V.I. Alekseev, G.M. Glebova, and G.N. Kuznetsov

MUTUAL POSITIONING OF SPATIALLY DEVELOPED RECEIVING ARRAYS OF VARIOUS TYPES AND EMITTERS IN NEAR-FIELD REGION

Wave Research Center of the General Physics Institute RAS
38 Vavilov street, 117942 Moscow, Russia
Phone: (095) 256-1790
E-mail: kuznetsovgn@mtu-net.ru, skbmt@mail.ru

The possibility to estimate the coordinates of horizontal and vertical scalar arrays, as well as spatially spaced vector-scalar modules using a towed broadband source, is considered. The technique and methodical recommendations on mutual positioning of receiving and emitting means are developed, when all the coordinates are measured simultaneously. The results of experimental accuracy check of positioning of the receiving vertical array in a shallow sea are considered. Recommendations on positioning methods and an orientation estimation in the space of vector-scalar modules are given. The study can be used to solve the problems of hydrophysical measurements in the short-range waveguide band for intermediate and high frequencies. This allows one to apply the ray beam approximation and to take into account the dependence of the structure of ***rays*** *and their characteristics on source and receiver depths and mutual distances.*

PACS {43.30.Xm}

Solution of a number of oceanologic and hydroacoustic problems requires calibration and tuning of receiving and emitting systems, which also requires their precise positioning and, in specific cases, estimation of absolute geographical coordinates. The algorithms considered below were developed for the general case, which allows simultaneous estimation of horizontal coordinates of sources and receivers, as well as their depths. As a particular case, we consider the possibility to estimate only horizontal coordinates of receivers and sources, which presupposes depth measurements using depth sensors. Preliminarily, before sea experiment designing, the phase differences between receiving channels and their absolute sensitivities should be measured. If these parameters are unknown, they may be measured by electric testing and decentralized acoustic absolute methods. This study takes into account the results of [1-7] and is their advancement.

For mutual positioning of receiving units and the emitter in the horizontal plane, a research ship towing the broadband emitter makes a number of rectilinear tacks in the receiving system region. The emitter is positioned at a preset controlled depth and emits short broadband pulses with specified parameters. Based on the emission simulation, it is proposed to employ broadband frequency-modulated pulses or sinx/x-type signals. Such signals are characterized by a narrow correlation function, which allows accurate determination of its maximum in the time axis, as well as identification of the maxima corresponding to the difference of the signal arrival times over various rays. A receiving ship or a coastal post receives and records the signal emitted. The emission and record are carried out in the common-timing system. In the course of experiments, the sound velocity profile c(z) is periodically measured. To obtain initial data, the emitter coordinates are measured with referencing to a navigation antenna position. Navigation systems, for example, GPS-type ones, can measure (in the common-timing system) (i) the absolute coordinates of the emitter, (ii) the motion velocity and course, and (iii) the absolute coordinates, velocity, and course simultaneously, depending on configuration. Therefore, the methods for measuring the emitter and array coordinates can be absolute or relative only in a frame of reference, associated with arrays.

The solution of the problem is reduced to the following sequential procedures: the times of signal propagation over the water beam and the beam reflected from the surface are measured and the corresponding horizontal distances are calculated; the emission point coordinates are calculated using the data from navigation systems; initial approximations of the coordinates of emitters and receiving units are selected; the receiver and emitter coordinates are estimated by functional minimization.

The times or time differences are calculated using the correlation function $R_m(k) = \sum_i p_m(i+k)p_0(i)$ of the received $p_m(t)$ $(m=1...M)$ and reference $p_0(t)$ signals; the summation is carried out in the time interval containing a pulse. Depending on a problem to be solved, the emitted (reference) signal or the signal $p_m(t)$ received by hydrophones is taken as the reference signal $p_0(t)$.

To make the time τ, corresponding to the peak position of the correlation function, more accurate, the three-point parabolic interpolation is used. Then the horizontal distance between the source and a separate receiver is calculated by the measured propagation time and taking into account the vertical distribution *c(z)* of the velocity of sound (to account for the beam curvature).

If the navigation system measures only absolute coordinates of emission points, the averaged estimates are calculated by linear approximation of the GPS readings at individual tacks (the typical accuracy of single measurements is 10 m < σ < 30 m). In the case of rectilinear tacks of the tug, according to the linear model of motion, we have: $\mathbf{x}_m = \mathbf{x}_0 + \mathbf{v}\cdot(t_m - t_0),\ \ 0 \le m \le M-1$, where $\mathbf{x}_m$ are the horizontal coordinates of the ship, measured at the instant of time t_m, $\mathbf{v}$ is the average velocity of motion, and *M* is the total number of coordinate measurements in the course of a given tack.

