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A STUDY OF ARTIFICIALLY COLORED SPOTS IN THE SEA WITH SATELLITE, AIRBORNE AND SHIPBORNE SENSORS*

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ABSTRACT

The results of seaborne and airborne experiments with dyed sea patches are discussed. These results include air and water temperature, optical properties, color and contrast. It was discovered that the contrast of dyed portions of the sea with respect to background water for altitudes up to six kilometers exceeds the threshhold contrasts for both human eye and photographic systems. It was also found out that in dyed spots the temperature increases in comparison with the temperature of the surrounding water - and this fact can be explained by the radiative heating of the seawater.

It is proposed to use artificially-dyed areas on the sea surface as benchmark color tests for fine-tuning methods in processing the remotely measured ocean color information.

1. INTRODUCTION

As observed by cosmonauts and astronauts from the manned orbital stations, the large areas of the world's ocean vary in color from light blue in central oceanic regions to bright green, yellow green and even brown in areas with upwelling and large river discharge. The visible color of the sea is determined by the spectral composition of the upward radiation. This composition depends on the ratio between the light diffusely scattered by seawater and the radiation reflected by the sea surface and atmosphere. Since the atmospheric conditions near the sea surface change, the color of any particular area in the ocean is also likely to change.

The true seawater color is determined by the spectral composition of the light diffusely backscattered by the surface layer. The seawater color varies according to turbidity, resident yellow matter and chlorophyll concentrations of the marine phytoplankton. The largest phytoplankton concentrations occur in the vicinity of oceanic fronts and areas of intense deep water rising. These areas are considered to be highly productive biologically, and as a result they are of great practical interest for fisheries.

Despite atmospheric distortion, ocean regions with large phytoplankton concentration are observable from the space as local fields of different color. Therefore, it becomes particularly important to develop methods for finding and observing the evolution of phytoplankton fields in the ocean. By reconstructing the inherent optical properties of the seawater from its color, it is possible to estimate the biological characteristics of that area.

During 1983-1984 a number of experiments which deal with some aspects of this approach were conducted in the Black Sea. In this paper we discuss the results of shipborne and airborne observations of artificially colored areas and their thermal characteristics.

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The logic behind these experiments is as follows. It is known that the luminescence spectra of water solutions of fluorescein (uranine), rhodamine-B, and rhodamine-C, have spectral radiance maxima at wavelengths centered at 525, 580, and 610 nm, respectively. These wavelengths correspond to bright green, yellow-green and orange colors. Thus, by creating relatively large artificial colored spots on the sea surface with non-toxic dyes (see Fig. 1), it is possible to model real oceanic areas with phytoplankton populations in various blossoming stages. One can then investigate spatial and spectral contrasts, as well as optical and hydrophysical parameters of the background waters and the dyed spots under controlled conditions.

The main goals of the 1983-1984 Black Sea experiment were:

– to model color hues of various phytoplankton concentrations under natural conditions by means of fast dyeing of a sea surface area with the concentrated non-toxic dyes;

– to study temperature and spectral radiance fields within the color spots and in the surrounding waters;

– to determine the color parameters of the sea surface layer in separate areas;

– to study the transformation of the original spectral fluxes of the spot radiation, as well as the radiances and spectral contrasts of the spot and background waters, from various heights in the Earth's atmosphere.

Fig. 1. The fluorescein-dyed spot on the sea surface as seen from the aircraft flying at an altitude of 150 m. One can see the arrow-shaped research vessel from which the water was dyed.

