Complex Satellite Monitoring of Coastal Water Areas

V.Bondur

Scientific Center of Aerospace Monitoring “AEROCOSMOS”, 4, Gorokhovsky per., Moscow, 105064 - vgbondur@online.ru

Abstract - Possibilities of applying satellite means for monitoring of sea and ocean water areas are considered. Significant parameters of water environment registered by modern advanced space means and problems than can be solved using these means are analyzed. Some results obtained during complex satellite monitoring of anthropogenic influences on Mamala Bay water area (Honolulu, Hawaii) in 2002-2004 are given in this paper. Based on analysis results for optical (panchromatic, multispectral, hyperspectral) and radar satellite image processing, manifestations of anthropogenic influence on water environment were studied. These manifestations are related to changes in hydrodynamic parameters, hydro-optical and hydro-biological characteristics of near-surface ocean layer. Effects of generation of “quasimonochromatic” spectral harmonics of sea waves (Λ~10...150 m) due to ultrahigh frequency internal wave manifestations caused by a deep outfall are detected. Parameters of harmonics revealed in satellite imagery coincide with parameters of internal waves obtained from the results of sea truth measurements. Based on the results of satellite monitoring we have worked out recommendations on nature-conservative measures in the studied recreational area that can be realized also for other coastal water areas.

Keywords: space monitoring; coastal water areas; anthropogenic influence; sea truth.

1. INTRODUCTION

One of the most important issues for the World Ocean studies is the study of its coastal areas. This is due to the fact that more than half of the Earth population lives in coastal areas and these areas undergo intense anthropogenic effects. Moreover, the shelf and continental slope are being developed nowadays for production of natural resources what increases the anthropogenic load on these areas.

The primary sources of anthropogenic effects on the oceans and seas, especially coastal waters, are: industrial production and maritime transportation; mining of natural resources and fossil fuels; discharging of industrial and household wastes directly into the ocean or via rivers; inflow from the land of various compounds used in agriculture and forestry; intentional burial in the sea of pollutants, including radioactive substances; leakage of various substances during routine maritime operation of sea vessels; accidents involving maritime transportation and military vessels; accidental discharges from ships and underwater pipelines; tourist and recreational activities; transfer of pollutants through the atmosphere, etc [Israel, Tsiban, 1989; Dolotov, 1996; Bondur, 2004]. The continuing increase and additive effect of these various pollution sources lead to a progressive eutrophication and microbiological contamination of water, making it substantially more difficult to use for human needs. A substantial concentration of anthropogenic pollutants in the near-surface layer of the ocean leads to a disruption in the ecosystem’s balance and a drop in environmental bio-productivity. As a consequence of the increasing threat to our environment, it is important to organize monitoring of the water environment, and create corresponding systems, including the most recent aerospace platforms [Bondur, 2004]. This paper gives an overview of contemporary aerospace methods and means, as well as possibilities of their application for coastal water area monitoring. Some results from the complex monitoring of anthropogenic effects on Mamala Bay water area (Oahu Island, Hawaii) in 2002 – 2004 are also presented.

2. ROLE OF SPACE MEANS FOR MONITORING OF COASTAL WATER AREAS

Significant success has been achieved recently in the area of development of aerospace methods and technologies for ocean remote sensing. These methods and instruments are promising due to the fact that modern advanced satellite instruments allow us to register a wide range of significant parameters of water environment, including the following [Bondur, 2004]:

- variations of hydrooptical parameters, above all color and turbidity, caused by fluctuations of light scattering and absorption coefficients due to changes in concentrations of suspended and absorber substances;
- changes in hydrodynamic parameters (current fields, internal waves, turbulence, circulating fluid motions, etc) resulting in surface wave deformations and ocean near-surface layer parameter changes;
- temperature variations in current fields, upwelling areas, in the areas of turbulence and internal wave interaction with water surface, etc;
- fluctuations of parameters of physical and chemical ocean fields resulting in variations of temperature, salinity, permittivity, heavy metal concentrations, etc.;
- variations of biological parameters (concentrations of main biogenic elements (nitrogen, oxygen, phosphorus), acidity, phytoplankton conditions, etc.);
- oil films and changes in surfactant film concentrations due to buoyancy of diluted organics leading to changes in color, temperature, amplitude-frequency parameters of waves;
- ocean level variations caused by tide-and-ebb phenomena, geostrophic currents, tsunami waves, etc;

Besides, satellite data processing comes up to rather high level as well as handling of large information volumes acquired during complex monitoring of various physical, chemical and biological ocean fields using satellite and sea/ground truth data.

