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RESEARCH OF HIGH-FREQUENCY INTERNAL WAVES AT THE SHORE BORDER USING SPECTRA OF SPACE OPTICAL IMAGERY

Introduction

Internal waves in the ocean essentially determine the variability of a water column over a wide range of spatial and temporal scales. They can participate in the redistribution of heat flux, momentum and energy, and wave breaking can create small-scale fluctuations. Consequently, studies of internal waves, especially their generation, development, distribution, and in particular, issues of instability and wave breaking, are becoming crucial for understanding exchange processes in the ocean. The reasons behind internal wave generation are diverse: they can be caused by fluctuations in atmospheric pressure, wind, underwater earthquakes, current flow over the bottom topography, and anthropogenic effects, etc. [1, 2]. In coastal waters, usually natural, tidally induced internal waves are observed. Due to dissipation during internal wave interaction with the continental slope, systems of short-period internal waves may be generated [3-5].

Affecting the water surface, internal waves cause significant changes in wave spatial and temporal structure. These can be seen both visually and with the help of remote sensing equipment [3-6].

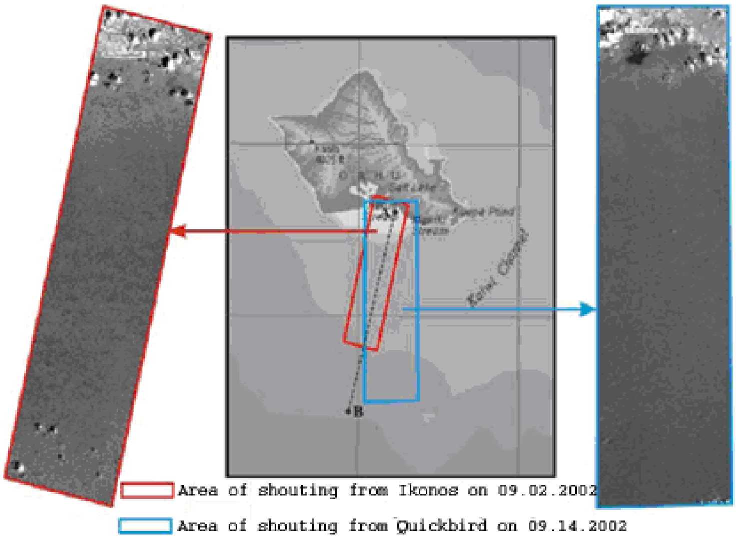


Fig. 1. Map of the study area and processed satellite images.

For monitoring of marine waters and manifestations of internal waves, it is appropriate to use space-based remote sensing, which provides global regularity and efficiency of observations, as well as reliability of the data [3]. The most efficient way of examining the surface display of internal waves is the spectral approach. It allows description of random spatial structure for surface waves, identification of its variability under the influence of various factors, as well as exploration of the physics behind the processes and the phenomena occurring [3].

In this work the spectral characteristics of natural, high-frequency internal waves generated by tidal flow in the zone of the continental slope are studied.

The study region

The study of surface manifestations of internal waves was carried out in the water area of Mamala Bay, Oahu Island. (Hawaiian archipelago) [6, 7]. Fig. 1 (center) presents a map of the study area showing Pacific Ocean zones observed from space. The bathymetry profile along the line AB (see Fig. 1) is shown in Fig. 2. As demonstrated in Fig. 2, after 50 - meters depth on the shelf there is an abrupt drop to a depth of 500 meters, and after a lengthy flat stretch of the continental slope (further than 40 km from the coast) depths change dramatically from 600 to 4500 m.