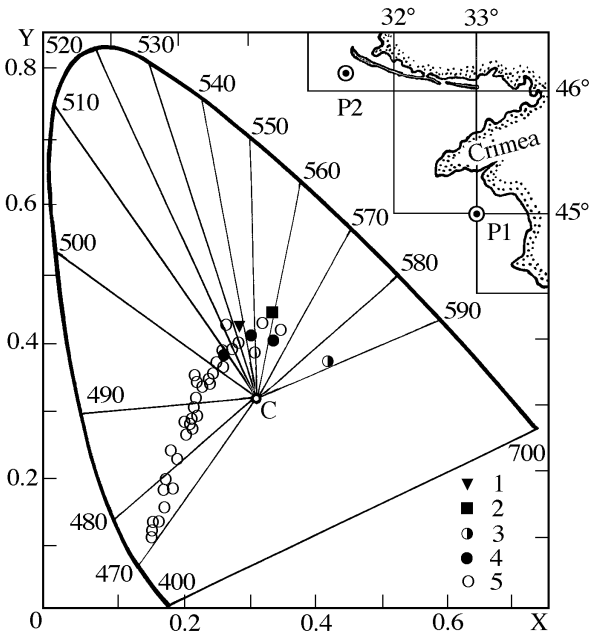

Fig. 2. Position of the X-Y coordinates of the radiation chromaticity of the sea ssurface with respect to the standard illuminant-C (CIE, 1931). The symbols denote the following: (1) the uranine-dyed spot; (2) the fluorescein-dyed spot; (3) the rhodamine-C-dyed spot; (4) the background seawater; (5) the coastal water of Central Atlantic. The (1)-(4) are related to the Black Sea. The insert shows geographical positions of test areas P1 and P2 in the Northwestern Black Sea.

2. MEASURING INSTRUMENTS AND EXPERIMENTAL TECHNIQUES

The field platforms used in an experiment were: the high-speed hydrofoil research vessel named KOMETA, the aircraft laboratory AN-30, and the orbiting space station SALYUT-7. Two marine test areas P1 and P2 were chosen in the northwestern Black Sea (see inset in Fig. 2). The first area with transparent waters was in the vicinity of the Kalamita Bay and the second one with turbid waters was near the Tendra Isthmus.

A number of submersible and remote sensing devices was used at various stages of the experiment to study the thermal and optical characteristics of the sea surface layer in the artificially dyed spots and surrounding background waters (for instruments used on the field platforms and their characteristics see Table 1 in Urdenko and Zimmermann, 1985; more detailed specifications of these instruments are given in Afonin and Kravtsov, 1987, and Lee, 1980). In addition to the data obtained with these instruments, the photographic images from the METEOR-PRIRODA satellite series were also used.

The method to produce a one-kilometer size color spot on the sea surface was as follows: a solution of 20-kg non-toxic dye in the drinking alcohol had been poured out via the inclined chute overboard the ship, which was moving at 15 knot speed. The ship circled the area once and then criss-crossed it, discharging the dye while moving. The resulting color spot assumed the shape shown in Fig. 1.

3. RESULTS OF THE INVESTIGATIONS

Analysis of the hydrological structure of the background waters in test area P1 showed that the seasonal thermocline was at 18-20 m, the sea surface temperature was 15.5 ˚C, and the thickness of the upper mixed layer was 16 m. The atmosphere was clear from clouds and the temperature near the sea surface was 18 ˚C. The wind speed was 7 m/s creating rough seas with a wave height of about 1 m. The hydrooptical observations showed the presence of a 9-m thick surface layer of higher turbidity, with the beam attenuation coefficient $c(420\,nm) \approx 0.22\,m^{-1}$. Below this layer the water was almost homogeneous and much more transparent with $c(420\,nm) \approx 0.08\,m^{-1}$. The standard Secchi disc visibility depth, measured at different points of the test area, averaged 17 *m* and the visually observed seawater color was blue-green. The wavelength of the maximum in upwelling radiance was 510 *nm*, which is typical for the waters of average biological productivity.

The spatial thermal and hydrooptical structure of the studied area P1 appears to be two-layered, with each layer being vertically and horizontally homogeneous. This pattern remained stable throughout the whole experiment.

