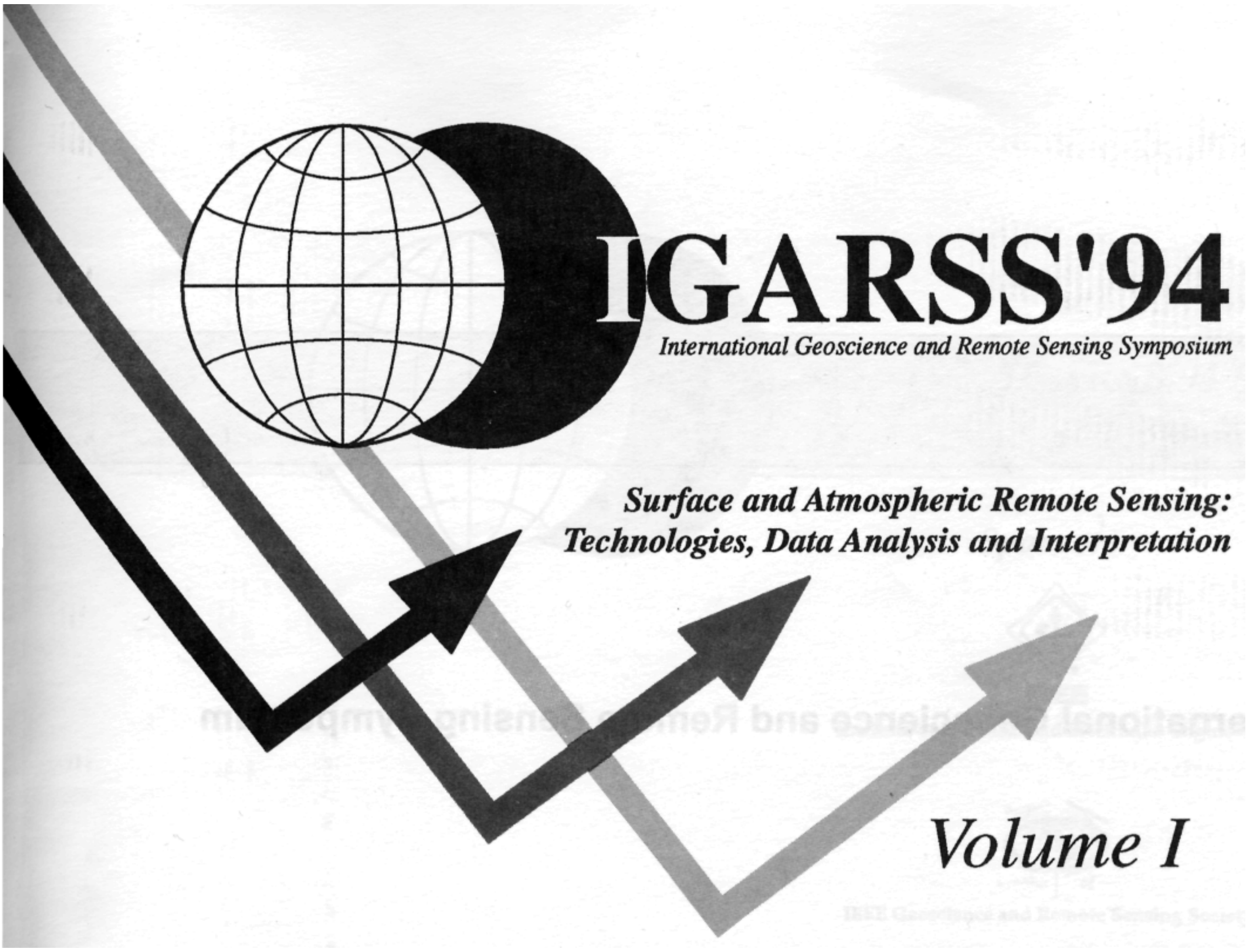

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Solution of Atmosphere Refraction and Radiometry Inverse Problems Determination of the Path Delay

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Abstract

The present work considers inverse problems of atmosphere remote sensing by measurements of refraction and thermal radio emission. Among the various problems it is possible to note two: the problem of the refraction index height profile retrieval by ground-based measurements of the radio refraction at positive elevation angles and the problem of the atmosphere temperature profile retrieval by satellite measurements of the brightness temperatures In the oxygen spectral lines centered at 60 *GHz* . Both problems consist In the solution of the integral Fredholm equation of the 1-st kind.

