Processing and measuring frequency of Doppler echo signals

Sviatoslav T. Baras*[a], Svitlana O. Romanyuk[a], Serhii V. Tsymbal[a],
Andrzej Smolarz[b], Zhazira Amirgaliyeva[c,d]
[a] Vinnytsia National Technical University, 95 Khmelnytske Shose, Vinnytsia 21021, Ukraine;
[b]Lublin University of Technology, Nadbystrzycka 38A, 20-618 Lublin, Poland;
[c]Institute Information and Computational Technologies CS MES RK, Almaty Kazakhstan;
[d]Al-Farabi Kazakh National University, Almaty, Kazakhstan

ABSTRACT

The method of measuring the frequency with the use of time fragmentation of the Doppler echo signal is proposed. The method of following narrow-band filtering of Doppler echoes is improved. The structural schemes are presented and recommendations for improving the means of pre-processing and measuring the frequency of filling echoes of the Doppler velocity meter are formulated.

Keywords: hydroacoustics, speed meter, Doppler signal, processing, frequency, measurement.

1. INTRODUCTION

Modern navigational devices used in moving objects of the surface and, in particular, scuba diving, should be characterized by high levels of accuracy and reliability. The class of such devices includes Doppler lags – autonomous navigational devices designed to measure absolute and relative to the speed of the navigation object and the path it traverses. The problems of reliable and accurate determination of the velocity vector components of a moving object with the help of these devices remain unsatisfactory to date and the potential of these devices is not fully realized.

2. FORMULATION OF THE PROBLEM

Recent studies in this research area have shown that the most important source of the random component of the error of measuring the speed of the navigation object by the Doppler meter is the error of determining the Doppler shifts of the frequency [1]. This error is due to the complicated structure of the Doppler echo signal, which is characterized by significant fluctuations of the bypass and high-frequency filling [2,3]. Methods and means of measuring echo signals used in modern Doppler speed meters, do not fully take into account the features of the structure of echo signals and do not provide reliable determination of Doppler shifts of the frequency, which negatively reflects on the definition of components of the speed vector of a moving navigation object.

It should also be noted that pre-treatment devices of the Doppler meter perform not only useful changes in echo signals, increasing the signal/noise ratio, but also distorting their structure. Thus, experimental research of the pre-treatment pathway revealed a significant dependence of the accuracy of the measurement of the frequency of radio signal filling on transient processes in frequency-sampling circuits of pre-processing devices preceding the direct measurement of frequency [4,5].

Thus, based on recent research on the structure of Doppler echo signals it is possible to formulate the main approaches to the creation of new or improved existing methods and means of processing echo signals and to measure the frequency of their filling. That will reduce the measurement error of Doppler shifts of the frequency and increase the accuracy of the definition components of the speed vector of the navigation object by the Doppler meter.

To do this, we will share the procedure for reaching the goal set at the following stages:
- reception and preparation (formation) of the Doppler echo signal to the process of measuring its filling frequency;
- direct measurement of the filling frequency of the Doppler echo signal, taking into account the features of its structure.

* barasst03@gmail.com

3. RESOLVING THE PROBLEM OF NARROWBAND FILTRATION OF DOPPLER ECHO SIGNAL

Consider the generalized structural scheme of the receiving tract of the Doppler speed meter (Fig. 1), which consists of a hydroacoustic antenna, pre-amplification cascades, a band-pass filter, basic amplification cascades, a frequency meter[1].

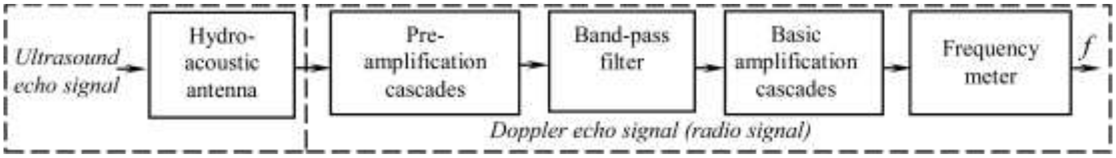

Fig. 1. Means of processing and measuring the filling frequency of echo signals of receiving tract of the Doppler speed meter

From Fig. 1 it follows, that in the receiving tract of the Doppler chip log, the echo signals frequency meters are structurally located after the pre-processing devices, which amplify the echo signal and improve the signal/noise ratio[6,7,8]. The bandwidth of the frequency-selective circuits of the receiving tract of the speed meter is determined by contradictory requirements: to ensure the maximum signal/noise ratio the band should be minimal, but the band should be wide to reduce the duration of the transient processes. On the other hand, the bandwidth of the frequency-selective circuits should be chosen taking into account the dynamic changes of the Doppler shifts of the input echo signal frequency, which correspond to the range of changes the speed of the navigation object. Possible positions of the echo signals spectrums relative to the bandwidth for cases of wide and narrow band respectively are shown at Fig. 2a and Fig. 2b. In both cases the measurement errors of Doppler shifts of frequency there will be significant[6].