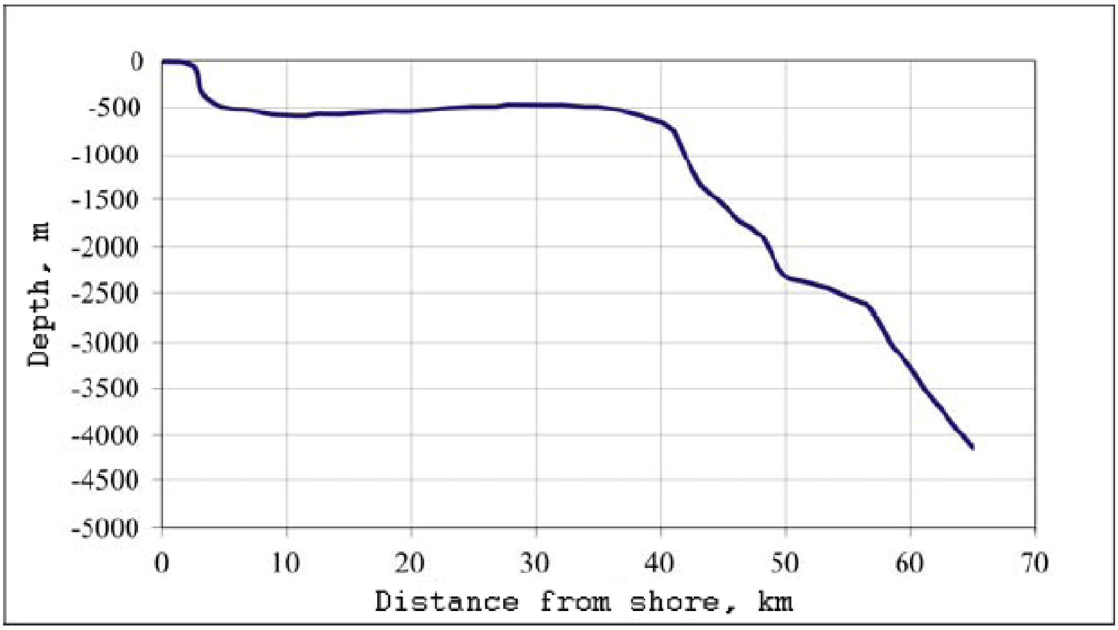


Fig. 2. Bathymetry profiles along the line AB (see Fig. 1) in the study region

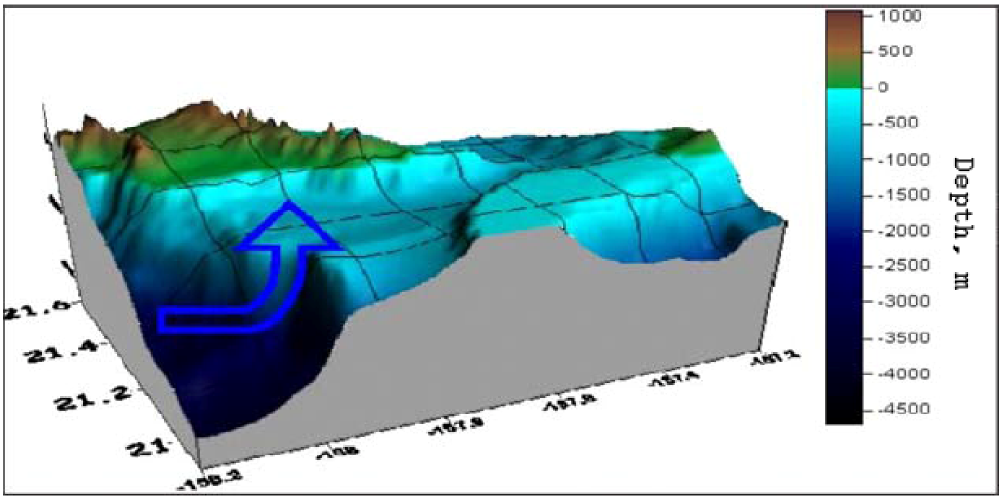


Fig. 3. Tidal flow over the continental slope in Oahu Island area

The Great Hawaiian underwater Ridge is a source of intense internal waves, spread over long distances within the ocean [7-10]. In the study area, continental slope, rising from higher depths almost to the ocean surface, creates sharp heterogeneity for a propagating barotropic tidal wave. Tidal currents, propagating over variable bathymetry, have a vertical component (Fig. 3). This results in a periodic shift of isopycnal surfaces, causing the internal waves of the tidal period [8-10]. In the Hawaii region, internal tides are generated not at the shelf edge as usual, but at considerable depth on the steep continental slope. This happens where the slope reaches critical values for the average stratification [8. 9]. Periodic upward and downward picnocline motion around the normal position leads to the formation of internal waves which propagate on both sides of the slope, with the internal wave front being approximately parallel to the continental slope [9, 10]. Generation of the internal waves on the continental slope varies greatly from place to place, depending on the bottom slope, the strength of tidal flow, and the density stratification of the water.

Internal waves with large amplitudes are generated by the deep part of the Hawaiian Ridge, and propagate in the open ocean from the underwater slopes, while a weaker dumping wave component is moving towards the coast, and in the process of dissolution may generate high-frequency internal waves [10]. One of the interesting places to study such manifestations of internal waves is a shelf break.

