A POSSIBILITY OF DETECTING ANOMALOUS INHOMOGENEITIES OF THE ATMOSPHERE (A TECHNIQUE OF NONLINEAR FILTRATION OF BACKSCATTERED SIGNALS)

Yu.A. Polkanov

A. N. Sevchenko Scientific-Research Institute of Applied Physics Problems at the Belorussian State University, Minsk
Received September 19, 1991

A technique of nonlinear filtration of signals is proposed, which allows one to smooth the regular inhomogeneities of the signal while amplifying signal drops due to anomalous inhomogeneities of a medium. The filtration made using this technique was compared (in numerical experiments) with the linear and median filtration. The comparison showed high efficiency of the proposed filtration technique. This has also been confirmed by the results of filtering the experimental data obtained in a turbid medium and in a medium with turbulent inhomogeneity.

1. INTRODUCTION

Detection of anomalous inhomogeneities of the atmosphere (accompanying its nonequilibrium state) from a backscattered signal of pulsed optical radiation recently attracted much attention. This is caused both by ambiguity and low accuracy of the techniques for reconstruction of optical characteristics of an inhomogeneous medium and by a large volume of calculations, and, consequently, by difficulties in the development of measuring systems capable of operating in real time.

Therefore it might be of interest to obtain needed information directly from a temporal structure of the scattered signal after it has been processed (filtered) that enables one to extract anomalous inhomogeneities of the signal against a background of a certain pseudoregular structure without reconstructing optical characteristics of the medium from return signals.

Possible application of such an approach is supported by the direct relationship between the intensity of the backscattered signal and the parameter being proportional to the function describing the aerosol structure along the path.[1] It should be noted that under different meteorological conditions there exists a substantial correlation between the shape of the backscattered signal and characteristics of optical inhomogeneities of the atmosphere.[2] A change in the meteorological situation results in rearrangement of the optical inhomogeneities structure due to the turbulent processes that directly determines the structure of the scattering signal being recorded.[3] Based on these data the method has been developed for detecting optical anomalies in the atmosphere from the analysis of temporal structure of the backscattered signal.

2. MEASUREMENT TECHNIQUE

The measurements are divided into the background ones related to a thermodynamically stable state of the atmosphere without rapid changes in the optical characteristics of the atmosphere and the basic ones in the presence of an optical anomaly (topographic object, cloud, clear atmosphere turbulence, smoke, and turbulent stream).

The technique involves:

1) The use of a specific nonlinear filtration smoothing the regular structure of inhomogeneities (a determined structure described by an analytical function at all points, a sinusoid in the simplest case) while making the signal jumps caused by irregular (anomalous) inhomogeneities in the atmosphere more pronounced (the steeper the jump the stronger is the filtered signal at the point of jump).[4]

2) Separation of the specific features in the signal behavior (jumps of a stepwise type) at the boundary of an inhomogeneity including the boundary layer of a turbulent anomaly.

Special filtration can be represented as a certain sequence of procedures.

Filtration is aimed at detecting the anomalous inhomogeneities in the temporal structure of a scattered signal and at determining the boundaries of such inhomogeneities.

For this to happen a pair of new (operating) counts are formed from the counts of each signal by summing an equal number of the initial values of the signal. At a successive increase of the reference counts for the pair a series of transformations is made and a digital sequence of new counts is formed, the amplitudes of these counts being proportional to the filtered signal jump at a step of discretization when the maximum jump is indicative of the position of the nearest boundary of the scattered signal anomaly and, hence, of the medium anomaly.

This algorithm can be analytically reduced to the relation

$$S_{t_n} = \frac{1}{t_{n/2}} \ln \left(\frac{\int\limits_{T_3}^{T_4} S(t)dt}{\int\limits_{T_1}^{T_2} S(t)dt} \right),$$

where $T_1 = t_0$, $T_2 = t_n$, $T_3 = t_n + 1$, $T_4 = 2t_n + t_0$ (with $n = 2, 3, \ldots, n_x$); $T_1 = t_n$, $T_2 = t_0$, $T_3 = 2t_n^* + t_0$, $T_4 = t_n^* + t_1$ (with $n = n_x + 1, n_x + 2, \ldots, n_{\max}$); when $t_n^* = t_n$, $t_1 = \Delta t$ (is the discretization step over the path), n_x is determined from the condition $|(S_{t_n} - S_{t_n^*})| = \min$.