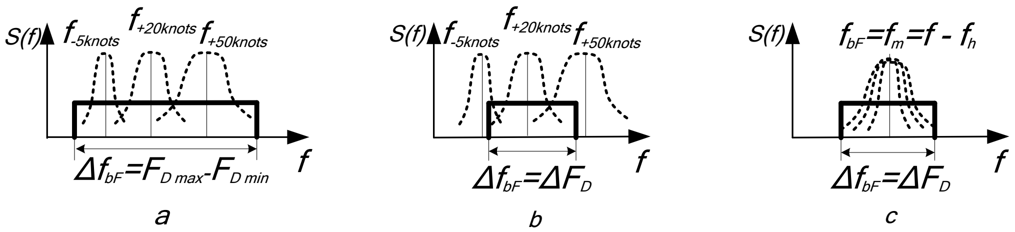

Figure 2. Filtering of Doppler echo signals at increasing of bandwidth (a),at decreasing of bandwidth (b), narrowband tracking filtering (c)

The degree of discrepancy between the values of the filling frequency of the pulse radio signal and the frequencies in the transient processes zones at the output of the narrowband filter was experimentally determined to estimate the influence of transient processes in frequency-selective circuits on the high-frequency filling of the Doppler echo signals[5]. The result is as follows. If there is a big difference between the carrier frequency of the input signal f and the average frequency of the filter bandwidth f_{0F}, then the accurate measurement of the filling frequency of the Doppler echo signal on the filter output is possible only if the measuring strobe (measuring interval) is outside of the transient processes zones. Provided that when the carrier frequency of the input radio signal f is close enough to the average frequency of the band-pass filter f_{0F}, the minimum distortions of the high-frequency filling of the output signal is observed during the duration of the transient processes. In practice, minimize the influence of transient processes on the filling frequency of the Doppler echo signal, and also reduce the minimum allowable signal/noise ratio by the narrowband tracking filtering, that is, by reducing the filling frequency of echo signal f to the value of the average frequency of the filter setting f_{0F} (Fig. 2, c).

For implementation of the narrowband tracking filtering of echo signals of the Doppler meter, the information on the average value of the input signals frequency f_{av} along the corresponding beam of the antenna system of the meter is required. The value of the averaged frequency can be determined over a long period of time by the results of measuring the filling frequency of echo signals received in Z previous cycles of radiating-receiving of the signals

$$f_{av} = \sum_{i=1}^{Z} f_i \,, \tag{1}$$

where Z is the number of cycles of radiating-receiving of the signals, during which the averaged value of the input echo signals frequency is determined.

Considering the significant inertia of the navigation object, the duration of the averaged time of the filling frequency of the input echo signals, which is determined by the Z-cycles of radiating-receiving of signals by the meter, can range from units to tens of seconds[1]. Thus, at the moment of receiving each Doppler echo signal the device has information about the current average filling frequency of the input echo signals.

For the subsequent input echo signal convertions, it is necessary to determine the difference frequency between the averaged frequency of the input echo signal f_{av} and the average frequency of the selective circuit f_{0F}, which is called the heterodyne frequency [9,10]

$$f_h = f_{av} - f_{0F}\,. \tag{2}$$

The value of the heterodyne frequency is used to create a heterodyne voltage, which, in conjunction with the input echo signal, is in working mode fed to a frequency mixer that changes the filling frequency of echo signal. Doppler echo signal frequency at the mixer output equals[5]

$$f_m = f - f_h\,. \tag{3}$$

After that, the echo signal arrives at the narrowband filter input, the average frequency of which is equal to the frequency of the input signal. The bandwidth of such a filter can be reduced to the maximum width of the spectrum of the Doppler echo signal. Only after this procedure the echo can be subjected to the procedure of precise measurement of the filling frequency [11,12].