Specifics of the satellite imagery and processing techniques

During an international project [6, 7] in 2002 – 2004, imaging of Mamala Bay coastal waters was performed by various satellites, including the satellites Ikonos and Quickbird, outfitted with high spatial resolution optical equipment, [6].

Fig. 1 shows examples of the imaging area and satellite images from September 2, 2002 made by the satellite Ikonos, and September 14, 2003 images made by the satellite Quickbird. Both imaging areas are longitudinally elongated and have sizes of about 11 x 50 km^2 and about 16 x 70 km^2, respectively. Satellite images of these regions allow exploration of surface manifestations for internal waves at a considerable distance from the coast, including in the region of steep bathymetry changes, located approximately 30-40 km from the coast (see Figs. 1, 2). Here the ocean depth changes by 4000m over a 20 km distance (see Fig. 2).

The methodology for processing satellite images to study the spectral characteristics of internal waves consists of the following steps [3]:

1. Splitting the original images into fragments, in our case, of size 2048 * 2048 pixels.
2. The formation of a two-dimensional spatial spectrum for fragments of the satellite images using a Fast Fourier Transform algorithm.
3. Processing of the obtained spectra in order to improve their quality, using such procedures as: equalization, color coding, filtering, smoothing, etc.
4. Locating, in the resulting two-dimensional satellite image fragment spectra, spectral maxima corresponding to systems of internal and surface waves.
5. Determining characteristics of the found spectral maxima such as: spatial frequency, wavelength, and maximum’s width and orientation.
6. Statistical analysis of the characteristics of the spectral maximums in order to determine the systems of internal waves and study their characteristics.
7. Obtaining additional meteorological data in order to separate surface waves (including wind waves) from internal waves.
8. Allocation of zones with surface manifestations of internal waves.

During the processing, satellite imagery fragments of size 2048 x 2048 pixels are accumulated. This corresponds to an ocean area size of about 1.3 x 1.3 km^2 (for images obtained using the satellite Quickbird) and about 2 x 2 km^2 (for images obtained using the satellite Ikonos).

Results of spectral processing for the satellite images and their analysis

Visual examination of remote-sensing imagery with high spatial resolution, shown as examples in Fig. 1, was not enough to reveal regions with surface manifestations of internal waves, which often occur in space images of other coastal ocean [3, 4.5]. Fig. 4 shows an example of spectral spatial processing of satellite image results obtained on September 2, 2002 from the satellite Ikonos, and on September 14, 2003 from the satellite Quickbird. Also shown are spectra of several image fragments corresponding to different parts of the analyzed images.

