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Effects of the topside ionosphere on radiowaves propagation from space objects

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The presence of artificial bodies in the outer space calls for a more accurate and strict treatment of problems concerning the radiocommunications with them. Irrespective of the numerous fragmentary studies (see for example our studies [1, 2, 3], as well as of their generalizations in monographs [4, 5, 6, 7]), the notions of the ionosphere used so far are inadequate and not precise enough. The formation of the International Reference Ionosphere (IRI) provided the background for global and precise specification of ionospheric parameters and of their impact on radiocommunications with satellites, rockets, orbital stations, interplanetary stations and other space platforms. Irrespective of a number of deviations from reality and the requirement for IRI perfection [8, 9], we have already got an analytical model for planetary calculations of radio networks and radio ways with space objects. This makes it possible to obtain more accurate analytical expressions and output data for the purposes of telemetry, telecontrol, information transfer and other communications with space aircraft. On the other hand, the reception of natural space radio signals, both for the purposes of radioastronomy and for ionospheric studies (e. g. for the absorption of space radio noise after A2 method), also requires good knowledge of the dependences between radiowaves parameters and those of the propagation medium. Finally, the reception of artificial radio signals from space objects for ionospheric studies (e. g. for Doppler's effect or for Faraday's fading) requires analytical expressions adequate to the real ionospheric effects.

Of all atmospheric parts, the topside ionosphere is the most difficult medium as far as analyses are concerned at least. For at $h > h_mF$ (where h_mF is the height of the maximum electron concentration N_mF or N_mF_2), there are no data available of the hundreds of ionospheric stations and other research equipment covering the Earth. Therefore, when space radio ways and networks are designed, and when research problems are solved, it is more common to use literature data for the topside ionosphere, while for other ionospheric areas the direct results of vertical ionospheric sounding can be applied. This requires even greater development, improvement and use of IRI references, which is also the subject of this work.

As a considerable part of the multifarious effects of the topside ionosphere on the parameters of radiowaves for space purposes propagating in it have been treated on IRI basis [19, 10, 11, 12, 13, 14, 15] and some other works, we are going to restrict our attention here to posing and solving the problems not treated so far with IRI data, and to giving initial and summary information about other published results.

In this work, similarly to [10, 11, 12, 13, 14, 15] and others, we have used IRI formulae in their first variant (IRI-75) for the sake of convenience of the analytical expressions, without committing ourselves, however, to the concrete IRI-75 data, which are to be improved.

The radiowaves passing through the outer ionosphere undergo deviation and retardation of the radio beam, absorption, refraction, frequency changes, polarization variations, attenuations, scintillations and other effects. We are going to present here in brief the effects untreated so far according to IRI-75, and for the studied ones we are going to make the corresponding references.

1. Radiowaves retardation in the ionosphere and virtual distance increase

The ionospheric impact on retardation refraction and on radio signals retardation is closely related to the accuracy of the satellite trajectory measurements and to other telecommunication problems which are discussed in [4, 5, 6, 7, 16], etc. The initial equation for the heightened distance increase Δl_i owing to the beam retardation in the topside ionospheric plasma is given by the expression (compare for example 17):

(1) $$\Delta l_i = -\gamma f^{-2} \int_{h_m}^{h_s} N_e(h)\,dl, \quad \text{(cf. [7])},$$

where: h_s is the satellite height or the distance to the magnetospheric boundary (if the space object is outside it or if we work with a radioastronomical source); $N_e(h)$ is the ionospheric profile of electron concentration; the linear element from the radiowaves trajectory dl is determined by the expression:

(2) $$dl = (a+h)\left[(a+h)^2 \cdot n^2 - a^2 \sin^2 Z_0 \cdot n_0^2\right]^{-1/2} dh,$$

where n is the coefficient of radiowave refraction, $a = 6370$ km is the Earth radius; Z_0 is the initial zenith angle of radiation. At $Z_0 < 85^0$, we can put in (2) $n \approx n_0 \approx 1$ [7]. In this case:

(3) $$dl = (a+h)\left[(a+h)^2 - a^2 \sin^2 Z_0\right]^{-1/2} dh.$$

The group retardation determines (with reading of the transfer coefficients: $\gamma = 40,4$, if the electron density is m^{-3}, and the frequency f in Hz) in this case the following extension of the way:

(4) $$\Delta l_i = \gamma f^{-2} \int_{h_m}^{h_s} N_e(h)\,(a+h)\left[(a+h)^2 - a^2 \sin^2 Z_0\right]^{-1/2} dh.$$

For the vertical profile $N_e(h)$ we use in the case of the outer ionosphere, according to IRI-75, the expression:

$$(5)\qquad N_e(h) = N_m F\left[\frac{A_1}{\left(1+\frac{h-h_m}{A_0}\right)A_2} + A_3 \exp\left(-A_4\frac{h-h_m}{A_0}\right)\right],$$

where A_1, A_2, A_3 and A_4 are constant, A_3 and A_4 are expressed by A_1 (so they are not independent), and constant A_2 has two values: $A_2 = 2$ (low solar activity) and $A_2 = 3$ (high solar activity). In accordance with this we will have the respective two cases in the following analysis:

1.1. Low solar activity ($A_2 = 2$)

We have for retardation:

$$(6)\qquad \Delta l_i = \gamma f^{-2}\int_{h_m}^{h_s}\frac{N_e(a+h)\,dh}{\sqrt{(a+h)^2 - a^2\sin^2 Z_0}} = \gamma f^{-2} N_m F(J_1 + J_2).$$

After replacing (5) in (6), and as a result of the corresponding processing and calculations, we obtain for J_1:

$$(7)\qquad J_1 = \frac{A_0^2 A_1}{\sqrt{b^2 - A^2}}\Bigg[\ln 2\,\frac{b^2 - A^2 + bx + \sqrt{(b^2 - A^2)(x^2 + 2bx + b^2 - A^2)}}{x}$$

$$+\frac{b\sqrt{x^2+2bx+b^2-A^2}}{x\sqrt{b^2-A^2}} - \frac{b}{b^2-A^2}\ln\frac{b^2 - a^2 + bx + \sqrt{x^2+2bx+b^2-A^2}}{x}\Bigg]_{x_s=h_s-h_m+A}^{x_m=A_i}$$

Using analytical replacements, we obtain for J_2:

$$(8)\qquad J_2 = A_3\int_{h_m}^{h_s}\frac{(a+h)\exp\left(-A_4\frac{h-h_m}{A_0}\right)dh}{\sqrt{(a+h)^2 - a^2\sin^2 Z_0}}.$$

To solve this integral, we develop the fast-falling exponential function in the numerator in range, we restrict ourselves to the 5th member of the range (which is quite sufficient), and for J_2 we finally obtain:

$$(9)\qquad J_2 = \frac{A_3A_4}{A_0}\sqrt{q}\Bigg(\frac{A_4^3}{24A_0^3}\Big\{q\Big[\frac{q}{5} + 2\left(g^2 + \frac{A^2}{3}\right) - gx^3 - g\left(2g^2 + \frac{3}{2}A^2\right)x$$

$$+(A^2+g^2)^2 + 4\Delta^2g^2\Big] - \frac{A_4^2}{6A_0^2}\Big[\frac{1}{4}x^3 + \left(\frac{3}{8}\Delta^2 - \frac{3g}{2}\right)x + 3g^2\Big] + \frac{A_4}{2A_0}\Big[\left(\frac{1}{3}x - d\right)x$$

$$+\frac{2}{3}A^2 + g^2\Big] - \frac{1}{2}x - g + \frac{A_0}{A_4} + \Big[\frac{gA^2}{\sqrt{g}}\cdot\frac{A_4^3}{24A_0^3}\left(\frac{3}{2}A^2 - 2g^2\right) - \frac{A_4^2}{6A_0^2}\cdot\frac{1}{\sqrt{g}}$$

$$\times\left(\frac{3}{8}A^2 - \frac{5}{2}A^2g - g^3\right) - \frac{A_4}{2A^0}\,gA^2 - \frac{A^2}{2}\Big]\cdot\ln(x+\sqrt{q})\Big\}\Bigg)_{x_m=a+h_m}^{x_s=a+h_s}.$$

In (7) and (9) we use the designations: $A = a\sin Z_0$, $b = a + h_m - A_0$ $g = a + h_m$; $q = x^2 - A^2$.

