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Modeling of the Propagation of LF–MF–SF Bands Electromagnetic Waves on Arctic Paths

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Abstract: *The article demonstrates that the conditions of LF–MF–SF bands electromagnetic wave propagation over the "ice-sea" structure with highly inductive impedance are more favorable than over the sea without ice because of the appearance of surface electromagnetic waves (SEW). It was determined that the conditions of radio wave propagation over ice paths depend on a frequency, ice thickness and distance from the transmitter within the 100 kHz – 5 MHz range on the paths with ice thickness from 0.6 to 2.7 meters.*

Keywords: *surface electromagnetic wave (SEW), attenuation function, surface impedance, sea ice, sea water, radio wave propagation.*

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1. Introduction

A study of radio wave propagation over the ice-covered sea areas is of great importance in the connection with the problem of the surface electromagnetic wave (SEW). Many of LW–MW–SW radio systems in the Arctic seas work in the range of 100 kHz to 5 MHz. The review of literature on the area of water of the Arctic and the Antarctic showed that the electromagnetic characteristics of the "ice-sea" stratified media with sharply contrasting electric properties and the processes of radio wave propagation over them are not sufficiently studied [1, 2].

The aim of this study is efficiency assessment of communication and navigation channels in the Arctic regions on the basis of analysis of numerical data of modeling of the LF–MF–HF radio wave propagation over the “ice-sea” stratified medium within the range of 100–5000 kHz (attenuation function *W*, electromagnetic field level *E*).

2. Electrical properties of seawater and ice

Let us consider the electrical characteristics of seas water and ice. Electric conductivity of water σ_w depends on its mineralization. For salt water σ_w varies within 0.3–15 S/m. Electrical resistivity of the White and Barents Seas water varies within 0.3 to 0.4 Ohm·m (σ_w = 2.5–3.33 S/m). Dielectric permeability of water ε_w weakly depends on its mineralization and varies within 87–80 at a temperature of 1–20 °C. Frequency dependence of σ_w and ε_w of water is manifested only at frequencies $f \geq$ 100 MHz. Ice is considered as an isotropic semi-conducting layer with a relatively complex dielectric permeability $\varepsilon_{ci} = \varepsilon_i + i60\lambda\sigma_i$, its thickness is $h_i \leq \lambda$, where λ is air wavelength. In scientific literature there is limited experimental data obtained in various seas of the Arctic and the Antarctic as well as in other aquatic areas [1, 2]. There is freshwater ice and sea ice. Electrical conductivity of ice σ_i depends on temperature, frequency and presence of admixtures. Within the 10 kHz – 100 MHz range σ_i does not depend on frequency and is determined by ice density. Values of σ_i get into the 10^{-4}–10^{-6} S/m interval. The electrical conductivity of sea ice is higher than that of freshwater ice by 1–2 orders. With the air temperature about 0 °C value of σ_i of ice significantly depends on the quantity of melt water. The dielectric permeability of ice ε_i depends on density, frequency, temperature and pressure. For sea ice ε_i is within 3–9 and depends on the temperature and salinity, large values are characteristic of high temperature and salinity. Thickness of sea ice depends on its age. For permanent pack ice the thickness equals 3–5 meters. For first-year ice, according to the literature, mean thickness in the area of Zhokhov Island equals (1.3 +/– 0.4) m. The maximum thickness of sea ice is equal to 6–7 meters. The obtained values of σ_i and ε_i are used for taking into account the ice layer during calculations of radio wave propagation on ice thickness maps [1] or geoelectric sections (GES), as well as for assessment of the influence of seasonal variations of electro physical parameters σ_i and ε_i of ice medium on radio wave propagation paths.