The following problems can be solved during satellite monitoring [Bondur, 2004]:

- study of littoral water dynamics (surface currents, oceanic fronts, turbulence, and circulating motions of various scales,

interactions between internal and surface waves, mechanisms of mass and energy transfer, etc.);
- study of various hydrophysical fields in the ocean depths through their effects on the surface and near-surface layers;
- study of the interactions between the ocean and the atmosphere, including short term and long term fluctuations in climate;
- evaluation of the global ocean's contribution into the carbon cycle of the Earth;
- studies of the bio-productivity and biodiversity of coastal water areas;
- monitoring of ocean pollution caused by various sources;
- study of changes in ecosystems of sea and ocean coastal zones under the effect of natural and anthropogenic factors;
- complex studies of conditions and variability of ocean coastal water areas including anthropogenic effects on their ecosystems;
- study of ocean upwelling zones;
- monitoring of ice conditions (for northern seas);
- defining of bottom topography and its variability under the influence of various processes;
- study of tide-and-ebb phenomena on regional scales;
- monitoring of catastrophic natural processes in coastal areas (tropical cyclones, underwater earthquakes, etc.) end evaluation of their consequences.

The abovementioned (but not complete) list of problems solved by satellite means of ocean remote sensing is the evidence of wide range of their possibilities. So, these days satellite methods play a significant role in the monitoring of ocean and its coastal areas. Their importance for solving this pressing problem will increase appreciably in the near future.

3. FEATURES OF COMPLEX MONITORING OF OAHU ISLAND (HAWAII) COASTAL AREA

Complex monitoring of anthropogenic influences on coastal water area of Mamala Bay (Honolulu, Hawaii) was performed in 2002-2004 in the framework of an international project. The main purpose of this project was the detection of negative effect of deep outfalls in Mamala Bay water area on recreational area of Oahu Island, Waikiki Beach especially.

Periodical space imaging of the bay water area was performed during the monitoring using:
- optical high resolution sensor of IKONOS and QuickBird satellites providing panchromatic imagery of 0.61 – 1.0 m resolution and multispectral imagery of 2.44-4.0 m resolution;
- radar sensor of RADARSAT (8 and 25 m resolution, $\lambda \approx 5.6$ cm wavelength, HH polarization) and ENVISAT (~ 25 m resolution, λ=5.6 cm, HH, VV, VH polarization);
- Hyperion hyperspectral sensor (~ 30 m resolution, 220 spectral bands in the range of 0.4-2.5 μm), as well as ALI sensor (~ 10 m resolution (panchromatic mode) and ~ 30 m (multispectral mode), 10 spectral bands in the range of 0.4-2.4 μm of EO-1 satellite;
- ASTER sensor (15 m resolution in visible and near-IR band, 30 m in mid-IR and 90 m in far-IR band), TERRA satellite;
- multispectral MODIS sensor (250 m resolution in visible and near-IR band, 500 m in mid-IR and 1 km in far-IR band), TERRA and AQUA satellites.

Besides, multispectral sensors of International Space Station were used (~ 2 m resolution (panchromatic mode) and ~ 5 m (multispectral mode)) and also data acquired by "Meteor-3M", "Resurs-O", NOAA and GOES were involved.

Fig. 1 presents the scheme of complex monitoring. In this figure we can see the map showing locations of stations for measurements of temperature vertical profile time dependences (termistors), as well as parameters of current velocity fields (ADP). Location of the Sand Island Outfall is shown. The outfall diffuser having 282 ports is located at the depth of 70 m 3.8 km from the shore. Navigation paths for CTD measurements, determination of hydro-optical (AC-9 sensor and Secchi disks) and hydro-biological parameters, as well as wave buoy paths for surface wave spectra measuring are given in Fig. 1. Dashed line denotes the bay area where vertical and horizontal measurements using dropped and towed microstructure sonde were carried out.

