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Selected problems in hydrodynamics, quantum electrodynamics, and laser spectroscopy (Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 14 May 2008)

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On May 14, 2008 a science session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held at the conference hall of the Lebedev Physical Institute, RAS. The following reports were presented at the session:

(1) **Davydov V S** (St. Petersburg Electrotechnical University, St. Petersburg) "Physical and mathematical foundations of the multialternative recognition and identification of hydrolocation fields produced by bodies of complex geometric shapes";

(2) **Shabaev V M** (St. Petersburg State University, St. Petersburg) "Quantum electrodynamics of heavy ions and atoms: current status and prospects";

(3) **Kolachevsky N N** (Lebedev Physical Institute, RAS and Moscow Institute for Physics and Technology, Moscow) "High-precision laser spectroscopy of cold atoms and the search for the drift of the fine structure constant."

Abridged versions of the above reports are given below.

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Physical and mathematical foundations of the multialternative recognition and identification of hydrolocation fields produced by bodies of complex geometric shapes

V S Davydov

1. Introduction

Observation of an underwater situation on the screen of a hydrolocation station (HLS) may reveal several targets simultaneously. The targets must therefore be recognized and identified for an appropriate decision to be taken.

Work on identifying bodies of complex shapes composed of individual structural elements whose size is several times larger than the wavelength of the wave irradiating them followed theoretical and experimental studies of the classification of information carried by hydrolocation fields reflected from bodies of simple geometric shapes (spheres, cylinders, etc.) and of the ability of dolphins to identify bodies of both simple and complicated shapes. In fact, a problem arose in creating automatic systems for identifying objects of complex shapes (this includes all real underwater objects in the sea, the sea bottom, and scuba divers) that would implement the dolphins' abilities. With this in mind, it was decided to use probe signals with a high resolution with respect to the distance between individual reflecting elements of bodies of complicated geometric shapes (short probe pulses whose spatial length is much shorter than the length of the target to be identified, long complex-shape probe pulses subsequently compressed in a correlated filter, or cross-correlation processing of hydrolocation signals with a copy of the probe pulse). Dolphins identify underwater objects by using short probe pulses. A detailed acoustic image can only be built at very short distances because of the limited size of hydroacoustic antennas. Arrival angles of reflected remote objects were measured with an accuracy of 10 to 15 degrees.

2. Multialternative recognition and identification of bodies of complex geometric shapes

The envelope of a reflected signal $S(t)$ (or the envelope of the cross-correlation function of hydrolocation signals with a copy of a complex-shape probe pulse) is a single-peak structure if probe pulses with a high resolution with respect to the distance to the reflecting elements are used. Significant maxima correspond to reflection from individual reflecting elements (Fig. 1). The envelope $S(t)$ displayed more than 30 attributes characterizing the structural and acoustic properties of the body to be identified. The most informative attributes had to be found.

In the present experimental study, algorithms were elaborated for identifying the attributes of $S(t)$, including the most complex algorithm for the identification of essential maxima, based on satisfying two relations for maximum maximorums and minimum minimorums [1]

$$\frac{S_j^{\max}}{S_{j-k}^{\min}} \geqslant \Delta\,, \qquad \frac{S_j^{\max}}{S_{j+n}^{\min}} \geqslant \Delta\,.$$

(The correctness and originality of these algorithms were verified by the St. Petersburg Division of the Steklov Mathematical Institute, RAS.)

Experimental physical hydroacoustic-pool modeling of hydrolocation fields of bodies of complex geometric shape has established that the amplitude components of significant maximums are extremely sensitive to changes in irradiation