Statistical and nonstatistical (Tikhonov's) methods are used to solve refraction inverse problem. The retrieved profile is used to determine the path delay of radio waves in the atmosphere. Only statistical methods have been used elsewhere to solve the corresponding incorrect integral Fredholm equation of the 1-st kind. They are inconsistent in the regions outside meteorological network as well as in a height interval above sounding level (ordinary about 30 - 35 km).

The nonstatistical method based on the Tikhonov's theory has been worked out to solve the problem.

GROUND-BASED REFRACTION INVERSE PROBLEM

At present, of great interest are possibilities of the remote sensing of the atmosphere parameters from refraction measurements. The inverse problems for the limb viewing space and intra-atmospheric measurements are well studied and have been applied by remote sensing of Earth and other planets atmosphere. In those cases the inverse problem reduces to inverse Abel's transformation. The present paper considers a more difficult problem of the refraction index height profile retrieval from ground-based measurements of the radio refraction at positive elevation angles θ_0. The retrieved profile can be used then to determine the various propagation parameters, in particular, path delay of the radio waves in the atmosphere.

Refraction measurements problem

It is well known that for precision refraction measurements large antenna sizes are necessary. Another measurement possibility is based on Doppler shift measurements of space sources, such as navigation satellite "Transit". In that case the relation between Doppler frequency ν_D and atmosphere parameters has a form :

$$\nu_D = \frac{\nu}{c r_H}\left(p_0 \cos(\theta_0) V_\perp + \sqrt{r_H^2 - p_0^2 \cos^2(\theta_0)}\, V_R\right), \quad p_0 = n_0 r_0 \ , \qquad (1)$$

where $r_H = r_0 + H$, r_0 - Earth radius, H - source high, $V_\perp$, V_R- velocity components relative to the ray direction, ν - signal frequency, θ_0 -elevation angle, n = $n_0(r_0)$ - ground value.

It is clear from (1), that one can derive the ground elevation angle θ_0 from Doppler frequency ν_D measurements and position-velocity components of source. Then, it is possible to determine refraction angle of equivalent infinitely remote along ray path source by coordinates of real source (α - central angle and r_H):

$$\varepsilon(\theta_0) = \alpha - \arccos\left(\frac{p_0 \cos(\theta_0)}{r_H}\right) + \theta_0 \ , \qquad (2)$$

which satisfies the equation

$$\varepsilon(\theta_0) = -p_0 \int_{r_0}^{\infty} \frac{d(\ln(n))}{dr} \frac{dr}{\sqrt{(nr)^2 - p_\theta^2}} \ , \qquad (3)$$

$$p_0 = n_0 r_0 \ , \quad p_\theta = p_0 \cos(\theta_0) \ ,$$

or, integrating Eq.(3) by parts one has

$$\int_{p_0}^{\infty} N(p) \frac{p p_\theta}{(p^2 - p_\theta^2)^{3/2}} dp = \tilde{\varepsilon}(p_\theta) \ , \qquad (4)$$

$$\tilde{\varepsilon} = -10^6 \varepsilon + N(p_0)\cos(\theta_0), \ p = nr,$$

where $N = 10^6(n-1)$. The Eq.(4) is integral Fredholm equation of the 1-st kind relative to the refraction index N(p) dependence, which can be transformed in height profile N(h) from

$$h = \frac{p}{1 + 10^{-6} N(p)} - r_0 \qquad (5)$$

Solution methods of inverse problem

It is well known, that without an essential a priori information the solution of Eq.(3) is, generally, unresolved, problem This information is provided by the specifics of concrete inverse problem. To solve the problem considered it is possible to use the information that N(p) belongs to functions from L_2 or W_2^1 - space (Tikhonov A.W.,1983), or the information on interlevel covariance relations (matrix B_{NN}). The Tikhonov's regularization method was used in the form of generalized mismatch principle (for more detail see Gaikovich,1994).

In the statistical regularization method the solution of the problem has the form of statistical estimation on ensemble with the covariance matrix B_{NN} according maximum entropy principle:

$$N = \langle N\rangle + (A^{*}W^{-1}A + B_{NN}^{-1})\,A^{*}W^{-1}(\varepsilon - \langle\varepsilon\rangle), \qquad (6)$$

where W - covariance matrix of measurement errors.