Fig. 1 presents the look of main spacecraft, vessels and some sensors used for complex monitoring, as well as offshore NOAA platforms where wind conditions were measured. Descriptions of sensors used for sea truth measurements and data analysis features are given in (Keeler et al., 2004, 2005; Bondur, Filatov, 2003, Wolk et al., 2004).

4. MONITORING RESULTS

Satellite imagery obtained during the monitoring were systematized and subjected to preliminary and thematic processing. Initial processing was carried out in situ immediately in Honolulu. Detailed processing was carried out after acquiring all sea truth and supplementrary data (Bondur, Tsidilina, 2005; Bondur 2004).

Some results of optical (multispectral and panchromatic) satellite imagery processing are given below. Fig. 2 presents the examples of multispectral QuickBird image processing (September 14, 2003; 11:16 LT imaging time). In this Fig. we can see: image fragment (16.5 x 16.5 km^2) synthesized from RGB bands of the original image (a); interim processing result consisting in obtaining pixel-by-pixel band signal ratios blue/green, in a convolution with mask and classification with further smoothing (b); result of combination of classes of similar brightness with color palette changing (c); final processing result obtained by re-combination of classes, detection and outlining of anomalies (d). Analysis of high resolution multispectral satellite image processing result shows that in the area of the Sand Island outfall diffuser (right part of Fig. 2,d) anomaly of subsurface ocean layer hydro-optical characteristics is evident. Maximal size of this anomaly is about 6 km. Inside of this area more contrast extensive anomaly (~ 3.5 km length) oriented in south – southeast direction, is detected. Another distinct surface anomaly (center of Fig. 2) caused by oil spill due to leakage from a tanker during pumping to onshore reservoirs is evident. We can also see this anomaly in the original satellite image before processing. Rather small anomaly of hydro-optical characteristics caused by another outfall (Honouliuli) in Mamala Bay is seen on the left (see Fig. 2,d). Similar results were obtained after processing other multispectral satellite imagery acquired during the monitoring (Bondur, 2004; Bondur, Zubkov, 2005).

Effectiveness of the applied processing technology is confirmed by the fact that on original images anomalies caused by the outfall are not seen. The presence of hydro-

