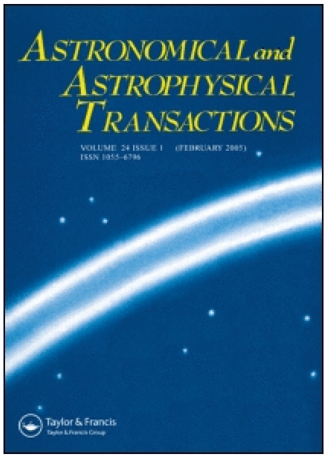

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A. Stotskii [a]; K. G. Elgered [b]; I. M. Stotskaya [a]
[a] Institute of Applied Astronomy, Russian Academy of Sciences, St.-Petersburg, Russia
[b] Onsala Space Observatory, Chalmers University of Technology, Onsala, Sweden

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STRUCTURE ANALYSIS OF PATH DELAY VARIATIONS IN THE NEUTRAL ATMOSPHERE

A. A. STOTSKII[1], K. G. ELGERED[2], and I. M. STOTSKAYA[1]

[1] *Institute of Applied Astronomy, Russian Academy of Sciences, 197042,
St.-Petersburg, Russia*
[2] *Onsala Space Observatory, Chalmers University of Technology S-43992 Onsala,
Sweden*

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An analysis of the temporal zenith path delay variations in the Earth's neutral atmosphere is presented for three sites with different climates. Using the radiosonde data the temporal structure functions for total path delay and separately for its hydrostatic and the wet components are calculated. The relation and the cross-correlation between the hydrostatic and the wet components are presented. An estimation of spatial structure function at the saturation level is given.

KEY WORDS Path delay, troposphere, structure functions, radio interferometry, VLBI

1 INTRODUCTION

The path delay variations arising when radio waves pass through the Earth's neutral atmosphere are important for many applications such as space geodesy using radio interferometry and satellite positioning systems, radar altimetry from satellites, and radio astronomy.

As a universal characteristic of the Earth's neutral atmosphere related to path delay variations it is convenient to use variations of path delay in the zenith direction. Structure functions are used to describe the statistical properties of these variations (Tatarskii, 1964) – temporal:

$$D_L(\tau) = \langle [L(t+\tau) - L(t)]^2 \rangle, \tag{1}$$

and spatial:

$$D_L(\rho) = \langle [L(\mathbf{r}+\rho) - L(\mathbf{r})^2 \rangle, \tag{2}$$

where L is the path length, t is the time, τ is the time interval between observations, $\mathbf{r}$ denotes the position coordinates of the points of observations, and ρ is the spatial separation between the points of observations. The angle brackets denote time or ensemble average.

Temporal and spatial structure functions may be connected by using the principle of frozen flow turbulence:

$$D_L(\tau) = D_L(\rho/v), \tag{3}$$

or

$$D_L(\rho) = D_L(t\,v), \tag{4}$$

where v is the average velocity of irregularity motions. The analysis of wind velocity height distribution and special measurements (Stotskii and Stotskaya, 1992) give the estimation $v \cong 10$ m/s. This value is consistent with the typical velocity of the air motions measured in synoptic processes.

When ρ and the corresponding value $t = \rho/v$ are small (ρ much less than the thickness of the troposphere layer) the statistical theory of three-dimensional isotropic turbulence can be used (Tatarskii, 1964). This gives the power law of 5/3 for path delay structure functions. If ρ exceeds the thickness of the troposphere two-dimensional turbulence must be taken into consideration. The power law of 2/3 is then obtained for the structure functions (Stotskii, 1972; Stotskii, 1992; Treuhaft and Lanyi, 1992). The border between these two domains of structure functions – the outer scale of three-dimensional turbulence for total zenith path delay in Earth's neutral atmosphere – was empirically estimated as 3.7 min for a temporal structure function and 2.2 km for spatial one (Stotskii, 1992).

For the very large spatial scales and time intervals exceeding the outer scale of troposphere turbulence ($r > 2400$ km and $t > 2.8$ days according to Stotskii (1992)) the saturation in structure functions of random path delay variations takes place.

The experimental parameters of the temporal structure function for short time intervals were obtained by Stotskii and Stotskaya (1992), where the power law of 5/3 was confirmed. Here we present the results of measurements of path delay variations for large time intervals, 12 hours and longer, and the analysis of the corresponding characteristics.