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[1] http://earth.esa.int/web/guest/missions/esa-operational-eo-missions

3. Surface impedance of the "ice-sea" stratified medium

The surface impedance of the stratified medium δ is determined as a ratio of tangential components of the electric E_τ and magnetic H_τ fields on the horizon "air-stratified medium" $\delta = E_\tau/(H_\tau Z_0)$ [3, 4]. In the LF–MF–HF radio wave ranges the ice layer renders a significant influence on the surface impedance. Therefore such structure should be considered as a two-layer "ice-sea" or three-four-layer with the presence of a snow layer and bottom soil. Let us consider the surface impedance δ of ice-covered sea for typical electrical properties and thicknesses of ice. In the LF–MF–HF range the 0.6–6 meters thick ice layer may be considered thin [1]. Let us take for calculations a two-layer model medium "ice-sea" with typical ice parameters $\sigma_i = 10^{-4}$ S/m, $\varepsilon_i = 4$. For seawater let us take $\varepsilon = 86$, $\sigma = 4$ S/m [1].

The calculations show that the ice layer with the accepted values σ_i and ε_i considerably changes a value of the surface impedance of the "ice-sea" stratified medium: increases the impedance module |δ| and shifts the φ_δ phase towards highly inductive impedances (to –88°). In LF–MF ranges and low-frequency area of SF range (on frequencies up to 5 MHz for ice thickness up to 6 meters) the ice-covered aquatic fields satisfy the impedance conditions since the condition $|\delta|^2 \ll 1$ is met. For the two-layered medium with highly contrasting properties such as "dielectric on conductor" the following ratio is correct:

$$\delta(h_i) = \mathrm{Re}\,\delta - i\left(|\mathrm{Im}\,\delta| + \frac{2\pi h_i}{\lambda}\right) \approx \delta_W - ikh_i,$$

where Reδ and Imδ are related to seawater without ice layer. Due to the presence of a thin weakly conductive ice layer on a highly conductive seawater medium an additive ikh_i component emerges in the impedance of the two-layered medium. It linearly depends on the thickness of a dielectric layer (ice) and shifts the impedance phase into the highly inductive area (Table 1). Thus, the frequency dependencies of the "ice-sea" structure impedance show that radio wave propagation over the ice-covered sea paths has peculiarities, characteristic of highly inductive paths due to the appearance of SEW.

Table 1.

h_{ice}, m	300 kHz		1000 kHz		2000 kHz	
	Re δ	***Im δ***	***Re δ***	***Im δ***	***Re δ***	***Im δ***
0	0.00182	–0.00182	0.0033	–0.0033	0.0047	–0.0047
1	0.00182	–0.0081	0.0034	–0.0243	0.0048	–0.047
2	0.00184	–0.0144	0.0034	–0.0454	0.0051	–0.089
3	0.00184	–0.0207	0.0036	–0.0666	0.0058	–0.133
4	0.00188	–0.027	0.0038	–0.088	0.0069	–0.179

4. Calculation results of radio wave propagation over the "ice-sea" homogeneous impedance radio path and their analysis

The methodology of calculation of the attenuation function *W* of the surface wave field over the impedance paths is thoroughly described in scientific works [3, 4]. It is based on the following main methods of calculation of the attenuation function *W* of the surface wave field: 1) a row of normal waves (V. A. Fock's row) [5]; 2) the Kalinin–Feinberg formula [6]; 3) the Hufford integral equation [7]; 4) the Fienberg integral equation [6]. Let us consider calculations of the attenuation function over the "ice-sea" impedance path within the range of 100–5000 kHz.

The vertical component of the electric field strength E_V at a distance *R* on the spherical surface of the Earth is represented in the form $E = E_0W$, where E_0 – the electric dipole field strength, which is located on a flat, infinite conductive surface, the *W* – attenuation function. The transmitter and receiver are located at the ice surface. The calculations adopted radiated power of 1 kW. The dependence of the field on the time taken in the form of the function exp$(-i\omega t)$. Module of the electric field $|E_V|$ is associated with the attenuation function module $|W|$ formula:

$$\left|E_{V[mV/\text{m}]}\right| = \frac{300\sqrt{P}}{R}\left|W(R)\right|$$

where *P* is the radiated power, kW; *R* is the distance from the source to the reception point, measured along the surface of the Earth, km. Calculation of the attenuation function *W* for a spherical Earth held in a number of V. A. Fock's row [5]:

$$W(x,y,q) = \sqrt{i\pi x}\sum_{s=1}^{\infty}\frac{e^{ixt_s}}{t_s - q^2}\frac{w(t_s - y)}{w(t_s)}.$$

