Stability and increased radio communication coverage of sea area infrastructure measurement antennas

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Abstract. This research presents a modified method of signal amplification over layered surfaces of absolutely thin ice over marine waters on condition of stable operation of communication networks, necessary for deployment of Big Information Management Communication Systems and the concept of E-Navigation development. The method was first tested when deploying a GMSSB(b) network in the Azov-Black Sea region. Peculiarity of radio wave behavior during propagation over thin layered ice is that mutual phase ratios make a part of field energy “sticking” to the surface and propagating along it, thus creating a surface wave effect. At that, attenuation function is above one, and the field may increase with distance, even above design limits, breaking the proportionality law of reduction with distance. There are several details requiring clarification and adjustments to local conditions. In the MF and LF radio bands, solid surface and sea water are good conductors of electromagnetic flow. Thus, antenna fields for radio communications are located immediately above the surface for reception and transmission of vertical polarization signals, while field calculations are conducted with an elementary dipole.

1. Introduction Radio wave propagation over marine surfaces.
The main patterns in radio wave propagation have been studied in detail by a number of prominent scientists: H. Bremmer, K. Norton, M.V. Shuleikin, Iu.K. Kalinin and others. In the modern world, it seems that radio communication is not holding any more secrets. However, there are several details requiring clarification and adjustments to local conditions. In the MF and LF bands, solid surface and sea water are good conductors of electromagnetic flow. Thus, antenna fields for radio communications are located immediately above the surface for reception and transmission of vertical polarization signals, while field calculations are conducted with an elementary dipole.

2 Mobile marine communication with channels over water surfaces, including absolute thin ice
For radio communication with vessels in areas АI, АII according to conventional requirements one shall use exclusively surface wave; then, in order to calculate a radio link, the path is divided into three regions: surface approach region, semi-shadow region and shadow region.

Then, the surface boundary corresponds to the distance

\[ r_{sar} \approx 7 \cdot \lambda^{3/2}, [km] \] (1)
For a wave of length $\lambda = 150 [m]$, the distance is $r_{aw} = 37 km \approx 21 ml$

Starting from this distance from base radio station, there is a semi-shadow region continuing up to

$$ r_{b,sh} \approx 7 \cdot \lambda^3 \approx 196 km \approx 109 ml $$ (2)

In reality, the AII area is almost completely in the semi-shadow region from the radio propagation point of view.

At the air-water boundary, radio wave propagation leads to excitation of secondary field currents, described by Huygens and Kirchhoff, as a result of superposition of induced fields. Over the surface, attenuation and energy reflection into the bottom hemisphere is more intensive than over the waters [1].

In order to calculate wave diffraction appearing in rounding the Earth’s surface, let us apply the attenuation factor

$$ F = \frac{\hat{E}}{E_0} = F \cdot \exp(-j\varphi) $$ (3)

where $F$, $\varphi$ is the module and phase of the attenuation factor; $\hat{E}$ is the electromagnetic field strength at a distance of $r$ from transmitting antenna, $E_0$ is the electromagnetic field strength in free space without Joulean attenuation.

The attenuation factor depends on wavelength and polarization of the radiation, antenna elevation gradient, soil structure, local relief, electrical parameters of the medium, length of the propagation path, etc..

In general form, the formula of the attenuation factor is

$$ F = (2\pi x)^{\frac{1}{2}} \left| \sum_{b=t}^{e} e^{j\kappa x} \cdot \frac{h_1(t_s + y_1)}{h_1(t_s)} \cdot \frac{h_2(t_s + y_2)}{h_2(t_s)} \right| $$ (4)

$$ q = j \cdot \left( \frac{\pi a_{aw}}{\lambda} \right)^{\frac{1}{2}} \cdot \frac{1}{(\varepsilon - j60\lambda\sigma)} $$ (5)

where $q$ are parametric properties of the surface at $\varepsilon - 60\lambda\sigma$. After formalization and modification, we get

$$ q \approx j \cdot \left( \frac{\pi a_{aw}}{\lambda} \right)^{\frac{1}{2}} \cdot \frac{1}{(j60\lambda\sigma)^{\frac{1}{3}}} $$ (6)

where $\lambda$ is the wavelength; $\varepsilon$ is a relative dielectric permeability of the surface; $\sigma$ is a specific conductance of the underlying surface; $x$ is the numeric distance at $x = r/L$;

