RECONSTRUCTION OF LASER BEAM INTENSITY FROM THE NOISY TEMPERATURE FIELD OF A TARGET. II. PROCESSING OF MODEL AND LABORATORY EXPERIMENTS

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Some results of processing the model and laboratory experiments on reconstruction of the intensity distribution over a laser beam cross section from noisy temperature field of a thin target by means of a regularization FFT algorithm developed by the authors are presented. This algorithm is compared with the smoothing one based on the sinc-function. The advantages of applying the regularization FFT algorithm to resolution of fine structure of images are shown.

In the first part of this paper (see Ref.1) we have proposed a stable algorithm for reconstruction of laser radiation intensity from noisy temperature field at a thin target surface. To remove noises generated during temperature measurements, the regularization fast Fourier transform algorithm (FFT) correlated with the noises in the initial data was used. The advantages of this algorithm are as follows: a) fast data processing with a relatively small number of iterations is possible; b) the regularization parameter is automatically selected according to the principle of discrepancy and therefore there is no need to search the parameter in the dialogue regime; c) the parameter correlates with the noises in the initial data; d) the algorithm is quasi-optimal.

The algorithm of that kind selects the regularization parameter on the basis of discrepancy and it is optimal in certain sense (see Refs. 2, 3). In contrast to intuitive regularizing factors, it resolves fine image structure. As an illustration, we present (see Fig. 1*a*) the noisy temperature profile convoluted over both transverse coordinates with the following non-optimal regularizing factor:

$$\mathrm{sinc}(x) = \sin(\varkappa_{\max}\, x)/\pi x \qquad (1)$$

(see starred curve in Fig. 1*a*) and using the FFT algorithm proposed (see curve marked by triangles in Fig. 1*b*). It is seen from Fig. 1 that factors of sinc(x) type, in contrast to the algorithm proposed, cannot resolve two pulses spaced by less than $2h$ (here h is discretization step).

Below we present the results of application of the regularization algorithm to processing of model and laboratory experiments.

The intensity $I(\rho, t)$ and temperature at the surface of a thin metal target $T(\rho, t)$ expressed in terms of heat flux $q(\rho, t)$ through the surface reconstructed from this temperature (if heat losses are ignored, $q(\rho, t) = (1 - R)I(\rho, t)$, R is the reflection coefficient) are related by the following expressions (the initial temperature at the surface is assumed to be equal to zero $T(0, \rho, 0) = T_i = 0$):

a) if the temperature of the opposite side of a plate is sustained at a constant value (cooled target) $(T(L, \rho, t) = 0)$

$$q(\rho, t) = \frac{kL}{a^2}\left[\frac{\partial}{\partial t}T(\rho, t) - a^2\,\Delta_\perp\,T(\rho, t)\right], \qquad (2)$$

here k and a^2 are the coefficients of heat and temperature conductivity, respectively; L is the thickness of a target; t is time, $\rho = \{x, y\}$ is the transverse coordinate, $\Delta_\perp = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}$ is the transverse Laplacian;

b) if the opposite side is thermally insulated $\frac{\partial T(L, \rho, t)}{\partial z} = 0$

$$q(\rho, t) = \frac{k}{L}\,T(\rho, t) + \frac{kL}{3a^2}\left[\frac{\partial}{\partial t}T(\rho, t) - a^2\,\Delta_\perp\,T(\rho, t)\right]. \qquad (3)$$

Reconstruction of the intensity in the thermophysical situation described by Eqs. (2) and (3) was simulated by numerical experiment in the following way.

The temperature field $T(\rho, t_l)$ was calculated for time $t = \{0, t_{\max} = 1\text{ s}\}$ in equal time intervals $\Delta t = t_{\max}/M$, $M = 25$. In such a manner a set of temperature frames $T^l(\rho) = T(\rho, t_l)$ was obtained. Moreover each frame contains a set of transverse temperature distributions $T^l_{mj} = T(x_m, y_j, t_l)$, $(x_m = mh$, $y_j = jh$, $h = (a_1 - a_0)/N$, $m, j = 1, N$, $x, y \in [a_0 = -1, a_1 = 1]$, $N = 64)$. Then, the heat flux through the surface of the plate $q(\rho, t_l)$ was calculated using the regularization FFT algorithm and the intensity $I^l(\rho) = I(\rho, t_l)$ was reconstructed at the same moments in time $(t_l = l\Delta t$, $l = 1, M)$.

