Monitoring of the aerosol formations travel velocity in the atmosphere by use of video and lidar data

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Received October 14, 2004

We discuss some problems in determining the travel velocity of aerosol formations from synchronous lidar and video observations carried out from the same point. Different atmospheric situations, in which the estimation of spatial scales of video images is to be done, are considered. The method of processing video information is based on the correlation tracking technique applied to moving objects. The spatial correlation analysis of video frames in the computer is carried out using the mixed-radix Fast Fourier Transform (FFT) algorithm. Experimental data on the estimated velocity of smoke plumes and cloud formations are presented as an example.

Introduction

The problem of rapid determination of wind parameters always is one of the most important problems in meteorology, because its solution is necessary for numerous practical applications.

Such applications include ecological studies of atmospheric pollution by harmful emissions. The key factor in the development and application of methods for calculation of a pollutant dispersal in the atmosphere is the possibility of operatively measuring the following atmospheric parameters: coefficients of horizontal and vertical turbulent mixing, wind velocity in the layer of the pollutant travel, and effective height of emissions, which also depends on the meteorological parameters.[1–5] Because the atmospheric parameters are usually to be determined in the atmospheric boundary layer, this calls for remote and contactless methods for measurement of the wind speed and direction.

Because the atmospheric aerosol can be considered as a wind tracer, analyzing the peculiarities of the space-time distribution of the aerosol field it is possible to determine wind velocity and atmospheric diffusion. Such investigations, when smoke plumes from the organized emission sources are used as an aerosol object, are being carried out for a rather long time with the use of passive methods based on film stereograms of plumes[6,7] and, recently, by the methods of digital stereophotogrammetry.[8,17]

In the laser sensing, wind parameters were determined from the correlation analysis of statistical characteristics of natural atmospheric inhomogeneities,[9,10] but then, based on the advances in lidar technologies, this method was replaced by a more promising one, namely, the method of Doppler-lidar measurements of the wind velocity.[11]

The active and passive sensing methods have their own advantages and drawbacks.

In stereophotogrammetric observations, photo cameras should be located at many (at least, two) positions and highly accurate synchronization of their exposures is necessary. As was noted in Ref. 8, the spatial arrangement of cameras is important, because the trajectory of an aerosol cloud depends on many factors and is hard to predict. It is clear that when the trajectory of the aerosol plume is directed perpendicularly to the base of the stereo system, such data cannot be used in processing. Therefore, multi-shot stereo experiments are quite laborious and expensive, and often they fail to ensure the needed quality of data at the remote parts of the plume, in particular, due to a decrease in the image contrast. The main advantage of the video filming is the instantaneous acquisition of the image of the plume as a whole.

When an aerosol cloud is sensed by a scanning lidar used as a rangefinder, it is easy to obtain the geometric dimensions of the object by scanning in the horizontal and vertical planes for a short time, usually, 1–2 min. At the same time, the main function of the lidar, in addition to the mapping of the distribution of aerosol formations, is the determination of the optical characteristics and microphysical parameters of the aerosol.[12–14] The attempts to use single-shot images of aerosol plumes for these purposes, in particular, to find the emission rate of a local source from the distribution of the brightness contrast in the image, were undertaken in Refs. 15 and 16. To do this, it is necessary to have a series of frames recorded in succession with the interval ~ 2 min for the observation period ~ 25 min under the condition of the relatively constant direction and speed of particle transport.[16] Naturally, for the observation period, these parameters, as well as irradiance of the object and the background can change significantly and distort the quantitative characteristics of plumes.

Since long ago, scanning lidar systems are equipped with video systems, mounted on the rotating platform of the lidar, with the properly aligned optical axes. Initially, video systems were used only as TV guides, searching objects in space and determining

0235-6880/04/12 885-06 $02.00

the boundaries of the lidar coverage sector. In recent papers (see, for example, Ref. 17) the possibility of combining the video and lidar technologies was demonstrated to construct 3D images of an aerosol cloud from a pulsed (explosive) source. For this purpose, four video cameras, spaced by 300–450 m from the source, and a lidar, separated by about 6 km from the source, were used. The absolute spatial positioning of the devices was performed with the use of the Global Positioning System (GPS).

