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Original Research Article

Model of complex weighting coefficients of adaptive spatial filtering algorithm based on conjugate gradient method

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Abstract: In recent years, GPS, GLONASS and other global navigation satellite systems (Galileo, BeiDou, IRNSS, QZSS) are widely used in both civilian and military applications for navigation, positioning, distance measurement, missile guidance, time synchronization and other applications. However, GPS, GLONASS, Galileo etc. signals are very weak and easily fall under the influence of radio frequency interference. Suppression GPS, GLONASS, Galileo etc. signals can have different types, intentional or not intentional. The paper presents a comprehensive definition of the weighting coefficients of adaptive spatial filtering algorithm based on conjugate gradient method. A distinctive feature of this model is the use of quasi-Newton method for finding the minimum objective function – conjugate gradient method; it can significantly reduce the computational cost of the calculation, while ensuring a given level of noise suppression. The research of potential characteristics of the adaptive interference compensator while suppressing to three interferences showed that the adaptive compensator allows doing the noise suppression for amount of interferences with the level of no worse than 40 dB.
Keywords: noise suppression, conjugate gradient, interference compensator, quasi-Newton method, spatial filtering, objective function, GPS, GLONASS, Galileo, BeiDou, IRNSS, QZSS.

INTRODUCTION

In recent years, GPS, GLONASS, Galileo etc. are widely used in both civilian and military applications for navigation, positioning, distance measurement, missile guidance, time synchronization and other applications. However, GPS, GLONASS, Galileo etc. signals are very weak and easily fall under the influence of radio frequency interference. Suppression of GPS, GLONASS, Galileo etc. signals can have different types, intentional or not intentional. Sufficient number of works are devoted to research in this area. [1-10]. In recent years, extensive work to improve immunity to GPS, GLONASS, Galileo etc. was carried out. There were developed many methods to improve radio frequency immunity. One promising method to improve the signal / noise ratio at the input of receiver is the use of devices that implement adaptive spatial filtering based on flexible hardware with the use of digital signal processors and programmable logic integrated circuits (PLIC).

Under these conditions, the algorithms of adaptive spatial filtering implemented at the appropriate hardware imposed strict requirements for their resultant computational complexity, because of the fact that it determines the value of used processors, integrated circuits and noise suppression device in general. Thus, the development of efficient algorithms for adaptive spatial filtering is an urgent task.

MAIN PART

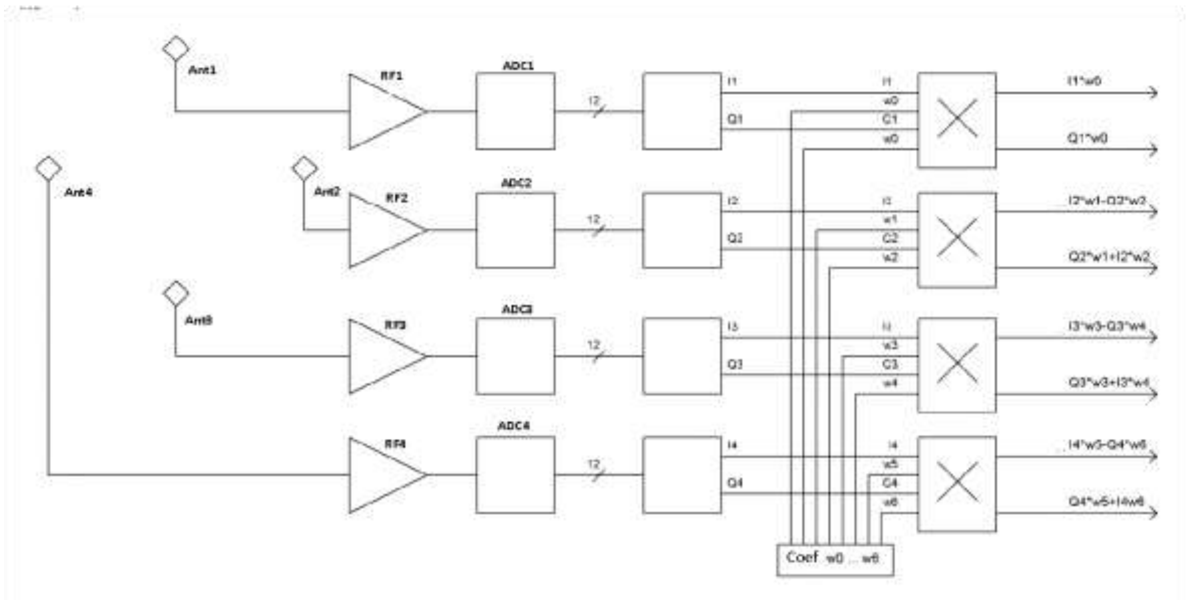
One out of possible approaches, which formed the basis of the adaptive spatial filtering devices, is a method of the minimum output power of the output signal suppression unit. According to this method, there is a main antenna in antenna array, the output of which contains the useful signal and noise, and additional (compensation) antenna that must not contain the desired signal.