$r$ is the path length;

$L$ is the calculated distance scale, equal to
\[ L = \left( \frac{\lambda^2 \cdot a^2}{\pi} \right)^{\frac{1}{3}} \]  

where \( y_1, y_2 \) are heights of radiating and receiving antennas normalized with respect to the elevation scale, that is, a transceiver antenna gradient

\[ y_n = \frac{H_n}{H} ; \quad H = \frac{1}{2} \left( \frac{\lambda^2 - a}{\pi^2} \right)^{\frac{1}{3}} \]  

(8)

\( h_2(t) \) is a designation of the Airy function, related to the Hankel function of the second kind of the order of 1/3 by a relation

\[ h_2(t) = \left( \frac{\pi}{3} \right)^{\frac{1}{2}} \cdot e^{-\frac{2\pi}{3} \cdot t^2} \cdot i^{\frac{1}{2}} \cdot H_{1/3}^{(2)} \left[ \frac{2}{3} \cdot i^2 \right] \]  

(9)

where \( t_s \) are roots of the equation, with increasing modulus

\[ h'_s(t_s) - q \cdot h_2(t_s) = 0 ; S = 1, 2, ..., H \]  

(10)

Thus, the attenuation module in the range may be approximated as

\[ \hat{F} \approx 2 (\pi x)^{\frac{1}{2}} \cdot \sum_{m=1}^{\infty} \frac{e^{x \sin \theta m}}{t_s + q} \]  

(11)

The number of terms of the series shall provide enough accuracy.

Soil as a medium is non-uniform with depth, and in general radio waves attenuate at a depth of 10-15m from the surface.

In winter, most of the waters of the Azov Sea are covered with a layer of ice.

In this case, underlying surface becomes a two-layer medium ice-sea water, at that, because of its thickness of up to 0.5m, the ice also has a layered structure [2].

Taking into account the concept of surface impedance in propagation, approximate path and large values of relative complex dielectric permeability \( \varepsilon \), we get:

\[ \varepsilon_{\omega} = \left( \frac{\mu_a}{\varepsilon_a} \right)^{\frac{1}{2}} \cdot \left( 1 - \frac{\sin^2 \Theta}{\varepsilon} \right)^{\frac{1}{2}} \]  

(12)

where \( \mu_a \) is the absolute magnetic permeability of the surface, which is almost the same for all mediums and equal to the magnetic permeability of free space

\[ \mu_a = \mu_0 = 4\pi \cdot 10^{-7} \left[ \text{G} / \text{m} \right] \]  

(13)

\( \varepsilon \) is a relative complex dielectric permeability of the surface;

\( \hat{\varepsilon} \) is the absolute dielectric permeability of the surface;

\[ \varepsilon'_a = \varepsilon_a \cdot \varepsilon' \cdot \varepsilon_0 = \frac{1}{36\pi} \cdot 10^{-9} \left[ \text{F} / \text{m} \right] \]  

(14)

where \( \varepsilon'_a \) is the absolute dielectric permeability of free space;

\( \Theta \) is the angle of incidence of the free wave, when \( \hat{\varepsilon} \equiv 1 \), \( \hat{\varepsilon} \) is omitted, and only relative dielectric permeability is left.
Then, impedance of free space is

\[ Z_0 = \left( \frac{\mu_0}{\varepsilon_0} \right)^{\frac{1}{2}} = 120\pi \frac{\varepsilon_{air}}{\varepsilon} \approx \frac{\varepsilon_0}{(\varepsilon)^{\frac{1}{2}}} \]  

(15)

From that, approximate impedance boundary condition is

\[ \hat{E}_i = \hat{Z}_{air} \hat{H}_i \]  

(16)

When using an impedance value, finding field over the layered surface is the same as for uniform soil. It means that the proposed method is the same for any surface of any number of layers [1,2]. In calculations of incidence of a plane vertical wave at the water-air interface, the surface impedance is

\[ \hat{Z}_{air} = \hat{Z}_{01} \hat{Q} \]  

(17)

where \( \hat{Z}_{01} \) is the surface impedance of the air-first layer interface boundary;  
\( \hat{Q} = |\hat{Q}| e^{j\alpha} \) is the corrective factor taking into account the influence from lower, more saline layers of the sea water.