The aim of this paper is to show the possibility of determining the parameters of aerosol plumes and cloud formations from synchronous lidar and video observations from a single site. It is clear that, in addition to this possibility, the lidar and video camera can also be used for determination of optical and microphysical parameters of aerosol objects, as shown in the literature cited.

1. Method and instrumentation

The main problem in analysis of video images of aerosol plumes is selection of spatial scales, especially, if a single-position video camera is used. That is why below we describe briefly the possible situations, in which this problem is solved with the use of only a single-position camera and the camera in combination with a lidar. The specifications of the LOZA-M lidar used in this work can be found in Ref. 13.

Thus, we have assembled a system for monitoring the velocity of aerosol objects (Fig. 1), which consists of the LOZA-M lidar *1*, standard SONY CCD-TR490E video camera *2*, computer equipped with a video capture card *3*, as well as the software developed specially for this system (mathematics in Visual Fortran 6.5, interface in Visual Basic 6.0).

This system allows one to estimate the velocity of aerosol formations by the following methods:

1. *Active and passive methods of data acquisition (general case).* This situation is characteristic of vertical and slant sensing, when there are no reference objects in the system's field of view. The geometry for realization of this method is shown in Fig. 2*a*.

The spatial scale of the object image and the object velocity are determined from the camera field of view α and the range to the object Z, which is determined with the lidar.

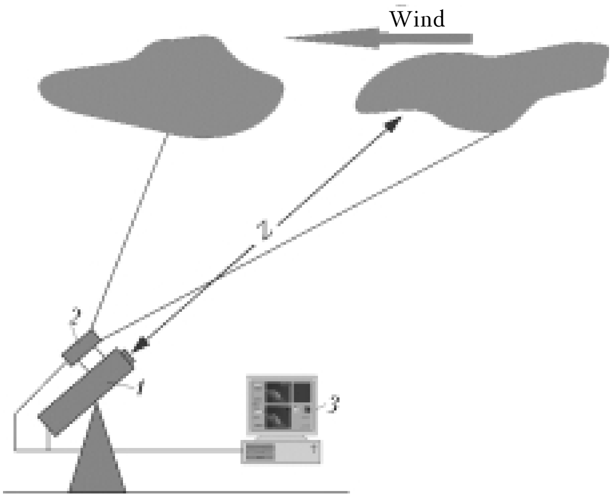


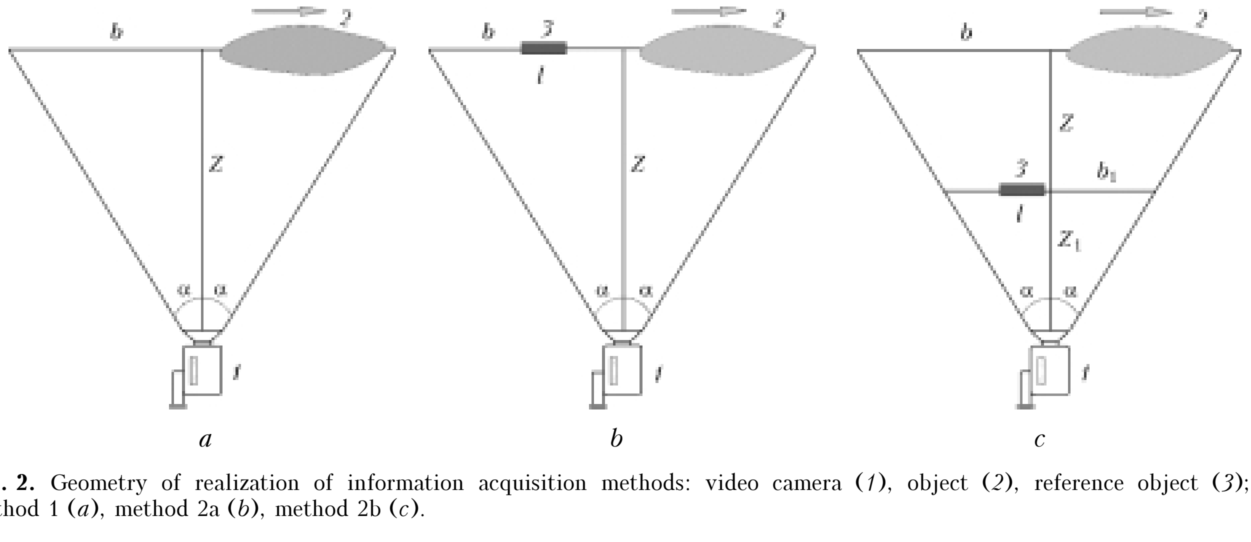
Fig. 1. System for monitoring of the velocity of aerosol objects.