In the literature and in practice there are two the most often seen arrays: with four and seven elements. The array with seven elements needs much more hardware capabilities to implement algorithms based on adaptive spatial filtering, therefore, further considering system with four elements is the most appropriate because of its much lower price.

Under these conditions, noise suppression algorithm implements digital adaptive four-element antenna array with the radiation pattern so as its zeros were oriented towards sources of interference signals. It is assumed that the zeros of radiation pattern diagram will be not less than -40 dB in depth, which would be consistent suppression of interference signals to the same level. For each of the frequency range of GPS/GLONASS (L1 or L2) signals antenna array consists of four elements indicated in Fig. 1 as Ant 1 ... Ant 4 and located on the sides of a square in the distance λ/2. All emitters have wide radiation pattern and receive signals in the upper hemisphere. Since both ranges of suppression have the same algorithm, then it is enough to consider this algorithm only for one range. It is assumed that the algorithm is fully implemented on PLIC (the first PLIC for a range L1 and the second for the range L2).

The basic idea of the algorithm is to compose signals from four emitters with amplitudes and phases in the way to form a zero of spatial radiation pattern toward the noise source. Herewith, this algorithm will select the amplitude and phase of each element to reduce signal noise. The amplitudes and phases for each element determined by multiplying the signal received from each radiator on a complex weight coefficient. Complex coefficients are selected with iteration for gradient quasi-Newton method. It is important that the signal noise by 40 ... 60 dB (and perhaps more) higher than the useful navigational signals from satellites. In addition, satellites and sources of noise are separated in space (in the corners). That is why, the antenna system of adaptive radiation pattern, which implements minimum output signal power at the summary output, will spatially suppress such interferences. Additionally, this formed chart leaves the most of the useful signals from the satellites, the location of which does not meet zeros radiation pattern. This will enable further ability to determine the coordinates, so to solve a navigation problem directly.

In Fig. 1 signals from four antenna outputs after high frequency emitters blocks containing amplifiers, mixers, filters, etc. (marked RF) are converted to analog signals. Then the signal from each emitter is digitized in analog-to-digital converters (ADC), the output of each of which is binary code. Then the signal in each channel is decomposed into quadrature components I and Q.