Obviously in (6) there is quite an adequate expression which can be used for making calculations in different cases.

1.2. High solar activity ($A_2 = 3$)

The retardation is also given by the expression (6). The calculations of J_1 are complicated because of the higher power in the denominator of the integral. In this case, for J_1 we finally obtain:

$$J_1 = \frac{A_0^3 A_1}{b^2 - A^2} \left[\left(\frac{1}{x} + \frac{b}{2x^2} - \frac{6b^2}{4x} \right) \sqrt{x^2 + 2bx + b^2 - A^2} \right. - \frac{-b}{\sqrt{b^2 - A^2}} \left(\frac{3b^2}{2(b^2 - A^2)} - \frac{1}{2} \right) \ln 2 \left. \times \frac{b^2 - A^2 + bx + \sqrt{(x^2 + 2bx + b^2 - A^2)(b^2 - A^2)}}{x} \right]_{x_s = a + h_s}^{x_m = a + h_m}. \tag{10}$$

For J_2, we have expression (9) in this case.

Therefore, at high solar activity we also have sufficiently accurate expressions for the electromagnetic package retardation and the virtual radiowave way extension. Conversely, from the expressions for Δl_i some ionospheric parameters can be found at known retardations and extensions. $N_m F$ is the easiest to determine. Possibilities exist for calculating $h_m F$ and A_0 and A_1 coefficients as well.

2. Refraction of radiowaves passing through the outer ionosphere

The refraction of radiowaves passing through the ionosphere is determined by the expression (compare [7, 17, 18], etc.):

$$\xi_i = -\gamma f^{-2} N_m F(a + h_D) \sin Z_0 \int_{h_D}^{h_s} n^{-1} \frac{dF(h)}{dh} [n^2(a + h)^2 - a^2 \sin^2 Z_0]^{-1/2} dh, \tag{11}$$

where h_D is the initial ionospheric height, and $dF(h)/dh$ is the electron concentration gradient. For the topside ionosphere in the case of the normally used operational frequencies f, which are considerably higher than the critical frequency $f_0 F (f_0 F_2)$, we can assume that $n \approx 1$ according to [6, 7, 17, 18] and other works. For the medium considered in this case, expression (11) is modified to:

$$\xi_i = -\gamma f^{-2} N_m F(a + h_m) \sin Z_0 \int_{h_m}^{h_s} \frac{dF(h)}{dh} [(a + h)^2 - a^2 \sin^2 Z_0]^{-1/2} dh. \tag{12}$$

In [7] we emphasize precisely the nonpermanent nature of the refraction part in the outer ionosphere, determined with (12). We should like to stress the fact that $dF(h)/dh < 0$ for the outer ionosphere, and for that reason ξ_i is positive for this medium. Thus, certain compensation is reached for the negative refraction in the ionospheric regions with $h \leq h_m$. We are further going to determine ξ_i using dF/dh distribution according to IRI-75 (see the expression for $N_e(h)$, shown here with formula (5)). Replacing dF/dh from (5) in (12), we obtain:

$$\xi_i = -\gamma f^{-2} N_m F(a + h_m) \sin Z_0 (J_1' + J_2'), \tag{13}$$

where

$$(14)\qquad J_1' = \int_{h_m}^{h_s} \frac{-A_1 A_2 dh}{A_0\left(1 + \frac{h - h_m}{A_0}\right)^{2A_2 - 1} \sqrt{(a + h)^2 - a^2 \sin^2 Z_0}};$$

$$(15)\qquad J_2' = -\frac{A_3 A_4}{A_0} \int_{h_m}^{h_s} \frac{\exp[-A_4(h - h_m)/A_0]\, dh}{\sqrt{(a+h)^2 - a^2 \sin^2 Z^0}}.$$

According to the two values of constant A_2, we have here two subcases as well: at low and at high solar activity.

