtained by subtracting the aligned reference signal from the main signal $y_1(k)$. By adaptively searching for the optimal value of τ_i based on the principle of the lowest SINR within the range of signal bandwidth, the subtracted signals with the lowest SINR obtained are considered as the blocked reference signals $y_{bi}(k)$ $(i = 3, 4, 5, 6)$.

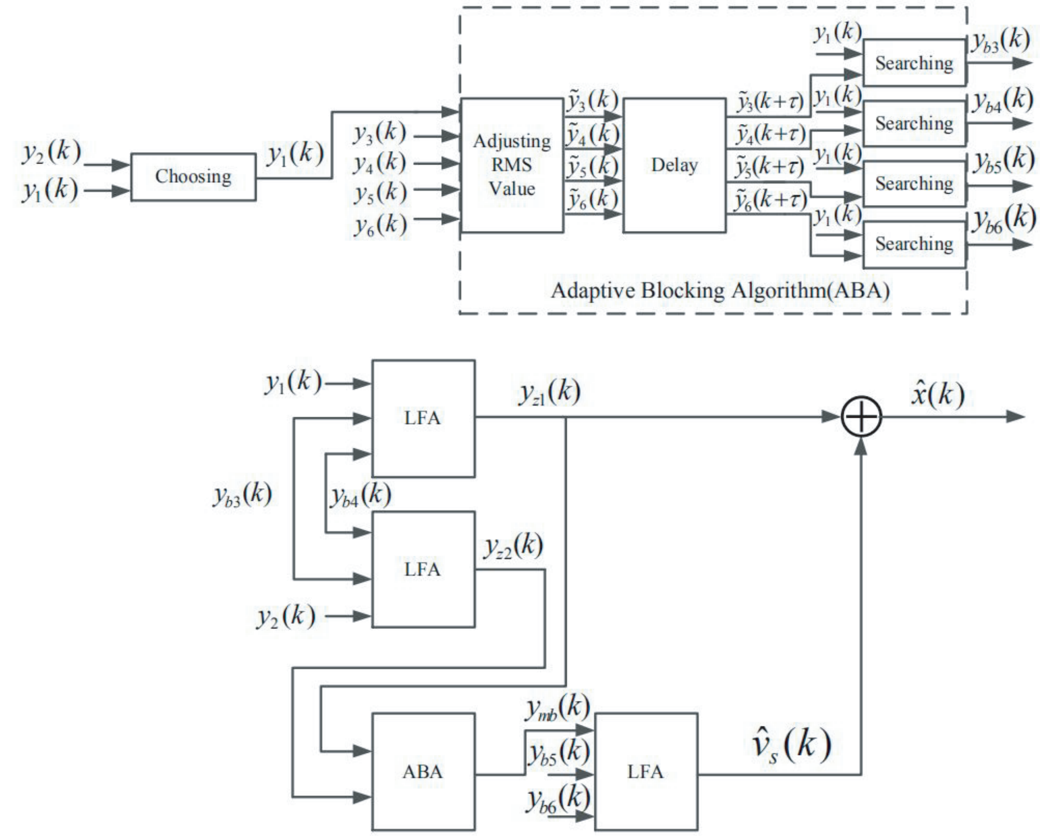

FIGURE 4. The schematic diagram of the proposed IGSCA.

In term of the signal enhancement in the main channel, main signal $y_1(k)$, received signal $y_2(k)$ obtained by the other main antenna, and the two blocked reference signals $y_{bi}(k)$ $(i = 3, 4)$ are sent to the main channel for signal grouping, making each grouped sequence $g_i(k)$ $(i = 1, 2)$ only contain one received signal obtained by the main channels, that is, $g_i(k) = .[y_1(k), y_{b3}(k), y_{b4}(k)]$. The grouped sequence is sent to the LF algorithm, which is composed of the optimal filter based on the minimum mean square error criterion. By the LF algorithm, the approximate solution of the filter coefficient is obtained. Therefore, the i-th coefficient can be expressed as

$$W_{o,i} = \hat{R}_n^{-1} E\left[\vec{n}(k) \cdot y_i(k)\right], \qquad \hat{R}_n = \frac{1}{N}\sum_{i=1}^{N}\left[\vec{n}(i)\right]^T \vec{n}(i) \tag{3}$$

