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PHYSICAL FOUNDATIONS OF ENGINEERING ACOUSTICS

# Acoustic Profiling of Bottom Sediments in Large Oil Storage Tanks

**V. D. Svet[a], * and S. A. Tsysar'[b]**

[a]*Andreev Acoustics Inctitute, Moscow, 117036 Russia*
[b]*Faculty of Physics, Moscow State University, Moscow, 119991 Russia*
**e-mail: vsvetd@mail.ru*

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**Abstract**—Characteristic features of acoustic profiling of bottom sediments in large oil storage tanks are considered. Basic acoustic parameters of crude oil and bottom sediments are presented. It is shown that, because of the presence of both transition layers in crude oil and strong reverberation effects in oil tanks, the volume of bottom sediments that is calculated from an acoustic surface image is generally overestimated. To reduce the error, additional post-processing of acoustic profilometry data is proposed in combination with additional measurements of viscosity and tank density distributions in vertical at several points of the tank.

*Keywords*: acoustic profiling, crude oil, bottom sediments, oil storage tanks

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## INTRODUCTION

Crude oil contains a vast variety of impurities, which settle to the bottoms of oil storage tanks. Determination of the volume of bottom sediments or sludge is one of the key problems of oil tank operation. A large volume of sludge prevents efficient use of a tank, accelerates its corrosion, and may cause tank damage leading to oil leakage. Therefore, bottom sediments must be periodically removed from a tank. The procedures of sediment removal or tank cleaning are difficult and expensive, and, to estimate their efficiency, it is necessary to know both the spatial distribution of sediments and their volume; in addition, it is especially important to evaluate the solid phase of sludge, which cannot be washed out or pumped out. One of the promising modern methods of sediment evaluation is acoustic bathymetry similar to oceanic bathymetry used for ocean bottom mapping. However, the closed structure of a tank, the difference between the parameters of crude oil and those of water, and the structure of sediments themselves lead to a number of specific phenomena, which impose certain limitations on the efficiency of acoustic methods. In this paper, we present experimental results of acoustic profiling of sediments in oil storage tanks and discuss specific features of acoustic bathymetry in these reservoirs. To estimate the efficiency of an acoustic bathymeter, it is important to know the basic oil parameters that affect its operation, namely, the sound absorption, the velocity of sound, the backscattering coefficient for sound scattered from the sludge surface, and the parameters of sludge itself.

**Table 1.** Parameters of crude oil

| Type of crude oil | Density, kg/m$^3$ | Dynamic viscosity range, η, mPa s |
|---|---|---|
| 0—extra light | 750.0–830.0 | <5 |
| 1—light | 830.1–850.0 | $5 < \eta < 10$ |
| 2—medium | 850.1–870.0 | $10 < \eta < 30$ |
| 3—heavy | 870.1–895.0 | $\eta > 30$ |
| 4—bituminous | 895.1–1000.0 | >200 |

## OIL PARAMETERS

In oil industry, crude oil is usually classified in four groups: see Table 1 (Russian state standard GOST R 51858-2002) where the data are presented for temperature $T = 20$°C.

Based on a large body of experimental data, it is generally agreed that absorption in crude oil is characterized by quadratic frequency dependence. Figure 1 shows calculated frequency dependences of absorption for different types of oil and sea water for comparison.

Note that the data given in Fig. 1 refer to clean oil, whereas, in crude oil and stock-tank oil, absorption may be higher because of the presence of various impurities, water droplets, and suspended gas bubbles. This is confirmed by experimental data obtained at a frequency of 150 kHz (see Table 2).