Similar measurements at the test area P2 revealed a three-layered hydrological structure: a 4-*m* thick upper mixed layer with a temperature $T \approx 22.5°C$, an intermediary layer with $T \approx 11°C$ reaching a depth of 10 to 12 *m*, and a winter-mixed layer with $T \approx 6-7°C$. As visually observed from the ship, the sea color in the test area was dark green, the Secchi disk visibility depth was 3 *m*. The maximum of the upwelling optical radiance was at 558 *nm*, which is indicative of a high biologically productive area. During the experiment involving the discharge of the dyes, the sky was clear, the wind speed was insignificant, the air temperature was 23 ˚*C*, and the wave height was 0.3 *m* at most.

The study of the vertical structure variability in these two dyed areas involved analysis of the deep-sea transparency and temperature profiles observed at different times in the center of the spots. Four hours after the initial discharge the dye saturated into the water column down to the

depth of $8-10\,m$. This can be regarded as the maximum depth of turbulent diffusion in the upper layer over the time of observations.

The spatial structures of optical characteristics and temperature in the test areas P1 and P2 for background waters and dyed spots are shown in Figure 3. This figure also contains typical examples of the simultaneously measured subsurface temperature and the color index measured during the ship crossing the spot (Fig. 3c). The color index is defined here as the ratio of two upward light radiances measured at nadir at 540 and 420 nm.

The analysis of the combined observations of optical and thermal characteristics of the near-surface layer revealed temperature anomalies induced by radiative warming in the two colored spot areas. The mean temperature of the upper 10-m thick layer in the uranine-dyed area was 0.5 °C higher than the surrounding waters while the rhodamine-dyed area was 0.4 °C higher . The rate of warming of this layer over a 4-hour period of observation, estimated from measurements of the vertical profile of the spot temperature T_S, was $\partial \mathrm{T}/\partial \mathrm{t} \approx 0.0048°C/\min$ in the uranine-dyed area and $\approx 0.003°C/\min$ in the rhodamine-dyed area. This effect merits discussing it.

It is known that the temperature field in the sea surface forms under the influence of radiation and turbulent thermal exchanges. A one-dimensional model of heat transfer in the upper layer is described by the equation

$$\frac{\partial \bar{T}}{\partial t} - \frac{\partial}{\partial t}\left(\overline{W'T'}\right) + \frac{1}{\rho C_S}\frac{\partial E_z}{\partial z} = 0, \qquad (1)$$

where $\bar{T}$ is the mean water temperature, ρ is the density, C_S is the specific heat coefficient, E_z is the penetrating solar radiation, T' and W' are the fluctuations of temperature and of the vertical current velocity component, and z is the depth of the layer. By the analogy with the molecular transport, it is assumed that the turbulent heat flux averaged over the period of observations will be

$$\left(\overline{W'T'}\right) = -k_0 \frac{\partial \bar{T}}{\partial z} \qquad (2)$$

where k_0 is empirically determined turbulent exchange coefficient. We estimate k_0 by applying an approximate formula for the passive admixture (*i. e.* the dye particles in the water) transport coefficient

$$k_0 = \ell^2 / t,$$

where ℓ is the time-dependent thickness of the dyed water column, and t is the time. If we accept $\ell \approx$ 8-10 m and $t \approx$ 4 h, then the turbulent exchange coefficient for the upper sea layer in the studied areas is within the range of 44 to 69 cm^2/s. This result is confirmed by the data compiled by Nelepo (1979).

Zaneveld *et al* (1981) show that velocity of radiative water heating varies from $6.8\cdot10^{-5}\,°C/\min$ for very clean ocean waters to $2.2\cdot10^{-4}\,°C/\min$ for very turbid coastal waters. Very elaborate calculations of water heating by the sun radiance at different wavelengths were made by Arst (1983). Absorption of energy in several spectral intervals was modeled by Bouguer's law and the spectral distribution of solar energy at the sea level was adopted from the standard atmospheric model. The computed speed of radiative heating of pure and hydrosol-containing water (without oil film) for a 10 m layer, spectral range of 300-900 nm, and the zenith sun, was found to be 0.0059 and $0.0098°C/\min$, correspondingly. These values are very close to the values retrieved by us from direct measurements of temperature profiles in colored sea areas.

