Study of Free Oscillations of Bays in the Northwestern Part of Posyet Bay

Vladimir Chupin 1,*, Grigory Dolgikh 1, Stanislav Dolgikh 1 and Sergey Smirnov 2

1 V.I. Il’ichev Pacific Oceanological Institute Far Eastern Branch Russian Academy of Sciences, 690041 Vladivostok, Russia; dolgikh@poi.dvo.ru (G.D.); sdolgikh@poi.dvo.ru (S.D.)
2 Institute of Automation and Control Processes Far Eastern Branch Russian Academy of Sciences, 690041 Vladivostok, Russia; smirnoff@iacp.dvo.ru
* Correspondence: chupin@poi.dvo.ru

Abstract: To study the specific features of free surface oscillations in the northwestern part of Posyet Bay (the Sea of Japan), a series of experimental works using an installation with a laser meter for measuring hydrosphere pressure variations were carried out in 2012 and 2014. In the course of the joint analysis, measurement results for oscillations with periods of 10–30 min and the results of calculations using a numerical model of shallow water with a difference approximation on an irregular triangular space grid, datasets of the space–time parameters for the resonance oscillations of the studied water area were obtained. The results of the numerical simulations confirm the manifestation of the resonance properties of Novgorodskaya, Expedicii, and Reyd Pallada Bays water areas on the oscillations singled out during the experimental studies. The positions of the peaks on the model resonance curves are consistent with the positions of the clearly pronounced peaks of the energy spectrum in the field data.

Keywords: resonance oscillations; Posyet Bay; laser meter for hydrosphere pressure variations; spectrum analysis; numerical model

1. Introduction

When analyzing the recordings of coastal laser strainmeters, it was found that in the area of oscillations in the range from the main spheroidal tone $S_2$ (about 54 min) of the Earth’s free oscillations to the diurnal tide, there are free oscillations in the Sea of Japan [1]. These oscillations are usually referred to as ultra-low-frequency. When conducting the experimental studies using laser-interference systems and model theoretical calculations, it was found that the oscillations with periods from 17 to 18 min are caused by free oscillations in the Vityaz Bay of the Sea of Japan [2], which became stronger after passing atmospheric depressions, surging phenomena, and nonlinear waves, such as sine-Gordon waves. The use of a numerical simulation for the shallow water in the irregular triangular space grid of Posyet Bay showed that the solution with a period of about 17 min 23 s becomes significantly stronger in Vityaz Bay.

When conducting multiple experimental studies with the use of laser-interference devices that are a part of the seismoacoustic hydrophysical complex, one of the tasks is to determine the primary source of oscillations and waves with a wide frequency range. Several experiments were carried out using a laser meter that measures hydrosphere pressure variations to solve the problem of determining the primary source of ultra-low-frequency oscillations. The device was installed at the bottom of the bays in the northwestern part of Posyet Bay. Our primary attention in these studies was given to the free oscillations of some of the bays of the Sea of Japan. The interest in resonant oscillations is caused by the need to solve applied problems and by the need to solve fundamental problems related to the disturbance of seiches, that is, their linear and nonlinear behavior [3,4]. In modern studies, the geography of oscillation studies in water basins is widespread. The availability
of experimental data obtained both in closed water basins of different volumes [5,6], in large sea areas [7], and in the small water spaces of natural and artificial origin connected to global water basins [8–10] shows the sufficient interest of researchers in this area of study.

Various experimental and model–theoretical studies have been carried out to solve the problem of determining the free oscillations of water basins and their parts [11–14]. In the northwestern part of the Sea of Japan, experimental measurements on resonant wave processes in some bays and a determination of the spatial structure of their oscillations have already been conducted [15,16]. Wang et al. solved the eigenvalue problem associated with homogeneous, linear shallow water equations to calculate the resonance characteristics in bays and harbors in Japan [17,18]. The latest review of studies on the oscillations in Posyet Bay is presented in [19].