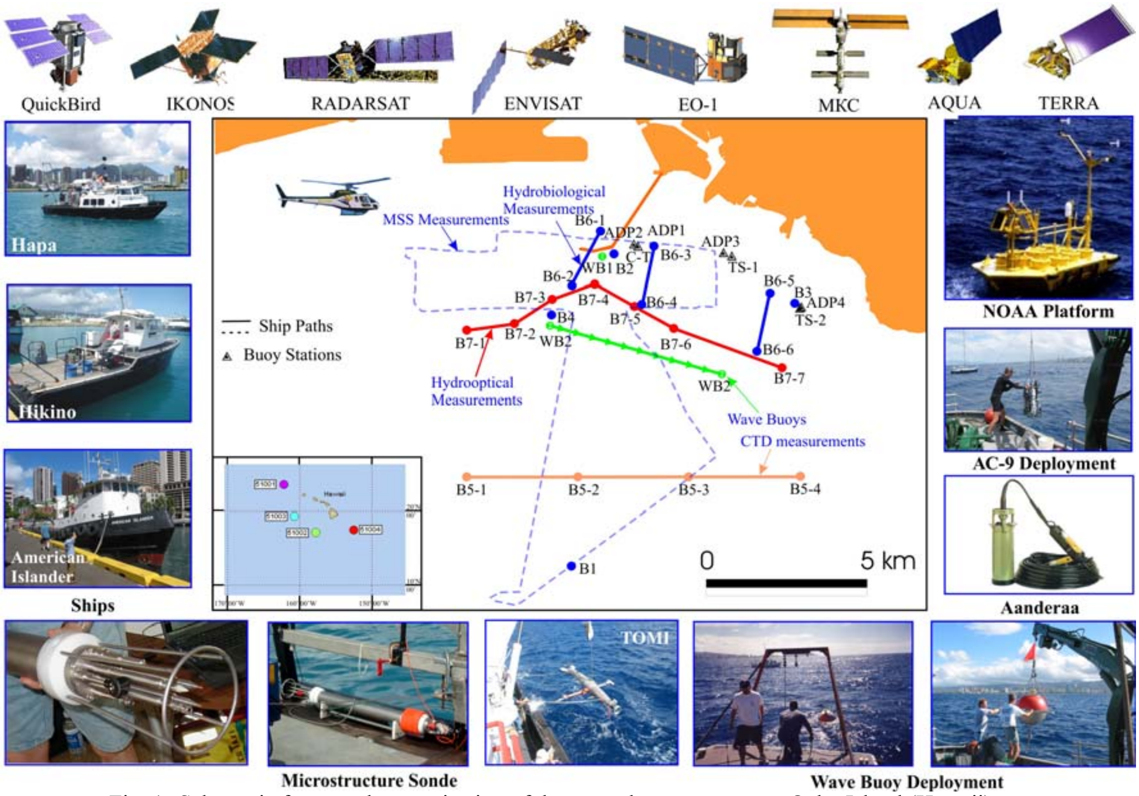


Fig. 1. Schematic for complex monitoring of the coastal water area near Oahu Island (Hawaii)

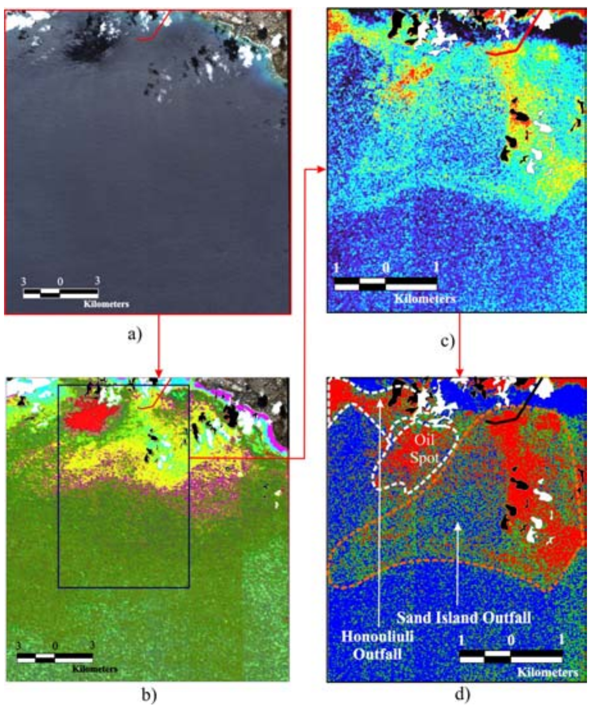


Fig. 2. Example of QuickBird multispectral image processing. a) original synthesized images; b) processed fragment; c) classification with smoothing by a window; d) combination of classes; e) final result with outlined anomalies

optical characteristic anomalies near deep outfalls is confirmed by the results of sea truth hydro-optical measurements using AC-9 and Secchi disk as well as hydrobiological data.

The method and some processing results for panchromatic satellite images acquired during the monitoring of Mamala Bay are given in (Bondur, 2004) and in (Bondur, Vorobev, 2005). Results of fragment-by-fragment spatial spectral analysis of QuickBird satellite image taken on September 3, 2004 are shown in Fig. 3 as an example. This Fig. presents the following: original satellite image with the outlined area of surface anomaly caused by a deep outfall (a), 2D spatial spectra (1x1...2.5x2.5 km^2) for the anomaly area in immediate proximity to south of the diffuser (b), and for the background (c). As we see in Fig. 3, multimode structure of narrow spectral harmonics are clearly seen in the anomalous spectrum. These harmonics are absent in the spectrum for background (Fig. 3 (c)). An important feature of the spatial spectrum in Fig. 3 (b) is the presence of a system of rather narrow spectral harmonics with average lengths $\overline{\Lambda}$ = 43; 86; 99; 117 and 160 m. Average width of these harmonics is $\overline{\Delta\Lambda}$ ~ 5 – 7 m. Thus, the condition $\overline{\Delta\Lambda} \ll \overline{\Lambda}$ is fulfilled that allow us to term these detected spectral components "quasimonochromatic". Such "quasimonochromatic" harmonics appear in all fragments in the area of surface anomaly (see Fig. 3 (a)). Different intensity of manifestations of these anomalies is marked with different colors of local fragments. Such "quasimonochromatic" components in surface wave spectra were described for the first time in (Bondur, 2001; 2004).

