ELECTRICAL MODEL OF THE ATMOSPHERIC OPTICAL TRANSFER FUNCTION

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A simple electrical model of the atmospheric optical transfer function is proposed in this paper, and is implemented by an elementary RC network. The use of an electrical analog allows for real-time visualization of image distortion due to the influence of the atmosphere, with varying atmospheric parameters.

In some systems for remote sensing of the Earth's surface it is necessary to take into account spatial frequency distortions of images introduced by the atmosphere[1]. In general, the resultant optical transfer function (OTF) of the atmosphere can be represented as a product of several components. Among these are the OTF of the air layer near the platform body, the OTF due to atmospheric turbulence, associated with refraction index fluctuations, and the OTF of the scattering layer itself[2,3]; these introduce linear distortions into an image because of the circular symmetry of the point-spectral function of the distorting media. The distortions caused by scattering properties of the atmosphere are more important at short wavelength. As shown in Ref. 4, atmospheric distortions can reduce the resolution of satellite TV systems by a factor of two or more.

Distortions can be by solving the appropriate three-dimensional radiative transfer equation for a point radiation source. However the exact solution requires a great deal of computation and does not provide one with a clear picture of the interaction among the many optical properties that determine the scattered radiation field. The necessity of taking atmospheric effects into account in optical systems engineering has forced many authors to suggest a number of approximations to the normalized OTF (frequency-contrast characteristic (FCC)) of the atmosphere by elementary functions. Analysis of the approximations suggested has shown that the following function provides for the best approximation at low frequencies:

$$T_\nu = (1 + \tau^2\nu^2)^{-1/2}, \tag{1}$$

where τ is a parameter and ν is the spatial frequency in rad^{-1}.

A characteristic feature of the scattering layer function is delta-function singularity due to direct, unscattered radiation. Taking this into account, one can see that the best approximation over all spatial frequencies can be achieved using the expression

$$T_\nu = (1-c)\ (1+\tau^2\nu^2)^{-1/2}, \tag{2}$$

where c is a constant.

Since different atmospheric conditions are described with their own sets of parameters in Eq. (2), it is necessary to have a table of c and τ values covering all atmospheric situations. Engineers designing observational instruments can obtain visual estimates of distortions using special-purpose devices for image processing, which do not enable allow one to investigate the dynamics of distortions, especially in real time.

The possibilities of modeling the scattering properties of the atmosphere under laboratory conditions are usually quite limited. Since the distortions mentioned above are linear and the distortions introduced into the image by the optical system and photodetector can also be assumed to be linear, it might be convenient to model the scattering properties of the atmosphere directly in the electrical circuitry of a TV system, enabling one to visualize their effects, for example, on the screen of a video monitor.

Such an electrical model of the atmosphere can be easily implemented because the approximation (2) is, in fact, a combination of the frequency response of an elementary RC circuit (low-pass filter), whose phase characteristic is practically linear, and an attenuated direct signal. In modeling the FCC of the atmosphere under changing atmospheric conditions, one needs to vary the parameters c and τ of the filter, which results not only in changing of the filter bandpass but the overall transmission coefficient as well.

One can minimize the number of computational parameters in the electrical model as follows. For the atmospheric conditions studied, let us find the best and worst, FCCs of the atmosphere and then approximate them with the frequency response of two circuits like (2) connected in parallel. In such an approach, the intermediate FCCs of the atmosphere will be determined by the partial distortions introduced into the total signal by each of the circuits. The resultant frequency reasponse of the electrical model can be written as

$$T_\nu = \left[(1-c_1)(1+\tau_1^2\nu^2)^{1/2}\right](1-a(\gamma)) +$$

$$+\left[(1-c_2)(1+\tau_2^2\nu^2)^{-1/2}\right]a(\gamma), \qquad (3)$$

where $\tau_{1,2}$ and $c_{1,2}$ are constants, and γ is a parameter describing the observation conditions. We see from Eq. (3) that the only varying parameter of the model is the weighting factor $a(\gamma)$, which does -not affect the frequency response of the low-pass filter.

Figure 1 shows the block diagram of an electrical model, where low-pass filters represent the best and worst observation conditions, respectively.

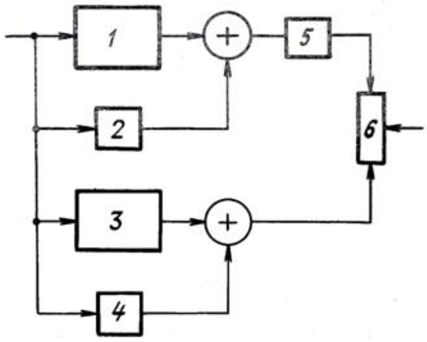

FIG. 1. Block diagram of the electrical model of the atmosphere. Here 1 and 3 are low-pass filters modeling the best and the worst observation conditions; 2, 4, and 5 are the delay lines for 1, 2, and 3; 6 is potentiometer.

The resulting frequency response of each branch is linearized (in order to create symmetrical distortions) using a delay line with time lag t_1 between the signal at the low-pass filter output and a direct signal, given by

$$t_{1_{1,2}} = \left|d\,\mathrm{arctg}(-w\tau_{1,2})/dw\right., \qquad (4)$$

$$t_{1_3} = t_{1_2} - t_{1_1},$$

where $w = 2\pi\nu v$, v is the scanning speed.