The radiation penetrating into the sea is absorbed by two mechanisms. The first one is absorption by water molecules, suspended particles and yellow substance; and this mechanism transforms the light energy into the heat, thereby increasing the water temperature. The second mechanism is associated with the photosynthetic absorption of energy by living phytoplankton

cells and bottom algae. The dyeing increases the concentration of absorbing material in seawater and changes its selective absorption of sun light.

The variability of the radiation temperature inside the patches is confirmed by the measurements of thermal radiation of the sea surface between 3 to 5 μm. These data were derived by an airborne infrared scanner. The artificially produced color spots were easily identified on the thermal images of the sea surface up to the altitude of 2600m. The dyed areas showed higher temperatures than the surrounding waters.

This demonstrates that the natural planktonic fields (which differ in color from surrounding waters) can form temperature anomalies. Direct measurements of the spectral radiance and infrared temperature of the seawater by NIMBUS-7 show that the color and thermal fronts frequently coincide either partially or completely (Mueller and La Violette, 1981). This may be considered as a qualitative confirmation of the results discussed above.

The adequacy of artificially dyed areas as simulators of the observed natural phytoplankton fields was verified by comparing the color coordinates of these objects in the X, Y, Z coordinate systems (Judd and Wyszecki, 1975).

Figure 2 shows the chromacity location of the upward radiation measured in various regions of the Atlantic. It also displays the radiation chromacity of the uranine (1), fluorescein (2), and rhodamine-C (3) colored areas of the Black Sea during this experiment. Comparison of the chromaticity points of the natural sea surface with the points of fluorescein- and uranine-colored areas indicates that these points lie within the color variation range of natural areas. Consequently, the indicated dyes may be used for modeling natural color hues in the sea. The chromacity coordinates of the rhodamine-C-colored sea surface is beyond the natural color limits. However, it may be considered as an instance of water coloration by industrially discharged pollutants.

Visual observations of colored surface areas from the ship and the aircraft have shown that their visible contrast depends on the color of the background waters. So, the bright green uranine spot in the relatively transparent waters of the test area P1 is well pronounced against the light green background. In the more turbid waters of the test area P2 the yellow-orange rhodamine-C spot distinctively stands out from the gray-green colored background waters. And the green hue of the fluorescein-colored patch contrasted with the background color.

Synchronous instrumental radiance measurements along the routes traversing the dyed spot centers were carried out from the research vessel and the aircraft-laboratory AN-30. Fig. 4a shows some examples of the sea surface radiance profiles obtained during the vessel's movement across the rhodamine-colored area, which initially has a closed circular shape. The measurements were conducted using the SPRUT-2 telephotometer in the test area P1 approximately one hour after the dye was discharged. The size of the spot was determined by two cross radiance profiles, with the average diameter being 1.4 km.

The intensively-colored sea spots display large radiance fluctuations (the variance coefficient was about 30%). These fluctuations occurr due to the inhomogeneous original dye concentration and diffusion processes in the upper sea layer. The signal amplitude retreaved from the *in situ* and remotely sensed observations in the color spots areas was from 2 to 5 times larger than the level of the background signal. The difference varied with the time elapsed since the creation of the spots. In some cases, the colored spot was reliably registered by remote sensors 24 hours after the release of dye. In clear weather the colored spots were visually and instrumentally observed from an aircraft at 6 km altitude.This was confirmed by the upward radiance measurements with the airborne SPRUT-3 spectrophotometer made along the routes above the colored spot (Fig. 4a).

The initial spot size was 1.1 km. The airborne observations indicate that the signal's level outside the colored spot increases with height, while the signal reflected by the colored surface decrease. This is so because the total radiance of the "air-water" system increases with height due to the multiple-scattered radiation by the underlying atmospheric layer, and the spot's proper upward radiation concentrated within a narrow spectral band is significantly attenuated by the

atmosphere. The combined action of the indicated processes results in the degradation of the visible colored spot contrasts with height.

