Special Features of Kirchhoff Method Application in Microwave Radiometry of Rough Sea Surface.

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***Abstract*- The use of hydrological (surface wind and sea wave slope) dependencies for calculation of microwave characteristics of the "ocean-atmosphere" system by Kirchhoff method is discussed here. As an important example, we review results of our experiment on bistatic sensing of the sea surface. In this experiment Sun is a powerful natural source of noise microwave radiation for the sea surface sensing. For the receiving of solar radiation in the region of quasi-specular scattering three two-polarization radiometers (0.8, 2.25 and 6.0 cm) are used. The results of joint hydrological and radiometric experiments (wind speed from 0 to 15 m/s) are reported.**

Currently there are several different methods to calculate the emission or scattering coefficients of microwaves, interacting with the rough sea surface [1, 2]. In the case of the microwave radiometry of the sea surface the basis for many techniques of calculation is a properly modified Kirchhoff method [1,2]. In this method only sufficiently large surface waves are taken into account, with the following relations having validity:

$$\begin{aligned} &\Lambda >> \lambda \\ &(2\pi / \lambda) \cdot R_C \cdot Cos^3\theta = k \cdot R_C \cdot Cos^3\theta >> 1 \end{aligned} \qquad (1)$$

where Λ is the length of large sea wave, λ is the length of microwave sensing wave, R_c is radius of curvature for local wave element and k is radio wave number. In the process of calculation these large and smooth waves are approximated by flat surfaces with size sufficiently large in relation to the wavelength λ of radiation. Local radiation parameters are calculated by Fresnel formulas. The final result is reached due to the averaging over all possible slopes. For the most practical tasks of sea surface radiometry quite adequate method of calculation is Kirhoff's method. In the practical calculations by Kirhoff's method the principle moment is quantitative concrete definition of theoretical limitation (1). There is no common opinion about wave number corresponding to this method, $K^{up} = 2\pi / \Lambda_{\min}$, which should limit from above the long wave fraction of real slopes spectrum. The real way to overcome this crucial moment in calculations is the use of sea waves slope distribution empirical dependencies.

The statistics of large wave slopes in modeling is taken often as a Gaussian or pseudo-Gaussian, which allows taking into account the surface anisotropy (to some extent). Such assumption agrees well with experiment in case of so-called "developed wind roughness", when one-to-one correspondence is reached between accelerating wind and field of wind-driven waves. The dependencies of such kind were obtained by different scientists while processing of corresponding statistics, gathered during wavegage studies in different areas of the World Ocean. The choice of equipment, methodology and conditions of experiments were individual for each researcher. Results of the experiments were related with specific band of surface waves spectrum in each case and depended considerably upon above mentioned conditions [2-8]. The essential distinctions between results of different researchers remain also in case when data on sea roughness obtained within the same region of the World Ocean is considered and compared. The results of Cox and Munk (1951-55), Pierson and Stacy (1973), Kalinin and Leikin (1974), Burtzev and Pelevin (1975), Bjerkaas and Riedel (1979), Phillips (1985), should be considered among dependences, most frequently mentioned in literature [2-8]. Most popular are the Cox-Munk dependences [3]. They are still broadly used in remote sensing and adjacent fields. However, by development of remote sensing methods, it was noted that the direct use of Cox and Munk dependences in case of microwave radiometry of sea surface led to significant discrepancy with experimental data. It was clearly brought out in the experiments of Hollinger performed on board of the oceanographic platform (Argus Island tower) in 1970-71 [4]. Then Wilheit applied these results of Hollinger to compare the satellite radiometric data obtained at some control points of the ocean (bands 6.6, 10.7, 18, 21 and 37 GHz) and data of simultaneous measuring of surface wind field, as supplied from the net of oceanographic buoys at those points [5]. The method, developed by Wilheit as a result of this research, was a generalization of Hollinger idea. Wilheit introduced half empiric corrections that allowed using the Cox-Munk dependencies and took into account the radiofrequency dependency [5]:

$$\begin{aligned} \sigma_r^2(f,V) &= (0.3+0.2f)\sigma_{cm}^2(V), \quad \text{for } f \le 35 \text{ GHz} \\ \sigma_r^2(f,V) &= \sigma_{cm}^2(V), \qquad\qquad\qquad \text{for } f \ge 35 \text{ GHz} \end{aligned} \tag{2}$$

where f is the frequency of microwave sensing wave in GHz, $\sigma_{cm}^2(V)$ is dispersion of big sea wave slopes in the model of developed wind roughness in rad^2, as per calculation according to Cox-Munk dependencies, $\sigma_r^2(f,V)$ is dispersion of sea wave slopes, which are "big for the sensing radio wave with frequency f" [5]. Therefore, in the most elaborate modern radiometer models, the usage of information about the state of sea roughness is based, as a rule, on the following assumptions:

1) The sea surface roughness consists mainly of full developed wind-driven waves;
2) The dependency of the dispersion of the large sea wave slope distribution by such waves versus the value of the surface wind (at the standard altitude) is in accordance with the Cox- Munk results [3];
3) The transition from the spectral fraction of wind waves, "large in accordance with Cox-Munk", to a fraction of surface waves, "large enough with respect to radio wave with length λ (frequency f) applied in the sensing" is done by the technique proposed by Hollinger [4] and Wilheit [5];
4) The influence of the foam cover is taken into account on the basis of modeled simulations and total statistical data for this region of the World Ocean [1-2].

These assumptions are crucial for the contemporary understanding of the Kirchoff method with its practical usage in calculations of interaction between the microwave radiation and rough sea surface in the region of quasi-specular scattering. However, if such approach is applied, these assumptions should be clearly confirmed by experiment! We can check assumptions 1)-3) with respect to the microwave radiometry of the sea surface in the most frequently used band from 3 to 50 GHz. For that let us discuss already available results obtained by us earlier.

Series of experiments focused on investigation of the solar microwave radiation in the band of 3 to 50 GHz, scattered from sea surface in the region of quasi-specular scattering, were performed by the authors in 1989-90. The experiments were conducted in the Black sea area in the spring and autumn of 1989, and in the summer of 1990. Some of the obtained results were reported at IGARSS and URSI [6] and published in various editions [7,8]. Direct measurement of parameters of solar microwave radiation flux, after it was scattered on the rough sea surface, was conducted in the process of the experiment. However, the following measurements were conducted simultaneously as well: 1) measurement of downwelling microwave solar radiation spectral levels, 2) measurement of the state parameters of near-surface atmosphere layer and upper water layer, 3) direct contact measurements of surface roughness field. Special experimental complex was compounded of three main blocks: radiometric block, block of registration and primary processing of obtained information, and contact measurements block (see Fig.1 and Abstract).

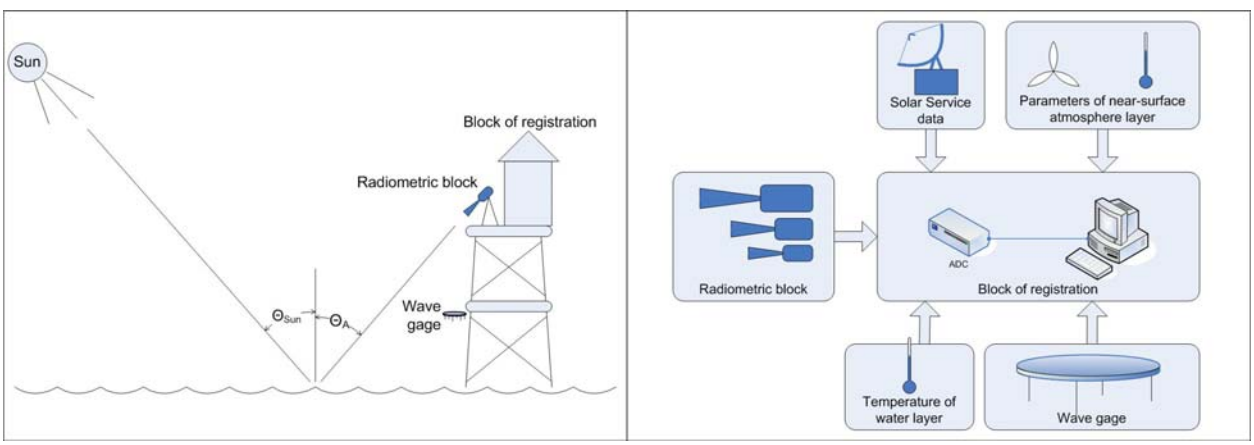

Fig.1 Configuration of the experiment.