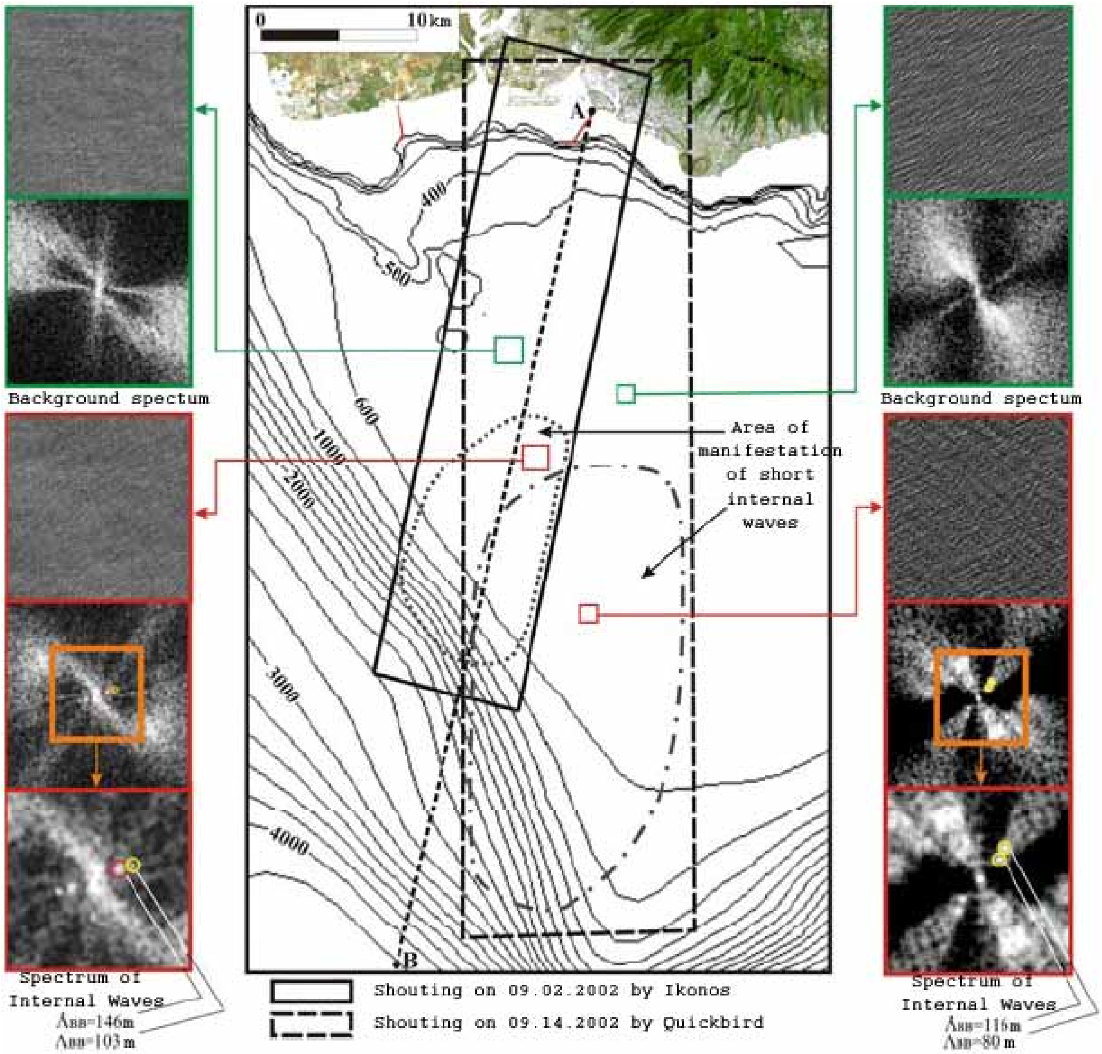


Fig. 4. Fragment of the studied area map for the region of Oahu Island (Hawaii) and the results of spectral processing of satellite image fragments.

In the central parts of the image fragment spectra covering the region with a sharp increase in the ocean depth (see Fig. 4), local maxima corresponding to internal high-frequency waves are clearly visible [3, 6]. The lengths of these waves are 103 and 146 meters for the images obtained in 2002, and 80 and 116 meters for the images obtained in 2003. Similar maxima were found in the spectra of other fragments, corresponding to the bottom part of satellite images in the area close to the shelf break. In the background spectra taken closer to the shore, such harmonics are missing (see Fig. 4, above).

For analysis of the shown spectral maxima, different characteristics were calculated, namely: spatial frequency (v), wavelength (L) and the direction of harmonics (O). The results of the statistical processing of these characteristics are given in Figs. 5, 6. These results were obtained from the image fragment spectra from images taken on September 14, 2003.

The histogram presented on Fig. 5 demonstrates that the selected spectral harmonics can be divided into two classes, according to their wavelength. The first class is characterized by wavelengths L ~ 30-60 m and corresponds to wind waves generated by the wind observed during this period of time (wind velocities WB = 6-8 m/s). The second class of spectral wavelength maxima corresponds to wavelengths L ~ 80 - 150 m. These maxima are caused by surface manifestations of high-frequency internal waves.