To qualitatively evaluate the height variations of the original contrasts between the colored spots and the background waters, let us consider the equations which couple optical radiances of the sea surface as observed from an aircraft with the radiances of atmospheric layer.

Let us write the radiances of the color spot $L_S(\lambda)$ and background water $L(\lambda)$ in the form:

$$L_S(\lambda) = L_S^0(\lambda)\tau(\lambda) + L_g^S(\lambda) \quad (4)$$

$$L(\lambda) = L^0(\lambda)\tau(\lambda) + L_g(\lambda) \quad (5)$$

where $L_S^0(\lambda)$ and $L^0(\lambda)$ are the original spectral radiances of the spot and the background water, respectively. $L_g^S(\lambda)$ and $L_g(\lambda)$ are the spectral radiances of the atmospheric haze over the spot and

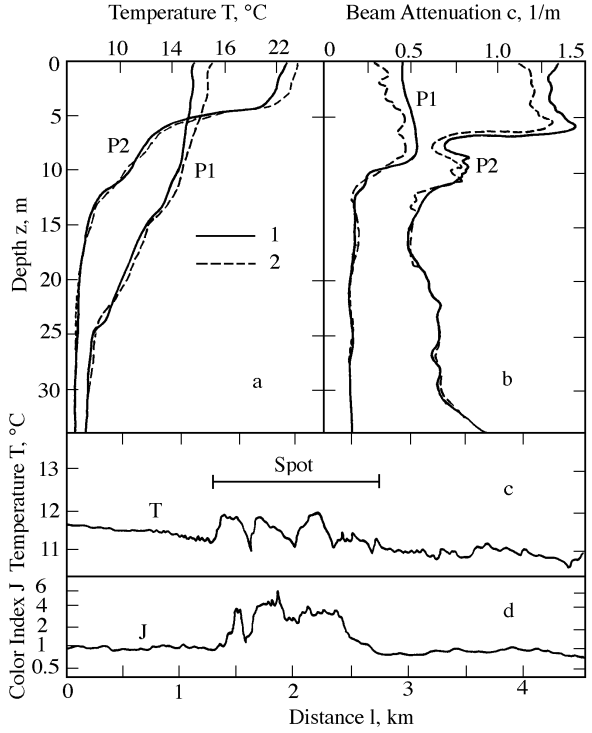

Fig. 3. Spatial structure of background waters (1) and of water within color spots (2) at the marine test areas P1 and P2: (a) vertical seawater temperature profile T° in centigrades, (b) vertical profile of the light attenuation coefficient c(420 nm), (c) sea surface temperature variation along the spot diameter, and (d) the color index (J) variation along the vessel's route crossing the uranine-dyed spot.