If the navigation system measures only the course and the velocity of rectilinear motion of the ship (emitter), the coordinates of emission points are calculated using only the ship velocity and course data in the relative frame referenced to the array geometric characteristics. Hence, the estimate accuracy depends on the accuracy of the ship velocity measurement.

The computing procedure requires an initial approximation, that is, the initial coordinates of emission points and receiving units. Their estimation is based on a triangle construction by three measured sides r_a, r_b, r_c. It is assumed that the triangle vertex C coincides with the reference receiving unit of the array, while the triangle vertices A and B are at any two emission points in the same tack. The length of the side between them is equal to the distance passed by the ship between two emission points (A and B). Since recording and emission are carried out in the common-timing system, the correlation processing between signals at point C and the reference emitted pulse yields the time of the signal propagation from the emission points to the receiving units. The determined times of signal propagation and the known depths of the reception points, taking into account hydrology, yield the sizes r_a and r_b of two other sides of the triangle under consideration. The initial estimates of the coordinates of the emitter and receivers are made more accurate in several ways. One of them continues the initial approximation algorithm and consists in averaging the data obtained over various pairs of emission points for each hydrophone and tack. Averaging should be carried out in the relative frame of reference associated with the receiving array.

In the second method, the receiver and emitter coordinates are simultaneously estimated using the overdetermined set of equations $\hat{t}_{sk} = t(|\mathbf{x}_s - \mathbf{x}_k|)$ relating the experimentally determined delays $\hat{t}_{sk}$ and the calculated values of all the delays. Simultaneously, the source position $\mathbf{x}_k$ at the instants of pulse emission t_k, *k=1,2,...,K* and the receiver coordinates $\mathbf{x}_s$, s=1,2,…N are made more accurate. The dimension of the set of equations is $K\cdot N$ if delays only over the forward beam are used. If the delays over the beams reflected from the surface and the differences of the delays over the forward beam between receivers are also used, the dimension of the set of equations increases in the former case by $K\cdot N$; in the latter case, additional $N\cdot K\cdot(K-1)/2$ equations arise.

To position the vertical arrays immersed from the ship deck, two auxiliary (reference) transmitter-receiver modules are simultaneously immersed from two decks. These modules are spaced by a maximum distance bounded by the ship dimensions. Each transmitter-receiver module incorporates an emitter and a reference hydrophone arranged in the immediate vicinity. The output of the latter is cable-connected to a unit (common with the receiving hydrophones of the array) of amplification and digital inputting the data into a computer. Measuring the times of signal propagation over the forward and reflected beams for each module and each array unit during alternate emission of short broadband pulses by each module, one can measure and monitor (in time) the geometric characteristics of an inclined deformed array. The distances are measured by the forward beam delay, and the hydrophone depths are determined by the reflected signal delay.

To improve the coordinate measurement accuracy of the receiving units 1,2, … ,N, the functional $\Phi = \sum \{(t_i - \tilde{t}_i)^2 + (\tau_i - \tilde{\tau}_i)^2\}$ is minimized, where $t_i, \tilde{t}_i$ are the times of signal propagation from the source to the i-th receiver over the forward beam, calculated taking into account *c(z)* and experimentally measured, respectively; $\tau_i, \tilde{\tau}_i$ are the differences of the times of signal arrival over the forward beam and the beam reflected from the open surface, calculated and experimentally measured, respectively.

To minimize the description and increase the calculation stability and accuracy, a priori technical information on the spacing between neighboring hydrophones is used [6]. Furthermore, it is assumed that the line approximating the array position is characterized by a three-dimensional spatial inflection sag [1].

The measurement accuracy of the distances and the geometric characteristics of the receiving system were experimentally checked in a shallow sea about 60 m in depth using piezoceramic emitters operating at a frequency of 2000 Hz, immersed from the ship deck to a depth of 15.6 m. A vertical 50-m 12-unit array spaced from the ship over a distance from 50 to 200 m was used as a receiving array. The study has shown that it is possible to estimate the array shape, to measure the inflection, and to determine the flow-caused displacement of the lower (and other) receivers even under nonstationary conditions. The measurement accuracy of the horizontal distance was no worse than 0.8-1.2 m, the measurement accuracy of the hydrophone depth was about 0.8 m. The interunit spacings were measured to an accuracy of 10-20 cm at the interunit spacing of 395 ± 3 cm. The data obtained show that regular radiation study from the receiving ship deck allows mutual positioning of receiving units and emitters, as well as estimation of the influence of tidal and internal waves on the array geometric characteristics and the receiver depth. In particular, it was ascertained that the depth of the last hydrophone in the array at the strongest flow approached to 30 m, and the inflection was about 8 m. In the case of the weakest flow, the array was virtually vertical, and the depth of the last hydrophone was 58 m. The monitoring of the geometric characteristics allowed us to take this time interval for the most important experiments, for example, to calibrate the waveguide.