wherein, $\overrightarrow{n}(k) = [y_{b3}(k); y_{b4}(k)]_{2\times N}$, N represents the number of data points contained in the received signal; $\hat{R}_n$ represents the covariance matrix formed by two blocked reference signals; and superscript T represents the transpose operation of a vector. Thus, the enhanced received signal obtained by the main antennas can be respectively expressed as

$$y_{zi}(k) = y_i(k) - W_{o,i}^T \overrightarrow{n}(k) \tag{4}$$

The reason that the received signal $y_2(k)$ by the other main antenna with lower SINR is also enhanced is mainly that it can provide the input signals for the ABA in the sidelobe cancellation channel. Considering that the amplitude of the desired signals received by the two main antennas is not much different according to the structure in Fig. 3, there is no need to adjust the signal amplitude. In addition, the aligned operation mentioned in ABA needs to search for a longer time, but for the blocking algorithm between two enhanced signals received by the two main antennas, the best blocking coefficient may be found in a relatively smaller range. Therefore, in order to improve the computational efficiency, referring to the ABA, a simpler blocking form is designed based on the principle of the lowest SINR within the signal bandwidth. The blocked main signal $y_{mb}(k)$ can be described as

$$y_{mb}(k) = \begin{cases} \min\limits_{\beta} SINR\left(y_{z1}(k) - \beta y_{z2}(k), f_c\right) \\ s.t. \qquad \beta \in [0 : 0.01 : T_\beta] \end{cases} \tag{5}$$

wherein, β is the adaptive blocking coefficient; T_β is the threshold value, which is used to control the range of parameter β; the adjustment step is set to 0.01.

The two other blocked reference signals $y_{bi}(k)$ $(i = 5, 6)$ and the blocked main signal $y_{mb}(k)$ are sent to the latter LF algorithm, and the filter coefficients are solved based on Equation (3), thereby obtaining the estimation $\widehat{v}_s(k)$ of the noise and

