METHOD OF THE HIGH ACCURACY RESOLVING RANGE/VELOCITY UNCERTAINTY FOR THE LASER SCANNER WITH LINEAR FM

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ABSTRACT

The laser scanning system on basis of CO_2 laser with continuous radiation with 10.6 μm wavelength situated onboard of aircraft is considered. The system is intended for remote sensing of surface ahead of aircraft. Simultaneously distance image of observed scene has to be formed and vehicle own velocity has to be measured. The system operates in a mode of azimuthal one-line scanning across a trajectory of flight. For distance measurement linear-frequency modulation with pulse compression is used. Pulse compression is produced with dispersive acoustic delay line. Mathematical expressions are known that permit to resolve distance/speed uncertainty in this case. These expressions need two sensing of each element of a surface. However in reality scanning is carried out continuously, so two neighbor sensings is made on different elements of surface.

Suggested method permit to increase noticeably the accuracy of vehicle own velocity measurement while permitting to measure distance to each element of surface in case of continuous scanning. For this purpose the fact is used, that value of the carrier own velocity is slowly varying function. So, averaging and extrapolation of the information is made line by line to increase accuracy of vehicle own velocity measurement. For each sensing, distance is calculated based on the extrapolated velocity value.

INTRODUCTION

The laser scanning system on basis of CO_2 laser with continuous radiation with 10.6 μm wavelength situated onboard of aircraft is considered. The system is intended for remote sensing of surface ahead of aircraft. Simultaneously distance image of observed scene has to be formed and vehicle own velocity has to be measured. The system operates in a mode of azimuthal one-line scanning across a trajectory of flight. For distance measurement linear-frequency modulation with pulse compression is used. Pulse compression is produced with dispersive acoustic delay line [Stephan, B., 1985; Dansac, J., Meyzonnette, J. L., 1985].

In the system realizing such kind of modulations (fig. 1), almost all laser output power goes to acoustic-optical modulator (AOM) where radiation gets linear FM with the triangular law of change of frequency. The modulated laser beam goes through optics and the scanner and is radiated in space, and the part of not modulated radiation branches off to the photodetector where it mixes up with the received reflected signal. As a result of this mixing optical heterodyning of received laser signal is carried out, and linear FM is transferred to intermediate frequency. At presence of vehicle own velocity frequency of the reflected signal is increased by the Doppler shift value. As vehicle own velocity can vary considerably, radio oscillator is used (unlike to [Stephan, B., 1985]) to maintain a necessary dynamic range on frequency.

Further the signal goes to a dispersive acoustic delay line (DADL) where it is compressed in the number of times equal to product of frequency deviation ΔF and linear FM half-cycle τ_0. An output of DADL is series of short pulses going with frequency that is equivalent of double modulation frequency of laser. The generated pulses are received by the counter which measures a time delay t_{del} between the compressed pulses and clock pulses marking the beginning of sensing.

Measured delay times goes to the processor of preliminary processing of the information. A task of the processor is range/velocity uncertainty resolution, radio oscillator management in real time and transformation of distance measurements to a kind convenient for the further processing. We shall accept periodicity of sensing equal to τ_{dev} = 20 μs, that corresponds to one linear section of triangular linear FM with deviation of frequency of radiation ΔF = 40 MHz. One sensing gives one element of distance image.

By results of double sensing slant-distance up to probed surface that is perpendicular to axis of beam (R) and a radial component of vehicle velocity (V) can be accordingly determined as [2, 3]:

$$R = \frac{c}{4}\left[t_{del}^{+} + t_{del}^{-}\right]$$
$$V = \frac{\Delta F \cdot \lambda}{4\tau_{dev}}\left[t_{del}^{-} - t_{del}^{+}\right] \qquad (1)$$

where c is the velocity of light; λ is the radiation wave-length; t_{del}^{+} is delay time of the compressed pulse for increasing section of linear FM of the reflected signal; t_{del}^{-} is delay time of the compressed pulse for decreasing section of linear FM of the reflected signal, ΔF is the deviation of radiation frequency, t_{dev} is the linear FM half-cycle.

