
ЕЛЕКТРОФІЗИКА

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E-mail: marik.doikov@gmail.com; ORCID iD: <https://orcid.org/0000-0001-5240-7097>***Visualization of lightning in dusty atmospheric plasma**

The visualization of processes in a dust-laden atmospheric plasma during the initiation of lightning discharges is considered. An analysis of the relaxation times of characteristic kinetic processes required for the formation of the radiative visual pattern of a lightning discharge is carried out. An algorithm is developed for the reconstruction of rapidly forming spectral images of lightning discharges. An attempt is made to develop new instrumental methods for analysis and control in solving inverse problems of reconstructing geometric images of the physical objects under study.

Keywords: *lightning spectroscopy; reconstruction and visualization of plasma configurations; binary detector; CsPbBr₃ semiconductors; non-equilibrium thermodynamic plasma with a condensed dispersed phase.*

Introduction. High-speed relaxation processes accompany lightning discharges in atmospheric plasma. Initially, an undisturbed atmosphere is subjected to a strong current discharge. In [1-3], it was theoretically demonstrated that in a strong electric field, electron velocities become relativistic and are limited only by the efficiency of energy losses in thunderclouds. Let the maximum time for the sequential transfer of a current impulse from an accelerated electron to atmospheric molecules and atoms be denoted as τ_m . We define τ_m as the ratio of the mean free path λ to the relativistic velocity v_{rel} : $\tau_m \approx \frac{\lambda}{v_{\text{rel}}} \approx \frac{10^{-7} \text{ m}}{2.9 \times 10^8 \text{ m/s}} \approx 3 \times 10^{-15} \text{ s}$. For most atmospheric atoms, the de-excitation time of electron shells at the K-levels after impact by a relativistic electron is constrained by the Heisenberg uncertainty principle. For K-shell energies in the range of 200–600 eV, the characteristic time is $\tau_{\text{ex}} \approx 4 \times 10^{-17} \text{ s}$. The only experimental evidence for the relativistic nature of electrons in atmospheric discharges is the detection of hard X-ray and soft gamma radiation produced by bremsstrahlung emission. Lightning channels exhibit cascade-like structures—linear segments followed by abrupt changes in the trajectory of the current-carrying cylinder. Each cascade can be associated with an avalanche-like amplification of the current accompanied by simultaneous energy dissipation.

The observation of hard radiation during such cascades provides information about the local parameters of the low-temperature plasma with a condensed dispersed



phase (non-equilibrium thermodynamic plasma with a condensed phase, LTP with CDP) formed within the lightning current channel.

Sources. The source of seed secondary electrons is the continuous process of primary ionization caused by cosmic radiation in the upper layers of the atmosphere. At sufficiently high concentrations of solid-phase particles, an additional flux of photoelectrons emitted from their surfaces is also present. Once the current is established and electrons are accelerated to relativistic velocities, the mechanism of ionization losses becomes dominant, exhibiting an unstable and irregular character. As both the energy and the number of electrons increase, the current-carrying plasma transitions into a relativistic regime. Within the cascade region, an avalanche-like process of electron multiplication develops, accompanied by simultaneous ionization of atoms and molecules.

Hard Radiation Spectra. Upon reaching relativistic velocities, radiative losses become significant in the form of bremsstrahlung and synchrotron radiation. Under lightning conditions, the deceleration of relativistic electrons can transfer energies of up to ~ 200 keV to emitted photons. The detection of high-energy gamma radiation can be attributed to interactions involving counter-streaming proton fluxes generated through hydrogen ionization. The theoretical upper energy limit of such protons can reach hundreds of MeV. As shown in [5], collisions of these protons with atmospheric nuclei produce gamma radiation in the energy range of 5–40 MeV. An important confirmation of the proton contribution is the presence of annihilation lines arising from electron–positron pairs, generated by gamma photons with energies exceeding 1.022 MeV in the nuclear field. The next evolution of the lightning discharge depends on the relative contributions of radiative losses and the thermodynamic energy transferred to the surrounding medium.