2 DATABASE

We analysed the time variations of the path delay in the zenith direction for three distant sites with different climates: Fairbanks (USA, Alaska), Landvetter (Sweden, near Goteborg) and West Palm Beach (USA, Florida). The coordinates of these sites are shown in Table 1.

The total path delay ΔL is considered to be the sum of hydrostatic ΔL_h and wet ΔL_w, components (Elgered, 1993):

$$\Delta L = \Delta L_h + \Delta L_w. \tag{5}$$

Table 1. Coordinates of the sites of observations

Site of observations	*Latitude (deg, N)*	*Longitude (deg, W)*	*Altitude (m)*
Fairbanks	65.5	147.4	135
Landvetter	57.4	347.8	155
West Palm Beach	26.4	80.0	7

The hydrostatic delay ΔL_h (cm) was obtained from the ground pressure P_0 (mbar). To simplify the calculations we used the approximate formula:

$$\Delta L_h = 0.2277 P_0, \tag{6}$$

that is we ignored the slight dependence on the latitude and the altitude of the site (Saastomoinen, 1972). This gives an error less than 0.2% in the absolute scale which can be ignored while we study the variations only.

The total pressure can be seen as the sum of the pressure of dry air and water vapour:

$$P_0 = P_d + P_w, \tag{7}$$

but as $P_w \ll P_d$ the hydrostatic component is often referred to as the dry component of the path delay.

The wet delay was calculated in the zenith direction using meteorological profiles obtained from radiosonde launches.

$$\Delta L_w = 1720 \int\limits_Z \frac{\rho_w(Z)}{T(Z)} dz, \tag{8}$$

where ΔL_w is the wet delay (cm), $\rho_w(z)$ is the mass density of water vapour (g/m^3), $T(z)$ is the temperature (K) and z is the altitude (m).

The measurements were performed during three years twice daily at noon and midnight universal time (UT) implying true solar times about 7 A.M. and P.M. in Florida, 1 A.M. and P.M. in Sweden, and 2 A.M.; and P.M. in Alaska. Thus the whole data set contains 19710 values of wet, hydrostatic and total delays for three sites.

The variations of the wet, the hydrostatic, and the total path delays for these three sites arc shown in Figure 1.

3 TEMPORAL STRUCTURE FUNCTIONS

The temporal structure functions are calculated separately for the hydrostatic and the wet components as well as for the total path delay and are shown in Figure 2.

One can see that for time intervals less than one year all the structure functions are monotonic functions, which means that the path delay variations are random.