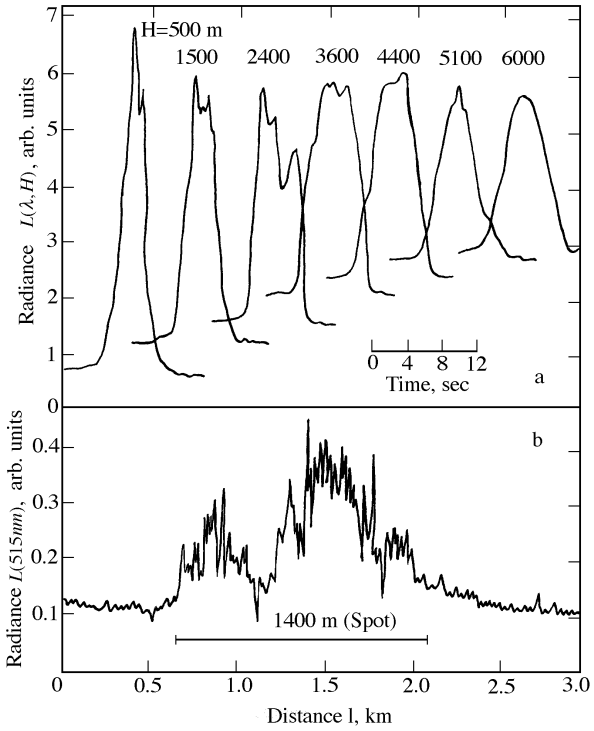

Fig. 4. Simultaneous measurements of the sea surface radiance $L(\lambda)$ at the 515 nm wavelength when crossing the uranine-dyed area: (a) from an aircraft for different altitudes *H*, and (b) from the ship. The test area P1, sea roughness is 0.5, cloudless sky, haze, mean angular altitude of the sun is 51°, the sun azimuth angle in respect to the ship is 90°.

the background water, respectively, while $\tau(\lambda)$ is the spectral transmittance of the upwar tradiation through the atmosphere between the sea surface and the receiver at the given altitude. The spectral contrast *k(λ)* between radiances of the spot and background waters can be written as

$$k(\lambda) = \frac{L_S(\lambda) - L(\lambda)}{L(\lambda)}. \qquad (6)$$

Because the linear dimensions of the dyed spots are small in comparison with the dimentions of the surrounding waters, the haze radiances are approximately the same over the spot and background water, *i.e.* in Eqs. (4) and (5)

$$L_g^S(\lambda) \approx L_g(\lambda).$$

Then by substituting Eqs. (4) and (5) into Eq. (6), we obtain the following formula:

$$k(\lambda) = \frac{L_S^0(\lambda) - L^0(\lambda)}{L^0(\lambda) + L_g(\lambda)\exp[h(\lambda)/\mu]}, \qquad (7)$$

where $h(\lambda)$ is the spectral optical depth of the atmospheric layer and $\mu = \cos(z_\oplus)$ is the cosine of the zenith viewing angle $z_\oplus$.When observing dyed spots from small altitudes the effect of atmospheric haze upon the observed radiance is negligeable. Therefore, to determine the original spectral contrast with Eq. (7), the second term in the denominator may be neglected. The calculations of the radiance contrast for the uranine-dyed water and the background water are based on the telephotometer SPRUT-3 data for the fixed 515 *nm.*

Results of the radiance contrast calculations for the uranine-dyed patch of water and background water are presented in Fig. 5. Curve 1 is based on the SPRUT-3 telephometer data, and curves 2 and 3 are derived through photometering of negative imagery provided by the MKF-6M camera for the two most sensitive channels. The curves show that with the increase of height the contrast increases and after reaching heights about 2.5 km monotonically decreases.

Over the range of altitudes from 0.5 to 6 km the contrast varies from 6-8 to 0.6-0.7 over a period of 2.5 hours. This variation being induced not only by the atmospheric influence, but also by the spot diffusion. If we assume that the 6-km thick atmospheric layer contain about half of the atmospheric mass, and the contrast between the dyed spot and background water at the top of this layer is reduced by an order of magnitude (as shown in Fig. 5), then the contrast value at the upper atmospheric boundary will be equal 0.1. With such small level of contrast the dyed spots may be observable from spacecraft only visually, since the threshold contrast value for the human eye is about 0.02.

The insert in Fig. 5 compares the radiance coefficient $\rho(\lambda)$ spectral measurements of dyed water areas and background waters. The radiance spectral coefficient was determined by the formula:

$$\rho(\lambda) = \frac{L(\lambda) - 0.02\,L_a(\lambda)}{L_0(\lambda)} \qquad (8)$$

where $L(\lambda)$, $L_a(\lambda)$, and $L_0(\lambda)$ are respectively spectral radiances of the sea surface (at nadir), sky (at zenith), and of a Lambertian horizontal standard white reflector.

Comparison of curves 4-6 indicates that the radiance coefficient for the rhodamine-dyed spot at $\lambda = 580\,\text{nm}$ is significantly larger than the similar quantity for the uranine-dyed spot. At the same time, a sharp reduction of $\rho(\lambda)$ below the background radiance coefficient is observed within the 530-550 nm wavelength range, which is due to the presence of a strip of water with high light absorption by rhodamine-C molecule.