In many cases, it is practically impossible to accurately reproduce in a numerical model the dynamics of the waters of the studied water area during experimental studies since there is no information on the disturbing effects on the surface and on the wave packets coming from the open sea. In this paper, we use an approach that includes calculating a set of scenarios with different locations of the model wave generator operating in a local area in a simple form. The solution is sought in the form of settled, forced oscillations, which correspond to the reaction of a water area to extremely-long incoming wave packets and prolonged periodic wind effects. Scenarios are selected in which the resonant properties of the studied water areas are manifested at the frequencies singled out in the experimental studies.

2. Experimental Studies

A series of instrumental measurements were carried out using a laser meter that measures hydrosphere pressure variations to determine the resonant oscillations of the bays of the northwestern part of Posyet Bay. This device was created based on the Michelson interferometer and uses a frequency-stabilized helium-neon laser with a long-term stability frequency of $10^{-9}$ as a light source. The use of a thin membrane fixed at the edges as a sensitive element makes it possible to detect variations in hydrostatic pressure in the frequency range from 0 (conditionally) to 1000 Hz with an accuracy of 1 $\mu$Pa and in an almost unlimited dynamic range [20].

The measurements in Novgorodskaya Bay were carried out at the coordinates $42^\circ39.499'$ N and $130^\circ51.176'$ E in the period from 16 August to 17 August 2012. The structure of Novgorodskaya Bay stretches for more than 12 km from west to east. The coastline is indented with small bays. In Expedicii Bay, the measurement station had the coordinates $42^\circ38.051'$ N and $130^\circ45.710'$ E, and the measurement period was from 10 to 12 September 2012. The bay is separated from the open sea by the Nazimov Bar and is almost not affected by wind waves coming from the open part of the bay, especially of small amplitude. The measurements in Reyd Pallada Bay were carried out on 31 August 2014 in its western area, the shallowest part, with the coordinates $42^\circ35.295'$ N and $130^\circ47.930'$ E. The measurements were carried out using the vessel and placing the instruments on the bottom. Mostly good weather with weak winds prevailed in the study areas.

Figure 1 shows the map of the experiments in the bays of the northwestern part of Posyet Bay in 2012 and 2014, where the green circles illustrate the centers of wave generators in the Sea of Japan.

The experimental work was carried out using a small vessel, adapted for hauling down the measuring equipment using a winch and providing the autonomy of the device’s operation for a long time. At different times, the laser meter used for hydrosphere pressure variations was installed on the bottom in different areas of Posyet Bay. The data on the variations of hydrostatic pressure via a cable line were transmitted to the registering computer onboard the vessel. The studies were conducted in Expedicii, Novgorodskaya, and Reyd Pallada Bays, at the points marked with diamonds in Figure 1. Point 1 corresponds to the measurements in Novgorodskaya Bay in 2012 (measurement duration was 27 h), point 2 corresponds to the measurements in Expedicii Bay in 2012 and 2014 (measurement...
duration 15 and 21 h, respectively), and point 3 corresponds to the measurements in Reyd Pallada Bay in 2014 (measurement duration 8 h). The experimental data were recorded at a frequency of 2000 Hz with a 1 h duration for each file. The total measurement duration at each station was no less than 8 h, and the data, after preliminary processing, were placed in the previously created experimental database for further processing. The preprocessing included high-frequency filtering by Hamming Window, filter order 1500, and a cut-off frequency of 1 Hz. After this procedure, the data were thinned with an average of 500. Thus, the extreme frequency in the spectral analysis was 500 mHz (2 s).

3. Numerical Model

The forced oscillations were calculated using the model described by Smirnov et al. [21]. The model is based on the system of differential equations of shallow water on a sphere. The wind effect is specified by periodical time force with an oscillation frequency of order 1500, and a cut-off frequency of 1 Hz. After this procedure, the data were thinned with an average of 500. Thus, the extreme frequency in the spectral analysis was 500 mHz (2 s).