The velocity of sound in crude oil depends on temperature and oil density; in addition, in contrast to water, the velocity of sound in crude oil decreases with increasing temperature, because, as in all organic liq-

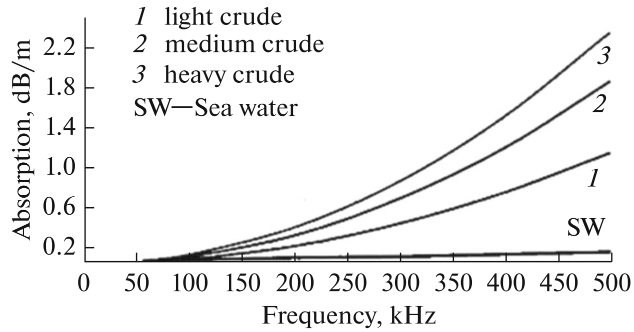


**Fig. 1.** Calculated frequency dependences of absorption in oil.

uids, compressibility of oil considerably increases with temperature, which leads to a decrease in sound velocity. In [1–3], several empiric formulas are proposed for calculating the sound velocity, but, most frequently, the following formula is used [2]:

$$C_{\text{oil}} = \frac{15450}{\sqrt{77.1 + \text{API}^\circ}} - 3.7T^\circ\text{C}, \qquad (1)$$

where the API° (American Petroleum Institute) degrees are related to oil density $\rho_{\text{oil}}$ by the formula

$$\text{API}^\circ = \frac{141.5}{\rho_{\text{oil}}} - 131.5. \qquad (2)$$

It should be noted that Eq. (1) is valid for oil cleaned from impurities and for settled oil. In a permanently used tank with crude oil, the sound velocity in oil may noticeably differ from the rated one, especially because of the presence of water. From numerous experimental measurements, we obtained the following empirical dependence of sound velocity on dynamic viscosity:

$$C = 29\ln\eta + 1321. \qquad (3)$$

Although parameter $\eta$ is not directly involved in the formula for sound velocity, dependence (3) correlates well with Eq. (1) and is convenient for practical calculations.

**Table 2.** Comparison of calculated and experimental data on the absorption coefficient at a frequency of 150 kHz

| Type of oil | Calculated absorption, dB/m | Measured absorption, dB/m |
|---|---|---|
| Light | 0.1 | 0.09 |
| Medium | 0.15 | 0.175 |
| Heavy | 0.2 | 0.25 |

## STRUCTURE OF BOTTOM SEDIMENTS AND THEIR PARAMETERS

From the results of numerous studies of sludge in oil storage tanks, it follows that the relative amounts of oil products, water, and mechanical impurities (sand, clay, rust, etc.) vary over wide limits: hydrocarbons make 5–90%, water 1–52%, and solid impurities 0.8–65%. Because of such wide variations in sludge composition, the physical-chemical characteristics of sludge also vary over wide limits. The density of sludge varies within 830–1700 kg/m$^3$, and the solidification temperature varies within –3 to +80°C. In the general case, sludge may consist of four layers. The upper layer is water-encroached oil product containing up to 5% finely dispersed mechanical impurities; it belongs to the class of water-in-oil emulsions. This layer contains 70–80 oils, 6–25 asphaltenes, 7–20 resins, and 1–4% paraffi ns. The content of water does not exceed 5–8%. This organic part of the upper layer of sludge is close in composition and properties to the original oil product stored in tanks and cannot be detected by an acoustic profiler. The second layer with a relatively small volume is an emulsion of oil-in-water type. This layer contains 70–80 of water and 1.5–15% mechanical impurities. The third layer completely consists of settled mineralized water with a density of 1.01–1.19 g/cm$^3$. Finally, the near-bottom fourth layer (bottom silt) is usually represented by a solid phase, which includes up to 45 organic products and 52–88% solid mechanical impurities, including iron oxides. Since bottom silt is a hydrated mass, its water content may reach 25%. Note that such a structure of sludge is typical of settled oil storage tanks. From Fig. 2 showing photographs of sediments, one can see that their rough surface may have different and arbitrary spatial scales.

Bottom sediments are characterized by high density and increased viscosity, which may fall within 950 to 985 kg/m$^3$ and 800 to 1800 mPa s, respectively [3, 4]. Specific examples of kinematic viscosity measurements are shown in Fig. 3 [12].