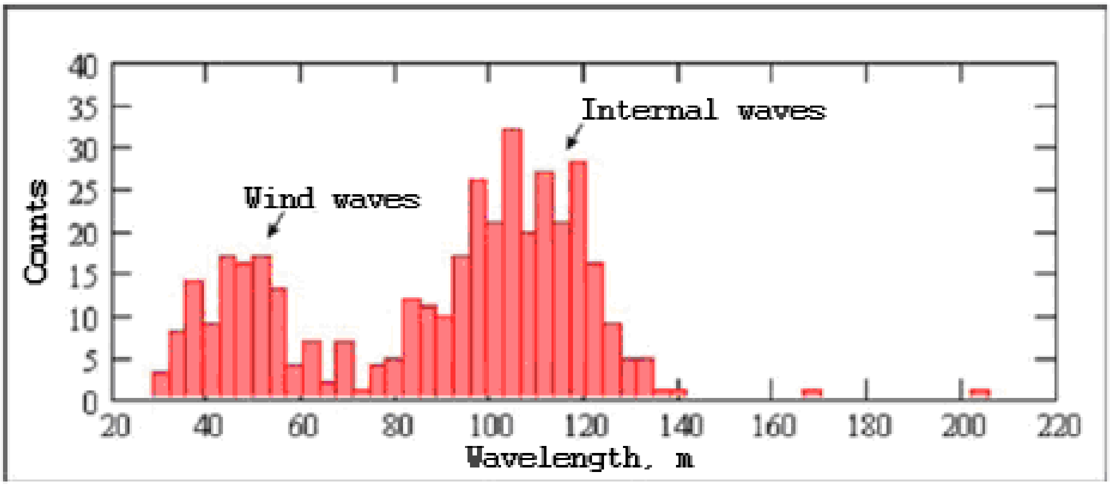
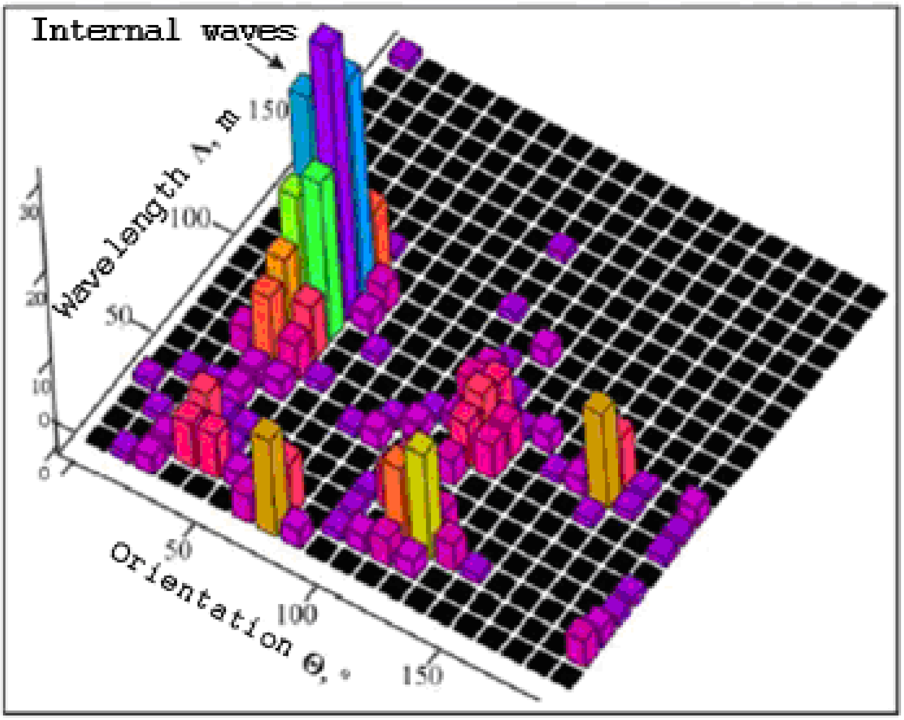


Fig. 5. The distribution of wavelengths registered from satellite image spectra.



Rig. 6. Three-dimensional distribution characteristics of spectral maxima in the space L O

For a more detailed analysis, a distribution of wavelengths L and orientations of the discriminated spectral harmonics O was constructed for all the fragments of the satellite images in the bottom part of imaging area. On Fig. 6 a cluster stands out clearly, which corresponds to wavelengths L ~ 80-200 m and tracks the propagation directions of O ~ 30-60 ° (nearly orthogonally to isobaths). Similar results were obtained from the processing of satellite images taken by the satellite Ikonos on September 2, 2002.

Thus, spatial spectral processing of the satellite images obtained from the high-resolution satellites Ikonos and Quickbird allowed us to establish that, at the shelf break and adjusted continental slope, short-period internal waves can be recognized, with lengths L ~ 80-200 m and directions O ~ 30-60 °. It is important to note that these internal waves cannot be distinguished by visual analysis of space images. Manifestation areas of such short internal waves, determined by the spectra of satellite images, are presented on Fig. 4. Analysis of Fig. 4 demonstrates that the surface anomaly related to manifestation of tidal internal waves occupies an area stretched in the direction of South-West – North-East (orthogonal to the ocean depth increase). This is caused by the specific features of the tidal current distribution and bathymetry.