Delay time is expressed as:

$$t_{\text{del}} = 2\frac{D}{c} + (-1)^n \frac{2 \cdot \tau_{dev}}{\Delta F \cdot \lambda} V_{\text{dop}} + \xi_t \qquad (2)$$

where D is slant-distance;

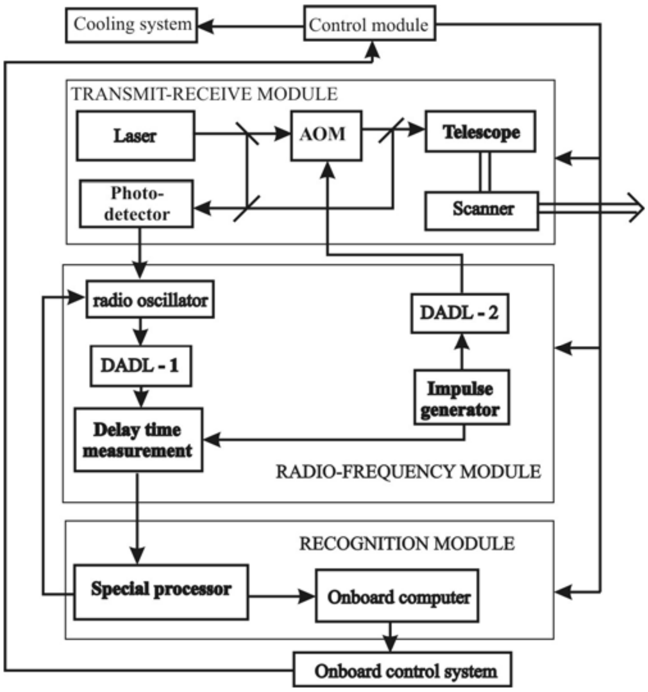

Figure 1. Distance measurement system based on linear FM with pulse compression.

n is the number of an image element (number of sensing) in a line;

V_{dop} is the Doppler velocity along a direction of a laser beam;

ξ_t is a delay time measurement error.

Mean square deviation of an error ξ_t depends on value of a signal/noise ratio on an output of radio-frequency module of laser locator and can be expressed in a first approximation as follows [Dansac, J., Meyzonnette, J. L., 1985]:

$$\delta(\xi_t) = \frac{1}{\Delta F\sqrt{A/A_N}} \tag{3}$$

A is intensity of the received signal;

A_N is average intensity of noise.

Table 1 shows how mean square deviation ξ_t depends on the signal/noise ratio in case of sensing of a frontal plane, and corresponding to it values of mean square deviations of measurements of distance and velocity.

Табл.1.

A/A_N	$\delta(\xi_{t\,2})$ с	$\delta(R)$ м	$\delta(V)$м/с
10	$0.8\cdot10^{-8}$	1.7	$0.6\cdot10^{-1}$
15	$0.65\cdot10^{-8}$	1.4	$0.5\cdot10^{-1}$
20	$0.56\cdot10^{-8}$	1.2	$0.42\cdot10^{-1}$
50	$0.35\cdot10^{-8}$	0.75	$0.26\cdot10^{-1}$

In reality, accuracy will be noticeably worse as scanning is carried out continuously and resolving of range/velocity uncertainty is made by results of sensings of different regions of a surface which can lie on essentially different distances.

THE METHOD DESCRIPTION

The way of processing of the delay times sequence is suggested, that allows to increase accuracy of vehicle own velocity measurement, with a simultaneous possibility of distance measurement on each sensing. For this purpose it is possible to use that fact, that value of vehicle own velocity is slowly varying function, whereas time of scanning of one line does not exceed 0.01 s.

