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COMPONENTS OF REMOTE SENSING REFLECTANCE OF NORTHERN BALTIC NATURAL WATER BASINS

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ABSTRACT

This paper analyses two components of remote sensing reflectance connected to the solar light reflected from the sea surface and the light diffusely reflected by the water mass. Results of this analysis are applied to the experimental spectral signatures of light reflected from the surface of various Estonian and Finnish lakes and coastal areas of Baltic Sea. The role of specular reflection of light from wind-ripened water surface and diffuse reflection of light by water body is discussed. Special emphasis is given to the analysis of experimental diffuse reflection spectra. The role of chlorophyll pigments present in the studied waters in formation of absorption and backscattering properties of natural water basins is discussed.

INTRODUCTION

It is well known, that the passive optical remote sensing of water bodies consists of the following two steps: at first, spectra of the upwelling solar radiance are measured by a telespectrometer; then, on the basis of the results obtained and the characteristics, describing the location of extreme values and shapes of these spectra, one tries to assess the transparency of the water, and the amount and type of optically active substances in the sea. This task is relatively easy if there is only one substance in the water. In such case all changes in the spectrum of the light backscattered from the water column into the atmosphere are caused by the absorbing and scattering properties of the pure water and of this single substance. But if we have several optically active substances in the water, their influence on the spectra of the upwelling light is quite difficult to distinguish. In conditions of multicomponent waters additional difficulties may arise. For example, strong absorption of light by yellow substance overshadows the influence of the chlorophyll absorption near 440 nm, which prevents the estimation of chlorophyll-a content with the remote sensing data. A large amount of mineral particles influences the whole spectrum of reflected light and can "overshadow" other components present in water. Consequently, in the case of multicomponent water, the task of solving passive optical inverse problem may became very complicated.

An optical remote sensing inversion always represents an "incorrect" problem: it is sensitive to minor errors in the initial experimental data and it has no unique solution. To obtain a reasonable solution, we need an additional information, and we have to apply some special mathematical procedures. It leads to different methods for the interpretation of the remote sensing data. One of the most popular is the classical correlation method, namely Gordon's method (1981, 1992), where the chlorophyll (or some other substance) retrieval algorithms are derived solely from regression techniques. Another method is based on a creation of model, that used to simulate a data bank of reflectance spectra for a wide range of combinations of the optically active substances in the water. Quite possibly, the most efficient method to determine concentrations of constituents of natural water is to compare theoretical and experimental spectra, and adjusting concentrations in theoretical spectra until satisfactory agreement is found. This, of course, requires basic understanding of optical properties of the constituents, which can be built only from careful *in situ* and laboratory experiments. Currently the modeling methods (or some of its variations) are widely used. In addition, some authors present an inverse technique for optical remote sensing based on the radiative transfer analysis. Other authors proposed an iterative approach, and a nonlinear statistical method.

So, the difficulties in remote sensing analysis are not only technical (accuracy of measurements and models), but consist of simultaneous influence of many factors, that include "an overshadow phenomenon", and a limited thickness of the "informative surface layer." As it is known, remote sensing measurements can be carried out on board of a vessel, aircraft or satellite. Each of these methods has some positive and negative features. It is clear that to obtain operative information on a global scale the use of satellite measurements is inevitable. However, the interpretation of satellite measurements is sometimes difficult, not only because of the influence of the atmosphere and clouds, but also due to some specific features of the objects under investigation. This is particularly noticeable for marginal seas and inland waters, where water constituents vary in type and amount over short spatial and temporal scales, with concentrations of these constituents often being significantly higher than in open ocean waters. Unlike clear oceanic waters, for which linear regression retrieval algorithms are valid, inland and coastal waters with a high degree of optical complexity need developments of more subtle retrieval approaches. Consequently, airborne and shipborne measurements are also have significant value and in need to be developed.