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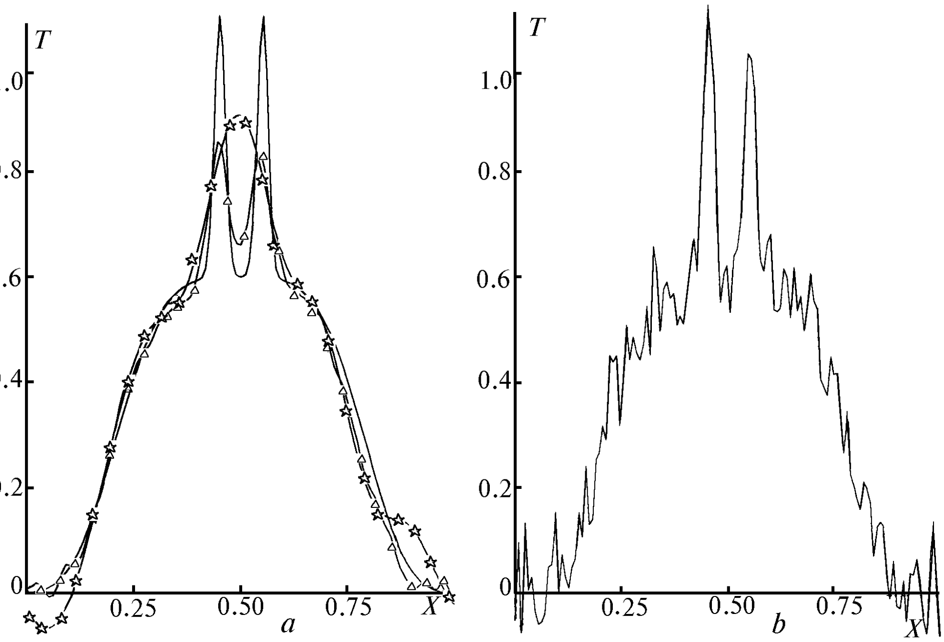

FIG. 1. Example of reconstruction of the noisy temperature profile: a) the model profile (smooth curve), the results of convolution of the model temperature profile with sinc function (stars), the convolution of this profile performed using the FFT algorithm proposed (triangles); b) the noisy temperature profile.

Besides, it was assumed that temperature distribution over spatial coordinates $T(\rho, t)$ measured at a given time had random measurement errors

$$T^l_{mj} = T(\rho_{mj}, t_l) + \xi^l_{mj} .$$

Here ξ^l_{mj} obeys normal distribution with the mean value being equal to zero and having the variance σ^2. Aluminum was chosen as a target material. The following function was used to simulate the initial intensity:

$$q(\rho, t) = \exp \{ -\alpha_1 (x^2 + y^2) \} \Theta(\tau) f(\tau) . \quad (4)$$

Here

$$\Theta(\tau) = \begin{cases} 1, & \tau \ge 0, \\ 0, & \tau < 0, \quad \tau \ge 1, \end{cases}$$

whereas $f(\tau)$ was given by

$$f_1(\tau) = 2.6\, I_0 \,[\exp(-(\tau - 0.5)^2\alpha_2) -$$

$$- 0.8 \exp(-(\tau - 0.5)^2\alpha_3)] \quad (5)$$

for a thermally insulated target or by

$$f_2(\tau) = I_0 \exp \left\{ - \frac{(\tau - 0.5)^2}{(0.5)^2 - (\tau - 0.5)^2} \right\} \quad (6)$$

for a cooled one. Here $I_0 = 1$ W/cm^2, $\tau = t/t_{max}$, $t_{max} = 1$ s. For both models $\alpha_1 = 4\ln(10)$, $\alpha_2 = 20$, $\alpha_3 = 60$. Dependence (4) at $t_{16} = 0.6$ (frame No.16) is shown in Figs. 2*a* and 3*a*. Results of reconstruction with the noise of 10% (which corresponds to $\sigma = 0.06$) without filtering of the initial data are presented in Figs. 2*b* and 3*b*. Figures 2*c* and 3*c* depict results of reconstruction of the heat flux with the use of the regularization FFT algorithm. In this case, the maximum reconstruction error was no more than 10%.

