DEFINITION OF RADIO REFRACTION FROM THE RESULTS OF RADIOMETRIC ATMOSPHERE SENSING

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ABSTRACT: *Rms errors have been investigated for definition of refraction R and electric path length L of radio waves from the retrieval values of meteorological elements derived from measurements of the atmospheric radiation from the Earth's surface in resonance regions O_2 (the band λ 5 mm), H_2O (rotational lines λ 1.35 cm and λ 1.64 mm) and using regression relations between values R , L and brightness temperatures of the atmosphere in optimal intervals of the spectrum. It is shown that in cloudless weather the refraction characteristics are found with a high accuracy from the results of one-channel sensing of the atmosphere. The effect of errors is discussed of radiometrical measurements of the atmosphere radiation on the definition accuracy of refraction Characteristics in cloudy weather.*

1. INTRODUCTION

Making prognoses of the astronomical radio wave refraction with a sufficient degree of accuracy is a problem arising from the beginning of refraction investigations in the radio range. Studies in this field are' carried put in different scientific directions. Here we present results connected with the refraction definition from the data of the remote sensing of the atmosphere from the Earth's surface. The need for the additional measurements in definition of the refraction R is associated with the fact, that the model methods of the prognosis of R do not provide the required accuracy in the whole range oi elevation angles (Naumov, et al, 1986)-The use of the remote sensing data for the. definition of the atmospheric refraction is possible in its turn in two different directions:

a) Meteorological elements of the atmosphere - temperature T , pressure P humidity q (Kitaj, at al. 1979; Gaikovich et al. 1983) are retrieved from the remote sensing of the atmospheric radiation in resonance regions of O_2 and H_2O, which then aroused for the definition of the vertical dependence of the refractive index N (h) and the refraction;

b) By the direct regression relations between the refraction and the brightness atmosphere temperatures T_B in some definite parts the brightness atmosphere temperatures T_B in some definite parts of the spectra (Gallop, Telford, 1973; 1975;Gaikovich 1980, 1983).

For radiointerferometric problems of interest is the electric path length of radio waves (EPLRW) in' the atmosphere, also being associated with the refraction of radio waves $L={}_0\int^H[n(l)-1]dl$. In the formula, n is the atmosphere refraction coefficient The paper considers possibilities of radiometric definition of the astrometric refraction R and the value of EPLRW -L.

2. THE ACCURACY OF DEFINITION OF REFRACTION AND EPLRW E^9M THE RETRIEVED METEOROLOGICAL ELEMENTS

Retrieval of meteorological elements is made from the results of spectral or angle measurements of the natural (thermal) radio emission of the atmosphere in resonance regions of the molecular oxygen (the band of spin—rotational spectrum 0_2 is located close to the wavelength λ =5mm) and water vapor (rotational line H_2O: λ= L35 cm and λ= 1.64mm). The relative content of toe molecular oxygen is rather stable in toe atmosphere ($f_0 \approx 21\%$) and the radio emission in O_2 band is defined mainly by the height temperature distribution. Radio emission in the atmosphere in O_2 lines is defined essentially by toe water vapor content Radio emission of atmospheric gases in resonance regions is formed at different heights. Thus, measurements of toe atmospheric radiation at a number of frequencies or at a fixed frequency in different elevation angles in O_2 and H_2O lines give information on toe temperature height profiles T an-d specific humidity q which together with the atmospheric pressure define values of toe refraction coefficients and refraction characteristics.

Inverse problems are solved at toe retrieval of meteorological elements from toe-results of remote atmosphere sensing. The initial equation of toe inverse problem of toe remote atmosphere sensing from toe ground has toe form (Markina, et al 1985):

$$\delta T_B = \int_0^{\infty} \left\{ \delta T(l)\, \bar{\gamma}(l) + \delta\gamma(l)\, [T(l) - T_B(l)] \right\} \exp\left(-\int_0^{l} \bar{\gamma}(l')dl'\right) dl. \tag{1}$$