2.1. Refraction at low solar activity $(A_2 = 2)$

$$(16)\qquad J_1' = \frac{2A_0^2 A_1}{b^2 - A^2}\left\{\left(-\frac{1}{2x^2} + \frac{3b}{2(b^2 - A^2)x}\right)\sqrt{(x + b)^2 - A^2} + \frac{3b^2}{(b^2 - A^2)} - \frac{1}{2\sqrt{b^2 - A^2}} \ln 2\, \frac{b^2 - A^2 + bx + \sqrt{(b^2 - A^2)[(x + b)^2 - A^2]}}{x}\right\}_{x_s = h_s - h_m + A_0}^{x_m = A_0}.$$

To find J_2', we develop the exponential subintegral function in the numerator in range, and with sufficient accuracy we restrict ourselves to the first five members. On this basis we finally obtain:

$$(17)\qquad J_2' = -\frac{A_3 A_4}{A_0}\,(J_{20}' + J_{21}' + J_{22}' + J_{23}' + J_{24}' + \cdots),$$

where:

$$(18)\qquad J_{20}' = \{\ln 2A_0[\sqrt{(A_0 x + h_m + a)^2 - A^2} + A_0 x + (h_m + A)]\}_0^{x_s' = \frac{h_s - h_m}{A_0}};$$

$$(19)\qquad J_{21}' = -\frac{A_4}{A_0}\{\sqrt{(A_0 x + h_m + a)^2 - A^2} - (h_m + A)\ln 2A_0 \times [\sqrt{(A_0 x + h_m + a)^2 - A^2} + A_0 x + (h_m + A)]\}_0^{x_s' = \frac{h_s - h_m}{A_0}};$$

$$(20)\qquad J_{22}' = \frac{A_4^2}{2A_0}\left\{\left(\frac{x}{2} - \frac{3}{2}\frac{h_m + A}{A_0}\right)\sqrt{(A_0 x + h_m + a)^2 - A^2} + \left[\frac{3}{2}(h_m + A)^2 - \frac{(h_m + a)^2 - A^2}{2}\right]\frac{1}{A_0}\ln 2A_0[\sqrt{A_0 x + h_m + a)^2 - A^2} + A_0 x + (h_m + A)]\right\}_0^{x_s'}.$$

$$(21)\qquad J_{23}' = -\frac{A_4^3}{6A_0}\left(\left[\frac{x^3}{3} - \frac{5}{6}\frac{(h_m + A)x}{A_0} + \frac{5}{2}\frac{(h_m + A)^2}{A_0^2} - \frac{2}{3}\frac{(h_m + a)^2 - A^2}{A_0^2}\right]\cdot \sqrt{(A_0 x + h_m + a)^2 - A^2} - \left\{\frac{5}{2}\frac{(h_m + A)^2}{A_0} - \frac{3}{2}\frac{[(h_m + a)^2 - A^2](h_m + A)}{A_0}\right\}\cdot \frac{\ln 2A_0}{A_0}[\sqrt{A_0 x + h_m + a)^2 - A^2} + A_0 x + (h_m + A)]\right)_0^{x_s' = \frac{h_s - h_m}{A_0}}.$$

$$(22)\quad J'_{24} = \frac{A_1}{96A_0^3}\Big(x^3\sqrt{(A_0x + h_m + a)^2 - A^2} - \frac{7(h_m + A)}{A_0}\Big\{\Big[\frac{x^2}{3} - \frac{5}{6}\,\frac{(h_m + A)x}{A_0}$$