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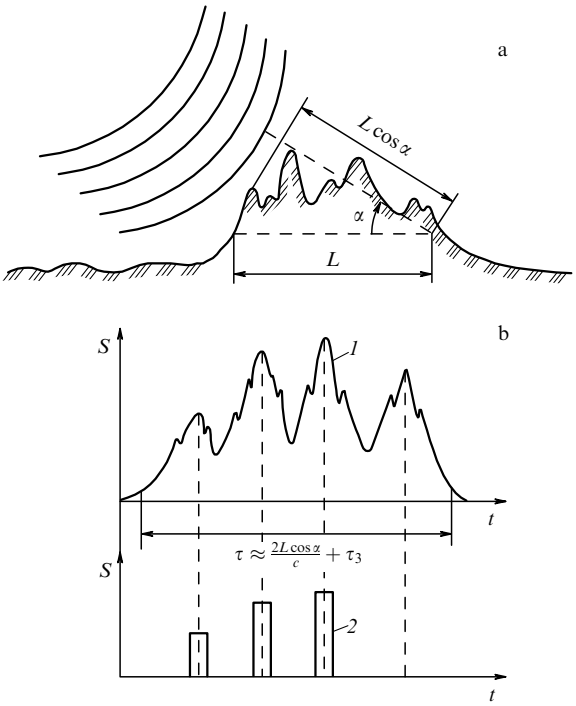

Figure 1. (a) Reflection of a short probe pulse from a body with a complex geometric shape. (b) Envelope of the echo signal reflected by a body with a complex geometric shape, of length L, obtained by using a short probe pulse of a length τ_ξ ($c\tau_\xi/2 \ll L$); *1*, experimental envelope; *2*, calculated envelope of the echo signal obtained when taking only its mirror component into account.

angles; histograms of the attribute spaces of amplitude values of the maximums of $\{S_j\}$ overlap to a great extent for different bodies of complex geometric shape. At the same time, the attribute spaces of the positions of maximums on the time coordinate $\{\tau_j\}$ are more stable relative to changes in the irradiation angle and differ greatly for different bodies of complex geometric shape in the range of locating angles of the order of 15°.

For an exact evaluation of the information content of the attributes, it was necessary to work out optimal decision rules for identifying hydrolocation signals from bodies of complex geometric shapes using multidimensional attribute spaces as a basis.

Physical studies showed that the distribution curves of the attributes $\{\tau_j\}$, $\{S_j\}$ and lengths τ of hydrolocation signals may generally have an arbitrary form, including a multimodal form. This statement was verified with experimental data by applying the nonparametric Kolmogorov–Smirnov agreement criterion [2]. Therefore, the approximation of conditional probability densities was satisfied. Because individual local maxima $S_j(t, \alpha, \beta)$ (where α and β are the angles at which the body is irradiated) in the envelope $S(t)$ are formed as a result of reflection of probe pulses from different reflecting elements with different directional characteristics, we can assume that fluctuations of positions in time $\{\tau_j\}$, the amplitude values $\{S_j\}$ of these maxima, and the time lengths τ are independent. This hypothesis was confirmed by testing the experimental data with the Spearman rank correlation criterion and the concordance coefficient [3]. The conditional multidimensional probability densities of the $\{\tau_j\}$, $\{S_j\}$, τ attribute spaces can be rewritten as the products

$$
\begin{aligned}
f\left(\bigcup_{j=1}^{n_i} \tau_j/A_i\right) &= \prod_{j=1}^{n_i} f(\tau_j/A_i)\,,\\
f\left(\bigcup_{j=1}^{n_i} \hat{S}_j/A_i\right) &= \prod_{j=1}^{n_i} f(\hat{S}_j/A_i)\,,\\
f\left(\bigcup_{j=1}^{n_i} \tau_j\,,\, \tau/A_i\right) &= \prod_{j=1}^{n_i} f(\tau_j/A_i)\, f(\tau/A_i)\,.
\end{aligned}
\tag{1}
$$

This transformation greatly simplified the construction of optimal decision rules. However, the dimension of attribute spaces changed continuously depending on the irradiation angles. In general, changes in the dimensions of the $\{\tau_j\}$, $\{S_j\}$ attribute spaces were calculated in the learning process by determining a priori probabilities of the formation and absence of significant maxima in certain local areas and by taking them into account in the process of recognition and identification. (The correctness and originality of this solution was confirmed by the St. Petersburg Division of the Steklov Mathematical Institute, RAS.) The rules of multialternative recognition of hydrolocation signals based on the multidimensional $\{\tau_j\}$, $\{S_j\}$ attribute spaces and the attribute τ were formulated in correspondence with the maximum likelihood criterion. These rules can be easily transformed to the Bayes criterion if the a priori probabilities of the presence of the bodies to be recognized are known and loss functions for mistaken recognition are known. For a one-dimensional attribute, the signal length τ, with the approximation of conditional one-dimensional probability densities taken into account using the Parsen–Rosenblatt method, the rule is given by