The calculation of the actual values of the Doppler shifts of the frequency should be made taking into account all the conversions that took place in the narrowband filtering device. This is simply implemented using equation (3), considering that the values of the frequencies f_m and f_h are known. Further calculations of the components of the speed vector are performed according to the traditional calculation expressions[1,6].

A functional diagram of the narrowband tracking filtering of the hydroacoustic Doppler speed meter is shown at Fig. 3. It consists of a series connected mixers 1, a narrowband filter 2, a frequency meter 3, a digital computing device 4, a control circuit 5, and a heterodyne 6.

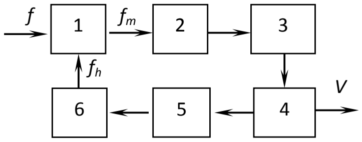

Fig. 3. Means for narrowband tracking filtering of echo signals of the Doppler speed meter

Means for narrowband tracking filtering of echo signals of the Doppler log works in this way. In the receiving tract of the lag, the amplified Doppler echo signal is fed to the band-pass filter 2 after the special frequency mixer 1 (Fig. 3). One of the inputs of the mixer 1 receives an echo signal, and the second input – heterodyne signal of such a frequency that would generate the frequency in the output signal equal to the average frequency of the band-pass filter or close to it. The heterodyne 6 must be controlled by the control circuit 5. The control signal must be determined by a sufficiently long measuring interval, which is associated with the speed of the navigation object, that is, with a certain frequency of the input signal. Note that the exact equality between the frequency of the output signal of the mixer 1 and the average frequency of the band-pass filter 2 is not required – it can be easily implemented in practice. Another important remark, that makes this tract different from the normal closed ring of phase auto-setting of the frequency, is directly when receiving an input Doppler signal, the frequency of the heterodyne voltage should not change.

In the proposed scheme, the determining the values of Doppler shifts procedure, which is used to calculate components of the speed vector by the digital computing device, will change somewhat. The fact is that the frequency meter will always measure the frequency, which is equal to or close to the average frequency of the band-pass filter. Let's consider this question in more detail [5].

The digital computing device 4 of speed meter calculates the value of the heterodyne frequency, with which the control circuit 5 generates a control signal supplied to the heterodyne 6 to generate a heterodyne voltage with a predetermined frequency (2). This frequency is measured immediately prior to the arrival of the Doppler echo signal by the standard frequency meter used in the speed meter circuit. There are no rigid requirements for the stability of the heterodyne frequency it is precisely because of the currently measurement. Thus, in the operating mode, the frequency mixer 1 receives a heterodyne voltage with frequency f_h and a Doppler echo signal with frequency f_1. The frequency of the Doppler echo signal on the mixer output is determined by the expression (3).

The Doppler echo signal at the mixer 1output is characterized by the frequency f_m (3), and it falls on the frequency meter 3. The last step is to determine the actual frequency of the Doppler echo signal *f*. This is implemented in a digital computing device using expression (3) and known frequency values f_m, f_h. Further calculations of speed vector components are performed according to the traditional calculation expressions [5,11]. Thus, one of the ways to reduce the measuring error of the filling frequency of Doppler echo signals, caused by the influence of noises and transient processes of devices of lag preprocessing, may be narrowband tracking filters, built on the principle of tracking to the spectrum of the Doppler echo signal.

4. TIME FRAGMENTATION OF THE DOPPLER ECHO SIGNAL

After preprocessing, the measurements of the filling frequency of echo signals of the Doppler speed meter are carried out. But considering the complex structure of the echo signal due to the peculiarities of its formation, spreading and processing, it can be argued that the most precise values of Doppler shifts of the frequency are concentrated within limits of this signal certain fragments. Thus, only the parts of the signal that are within these fragments can be subjected to the measurement process. This is an obvious condition for reducing the measuring error of the Doppler shifts of the frequency, and, consequently, increasing the accuracy of the measurements of the speed vector components of the navigation object by the Doppler meter.

An analysis of the structure of Doppler echo signals, performed in[2,3], suggests that useful information about Doppler shifts of frequency is concentrated in those fragments of the Doppler signal, where the amplitude of its envelope accepts maximum values (except for fronts zones). Considering such features of the structure of the Doppler echo signal can offer a method of fragmentation of this signal in time. In this case, it is necessary to take into account the changes due to the influence of the transient processes of tract of preprocessing information of the speed meter that distort the envelope and high-frequency filling of the Doppler echo signal, violating the links between them [15].