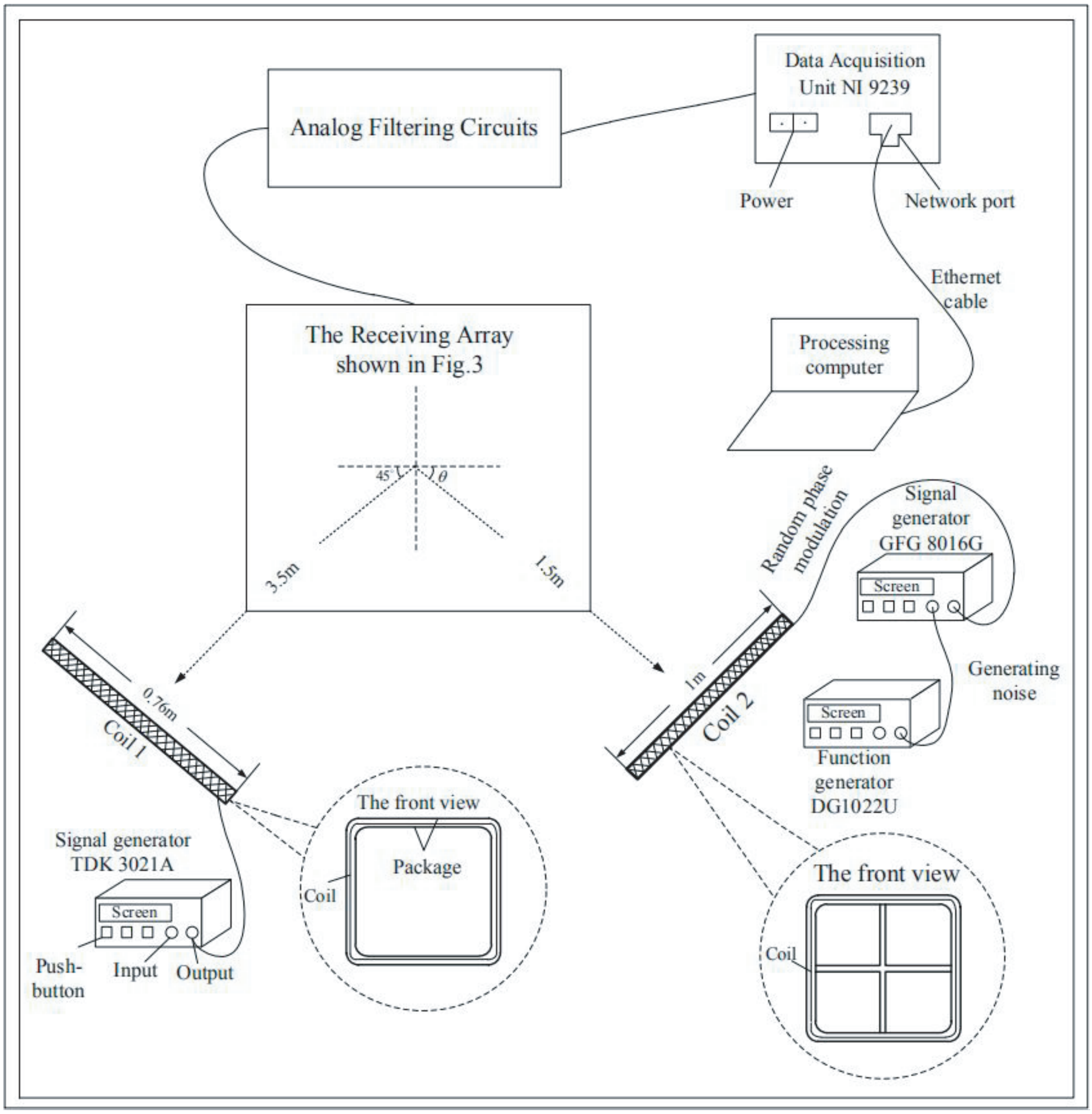

FIGURE 5. The schematic diagram of the experimental scene from the top view.

interference component in main channel. Finally, the estimation $\widehat{v}_s(k)$ is subtracted from the enhanced main signal $y_{z1}(k)$, and the desired signal $\widehat{x}(k)$ is obtained.

4. EXPERIMENT RESULTS AND DISCUSSIONS

In order to test the effectiveness of the algorithm on interference suppression in actual environment, an experimental platform was built in the laboratory. The schematic diagram of the experimental scene can be seen from Fig. 5, and the physical structure of the data acquisition unit is shown in Fig. 6. Some parameter settings are explained as follow: in Equation (2), the upper and lower limits of delay time τ_i are set as $[2, 100]$, and in Equation (5), it is found through experiments that when the threshold is set to 2.5, the blocking algorithm can achieve better blocking effect.

The signal generator TDK AFG3021 generates the desired signal with a frequency of 130 Hz and an amplitude of 10 mV, which is sent to a receiving array at a distance of 1.5 meters through the transmitting coil 1. The function generator DG1022U generates broadband Gaussian white noise of 5 V amplitude and sends it to the signal generator GFG-8016G, which performs random phase modulation to generate strong interference. Strong interference is transmitted to the receiving array at a distance of 1.5 meters through transmitting coil 2. The transmitting coils 1 and 2 are both located in the 45 degree direction of the receiving array. The signal obtained by the receiving array is sent to the data acquisition unit NI 9239 for real-time interference suppression. The sampling frequency is set to 5 kHz, and the interference suppression results are shown in Fig. 7. In addition, the influence of the number of reference antennas on the interference suppression effect was also compared. The third subgraph in Fig. 7 shows the interference sup-