$$
\sup_i \{\varphi_i\} = \sup_i \left\{ \frac{1}{N_i N_i^{-1/4}} \sum_{k=1}^{N_i} \frac{1}{\sigma\sqrt{2\pi}} \exp \frac{-1}{2\sigma^2} \left(\frac{\tau - \tau_{ki}}{N_i^{-1/4}} \right)^2 \right\}, \tag{2}
$$

where τ is the length of the measured echo signal, τ_{ki} are the sampled values of the lengths of the echo signals measured in the ranges $\Delta\alpha$ and $\Delta\beta$, N_i is the number of terms in the learning sample for the ith body, and σ is the rms deviation of lengths τ of the echo signals.

In the recognition following rule (2), the length τ of the echo signal and irradiation angles α_r and β_r for i bodies are measured, the sampled values τ_{ki} of attributes are taken in correspondence with the range of irradiation angles $\Delta\alpha$ and $\Delta\beta$ that contains α_r and β_r, the likelihood functions φ_i are calculated, and a decision is made on assigning the measured attribute τ to the ith body, if φ_i is the largest of all the φ_i, $i = 1, \ldots, M$.

The optimal decision rule for identifying and recognizing an object based on multidimensional attribute spaces of temporal positions of maximums of echo signals $\{\tau_j\}$ based on the maximum likelihood criterion is formed using master curves built as conditional probability densities in the angle irradiation range $\Delta\alpha$ and $\Delta\beta$ with the dimensions of the attribute spaces taken into account as a priori probabilities of finding (k_{ji}) and not finding $(1 - k_{ji})$ the values of the attributes in the jth reference areas for i bodies [4, 5]:

$$
\sup_i \{\varphi_i\} = \sup_i \left\{ \prod_{j=1}^{m} k_{ji}\, f(\tau_j/A_i) \prod_{j=m+1}^{n_i} (1 - k_{ji}) \right\}, \tag{3}
$$

where m is the number of maxima in the measured echo signals whose temporal positions $\{\tau_j\}$ fall within the jth reference area of the ith body, n_i is the number of the jth reference area of the ith body, and $n_i - m$ is the number of reference areas of the ith body that did not receive the temporal positions of maximums $\{\tau_j\}$ in the measured echo signal.

With the approximation of conditional one-dimensional probability densities based on the Parsen – Rosenblatt method, decision rule (3) takes the form [4, 5]

$$\sup_i \{\varphi_i\} = \sup_i \left\{ \prod_{j=1}^{m} k_{ji} \frac{1}{N_{ji} N_{ji}^{-1/4}} \sum_{k=1}^{N_{ji}} \frac{1}{\sigma_\tau \sqrt{2\pi}} \times \exp \frac{-1}{2\sigma_\tau^2} \left(\frac{\tau_j - \tau_{jik}}{N_{ji}^{-1/4}} \right)^2 \prod_{j=m+1}^{n_i} (1 - k_{ji}) \right\}, \quad (4)$$

where τ_j is the number of maximums in the envelope of the measured echo signals, τ_{jik} are the sampled values of temporal positions of maximums for the jth reference position of the ith body corresponding to the range of irradiation angles $\Delta\alpha$ and $\Delta\beta$, N_{ji} is the number of sampled values of τ_{jik} for the jth reference position of the ith body, and σ_τ is the rms deviation for the $\{\tau_j\}$ attribute space.