The methods for absolute positioning in space and estimating the orientation of the vector-scalar receiver axes are considered in [7]. The receivers and sources are mutually positioned using the signals from pressure receivers. In the general case, the signal at the vector receiver output is given by $\hat{V}_q = l_{qx}V_x + l_{qy}V_y + l_{qz}V_z$, $q = x, y, z$, where l_{qx}, l_{qy}, l_{qz} are the sensitivity coefficients depending on the receiver technical parameters and axis orientation in space with respect to the emitter; V_x, V_y, V_z are the vibrational velocity components. If all the three components are measured in the receiving module, they are related to the actual values of the vibrational velocity V components as $\hat{V} = LV$. The actual components of the vibrational velocity are given by $V = L^{-1}\hat{V}$. To determine the coefficients l_{qx}, l_{qy}, l_{qz}, it is convenient to pass from the set of equations relating the experimentally measured and calculated components of the vibrational velocity to a set of equations written in terms of normalized flux power. Analytical expressions of such equations were derived taking into account the fact that the forward and reflected signals mainly contribute to the received signals at short distances [7]. To improve the accuracy and stability of estimates and to increase the matrices conditionality, it is expedient to tow the broadband emitter in the horizontal plane at two or three depths, for example, over a square around of the module, and to move the emitter in the vertical plane. In the case of emission at several harmonics or in a broad band, the estimates are combined (collected), since the angular coordinates of the vector-scalar receivers are independent of frequency. Simulation shows that the estimation accuracy of the angular coordinate axes is 3° and 4-5° in the horizontal and vertical planes. Thus, the methods developed rather accurately estimate the orientation of the vector-scalar receiver axes and their spatial coordinates, which allows one to apply these method to solve measuring and other problems. If necessary, dynamic monitoring is possible, which takes into account the temporal variation of the receiver axis orientations. It is evident that variations of these axes even by 5-10° should not have an appreciable effect on the measurement accuracy due to the weak angular dependence of the vector receiver sensitivity in the region of maxima.

The study carried out allows the conclusion that the algorithms suggested are operational and can be in principle applied to the problems of positioning of receiving units and emitters in the relative or absolute frames of reference. However, the practically attainable accuracy should be additionally studied in each particular case, taking into account specific properties of a waveguide. Special emphasis should be on methodical errors, which as a rule cause biased estimates and systematic errors. After a certain revision, the methods developed can be applied to position emitters in the emitting multiunit array as well.

REFERENCES

1. Burov V.A., Sergeev S.N., and Sergievskaya N.P. Acoustic Tomography of the Ocean According to the Data of the Vertical Mode Array Randomly Curved by Undercurrents. Akust. Zh. 1992, 38(2), 350 (Acoust. Phys.). [in Russian].
2. Katsnelson B.G. and Petnikov V.G. Shallow Sea Acoustics. Moscow: Nauka, 1997 [in Russian].
3. Kravchun P.N. Linear Hydroacoustic Arrays in Flows: Mathematical Models and Optimization. In: Acoustics of Ocean. Moscow: GEOS, 2000, p.101 [in Russian].
4. Dremuchev S.A., Kuznetsov V.N., Kulikov A.V. et al. Distributed Acoustic Array with a System for Determining its Spatial Configuration. Okeanologiya 1989, 29(2), 326 (Oceanology). [in Russian].
5. Feizkhanov U.F. Estimation of the Position of a Vertically Distributed Receiving System under Natural Conditions. Abstr. of the Sci.-Tech. Conf. "Problems of Metrology of Hydrophysical Measurements PMGI-2001". Moscow: VNIIFTRI, 2001, p.32 [in Russian].
6. Alekseev V.I., Belov A.I., Glebova G.M., et al. Positioning of a Vertical Multiunit Receiving Onboard Array. Ibid., p.122.
7. Kuznetsov G.N., Alekseev V.I., and Glebova G.M. Posing of Horizontal-Vertically Development Multiunit Arrays and Vector-Scalar Modules. BRAS Phys. Vibr. 2001, 9(4), pp. 235-241.