## ACOUSTIC PROFILING OF BOTTOM SEDIMENTS

As a rule, acoustic profilers intended for sludge inspection [5–9] use the same operation principle as that used by multibeam oceanic bathymeters. They employ either transceiver arrays in the form of a Mills cross [13] or interferometric arrays with a linear radiator. The latter are more complicated from the viewpoint of their mechanical structure and have reduced vertical directivity. In arrays of the Mills cross type, a multielement vertical array is used as the transmitting one with phased radiation in the vertical plane, whereas a horizontal multielement array is used as the receiver. Since, in a tank, horizontal displacement of the profiler is impossible, mapping is performed using rotation of the transceiver antenna about its axis in the

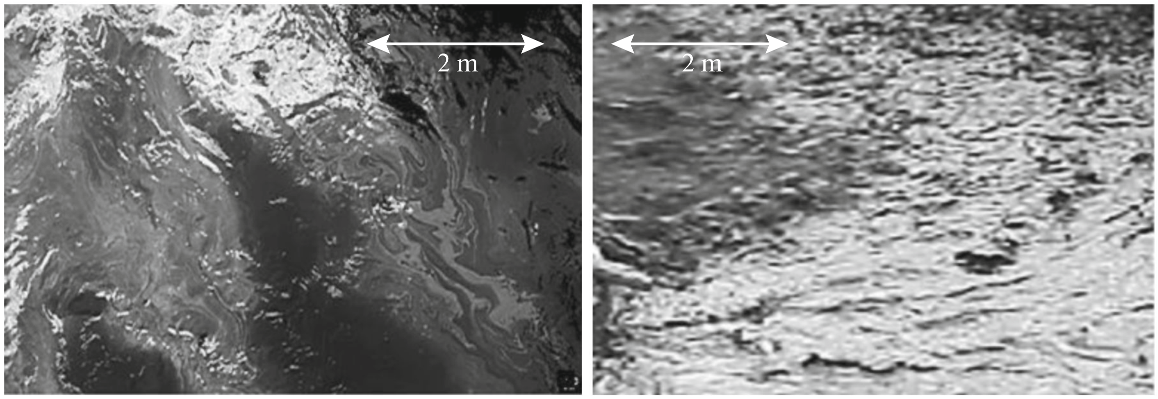


**Fig. 2.** Photographs of sludge surfaces in different tanks.

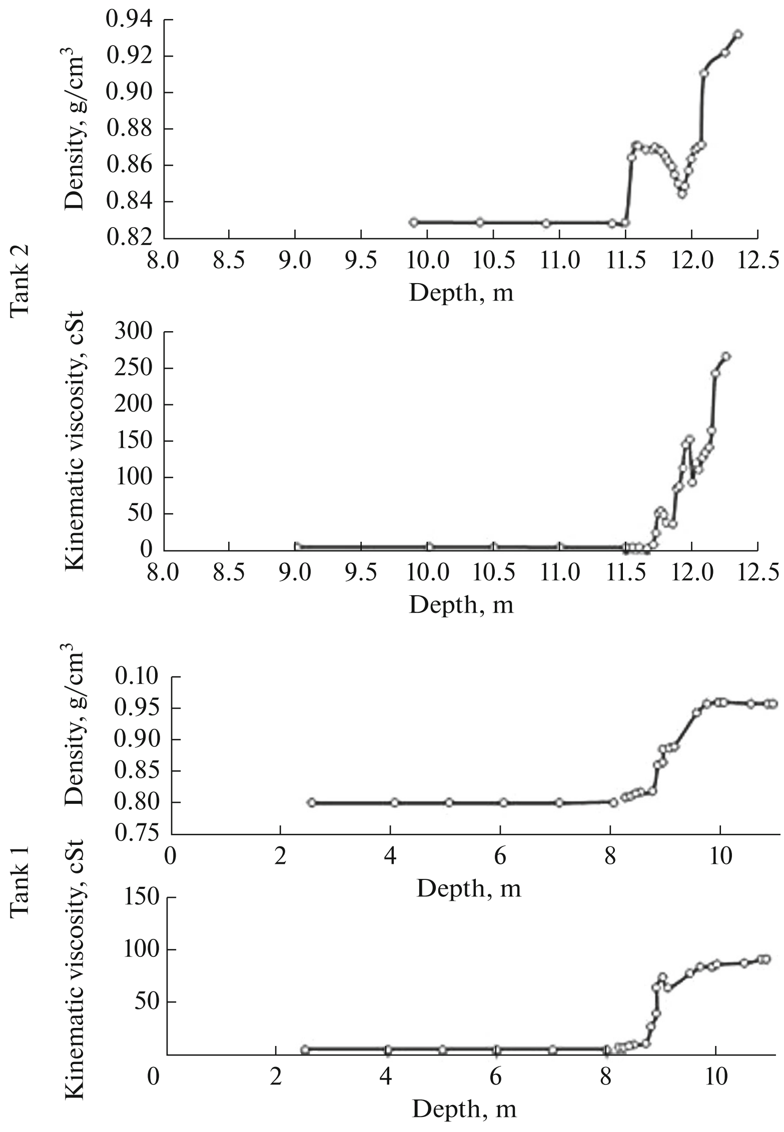


**Fig. 3.** Vertical viscosity and density profiles for two tanks with diameters of 50 m.

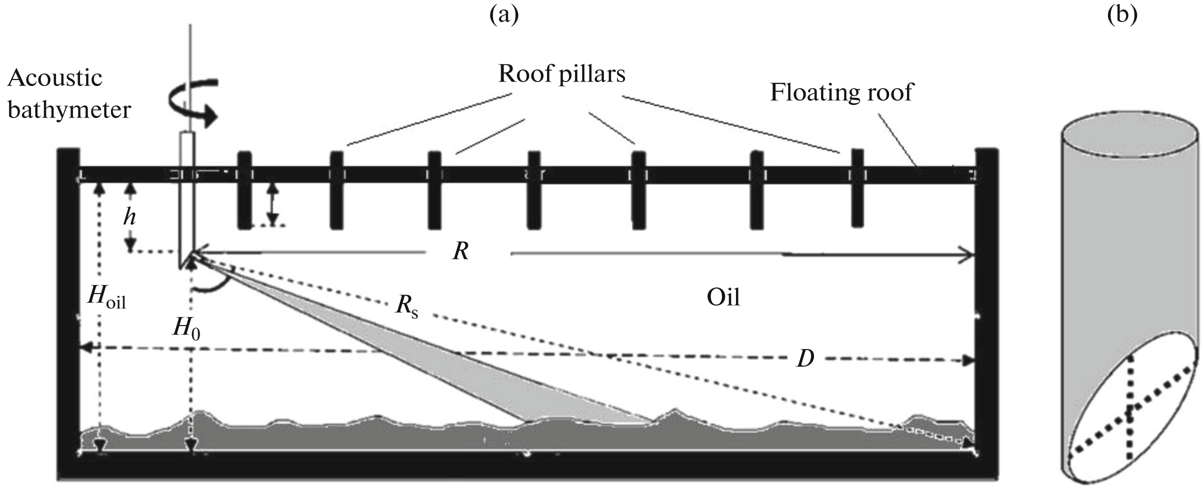


**Fig. 4.** (a) Geometry of the position of an acoustic bathymeter lowered through the sleeve of a roof-supporting pillar. (b) Mills cross.

course of its immersion in oil from a particular entrance point. The array system itself is usually inclined at an angle of 45° with respect to vertical (see Fig. 4).

In Russian oil industry, for the most part, vertical steel tanks of the RVS and RVCPK types are used [10]. An RVS tank has a rigid fixed roof and a diameter not exceeding 50 m. An RVSPK tank has a floating roof and a diameter of 50 to 120 m. The heights of the tanks vary from 18 to 23 m. The RVSPK tanks have special pillars (supports), which support the roof at a given height in the course of oil draining. The number of pillars depends on the structure and weight of the roof; as a rule, one pillar is intended for an area of 24 to 36 m$^2$. The pillars are removable, and, therefore, an acoustic profiler is constructed so that it can be introduced in oil through the pillar sleeves with diameters of 90 to 100 mm. At the bottom of a tank, heaters, filling and drain pipes, and other structures may be present.