0235-6880/92/07 456-03 $02.00

3. RESULTS

Efficiency of special filtration was first checked in a numerical experiment by comparing it with linear and median filtrations.[5,6] The peculiar feature of the filtration under study is the use of *a priori* information on a possible jump of a lidar return, within the limits of a single discrete, (based on information about realistic behavior of the atmospheric optical characteristics), when constructing the filtration algorithm.

3.1. Numerical simulations

Numerical simulations were carried out on a minicomputer with an interactive system for spectral and statistical processing of a model noisy signal. We used an exponentially decreasing signal with a jump at the center of the sample of 50 counts.

Averaging for the linear and median filtration were made over three counts with one recursive count for a median filtration (3, 1). To detect a front of the introduced signal jump and to estimate its deformation we used a repeated search for a maximum jump of the filtered signal after the previously determined jump was eliminated from the consideration.

The criterion for filtration efficiency was the ratio between the variances of the filtered and reference (without noise) signals both for the entire sample and for some portions of it before and after the jump.

An example of the obtained results is shown in Fig. 1. The ratios of the maximum signal to the introduced jump and the noise level are taken 10, 1, and 10, respectively. In this case the signal–to–noise ratio at the point of a jump is equal to 0.32. The position of the jump is marked with the symbol *T*.

The results of special filtration are shown in Fig. 2, where the upper plot is the filtered signal and the lower plot is the results of the analysis of the signal dips. Solid line stands for the repeated search, which more reliably determine the jump, but displaced with respect to a real position of the jump. On the lower plot the delta pulses are related to the maximum jump of the signal in a dip with respect to its amplitude and position.

In the given example the linear and median filtrations are not effective and make it impossible to separate out the jump introduced into the signal.

General estimates of the filtration efficiency are given in Table I, in which the following designations are used: LINF is for a linear filter, MEDF is for a median filter, GRAN (0) and GRAN (1) are for special filtrations (0 and 1 denote the number of repeated searches for the maximum jumps in the filtered signal), DISP1 and DISP2 are the variances before and after the introduction of the jump into the signal, SIG1, 2, 3 are the signals with the ratios of the maximum value, jump, and noise: 10 : 1 : 1, 10 : 1 : 5, and 10 : 1 : 10, respectively.

TABLE I.

	SIG 1	DISP 1	DISP 2
LINF	1.021	0.990	1.198
MEDF	1.008	0.992	1.055
GRAN (0)	33.62	15.900	1.055
GRAN (1)	3.738	2.000	2.016

	SIG 2	DISP 1	DISP 2
LINF	1.131	1.198	2.888
MEDF	1.070	1.148	2.492
GRAN (0)	2.438	2.420	1.420
GRAN (1)	4.651	3.148	–

	SIG 3	DISP 1	DISP 2
LINF	1.487	1.494	3.109
MEDF	1.400	1.383	2.893
GRAN (0)	5.193	6.908	3.969
GRAN (1)	4.789	4.320	4.355

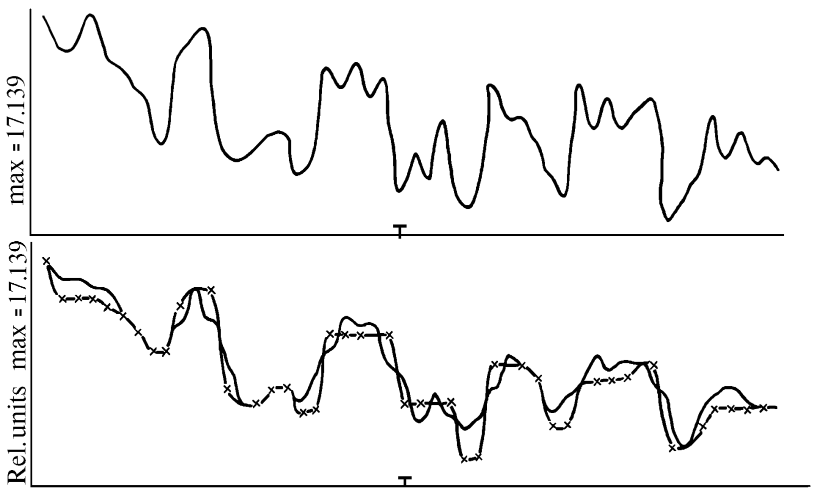

FIG. 1. A reference signal with the signal drop-to-noise ratio = 0.1 *(upper plot); the results of linear (solid line) and median (line with crosses) filtrations (lower plot).*