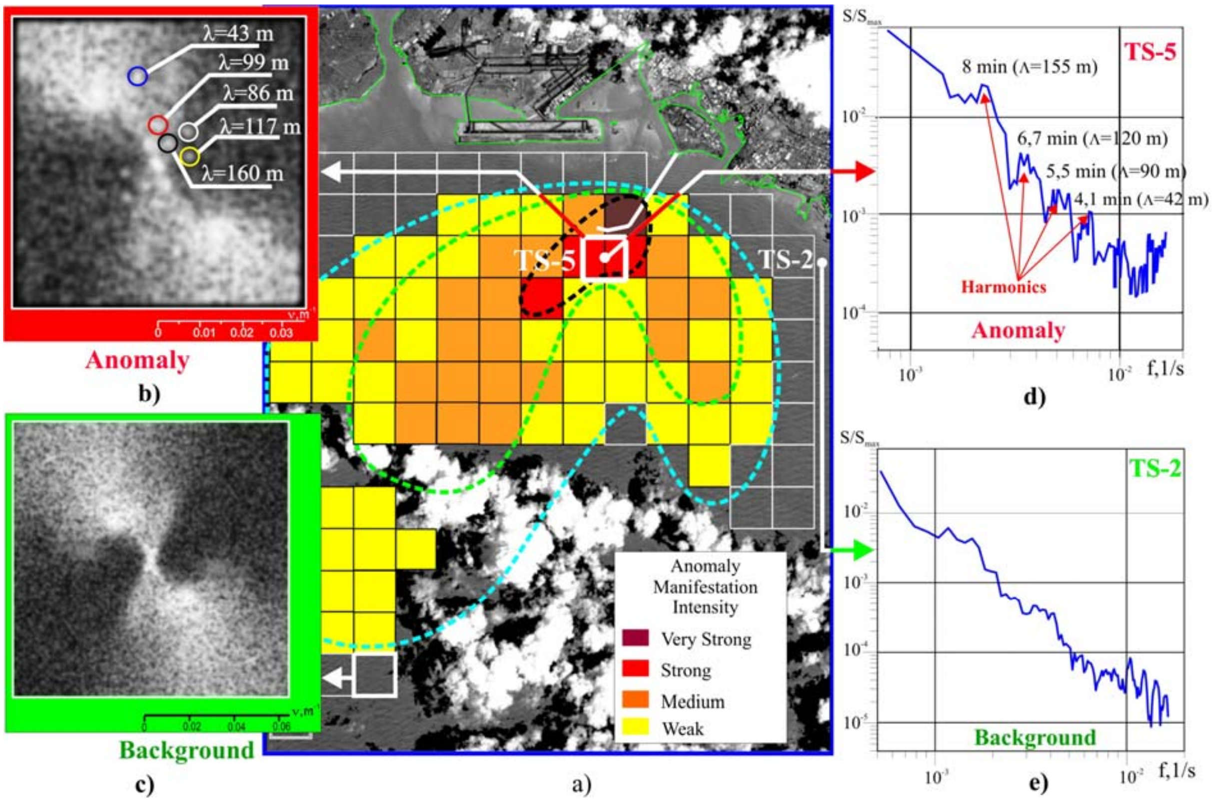


Fig. 3. Detection of "quasimonochromatic" wave components in satellite image spectra: original image (QuickBird, September 3, 2004) showing deep outfall manifestation area - (a); spectrum with multimode harmonic system - (b); background spectrum - (c); internal wave spectra near the diffuser (TS-5) - (d); and outside the anomaly - (d)

Appearance of surface anomalies related to discharges of non-salty water into salty marine environment is caused by a series of hydrophysical mechanisms (turbulence, buoyant vortexes, internal waves, etc.), most important of them is an interaction of short-period internal waves and surface waves (Bondur, 2001; 2004; Bondur, Grebenyuk, 2001).