![Figure 1. Map of experiments in the bays of the northwestern part of Posyet Bay in 2012 and 2014. Red dots—settlements, green circles—zones of wave generators, diamonds—points of oscillation measurements.](image)

$$\frac{\partial u}{\partial t} - f v = -\frac{g}{a \cos \phi} \frac{\partial \zeta}{\partial \lambda} + F^\lambda - \frac{r_B}{\max(H, H_B)} u,$$

(1)

$$\frac{\partial v}{\partial t} + f u = -\frac{g}{a \cos \phi} \frac{\partial \zeta}{\partial \phi} + F^\phi - \frac{r_B}{\max(H, H_B)} v,$$

(2)

$$\frac{\partial \zeta}{\partial t} + \frac{1}{a \cos \phi} \left( \frac{\partial H u}{\partial \lambda} + \frac{\partial H v}{\partial \phi} \right) = 0,$$

(3)

$$F^\lambda = F_1^\lambda (\lambda, \phi) \cos \sigma t + F_2^\lambda (\lambda, \phi) \sin \sigma t, \quad F^\phi = F_1^\phi (\lambda, \phi) \cos \sigma t + F_2^\phi (\lambda, \phi) \sin \sigma t,$$

(4)

where $a$ is the mean radius of the Earth; $\lambda$ and $\phi$ are the geographic longitude and latitude; $t$ is time; $g$ is the acceleration of gravity; $H$ is the depth of the undisturbed layer of fluid; $u$ and $v$ are the components of the velocity vector along the directions $\lambda$ and $\phi$ respectively; $\zeta$ is the elevation of the free surface over the undisturbed position; $f$ is the Coriolis parameter,
assumed to be constant; $F_{\lambda}$ and $F_{\phi}$ are the forcing components; $H_B$ is the thickness of the bottom boundary layer. On the solid vertical boundary $\Gamma$, the impermeability condition is set:

$$n^{\lambda}u + n^{\phi}v\bigg|_\Gamma = 0,$$

where $n^{\lambda}$ and $n^{\phi}$ are components of the normal to the boundary. On the liquid boundaries, the radiation conditions are set [22]. The resonance response of the reservoir is calculated for the specified values of frequency $\sigma$ and distribution of the forcing amplitude. We seek the solutions in the following form:

$$u = u_1 \cos \sigma t + u_2 \sin \sigma t, \quad v = v_1 \cos \sigma t + v_2 \sin \sigma t, \quad \zeta = \zeta_1 \cos \sigma t + \zeta_2 \sin \sigma t,$$

where $u_1$, $u_2$, $v_1$, $v_2$, $\zeta_1$ and $\zeta_2$ do not depend on time. In the complex variables terms

$$U = u_1 + iu_2, \quad V = v_1 + iv_2, \quad Z = \zeta_1 + i\zeta_2, \quad F_{\lambda}^C = F_{\lambda}^1 + iF_{\lambda}^2, \quad F_{\phi}^C = F_{\phi}^1 + iF_{\phi}^2,$$

With new variables, Equations (1)–(3) and boundary condition (5) have the following form:

$$-i\sigma U - f V = -\frac{g}{a \cos \phi} \frac{\partial Z}{\partial \lambda} + F_{\lambda}^C - \frac{r_B}{\max(H, H_B)} U,$$

$$-i\sigma V + f U = -\frac{g}{a \cos \phi} \frac{\partial Z}{\partial \phi} + F_{\phi}^C - \frac{r_B}{\max(H, H_B)} V,$$

$$-i\sigma Z + \frac{1}{a \cos \phi} \left( \frac{\partial H u}{\partial \lambda} + \frac{\partial H v \cos \phi}{\partial \phi} \right) = 0,$$

where $n^{\lambda}$ and $n^{\phi}$ are components of the normal to the boundary. On the liquid boundaries, the radiation conditions are set [22]. The resonance response of the reservoir is calculated for the specified values of frequency $\sigma$ and distribution of the forcing amplitude. We seek the solutions in the following form:

$$u = u_1 \cos \sigma t + u_2 \sin \sigma t, \quad v = v_1 \cos \sigma t + v_2 \sin \sigma t, \quad \zeta = \zeta_1 \cos \sigma t + \zeta_2 \sin \sigma t,$$

where $u_1$, $u_2$, $v_1$, $v_2$, $\zeta_1$ and $\zeta_2$ do not depend on time. In the complex variables terms

$$U = u_1 + iu_2, \quad V = v_1 + iv_2, \quad Z = \zeta_1 + i\zeta_2, \quad F_{\lambda}^C = F_{\lambda}^1 + iF_{\lambda}^2, \quad F_{\phi}^C = F_{\phi}^1 + iF_{\phi}^2,$$