Therefore, to increase accuracy of velocity measurement it is possible to accumulate and average information on each line. At that it is possible to consider velocity to be constant during a line. Then having averaged value of velocity with use of all sensings on a line, it is possible to calculate distances in each element of a previous line. In practice, however, it is more convenient to calculate distances for each element right after information is received. To do this, it is necessary to make extrapolation of velocity value for the period of the next line, and to calculate distances for each sensing based on this value. Thus, two loops of calculation are formed: a vehicle own velocity calculation and oscillator management loop; and a distance calculation on elements of a line of sensings and image transformations loop.

Let's obtain necessary expressions. Doppler shift of frequency ΔF_{dop} is determined as

$$\Delta F_{dop} = \frac{2V_R}{\lambda}$$

where λ is radiation wave-length; V_R is radial velocity.

To maintain system mode of operation in an operating range the part of Doppler shift of frequency is compensated by radio heterodyning. Then the signal delay time, caused by Doppler effect and heterodyning, is expressed as

$$t_{dop} = \frac{\partial t}{\partial F_{dev}} \cdot \Delta F_{\Sigma} = \frac{\tau_{dev}}{\Delta F_{dev}}\left(\frac{2V_R}{\lambda} - F_{het}\right) = \\ = \frac{\tau_{dev}}{\Delta F_{dev}}\left(\frac{2V \cdot \cos\alpha \cdot \cos\beta}{\lambda} - F_{het}\right)$$

Where ΔF_{dev} is deviation of frequency; τ_{dev} is linear FM half-cycle; F_{het} is frequency of heterodyning; V is the vehicle horizontal velocity; α and β are viewing angles of a scanning beam

Total delay time of a signal is a sum of delay caused by distance up to probed surface and delay caused by Doppler effect. And the second part could be positive or negative depending on what happens with linear FM frequency - does it increases or decreases during this sensing.

Thus

$$t_{del}^{+} = \frac{2D}{C} + \frac{\tau_{dev}}{\Delta F_{dev}}\left(\frac{2V \cdot \cos\alpha \cdot \cos\beta}{\lambda} - F_{het}\right) \\ t_{del}^{-} = \frac{2D}{C} - \frac{\tau_{dev}}{\Delta F_{dev}}\left(\frac{2V \cdot \cos\alpha \cdot \cos\beta}{\lambda} - F_{het}\right) \quad (4)$$

From here it is easy to obtain the necessary expressions:

$$V = \frac{\lambda}{2} \cdot \frac{1}{\cos\alpha \cdot \cos\beta}\left(\frac{\left(t_{del}^{+} - t_{del}^{-}\right) \cdot \Delta F_{dev}}{2\tau_{dev}} + F_{het}\right) \quad (5)$$

for section of linear FM where frequency is increasing:

$$D = \left\{t_{del}^{+} - \frac{\tau_{dev}}{\Delta F_{dev}}\left(\frac{2V \cdot \cos\alpha \cdot \cos\beta}{\lambda} - F_{het}\right)\right\} \cdot \frac{C}{2} \quad (6)$$

for section of linear FM where frequency is decreasing:

$$D = \left\{t_{del}^{-} + \frac{\tau_{dev}}{\Delta F_{dev}}\left(\frac{2V \cdot \cos\alpha \cdot \cos\beta}{\lambda} - F_{het}\right)\right\} \cdot \frac{C}{2} \quad (7)$$

Processing in a velocity measurement loop

Let's consider how vehicle own velocity measurement loop operates.

1. By results of sensing of each two neighbor elements in a line vehicle own velocity is calculated according to expression (5). At that, for each pair of measurements angles α and β are considered identical. At the same time, sensings in which there is no received signal are excluded by threshold processing; also sensings are excluded in which calculated velocity differs from the current one on some preset value. Quantity N of values that passed thresholding is counted. Such logic processing allows to compensate influence of situations, when the next elements lie on the surfaces located on essentially different distances (for example, at transition of the laser beam from a wall of a building to underlying surface), and also cases of a false alarm, i.e. when noise burst is accepted for a signal.