To confirm this physical mechanism, let's analyze spectral parameters of internal waves near and at the distance from the diffuser. The results of measurement of temperature profiles (every 30 s) using moored Thermistor Strings will be used for this purpose.

Study of high-frequency internal waves will be carried out using analysis of 27.5ºC isotherm depth spectra for 2 hour time period (10:00 – 12:00 LT). The selected isotherm is in the thermocline's core. Fig. 3,d presents such a spectrum created using data obtained at TS-5 located 600 m to the south from the outfall diffuser (see Fig. 3,a). A similar spectrum for TS-2 far from the diffuser near Waikiki Beach (see Fig. 3,a) is given in Fig. 3,e).

Unlike in the background spectrum (TS-2), ultrahigh frequency spectral components (with 4.1 – 8 min periods) caused by internal wave solitons generated by deep outfall are clearly seen in the spectrum of T=27.5ºC isotherm depth near the diffuser.

Lengths of such ultra short internal waves estimated based on measurement results for their periods using the dispersion relation for such waves and measured in the experiment Brunt-Väisälä frequencies $N=(gd\rho/\rho dz)^{1/2}$, where ρ is density and z is depth are Λ = 42; 90; 120 and 155 m (see Fig. 3,d). Similar harmonics are absent in the internal wave background spectrum (see Fig. 3,e), what is the evidence of their direct relation with such a determined source as a permanent deep outfall.

Comparison of spectral harmonic lengths of internal wave solitons (TS-5 Station, Fig. 3) with "quasimonochromatic" harmonic lengths of 2D spatial spectrum for the satellite image fragment covering the area around this station confirms their very good correlation (1 – 5 % difference). This is the evidence of the validity of "internal wave" hypothesis of generation of multimode system of "quasimonochromatic" surface structure caused by a deep outfall.

The schematic of radar imaging of the studied area by satellites RADARSAT and ENVISAT is given in Fig. 4 (top). This Fig. 4 (bottom) presents also examples of some original pre-processed radar images for different days of experiments under various hydrometeorological conditions. In (Bondur, 2004) basic physics for ocean surface radar image formation is described, as well as registered parameters and some examples of detection of anomalies caused by a deep outfall in Mamala Bay water area. Examples of such anomalies automated classification using RADARSAT and ENVISAT radar imagery are given in the present proceedings (Bondur, Starchenkov, 2005).