Before identification according to rule (4), or using attribute τ, it is necessary to measure the irradiation angles α_r and β_r and sample values of attributes τ_{jik} for the angle ranges $\Delta\alpha$ and $\Delta\beta$ that contain α_r and β_r. The decision whether the τ_j attribute space selected from the measured echo signal belongs to the ith body is taken according to the maximum value of the likelihood function φ_i among all the φ_i, $i = 1, \ldots, M$. Figure 2 gives an example of a three-alternative identification of bodies based on temporal positions of maximums in the envelopes of echo signals $\{\tau_j\}$. Reference attribute spaces $\{\tau_j\}$ for a 15° range of irradiation angles are given as conditional probability densities with the a priori probabilities $k_{ji} f(\tau/A_i)$ of finding attributes in the jth areas taken into account. Given below are the results of measurements of temporal positions of maximums $\{\tau_j\}$ in the echo signal. The values of likelihood functions φ_1, φ_2, and φ_3 were calculated for three bodies on the basis of these data. The highest value is reached by φ_1, and therefore the result of the identification is the decision that the measurement data $\{\tau_j\}$ belong to body 1.

The optimal rule for identifying bodies using normalized amplitude ratios of the maximums in the envelopes of echo signals $\{\hat{S}_j\}$ is formed, just as rule (4), by using their reference signals as conditional probability densities and with the a priori probabilities of finding (k_{ji}) and of not finding $(1 - k_{ji})$ the attributes in certain reference areas calculated on the basis of the $\{\tau_j\}$ attribute spaces.

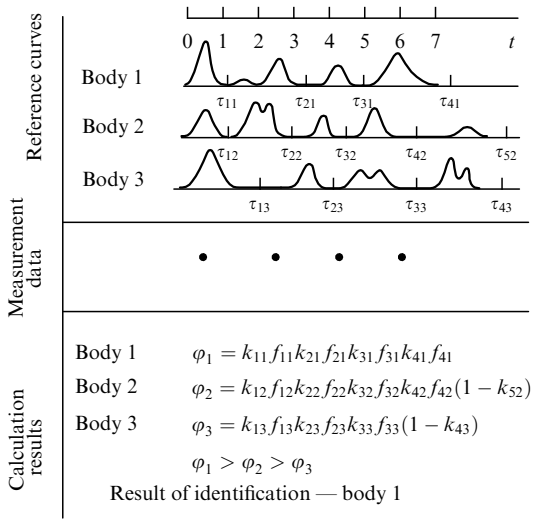

Figure 2. An example of the three-alternative identification of bodies of complex geometric shapes based on the attribute space of temporal positions of maximums on the envelopes of hydrolocation signals using the optimal decision rule.

Using the property of joint independence of the attributes $\{\tau_j\}$, $\{\hat{S}_j\}$ and $\{\tau_j\}$, τ, by analogy with the above procedures, we can construct the decision rules for jointly using these attributes [4]:

$$\sup_i \{\varphi_i\} = \sup_i \left\{ \prod_{j=1}^{m} k_{ji} f(\tau_j/A_i) f(\tau/A_i) \prod_{j=m+1}^{n_j} (1 - k_{ji}) \right\},$$
$$\sup_i \{\varphi_i\} = \sup_i \left\{ \prod_{j=1}^{m} k_{ji} f(\tau_j/A_i) f(\hat{S}_j/A_i) \prod_{j=m+1}^{n_j} (1 - k_{ji}) \right\}. \quad (5)$$

Computer algorithms and software have been written for identifying bodies on the basis of attributes $\{\tau_j\}$, $\{\hat{S}_j\}$, and τ. The results of alternative identification of four bodies of complex geometric shapes for the range of irradiation angles of 10 to 15° are given in Table 1.

The highest probability of correct identification of bodies was obtained by using the $\{\tau_j\}$ attribute space [4, 5]. This therefore confirms the maximum information content of the attribute space of temporal positions of maxima in the envelopes of echo signals, $\{\tau_j\}$, dictated by the relative positions of reflectors on bodies of complex geometric

Table 1. The results of a separate identification of 1:100 scale models based on the attributes $\{\tau_j\}$, $\{S_j\}$, τ.

