TWO-WAVE INVESTIGATION OF TEMPORAL LASER BEAM FLUCTUATION SPECTRA IN THE ATMOSPHERE

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A comparative method of two wave sounding to investigate laser beam fluctuations has been developed experimentally. One of the waves has been partly absorbed by water vapor in a turbulent atmosphere. It has been found that the spectral power of laser beam fluctuations is periodically modulated, which can be accounted for by the transport properties of water vapor in a turbulent atmosphere.

1. The permittivity ε of an atmosphere in motion, with extensive local temperature and density fluctuations, varies in space and time. This gives rise to a stochastic modulation of propagating electromagnetic fields, where the depth and spectrum of the modulation are determined by the propagation conditions. This complicated system, which is of great practical importance, has been widely studied, both theoretically and experimentally.

Water vapor is the most massive and nonstationary component of the earth's atmosphere. Apart from the variability of water-vapor content, atmospheric conditions can arise in which water vapor molecules or molecular conglomerates are transferred by wind flows in different ways for different scales of turbulence. Concentration fluctuations, and the finite correlation time between water vapor transfer processes and wind flow speed fluctuations, may specifically influence the propagation characteristics of optical and submillimeter-wave.

According to theory[1–3], electromagnetic waves with frequencies near the resonance absorption frequency of the medium are subject to variations of intensity and phase fluctuations that are correlated with fluctuations of the real and imaginary parts of the refractive index of the medium. The variance of fluctuations in the logarithm of the wave amplitude can then be written in the form

$$\sigma^2 = \sigma_0^2(1 \pm \Delta),$$

where σ_0^2 is the variance of fluctuations for wave propagation in a transparent medium, and Δ is the increment due to absorption coefficient fluctuations. The magnitude and sign of Δ depend on the nature (i.e., the a probability distribution function) of fluctuations in the absorbing component's concentration, as well as on the beam parameters.

The mutual correlation of frequency-diversity electromagnetic waves propagating in a turbulent absorbing medium was analyzed in Ref. 4, assuming a Karmann spectrum of microinhomogeneities for both the real, and imaginary parts of the refractive index. It was found that asymptotically the mutual correlation coefficient of the two waves is a function of a mutual correlation of two turbulent microspectra, even in the presense of only weak one-wave absorption.

The experimental verification of the approaches presented in Refs. 1–4 is of definite interest in developing techniques and means to investigate the turbulent atmosphere.

The present paper discusses the results of a sounding with a combination of two monochromatic laser beams. The atmospheric path is transparent to one of the beams, , while for the other beam, (wavelength λ_2) there is moderate absorption by atmospheric water vapor.

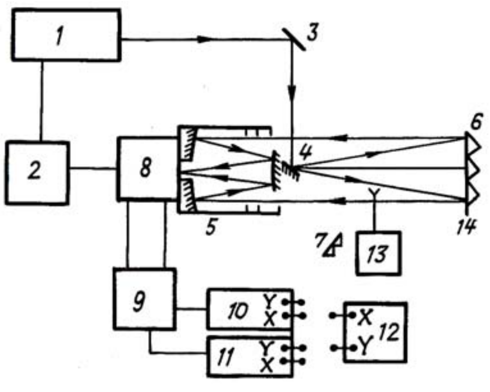

Fig. 1. Block diagram of the experimental device.

In this experiment, we recorded and compared Fourier spectra of the autocorrelation functions of intensity fluctuations of the received beams for both wavelengths simultaneously.

2. A block diagram of the experimental setup is presented in Fig. 1. A modified[5] LG-126 He-Ne laser (1) was used as a light source. Its design enables one to implement the following sounding regimes:

a) continuous generation of $\lambda_1 = 0.63$ μm and $\lambda_2 = 1.15$ μm simultaneously;

b) alternation between $\lambda_1 = 1.084$ μm and $\lambda_2 = 1.15$ μm, with a switching frequency of 10^3 Hz;

c) CW generation at either $\lambda_1 = 1.084$ μm or $\lambda_2 = 1.15$ μm.

The radiation at $\lambda_2 = 1.15$ μm is moderately absorbed in the atmosphere by water vapor; the absorption of ligth at $\lambda = 1.084$ μm is several orders of magnitude weaker than that at λ_2, and the radiation at $\lambda = 0.63$ μm is in the atmospheric transmission window.