With new variables, Equations (1)–(3) and boundary condition (5) have the following form:

$$-i\sigma U - f V = -\frac{g}{a \cos \phi} \frac{\partial Z}{\partial \lambda} + F_{\lambda}^C - \frac{r_B}{\max(H, H_B)} U,$$

$$-i\sigma V + f U = -\frac{g}{a \cos \phi} \frac{\partial Z}{\partial \phi} + F_{\phi}^C - \frac{r_B}{\max(H, H_B)} V,$$

$$-i\sigma Z + \frac{1}{a \cos \phi} \left( \frac{\partial H u}{\partial \lambda} + \frac{\partial H v \cos \phi}{\partial \phi} \right) = 0,$$

The finite volume method was used to construct the difference analogues of Equations (8)–(10), taking into account (11). The procedure is described in detail, for example, in [23] (3.2.1. The 2-D External Mode, 3.5. Finite-Volume Discrete Methods in Spherical Coordinate System). The result is a system of spectral-difference equations for the grid functions $U_m$, $V_m$, and $Z_n$.

Using the SuperLU_MT [24] linear algebra software, we numerically solved the system of linear equations for grid functions $U_m$, $V_m$, and $Z_n$, where the right sides depend on the forcing. We received the spatial distributions of level oscillations and complex amplitudes corresponding to given frequencies. The model grid of Posyet Bay is shown in Figure 2.

Posyet Bay is a semi-enclosed reservoir with a wide entrance. To avoid difficulties with the formulation of conditions on the liquid boundary and their difference analogs, in this paper, the Sea of Japan was included in the computational area. In model straits, the radiation conditions are set. The following values for the model parameters were set: $r_B = 1.5 \times 10^{-4}$ m/s, $H_B = 3$ m. To reduce the influence of a rough grid resolution over most of the Sea of Japan, at distances greater than 200 km from Posyet Bay, the coefficients of bottom friction were increased up to five times. The basis for constructing the digital bottom relief of Peter the Great Bay coastal zone were fragments from nautical charts. For the remaining part of the computational area, ETOPO1 data were used [25]. The water areas characterized by a relatively narrow entrance: Expedicii, Novgorodskaya, and Troitsa Bays, are described with the highest grid resolution. The sides of the grid triangles were set in the range from a specified value near the coastline to a multiple value in the internal part of the water area: from 10 m up to 40 m in Expedicii, Novgorodskaya, and Troitsa Bays, from 20 m up to 80 m in Reyd Pallada Bay, from 20 m up to 160 m in Posyet Bay, from 80 m
up to 320 m in Peter the Great Bay, and from 1.25 km up to 5 km in the Sea of Japan. The forcing parameters in Equations (8) and (9) were specified using the following expressions:

\[ F_C^\lambda = \frac{A_\tau B(r)}{H} \sin \theta, \quad F_C^\phi = \frac{A_\tau B(r)}{H} \cos \theta, \quad B(r) = \begin{cases} \frac{1}{2} \cos \pi \frac{r-r_1}{r_0-r_1} + \frac{1}{2}, & r_1 < r < r_0, \\ 0, & r \geq r_0 \end{cases} \]