First of all, from the process of measurement it is necessary to remove the zones of the front and rear fronts of the Doppler echo signal. These zones are characterized by significant frequency distortions, which are caused by two factors. The first is the time of the sounding of the scattering area of the bottom t_c, during which the formation of fronts of the Doppler echo signal occurs not with all the scattering elements of the sounded section of the bottom[1]. The fact is that the radiation and reception of signals of end-time duration at an angle to the bottom by an antenna of the Doppler meter leads to an increase the duration of the adopted Doppler echo signal, as well as the emergence in its composition of not only established but also not established zones at the beginning and at the end of this signal. These zones will be characterized by an incomplete structure compared to the structure of the median established zone of the Doppler echo signal. As a result, in the not established zones of the fronts, there are significant fluctuations of the amplitude and frequency of high frequency filling, which lead to significant measurement errors of the Doppler shifts of frequency F_D.

The second factor is the transient processes t_{tp} that arise in the frequency-selective circuits of the receiving tract of the speed meter during the processing of Doppler echo signals[5]. At the time of the appearance and end of the Doppler echo signal there are transient processes that during the time of their existence distort the filling frequency at the beginning and the end of the Doppler echo signal [12,13,4].

To remove the zones of the front and rear fronts of the Doppler echo signal, it is necessary to compare the duration of the sounding process of the scattering area of the bottom and the duration of the transients processes. The time of covering the bottom area is equal

$$t_c = \frac{H}{c}\left[\frac{1}{\sin\left(\alpha_0 - \gamma/2\right)} - \frac{1}{\sin\left(\alpha_0 + \gamma/2\right)}\right] \tag{4}$$

and the transient processes duration

$$t_{tp} \geq k / \Delta f_F\,, \tag{5}$$

where *k* is the coefficient, which depends on the coefficient of rectangularity of the amplitude-frequency characteristic of the band-pass filter; Δf_F is the filter bandwidth; *H* is the depth of the water area; *c* is the speed of ultrasound in aquatic environment; α_0 is the is the angle relative to the horizon under which the radiation and reception of signals are carried out; γ is the width of the antenna directivity characteristic.

After this, a higher value is selected and on its basis a strobe τ_F of the measurement prohibition is established at the beginning and ending of the echo signal (Fig. 4).

The average part of the Doppler echo signal, obtained as a result of separating from the reception signal of its front zones, contains a fully formed structure[3]. Within the middle part of the Doppler echo signal can distinguish two types of fragments: fragments that correspond to the maximum values of the amplitude of the Doppler echo signal envelope and contain the most exact values of Doppler shifts of frequency, and fragments that correspond to the minimum values of amplitude of the envelope, characterized by high-frequency filling, which changes with a certain modulator law, contain phase manipulation and can’t be used to exactly measuring of Doppler shifts. Taking into account the structure of the middle part of the Doppler echo signal, as well as the relationship between its amplitude and high-frequency filling, it is advisable to apply the threshold method for selecting amplitudes to select the Doppler echo signal fragments, which contain the most exact values of the Doppler shifts of frequency[3]. For this purpose, in the middle part of the Doppler echo signal, zones (fragments), in which the amplitude of the Doppler echo signal envelope exceeds the C_a, are isolated (Fig. 4). When the amplitude of the Doppler echo signal envelope is increase by a certain threshold C_a, the front edge of the measuring strobe is formed, and when of amplitude is decrease in the relative to the set threshold, the rear front of this pulse is formed (Fig. 4). Thus, measuring strobes can be oriented within the middle part of the Doppler echo signal, which is characterized by constant high-frequency filling. The number of these measuring strobes will depend on the number of oscillation periods of the envelope of middle part of the Doppler echo signal, which, in turn, depends on the speed of the navigation object, as well as on the duration of the radiopulse that is radiated.

But from a technical point of view, for the allocation of such zones, it is necessary to constantly analyze the state of the envelope using amplitude detection. The use of such a device leads to a delay the envelope of the Doppler echo signal in relation to its high frequency filling. In addition, narrowband filtration leads to an increase in the inconsistency between the time intervals of the existence of large amplitude of the envelope and the Doppler echo signal zones with the smallest frequency fluctuations. Therefore, measuring strobes must be adjusted in accordance with the above-mentioned features of the equipment of the Doppler speed meter[7].