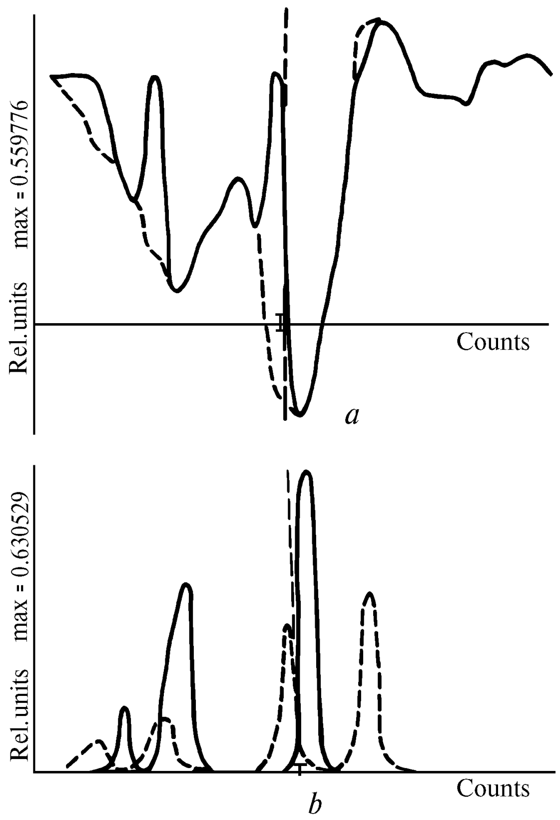

FIG. 2. The results of signal filtration under study with the signal drop–to–noise ratio = 0.1: *a) Solid line corresponds to the repeated filtration, and b) the result of detecting the maximum jumps (a number of counts are* $2n$*).*

In the table the variances are normalized by the variance of the reference signal. For special filtrations DISP1 and DISP2 are much higher than unity, that is indicative of the nonlinear feature of the filtration and its high sensitivity to individual jumps in the signal.

3.2. Field experiment

A backscattered signal in the field experiment was recorded in the presence of: (a) a topographic object, (b) smoking of a portion of the path, and (c) a turbulent stream.

A reflecting surface with the reflectivity $k \sim 0.3$ was used as a topographic object.

Two types of smoking created the conditions for multiple scattering of radiation and corresponded to a meteorological visibility range of tens of meters (in the first case) and of several meters (in the second case).

A turbulent stream was generated with a jet engine under the meteorological visibility range of several kilometers.

The signal reflected from the topographic object was reliably recorded without smoking on the path. The object partially screened the radiation field and a portion of sounding path thus resulting in a certain jump of the recorded signal of the atmospheric backscatter.

Even in the case of a weak smoking of the path it is impossible to judge by the presence of an individual optical inhomogeneity on the path (the plots "Signal" in Figs. 3 and 4, respectively, where 18 counts of the signal are represented which are related to the zone of smoking with 520 points on the whole plot).

With a sufficiently high accuracy of signal measurements the special filtration allows one to obtain the signal which repeats the behavior of the extinction along the path. At the same time, a jump of this signal not corresponding to the signal variation for a stable atmosphere in the background measurements indicates the presence of an anomaly somewhere on the sounding path.

This is well illustrated by the results of the scattering signal filtration (plots "Anomaly" in Figs. 3 and 4, respectively) where the reflecting surface on the path strongly changes the general behavior of the filtered signal: a smooth rise with the subsequent rapid fall off at the boundary of the smoke is changed for a rapid jump of the signal (two counts) on the interval corresponding to the position of the topographic object with subsequent smoother fall off at the boundary of the smoke (due to the screening effect).

The position of the local maxima of the signal determines unambiguously the boundaries of the smoke zone. For a strong smoking the reflecting surface on the path changes the reflected signal much less than it does in the case of a weak smoking. However, the position of the reflecting surface can be found from the maximum of signal difference.

The estimates are related to the experimental conditions within the limits of the introduced range resolution of 1.5 m along the path being sounded and they can be assumed to be quite satisfactory.