An automated IR imaging system (see Refs. 4 and 5) was used in laboratory experiment for measurement of the temperature distribution over the target surface. An AGA-750 IR imager operating at the wavelengths from 3 to 5 μm was used. Recording frequency was as high as 25 Hz. Aluminum plate with the sandblasted surface was used as a target. Its size and thickness were 40×40 cm^2 and 3 mm, respectively. A CO_2 laser with the output of 8–20 W operating in a nearly single-mode regime was used as the radiation source. The laser output was measured with IMO-2 calorimeter. The IR imager was calibrated using absolutely black body taking into account radiation coefficient of the target.

Twenty five consecutive frames of temperature distribution in 0.4 s intervals with the spatial resolution of $100\times100(N_x\times N_y)$ points were used as the initial data. The Fourier parameter for the initial experimental conditions ($a^2 \approx 9.28$ cm^2/s for aluminum, $L = 3$ mm, $t_{max} = 2$ s) was equal to $F_0 = a^2t/L^2 \approx 222 > 1$, what corresponded to the case of a thin target.

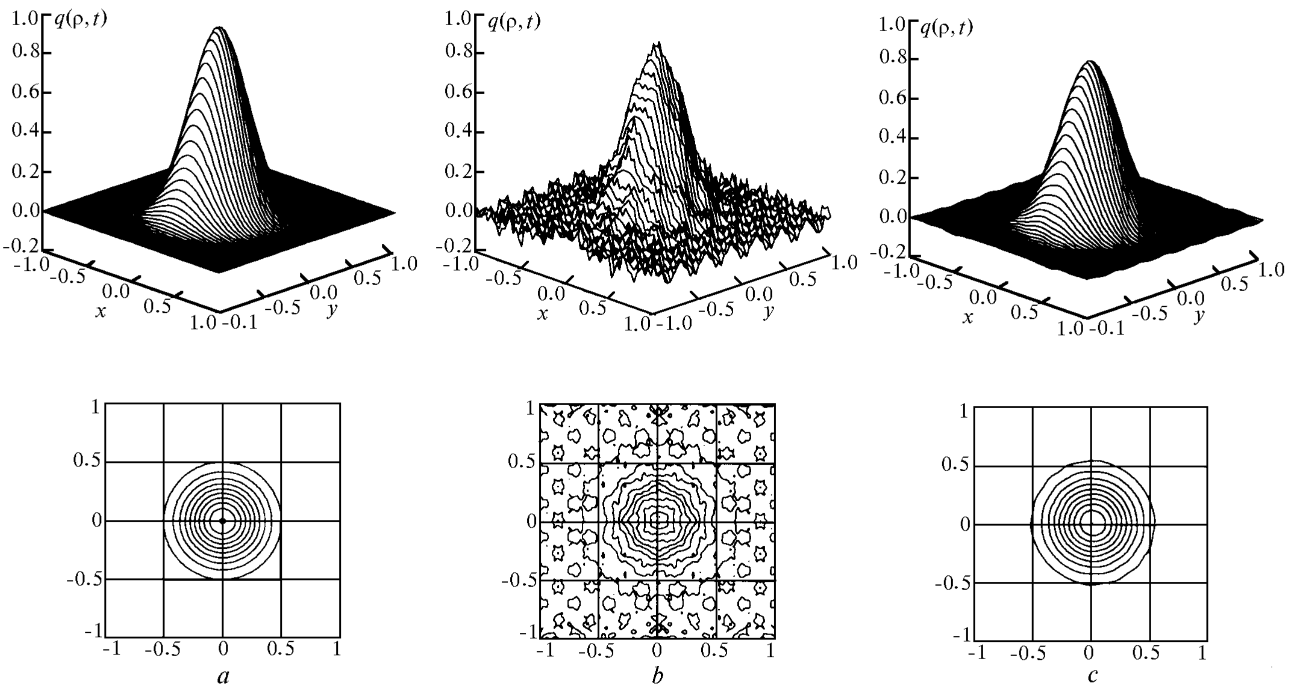

FIG. 2. Reconstruction of the heat flux through a cooled target: (a) model dependence, (b) the flux reconstructed without filtering of the initial data, (c) that reconstructed using the regularization FFT algorithm.