For a two-layer surface model, at \( 60\lambda \varepsilon \) the corrective factor \( \hat{Q} \) will be:

\[ Q = \left( \frac{\sigma_1 \sigma_2}{1 + \sigma_1 \sigma_2} \right)^{\frac{1}{2}} + \frac{\text{th}(jM)^{\frac{1}{2}}}{1 + \sigma_1 \sigma_2 + \text{th}(jM)^{\frac{1}{2}}} \]  

assuming

\[ M = \left( 2\pi f \mu_0 \sigma_1 h_1 \right)^{\frac{1}{2}} \]  

(19)

where \( \sigma_1, \sigma_2 \) are conductivity of the 1st and the 2nd layers;  
\( h_1 \) is the thickness of the first (topmost) layer.

Then

\[ M \approx 48.7 \left( \sigma_1, \sigma_2 \right)^{\frac{1}{2}} h_1 \]  

(20)

If applying with the assumption of

\[ \sigma_1 \approx \sigma_2 \text{ then } Q \approx \text{th}(jM)^{\frac{1}{2}}, \text{ and if } \sigma_1, \sigma_2, \text{ then } Q \approx c\text{th}(jM)^{\frac{1}{2}} \]

Field strength over the layered surface may be found with the formula

\[ E(R) = \frac{300 \cdot (P[kV]) \cdot KHD}{R[km]} \cdot F_{\text{laer}} \left[ \frac{mV}{m} \right] \]  

(21)

where \( F_{\text{laer}} \) is the attenuation function of a uniform surface, as a dipole gradient of layered and absolutely conductive surface.
Figure 1. Dependence of the electric field strength of the surface wave on ice thickness in the area where radio waves propagate at a conventional coverage of 200km [3].

For two-layered ice-seawater surface of the Azov Sea and absolutely thin ice, we get

$$Z_{\text{layer}} \approx \frac{Z_0}{2}$$

where $Z_0 = 120\pi = 377[\Omega m]$ is the free space resistance.

Let us show calculations for roots $i$ which are interdependent with the $Z_{\text{layer}}$ value:

For $-\frac{\pi}{2} \leq \text{arg} Z_{\text{layer}} \leq -\frac{\pi}{6}$, then

$$i_s = i_s^0 + \frac{h_0 + h_i q + \left(\Phi_0 + \Phi_1 q + \Phi_2 q^2\right)^{1/2}}{W_0 + W_i q}$$

(23)

If $-\frac{\pi}{2} \leq \text{arg} Z_{\text{layer}} \leq -\frac{\pi}{3}$, then

$$i_s = i_s^0 + \frac{h_0 + h_i q + \left(\Phi_0 + \Phi_1 q + \Phi_2 q^2\right)^{1/2}}{W_0 + W_i q}$$

(24)

$$0 \leq \frac{1}{Z_{\text{layer}}} \leq 0.05$$

If $0 \leq \frac{1}{Z_{\text{layer}}} \leq 0.05$, then

$$i_s = i_s^0 + \frac{\mu_0 + \mu_i q + \left(\mu_0 + k_1 q + k_2 q^2\right)^{1/2}}{N_0 + N_i q}$$

(25)

In common mathematical notation

1. $i_s^0, i_s^x$ are the roots corresponding to $q = \infty, q = 0$

$$q = \left(\frac{\pi \cdot a}{\lambda}\right)^{1/3} \cdot j \cdot \frac{Q}{(\varepsilon - 60\lambda \sigma j)^{1/3}}$$

2. $\dot{\mu}_0 = -\dot{\varepsilon} \cdot i_s; \dot{\mu}_1 = \frac{1}{12} (i_s^0)^2; \dot{\mu}_3 = -\frac{1}{3} (i_s^x)$

(26)

(27)
4. \( k_1 = 2e^2 - \frac{1}{6}e\left(\frac{1}{t_s^0}\right)^3; k_2 = -t_s^0 \left[ 2\zeta^2 + \left(\frac{1}{144} - \frac{2}{9}\right)(-t_s^0) \right] \)