Similar results were obtained from processing of other satellite images made in 2002-2004. Based on the above, it is possible make the following explanation for the observed phenomena. A long barotropic tidal wave is coming from the open ocean to the continental slope. The vertical component of tidal currents is generated on the obstacle, which in turn cause fluctuations in isopycnal surfaces, and, consequently, the production of internal waves. For waves propagating towards the shelf, there is the effect of constant energy injection, which could lead to an intensification of waves [4, 9, 10]. At some point, the growth of wave energy creates critical conditions, causing wave breaking and energy transfer to short-period internal waves [4,8]. Such dissipation of the long tidal wave's energy results in the generation of a system of shorter waves, which was detected by spectral analysis of satellite images. The original long tidal wave is difficult to recognize using high-resolution satellite imagery. The size of the processed fragments is ~ 1.3 x1.3 km^2 (for images from the satellite Quickbird) and ~ 2x2 km^2 (for images from the satellite Ikonos), while the semi-diurnal tidal wave length is several kilometers [4.9].

To create such system of waves, it is necessary for the tide to propagate orthogonally to the ocean depth gradient. Model data on the direction of the high tide propagation has been used to confirm this hypothesis. The isotherm distribution in a given area at consecutive times, obtained by mathematical modeling of water mass circulation in the Hawaii region, is presented at Fig. 7 [11]. The isotherm's location at different times gives an idea of the tide's direction. Analysis of Figs. 3 and 7 shows that the tide propagates almost orthogonally to the depth gradient. Consequently, in this area, effects associated with dissolution of a long tidal wave into short internal waves can be observed. These effects have been identified by spatial spectral analysis of high-resolution satellite imagery.

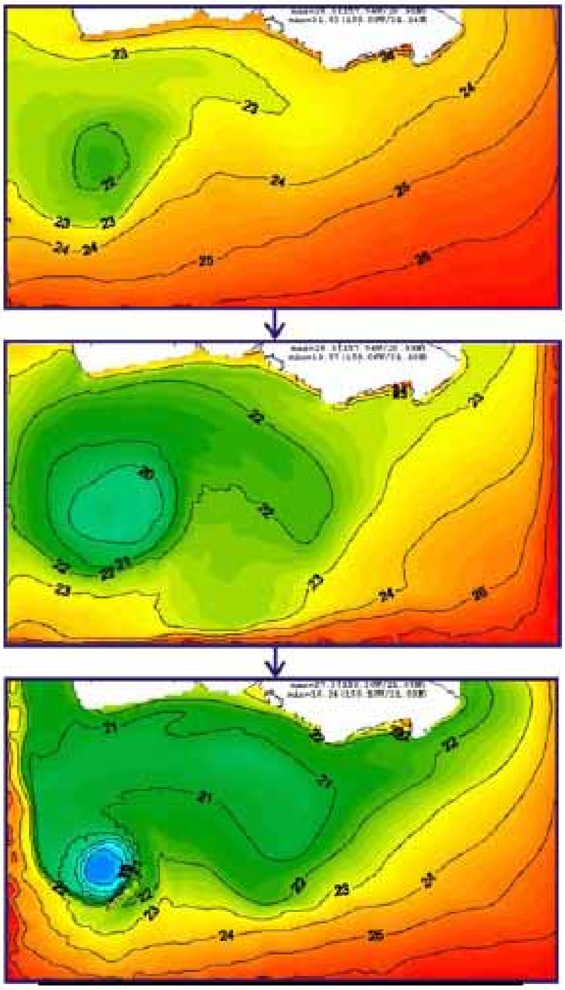


Fig. 7. Isotherm distribution in the explored region at different times.

Conclusions

As a result of spatial spectral processing of optical high-resolution satellite imagery, and statistical analysis of characteristics for the spectral maxima corresponding to surface manifestations of internal waves in the coastal zone of the island of Oahu (Hawaii), the following conclusions are made:

1. At the shelf break and in the adjacent part of the continental slope (at a distance of 20-50 km from the coast), internal high-frequency waves are formed by the breakup of the long tidal wave. These short internal waves propagate almost orthogonally to the isobaths corresponding to the bathymetry gradient in the explored region (direction ~ 30 -60 °, length of 80 to 200 m).

2. Such high frequency internal waves are not detected visually in space images, and are identified only by spectral harmonics of two-dimensional spatial spectra of these images fragments.

3. The surface anomaly related to manifestation of internal tidal waves in the studied part of Mamala Bay covers an area of about 400 km^2, stretching in the southwest - northeast direction (orthogonally to the depth gradient).

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