Frequency, kHz	Model number	Range of location angles, deg	Probability of correct identification using the optimal decision rule, %		
			based on $\{\tau_j\}$	based on $\{S_j\}$	based on τ
100	1, 2, 3, 5	5 – 20	89 (85 – 93)	55 (47 – 63)	65 (57 – 73)
1000	1, 2, 3	5 – 20	67 (57 – 77)		
350	1, 2, 3, 4	5 – 20	92 (87 – 97)	57 (47 – 67)	75 (65 – 85)
350	1, 2, 3, 4	22 – 38	79 (69 – 88)	39 (29 – 49)	40 (30 – 50)
350	1, 2, 3, 4	45 – 60	86 (79 – 92)	43 (33 – 53)	50 (40 – 60)
350	1, 2, 3, 4	60 – 75	76 (66 – 84)	43 (33 – 53)	32 (22 – 44)
350	1, 2, 3	105 – 120	76 (66 – 84)	48 (38 – 58)	24 (15 – 34)
350	1, 2, 3	135 – 150	95 (90 – 99)	62 (52 – 72)	62 (52 – 72)
350	1, 2, 3	160 – 175	100 (96 – 100)	76 (66 – 84)	71 (61 – 80)

shapes, in comparison with attributes related directly to the amplitude values of envelopes of echo signals. Appending the attributes $\{\hat{S}_j\}$ and τ to the attribute space $\{\tau_j\}$ increases the correct identification probability only insignificantly (by 3–5%). Identification on the basis of the $\{\tau_j\}$ but without taking the a priori probabilities k_{ji} of finding attributes in the jth reference areas into account reduced the probability of the correct identification of objects.

3. Method of analyzing reference signals

In using probe pulses with a high resolution with respect to the distance between reflecting elements, the level of the reflected signal $S(t)$ is somewhat lower than in the case of a long probe package covering the entire object to be recognized. For real objects, this difference amounts to 8–12 dB. Identification of bodies of complex geometric shapes in the sea meets with additional difficulties because of multipath propagation of signals in maritime conditions (this can sometimes be eliminated by adapting identification rules). A new principle of formation of hydrolocation signals was therefore suggested and a method of sending reference signals was developed resulting in incorporating the information on the targeted body of complex shape, in the form of the $\{\tau_j\}$ attribute space, into the probe signal.

To increase the noise immunity of the identification of bodies of complex shape from the effects of high-intensity noise and reverberation interference, it is suggested to form a reference probe signal as a sum of short pulses $\xi_k(t)$ [or long complex-shape probe pulses $\xi_c(t)$] such that the delays between them correspond to the reference values, arranged in reverse order, of the mutual positions of maximums $\{\tau_j\}$ on the echo signals of the identified body in a certain range of irradiation angles [4, 6]. The reference values for each jth maximum are then determined as mean values of the τ_j for all τ_j found at the learning stage in the jth region in the angular ranges $\Delta\alpha$ and $\Delta\beta$. Figure 3a shows an example of the envelope of the reflected signal $S(t)$ from a body of complex shape when using a short probe pulse $\xi_k(t)$ as the envelope of the generated reference signal $S_2(t)$, with delays $\{\tau_v\}$ between pulses with amplitudes a_v (assumed to be equal); envelopes of the signals $S_3(t)$, $S_4(t)$, and $S_5(t)$ reflected from each of the three elements of the body and the envelope of the total signal $S_\Sigma(t)$ reflected by the body as a whole are plotted only schematically. Representing the transmission function for a body of complex shape as a series of delta functions with delays $\{\tau_j\}$ and amplitudes a_j,

$$\varphi(t) = \sum_{j=1}^{n} a_j \delta(t - \tau_j)\,,$$

we can write the echo signal as a convolution

$$\begin{aligned} S_\Sigma(t) &= \int_{-\infty}^{\infty} S_2(t)\,\varphi(t-\tau)\,\mathrm{d}\tau \\ &= \int_{-\infty}^{\infty} S_2(t) \sum_{j=1}^{n} a_j \delta(t - \tau_j - \tau)\,\mathrm{d}\tau \\ &= \int_{-\infty}^{\infty} \sum_{v=1}^{n} a_v \xi(t)\,\varphi(t+\tau_v) \sum_{j=1}^{n} a_j \delta(t - \tau_j - \tau)\,\mathrm{d}\tau \\ &= \sum_{v=1}^{n} \sum_{j=1}^{n} a_v a_j \xi(t + \tau_v - \tau_j)\,. \end{aligned}$$