In the case of the uranine-dyed spot, the value of $\rho(\lambda)$ is 1.5 to 3 times larger than the background value in the short wavelength part of spectrum, attaining a maximum within the 530-550 nm wavelength range. The radiance coefficient spectrum for the fluorescein-dyed spot has a similar dependence.

Sea surface radiance spectral coefficients, $\rho(\lambda)$ were used to calculate spectral contrasts $k(\lambda)$ of dyed patches at the sea surface using Eq. (6). The shape of the $k(\lambda)$ curves for the fluorescein- and rhodamine-C-dyed areas is shown in Fig. 6 with respect to the background waters. For the pair "fluorescein-dyed spot/background water", characteristics are large contrast values in the short-wave part of spectrum with a maximum located at $\lambda = 490 - 520\,\text{nm}$ and then falling off to threshold values at $\lambda = 700\,\text{nm}$.

For the pair "rhodamine-C/background water" an inverse situation occurs, *i.e.*, the value of $k(\lambda)$ is small within the 400-540 nm wavelength range. However, the contrast is enhanced by the order of magnitude with the increase in wavelength for the 600-630 nm wavelength range.

To estimate the possibility of finding color spots on the sea surface from satellites using contrast values given by Eq. (7) for the upper atmospheric boundary were calculated. Spectral radiances at measured spectral maxima were used as input parameters. To calculate the radiance of haze, $L_g(\lambda)$, the Shifrin and Minin (1957) model for the standard atmosphere was applied for the optical cover, which corresponds to a slightly cloudy atmosphere with an optical thickness h = 0.2 and with a meteorological horizontal visibility equal to 20 *km*.

The calculated data have shown that contrasts of colored sea surface areas at the upper atmospheric boundary with respect to the contrast at the sea surface decreased by 1.8 to 2 times amounting to $k(520\,nm)$ = 0.41, $k(580\,nm)$ = 0.32, and $k(580\,nm)$ = 1.1 for the uranine, fluorescein, and rhodamine-dyed spots, respectively. Hence, the contrasts for all spots at the upper atmospheric boundary are considerably larger than the human eye's threshold contrast *(k~0.02*), but in the case of uranine and fluorescein they are comparable with the threshold contrast for photographic systems (*k*~0.3-0.4*)*. The contrast of the rhodamine-C-dyed spots is approximately 3 times larger than the photosystem's threshold value. This allows us to conclude that the rhodamine-C-dyed spot will be observed by satellite sensing systems.

Examination of black-and-white pictures of the studied areas provided by the MSU-S scanner and KATE-140 camera do not show the dyed patches of the sea surface. In our opinion this is accounted for by insufficient spatial resolution and inappropriate conditions under which the areas were being photographed. All images contain sun glitter which partially covers the areas studied and solid sun glitter streaks that hinder identification of color spots. At the same time, these patches were visually observed by cosmonauts from SALUT-7, which confirms the correctness of the contrast estimates at the upper atmospheric boundary mentioned above.

4. CONCLUSIONS

Analysis of the experiments with the artificially dyed sea surface areas may be summarized as follows:

1. In the absence of cloudiness and haze the color spots on the sea surface were easily detectable from the aircraft. The optical conditions for the observation were as follows: the sun zenith angle was within 20 to 70˚, the sun's azimuth relative to the aircraft flight direction was about 90˚. For the wavelengths in the spectral fluorescence maximum of the dye the registration of the upwelled radiance must be performed at nadir.

2. The radiance contrast of the two color spots with the background waters was large and at the altitude of 6 km corresponded to 0.6-0.7 (2.5 after the discharge of dye).

3. Within the color spots a significant rise in the sea surface temperature was observed. It can be explained by the increase of the absorption coefficient of light in the upper sea layer . In the 3-5

μm wavelength range the heat anomaly in the color spots was reliably registered by infrared instrumentation.