$$+ \frac{5}{4}\,\frac{h_m + A}{A_0^3} - \frac{2}{3}\,\frac{(h_m + a)^2 - A^2}{A_0^2} + \frac{3}{8}\,\frac{(h_m + a)^2 - A^2}{A_0^2}\Big]\cdot[x - 3A_0(h_m + A)]$$

$$\times\sqrt{(A_0x + h_m + a)^2 - A^2} - 5\,\frac{(h_m + A)^3}{2A_0^3} - \frac{3}{2}\,\frac{[(h_m + a)^2 A^2]\,(h_m + A)}{A_0^3}$$

$$+ \frac{3}{2}\,(h_m + A)^2 - \frac{(h_m + a)^2 - A^2}{2A_0^2}\Big\}\cdot\frac{\ln 2A_0}{A_0}\,[\sqrt{(A_0x + h_m + a)^2 - A^2}$$

$$+ A_0x + (h_m + A)]\Big)_0^{x'_s}.$$

2.2. Refraction at high solar activity $(A_2 = 3)$

From (14) at $A_2 = 3$, we obtain:

$$(23)\qquad J''_1 = \Big[-\frac{1}{3}\,\frac{x^3}{\sqrt{x^2 + 2bx + b^2 - A^2}} - \frac{1}{3}\,(I''_1 + I''_2)\Big]_{x_m = A}^{x_s = h_s - h_m + A_0}.$$

$$(24)\quad I''_1 = \frac{1}{b^2 - A^2}\Big\{-\frac{1}{x} + \frac{b}{b^2 - A^2} + \frac{[12b^2 - 3(b^2 - A^2)]x}{4(b^2 - A^2)^2}\cdot\frac{1}{\sqrt{x^2 + 2bx + b^2 - A^2}}$$

$$+ \frac{3\,b}{\sqrt{b^2 - A^2}}\ln 2\,\frac{b^2 - A^2 + bx + \sqrt{(b^2 - A^2)(x^2 + 2bx + b^2 - A^2)}}{x}\Big\}_{x_m}^{x_s};$$

$$(25)\qquad I''_2 = \frac{b}{b^2 - A^2}\Big(\Big\{-\frac{1}{x^2} + \frac{5b}{x} - \frac{120b^4 - 62(b^2 - A^2)b + 12(b^2 - A^2)}{4(b^2 - A^2)^3}$$

$$- \frac{b[60\,b^2 - 52(b^2 - A^2)]x}{(b^2 - A^2)^4}\Big\}\frac{1}{2\sqrt{x^2 + 2bx + b^2 - A^2}} + \frac{15b^3 - 3(b^2 - A^2)}{2(b^2 - A^2)}$$

$$\times\frac{1}{\sqrt{b^2 - A^2}}\ln 2\,\frac{b^2 - A^2 + bx + \sqrt{(b^2 - A^2)(x^2 + 2bx + b^2 - A^2)}}{x}\Big)_{x_m = A}^{x_s = h_s - h_m + A_0}.$$

The second part J_2 is the same at low and high solar activity. Hence, the expressions (17, 18, 19, 20, 21, 22) will be used for J'_2.

The diurnal, seasonal and cyclic variations of refraction are determined by the corresponding variations of $N_mF(N_mF_2)$, the height h_m and the changes of A_0 and A_1. The additional irregular fluctuations of ξ_i depend on the heterogeneities in the electron concentration. We shall consider the effects of heterogeneities in more detail in another part of this work. We should stress, however, the fact that refraction is more strongly affected by these heterogeneities, because usually in their boundary regions there are strongly pronounced local *dF/dh* gradients. For that reason, the effects of heterogeneities on refraction should not be restricted merely to an analysis of differences in electron concentration $\Delta N_e = N_{\text{norm}} - N_{\text{inhom}}$ in the normal and heterogenous structure, but should be concentrated on the boundary region of dispersion or condensation of the plasma, where the gradient is very high.