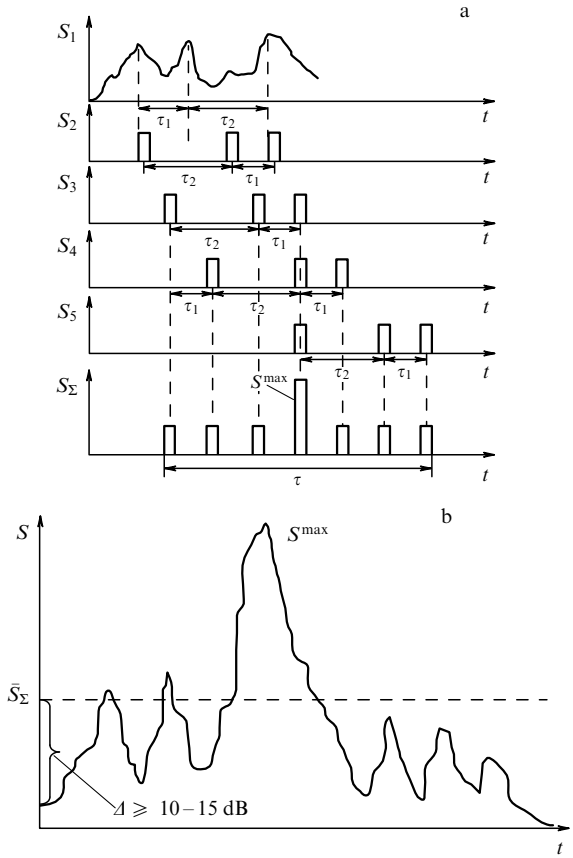

Figure 3. (a) A schematic representation of the formation of a global maximum $S^{\max}$ in the total signal $S_\Sigma(t)$ obtained by summing the reflections of the sent signal $S_2(t)$ from all three reflectors of a body of complex shape; $S_3(t)$, $S_4(t)$, and $S_5(t)$ are the respective signals reflected by the first, second, and third reflectors. (b) An example of a resulting global maximum $S^{\max}$ in $S_\Sigma(t)$.

If $\{\tau_j\}$ and $\{\tau_v\}$ coincide, then the signal $S_\Sigma(t)$ is equal to the sum of all reflected signals from all elements of the body. The shape of $S_\Sigma(t)$ displays a global maximum $S_\Sigma^{\max}$ greater than the average level of the envelope $\bar{S}_\Sigma(t)$ [4, 6]. If $S_2(t)$ is formed as a sum of long complex-shape probe pulses $\xi_c(t)$, then a short $S_\Sigma^{\max}$ is observed after correlated filtration and detection of $S_\Sigma(t)$. Identification of a complex-shape body is carried out, for instance, when the ratio $S_\Sigma^{\max}/\bar{S}_\Sigma$ exceeds the threshold level. In this way, it is possible to identify a complex-shape body for which the reference values $\{\tau_j\}$, its identification against the background of signals from other complex-shape bodies, or the reverberation or noise interference is known.

Figure 3b gives an example of the envelope $S_\Sigma(t)$ [in the case of using $\xi_k(t)$] after sending $S_2(t)$. Identification of a body of complex shape is then carried out for $S_\Sigma^{\max}/\bar{S}_\Sigma > \psi$, in which case the noise level may be comparable with $\bar{S}_\Sigma$, that is, the noise immunity increases by Δ [dB] relative to the noise immunity with identification methods using only one probe pulse.

This method of sending reference signals was investigated in model hydrolocation measurements in a hydroacoustic tank.

The curves $S^{\max}/\bar{S}_\Sigma$ and $S^{\max}/\bar{S}_{\Sigma_{1/3}}$ were plotted (where $\bar{S}_{\Sigma_{1/3}}$ indicates that the mean value of the signal was measured at 1/3 of the length of $S_\Sigma(t)$ before $S^{\max}$ was