2. All other calculations in a velocity measurement loop are made after the end of the working part of a scanning line. First, average value of vehicle velocity is calculated for the current scanning line

$$V_{av} = \left(\sum_{i=1}^{N} V_i\right) \Big/ N$$

Then averaging on two consecutive scanning lines is made.

$$\left(V_{\tilde{n}\check{\partial}}\right)_i = \frac{\left(V_{av}\right)_i + \left(V_{av}\right)_{i-1}}{2}$$

Such averaging is necessary for distortion compensation in a case when most of objects that form scene are oriented the same way relative to the flight direction, i.e. the scene "is warped". As the direction of scanning varies from a line by the line averaging compensates the systematic inaccuracy arising within the limits of one line.

3. To increase stability of algorithm the estimation of true velocity is made by a filtration, which uses the calculated value of velocity and the value of velocity extrapolated for this line in the previous cycle

$$\left(V_{filtr}\right)_i = k_1 \cdot \left(V_{\tilde{n}\check{\partial}}\right)_i + k_2 \cdot \left(V_{ext}\right)_i \quad (8)$$

где k_1 и k_2 - коэффициенты ($k_1 + k_2 = 1$).

Where k_1 and k_2 are some coefficient ($k_1 + k_2 = 1$).

Then new value of extrapolated velocity is calculated based on the first difference of velocity estimations on last two lines

$$\left(V_{ext}\right)_{i+1} = 2\left(V_{filtr}\right)_i - \left(V_{filtr}\right)_{i-1} \quad (9)$$

This value of extrapolated velocity is used in a distance calculation loop for calculating distances on the next scanning line.

4. In other part of a velocity calculation loop the value of change of oscillator frequency for the next line is determined.

In order to prevent overcorrection oscillator is tuned on velocity value that is smaller than the calculated one on some value Q:

$$V^{*} = \left(V_{ext}\right)_{i+1} - Q$$

Since for fine tuning of oscillator it is necessary to determine value of change of its frequency relative to the current frequency, from the obtained velocity value V^* the value of velocity corresponding to the current tuning of oscillator is subtracted, and the correction of oscillator frequency ΔV_{het}, divisible by minimal quantization step of oscillator fine tunings is determined.

$$\left(\Delta V_{het}\right)_{i+1} = \left\lfloor V^{*} - \left(V_{het}\right)_i \right\rfloor_{\Delta V_{\min}}$$

and

$$\left(\Delta f_{het}\right)_{i+1} = \frac{2\left(\Delta V_{het}\right)_{i+1}}{\lambda}$$

At that value ΔV_{min} is determined by the following expression

$$\Delta V_{min} = 0.5 \cdot \left(\Delta f_{het}\right)_{min} \cdot \lambda$$

Where $\left(\Delta f_{het}\right)_{min}$ is minimal quantization step of oscillator frequency changes; ΔV_{min} is corresponding quantization step of velocity changes; λ is radiation wave-length.

Simultaneously, value of oscillator tuning frequency is calculated that will be used for the next line in a distance calculation loop

$$\left(V_{het}\right)_{i+1} = \left(V_{het}\right)_i + \left(\Delta V_{het}\right)_{i+1}$$

Thus, output of algorithms of a velocity calculation loop were values of change of oscillator frequency $(\Delta f_{het})_{i+1}$, value of velocity which will be compensated by oscillator on the next line $(V_{het})_{i+1}$, and value of predicted vehicle velocity $(V_{ext})_{i+1}$ on the next line. Value $(\Delta f_{het})_{i+1}$ goes to radio-frequency module, values V_{ext} and $(V_{het})_{i+1}$ go to the distance calculation loop.

Processing in a distance calculation loop.

Let's consider how distance calculation loop operates. The loop operates in the rate of measurements arrival. I.e. calculation of distance to probed surface is carried out right after current time delay measurement arrives and before the next measurement arrives.