The camera resolution is 352:288 pixels; the camera field of view in the horizontal plane is known for two cases: zero zoom ($2\alpha = 45°$) and 12-fold zoom ($2\alpha = 4°$). One pixel of the image in the horizontal plane amounts to 7′40.23″ and 20.45″, respectively.

In this case, the spatial scale of the image can be determined by the geometry laws:

$$b = Z \tan\alpha. \quad (1)$$

2. *Passive method of the data acquisition.* The use of only a passive method is characteristic of slightly inclined and horizontal paths, when the camera sees a reference object with known geometric parameters. Two cases are possible here:



a *b* *c*

Fig. 2. Geometry of realization of information acquisition methods: video camera (*1*), object (*2*), reference object (*3*); method 1 (*a*), method 2a (*b*), method 2b (*c*).

2a. Equal separation of the reference and analyzed objects from the measuring system. The spatial scale is determined, if the reference object with known geometric parameters is present in the frame (Fig. 2*b*). Aerosol formations should lie in the plane the reference object lies in, and this plane should be orthogonal to the observation vector (plume from a smoke stack).

The spatial scale of the image is determined by the following equation:

$$b = (l_r\, b_p)/l_p, \tag{2}$$

where l_r is the absolute length of the reference object, in m; l_p is the relative length of the reference object, in pixels; b_p is the half-width of the image raster (176 pixels).

2b. Different separations of the reference and analyzed objects from the measuring system. The spatial scale is determined when the reference object *3* with the known geometric parameters and the range Z_1 is present in the frame. This information allows the camera field of view α to be changed whenever it is necessary to scale the aerosol cloud image. Since the aerosol formation under study and the reference object are in different planes, it is necessary to determine the range to the cloud Z (Fig. 2*c*).

The camera field of view and the spatial scale of the image are determined as follows:

$$\alpha = \arctan(b_1/Z_1), \tag{3}$$

$$b = Zb_1/Z_1, \tag{4}$$

where b_1 is determined by Eq. (2).

Although the realization of only passive method is possible in the most cases, it is still desirable to have a lidar to check the hypothesis that the aerosol plume lies in the plane orthogonal to the observation vector, at least. This can easily be done by ranging the plume with the lidar at its opposite edges.

The estimation of the distance to an object with a lidar is an easy task, and therefore the main attention is paid to the description of the passive method.

The processing of the video information is based on the correlation technique in tracking moving objects, which is applied in various fields of science and technology, such as observation systems (machine vision), adaptive optics, etc.[18]

Figure 3 shows the main window of the program used.

This program allows performing the following functions:

– to display the image of an aerosol object as a whole;

– to monitor the object velocity along the orthogonal axes (V_x, V_y), as well as the resultant velocity;

– to select the correlation analysis window, as well as the information acquisition interval depending on the atmospheric situation;

– to select the operation mode of the system, thus providing for: a) image browsing, b) measurement;

– to save the current image as a file.

The correlation technique for measuring the displacement of an image fragment consists in the following:

– a characteristic zone is selected on the frame of a dynamic video image (size and position of the rectangular correlation analysis window);

96 x 96

V 8.501678

X-shift 2

Y-shift 1

Fig. 3.

– by the command “start tracking” the reference frame (rectangular array of brightness of image pixels in the analysis window) is stored;

– then the two-dimensional mutual correlation function of the reference and the current frames is calculated in real time, and the coordinates of its maximum are found, which determine the displacement of the current frame with respect to the reference one;

– by the signal from the program timer (as a given time is elapsed) the reference signal is updated, and the results of the correlation analysis are displayed in the form of the wind vector and the absolute values of its components.

The spatial correlation analysis of the video frames entered into the computer is performed with the use of the mixed-radix Fast Fourier Transform (FFT) algorithm.[19] This algorithm does not restrict the size of the window $N = 2^m$, which significantly facilitates the selection of the program parameters in the experiment (for example, in Fig. 3 the correlation window has the size of 96×96 pixels).