4. The computations of color spots spectral contrasts, with respect to background waters for standard atmosphere model, have shown that contrast values at the upper atmospheric boundary are larger than the threshold contrast perceivable by the eye (0.02) or photographic systems (0.3-0.4). However, color spots were observable from the satellites. The negative results obtained in the case of photographic system application are accounted for by unfavorable surveillance conditions (sun glitter and slick bands).

5. The artificially produced color spots on the sea surface may be utilized as color test areas with easily controlled hydrooptical characteristics. They can be used to improve remote sensing techniques for observation of the sea surface and ocean interiors in the optical and infrared bands of spectrum. For the purposes of simulating the natural color of phytoplankton fields in the ocean the variety of non-toxic organic dyes such as fluorescein, uranine, and rhodamine may be used.

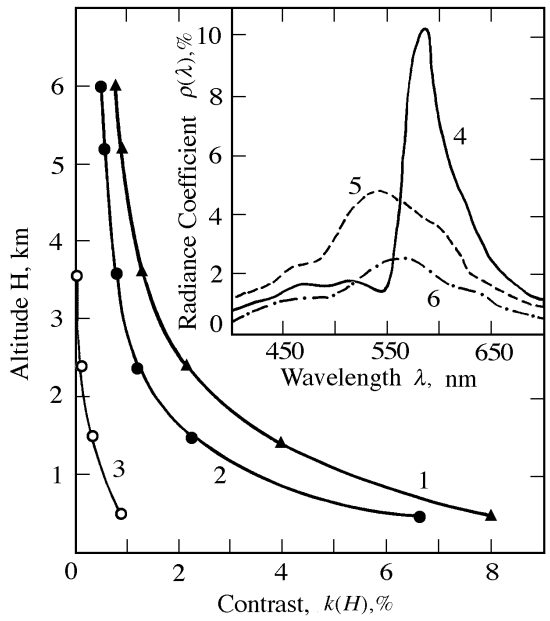

Fig. 5. Variation of radiance contrast k of the uranine-dyed spot with respect to the background water depending on the altitude of observation H: (1) telephotometer SPRUT-3 measurements at $\lambda = 515nm$; (2) and (3) are recovered from the telephotometry of the negatives of the camera MKF-6 four channels. The insert shows the spectra of radiance coefficient $\rho(\lambda)$ for the sea surface dyed with rodamine-C (4) and uranine (5) and for the background water (6) measured by the telephotometer SPRUT-2 from the ship.

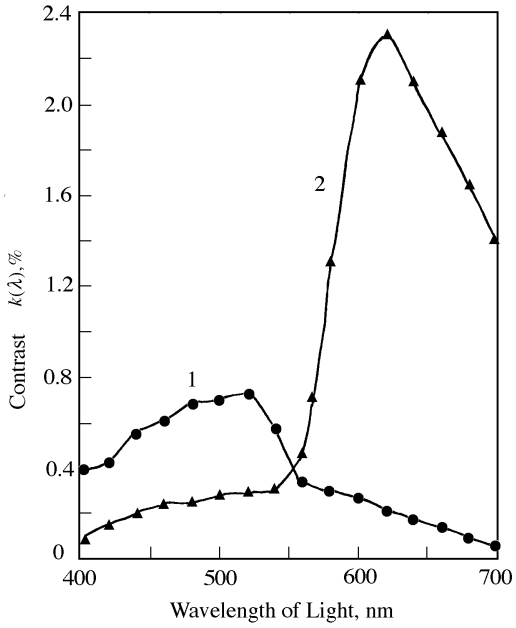

Fig. 6. Spectral contrasts for sea-surface areas dyed with fluorescein (1) and rodamine-C (2) with respect to the background waters. Mean altitude of the sun is 65°30''. The cloudless sky, haze. Sea roughness is 1.

5. ACKNOWLEDGMENTS

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