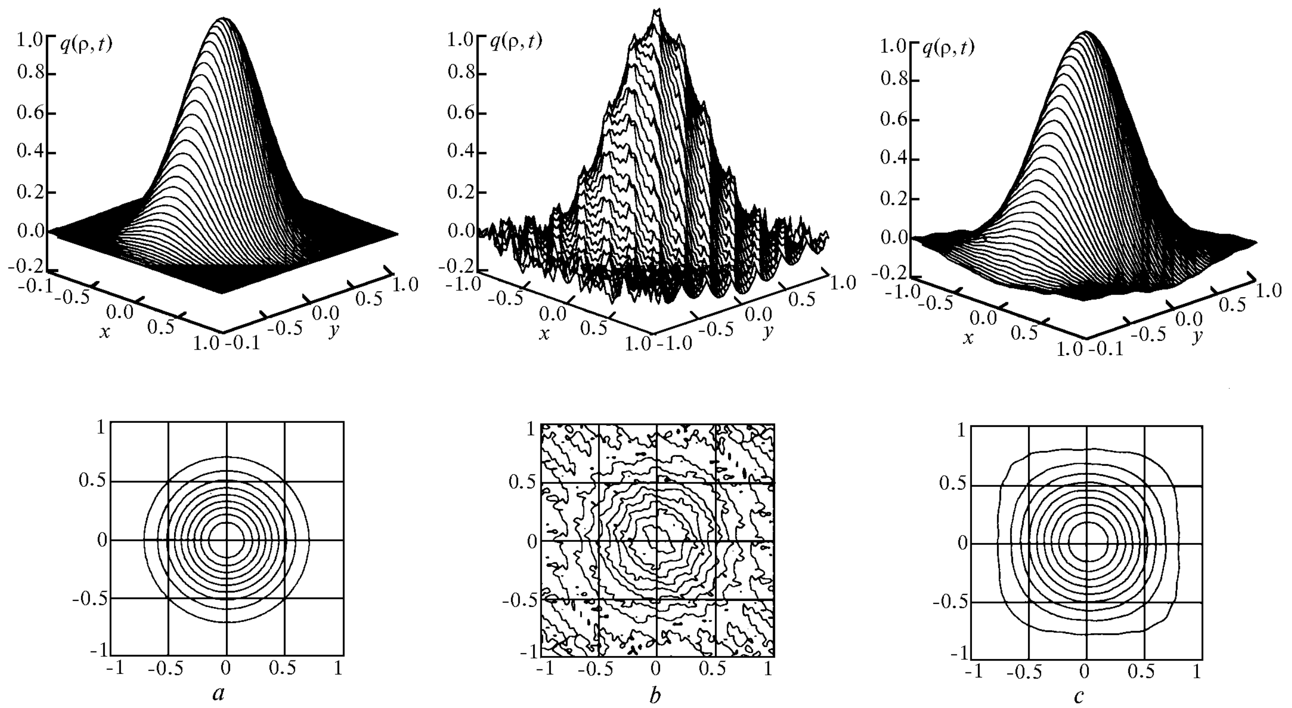

FIG. 3. Reconstruction of the heat flux through a thermally insulated target: (a) model dependence, (b) the flux reconstructed without filtering of the initial data, (c) that reconstructed using the regularization FFT algorithm.