The application variant of adaptive threshold[7] is shown at Fig. 4. The algorithm of its formation is as follows. In the Doppler signal standby mode, the minimum value of the threshold C_{amin}, which determines the start time (t'_1, t'_3), is set. The value of the threshold up to C_{amax} increases sharply simultaneously with the moment of operation of the comparator (at moments of start). Therefore, the moments of the end operation of the frequency meter will be formed by a comparator before - (t'_2, t'_4). Thus, the time interval (measuring strobe) generated by the comparator will be as close as possible to the zone with minimal frequency fluctuations. At these moments (t'_2, t'_4), the threshold jumps back to its original state to fix the new start of the frequency measurement procedure. It should be noted that the initial values of the thresholds C_{amin} and C_{amax} are set in the process of device setup.

After the adoption of these measures, it can be argued that the overwhelming majority of the instantaneous frequencies within the measuring strobe will be characterized by slight fluctuations. At the same time, it is impossible not to take into account the above-mentioned features of the influence on the structure of the Doppler echo signal of the narrowband filter, and the nature of the high-frequency filling, which is the result of the formation of this signal in the water environment. In addition, an important factor for measuring the frequency is the presence of transient processes that occur when passing the Doppler echo signal through the narrowband filter and that the carrier frequency during the transient process is influenced by the average bandwidth of the narrowband filter. Thus, there are sufficient grounds to deepen and complete the Doppler echo signal preparation procedure to measure its filling frequency.

In terms of practical implementation, it is proposed to take one more step. It consists in introducing an additional division of high-frequency filling segments within the measuring strobes on the identical series of 100-200 periods - partial signals. Than it necessary the measurement of the average frequency in each such partial signal is carried out and the subsequent statistical processing of the obtained results is performed by methodology[1]. The logic of this sentence is that significant deviations of the frequency in any partial signal will induce the complete removal of this partial signal by the results of statistical processing.

The final stage is the direct process of filling frequency measuring in the selected fragments by a modified method of counting the zeros. To do this, in the selected fragment, the number of whole periods of the measuring frequency n_{mf} of filling the Doppler echo signal (Fig. 4, d) and the number of periods of the reference frequency n_r of the reference generator are calculated (Fig. 4, d). At the results of these measurements the filling frequency of the echo signal is determined according to the known expression

$$f = n_{mf} / (n_r T_r)\,, \tag{6}$$

where T_r is the reference frequency period.

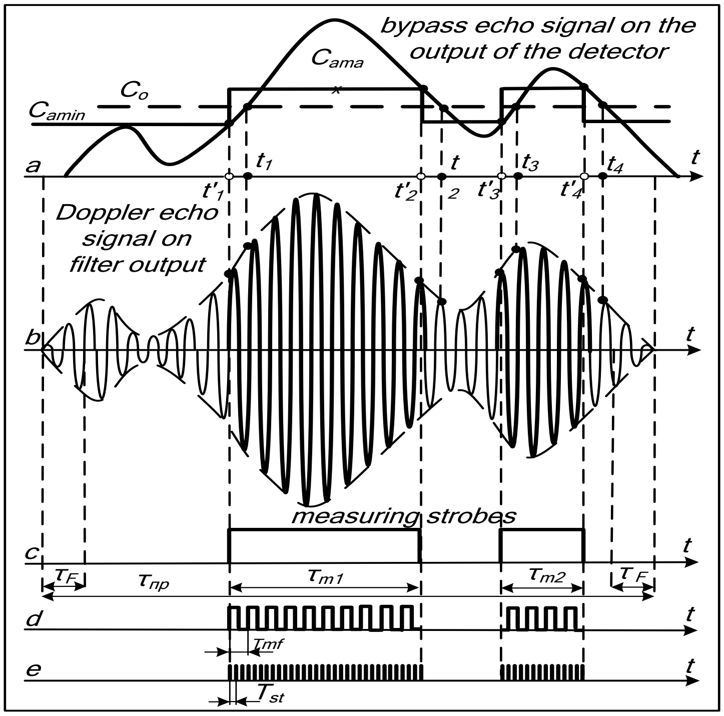

Fig.4. Explanation of time fragmentation methods and measurement of filling frequency of the Doppler echo signal