REMOTE SENSING REFLECTANCE

Let's clarify some definitions. What meaning have the terms "water-leaving radiance" and "remote sensing reflectance?" By our opinion (Arst et al., 1984, 1994) we have to take into account following objectives of the optical remote sensing of water: determination of the types and concentrations of the optically active substances in the water; and investigation of the sea surface phenomena. The goal of the remote sensing is to be determined in each particular case: sometimes we are interested only in the conditions inside water column, but sometimes our task is to identify surface pollution or to investigate undulation, and sometimes we need all the information we can obtain. Thus, as "a water-leaving radiance" it is logical to accept an upwelling radiance just above the water surface (L_u). Similarly, "a remote sensing reflectance" (r) is determined by normalizing L_u to the value of E_d / π, where E_d is the incident irradiance on the level of the sea surface:

$$r(\lambda) = \pi L_u(\lambda) / E_d(\lambda), \qquad (1)$$

here λ is a wavelength of light.

However, in various publications the definition of the remote sensing characteristics is not always performed in the same way (sometimes these definitions are missing). For example, in the paper by Lee et al. (1996) the $r(\lambda)$ is named "total remote sensing reflectance" and it is proportional to the radiation, diffusely backscattered from the water column. Vertucci and Likens (1989) call the radiance measured by the remote sensing device at some height in the atmosphere as "apparent radiance at the remote platform", Gordon and Wang (1992) use there the term "sensor radiance" and for its diffusely backscattered from the water column component the term "ocean-leaving radiance". We agree to use the term "apparent radiance" (containing the contributions from water depths, water surface and atmosphere) and decided to call the respective reflectance as the "apparent remote sensing reflectance". After the procedures of determining the atmospheric correction from the data of "apparent radiance" the values of water leaving radiance will be calculated. Then the water leaving radiance is consisting of two main components:

$$L_u(\lambda) = L_R(\lambda) + L_D(\lambda). \qquad (2)$$

Here L_R is the solar radiation (direct + diffuse), that is specularly reflected from the rough water surface (reflected component of the L_u), L_D is the light, diffusely backscattered from the water column (diffuse component of the L_u). Thus, taking into account Eq. (1), we obtain the remote sensing reflectance r (describing the situation just above the water surface):

$$r = \pi L_R / E_d + \pi L_D / E_d = r_R + r_D, \qquad (3)$$

where r_R and r_D are respectively the reflected and diffusely backscattered components of the remote sensing reflectance r. Note that here the wavelength dependency has been suppressed for brevity.

As known, the component r_R is formed under the influence of the following factors: (1) specular reflection of the sky radiation from the water surface, (2) specular reflection of the direct solar radiation from the water surface (Sun glitter), (3) sea foam or some kind of pollution (e.g.oil) on the water, (4) wind (or some other reason) generating waves on the surface. Most of these results

have been obtained by model calculations for idealized case of the infinitesimal aperture angle of the measuring device.

Two examples of the separating of the components r_R and r_D using the approximation $L_u = 0.02 L_z$ are shown in Fig. 1 (because measurements were carried out in nadir direction, L_s is equal to the radiance of the zenith point, L_z). As we can see, to the different values of the water transparency correspond the different shapes of the remote sensing reflectance spectra, but the curves of r_R show in both case monotonous decrease from wavelength of 400 to 700 nm. This kind of dependence of r_R on the wavelength is explained: (1) by decrease of the L_z / E_d ratio with increasing of the wavelength of light (in the visible region the spectral curve of E_d depends rather weakly on the wavelength, but that of diffuse solar radiation is more or less monotonously decreasing towards the longer wavelengths), (2) by weak dependence of the reflectance factor of water on the wavelength in the visible region of the spectrum. However, the contribution of r_R in the r value can vary rather big limits, the numerical values of r_R being influenced by the optical properties of the sea surface (oil-pollution, foam, dead algae agglomerations floating on the surface) and in the great deal also by cloudiness. The last can be explained by angular distribution of the sky radiance, which is different in clear and overcast weather.

In the case of thick homogeneous cloud cover the maximal sky radiance is usually observed in the zenith area, but in the clear weather the L_s in (and near) the zenith area can be far from its maximal value, which is placed around solar disk. From the other side, the values of E_d in clear weather usually exceed those in conditions of overcast sky. As a result, the L_z / E_d ratio (and consequently, also the r_R value) for overcast sky can be much bigger than that for clear sky.