Input of a distance measurement loop algorithms are values of a delay times $t_{del}^{+/-}$.

To do calculation in distance measurement loop the value of the correction of delay time (t^{∇}) is required. It is connected to incomplete compensation of velocity by oscillator and is determined for each element of a scanning line as:

$$t^{\nabla} = (V_{ext} \cdot \cos\alpha \cdot \cos\beta - \left(V_{het}\right)_{i+1}) \cdot k \quad , \qquad (10)$$

Where V_{het} is value of velocity compensated by oscillator; $k = \left(2 \cdot \tau_0\right) / \left(\Delta F \cdot \lambda\right)$ is constant of proportionality.

Slant-distance in an element of the image depending on linear FM section is determined as:

$$D_{incl} = (t_{del}^{-/+} \mp t^{\nabla}) \cdot c/2$$

Where $t_{del}^{-/+}$ is delay time in an element of the image; t^{∇} is the correction of the delay time, calculated by expression (10) which follows from (6) and (7); c - velocity of light.

Horizontal distance is:

$$D = D_{incl} \cdot \cos\alpha \cdot \cos\beta$$

Where α and β are viewing angles of a scanning beam.

The horizontal distance R reduced to a motionless point at the moment of the beginning of formation of the image, is calculated as

$$R = D + V_{ext} \cdot (\tau_{line} \cdot (m-1) + \tau_{dev} \cdot n))$$

Where V_{true} is vehicle horizontal velocity, τ_{line} is the scanning line period, m is number of the current line of the image, τ_{dev} is linear FM half-cycle, n - number of the current element in the line.

Output of distance measurement loop algorithms is the image in which each pixel represents value of the reduced horizontal distance up to a corresponding point of a scene.

The block diagram of algorithms of distance and velocity determination by the suggested method is displayed on fig. 2. Algorithms are adapted for realization on computational structure of conveyor type that provides an opportunity to carry out calculations in real time.

Preprocessing algorithms simulation

At use of an offered method of distance measurement according to expressions (6) and (7) distance measurement error is determined by two components: errors of pulse-delay time measurement and an error of extrapolated vehicle velocity determination, i.e.

$$\delta_D = \sqrt{p^2 \cdot \delta^2\left(\xi_t\right) + k^2 \cdot \delta^2\left(V\right)} \qquad (11)$$

Where, $p = c/2$ $p = c/2$ and $k = \left(2 \cdot \tau_{dev}\right) / \left(\Delta F \cdot \lambda\right)$. At that $\delta^2(\xi_t)$ is determined according to (3).

As a performance criterion at mathematical simulation the absolute maximum error of slant-distance measurement (ΔD_{max}) determined by vehicle own velocity determination errors was accepted.

$$\Delta D_{max} = \max_j \left(\frac{c \cdot \tau_{dev}}{\lambda \cdot \Delta F_{dev}} \cdot \Delta V_j \cdot \cos\alpha \cdot \cos\beta \right)$$

where ΔV_j is vehicle own velocity determination error for j^{th} scanning line (j = 1–128).

Vehicle velocity was modelled by slowly varying functions of time. At simulating the structure of algorithms, factors k_1 and k_2 ratio, a method of velocity extrapolation were varied.

Mathematical simulation has allowed to reveal dependence of the maximal distance error ΔD_{max} on values of factors k_1 and k_2. This dependence has the expressed minimum (fig. 3). At that the best result was $\Delta D_{max} = 0.8$ m at $k_1 = 0.41$ and $k_2 = 0.59$. As the error of velocity determination is formed as a result of influence of many random factors it is possible to consider that it has normal distribution. Then standard deviation of the distance error originated in the inaccuracy of velocity determination, will make $\delta D(V) \leq \Delta D_{max}/3$. At the values of factors k_1 and k_2, specified above, transitional period duration did not exceed 35–40 lines of scanning.