Here $x = \frac{R}{a}\left(\frac{ka}{2}\right)^{\frac{1}{3}}$, $y = \left(\frac{2}{ka}\right)^{\frac{1}{3}}kh$, $q = i\delta\left(\frac{ka}{2}\right)^{\frac{1}{3}}$, where *a* is the radius of the Earth; δ is normalized surface impedance of the radio path; *h* is the height of the signal reception point over the ice surface; t_s parameters are the roots (zeros) of the transcendental equation:

$$w'(t) - qw(t) = 0,$$

where $w(t)$ and $w'(t)$ are Airy's function defined by the Airy's equation $w''(t)-tw(t)=0$, and its derivative, respectively [5].

From the theory of radio wave propagation over stratified media [3, 4] it follows that the SEW appears over the paths with highly inductive impedance. This wave, exponentially decaying in height, represents a practical interest since its energy decreases in inverse proportion to distance from the source, while the energy of the extensional electromagnetic wave decreases in inverse proportion to squared distance from the source. The attenuation function *W* over a highly-inductive flat path contains the term $W_{surf} = 2i\sqrt{\pi SR}e^{-SR}$ corresponding to the surface wave. The maximum of the surface wave equal to $\left|W_{surf}\right| = 2\sqrt{\pi|S|R}e^{-kR|\mathrm{Im}\,\delta|\cdot\mathrm{Re}\,\delta}$ is observed at a distance of $R_{\max} = \dfrac{\lambda}{4\pi\,\mathrm{Re}\,\delta|\mathrm{Im}\,\delta|}$. The comparison of the Fock's row-derived numerical data for the attenuation function and the level of the field for a homogeneous "ice-sea" path with the surface impedance considered above and ice thickness from 0.6 to 2.7 meters at the distances of up to 2000 km showed (Figs. 1a, b, c) that the conditions of radio wave propagation over the ice-covered sea paths with highly-inductive surface impedance are more favorable than over a homogeneous conducting sea surface due to the emergence of SEW. On Fig. 1 the graphs |*W*| and field level *E* over the "ice-sea" radio path on the frequencies of 300 (a), 500 (b) and 1000 (c) kHz at distances from the transmitter of up to 2000 km are presented. On Fig. 2 and 3 similar graphs grouped by frequency of 1500 kHz (distance up to 1000 km) and 2 and 5 MHz (distance up to 300 km) are presented. From these graphs it is plainly seen that the emergence of SEW over ice-covered sea paths and distances of its existence far away from an transmitter significantly depend on frequency. This can well be traced on the example of 2 MHz frequency represented on Fig. 3a. If on the 300 and 500 kHz frequencies the field over a 2000-km ice path is always higher than the field over the homogeneous well-conducting sea surface, then at the 1000 to 1500 kHz frequencies this excess takes place at the distances from 500 to 150 km. Let us note a considerable similarity of |*W*| graph forms on the frequencies of 300–500 kHz (Fig. 1a, b) as well as frequencies from 1.5 to 5 MHz. On the frequencies from 2 to 5 MHz the range (distance) of SEW emergence significantly decrease to 10–50 km. However |*W*| grows and reaches values |*W*| = 4. These ranges seemingly have no prospects of use in Arctic radio lines. However, they can efficiently be used for local search-and-rescue and search radio communication network and navigation at drifting stations. It requires the development of portable transmitter-receivers with efficient and ultra-compact antenna devices.

Let us carry out an analysis of spatial dependence of |*W*| on various frequencies. From the graphs on Figs. 1–3 it follows that starting from 300 kHz frequency and higher |*W*| has an SEW-characteristic spatial maximum $|W|_{\max}$ at $R_{\max}$ distances. In Table 2 the estimated values $|W|_{\max}$ and $R_{\max}$ are presented with the change in ice thickness from 0.6 to 2.7 m. From Table 2 it follows that on the 300–5000 kHz $|W|_{\max}$ grows with the increase of ice thickness. However, in doing so $R_{\max}$ increases linearly only on 300 and 500 kHz frequencies. On the frequencies from 300 to 500 kHz R_{max} does not exceed 160 km and sharply decreases to 1 km on the frequency of 5000 kHz with ice thickness of 2.7 m. Consequently, the most favorable conditions of radio wave propagation over the ice paths will be in the frequency range from 300 to 1000–2000 kHz.