The mutual correlation function of the current and the reference frames is calculated as

$$C_{\mathrm{RC}}(\mathrm{d}x,\mathrm{d}y) = \iint I_{\mathrm{R}}(x,y) I_{\mathrm{C}}(x+\mathrm{d}x, y+\mathrm{d}y)\,\mathrm{d}x\mathrm{d}y,$$
$$C_{\mathrm{RC}} = F^{-}\left[F^{+}(I_{\mathrm{R}})F^{+}(I_{\mathrm{C}})\right], \qquad (5)$$

where I_{R} is the reference frame; I_{C} is the current frame; F^{+}, F^{-} are the direct and inverse discrete Fourier transforms.

To improve the accuracy of the algorithm used for determination of the object velocity, it is necessary first to set the following parameters: a) dimensions of the correlation window (pixels), which are set along the coordinates x and y (independently); b) interval between the reference and the current frames (seconds). These parameters are specified by the user in the program window based on the particular conditions of the experiment. The algorithm can be modified for the automatic selection of the parameters after a series of tests.

Before the beginning of operation (measurements), it is necessary to calibrate the window – to set the metrics. To do this, the reference object is selected in the window of the video image and its parameters (in meters) are set.

Now the pixel scale factor in the screen is determined as

$$d_{\mathrm{p}} = Base / L_{\mathrm{p}}, \qquad (6)$$

where *Base* is the base length of the reference object, in m; L_{p} is measuring tape size, in pixels.

The object velocity is determined as

$$V_x = |\mathrm{d}X_{\max}| d_{\mathrm{p}}/t,\ V_y = |\mathrm{d}Y_{\max}| d_{\mathrm{p}}/t,\ V = \sqrt{V_x^2 + V_y^2}, \qquad (7)$$

where $\mathrm{d}X_{\max}$, $\mathrm{d}Y_{\max}$ are the displacements of the maximum of the cross correlation function, determined by Eq. (5); t is the delay between the reference and the current frames, by which the correlation is calculated (specified by the user in the program window as the correlator time, in seconds).

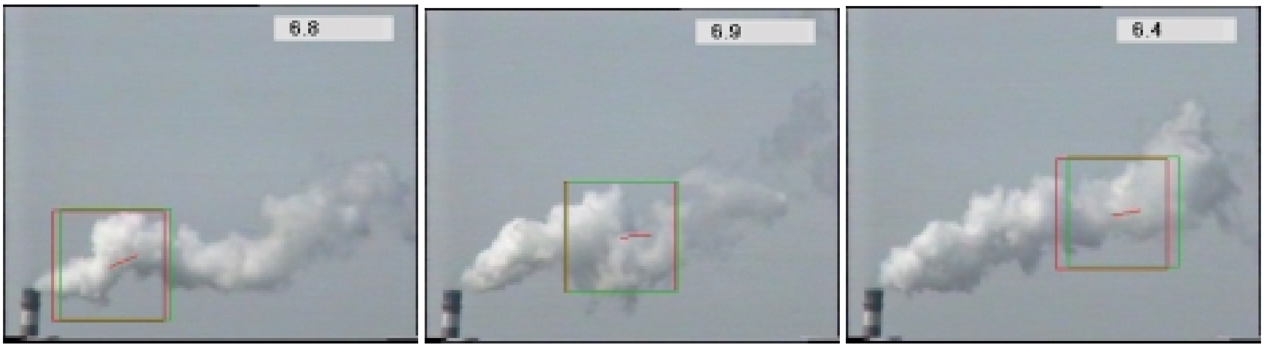
2. Experimental results

The experiments on the estimation of the velocity of aerosol objects, namely, a smoke plume (passive information acquisition method), and cloud formations (combination of the active and passive methods) were carried out under field conditions.

2.1. Smoke plume

As a source of aerosol emissions, we selected the smoke stack of the GRES-2 heat and electric power plant of Tomsk. The information retrieval was carried out at 15 LT on April 20 of 2004 at the line-of-sight distance of 3200 m. The height and the diameter of the smoke stack were, respectively, 100 and 8 m. The stack served a reference object, used to calculate the camera field of view (with the selected zoom values), the spatial scale of the object, as well as the object velocity (processing method 2a).