Thus, it seems that because of the monotonous spectral distribution of the r_R the shape of the remote sensing reflectance curve (especially the variation of minima and maxima) depends mainly on its diffuse component, r_D. It means that some rough estimations about of the optical properties of the water column can be made even by visual observation of the r spectra. The best way is to analyze the spectra normalized (to some reference wavelength). An example is shown in Fig. 2, where the curves $r(\lambda) / r(540 \text{nm})$ for Skagerrak (Baltic Sea) and two Estonian lakes are presented. As we can see, these curves differ very much from each other. The transparency of the Skagerrak waters exceeds that for Lake Võrtsjärv by about 10 times and the shape of the spectrum is entirely different. The spectrum of Lake Nohipalu Mustjärv deserves special attention. Although the relative transparency of its water is close to that of the Lake Võrtsjärv (0.6 and 0.8 m), the $r(\lambda)$ spectrum of Lake Nohipalu Mustjärv is very different. The reason is, that in Lake Võrtsjärv the low water transparency is accompanied by high values of backscattering coefficients, which causes the values of r_D to be higher than r_R (or comparable to it).
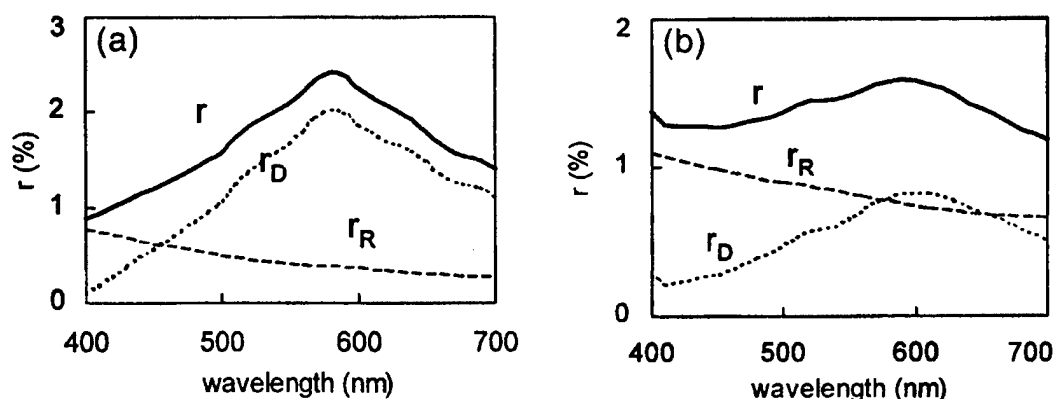

Fig. 1. Remote sensing reflectance $r(\lambda)$ and its components $r_R(\lambda)$ and $r_D(\lambda)$ in two measuring stations: (a) Pärnu Bay, Station No. 7, June 7,1993 (Secchi disk depth $z_{SD} = 0.8$m), (b) Lake Kurtna Valgejärv, May 16, 1993 ($z_{SD} = 3.3$ m).

In the Lake Nohipalu Mustjärv very strong absorption of light takes place and backscattering is low, which leads to extremely small values of r_D The shape of the r curve is rather strongly determined by the shape of r_R curve. In nature, this type of water can be found in brown-colored lakes with very high concentration of dissolved organic matter. Probably, the water bodies with very strong absorption and small backscattering of light must be considered as a separate group and detailed investigation of these waters by optical remote sensing methods is questionable [28].

Vertucci and Likens (1989) investigated 44 lakes in the region of Adirondack mountain, measuring 123 remote sensing spectra. They convert the obtained results to diffuse reflectance (R_D) spectra, which correspond to the component r_D just below the water surface (before the refraction of the upwelling radiation at the air-water boundary). Relaying on the results obtained they classified the lakes under investigation into five types.

The approach used by Vertucci and Likens (1989) corresponds to the conclusions of the other authors, which lead to the investigation of relations between the values of r_D and water constituents through the irradiance reflectance (or "diffuse reflectance") just below the water surface, $R_D(z = -0)$. According to Sathyendranath (1986) the value of L_D can be expressed by means of the upwelling radiance just below the water surface ($L_{Du}(z = -0)$ by the following way:

$$L_D(z = +0,\theta,\varphi) = L_{Du}(z = -0,\theta,\varphi)\left[1 - r_F(\theta,\varphi)\right]/n^2, \tag{4}$$

where n is the refractive index of the water, r_F is the Fresnel reflectivity, θ and φ are the spherical coordinates. For nadir viewing angles of about 40° or less the radiance distribution is generally found to be insensitive to changes in θ and φ. Therefore, for small nadir viewing angles is possible to simplify Eq. (4) to the following:

$$L_D \approx 0.544 L_{Du}. \tag{5}$$

Taking into account, that the irradiance reflectance at the depth $(z = -0)$ is defined :

$$R_D(z = -0) = E_u(z = -0)/E_d(z = -0), \tag{6}$$

where E_u and E_d are the upwelling and downwelling irradiances just below the water surface, and

$$L_{Du}(z = -0) = E_u(z = -0)/Q, \tag{7}$$

we can found the connections between L_D, L_{Du} and R_D. For perfectly diffuse medium, $Q = \pi$, but for nadir and near-nadir angles in the ocean the value of Q is close to 5.
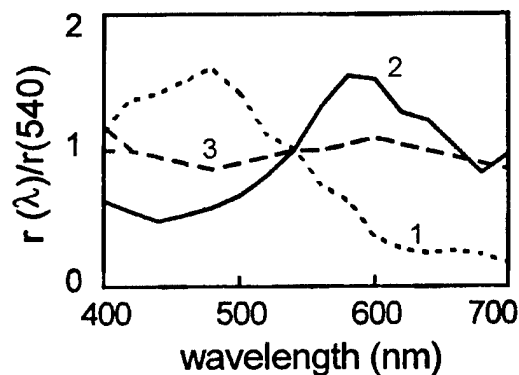

Fig. 2. Spectral distribution of the remote sensing reflectance, normalized to the wavelength 540 nm: (1) Skagerrak region of the Baltic Sea (July 1987, $z_{SD} = 8$ m); (2) Lake Võrtsjärv in Estonia (July 1995, $z_{SD} = 0.8$ m); (3) Lake Nohipalu Mustjärv in Estonia (June 1993, $z_{SD} = 0.6$ m).

DIFFUSE REFLECTANCE

Thus, to examine how the remote sensing reflectance (*i.e.* its diffuse component r_D) can be related to the water transparency and to the type and concentrations of the optically active substances in the water, an analysis of the formation of the irradiance reflectance just below the water surface have to be performed. Widely used is the classical linear formula by Morel and Prieur (1977):

$$R_D(\lambda) = 0.33 b_b(\lambda)/a(\lambda)),\tag{8}$$

where b_b is a volume backscattering coefficient and a is an absorption coefficient of the aquatic environment. Afterwards some variations and improvements of this equation are proposed by other authors. Gordon et al. (1975) gives a variant in the form of a sum:

$$R_D = 0.001 + 0.3244\,x + 0.1425\,x^2 + 0.1308\,x^3, \quad x = b_b/(a+b_b),\tag{9}$$

for the depth just below the water surface. Haltrin (1998) considered the dependence of R_D in a more complicated manner:

$$R_D = \left[(1-\bar{\mu})/(1+\bar{\mu})\right]^2, \quad \bar{\mu} = \sqrt{1 + 3 b_b/a + \sqrt{(b_b/a)(4 + 9 b_b/a)}}\tag{10}$$

and investigated the dependence of R_D on the illumination conditions (diffuse or total radiation), proposing the respective corrections. By his results R_D (total) differs from R_D(diffuse) from 0 to 20%, in dependence of combination of $\bar{\mu}$ and solar zenith angle (in most cases R_D (diffuse) > R_D (total), but the opposite relation is also possible).

Investigations by Gordon (1975) and Kirk (1981) show, that R_D depends noticeably on the angular distribution of the incident radiance, increasing with the increase of solar zenith angle. Kirk (1984) presented the following relationship:

$$R_D(Z_\oplus) = k(Z_\oplus) b_b/a,\tag{11}$$

and

$$k(Z_\oplus) = 0.975 - 0.629 \cos(Z_\oplus),\tag{12}$$

where $Z_\oplus$ is the angle of the direct solar beam to the vertical just below the water surface (after refraction). Thus, instead of the constant 0.33 in the Morel's Eq. (8) there will be a function of $k(Z_\oplus)$, which numerical value always exceeds 0.33 (its minimal value is 0.346). For example, for direct sunlight at a solar zenith angle of 46.3° the $k(Z_\oplus)$ will be 0.437 and for overcast conditions it is 0.427.