An oil storage tank filled with crude oil represents a complex inhomogeneous medium. In such a tank, in the course of profiler operation, strong interfering echo signals caused by wave reflections from tank walls, pillars, and bottom structures are always present. Vertical temperature gradients often take place, and, sometimes, horizontal temperature anisotropy is observed. The frequency range used in acoustic profilers lies within 130 to 150 kHz. The emitted signal is usually a tone transmission with durations from several microseconds to 10–15 milliseconds. Transmission of complex signals with subsequent correlation processing is also used, but their efficiency strongly depends on the type of the scattering surface. In most cases, the sludge surface is of diffuse nature (see Fig. 4); i.e., it contains no regions of coherent ultrasound reflection (mirror points), and, therefore, the advantage of using complex signals for such scattering surfaces is close to nothing. As far as we know, the coefficients of backscattering from sludge and their angular dependences had never been measured experimentally, but indirect measurements of echo signals show that, for the aforementioned frequencies, the backscattering coefficients should be within −28 to −36 dB for glancing angles from 15° to 50°. According to [12], such backscattering levels are characteristic of fine sand or silty soil with surface roughness exceeding the wavelength. In view of the aforesaid, an acoustic profiler must have a sufficiently high radiation level (no less than 200–205 dB with respect to 1 μPa/(V m) or 10–18 kPa) and a high input dynamic range: no less that 75 dB. The volume of sediments is calculated from the local values of surface heights, which are calculated from the measured values of local slant distances $R_s$, (see Fig. 2). Therefore, the main errors in local height values are determined by the error in measuring the slant distance $R_s$, which, in its turn, depends on the error in measuring the velocity of sound $C_s$ in crude oil. Some of foreign-made bathymeters contain built-in sound velocity meters [6], but, in most cases, the sound velocity is directly measured by the profiler itself. For this purpose, the acoustic array emits a short signal along the normal to the nearest tank wall, receives the reflected signal, and measures its delay. Simultaneously, distance $R_w$ from the array center to the tank wall is measured. Knowing this distance and the measured delay time, the actual sound velocity $C_{oil}$, is determined to be used in subsequent calculations. Since the sound velocity in oil is the decisive parameter for correct determination of the surface shape and the corresponding volume, experiments were performed to compare the actually measured sound velocity with its values calculated from Eq. (1) (see Fig. 5). The experiments were carried out in an oil storage tank filled with crude oil with API° = 45 at a

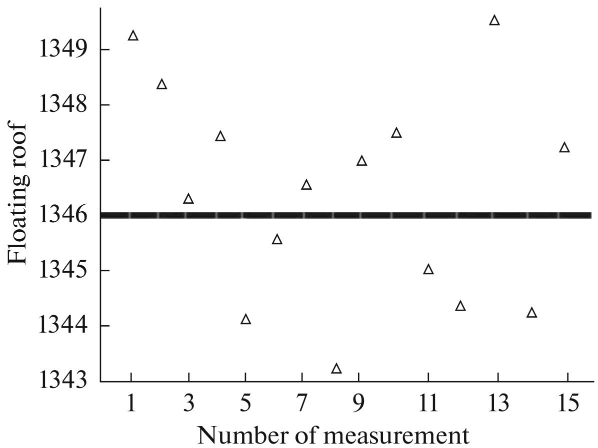


**Fig. 5.** Comparison of calculated velocity of sound with experimental data.

temperature of 20°C from several entrance points. In each of the experiments, the sound velocity was measured three times. The average velocity values obtained from individual experiments are shown in Fig. 5 by triangles. From these data it follows that, for light crude, the maximal scatter of experimental sound velocity values with respect to the calculated value is ±3 m/s or ±0.22%. A much greater difference is observed for medium and heavy crude. Namely, for medium crude with API° = 35 at a temperature of 20°C, $C_{calc}$ = 1400 m/s and the measured values exhibit a maximal scatter of up to ±1.15%.