The operating mode is switched mechanically, and is controlled by the electronic module 2. The beam-steerer consisting of mirrors 3 and 4 is used to align the optical axes of the laser and receiving telescope (5). The passive reflector 6 consisted of a set of retroreflecting prisms on the flat mount 14; the prisms here assembled to an accuracy no worse than 20″. The near reflector 7 was used for optical alignment and calibration of the electronics. The reflected laser beam, received by a 0.25-m Cassegrain telescope, was focused on the field stop of the opto-electronic converter block 8. An FEU-83 photomultiplier was used as an IR detector, and was preceded by a set of optical filters. The array of filters included an optically polished silicon plate about 20 pm in thickness, and an interference filter with maximum transmittance near 1.15 μm. Visible light reflected from silicon plate was used as the detection channel for radiation at $\lambda = 0.63$ μm. The analog signals from the photodetectors was applied to the electronic processing block 9, where mean values of the signals were estimated, and fluctuating components of the signals were also extracted and amplified in this block, in parallel for the two channels corresponding to radiation at λ_1 and λ_2. The signal spectra were then analyzed in real time for the two channels (10 and 11) using SK4-72 analog -to -digital analyzers. A set of 1024 random spectra of intensity fluctuations in each channel were averaged with digital integrators, giving a total of about 20 minutes of measurement time in the Fourier frequency range from 0 to 500 Hz. Thus, the integration time was long enough to satisfy the condition of stationarity in the presence of gusty wind flows in the real atmosphere. The Fourier power spectra were output in analog form as spectrograms to the X–Y recorder 12. The X-axis of the spectrograms represents frequency.

Along the sounding path were installed sensors of meteorological parameters[13]. A TAIK-3 used in the experiment provided for local measurements of mean velocity $\bar{v}$, its variance σ_v^2, as well as mean local temperature $\bar{t}$ and its variance σ_t^2. Vertical and horizontal gradients of these quantities were also measured along the path. Mean values of absolute humidity were estimated from psychrometric data and local measurements of water vapor partial pressure with an uncertainty of ± 5%.

Field investigations were carried out on paths with lengths L up to 300 m, so that $2L \le 600$ m.

The paths were either horizontal, or inclined with a difference between ends of up to 30 m. The experimental conditions and geometry satisfied the criterion of weak turbulence.

The simultaneous recording of Fourier-spectrograms for the two sounding beams enables one to improve the accuracy of a comparative analysis in the presence of short time gusty velocity components of wind flows in the real atmosphere.

3. The analysis of the experimentally obtained fluctuation spectra $W_1(f)$ and $W_2(f)$ for the slightly absorbed beam at λ_1 and nonabsorbed beam at has shown the following.

The overall frequency behavior of $W(f)$ corresponds to an inertial turbulence spectrum described by the previously published asymptote $W(f) \sim f^{-8/3}$ for high frequencies[6] (> 500 Hz).

At the same time, a comparative analysis of the functions $W_1(f)$ and $W_2(f)$ has revealed fundamental differences at frequencies below 100 z.

Figure 2 presents the experimentally derived ratio $\log W_{1,2} = \log(W_1/W_2)$, plotted for convenience of comparison of the spectra $W_1(f)$ and $W_2(f)$ on a log-log scale. The distinctive feature of the behavior of $\log W_{1,2}$ is that it is decidedly nonmonotonic.

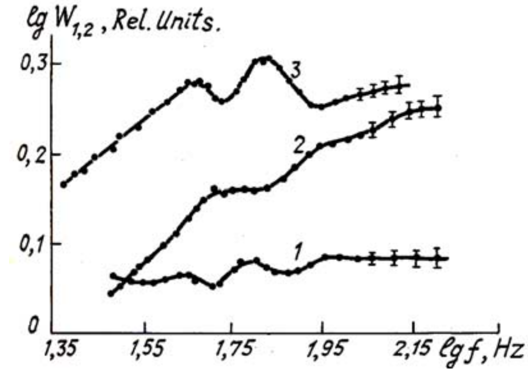

Fig. 2. The frequency dependence of the ratio of two fluctuation power spectra under the following sounding conditions:

1. $\lambda_1 = 0.63$ μm; $\lambda_2 = 1.15$ μm; $\Omega_1 = 4\times10^{-3}$ rad. $\Omega_2 = 6\times10^{-3}$ rad.; 2L = 520 m; $\bar{v} = 0.5$ m/s; $\sigma_v^2 = 0.35$ (m/s)^2; $e = 8.7$ mBarr; $\bar{t} = 9.7$°C;
2. $\lambda_1 = 0.63$ μm; $\lambda_2 = 1.15$ μm; $\Omega_1 = \Omega_2 = 10^{-3}$rad; $\bar{v} = 0.5$ m/s; $\sigma_v^2 = 0.35$ (m/s)^2; $e = 8.7$ mBarr; $\bar{t} = 9.7$°C;
3. $\lambda_1 = 1.084$ μm; $\lambda_2 = 1.15$ μm; 2L = 520 m; $\bar{v} = 0.8$ m/s; $\Omega_1 = \Omega_2 = 10^{-3}$rad; $\bar{v} = 0.5$ m/s; $\sigma_v^2 = 0.5$ (m/s)^2; $e = 8.1$ mBarr; $\bar{t} = 8.2$°C;

Curves 1 and 2 in Fig. 2 are obtained for the same meteorological parameters over the path, but for different angular divergences Ω of the two beams at $\lambda_1 = 0.63$ and $\lambda_2 = 1.15$ μm: 1) $\Omega_1 \approx \Omega_2$; 2) $\Omega_1 < \Omega_2$. Obviously, different diameter sounding beams will interact differently in time with the same inhomogeneities in the medium. The smaller the beam diameter, the larger the contribution of the smallest-scale refractive index inhomogeneities to the overall pattern of received signal fluctuations. Therefore, the $f^{-8/3}$ dependence is displaced to higher frequencies as the beam diameter decreases. The different spatial characteristics of the beams at λ_1 and λ_2 thus change the slope of the log curves, but have little effect upon their fine structure. The only result may be a loss of resolution (see curve 2, Fig. 2).

Curve 3 in Fig. 2 was obtained for beams at $\lambda_1 = 1.084$ μm and $\lambda_2 = 1.15$ μm in operating mode c. The meteorological parameters along the path differed from those of the previous measurements: water vapor content was enhanced, while all other parameters were the same, as before. It was experimentally ascertained that these parameter deviations do not cause the visible enhancement of fine structure represented by curve 3, Fig. 2. The enhancement can evidently be explained by the smaller difference between sounding wavelengths λ_1 and λ_2, as compared with the previous pair (curve 1, Fig. 2).

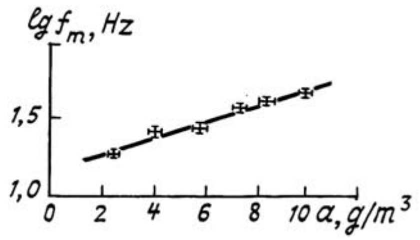

Fig. 3. The dependence of f_m on mean humidity, path length 2L = 200 m. The experimental points are obtained by averaging from 4 to 6 measurements at different values of the path parameters $\overline{v}$, σ_v^2, $\overline{t}$, at constant values a within the measurement uncertainities.

Measurements obtained under different meteorological conditions (wind velocity $\overline{v}$, its variance σ_v^2, temperature $\overline{t}$, and absolute humidity $\overline{a}$) have demonstrated that the location of fine structure extrema of $\log W_{1,2}(f)$ varies, and correlates with variations in the atmospheric humidity a. The experimentally obtained values of frequency f_m corresponding to the valley between two maxima in $\log W_{1,2}(f)$ (Fig. 2) are shown in Fig. 3 as a function of the mean humidity $\overline{a}$.

4. The results discussed above enable one to conclude that the correlation relationships between stochastic components of two waves propagating through a turbulent atmosphere are more complicated than indicated in Refs. 1–4, if one of the waves is slightly absorbed by atmospheric water vapor. The influence of water vapor absorption fluctuations on the spectral power of beam intensity fluctuations is frequency-selective, which can be explained by the existence of a characteristic interaction time between fluctuations of wind velocity and water vapor concentration.

This evidently occurs because turbulent flows on different scales interact with a random field of water vapor density in different ways.

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