where \( A_\tau \) is the amplitude of wind stress; \( \theta \) is the azimuth of the forcing direction; \( r = r(\lambda_0, \phi_0; \lambda, \phi) \) is the distance between the points with the coordinates \((\lambda_0, \phi_0)\) and \((\lambda, \phi)\). The calculations were carried out for one hundred scenarios in which different center positions of the circles of the wave generators \((\lambda_0, \phi_0)\) were specified on a grid with a step of 0.1° for latitude and longitude. In all of the scenarios, the forcing amplitude was set equal to zero outside the circle of radius \( r_0 = 55 \) km and a constant value inside the circle of radius \( r_1 = 50 \) km. Since the used model is the linear one, in each scenario, it is sufficient to perform calculations only for the meridional and zonal wind directions. Solutions for arbitrary directions can be obtained by the linear combination of these two solutions with weights depending on the chosen direction. To present the calculation results, the resonance curves and amplitude distributions over the simulated water area are shown in the figures, in Section 4 where the position of the vessel during measurements is marked by ♦. Together with them will be given resonance curves describing the dependence of the amplitude of the forced oscillations on the frequency at the fixed forcing amplitude \( A_\tau \). The corresponding areas of the wave generator are shown in Figure 1 and are marked with the numbers 1, 2, and 3. The curve for each frequency value shows the normalized maximum amplitude value from the range that covers all forcing directions. The computational work was aimed at searching for scenarios in which the peak on the model resonance curve will best match the spectral peak according to field measurements, and significant oscillation amplitudes were observed in the studied site of the model water area.

Figure 2. Posyet Bay with adjacent areas as resolved by numerical model. The digits indicate: 1—Expedition, 2—Reyd Pallada, 3—Novgorodskaya.
4. Results of Resonance Oscillations Calculations and Their Comparison with Field Observations

4.1. Novgorodskaya Bay

Novgorodskaya Bay is located eastwards from Expedicii Bay and is separated from the main water area of Posyet Bay by the Krabbe Peninsula. Several bays protrude into the northern shore of the Novgorodskaya Bay on a coast where the piers of Posyet Port are located.

Figure 3 shows the spectrum of the recording fragments of the laser meter used for measuring the hydrosphere pressure variations (upper) and the resonance curve of the scenario (lower) with the coordinates of the center of the model wave generator, \( \lambda_0 = 131.5^\circ \text{E} \), \( \varphi_0 = 41.5^\circ \text{N} \), which corresponds to the situation with wave packets coming from the southeast direction.

![Figure 3](image)

Figure 3. Spectrum of recording fragment of laser meter for hydrosphere pressure variations (a) and resonance curve (b).

A peak with a period of 18 min 12 s is clearly pronounced on the recording spectrum of the laser meter used for measuring the hydrosphere pressure variations, and the resonance curve contains a peak corresponding to the value of the oscillation period of 18.165 min. For this solution, the largest amplitudes are observed in the middle part of Novgorodskaya Bay. Figure 4 shows the distribution of the oscillation amplitude corresponding to the period of 18.165 min during the meridional wind. The wave pattern is relatively simple since Novgorodskaya Bay has an elongated configuration. In the middle part of the bay, there are two nodal lines and two antinodes with maxima in shallow areas. The amplitudes at the position of the meter are relatively large. Thus, for this oscillation, the position of the vessel with the meter was optimal.

4.2. Expedicii Bay

Expedicii Bay is located to the northwest of Reyd Pallada Bay and is separated from it by a long narrow Nazimov Bar. Most of the bay’s water area is shallow; only its southeastern part is comparatively deep, where the depths reach 6–10 m. The bottom topography of the shallow water area of the bay is very sparsely presented on navigational charts.

Figure 5 shows the spectrum of the recording fragment of the laser meter used for measuring the hydrosphere pressure variations and the resonance curve of the scenario.
where the center of the model wave generator coordinates are $\lambda_0 = 131.1^\circ$ E, $\varphi_0 = 42.1^\circ$ N, which corresponds to long-wave packets coming to Posyet Bay from the south.

Figure 4. Distribution of oscillation amplitude with period of 18.165 min during the meridional wind. Diamond—point of oscillation measurements.

Figure 5. Spectrum of recording fragment of laser meter for hydrosphere pressure variations (a) and the resonance curve (b).