For heavy crude, the difference exceeds ±2.5%. The increase in scatter is most likely related to higher inhomogeneity of heavy crude and greater contents of various impurities, water droplets, and gas bubbles. Therefore, Eq. (1) is suitable for preliminary qualitative estimates, whereas, for correct profiler operation, it is necessary to apply direct methods of sound velocity measurement; in addition, in so doing, it is desirable to use average measured sound velocity values obtained from several entrance points.

Now, we present the results of acoustic profiling of bottom sediments in tanks filled with different types of oil [6] (see Figs. 6a and 6b). From the latter figures, one can see that, for light crude, the sludge volumes can be much smaller, as compared to those for heavy crude, which is explained by lower impurity contents in light crude. One can also see that the sludge distribution over the tank bottom area is highly nonuniform. For example, the surface exhibits elevations of more than one meter high (see Fig. 6a). As a rule, such formations appear as a result of the procedure of sludge wash-out with a jet, when part of sludge is shifted in the jet direction.

A question arises: what bottom sediments are detected by an acoustic profiler? As was mentioned above, sediments have a multilayer structure, a smooth density gradient in the transition layer, and an unknown shape the scattering and reflecting surface. Therefore, it is next to impossible to determine by calculation from what part of the sludge surface the reflected signal arrives, especially in view of the broad spectrum of spatial frequencies of the scattering surface. The data represented in Fig. 3 clearly reveal the transition layers with their thicknesses being unpredictable and widely different for different tanks. Evidently, not all of the transition layer volume contributes to the general volume, but, from the acoustic image alone, this contribution cannot be quantitatively estimated because of the complex nature of sound scattering from the transition layer with smooth acoustic impedance variations. A review of theoretical approaches to solving a similar problem of acoustic backscattering from a rough layered bottom and their comparison with experimental results are presented in [13]. From the cited publication, it follows that theoretical estimates are fairly complicated and can only be performed for certain specific cases, so that, for the

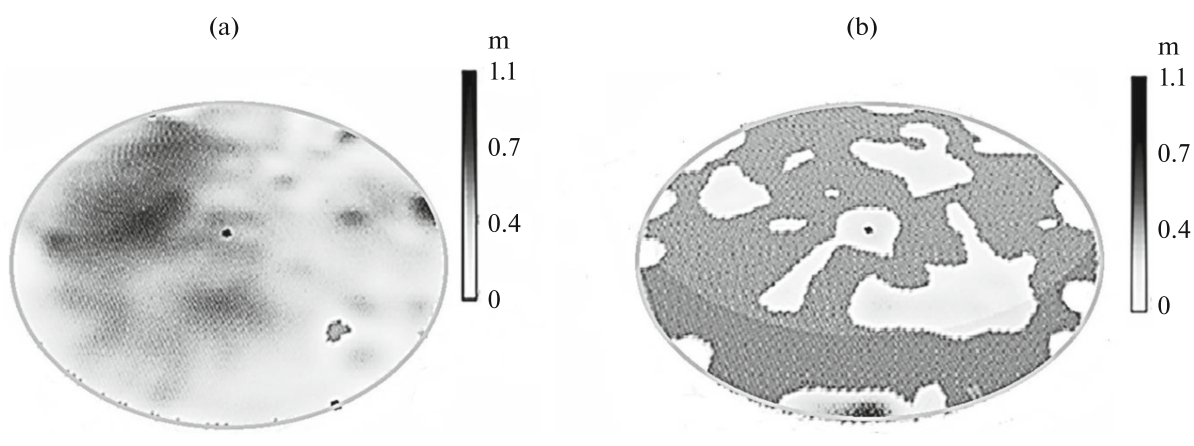


**Fig. 6.** Acoustic images of bottom sediments [6]: (a) tank with a diameter of 65 m, medium crude, a sludge volume of 1051 $m^3$; (b) tank with a diameter of 65 m, light crude, a sludge volume of 234 $m^3$.