Contours of anomaly propagation areas caused by a deep

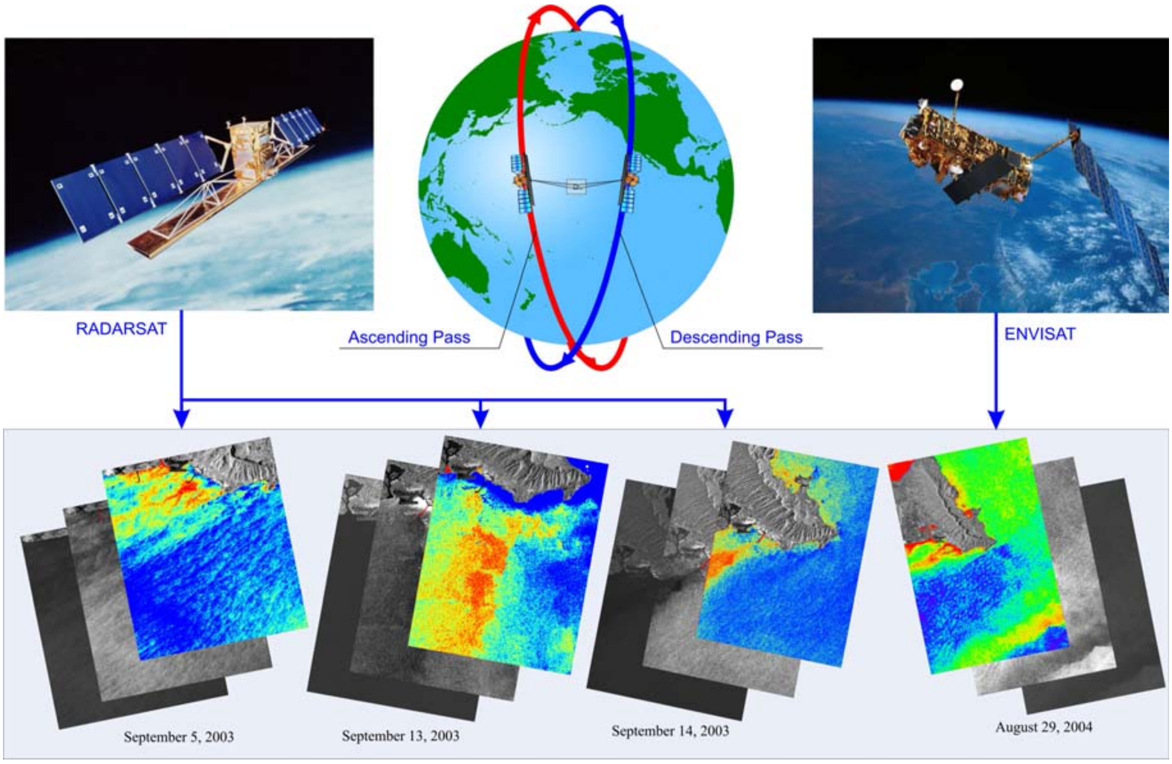
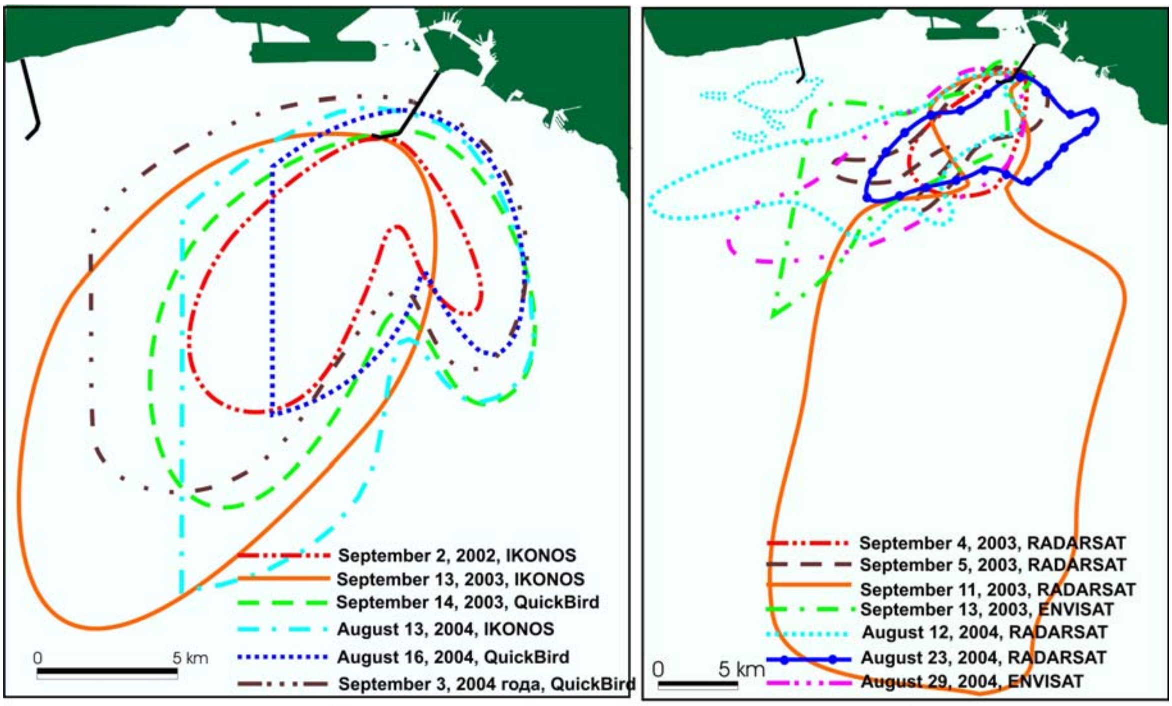