Table 2.

h, m	**300 kHz**		**500 kHz**		**1000 kHz**		**5000 kHz**	
	$\|W\|_{max}$	R_{max}, km	$\|W\|_{max}$	R_{max}, km	$\|W\|_{max}$	R_{max}, km	$\|W\|_{max}$	R_{max}, km
0.6	1.025	27	1.055	45	1.2	74	2.69	16
1.0	1.05	50	1.12	69	1.44	111	3.32	7
1.5	1.09	67	1.23	105	1.8	131	3.77	4
2.0	1.14	95	1.35	131	2.1	116	3.88	2
2.7	1.23	128	1.56	160	2.33	81	3.9	1

In Table 3 the space domain of SEW existence ($|W| > 1$) is presented depending on a frequency and ice thickness. The range of the SEW radio lines on ice paths increases with the increase of ice thickness on 300 and 500 kHz frequencies and reaches 580 km. On frequencies from 2000 to 5000 kHz the SEW radio lines range considerably shrinks with the increase of ice thickness. This frequency range is characterized by poor radio wave propagation conditions over ice paths at great distances. The obtained numerical results should be taken into account for selecting operation frequency of LW-MW radio-positioning and communications systems in Arctic regions.

In Table 4 the Fock's row calculations of the attenuation function's module $|W|$ and field level E on the 500 kHz frequency at the distances of 100, 200, 500, and 1000 km from an transmitter depending on an ice layer thickness with the emitted power of 1 kW. The analysis of numerical data testifies to the fact that the conditions of radio wave propagation over ice paths due to the emergence of SEW are more favorable than over the open sea. For instance, at the distance of 500 km the field level over the sea is E = 180 μV/m and over the "ice-sea" path with ice thickness of 2 m is E = 530 μV/m.

The increase of the field level is equal to 2.95 times. At the 1000-km distance this increase already reaches 6.4 times.

A comparison of the Fock's row-derived numerical data for $|W|$ and field level for the homogeneous "ice-sea" path with ice thickness from 0.6 to 2.7 meters at the distances of up to 2000 km showed that with the highly-inductive surface impedance the radio wave propagation conditions over ice paths depend on the frequency and distance from an transmitter. With $|W| > 1$, significantly depending in the range of 100–5000 kHz on the frequency, the propagation conditions are more favorable than over the homogeneous ideally conducting surface. The modeling results indicate a strong influence of ice cover on radio wave propagation in LF–MF–SF ranges.

Table 3. Space domain of SEW existance depending on the frequency and ice layer thickness

h, m	**100 kHz**	**500 kHz**	**800 kHz**	**1 MHz**	**1,5 MHz**	**3 MHz**	**5 MHz**
	R, km	***R, km***	***R, km***	***R, km***	***R, km***	***R, km***	***R, km***
0.6	36	117	177	219	316	167	49
1.0	53	200	307	378	400	93	30
1.5	77	311	462	491	273	59	18
2.0	101	428	536	430	174	38	10
2.	138	580	495	277	108	23	6

Table 4.

h_{ice}, m	**100 km**		**200 km**		**500 km**		**1000 km**	
	|*W*|	***E*, *mV/m***	|*W*|	***E*, *mV/m***	|*W*|	***E*, *mV/m***	|*W*|	***E*, *mV/m***
0	0.89	2.7	0.73	1.1	0.31	0.18	0.05	0.015
0.6	1.02	3.0	0.89	1.23	0.44	0.26	0.095	0.028
1	1.11	3.3	1.0	1.5	0.55	0.33	0.14	0.042
1.5	1.22	3.7	1.16	1.73	0.71	0.43	0.22	0.067
2	1.35	4.0	1.32	1.98	0.89	0.53	0.32	0.097
2.7	1.53	4.6	1.55	2.33	1.13	0.68	0.47	0.14