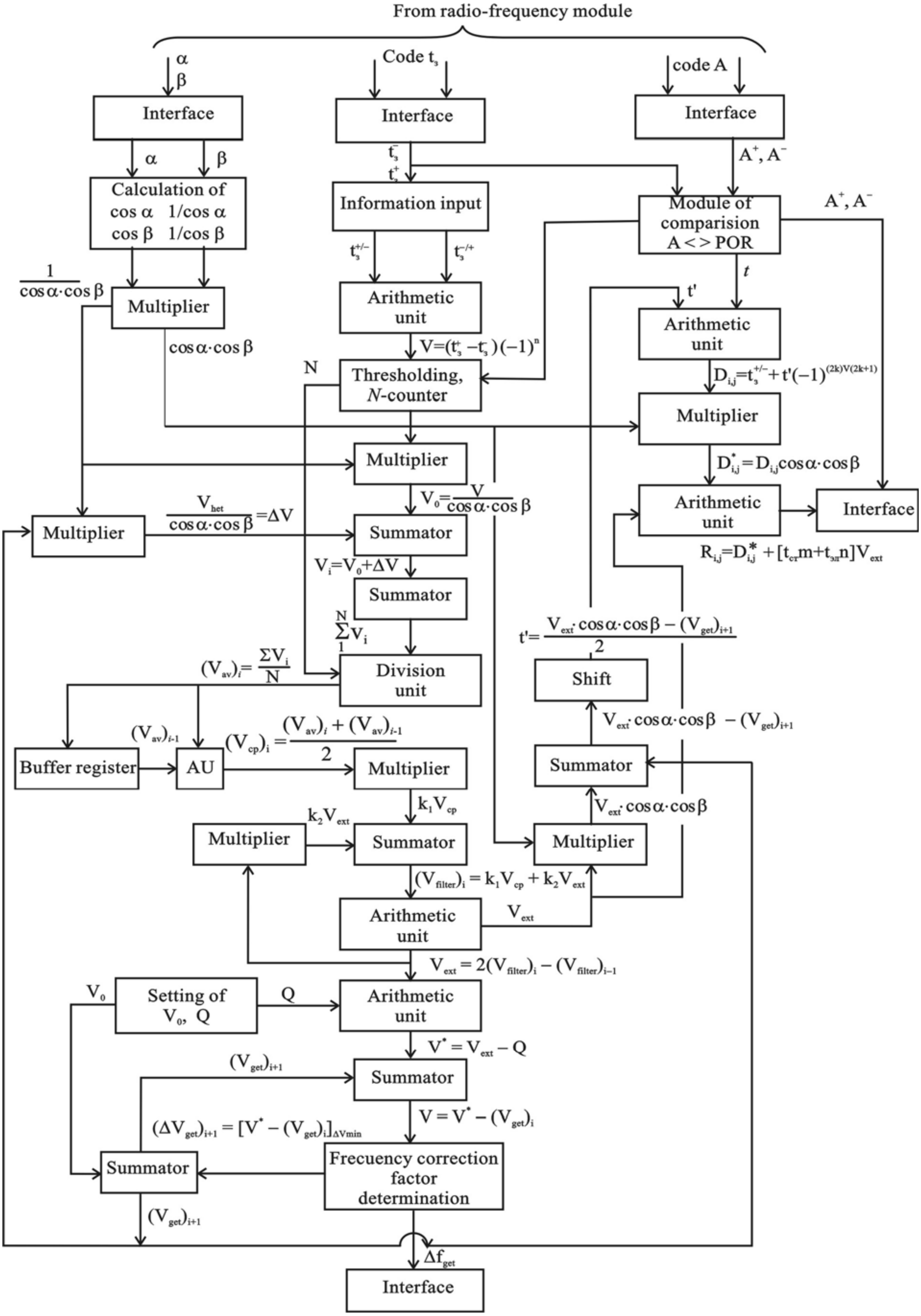

Figure 2. The block diagram of algorithms of distance and velocity determination.