A turbulent stream is reliably detected with a special filtration including the residual phenomena during several minutes after the jet engine shutdown (a series of 30 measurements). The measurement results are shown in Figs. 5 and 6, where the plot "Anomaly" (Fig. 6) was obtained by separating out the maximum jumps whose positions are related to the boundaries of a medium anomaly.

4. CONCLUSIONS

The above–done study has revealed higher efficiency of the special filtration technique compared to the linear and median ones in application to problems of detecting anomalous inhomogeneities under strong turbidity of the medium (numerical experiment). The field experiment confirmed the possibility of discriminating anomalies against a background of pseudoregular atmospheric inhomogeneities having a certain structure. Such a filtration can be used for detecting clear air turbulence, aerosol clusters, and processes of the cloudiness formation.

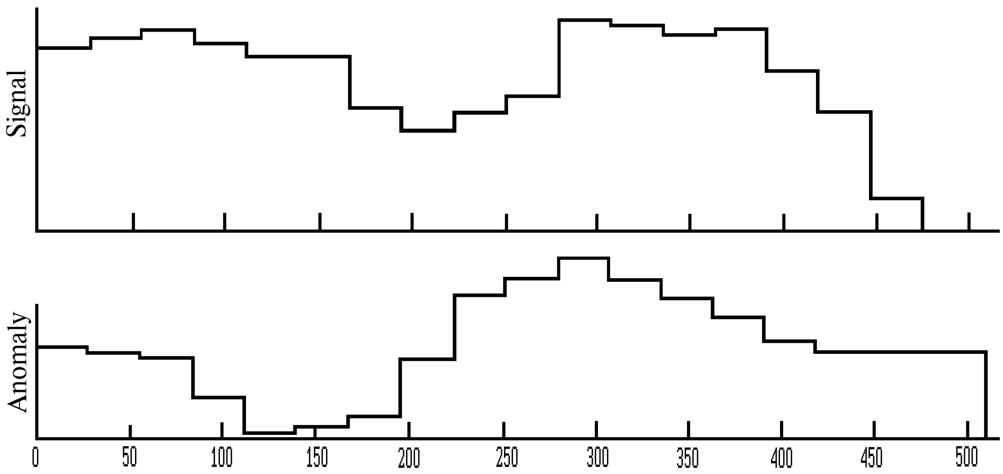

FIG. 3. The signal obtained under the meteorological visibility range (MVR) of tens of meters (weak smoke) (upper plot) and the results of the special filtration (lower plot).

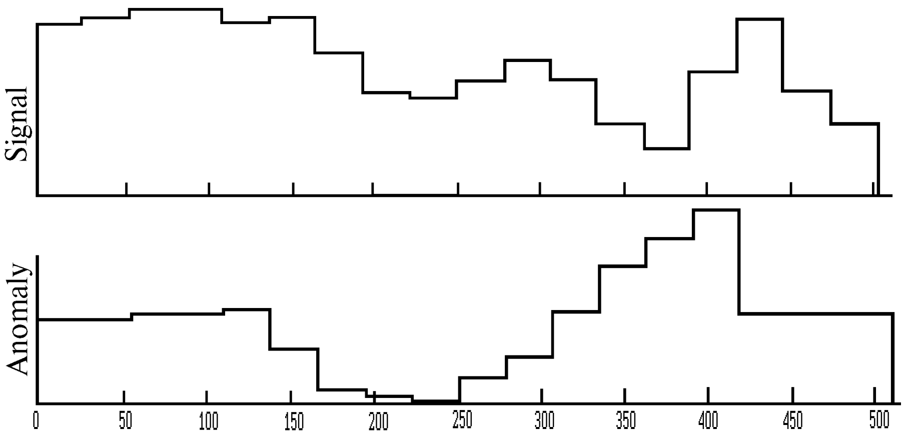

FIG. 4. The signal backscattered from a weak smoke in the presence of the reflecting topographic object (upper plot) and the results of the special filtration (lower plot).