5. Conclusion

According to the results of numerical data of the modeling of conditions of radio wave propagation within the range of 100–5000 kHz (attenuation function *W*, electromagnetic field level *E*) over the stratified “ice-sea” medium the efficiency assessment of communication channels and navigation in the Arctic regions was carried out. The results of the modeling displayed a strong influence of the ice layer on the LF–MF–SF range radio wave propagation. The electromagnetic field of a vertical electric dipole over the ice surface of the sea with the highly-inductive impedance may considerably exceed the field over the sea without ice due to the emergence of SEW. The values of the attenuation function’s module $|W|$ exceeding 1 and reaching $|W| = 4$, which are due to SEW, were obtained. With $|W| > 1$ the propagation conditions are more favorable than over a homogeneous conducting sea surface. In the course of analysis of the numerical data for $|W|$ and field level *E* on the paths with ice thickness from 0.6 to 2.7 meters it was established that with the highly-inductive surface impedance the LW–MW–SW radio wave propagation conditions over the ice paths depend on frequency, ice thickness and distance from an transmitter.

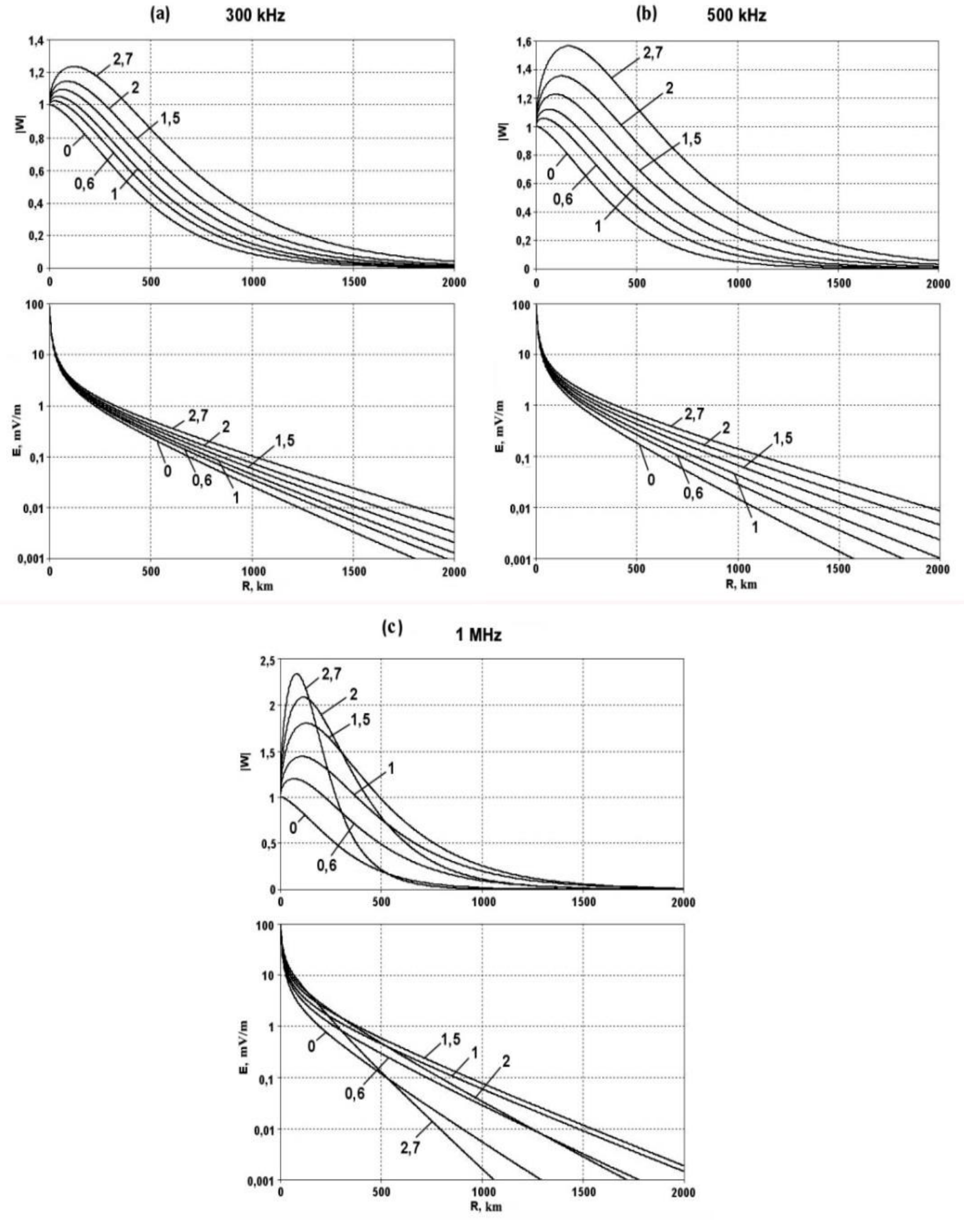

Fig. 1. Graphs |*W*| and field level *E* over the radio path "ice-sea" on the 300 (a), 500 (b), and 1000 (c) kHz frequencies at the distance of up to 2000 km from an transmitter (numbers on graphs indicate ice thickness in meters)

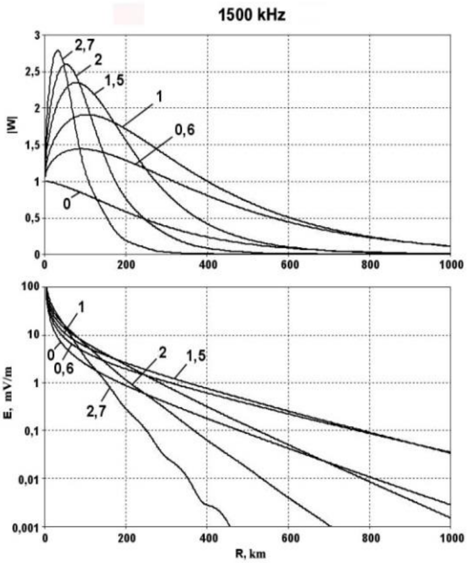

Fig. 2. Graphs |*W*| and field level *E* over the radio path “ice-sea” on the 1500 kHz at the distance of up to 1000 km from an transmitter (numbers on graphs indicate ice thickness in meters)

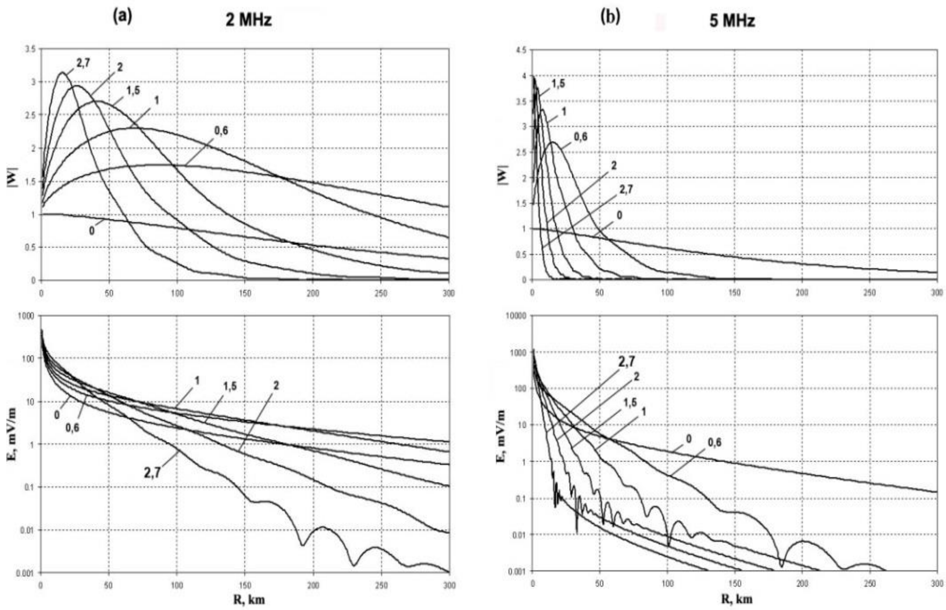

Fig. 3. Graphs |*W*| and surface wave field level *E* over the “ice-sea” radio path on the 2 (a) and 5 (b) MHz

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