The only way to estimate retrieval errors in the incorrect problems is the numerical simulation on the properly chosen class of possible distributions or on statistical basis.

Statistical results of N(h) retrieval

In the fig.1 one can see the height dependence of retrieval errors for statistical regularization method for ocean conditions (the errors in continental conditions are lese). Tho refraction values at $\theta_0 < 5^0$ were used because the refraction at higher angles depends only on surface value N_o but not on the profile ("Laplace theorem"). The measurements contain the information on profile N(h) only if accuracy is $\delta\varepsilon < 30$ sec, which value is close to the refraction variations at $\theta_0 < 5°$. The retrieval accuracy is not sensitive to the refraction measurements number in the angle interval. It in enough to use 5 - 10 measurements at $\theta_0 < 5°$. The results for Tikhonov's method were almost the same.

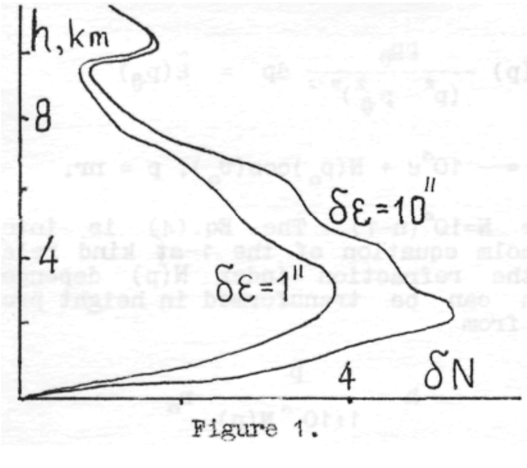

Figure 1.

Path delay determination

The retrieved profiles can be used to determine some integral wave propagation parameters in the atmosphere. One of the most important parameter *is* path delay of the signal in the atmosphere:

$$L = \int_{r_o}^{\infty} (n-1)dr/(1-(n_o r_o/nr \cos\theta_o)^2)^{1/2} \quad .(7)$$

In the fig.2 the accuracy of determination of L using retrieved profiles N(h) in correspondence with fig.1 is shown. One can see real possibilities of the radio refractometry in path delay monitoring.

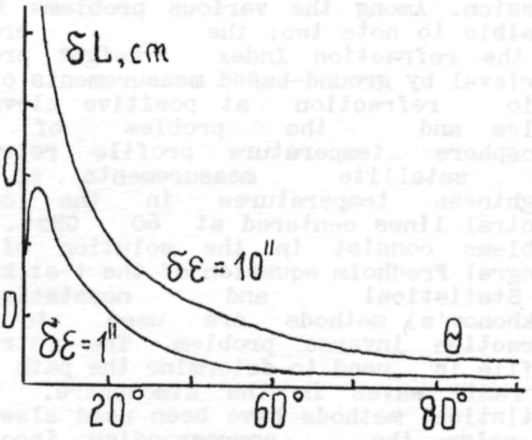

Figure 2.

The accuracy of refraction depends on accuracy of Doppler frequency measurements. For the system "Transit" (ν = 400 MHz. H = 1000 km) $\delta\varepsilon$(sec) = 10^3 $\delta\nu$(Hz).

ATMOSPHERE RADIOTHERMOMETRY PROM SPACE

Problem formulation

The inverse problem of the temperature sounding by measurements of thermal radio emission in O_2 spectral lines centered nearly 60 GHz have been solved both for space-borne and ground-based radiometer measurements. First, only statistical methods were applied to solve the inverse problem (Westwater E.R.,1984, Askne J.,1985, Gaikovich K.P.,1983, Falcone J. ,1983). But the atmosphere is known as nonstationary medium, where the mean values of parameters do not exist. It is especially important for the problem of the boundary layer sounding. Because of that reason nonstatistical method of the solution of boundary layer inverse problem based on the Tikhonov's theory has been worked out (Troitsky A.V., 1983). Another restrictions of statistical methods are related with their dependence on date base. They are inconsistent in the regions outside meteorological network as well as in a height interval above sounding level (ordinary about 30 - 35 km). The nonstatistical method based on the Tikhonov's theory has been worked out to solve the problem for space borne measurements.