When solving (1) we use the method of statistical regularization (Malkevich, 1973). The solution of eq. (1) has the form

$$\delta X^r = [K^* W K + (B_{xx}^{ext.})^{-1}]^{-1} K^* W \delta T_B. \tag{2}$$

In (1), (2) T_B is the atmospheric brightness temperature, γ is the absorption coefficient, δ characterizes variations of values ($5T_B = T_B - \bar{T}_B$); X= T or X= q; K is the matrix, corresponding to toe kernel of the integral equation, W is the matrix of measurement errors, B_{xx}^{ext}- is the modified covariance matrix; the asterisk represents toe matrix transposition, a dash on the top is the averaging symbol. From the retrieval values of temperature $T^r(h)$, specific humidity $q^r(h)$ and ground pressure p_Q the pressure height profile is retrieved

$$p^r(h) = P_O \exp\left[-10^5 g(h - h_O)/R_c T_{\sigma m}\right]. \tag{3}$$

In (3) $T_{\sigma m}$ is the mean virtual temperature, the free fall acceleration g is expressed in cm/s^2, the heights h, h_Q – in km, R_c is the gas constant of dry air.

Rms errors of the temperature retrieval σ_T^r at heights h = 0.5-6 km with the state of art measurement accuracies of values T_B amount ~ 0.3 — 1.8 degrees in summer and ~ 1 - 2,5 deg. in winter (Gaikovich, et al. 1983). Rms errors of the pressure definition amount to (σ_P^r =* 0.3 - l.8mbar. The corresponding relative errors of the specific humidity (σ_q^r /<q>) retrieval are equal to ~4% in lower layers of the atmosphere and increase up to ~30% at the height h ≈ 5 km. The given errors of meteorological element retrieval lead to rms errors of the refractive atmosphere index N = (n - 1)10^6 definition in the radio range ~2 — 1.5 units N at the same heights. The accuracy of meteorological emement retrieval is improved if we use combined (from the Earth's surface and from satellite) measurements of the atmospheric radiation, or introduce and additional information in the inverse problem solution - for example, on the tropopause height which is detected by the active location (Westwater et al., 1983; 1984). In this paper we estimate the definition accuracy of refraction and EPLRW from the data of only ground-based remote sensing of the atmosphere. Here, to calculate the refraction and EPLRW, the results of the refraction index profile $N^r(h)$ retrieval from the retrieved values of meteorological elements in the atmospheric layer from h_Q up to 6 km are supplemented by profiles N^{ext} (h) statistically extrapolated over height, being constructed with respect to the correlation dependences N in lower layers with the values N at heights h>6km (Naumov et al. 1985).

Table 1: Mean seasonal values of the astronomical refraction <R>, rms errors for the refraction definition from statistically extrapolated profiles of the refractive index σ_R^{ext} and from the retrieval value of meteorological elements (σ_R^r) in summer in the central part of the European territory of the USSR.

θ	<R>	σ_R^{ext}	σ_R^r
85°	11′10"	2.6"	2.6"
87°	16′30"	11"	7"
89°	28′43"	27"	14"

Rms errors of R and L definition according to the above method for zenith angles θ = 85°- 89° in summer, when humidity contribution in the refractive index N is the largest, are given in Tables 1,3 (values (σ_R^r and σ_L^r).

3. ACCURACIES OF REFRACTION AND EPLRW DEFINITION BY THE REGRESSION METHODICS

The regression method of refraction and EPLRW definition by remote sensing is given in papers by Gallop et al.(1973, 1975), Shaper ct al.(1970), Wu (1979), Gaikovich et al. (1980, 1983). The initial relation for the refraction calculation over this method has the form:

$$R(\theta) = A + B N_0 + \sum_i C_i(\theta, \theta', \lambda) T_{Bi}(\theta', \lambda) \tag{4}$$

In (4) A, B, C_j are the regression coefficients, θ is the zenith angle where the refraction is defined, θ′ is the zenith angle of the remote atmosphere sensing. At small zenith angles ($\theta<70^0$) the coefficients C_j are small and the refraction is defined by the ground values N_0 (fulfillment of the „Laplace theorem" in the radio range). The contribution of the sum $\sum C_j T_{Bj}$ into the refraction value increases with the increase of zenith angles θ. When the remote sensing of the atmosphere is made in the same direction as the refraction is defined *(*θ = θ′*)* the horizontal inhomogeneities of the atmosphere are taken into account in a better way. Table 2 presents rms errors σ_R^{regr} for the refraction definition at angles θ = 80°- 89°, obtained by formula (4) in the numerical statistical experiment for two cases of one-frequency (i = 1) remote sensing of the atmosphere: a) sensing is performed at the slope of H_20 λ = 1.35 cm (frequency *v*= 21.5GHz) at the fixed zenith angle θ′ = 0; b) sensing is made at the frequency *v* = 10GHz at θ' = θ. In both cases it is considered that the error of radiometric measurements T_B ~ 1 K.