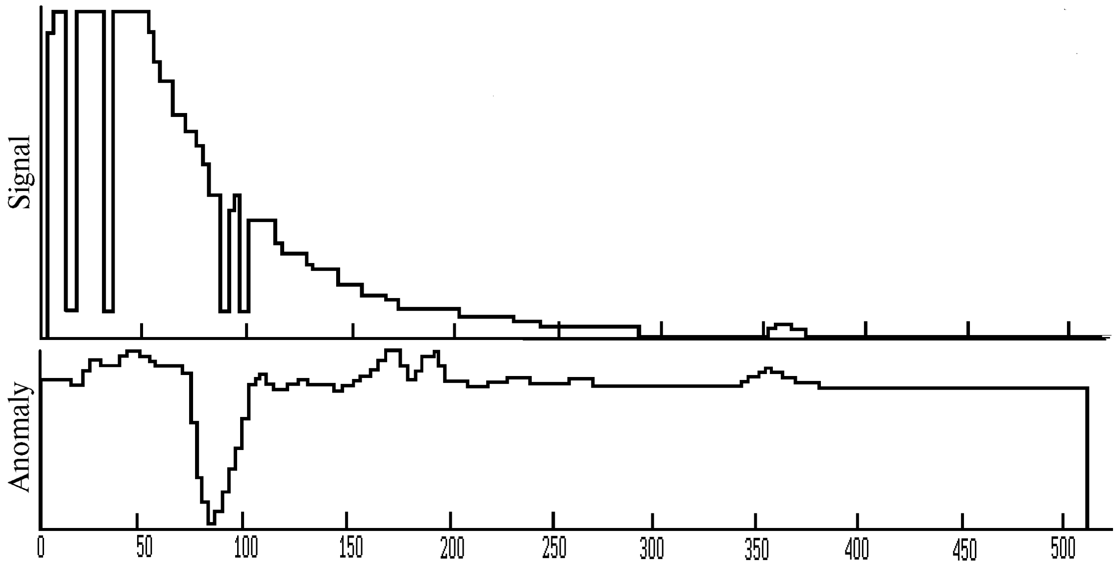

FIG. 5. The signal backscattered from a turbulent stream (upper plot) and the results of special filtration (lower plot).

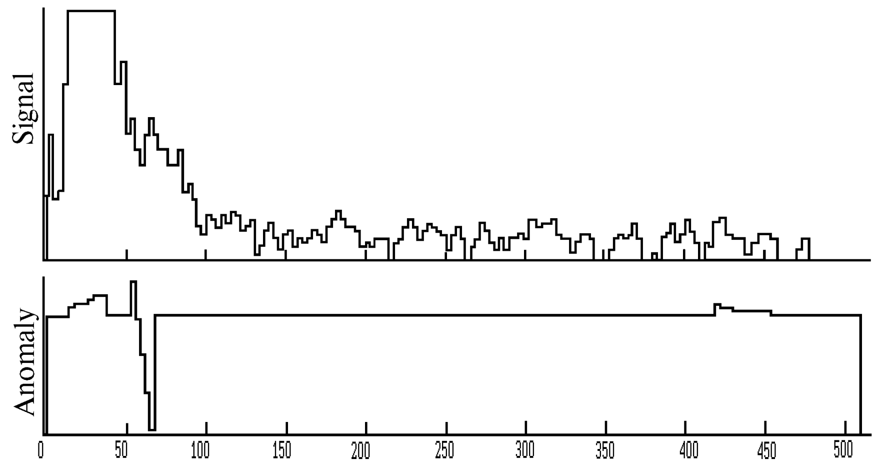

FIG. 6. The signal backscattered from a turbulent stream (upper plot) and the results of detecting the maximum jumps (lower plot).

REFERENCES

1. G.O. Zadde, V.E. Zuev, V.P. Tarasenko, and N.I. Yurga, in: *Optical Wave Propagation through the Atmosphere* (Nauka, Novosibirsk, 1975), pp. 174–179.
2. V.P. Pashchenko, Meteor. Gidrol., No. 5, 112–119 (1982).
3. R.W. Fenn, E.L. Shettle, W.S. Herring, and R.W. Johnson, Atmos. Environ. **15**, Nos. 10–11, 1911–1918 (1981).
4. Yu.A. Polkanov, Inventor's Certificate No. 1448907 USSR, G01W1/00. "The method for determining the location of optical inhomogeneity of the atmpsphere". Priority June 1, 1986, publ. September 1, 1988.
5. T.S. Hung, ed., *Rapid Algorithms in Digital Processing of Images. Transformations and Median Filters*(Radio i Svyaz', Moscow, 1984), 221 pp.
6. L.P. Yaroslavskii, *Digital Processing of Signals in Optics and Holography (Introduction into Digital Optics)* (Radio i Svyaz', Moscow, 1987), 296 pp.