The variations of dN_e/dh gradient in different cases, including these from IRI data, have been considered in [19]. It follows from this work that the height h_e of which *dF/dh* has a maximum, is very close to h_mF. Hence, the supramaximum region about h_mF has the most essential contribution to refraction. An area with rapid and nonoriented changes of dF/dh has been observed in the region of about $h \approx 600$ km according to rocket data from the VERTICAL series. This region additionally increases refraction.

3. Radiowaves absorption in the topside ionosphere

The radiowaves absorption in the topside ionosphere with $N_e(h)$ distribution according to IRI has been considered in our work [20]. In this work, complete and exact expressions are deduced for the nondeviating absorption at low and high solar activity over middle geographical latitudes. The limiting condition for middle latitudes is required because of the use of linear presentation of the temperature profile $T_e(h)$ with three straight lines in [20], which coincides with the latest IRI variants [21], and is close to the results obtained with the help of the heavy VERTICAL rockets [22, 23]. For the cases of low and high geographical latitudes, the data for ν_{e_i} according to IRI should be used published in [24, 25], and the corresponding data for $N_e(h)$ from IRI.

4. Radiowaves polarization in the topside ionosphere

The polarization losses of radiowaves in the topside ionosphere according to IRI have been presented with the corresponding analytical expressions in [26]. They can be used to calculate the polarization of radiowaves and its equivalent absorption. In [27] a method is shown for IRI adaptation to the concrete data from measurements with a ionospheric satellite and for calculation of polarization losses from the corrected $N_e(h)$ profile. The application of the method to the data from the IC-BULGARIA-1300 satellite has also been demonstrated [27].

5. Topside ionosphere impact on the frequency of radiowaves passing through

The studies of these effects on the basis of the vertical profile $N_e(h)$ according to IRI and present-day data of spatial changes of the Earth's magnetic field, of electron production, the effective neutralization coefficient β_{eff} and the motions in the ionosphere, have been made in [29]. The standard variations of frequency deviations at temporary diurnal, seasonal and cyclic changes of $N_e(h)$ and the other values determining the frequency have also been studied in the same work.

6. Fluctuations of the radio signals phase during the transition through the topside ionosphere

So far there are no generally accepted references of the heterogenous structure of the ionosphere in IRI. For that reason, in [29] on the basis of some materials presented at the COSPAR PANEL and URSI about IRI, and proceeding from the information obtained from INTERCOSMOS-2, 8, 12, 14, 19 and IC-BULGARIA-1300 satellites, some averaged data have been obtained about the fluctuations of different radio signals during their transition in the topside ionosphere.

7. Conclusions and inferences

The expressions obtained here for refraction, retardation and virtual extension of radiowaves way from and to space objects directly solve the problem of the respective effects of the topside ionosphere on radiowaves propagation, a problem not sufficiently tackled so far. Thus a basis is created for an adequate use of IRI in present-day calculations of radio ways and networks. There is a possibility to use the formulae obtained so far for calculating the reverse problem of finding some ionospheric parameters with respectively measured refractions or radiowaves retardations.

We generalized the information about the topside ionosphere impact according to IRI on the propagation of radiowaves passing through (absorption, polarization, frequency deviations, phase fluctuations, etc.) by pointing out the respective sources. Thus, a basis of background data is created for complete use of IRI in studies of radiowaves transition through the topside ionosphere.

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Воздействия внешней ионосферы на распространение радиоволн из космических объектов

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(Резюме)

Проанализированы основные воздействия внешней ионосферы на проходящие через нее радиоволны. На основе Международной референтной ионосферы получены выражения для: а) запаздывания радиоволн и виртуального увеличения расстояния их распространения; б) рефракции радиоволн; в) поглощения; г) флюктуации фаз радиосигналов при переходе через внешнюю ионосферу. Сделан анализ условий нижней и высокой солнечной активности. Даются рациональные рекомендации и подводятся исходные зависимости. Даются рациональные рекомендации для определения основных параметров радиосвязи с космическими объектами.