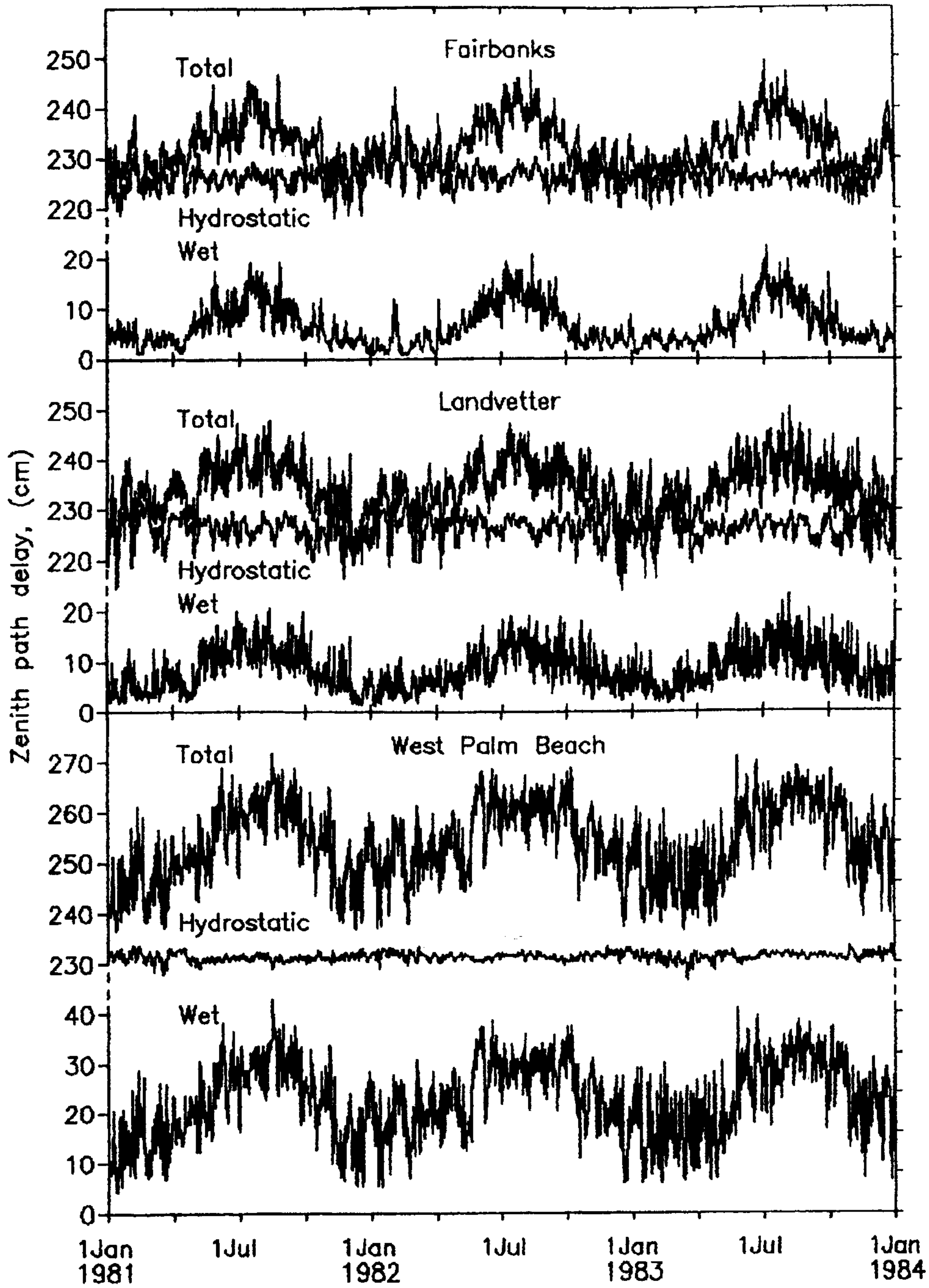

Figure 1 The variations of the wet, hydrostatic, and total path delays in the zenith direction at Fairbanks, Landvetter and West Palm Beach during three years.