The radiometric block contained 3 dual-polarized microwave radiometers working at 0.8, 2.25 and 6.0 cm (frequencies 37.5, 13.3 and 5.0 GHz). The antennas and microwave blocks were situated at the special precision-built rotary table. Contact measurements block consisted of a set of meteorological gauges for measurements of parameters of near-surface atmosphere layer and upper water layer, and 4-string wave gage with spatial matrix of 30 or 42 cm, for measurement of large sea waves slope dispersion. A large volume of wave-measuring and radiometric measurements was performed during these experiments. These experiments were conducted both simultaneously and separately in time. Thus, we have a real possibility to check the validity of theoretical assumptions 1)-3), used in calculation procedure (see above), as well as to try to improve the present calculation method.

Only those situations when wind direction and incoming swell were in direction from open sea towards the coast, or parallel to the coast, were considered to approach the open sea conditions in the process of this experiment. In that case it was discovered that the presence of one or several swell systems is observed about 60 or 65% of all cases , and the situation with pure (more or less) wind –driven waves is observed much more rarely, in 35 or 40% of the rest occasions. Fig. 2 shows aggregate results of wave measurements during October-November, 1989, and June-July, 1990. Values of the large wave slopes dispersion along and across the accelerating wind direction are combined in separate groups. So we ascribed only 35 to 40% of total volume of realizations to wind-driven waves. Roughness was in process of development or decay in half of all the studied cases of wind-driven waves (15-20% of total number of realizations). Depending on the wind regime, the values of slopes dispersion along and across the wind direction could have magnitudes in rather broad range around magnitude corresponding to quasi-equilibrium, "developed enough" case. In other half of cases (15-20% of total number of takes), the roughness was interpreted by us as practically developed wind-driven waves. Let's consider dependency of slopes dispersion upon accelerating wind, obtained for our version of criterion for developed wind roughness. Two ranges can be distinguished quite clearly: Range I (the accelerating wind has values from 0 to 8-9 m/s) and Range II (wind from 9 to 15 m/s). The decrease of curve slope (practically half) gets noticeable in Range II (see Fig.3).

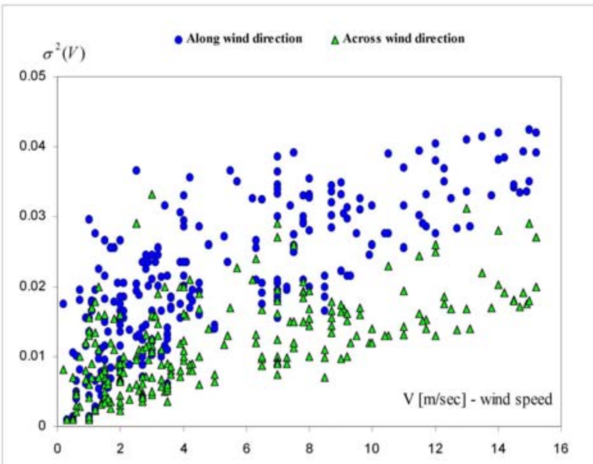

Fig. 2 The total wind-wave situation .

Range I:

$$\sigma_x^2(V) = 0.0016 + 0.0028 \cdot V$$
$$\sigma_y^2(V) = 0.0014 + 0.0014 \cdot V$$
$$\sigma^2(V) = \sigma_x^2(V) + \sigma_y^2(V) = 0.003 + 0.0042 \cdot V \pm 0.004$$
$$\langle \sigma_y^2(V) / \sigma_x^2(V) \rangle \approx 0.53$$

Range II:

$$\sigma_x^2(V) = 0.0153 + 0.0014 \cdot V$$
$$\sigma_y^2(V) = 0.0063 + 0.0008 \cdot V$$
$$\sigma^2(V) = 0.0216 + 0.0022 \cdot V \pm 0.004 \tag{3}$$
$$\langle \sigma_y^2(V) / \sigma_x^2(V) \rangle \approx 0.51$$