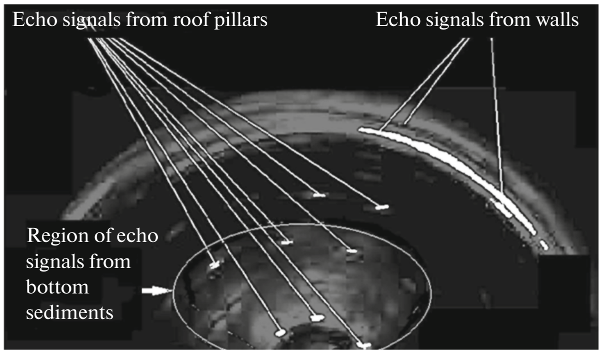


**Fig. 7.** Fragment of a two-dimensional acoustic image of sludge surface obtained from a profiler positioned at the center of the roof of a storage tank filled with heavy crude [6].

time being, the only way is to obtain experimental data.

Oil storage tanks are closed metal structures containing many elements that cause strong reflection of sound. According to the data obtained, intense echo signals caused by the side field of the transmitting array are always present. Taking into account that these echo signals are reflected from metal elements whose size far exceed the wavelength, their level, even received from the side field, may exceed the backscattering echo signal level due to radiation by the principal lobe of the transmitting array. Introduction of apodization in both transmission and reception mode reduces the aforementioned effects, but this is accompanied by a decrease in the angular resolution of arrays, this effect being the greater the stronger the side field suppression is. A decrease in the angular resolution of arrays is undesirable, especially for arrays with a small wave size, which can be introduced in a tank through the pillar sleeves. Figure 7 shows a fragment of an acoustic image of sludge surface. The image was obtained at a frequency of 150 kHz in a tank that had a diameter of 52 m and was filled with heavy crude [6].

First of all, one can see that, because of high absorption and increased glancing angle, echo signals from the surface are detected in only the central part of the tank (in Fig. 7, the corresponding region is indicated by an arrow) and the acoustic contrast of this region is fairly low. Therefore, for heavy crude, profiling is usually performed from several entrance points and the respective images are sewed together. In Fig. 7, one can see traces of strong echo signals from the pillars supporting the roof, their origin being indicated by their discreteness and periodicity. Since the transceiver array is inclined at 45° and the position of the device is 0.5 m below the pillar length (2 m), these echo signals are most probably formed by the side radiation of the array. The echo signals from the tank wall are also clearly visible. In the course of surface reconstruction, interfering echo signals falling within the region of scattered signals cause false peaks or false surface heights, which can be considerable. This means that the calculated volume corresponding to

