EXPERIMENTAL STUDY OF REGULAR REFRACTION OF LASER RADIATION ON SHORT HORIZONTAL PATHS IN THE SURFACE ATMOSPHERIC LAYER

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This paper summarizes the results of several cycles of experimental investigations on the refraction of laser radiation on short horizontal paths in the surface atmospheric layer. The efficiency of algorithms for predicting such refraction from operational measurements of the average values of the corresponding meteorological parameters is analyzed.

Regular vertical refraction of laser radiation strongly hinders the operation of lidar surface measurement systems. Refractive distortions cause the laser beam axis to deviate from its initial direction. On short horizontal paths less than 2000 m long such deviations may even be as high as 1′ or more, at an average beam elevation above the ground of 1–3 m. These conditions are typical of the entire class of locating systems, especially those used for referencing. Meanwhile, the data on the specifics of refraction under such conditions are still far from exhaustive.

The present paper is dedicated to an experimental study of refraction of laser radiation and investigated possibilities to predict it from the data of routine meteorological measurements. The refraction of laser radiation is known to result from variations in the refractive index of the medium along the beam path. In turn, such variations depend on the temperature and temperature gradient variations along the same beam path[1] (the contribution from other thermodynamic parameters and atmospheric meteorological factors is small).

Starting from these premises we formulated our first experimental task as a search for correlations between the linear deviation of the laser beam axis Δ from its initial position at a fixed range L and given wavelength λ and the two relevant atmospheric meteorological parameters, the air temperature T and the temperature difference at two levels within the beam path layer ΔT. Such a formulation allows one to construct an empirical algorithm for predicting the value of Δ from the measured values of ΔT (at the beam path starting point) by formulating the regression equations in the form

$$\Delta = A(L) + B(L)\Delta T, \quad (1)$$

where $A(L)$ and $B(L)$ are coefficients which depend on the distance along the beam path L.

We based our solution of this problem on parallel synchronous measurements of fluctuations in the position of the beam axis at the end of the path, and temperature and wind profiles at its beginning. These were taken as diurnal series at distances from 100 to 2000 m along the path above a homogeneous surface stretch for a beam propagating at am average height of 2 m. We used a laser emitter (wavelength 0.6328 μm, output power 0.5 mW), a photodetector unit with a beam axis position measurement accuracy of ± 10 mm, and standard meteorological instruments.[2] In order to obtain statistically reliable results, the measurements were taken in various climatic zones: in the Volga river basin, in the Crimea, and in the Western Siberia. In the latter case the application of certain nonstandard equipment made it possible to reduce the measurement errors to ± 100 μm in Δ and to ± 0.1°C in ΔT.

Diurnal series (about 30 such series in all) were used to construct the empirical regressions needed to predict the value of Δ. Following Ref. 3, the data set was grouped into various distance ranges and stratifications (classified according to the Richardson parameter R1 for each region). Classification into stratifications accounted for the measurement error in the temperature difference $\Delta\tilde{T}$.

Four classes were selected: class I (unstable stratification) — $\Delta T < \Delta\tilde{T}$; two classes of neutral stratification: II — $0 > \Delta T > -\Delta\tilde{T}$ and III — $\Delta T > \Delta T > 0$; and, class IV (stable stratification) — $\Delta T > \Delta T$. Confidence intervals were calculated for each data group and the respective regression equations.

Such forecasting algorithms for the refraction amplitude from Ref. 3 were based on the use of similarity theory:

$$\Delta = 0.46\cdot 10^{-6}L^2 \begin{cases} 0.0367 - 0.72\Delta T/z, & |\Delta T| < \Delta\tilde{T}, \\ 0.0367 + 2.14\Delta T/z, & \Delta T < -\Delta\tilde{T}, \\ 0.0367 - 0.66\Delta T/z, & \Delta T > \Delta\tilde{T}. \end{cases} \quad (2)$$

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Here L is the distance (in meters): ΔT is the air temperature difference between the altidues $2z$ and $z/2$ (in °C); z the average beam elevation above ground (in meters); $\Delta\tilde{T}$ is the temperature difference measurement error (in °C). Figure 1 compares the empirical regression lines with those computed from Eq. (2). The experimental results correspond to a distance of 500 m and to two principal stratifications of the surface atmospheric layer (SAL): unstable (class I) and stable (class IV). Figure 1a combines experimental regression lines from the Volga river basin, the Crimea, and the Western Siberia (curves 1, 2, 3, respectively); curve 4 is theoretical (relationship (2)). Dots show the confidence margins of empirical regression. Figure lb presents a case study of the measured diurnal trends in ΔT and Δ (at the distance of 500 m).