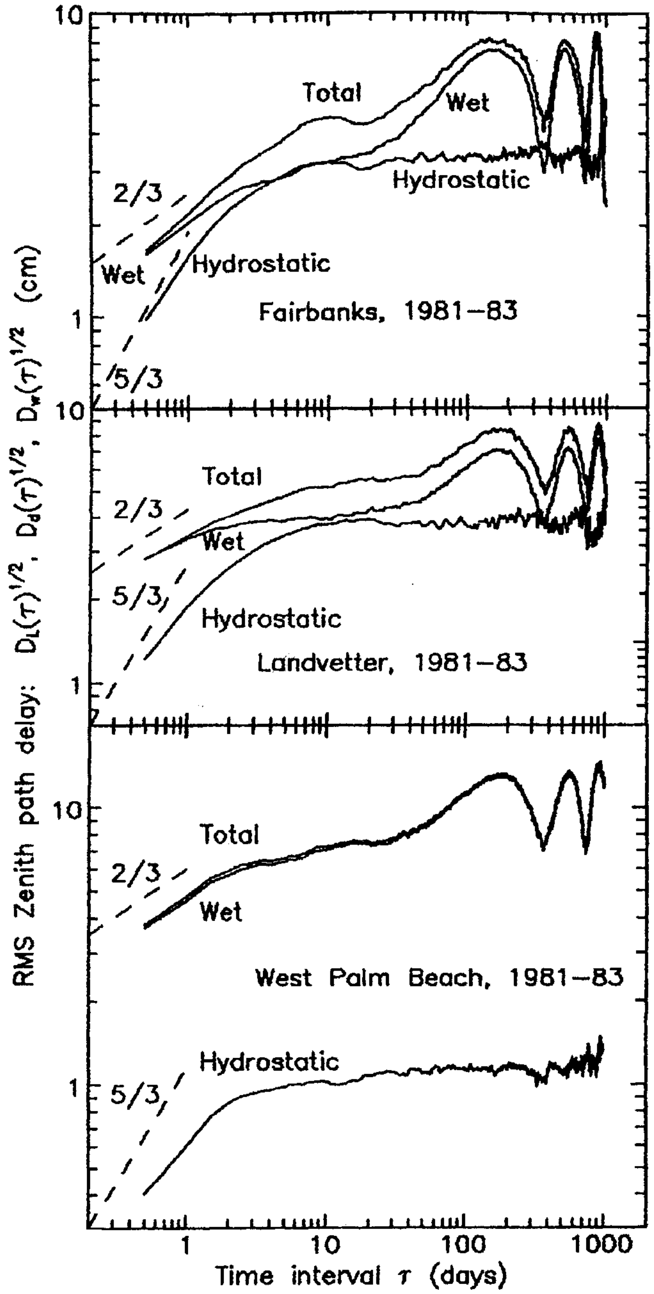

Figure 2 The temporal structure functions of wet, hydrostatic, and total path delay variations in the zenith direction for Fairbanks, Landvetter and West Palm Beach. For convenience there are shown with the rms values = $[D(\tau)]^{1/2}$. Dashed lines show the approximations of structure functions by power functions with exponents of 2/3 and 5/3.

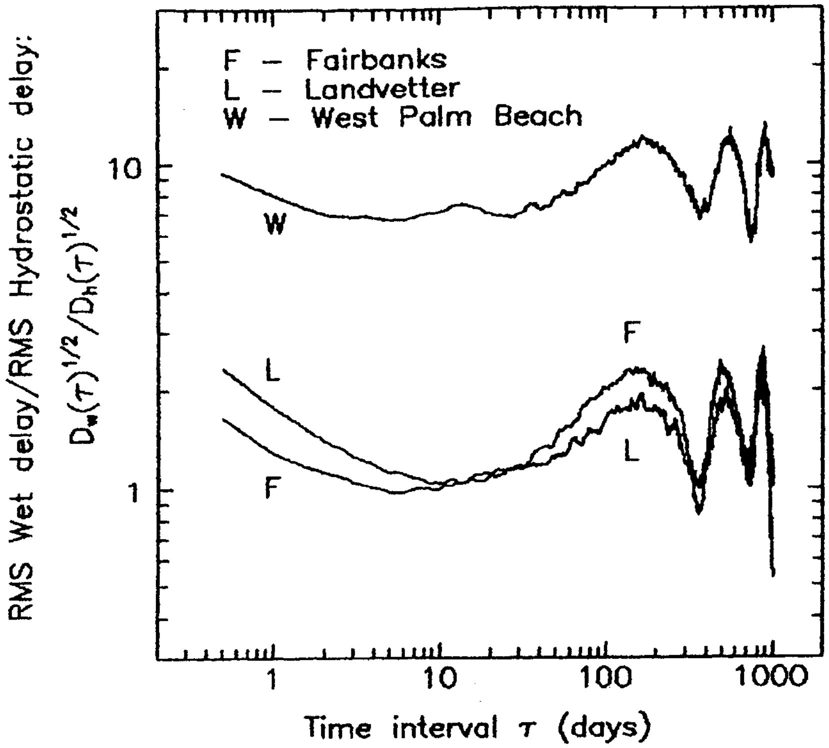

Figure 3 The ratio between the rms of the wet and hydrostatic components of path delay variations in the zenith direction for Fairbanks, Landvetter and West Palm Beach.

But in the larger interval domain for the wet delay variations, a periodical term with a 1-year period exists. This is also seen in the total path delay variations. It is important to note that there are no regular oscillations with a 24-hourly period.

To characterize the relative contribution of hydrostatic and wet components for the different characteristic time intervals of variations the ratio of corresponding structure functions were calculated (Figure 3).

At Fairbanks and Landvetter the wet and the hydrostatic components are comparable with some predominance of the wet one for the short time intervals. For the large intervals the wet component is larger only due to the periodical term. At West Palm Beach we see the same dependence on the time interval but there is also a large general predominance of the wet delay variations. The hydrostatic variations also become smaller towards the equator.

In addition to the existence of the periodical term the wet structure functions have another difference in shape from the hydrostatic one. Both the structure functions (random term of the wet one) have two characteristic domains: the power function for short time intervals and the saturation for large intervals.

The slopes of wet and hydrostatic power functions are, however, different. Bearing in mind the turbulent model of path length fluctuations through the Earth's troposphere (Stotskii, 1992) we can approximate the slope of the wet structure function by 2/3 and the hydrostatic one by 5/3 (1/3 and 5/6 for the rms curves in Figure 2). This means that the turbulence in this domain is two-dimensional for water vapour and three-dimensional for dry air. This may be explained if we take into account that the water vapour is concentrated in a rather thin layer in comparison to the distribution of dry air.