ABSORPTION AND BACKSCATTERING COEFFICIENTS

Consequently, critical factors describing dependence of R_D and r_D on the water constituents are backscattering and absorption coefficients (b_b and a). These data are necessary for the interpretation of the optical remote sensing data by the method of comparison with the model results. As known, the main optically active substances in the water are phytoplankton, dissolved organic matter (yellow substance) and suspended matter. The total absorption and total backscattering coefficients can be expressed as the sums of the corresponding coefficients of these substances. Often the phytoplankton absorption is characterized through chlorophyll-*a* concentration in the water. There are some variations in the meaning of the term "suspended matter" by different authors: sometimes only the hydrosols (mineral particles), sometimes a mixture of organic (dead algae, humic particles, detritus) and mineral particles are considered. Thus, the total absorption coefficient a can be expressed in following way:

$$a = a_w + a_{ph}^0 C_{Chl} + a_y^0 C_y + a_s^0 C_s,\tag{13}$$

where a_w is the absorption coefficient of the absolutely pure water, a_{ph}^0 , a_y^0 and a_s^0 are, respectively, specific absorption coefficients of phytoplankton, yellow substance and suspended matter, and C_{Chl}, C_y and C_s are their concentrations in water. As also mentioned above, the wavelength dependence notation is omitted for brevity.

As known, the optical influence of the phytoplankton consists of several components: the different species of living clorophyll (a,b,c) and its pigments, the different natures and sizes of phytoplankton cells and the production of their developing and dying. There are a big variability in the values and shapes of the phytoplankton specific absorption spectra, presented by different authors. This is caused not only by the variations of the contributions of different groups of pigments and chlorophyll, but also by the "package effect" and by different light conditions during the growth of the phytoplankton cells. Some formal reasons of the differences in these spectra are the different approach to the matter under investigation: in some works the phytoplankton is considered together with detritus; in most publications the specific absorption coefficient is defined, dividing the phytoplankton absorption coefficient to the chlorophyll-a content, but in others it is divided to the sum of chlorophyll and phaeophytin.

Variability in the chlorophyll a-specific absorption coefficients of living phytoplankton $a_{ph}^0(\lambda)$ was analyzed by Bricaud et al. (1995) using a data set including 815 spectra, which covered the chlorophyll concentration range $0.02 - 25$ mg/m^3. Empirical relationships between a_{ph}^0 and C_{Chl} were derived by least squares fitting to power functions. The results have shown, that a_{ph}^0 depends of the chlorophyll concentration by the following way:

$$a_{ph}^0(\lambda) = A(\lambda)C_{Chl}^{-B(\lambda)}, \qquad (14)$$

where $A(\lambda)$ and $B(\lambda)$ are positive, wavelength-dependent parameters (they are tabulated in Bricaud et al., 1995). The respective correlation coefficients are not high (only in the region $400 - 500$ nm they exceed 0.7), but Eq. (14) seems to be a big help in the field of problems, connected with phytoplankton absorption properties. An example of the a_{ph}^0 spectra, taken from Bricaud et al. (1995) is presented in Fig. 3.

When considering the problems of the determining the chlorophyll content in the waters of different transparency, the overshadowing of the influence of chlorophyll by other water constituents is worth to discuss. Figure 4 demonstrates the change of the spectral curve of R_D, caused by increase of the chlorophyll concentration from 0 to 2 mg/m^3 for three variants of the content of the other optically active substances in the water. As we can see, under conditions of high concentrations of yellow substance and hydrosols the differences between the R_D spectra, that correspond to $C_{Chl} = 0$ and $C_{Chl} = 2$, are probably in the range of remote sensing measurement errors.

Similarly to total absorption coefficient, the total backscattering coefficient (b_b) can be expressed as the sum of contributions from different substances:

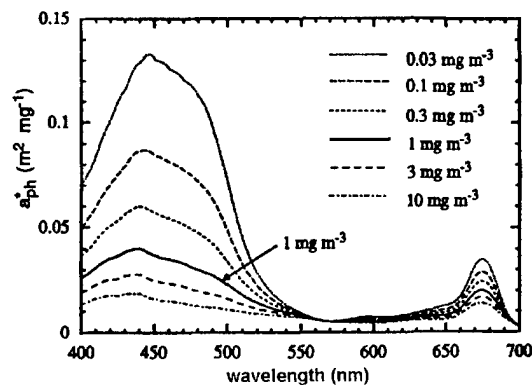$$b_b = B_w b_w + B_{Chl} b_{Chl} + B_s b_s, \qquad (15)$$

Fig. 3. Chlorophyll-specific absorption spectra of living phytoplankton a_{ph}^0 for various values of chlorophyll concentration (from 0.03 to 10 mg/m^3), as reconstructed from Eq. (14).