The brightness temperature T_B satisfies

$$T_B(\theta_0,\nu) = \int_l T(l)\ \gamma(l)\ e^{-\int_l \gamma(l')dl'}\ dl\ . \qquad (8)$$

where l ray path, ν - frequency, γ - absorption coefficient. In proposed method (10) must be expressed as

$$T_B(h_0) = \int_0^\infty T(h)\ K(h_0,h)\ dh\ , \qquad (9)$$

where h_0 satisfies

$$\frac{1}{\sin(\theta)} \int_{h_0}^\infty \gamma(h)\ dh = 1\ . \qquad (10)$$

Values of ν and θ must be chosen so that parameter h_0 was uniformly distributed in as wide as possible height range. Such approach permits to make the optimal combination of radiometer channels and for the solution of integral Fredholm equation (11) the Tikhonov's method has been applied.

The numerical simulation shows that by using the measurements in no more than 10 channels at properly chosen frequencies (5 frequencies near the resonance 55.7841 GHz in 5 - 200 MHz range of frequency shifts and other - in the lines slopes at frequencies ν > 52 GHz) it appears possible to retrieve the temperature profile in the height interval 4 -15 km with about the same accuracy as by using statistical methods (in the common height interval). In the fig.3 one can see an example of retrieved temperature profile at simulated measurement error δT_B = 0.5 K. The mean accuracy of retrieval is 1.5 K. It should be mentioned, that it is possible to retrieve the profile at higher altitudes using frequencies shifts lees then 5 MHz, but it needs to take into account the Earth magnetic field Influence.

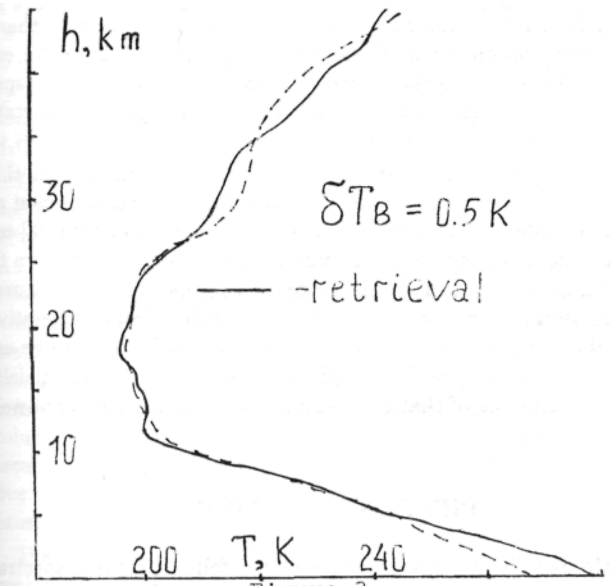

Figure 3

REFERENCES

Tikhonov A.N., Gonoharskii A.V., Stepanov V.Y. Yagola A.G. Regularizing algorithms and a *priori* information. Moscow, Nauka, 1983, 200 p.

Gaikovich K.P. "Tikhonov's Method of the Ground-Based Radiometric Retrieval of the Ozone Profile," in International Geoscience and Remote Sensing Symposium Digest, 1994.

Westwater E.R., Sweezy W.B., McMillin L.M., Dean C. " Determination of Atmospheric Temperature Profiles from a Statistical Combination of Ground-Based Profiler and Operational NOAA 6/7 Satellite Retrievals." J. Climate and Applied Meteorology, 23, 5(1984): 689-703.

Gaikovich K.P., Markina N.N, Naumov A.P., Plechkov V.M., Sumin M.I. "Investigation of Remote Sensing Possibilities of the Lower Atmosphere in the Microwave Range and Some Aspects of Statistical Data Use."Int.J.RemoteSensing,4,2(1983):4 19-431.

Falcone V.J., Abreu L.W. "Analysis of the DMSP Microwave Temperature Sounder Data," in International Geoscience and Remote Sensing Symposium Digest, 1983, pp.5.1-5.3.

Troitsky A.V., Gaikovich K.P., Gromov V.D., Kadygrov E.N., Kosov A.Б. "Thermal Sounding of the Atmosphere Boundary Layer in the Oxygen Band Center at 60 GHz," IEEE Trans.Geoski.Remote Sensing, 31, 1(1993): 116-120.

Askne J., Skoog G., Winberg E. " Test of Ground- Based Microwave Radiometer For Atmospheric Temperature Profiling with Meteorological Applications." Int.J.Remote Sensing, 6, 7 (1985) :1241-1256.