As the wet delay structure function in this domain is always in excess of the hydrostatic one the structure function of the total path delay is close to the "law of 2/3" in this region. This is consistent with other experimental data (Stotskii, 1992).

4 SPATIAL STRUCTURE FUNCTIONS

The data of the path delay also give the possibility of getting some information about the spatial structure function using the differences of path delays at the ends of the three baselines between the three sites of the observations (Table 2).

Table 2. Baselengths between sites of observations

Fairbanks –Landvetter(F-L)	$\rho = 6100$ km
Fairbanks – West Palm Beach (F-W)	$\rho = 7800$ km
Landvetter – West Palm Beach (L-W)	$\rho = 7600$ km

Taking in consideration that for every baseline there are many independent samples, we can consider the rms values of the differences between the variations as a good approximation for the meanings of a spatial structure function for these distances and locations. Such estimations of the spatial structure function obtained on the basis of averaging all the data of the three years of observations are shown in Table 3.

Table 3. Estimations of spatial structure function

Baselength	*Wet delay* $[D_w(\rho)]^{1/2}$ *(cm)*	*Hydrost. delay* $[D_h(\rho)]^{1/2}$ *(cm)*	*Total delay* $[D_L(\rho)]^{1/2}$ *(cm)*
F-L	3.80	3.60	4.88
F-W	6.33	2.46	6.40
L-W	6.45	2.88	6.51

The values of ρ for all the three baselines are larger than the outer scale of the Earth's atmosphere turbulence ($\approx$ 3000 km (Stotskii, 1972; Stotskii, 1992)) so they are to be found in the saturation branch of the spatial structure function and in

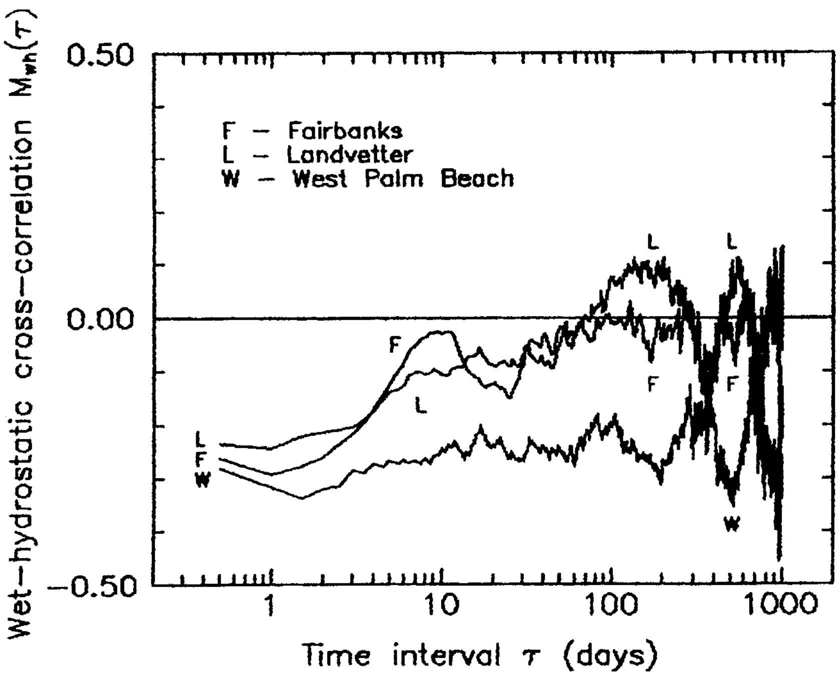

Figure 4 The structure coefficient of the cross-correlation between the wet and the hydrostatic components of path delay variations in the zenith direction for Fairbanks, Landvetter and West Palm Beach.

this region they must be independent of the baseline length value. This means that we can consider the values in Table 3 as the estimations of the spatial structure function saturation level. The results for the F-W and L-W bases are rather close but differ from the F-L base. This may be explained by the location of the sites in different climatic zones.

The obtained values are in satisfactory agreement with estimations obtained earlier and used for the construction of the turbulent model of path delay in Earth's troposphere (Stotskii, 1992).