With the analysis window of 96×96 pixels, different versions of object ”lock-on” were considered: at the beginning, middle, and end of the aerosol plume (Fig. 4). The method appeared to be stable, and the variance of the velocities was low.



a *b* *c*

Fig. 4. Aerosol plume: (*a*) start; (*b*) middle; (*c*) end, digits indicate the absolute value of the wind velocity, m/s.

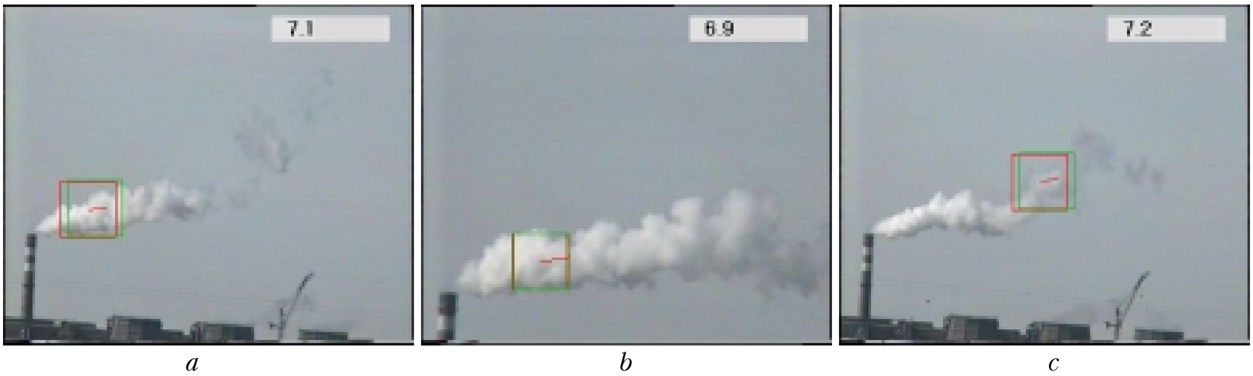


Fig. 5.

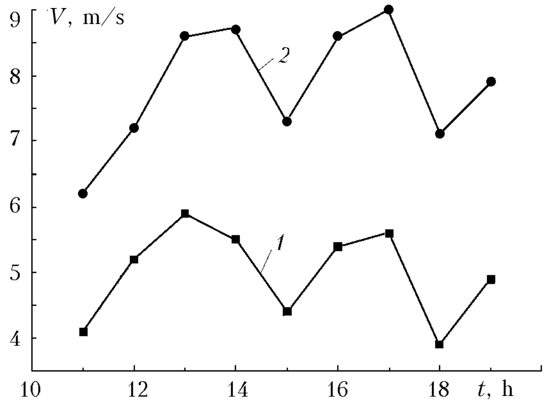


Fig. 6. Wind velocity V at the heights of 10 (*1*) and 40 m (*2*).

In addition, the versions with different filling of the window by the object (smoke plume) were considered: 1) when the object fits within the window and is clearly seen (Fig. 5*a*); 2) when the object fully fills the correlation window, and its contours are beyond the window (Fig. 5*b*); 3) with remains of the smoke plume considered as an object (Fig. 5*c*). In the first case the method works stably. This is the ideal version for the analysis: clear boundaries of the object fit within the window, the object moves monotonically and keeps its shape. In the second case, the method also works, but with failures. To avoid them, the structure of the studied object in the correlation window should be nonmonotonic. In the third case, when the correlation at the end of the plume is considered, the method is stable (MCF is significant) until the field of aerosol inhomogeneities keeps its shape.

Under these conditions, the data processed showed that the mean velocity of the aerosol plume was 7 m/s. According to the data of the TOR-station of the Institute of Atmospheric Optics, the wind velocity at the height of 40 m at that time was 7.3 m/s (Fig. 6) with the southern direction, that is,