Disturbances penetrate Expedicii Bay through the narrow strait between the Nazimov Bar and the Krabbe Peninsula. The resonance curve contains a peak corresponding to the value of the oscillation period of 15.29 min, which, in turn, is quite close to the value of 15 min 10 s singled out from the processing of the experimental data of the hydrostatic pressure. Figure 6 shows the distribution of the oscillation amplitude corresponding to the period of 15.29 min during the meridional wind. In the simulated water area of Expedicii Bay, a standing wave of complex shape is observed due to reflections from the winding coastline.
coastline. White areas with small amplitudes, in fact, form lines that would turn into nodal lines in the absence of rotation. The amplitudes at the position of the meter are relatively small since the vessel with the meter was in the deeper part of the bay. Significant oscillation amplitudes are also observed in the relatively shallow bays of the northeastern part of Posyet Bay.

![Figure 6. Distribution of oscillation amplitude with the period of 15.29 min during the meridional wind. Diamond—point of oscillation measurements.](image)

4.3. Reyd Pallada Bay

Reyd Pallada Bay is located in the western part of Posyet Bay. Figure 7 shows the spectrum of the recording fragment of the laser meter used for measuring hydrosphere pressure variations and the resonance curve of the scenario with the center of the model wave generator coordinates at $\lambda_0 = 132.5^\circ$ E, $\varphi_0 = 42.5^\circ$ N.

![Figure 7. Spectrum of recording fragment of laser meter for hydrosphere pressure variations (a) and the resonance curve (b).](image)
The curve contains peaks corresponding to the values of the oscillation period of 24.83 and 27.035 min. When the processing obtained experimental data on the hydrostatic pressure, the values of 24 min 50 s and 27 min 18 s were singled out. The discrepancy between these periods exceeds one for the Expedicii and Novgorodskaya Bays. A possible reason is the distortion of the frequency properties of the model reservoir due to the relatively rough description of the main part of the Sea of Japan and the natural limitations of computing resources. The entrance to Reyd Pallada Bay is relatively wide. This fact is the main difference between the resonance properties of Reyd Pallada Bay and Expedicii and Novgorodskaya Bays, which are connected to Reyd Pallada Bay through a narrow strait. For example, the solution shown in Figure 8 a is, in fact, the joint oscillation of Reyd Pallada and Posyet Bay. In its turn, Posyet Bay is also characterized by a wide entrance, and there may be joint oscillations of the bay and the sea. The increased dissipation was used in the paper to suppress the influence of the simulated open sea in the solution. However, this technique, of course, does not prevent the distortion of frequency properties in the model reservoir.

Figure 7a shows the distribution of the oscillation amplitude corresponding to the period of 24.83 min during the zonal wind. The waters of Expedicii Bay are not involved in this movement. In Novgorodskaya Bay, the oscillation is characterized by small amplitudes and three nodal lines. In Reyd Pallada Bay, one can note one nodal line in the internal part. The largest amplitude values for the entire solution were recorded in the shallow bay, jutting out into the north shore of the Posyet Bay. In Posyet Bay, we note two nodal lines of longitudinal oscillation, one of which is located on the border of the Bay.

Figure 7b shows the distribution of the oscillation amplitude corresponding to the period of 27.035 min during the meridional wind. The waters of Expedicii and Novgorodskaya Bays are substantially involved in this movement. In the eastern part of Novgorodskaya Bay, transverse oscillation is observed, with amplitudes most significant for the entire solution. In Reyd Pallada Bay, one can note one nodal line in the internal part. In Posyet Bay, a nodal line of longitudinal oscillation can be singled out.

![Figure 8. Distribution of oscillation amplitude with period of 24.83 min during the zonal wind (a) and with the period of 27.035 min during the meridional wind (b). Diamonds—points of oscillation measurements.](image-url)
5. Conclusions