In order to illustrate the possibilities of modeling, consider the case of observations in the near UV (0.3 to 0.4 μm), where atmospheric scattering is strongest[5]. In our calculations, we shall use the expression derived in solving the radiative transfer equation for a horizontally homogeneous atmosphere, using the modified method of spherical harmonics[6], i.e.,

$$T_\nu = \exp\left\{-\int_0^H æ(\xi)\,d\xi + \frac{H}{\sqrt{\chi}}\int_0^{\sqrt{x}} \sigma\left[\frac{H\xi}{\sqrt{\chi}}\right]x(\xi)\,d\xi\right\}, \qquad (5)$$

where $\chi = \sqrt{\nu(\nu+1)}$, $x(\xi)$ is the scattering phase function, $æ(\xi)$ is the absorption coefficient of the medium, σ is the scattering coefficient, and H is the height of the observation platform. The atmospheric parameters at a wavelength 0.35 μm were taken from Green s UV model[7].

Note that at a constant observation height, the best observation conditions can be set by calculating FCC of a Rayleigh atmosphere (visibility V_M = 250 km), while the worst could be determined experimentally. Let us now model the influence of the meteorological visibility, which varies along the path of observations when the observer is at 5 km height (see Fig. 2).

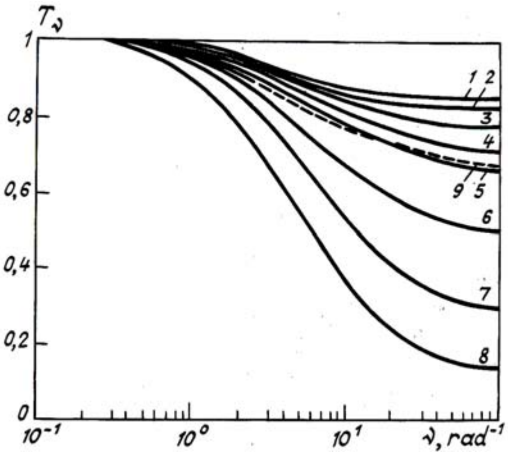

FIG. 2. Approximation of calculated FCC of the atmosphere by frequency response of the electric model. Curves 1 to 8 correspond to V_M from 250 km to 3 km. The height of the observation is platform H = 5 km, the wavelength λ = 0.35 μm. Curve 9 presents an example of the calculated FCC of the atmosphere.

The parameters τ_1 and τ_2 of the filters are 0.673 and 0.294, and c_1 and c_2 are 0.843 and 0.1, respectively. The accuracy of approximation for the boundary and intermediate weighting factors is as follows:

V_m, km	250	100	50	30	20	10	3
$a(V_m)$	0	0.035	0.091	0.16	0.245	0.458	1

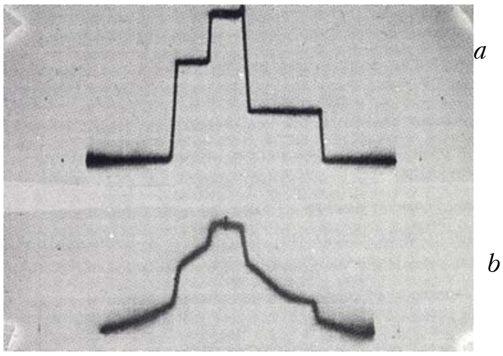

FIG. 3. Oscillograms of the electrical *test-signal for a TV system; (a) is the case with no aperture distortions; (b) represents the case involving distortions introduced by the opto-electronic channel of the system and by the scattering properties of the atmosphere.*

The monotonic behavior of the weighting factor as a function on the meteorological visibility enables one to smoothly change the atmospheric conditions of observations in the modeling process.

Figure 3 presents oscillograms showing the signals from a test-object equivalent to the input optical signal and to the signal distorted by the opto-electronic part of the system and the electrical model of the atmosphere.

The foregoing one-dimensional electrical model of the atmosphere can serve as an analog prototype of a digital device which, in turn, can be easily generalized to the two-dimensional case, enabling one to synthesize an inverse linear filter correcting for atmospheric distortions.

REFERENCES

1. K.Ya. Kondrat'yev, O.I. Smoktii and V.V. Kozoderov, *Influence of the Atmosphere on Investigations of Natural Resources from Space* (Mashinostroenie, Moscow, 1985).

2. V.N. Ovechkin, *Determination of the Atmospheric Modulation Transfer Function Taking into[1]Account Scattering and Turbulent Properties of Media,* Izv. Vyssh: Uchebn. Zaved.Ser. Geodezia i Aerofotos'emka, No. 4, 81 (1985).

3. *Computers in Optical Research*, Ed. by B. Frieden (Mir, Moscow, 1983).

4. Y.J. Kaufman, *Atmospheric Effect on Spatial Resolution of Surface Imagery,* Appl. Optics, **23**, No. 22, 4164 (1984).

5. V.A. Selivanov, *Remote Sensing of the Earth's Surface in the UV Region,* Investigations of the Earth from Space, No. 1, 111 (1988).

6. V.P. Budak, G.A. Melnikov, V.I. Savenkov, and V.P. Fedosov, *Small Angle Modification of the Spherical Harmonics Method* IX-th Plenum of the Workshop on Oceanic Optics. Oceanic and Atmospheric Optics. (GOI, Leningrad, 1984).

7. F.R. Riewe and A.E.S. Green, *Ultraviolet Aureole around a Source at a Finite Distance*, Applied Optics, **17**, No. 12, 1923 (1978).