Mean square deviations ξ_t and $\delta(V)$ dependence on signal/noise ratio, obtained according to (3) and as a result of simulation accordingly, are presented in Table 2. Furthermore, standard deviation of distance determination error corresponding to values of ξ_t and $\delta(V)$ at use of expressions (6)–(7), and also the total error calculated by (11), are presented in the same table.

Табл.2.

A/A_N	$\delta(\xi_t)$ c	$\delta(R)$ м	$\delta(V)$м/c	$\delta D(V)$ м	δD_Σ м
10	$0.8{\cdot}10^{-8}$	2.4	$0.25{\cdot}10^{-1}$	0.38	2.43
15	$0.65{\cdot}10^{-8}$	2.0	$0.21{\cdot}10^{-1}$	0.31	2.02
20	$0.56{\cdot}10^{-8}$	1.7	$0.17{\cdot}10^{-1}$	0.25	1.72

From Table 2 it follows, that the distance determination errors, originated from inaccuracy of the velocity determination, are insignificant in comparison with the errors caused by inaccuracy of measurement of pulse-delay time.

Mathematical simulation allowed:

- to choose rational structure of processing algorithms and to confirm their efficiency;
- to choose optimum values of factors of a filtration k_1 and k_2, that minimize an error of distance determination by a minimax criterion;
- to define time of transient in a velocity measurement loop;
- to estimate values of errors of distance determination and vehicle own velocity determination.

CONCLUSIONS

1. The developed algorithms allow:

- to carry out fine tuning of radio oscillator in real time with frequency of 100 Hz;
- to determine vehicle own velocity with high accuracy;
- to form distance image of a scene reduced to a motionless point in the Cartesian system of coordinates;
- to maintain a dynamic range of system at the set level regardless of the vehicle velocity.

2. The carried out mathematical simulation allowed

- to optimize structure of algorithm and values of its parameters by criterion of minimization of the maximal error of distance determination;
- to estimate values of standard deviation of the distance determination errors, caused by inaccuracy of velocity determination which amount to 0.25 – 0.38 m;
- to estimate values of standard deviation of vehicle own velocity determination errors which amount to $0.17{\cdot}10^{-1}$–$0.25{\cdot}10^{-1}$ м/с.

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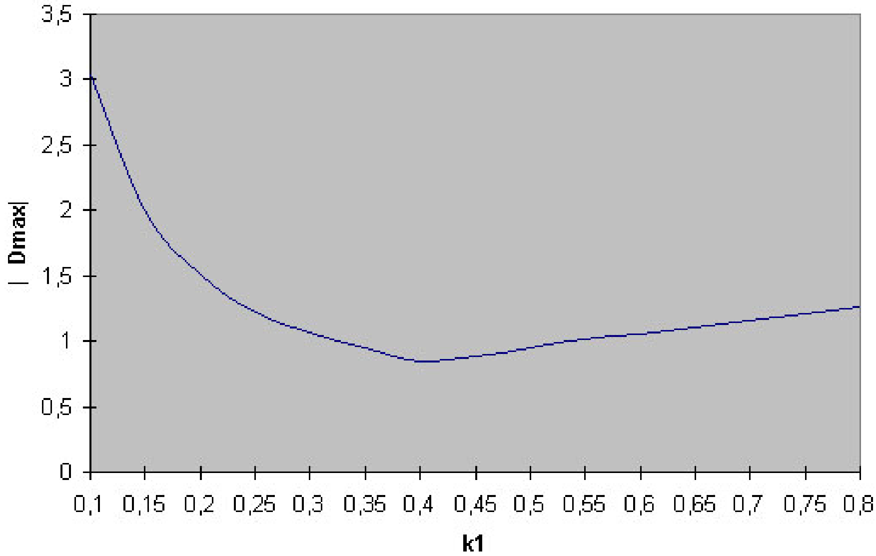

Figure 3. Dependence of the maximal distance error ΔD_{max} on values of factors k_1 and k_2.