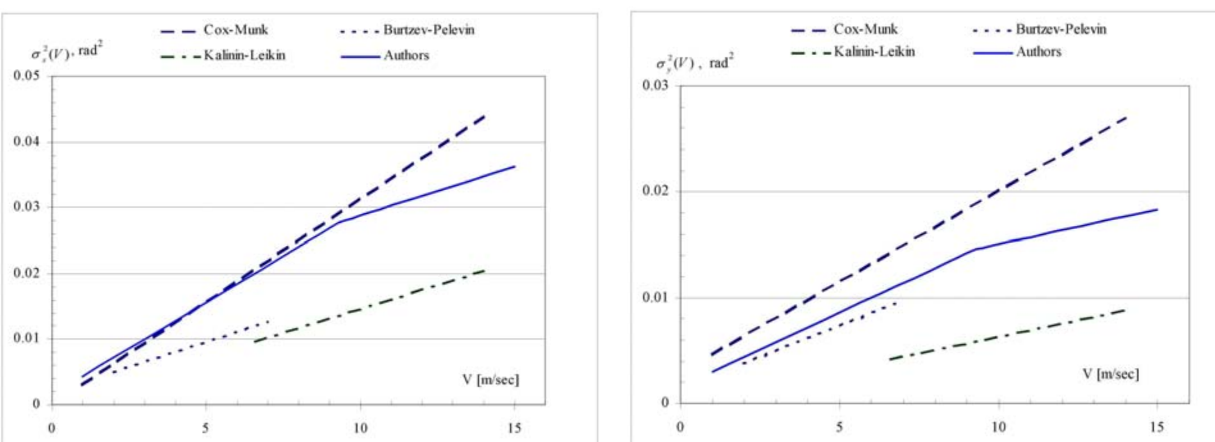

Fig. 3a & 3b: Comparison of the results obtained by authors and the above mentioned of Cox- Munk [3], Burtsev- Pelevin and Kalinin- Leikin [8] (all dependences are normalized to the height of 19.5 m).

After a primary processing of the results of radiometric measurements about 60 experimental series suitable for further analysis were obtained. These series consisted of complex data on scattering of incident solar microwave radiation on a rough sea surface at relatively low fixed position of the Sun over horizon (see above Fig.1), i.e. in the “Sun track” mode. Each of these tracks consisted of measurement data of scattered solar radiation at vertical and horizontal polarizations in the bands of 6 cm (5 GHz), 2.25 cm (13.33 GHz) and 0.8 cm (37.5 GHz) at different nadir angles of receiving antenna, at practically unchanged angle of the Sun. Each track was additionally set in correspondence with the value of the brightness temperature (or spectral flux) of the source in used bands, meteorological data of near-surface layer of atmosphere and upper water layer, as well as data of wave-measuring complex about parameters of large sea wave slopes spectrum.

The values of contribution of scattered solar radiation into measured antenna temperature at light and moderate winds are large enough. Sensitivity of these values to change in degree of sea surface roughness is also noticeable. Let us repeat Hollinger and Wilheit conclusion procedure [4,5]. But now our conclusions will be based on the large sea waves slope real data and not just information about wind speed as Hollinger and Wilheit done. Thus, large wave slopes dispersion formed only by fraction of waves, "large for sensing microwave radiation with frequency f" is obtained. Next values of correction coefficient 0.36 (± 0.05), 0.47 (± 0.07) and 0.62 (± 0.08) correspond to the bands of 6.0 cm (5 GHz), 2.25 cm (13.33 GHz) and 0.8 cm (37.5 GHz), respectively. These reference values of coefficient are transformed in correction function $C(f)$, depending upon sensing frequency f (in GHz), by method of linear interpolation, so that $C(f) = 0.34 + 0.0076 \cdot f$ (see Fig.4). The validity of our version $C(f)$ is deliberately limited to the band of 3 to 50 GHz.

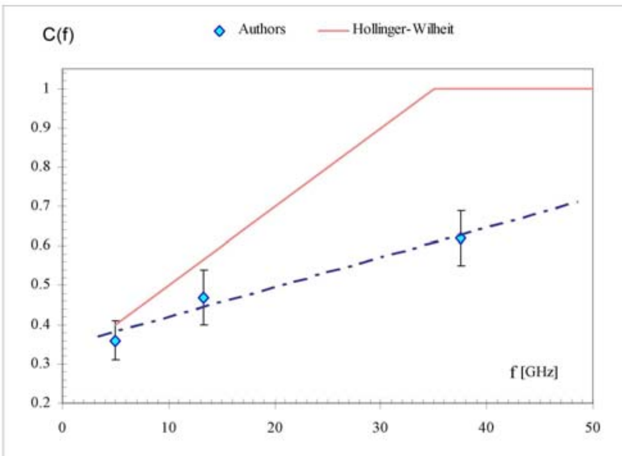

Fig. 4 Hollinger-Wilheit and authors approximation variants of $C(f)$ function.

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