Analyzing the results from the first group of measurements we conclude:

1. Regular refraction of laser radiation on a short horizontal SAL path in every climatic zone features a typical diurnal trend (Fig. 1b) with maximum fluctuation amplitude equal to ±1.

2. Taking the error of experimental prediction into account (at the 95% confidence level this error amounts to ±30 mm at 500 m) the programmed techniques of refraction corrections are found to be applicable to short beam paths up to 500 m in length under unstable stratification conditions. A forecast is possible at an error level of about 20–30%.

The above algorithm for predicting regular refraction assumes constant beam curvature along the path and a linear dependence of the refraction angle on distance.

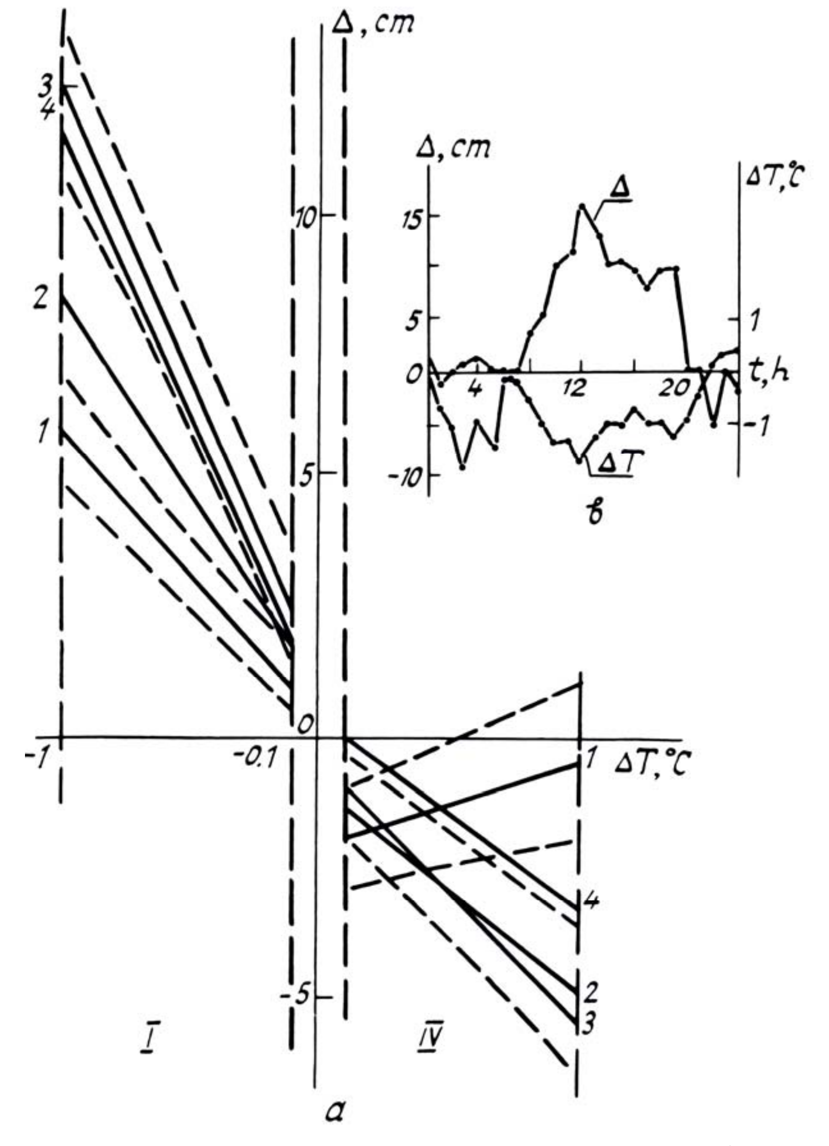

FIG. 1. Refraction distortions: experimental vs computed regression lines (based on formula (2), for a distance of 500 m*).*