5. \( N_1 = -t_s^0 \left[ -\zeta + \frac{1}{9}(-t_s^0)^3 \right]; N_0 = \frac{1}{6}(-t_s^0) - \zeta \)

6. \( h_0 = 0.25; h_1 = -\mu \)

7. \( \Phi_0 = 4\mu^3 + \frac{1}{16}; \Phi_1 = 0.25\mu; \Phi_2 = \mu^2 \)

8. \( W_l = 0.5; W_0 = 2\mu^2 \)

where \( \zeta = -\frac{1}{4} + \frac{1}{3}(-t_s^0)^3 \).

Having found the roots \( i_s \) of the attenuation factor \( F_{layer} \), let us calculate the field strength in a given point in the path. The calculation consists in determining electrical parameters of the underlaying surface layers and the complex parameter of water-surface interactions [4].

Then

\[
q = \left(\frac{\pi \cdot a}{\lambda}\right)^\frac{1}{3} \cdot j \cdot \frac{Q}{(\varepsilon - 60\lambda\sigma, j)^\frac{1}{3}}
\]

(34)

The root \( i_s \) of the characteristic equation:

\[
h_s'(i_s) - q \cdot h_s(i_s) = 0
\]

\[
t_s = t_s^0 + \frac{h_0 + h_1q + (\Phi_0 + \Phi_1q + \Phi_2q^2)^\frac{1}{2}}{N_0 + N_1q}
\]

(35)

For \(-\frac{\pi}{2} < \arg Z_{layer} \leq -\frac{\pi}{6} \):

\[
t_s = t_s^0 + \frac{h_0 + h_1q - (\Phi_0 + \Phi_1q + \Phi_2q^2)^\frac{1}{2}}{W_0 + W_1q}
\]

(36)

\[
t_s = t_s^0 - \frac{\mu_0\mu_1\mu_2 + (\mu_0 + k_1\mu_1 + k_2\mu_2)^\frac{1}{2}}{N_0 + N_1q}
\]

(37)

Let us find the diffraction attenuation factor with the Fock series

\[
F \approx 2(\pi x)^\frac{1}{3} \cdot \sum_{s=1}^{\infty} \frac{x^{ln(t_s)}}{t_s^0 + q^2}
\]

(38)

(39)

Then, electric field of ground wave depending on the distance and taking into account the diffraction attenuation factor is

\[
E(R) = \frac{300 \cdot \left( P[kV] \cdot KHD \right)^\frac{1}{2}}{R[km]} \cdot F_{layer} \left[ \frac{mV}{m} \right]
\]

(40)
Figure 2. Ground wave electric field ratios in propagation over the ice-free and ice-covered sea surface, depending on ice thickness

The calculations were performed in a computer system and served as a basis for a graphic chart [4]. Field strength shows an abrupt spike. This is an inductive effect, when a good conductor is covered with a dielectric. When conductivity of the top layer is better than that of the bottom one, there is a capacitative effect. This is a phase ratio between electric and magnetic components.

When the surface is multi-layered, it is characterized by the value of the argument of its surface impedance [5].

When
\[
\frac{\pi}{4} \langle \arg \hat{Z}_{s,layr} \rangle \leq \frac{\pi}{2}
\]  

we get a strongly inductive surface and the value of the attenuation function may be larger than one,
\[
0 \langle \arg \hat{Z}_{s,layr} \rangle \leq \frac{\pi}{4}
\]  

We get a weak inductive surface,
\[
-\frac{\pi}{4} \leq \arg \hat{Z}_{s,layr} \langle 0
\]  

Weak capacitative,
\[
-\frac{\pi}{2} \leq \arg \hat{Z}_{s,layr} \langle -\frac{\pi}{4}
\]  

Strong capacitative . A uniform surface may only we weak inductive, all the other cases are characteristic of various multi-layered mediums [6].

3 Conclusion
Peculiarity of radio wave behavior during propagation over thin layered ice is that at mutual phase ratios a part of field energy is “sticking” to the surface and propagates along it, thus creating a surface wave effect. At that, attenuation function value is above one, and the field value may increase with distance, even above design limits, breaking the proportionality law of reduction with distance.
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