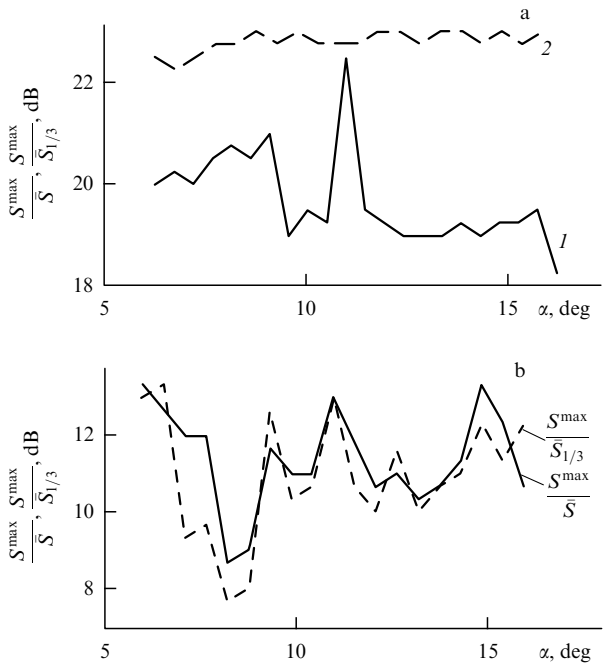

Figure 4. (a) The ratio of the amplitudes of global maximums $S^{\max}$ to the average levels of the envelopes $S(t)$ as a function of the irradiation angle α in response to irradiation by a reference signal: *1*, $S^{\max}/\bar{S}$ as a function of α; *2*, $S^{\max}/\bar{S}_{1/3}$ as a function of α. (b) The ratio of the amplitudes of global maximums $S^{\max}$ to the average levels of the envelopes $S(t)$ as a function of the irradiation angle α in response to irradiation by a train of seven equidistant pulses.

formed). Figure 4a gives an example of this dependence on the irradiation angle for a body in the horizontal plane, $\alpha = 5-15°$; the reference signal was formed in the irradiation of the body at $\alpha_0 = 10°$. Figure 4b gives an example of these curves for irradiation of the same body with seven equidistant pulses [the number of maximums in $S_\Sigma(t)$ is also roughly equal to 7]. These curves were plotted for probe pulses of equal length and for equal ranges of the body irradiation angle. On average, the ratios $S^{\max}/\bar{S}_{\Sigma_{1/3}}$ were greater than $S^{\max}/\bar{S}_\Sigma$, but the difference was insignificant. A comparison of the plots shown in Figs 4a and b demonstrates that the ratios $S^{\max}/\bar{S}_\Sigma$ and $S^{\max}/\bar{S}_{\Sigma_{1/3}}$ obtained for irradiation by reference signals at all angles were greater than the values in the case of equidistant pulses, which corresponds to irradiating a body with an extraneous reference signal. In this case, correct identification was faultless at all irradiation angles.

With this approach, the problem of identification is greatly simplified and in fact reduces to the problem of locating the global maximum. The price paid for increasing the noise immunity under multialternative identification is the need to send several reference signals whose number equals that of the bodies to be recognized. If reference signals are sent, the total information on the distribution of reference values $\{\tau_j\}$, incorporated in the conditional probability densities $f(\bigcup_{i=1} \tau_j)$, is not used. However, identification can be achieved by using the optimal criterion.

The suggested method is most convenient for identification of a known body against a background of noise and reverberation interference and in identifying complex-shape bodies in a multipath environment. Multipath propagation of signals in marine environments produces not one but several maxima $S_\Sigma^{\max}$ on $S_\Sigma(t)$ (depending on the hydrological environment). However, the procedure for identifying complex-shape bodies does not change in this case.

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Quantum electrodynamics of heavy ions and atoms: current status and prospects

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1. Introduction

Quantum electrodynamics (QED), whose underlying principles were formulated by Dirac, Heisenberg, Born, Fock, Pauli, Wigner, Jordan, Fermi, and others by the early 1930s, has been quite successful in describing the emission (absorption) of a photon by an atom and the creation (annihilation) of electron–positron pairs, but second-order perturbative QED calculations yielded infinite results for some effects. This problem remained unsolved until about the late 1940s, when experiments by Lamb and Rutherford revealed what is now known as the Lamb shift, the splitting of the 2s and $2p_{1/2}$ energy levels in the hydrogen atom. Because there was virtually no doubt about the quantum-electrodynamic origin of the Lamb shift, this discovery paved the way to the solution