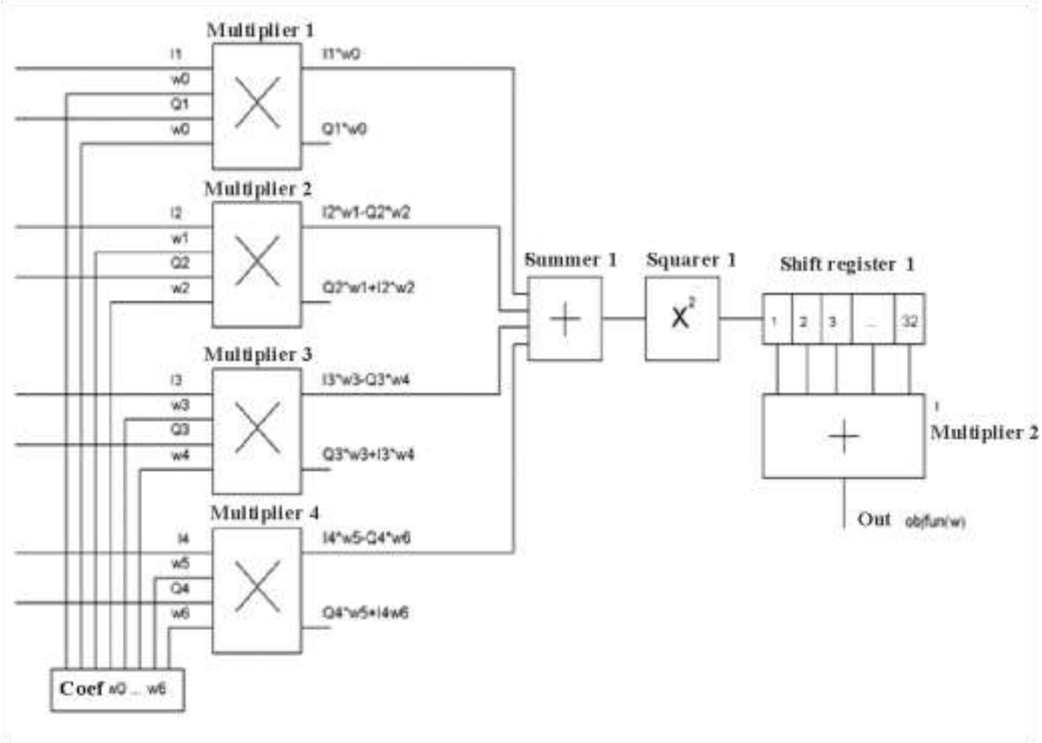


Fig-1: Multiplication of emitters signal on complex coefficients (upper scheme) and the calculation of the objective function (bottom scheme)

Quadrature signal components are marked as *I1 Q1, I2 Q2, I3 Q3, I4 Q4*. These signals are then used as the formation of the total signal on the output of suppressor and for the work of adaptive suppression algorithm. Quadrature signal components are used to calculate the objective function *objfun*. This algorithm will seek to reduce this objective function, respectively reducing the power of noise.

Current complex weighting coefficients are stored in the memory of the PLIC in a column of 6×1 vector.

$$W = \begin{pmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \end{pmatrix}. \qquad (1)$$

This first emitter has a real, unchanging during the algorithm work, weight coefficient $w_0 = 1$. Other coefficients will change dynamically for adjusting to the type of radiation pattern with the aim to reduce the function *objfun (W)*.

A gradient of the objective function is calculated for each *W* (Fig. 1) for each coefficient (6 values), which are also presented in a column 6×1.

$$gradW = \begin{pmatrix} gradient(w_1) \\ gradient(w_2) \\ gradient(w_3) \\ gradient(w_4) \\ gradient(w_5) \\ gradient(w_6) \end{pmatrix} = \begin{pmatrix} \frac{objfun(w_1+dw_1, w_{2...6}) - objfun(w_{1...6})}{dw_1} \\ \frac{objfun(w_1, w_2+dw_2, w_{3...6}) - objfun(w_{1...6})}{dw_2} \\ \frac{objfun(w_{1..2}, w_3+dw_3, w_{4...6}) - objfun(w_{1...6})}{dw_3} \\ \frac{objfun(w_{1..3}, w_4+dw_4, w_{5...6}) - objfun(w_{1...6})}{dw_4} \\ \frac{objfun(w_{1..4}, w_5+dw_5, w_6) - objfun(w_{1...6})}{dw_5} \\ \frac{objfun(w_{1..5}, w_6+dw_6) - objfun(w_{1...6})}{dw_6} \end{pmatrix}, \quad (2)$$

where $dw_1 = dw_2 = dw_3 = dw_4 = dw_5 = dw_6$ are small increments to calculate the gradients in digital form for each weight.

According to the conducted research, value $dw_1 \ldots dw_6$ must have $10^{-6} \ldots 10^{-8}$ (less-better) orders of magnitude. To implement gradient calculation as (2) for the scheme (Fig. 1) does not cause difficulties.