Fig. 4. Schematics of RADARSAT and ENVISAT imaging of the water area and examples of original and processed radar images for different days



a) b)

Fig. 5. Propagation areas for anomalies caused by the deep outfall in Mamala Bay (Hawaii)detected in optical (a) and radar (b) satellite images for different days under various hydrometeorological conditions

outfall and detected by spatial spectral processing of optical satellite imagery (a) and radar satellite imagery (b) are summarized in Fig. 5. These results were obtained for various days of complex monitoring (2002 – 2004) under various meteorological conditions (tide-and-ebb phases, current and wind directions and velocities, surface waves, thermocline location, etc.). The analysis of Fig. 5 shows that despite of having significant difference (in dimensions, shape, propagation area) in the studied anthropogenic influence manifestations they have definite common features for each of data class obtained using various sensors. These features are appearing in rather local nature of similar anomaly manifestations, and relative shape stability for each type of sensors. The exclusion is the anomaly detected from RADARSAT image (September 11, 2003) under conditions of calm (wind speed was 1-1.5 m/s) (Bondur, 2004).

Differences in anomaly manifestations detected from optical and radar imagery denote various significant environment parameters registered by these sensor types.

Satellite image processing results combined with in situ data let us not only detect laws of such anthropogenic influence on coastal water area manifestation but also give recommendations on nature-conservative measures.

5. CONCLUSIONS

Analysis of the presented results shows the effectiveness of aerospace methods and technologies for monitoring of anthropogenic influences on coastal water areas.

Monitoring of Mamala Bay water area (Hawaii) has shown that hydrodynamic and meteorological conditions near the southern coast of Oahu Island are very changeable. They are determined by seasonal and diurnal variability of meteorological parameters and are strongly affected by flood-and-ebb phenomena. All this results in changes in nature of current fields in Mamala Bay, strong variations of temperature fields and thermocline location variability, and so in variations of a series of major hydro-physical parameters of the water area related to them.

Taking into account the big volumes of wastewater discharged into the water area of Mamala Bay (~ 70 mln. gallons/day), the presence of significant quantity of polluting substances (despite of good treatment system) and high requirements to seawater conditions in recreational zone of Honolulu city, some measures aimed to decrease anthropogenic load on the ecosystem of Mamala Bay are proposed based on the results of satellite monitoring.

1. Recommendations on management of outfall regimes operating modes.

In case of unfavorable conditions (tides, onshore current and wind directions (to Waikiki Beach), absence of thermocline), it is expedient to reduce the discharge rate as much as possible by accumulating wastewater in special WWTP reservoirs.

Under favorable conditions (ebbs, southern and southwestern directions of currents, south and southwest winds, expressed thermocline) it could be advised to increase the discharge rates since this is the best circumstances for their disposal.

2. Providing information

To provide reliable information on favorable and unfavorable conditions and on water area environmental situation, it is necessary to maintain permanent monitoring of major parameters in Mamala Bay water area (current fields, CTD-measurements, wind speed and direction, air temperature, etc.), as well as to perform permanent aerospace monitoring by means of processing and analysis of remotely sensed data comparing it with the results of in-situ measurements.

3. Technological and technical measures.

Increase the density of wastewaters for their better disposal, e.g. by adding salt or diluting with seawater. Decrease volume of discharged waters in the coast part by closing a part of diffuser ports at its north side. Increase the level of wastewater treatment by applying new technologies.

These nature-preserving measures proposed based on satellite monitoring results allow us to reduce significantly anthropogenic load on the studied water area. These measures can be undertaken also for other water areas under intensive anthropogenic influence.

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