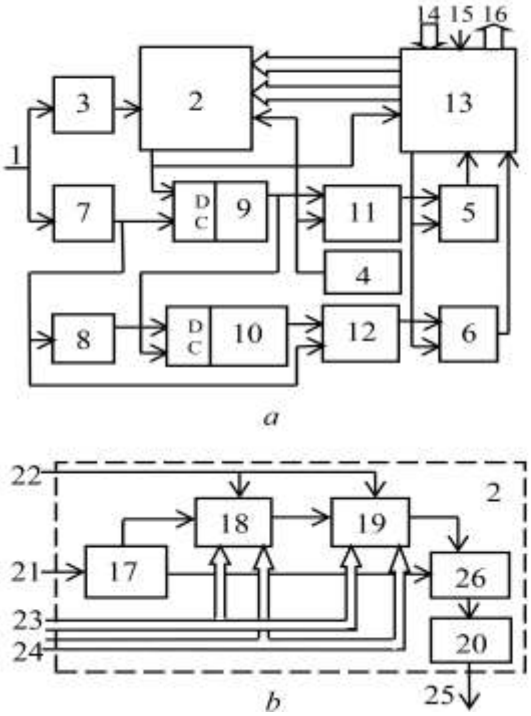

Fig.5. Means of measuring the filling frequency (a) and time fragmentation (b) of the Doppler echo signal

In practice, the processes of fragmentation of the Doppler echo signal and the measurement of the filling frequency can be realized by a means based on the time fragmentation method using an adaptive threshold and a modified zero counting method. The structure of the device is shown in Fig. 5

The echo signal (Fig. 4, b) on the first input bus 1 enters to the input of the limiter signals 7 and the detector 3 (Fig 5, a). The detector 3 selects the envelope of this signal (Fig. 4a), which supplied to the first input of the control unit 2 (Fig. 5, a). The limiter 7 forms a sequence of pulses of the measuring frequency. At the output of block 2, the N measurement strobes τ_{m1}, τ_{m2}, ..., τ_{mN} are formed (Fig. 4, c), the duration and orientation of which depends of the threshold level C_a of the comparator 17 (Fig. 5, b), of the delay time by the detector of the envelope, of the duration of the front and rear fronts, which are taken into account by timers 18, 19 (Fig. 5, b). Within each measuring strobe, the number of periods n_{mf} of the measuring frequency of filling of the Doppler echo signal filling (Fig. 4, g) is calculated by the counter 11 (Fig. 5, a). Within each measuring strobe, and the number of periods n_r of the reference frequency (Fig. 4, d) of the reference generator 4 (Fig. 5, a) is calculated by the counter 12 (Fig. 5, a).

The measurement results are sent to the control division block 13 (Fig. 5a), which calculates the frequency by the expression (6). The results of measuring the filling frequency in the selected fragments in the form of a data array are received in the device of the secondary processing of information, where additional statistical processing and definition of Doppler shifts of frequency and calculations of components of the speed vector are performed.

It should be noted that presentation of the results of the measurement in the form of an array is extremely convenient for further secondary processing. Additional processing and correction of data arrays, for example according to the method outlined in[1], makes it possible to significantly improve the accuracy of the Doppler speed meter. The speed of a modern element base allows doing this in real time without difficulty.

5. CONCLUSIONS

It is shown that in order to create the best conditions for accurate measurement of the carrier frequency of the Doppler signal, it is necessary to use the method of narrowband tracking filtration during its preprocessing. This ensures minimal distortion of the structure of the Doppler echo signal during its passage through the band-pass filter. It is important that at the same time, the minimum distortion of the filling frequency of the output echo signal with noises and transient processes of the devices of pre-processing of the speed meter is taking place. But the proposed method of filtration allows decreasing the measuring errors of the filling frequency of Doppler echo signals, and therefore, increases the accuracy of the measurement of speed vector components of the navigation object by the Doppler meter.

It has been established that due to the fragmentation of the input signal and the measurement of the frequency of high-frequency filling of the Doppler signal within the limits of certain fragments there is an increase in the accuracy of the measurement of frequency. These fragments in which the envelope of echo signal exceeds a certain (adaptive) threshold value (with the exception of the signal fronts) are free from frequency fluctuations due to the nature of the Doppler echo signals and the influence of the equipment of the receiving path of the speed meter, and their Doppler shifts of frequency adequately correspond to the component speed of the navigation object. Consequently, the accuracy of measuring the speed vector components of the navigation object by the Doppler meter is increased.

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