At the end of the work of the minimizing algorithm, summarized quadrature signals I and Q (received in the same way as a signal *I* in the diagram Fig. 1) are used for decoding of GPS/GLONASS signal.

To verify and determine the best algorithm parameters to minimize the objective function *objfun*(W) for the scheme of Fig. 1 model was developed in MatLab. The study tested the effectiveness and speed of noise suppression algorithm based BFGS method, conjugate gradient method, and steepest descent method. To ensure the stability of the algorithms, it is necessary to set the condition of the end determination of iterative search process of the minimum of function that provides small function increment at the end of the algorithm. The results of algorithm emulation in Matlab shows that the effective value is 10^{-9}–10^{-10}.

BFGS method relates to the optimization methods that are based on the accumulation of information about the curvature of the objective function for tracking changes of gradient. The method takes into account the quadratic nature of the objective function, and thus in many optimization problems it is more effective than gradient descent. The disadvantage of this method in its implementation in PLIC or microcontroller is Hessian calculation matrix with dimensions of 6×6. In the method of conjugate gradient (Fletcher-Reeves) the sequence of search directions that are linear combinations of the current and previous directions are built, and those to make search directions conjugated. For calculating this new direction search using only the current and penultimate gradients. For some optimization problems conjugate gradient method is more efficient than the method BFGS. Gradient descent uses the value of gradient only on current step to solve the optimization problem [1-3].

The algorithm works continuously, so the value of weighting coefficients of radiator arrays must be replaced with new ones in their calculation. Since interference is considered as stationary, then the objective function values taken for 32-64 counts time and its gradient weakly dependent on time, and depend only on the weights coefficients. Most countdowns do not require being stored in memory. The number of countdown of signals that must be considered in the objective function determined by the complexity of noise (wideband, modulation).

For interference with the band 15-40 MHz that used in the study of the efficiency of algorithms, the optimum number of time samples is 32-128. Coefficients, found by using the objective function in 16 times, provide the level of suppression of 5-10 dB lower than coefficients found using the objective function in 64 countdowns.

To simulate the input signals in the antenna compensator in program Matlab Simulink there was a scheme of radio-frequency section set up (Fig. 2). The input of 3 input receives noise that modeled in the scheme with pseudorandom sequence generators that implement Gold's code. Attenuator that are standing after the pseudorandom sequence generators regulates the number of interferences and its level. A mixture of interferences coming in each of the four channels (the number of antennas involved in suppressing interferences).

In each channel, taking to consideration the direction of arrival of interference (set in the program, which runs Matlab) and location of antennas at array, interferences delayed in time, emulating the direction coming from the given angles, and then summarized.

To test the algorithm performance there were simulated models, in which signals are, for example, in the following directions: theta = 10º, phi = 30º; theta = 75º, phi = 135; º theta = 40º, phi = 270º.

The level of noise suppression depending on the number of iterations while using the step to calculate the gradient $dw_1 = \ldots = dw_6 = 10^{-8}$, 64 countdowns to calculate the objective function and relation of interference / noise ratio of 70 dB.