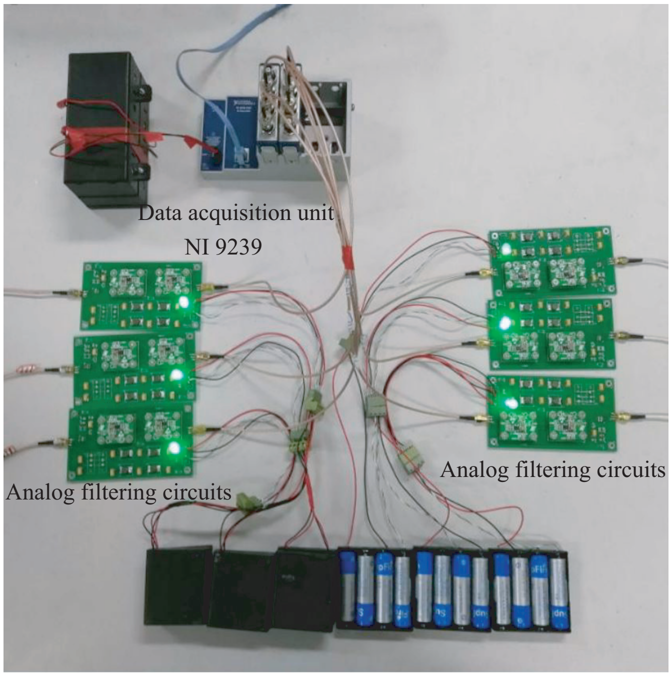

FIGURE 6. The physical structure of data acquisition unit.

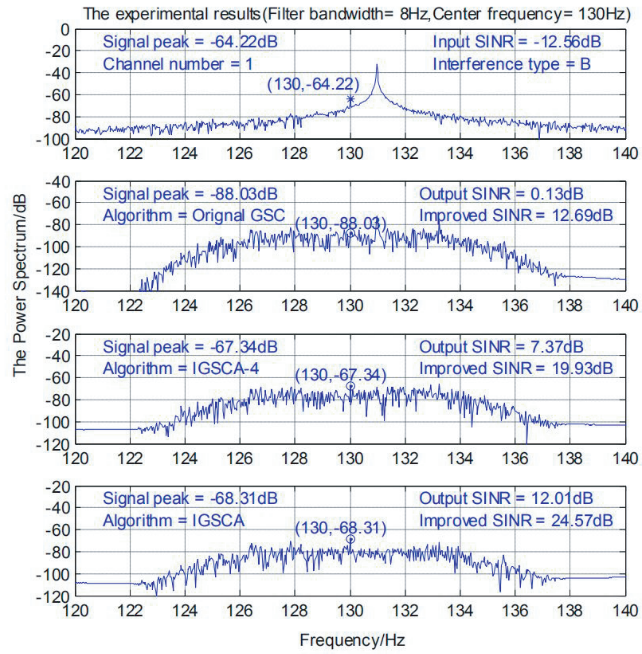

FIGURE 7. The interference suppression result of IGSCA.

pression effect of a receiving array composed of four magnetic antennas $\{C_{m1}, C_{m2}, C_{r1}, C_{r2}\}$.

It can be seen from Fig. 7 that compared with the original GSC algorithm, the proposed IGSCA in this paper greatly improves the SINR gain (about 12 dB) within the signal bandwidth. The experimental results are consistent with the theoretical derivation of the previous section. On one hand, the proposed receiving array structure composed of the main antennas with higher sensitivity and the reference antennas with lower sensitivity reduces the possibility of the reference antenna receiving the desired signal to some extent. On the other hand, the main signals and reference signals are respectively blocked by the ABA, which can address the leakage problem of the desired signal effectively. Besides, those blocked signals can provide more reference information without the desired signal component for estimating the noise and interference in the main channel, thereby improving the estimation accuracy. By comparing with the latter two subfigures in Fig. 7, the more the number of reference antennas is, the more obvious the performance improvement is. This is mainly because the reference antennas in the receiving array proposed in this paper can collect the noise and interference information from different directions, and after being processed by the ABA, can provide more reference information without the desired signal. For the receiving array containing only two reference antennas, due to the insufficient number of reference antennas, the LF algorithm in the sidelobe cancellation channel has reused the reference signals that have already been used in the signal enhancement of the main channel. In this case, it is difficult for the LF algorithm to obtain other useful reference information from the used reference signals, which limits the performance improvement of the algorithm to some extent.

5. CONCLUSIONS

In order to improve the quality of ELF communication, a new receiving array structure was designed to address two problems in ELF communication. A signal preprocessing scheme for the receiving front-end was proposed, effectively suppressing 50 Hz interference and its harmonic components. The GSC algorithm used widely in speech signal enhancement is introduced into the ELF communication. Based on the principle of the lowest SINR within the signal bandwidth and combined with the LF algorithm, an IGSCA algorithm based on ABA is proposed, which solves the problem of signal leakage in traditional algorithm, improves the estimation accuracy of noise and interference in main channel, and achieves a relatively stable suppression effect. This provides a new approach to solving the interference suppression problem in ELF communication.