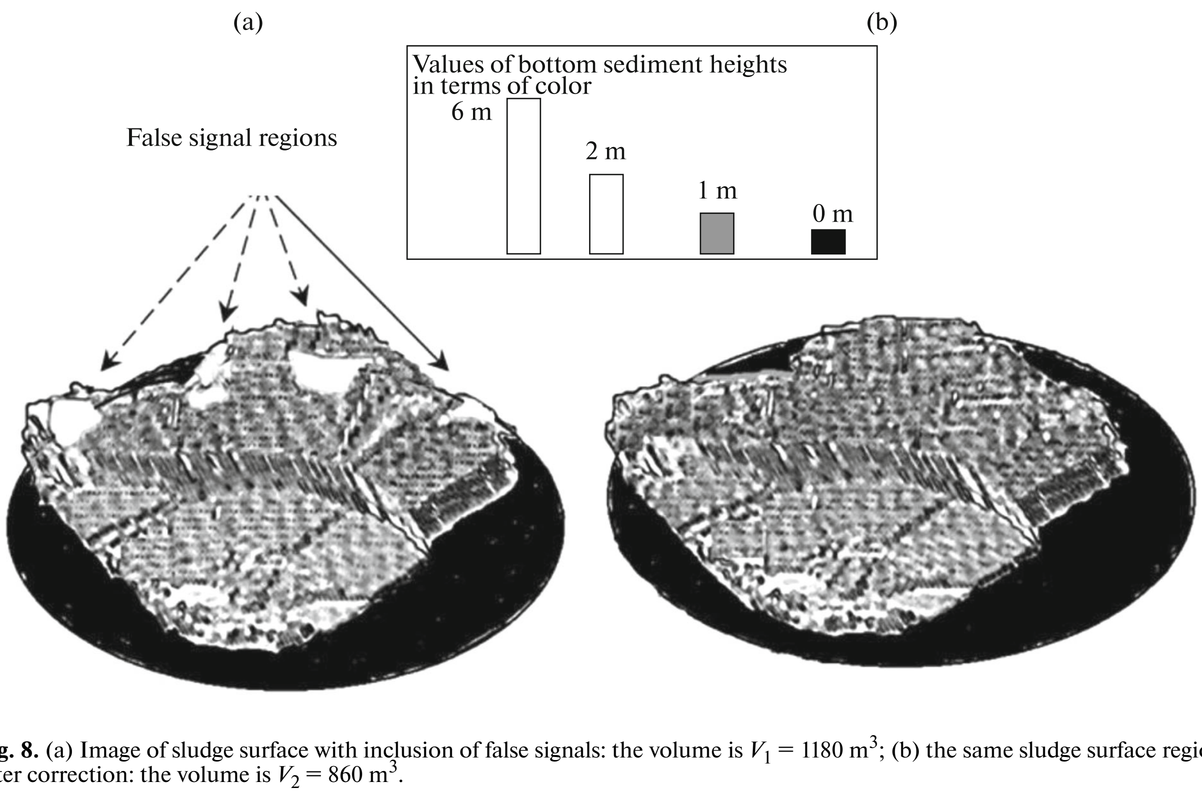


**Fig. 8.** (a) Image of sludge surface with inclusion of false signals: the volume is $V_1 = 1180$ m$^3$; (b) the same sludge surface region after correction: the volume is $V_2 = 860$ m$^3$.

the reconstructed surface will be overestimated, which is illustrated in Fig. 8.

From the above consideration it follows that an acoustic profiler constructs a certain three-dimensional image of sediment surface from which one can calculate the sediment volume. However, this volume is formed not only by useful signals but also by false echo signals reflected from different metal structures that are present in the tank and, partially, by the structures of the transition and bottom layers. In other words, the sediment volume calculated from the surface reconstructed by an acoustic profiler with inclusion of interfering echo signals is always overestimated.

Note that, in practice, the most important estimate is that of the volume of solid-phase sludge, which cannot be washed out and pumped out.

## CONCLUSIONS

Compared to other methods of bottom sediment evaluation, acoustic profilometry makes it possible to promptly obtain detailed acoustic images of sediment surface in oil storage tanks with large diameters. However, in the general case, the sediment volume measured by this method includes a considerable error due to the presence of false echo signals and the transition layer and, hence, in most cases, the volume is overestimated. To reduce the error of acoustic profiling, it is necessary to apply additional post-processing of acoustic images, which eliminates false echo signals, and additional measurements of viscosity and density of the tank content throughout the entire tank depth, at least at several points, to estimate the parameters of the transition layer. Measurements of these parameters make it possible to eliminate the volumes of the transition layer regions where the viscosity and density values are close to those of oil and to obtain information on viscosity and density of other layers, including the lowest bottom layer. In this case, after oil drainage, knowing the parameters of pumps, it is possible to estimate the volume of sediments that can be pumped out. Then, after the tank is opened, it is possible to estimate the volume of the remaining sludge in the solid phase and, hence, the complexity of work on its removal. The volume of the solid phase of sludge can be represented in the form

$$V_{SP} = V_{AP} - V_{IE} - V_{TL}, \quad (4)$$

where $V_{SP}$ is the volume of the solid phase of sludge, $V_{AP}$ is the volume measured by the acoustic profiler, $V_{IE}$ is the volume due to interfering echo signals, and $V_{TL}$ is the pumped-out volume of the transition layer. The difference between the volume measured by an acoustic bathymeter $V_{AP}$ and the volume of solid sediments $V_{SP}$ may vary from 15% to 50% depending on the type of oil, the conditions of tank operation, and the equipment used for cleaning.

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