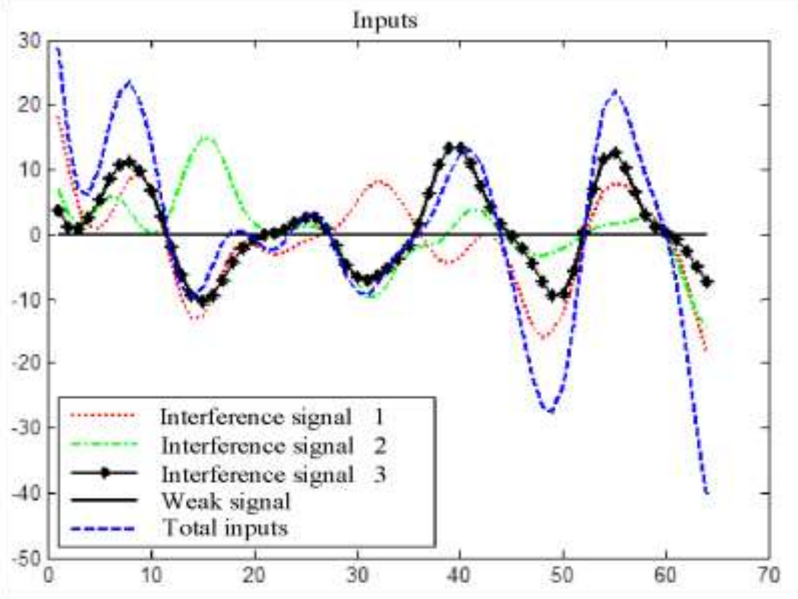


Fig-2: Input signals

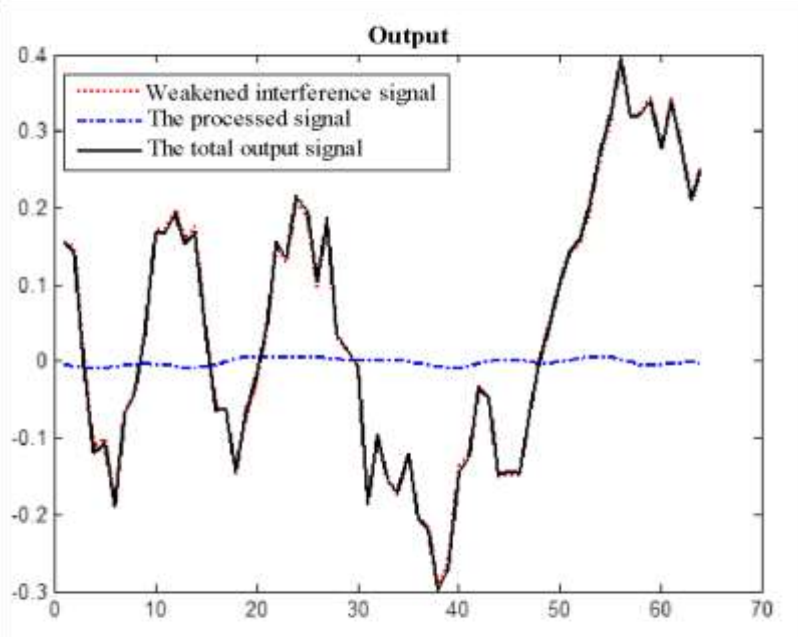


Fig-3: Output signals

In addition, algorithm performance with antenna system was tested. For this, for antennas, 1-4 (Fig. 1) is calculated amplitude and phase of the received signals (Fig. 3). These data are transferred to Matlab, where necessary coefficients are calculated by conjugate gradients. Considering the received coefficients (in a conjugate complex form), radiation pattern of array is calculated from the antenna 1-4. As a result, the resulting optimization coefficients allow getting noise suppression no worse of 50 dB (Fig. 4, 5).