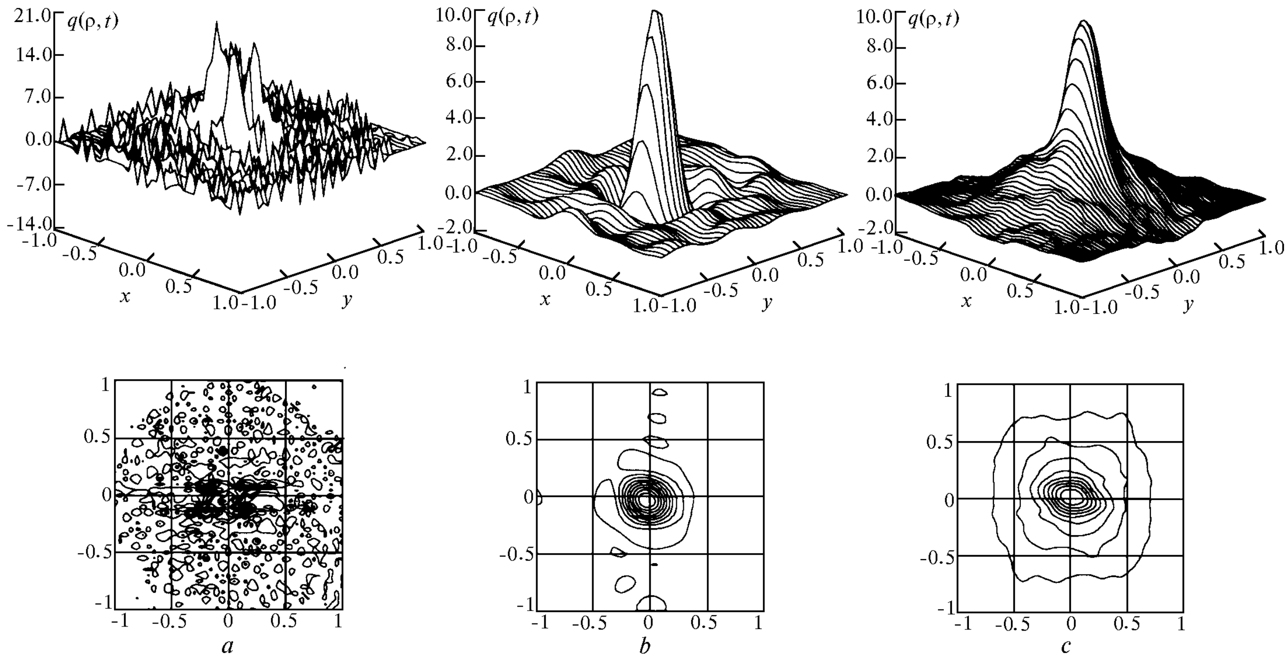

FIG. 4. Data of processing laboratory experiment: (a) the flux reconstructed without filtering of the initial data, (b) that reconstructed with the use of a sinc-function, (c) that reconstructed with the use of the regularization FFT algorithm.

Figure 4 depicts results of processing of one of the 25 experimental frames. Results of the heat flux reconstruction from measured temperature values without noise suppression are shown in Fig. 4*a*. Figure 4*b* illustrates those obtained using regularizing factor sinc(x). As is seen from the figure, some uncontrollable artifacts like negative intensity values appear during the processing. The flux reconstruction with the FFT algorithm is shown in Fig. 4*c*.

In this paper, some results of the laser radiation intensity reconstruction from the temperature field of a thin target obtained from numerical and laboratory experiments using regularization FFT algorithm are presented. The results are compared with those of the dada processing obtained with the use of non-optimal regularizing factor. Moreover, advantages of the algorithm are shown.

It should be pointed out that when solving such a three-dimensional spatiotemporal inverse problem, we restrict its regularization to spatial variables. Regularization of the temporal behavior was fully considered for one-dimensional target (case of a uniform flux) (see Ref. 6). In our opinion, since the time discretization is predetermined by measurement conditions (frame scan rate of the IR imager), the temporal regularization is made inevitably through limitation on the transmission band of the filter. Ill-posed character of the problem relative to time scale can manifest itself only with the increasing discretization frequency. It may also appear during measurements of integral, over space, moments of the intensity distribution (see Ref. 7). In this context two-dimensional spectral approach to the problem of correct reconstruction can be extended to spatiotemporal case by introducing of a generalized Fourier transform with two real and one imaginary frequencies. Regularizing procedures obtained in this way can provide not only given spatial resolution of measurements, but also a given temporal one which are limited only by the random errors of temperature measurements.

REFERENCES

1. Yu.N. Isaev and E.V. Zakharova, Atmos. Oceanic Opt. **9**, No. 10, 859–862 (1996).

2. V.K. Ivanov, V.V. Vasin, and V.P. Tanana, *Theory of Linear Incorrect Problems and Its Applications* (Nauka, Moscow, 1978).

3. V.P. Tanana, *Methods for Solution of Operator Equations* (Nauka, Moscow, 1981).

4. A.A. Dobotkin, A.V. Isakov, A.B. Il'in, et al., Atmos. Oceanic Opt. **7**, No. 5, 355–357 (1994).

5. A.V. Isakov, A.B. Il'in, A.P. Petrenko, et al., *Abstracts of Reports at the Eleven Interrespublic Symposium on the Propagation of Laser Radiation through the Atmosphere and Water Media*, Tomsk (1993), p. 188.

6. V.P. Aksenov and Yu.N. Isaev, Atmos. Oceanic Opt. **5**, No. 5, 332–336 (1992).

7. V.P. Aksenov, Yu.N. Isaev, and E.V. Zakharova, Inzh.-Fiz. Zh. **67**, Nos. 3–4, 275–280 (1994).