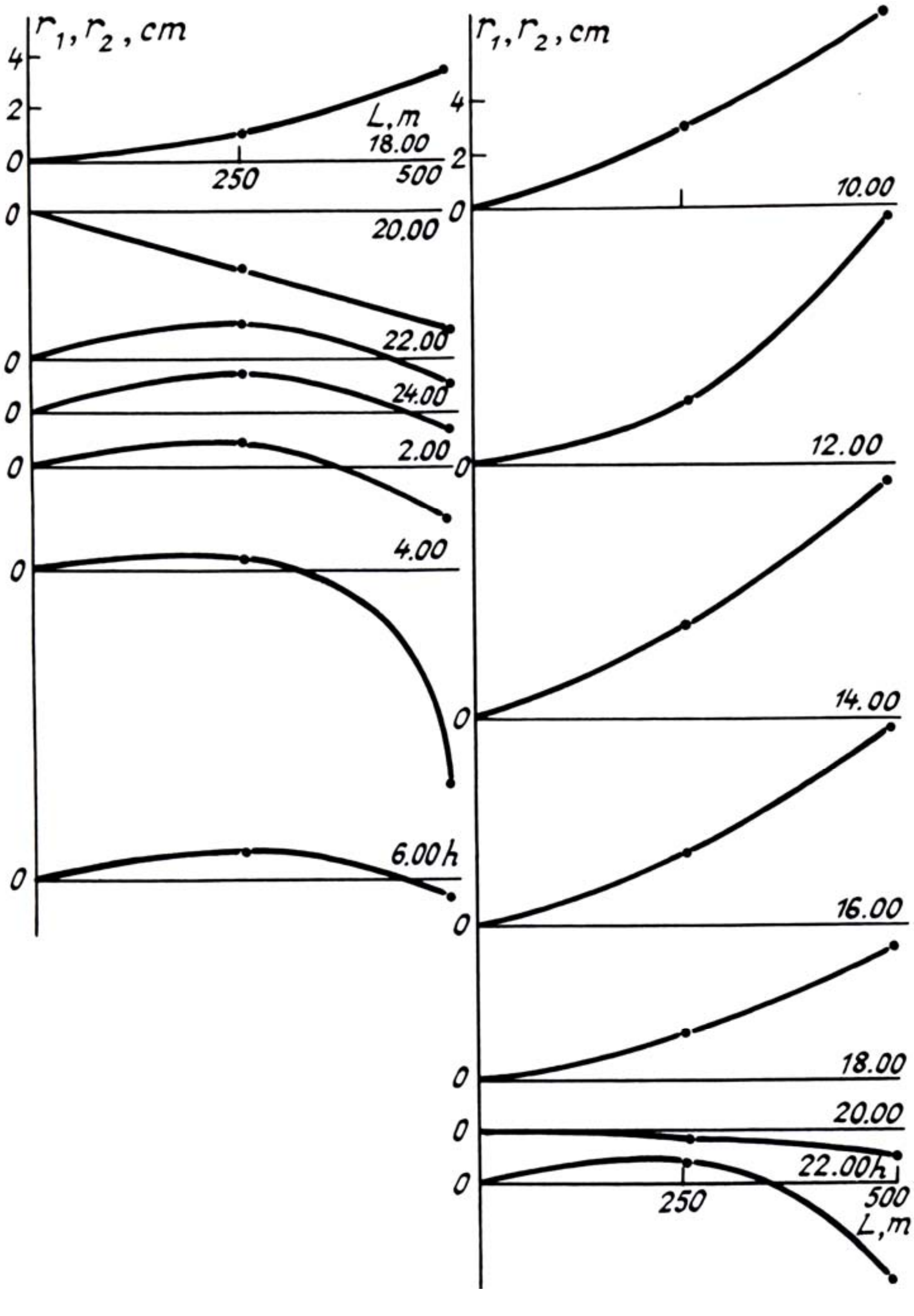

FIG. 2. Temporal trends of refract distortions at distances of 250 and 500 m.

The second series of experimental studies was directed at testing the assumed constancy of this beam curvature. We synchronously measured the refraction angle at two positions along the path (250 and 500 m down from the starting point). A standard theodolite technique was used employing an 0T-02 theodolite. The average elevation of the sighting beam above level ground was 1.5 m. Measurement results are presented in Fig. 2, giving as ordinates the linear values of the refraction angle at the mid-point r_1, and at the end r_2 of the 500 m path. Measurements started at 1800 LT and were terminated at 2200 LT, the next night. These data indicate a variable curvature of the trajectory on short horizontal paths, in particular, for stable and neutral SAL stratifications. For an unstable stratification the dependence of the refraction angle on distance is practically linear (see Fig. 2, 1000–1800 LT). Thisfact supports the conclusions yielded by the first set of experimental data.

The final task of our study consisted in an experimental investigation of the dependence of regular refraction on the degree of radiation coherence. The experiment consisted of synchronous measurements of the refraction angle along the same path for two kinds of source: a completely incoherent source (a geodesic marker during the day, and an electric lamp – at night; a theodolite was used for these measurements) and a coherent source (λ = 0.6328 μm gas laser; a laser system[2,3] was then used to measure refraction).

These measurements show that linear regular refraction for a coherent source is, on the average, twice as large as for an incoherent source.[4] Theoretical calculations presented in Ref. 5 support this experimental result.

To summarize, experimental studies have shown at a high confidence level that regular refraction of laser radiation on short near-ground paths possesses certain peculiarities which need further detailed investigation. The wide use of modern laser measurement systems makes such a task especially urgent.

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