5 CORRELATION BETWEEN WET AND HYDROSTATIC COMPONENTS

In order to obtain information about a possible correlation between the wet and the hydrostatic components of the path delay we used the structure coefficient of the cross-correlation $M_{\mathrm{wh}}(\tau)$ which estimates the degree of the cross-correlation separately for the variations at the different time intervals:

$$M_{\mathrm{wh}}(\tau) = \frac{D_{\mathrm{wh}}(\tau)}{[D_w(\tau)D_h(\tau)]^{1/2}}$$

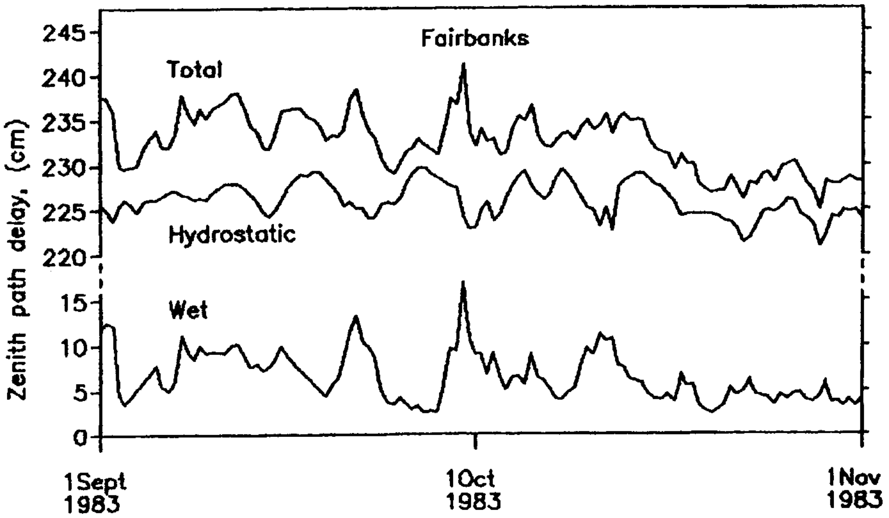

Figure 5 An example of wet, hydrostatic, and total path delay variations represented on a large; scale than in Figure 1. One can see the partial anticorrelation between the wet and hydrostatic components.

$$= \frac{\langle [L_w(t+\tau) - L_w(t)][L_h(t+\tau) - L_h(t)]\rangle}{[\langle [L_w(t+\tau) - L_w(t)]^2\rangle\langle [L_h(t+\tau) - L_h(t)]^2\rangle]^{1/2}}. \qquad (9)$$

The obtained structure coefficients of the cross-correlation are shown in Figure 4. All the curves show the existence of a slight but clear negative cross-correlation: for all the time intervals at West Palm Beach and for short intervals (to several days) at Fairbanks and Landvetter. The same effect was detected in observational data from Voejkovo (Stotskii and Stotskaya, 1993).

The presence of the wet-hydrostatic anticorrelation means that total path delay variations are less than the sum of the wet and the hydrostatic components. This effect takes place in data displayed in Figure 2 and Table 3. The partial anticorrelation can also be seen if comparing at once the forms of the variation curves in the large scale representation (Figure 5).

References

Elgered, G. (1993) In: M. A. Janssen (ed.), *Atmospheric Remote Sensing by Microwave Radiometry*, Wiley, New York, 215–258.

Saastomoinen, J. (1972) In: S. W. Henricsen *et al.* (eds.), *The Use of Artificial Satellites for Geodesy*, Geophysical Monograph Series, American Geophysical Union, Washington **15**, 247–251.

Stotskii, A. A. (1972) *Radiophys. Quant Electron.* **16**, 620–622.

Stotskii, A. A. (1992) In: J. C. De Munck and T. A. Th. Spoelstra (eds.), *Refraction of Transatmospheric Signals in Geodesy* Netherlands Geodetic Commission Publication on Geodesy, New Series, No. 36, 179–182.

Stotskii, A. A. and Stotskaya, I. M. (1992) *Astron. Astrophys. Trans.* **2**, 327–339.

Stotskii, A. A. and Stotskaya, I. M. (1993) *Communication of the Institute of Applied Astronomy*, No. 56, St.Petersburg.

Tatarskii, V. I. (1964) *Wave Propagation in a Turbulent Medium*, McGraw-Hill, New-York.

Treuhaft, R. N. and Lanyi, G. E. (1987) *Radio Sci.* **22**, 251–265.