The determination of the natural oscillations of bays and gulfs is important from the point of view of the safety of performing various human functions in such waters. In addition, the excited natural oscillations of these bays can cause variations in the stress–strain field of the Earth on the land bordering these waters. As a typical example of the conversion of seiche energy into the energy of microdeformations of the Earth’s crust, we can cite the events of 2011, when a powerful earthquake occurred east of Japan on 11 March, and geodynamic processes led to the formation of a destructive tsunami. As a result of the earthquake and the subsequent change in the water level of the Pacific Ocean, a change in the water level in the Sea of Japan was observed. According to various literature data, the water level in the Sea of Japan varied up to 40 cm. It should be noted that the amplitude of the tide in the Sea of Japan reaches about the same magnitude. A sharp change in the water level in the Sea of Japan led to a significant increase in the amplitudes of natural oscillations in the Sea of Japan and its bays and gulfs. Unfortunately, during this period, our measuring systems were not standing in Vityaz Bay, but a 52.5-m laser strainmeter was functioning at Cape Schultz [26]. The laser strainmeter recorded all of the disturbances associated with this earthquake and its consequences. In the context of this article, we paid attention to the occurrence of powerful oscillations with a period of 16 min 33 s on the recording of the laser strainmeter. The excitation of these oscillations was preceded by a sharp change in the level of microdeformations in the Earth’s crust, which was registered by the device. This period corresponds to the period of the natural oscillations in Vityaz Bay. Its period is less than the above (17 min 23 s), which, apparently, is due to the magnitude of the exciting force [2].

As a result of the experimental studies conducted in 2012 and 2014, the water level oscillations with periods of 10–30 min were studied in three large bays of the northwestern part of Posyet Bay (the Sea of Japan). Peter the Great Bay, which is located on the Sea of Japan, and its inner water areas, are a complex oscillatory system with a huge number of possible resonant oscillations. At each moment of time in this system, resonant oscillations corresponding to the current specific perturbing factors are excited. We can talk about a complete system of oscillations in the studied water area, but only weak, decaying resonant oscillations that are capable of accumulating energy have practical significance. To identify these oscillations, long-term in situ measurements of the level in some points of the water area are required. Among these oscillations, we singled out the most significant ones, the manifestation of which can be traced to a number of measurements made at different times. This fact indicates the possible resonant nature of these oscillations. The joint analysis of the oscillation measurement results and the calculation (using a numerical model of shallow water with difference approximation on the irregular triangular space grid) results was carried out. The results of the numerical simulations confirmed the manifestation of the resonance properties of water areas in the Novgorodskaya, Expedicii, and Reyn Pallada Bays and oscillations with periods of 18 min 12 s, 15 min 10 s, 24 min 50 s, and 27 min 18 s, were singled out during the experimental studies. During the periods of experimental observations, no fluctuations in atmospheric pressure at the respective frequencies were detected. The spatial distributions of the amplitudes of these oscillations are presented, allowing for the identification of potentially dangerous coastal areas. Thus, although the approach used in the modeling allows us to obtain a large number of theoretical results corresponding to various scenarios, the limited measurements make it possible to confirm the significance of only several individual modeling scenarios. Nevertheless, the entirety of the simulation results can be used when planning subsequent in situ measurements to determine optimal sensor placement. The use of simulation can significantly supplement the results of experimental studies obtained from a limited number of points.

To clarify the results, additional data are needed to build a detailed digital topography of the bottom, and long-term measurements using the spatially distributed system of synchronous level sensors are needed. At that, the studies of Novgorodskaya and Expedicii Bays can be carried out separately only for relatively fast oscillations, when water exchange
through the narrow strait separating these bays from the Reyd Pallada Bay can be neglected. The study of oscillations in Reyd Pallada Bay, characterized by a relatively wide entrance, should be accompanied by measurements in the Posyet Bay water area to register the joint oscillations of the bay and the external water area.

**Author Contributions:** Conceptualization, G.D.; investigations, S.D., V.C. and S.S.; visualization, S.S.; project administration, S.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by RSF grant number 22-27-00678—“Microdeformations of the Earth’s crust caused by marine infragravitational waves according to laser-interference devices”.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** Numerical results were obtained with use of IACP FEB RAS Shared Resource Center “Far Eastern Computing Resource” equipment.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**


11. Magdalena, I.; Karima, N.; Rif’atinn, H.Q. Resonant periods of seiches in semi-closed basins with complex bottom topography. *Fluids* 2021, 6, 181. [CrossRef]