REFERENCES

[1] Ying, W., Y. Jiang, Y. Liu, and P. Li, "A blind receiver with multiple antennas in impulsive noise modeled as the sub-Gaussian distribution via the MCMC algorithm," *IEEE Transactions on Vehicular Technology*, Vol. 62, No. 7, 3492–3497, 2013.

[2] Rowe, H., "Extremely low frequency (ELF) communication to submarines," *IEEE Transactions on Communications*, Vol. 22, No. 4, 371–385, 1974.

[3] Chen, J., J. Benesty, and Y. A. Huang, "On the optimal linear filtering techniques for noise reduction," *Speech Communication*, Vol. 49, No. 4, 305–316, 2007.

[4] Ferrara, E. and B. Widrow, "Multichannel adaptive filtering for signal enhancement," *IEEE Transactions on Circuits and Systems*, Vol. 28, No. 6, 606–610, 1981.

[5] Gorriz, J., J. Ramirez, and A. Cruces, "A novel IMS algorithm applied to adaptive noise cancellation," *IEEE Signal Processing Letters*, Vol. 16, No. 1, 34–37, Jan. 2009.

[6] Yu, H., N. Liu, L. Zhang, Q. Li, J. Zhang, S. Tang, and S. Zhao, "An interference suppression method for multistatic radar based on noise subspace projection," *IEEE Sensors Journal*, Vol. 20, No. 15, 8797–8805, 2020.

[7] Jiang, Y.-Z., P. Zhao, Q. Zhai, W.-W. Ying, and Q.-L. Hu, "Signal enhancement techniques for through-the-earth communication based on multiple references and beamforming," *AEU — International Journal of Electronics and Communications*, Vol. 86, 86–91, 2018.

[8] Zilli, G. M., A. Ciro, L. Eduardo, *et al.*, "LCMV-based reduced-rank beamforming algorithm with enhanced tracking capability," *IEEE Wireless Communications Letters*, Vol. 5, No. 31, 328–331, Jun. 2016.

[9] Li, C., Y. Jiang, and F. Liu, "New insights about interference suppression algorithm based on analog circuits and linear filtering method in ELF communication," *Aeu-international Journal of Electronics and Communications*, Vol. 93, 154–162, 2018.

[10] Huang, Z., Y. Jiang, and X. Xie, "Motion-induced noise mechanism analysis and reduction algorithm of ELF magnetic receiving antennas," *IEEE Transactions on Antennas and Propagation*, Vol. 71, No. 7, 5637–5652, 2023.

[11] Li, C., Y. Jiang, and F. Liu, "Improved generalized sidelobe cancelation algorithm combined with signal preprocessing about interference suppression in ELF communication," *Journal of Electromagnetic Waves and Applications*, Vol. 33, No. 11, 1477–1485, 2019.

[12] Li, C.-T., Y.-Z. Jiang, F.-J. Liu, and T.-T. Jiang, "Interference suppression algorithm based on analog circuits combined with transform algorithm in ELF communication," *Progress In Electromagnetics Research M*, Vol. 71, 31–40, 2018.

[13] Li, C., Y. Jiang, and F. Liu, "Interference cancellation algorithm based on improved generative model combined with improved generalised sidelobe cancellation in ELF communication," *IET Communications*, Vol. 13, No. 12, 1787–1792, 2019.

[14] Griffiths, L. and C. W. Jim, "An alternative approach to linearly constrained adaptive beamforming," *IEEE Transactions on Antennas and Propagation*, Vol. 30, No. 1, 27–34, 1982.

[15] Yao, K.-F., L.-X. Shi, S.-Q. Chen, Y. Shao, N. Chen, and J.-L. Jia, "Research progress and application prospect of Fe-based soft magnetic amorphous/nanocrystalline alloys," *Acta Physica Sinica*, Vol. 67, No. 1, 016101, 2018.