Table 2. A comparison of rms errors of the refraction definUion from statistically extrapolated profiles of the refractive index (O^.⁴) anil from remote sensing data (0^8Г-) in summer in the central pan of th4r Luropcan territory of the USSR, •

θ	σ_R^{extr}	σ_R^{regr}	
		a	b
80°	1"	0.6"	0.16"
85°	2.6"	1.3"	0.31" '
87°	IP	4.5" .	2"
89°	27"	15"	10"

The regression relation for EPLRW value deviation from the mean values (L' = L - L) has the form

$$L'(\theta) - 0.227(P_0 - \overline{P}_0) = \sum_j b_j T'_{Bj} \tag{5}$$

Very often, relations (4), (5) are written in the generalized vector from

$$Z' = D^* T_B'. \qquad (6)$$

In (6) D = [$D_1 \ldots D_m$]- is the m-dimensional vector of regression coefficients.
Here it is considered that the generalized vector T_B includes also deviations of ground meteorological elements.

Optimal frequencies of remote sensing of the atmosphere for EPLRW definition are found by minimization of rms errors for detection of L at different parameters of sensing. It turns out that in the case of one-frequency (j = 1) sensing, the optimal value ν decreases with the increase of θ and for $\theta \approx 80^0$ it is in the interval 10-19GHz. Rms error (σ_L^{regr}) for L definition at angles θ = 60-89° over the regression method (at optimal frequencies of the remote sensing for each angle) are given in Table 3.

Table 3: Rms errors for EPLRW definition from statistically extrapolated profiles of the refraction index (σ_L^{ext}) from retrieval values of meteorological elements (σ_L^{r}) and over the regression method (σ_L^{regr}) in summer in the central part of the European territory of the USSR.

θ	σ_L^{ext}	σ_L^{r}	σ_L^{regr}
60°	4.5	1.0	0.9
80°'	12.2	3.8	3
85°	22.8	6.1	5
89°	48.5	12.0	9

4. EFFECT OF CLOUDS

All the above results have been obtained for cloudless atmosphere. EPLRW and refraction values are practically unchanged with cloud occurrence, while values of (lie atmosphere brightness temperature in centimeter and millimeter wave ranges are rather sensitive to the presence of water—drop clouds. Thus, for cloudy atmosphere relation (6) has the form

$$Z' = D^* \tilde{T}_B', \qquad (7)$$

where - $\tilde{T}_B' = T_B' - \Delta T_B$, T'_B is the measured value, and ΔT_B is a correction for the cloudiness of the atmosphere. Numerical values of the brightness atmosphere temperature increment due to cloud occurrence in the frequency range l0-120GHz for different water content and temperature of clouds are given in the paper by Mitnik (1974).

At operating frequencies $\Delta T_B = \overline{\psi}$ M where $\overline{\psi}$ is the mean weight function, and M is the integral liquid water content of a cloud. Values of M are measured by additional channels of sensing - for example, at the wavelength λ = 8 mm (Basharinov et al. 1974).

Values $\overline{\psi}$ are calculated from the mean regional models of иге atmosphere. With the typical errors of the radiometric definition of the liquid water content of clouds ~0.05-Q1 kg/m^2, errors of refraction atmosphere characteristics according to (7) amount ~0.65- 1.9cm for L(θ = 0°), ~ 2-9cm for L (θ = 80°) and ~ 19"~'23" for R (θ = 89°). The above indefiniteness of the refraction and EPLRW are smaller than rms error σ_R^{ext} and σ_L^{ext} (see Tables 1,3).

5. CONCLUSION

The given results characterize a rather high efficiency of refraction and EPLRW definition by remote sensing of the atmosphere radiation in definite (optimal) intervals of the spectrum. Regression methods are preferable when defining these values through all the depth of the atmosphere. The retrieval values of meteorological elements are helpful for definition of refraction, and EPLRW at distances comparable with the range of meteorological element correlation.

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