Note: the values of the spectrum for $C_{Chl} = 1$ mg / m^3 correspond to the values of $A(\lambda)$ in Eq. (14).

where B_w, B_{Chl} and B_s are respectively the backscattering to total scattering ratios (or probabilities of backscattering) by pure water, phytoplankton and non-chlorophyll particles ($B_w = 0.5$); b_w, b_{Chl} and b_s are scattering coefficients for these substances. The other way to determine b_b is by means of specific backscattering coefficients (b_b^0) for water constituents:

$$b_b = b_{b,w} + b_{b\,Chl}^0 C_{Chl} + b_{b\,s}^0 C_s,$$

(16)

where $b_{b,w}$ is the backscattering coefficient for the pure water.

In the Eqs. (5) and (6) the scattering (and backscattering) by yellow substance is not taken into account. The main reason is very small values of its scattering coefficients. However, it may have some importance in waters with high concentrations of the yellow substance. As known, the natural water remains a scattering medium even after filtration, because small particles pass through the filter. These scattering particles may include fine inorganic particles as well as colloidal forms of aquatic humus which appear to coexist with yellow substance. Thus, the yellow substance absorption spectra values, determined from filtered water, are really the attenuation coefficients, where some contribution gives the scattering by these small particles and colloids.

The problem of authentic information on the numerical values of the backscattering coefficients is extremely important for building the remote sensing reflectance models. The absolute values of b_b are usually small, much less than the values of absorption coefficient. Because of its small values, b_b usually determined with big relative error, which critically influences results of computing R_D using Eqs.(8)-(11). Most b_b-related data are obtained for oceanic and sea waters (*in situ* or laboratory results). The data for coastal and inland waters are rather rare and often do not coincide with oceanic data. We note also, that by building algorithms for determination of backscattering coefficients often only the backscattering by chlorophyll particles is taken into account. In this case the general formula for $b_{b\,Chl}^0$ is usually given in the form:

$$b_{b\,Chl}^0(\lambda) = k_1(\lambda) C_{Chl}^{k_2(\lambda)},$$

(17)

where $k_1(\lambda)$ and $k_2(\lambda)$ slightly depend on wavelength.
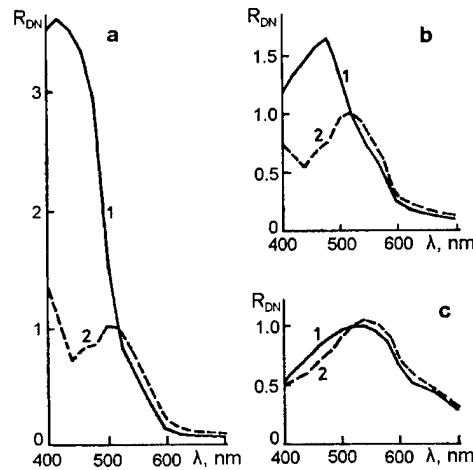

Fig. 4. Change of the irradiance reflectance coefficient spectrum $R_{DN}(z = -0)$ (R_D is normalized to the wavelength 520 nm) in dependence on the variations of the amount of the water constituents (curves 1 correspond to $C_{Chl} = 0$, curves 2 to $C_{Chl} = 2$ mg/m^3) . The values of R_{DN} were computed using the data on the absorption and scattering by chlorophyll, yellow substance and hydrosols,: (a), (b) and (c) correspond to the values of C_y and C_s, both equal to 0.1, 1 and 10 (in relative units).

Generally, the results presented by different authors often do not coincide in the backscattering coefficient values and also in the character of its spectral distribution: some data are suggesting the decrease of b_b with the increase of wavelength, some the irregular dependence of b_b on λ, and even its increasing with wavelength in productive waters.

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