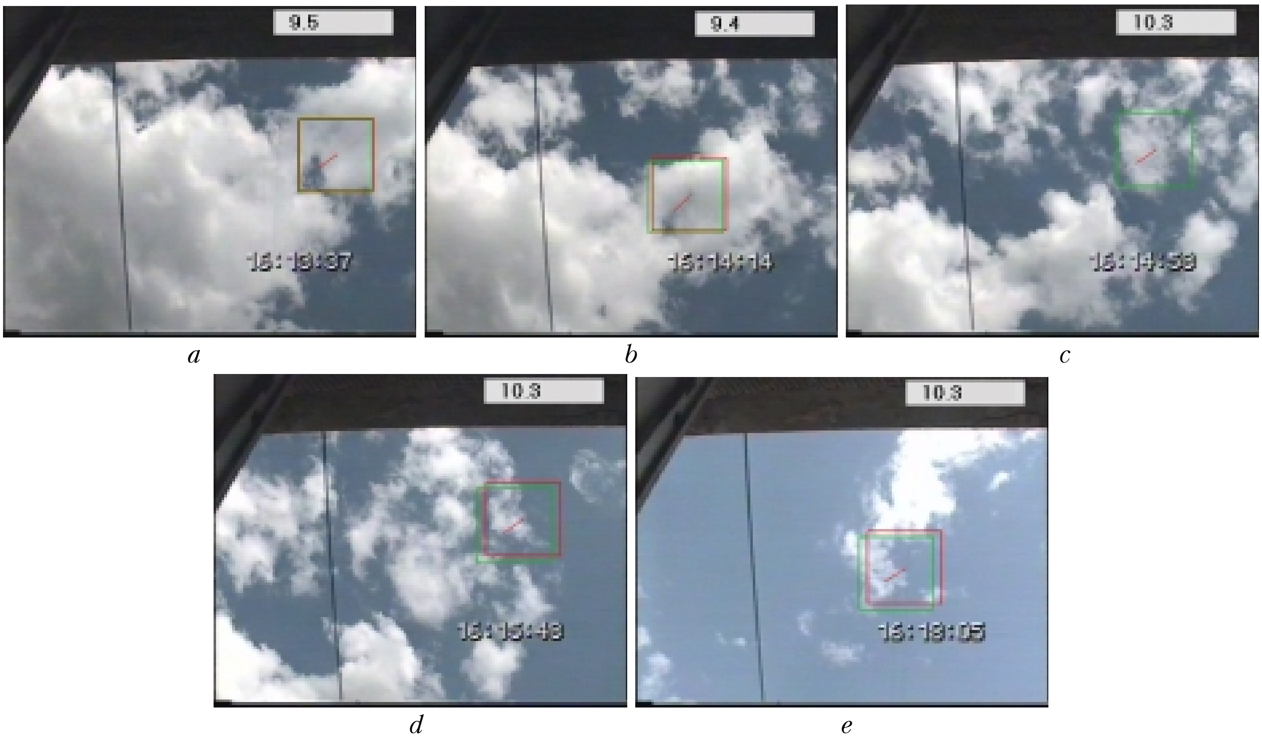


Fig. 7.

the velocity vector of the smoke plume was almost perpendicular to the observation vector (≈ 7°). Thus, our experimental data do not contradict the data of the TOR-station.

2.2. Cloud fields

The information was retrieved on June 6 of 2004 at the angle of 45° to the horizon with the stratocumulus clouds. The range to the clouds was 2 km, and the cloud height was 1.4 km. With the zero zoom, the camera field of view is 45° (that is, the half-width $\alpha = 22.5°$); correspondingly, the spatial scale of the image was 1400 m. Figure 7 shows the experimental results, according to which the mean velocity of clouds was 9.9 m/s with the southwestern direction.

Thus, the results obtained do not contradict the data of the existing models of wind stratification.[20]

To determine the speed and direction of motion of cloud formations, the ideal case is vertical sounding. In this case, the measurement error is minimum, while the accuracy is maximum.

Conclusions

The instrumental system has been designed for monitoring the velocity of aerosol formations in the atmosphere, combining the passive and active information acquisition methods with the following correlation processing. This system allows the dynamics of aerosol formations, namely, the position, velocity, and structure, to be studied in real time. The method has been tested under field conditions, and the error in determination of the velocity of aerosol formations was approximately estimated to be 5–7%. The stability of the method and the reliability of the results keep as the scale is changed.

The further development of the instrumentation and methodology of data acquisition and processing should be associated with the use of digital video cameras with the direct real-time input of the image into the computer, as well as with the modification of the image processing technique, allowing the analysis of aerosol fields with lower contrast. This will permit this system to be used in almost any atmospheric situation, in particular, in an automated mode.

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