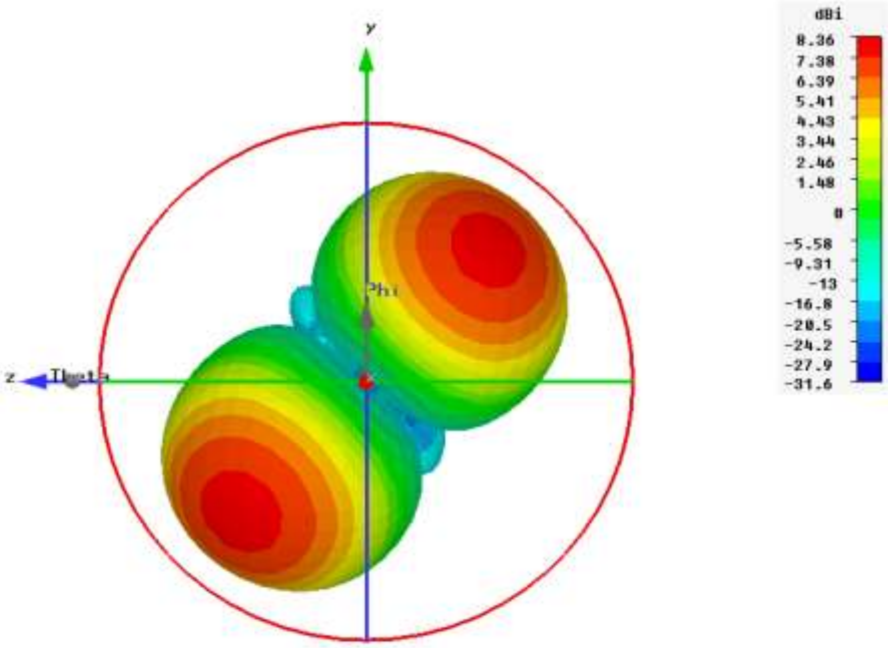


Fig. 4: Radiation pattern of antenna without interference suppression (in dB)

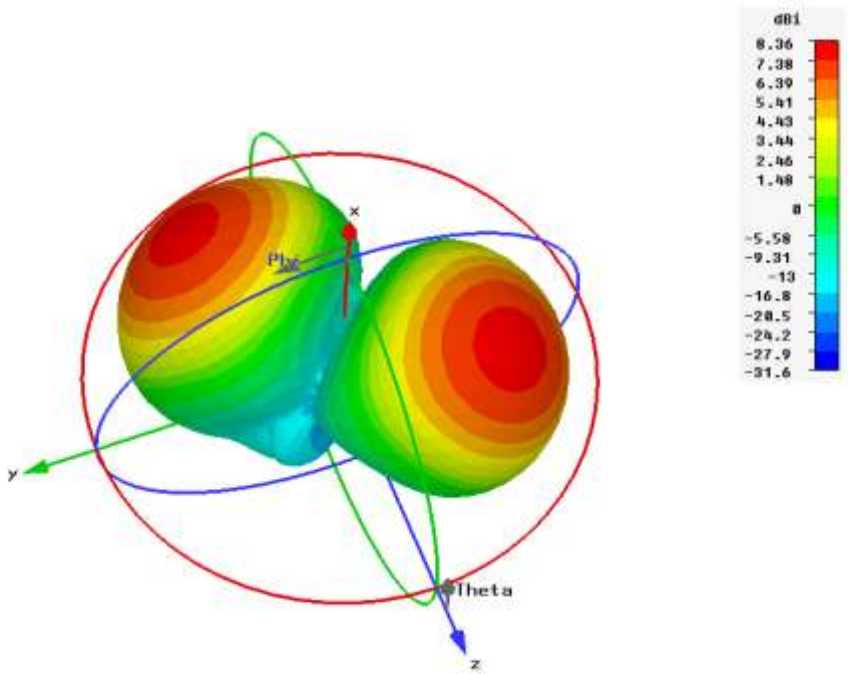


Fig- 5: Radiation pattern of antenna without interference suppression (in dB)

The comparison of the speed of the algorithms shown in (Table. 1). Conjugate gradient method shows a higher rate optimization, than the BFGS method, providing after 30-40 iterations suppression that is not worse than 40 dB. Gradient descent on speed a little bit inferior than conjugate gradient method.

Table 1

Method	BFGS	Conjugate gradients	Gradient descent
Achieving the maximum level of suppression, iterations	200-250	30-40	50-60 (maximum is less of 2-4 dB)

Based on the analysis of the data presented in Table 1 conjugate gradient method should be used for noise suppression.

Thus, as a result of the research, for the first time, the model of definition of complex weighting coefficients of the algorithm of adaptive spatial filtering on the basis of conjugate gradient was developed. Its distinctive feature is the use of quasi-Newton method for finding the minimum of the objective function using the method of conjugate gradients; it can significantly reduce computing calculation costs, while ensuring a given level of noise suppression.

CONCLUSION

Developed the model of definition of complex weighting coefficients of the algorithm of adaptive spatial filtering. For its development provided a comparison of various quasi-Newton methods for minimizing the objective function of a vector argument with different settings. All algorithms provide reaching potential characteristics of spatial processing at acceptable cost of computing.

The research of potential characteristics of the adaptive interference compensator while suppressing to three interferences showed that the adaptive compensator allows doing the noise suppression for amount of interferences with the level of no worse than 40 dB.

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