In plumes, the partial or complete de-excitations of atoms begins with the filling of vacancies in the K and L shells, resulting in characteristic fluorescence lines. Simultaneously, due to the presence of vacancies in higher electronic levels, less probable recombination lines are expected, arising from three-body collisions. In the optical and infrared spectra, this manifests as plumes (or halos) following an X-ray or gamma-ray burst. Such plumes are explained as a consequence of Compton scattering [4,5]. The production of gamma photons with energies exceeding ~ 1.1 MeV in lightning discharges leads to the formation of electron–positron pairs in the nuclear fields of atmospheric atoms. Positron spectroscopy, analogous to Positron Emission Tomography combined with computed tomography (PET/CT) in medical applications, has enabled the detection of structural inhomogeneities in irradiated biological media. By analogy, the same approach is proposed here for detecting inhomogeneities in localized regions of thunderclouds, in terms of the fractional composition of the dispersed phase (solid or liquid particles). The following sections will describe the design of high-speed monitoring spectrographs for hard radiation.

The dynamic spectra is next step to estimate of the formation rate in hard radiation dynamic spectra. The study of local processes within lightning discharges is no longer

feasible without the registration of hard radiation spectra. The lower limit of the ionization front propagation time τ_{shock} can be estimated using the average relativistic velocity v_{rel} : $\tau_{\text{shock}} \approx \frac{\lambda_{\text{casc}}}{v_{\text{rel}}} \approx \frac{10^2 \text{ m}}{2.9 \times 10^8 \text{ m/s}} \approx (0.3-1) \times 10^{-6} \text{ s}$. Under realistic physical conditions and geometric parameters within the cascade region, the rate of energy dissipation significantly increases the duration of the ionization shock front τ_{shock} by several orders of magnitude. Thus, the characteristic time range can be expressed as: $10^{-6} \text{ s} \leq \tau_{\text{shock}} \leq 10^{-3} \text{ s}$. It follows that the dynamic spectra of lightning contain information about the full set of characteristic times associated with the fundamental physical processes in the plasma.

The optical spectra in lust centuries, have been primary sources of information about lightning discharges during flashes. The temporal delay between the optical and gamma-ray flashes of lightning typically begins at milliseconds and extends to longer timescales. The growth of the low-energy tail in the electron energy distribution within the current-carrying channel is associated with secondary radiation processes occurring inside the channel. In other words, ultraviolet and soft X-ray radiation stimulate further optical emission and induce a rapid thermal perturbation. Synchrotron radiation may also contribute to this process. In previous studies [5], the absorption properties of the atmosphere were analyzed, and spectral transparency windows for radiation escaping from the current layer of an atmospheric discharge were identified. These windows were found at energies above approximately 80 keV. Most soft X-ray and hard ultraviolet photons remain effectively confined within the current channel due to photoabsorption; their energy is efficiently converted into further ionization and heat, ultimately reaching the observer in the form of lower-energy photons and acoustic shock waves.

High-Speed Spectrograph for Hard Radiation. The investigation of the dynamic and geometric structure of lightning discharges requires hard radiation detectors and acquisition interfaces operating on microsecond time scales, similar to those used in computed tomography (CT) [6]. Following the CT paradigm, we adopt analogous interfacing principles. However, instead of a planar detector array, we employ a different concept of information acquisition. Modern detection of hard X-ray and soft gamma quanta is based on semiconductor crystals composed of high atomic number (high-Z) elements. The dead time of such detectors typically ranges from nanoseconds to microseconds. At present, cost limitations associated with high-speed electronic interfaces have largely been eliminated, and the necessary components are commercially available. In works [4,5], codes were developed for interfacing electronic systems operating in photon-counting mode. Thus, instead of a multi-element detector matrix, we utilize a single monocrystalline detector of cubic geometry with a side length of approximately 1 cm. Spectral reconstruction is based on the registration of the current pulse generated by each detected photon. Detector calibration is performed using standard radioactive isotopes, whose emission lines cover the entire relevant spectral range. The choice of monocrystalline semiconductor detectors is determined by the presence of heavy elements in CsPbBr₃, which ensures high efficiency in photon-counting mode. Incident photons interacting within the CsPbBr₃ detector generate current pulses in the

volume between crystal faces, across which a potential difference of $\varphi \sim 10^2\text{--}10^3$ V is applied. As a result, instantaneous spectra can be obtained. However, image reconstruction with such spectrographs cannot be achieved within a single telescope configuration. Spatial visualization of lightning discharges requires a sufficiently complete set of basis measurements obtained from multiple observational units. A minimal configuration implies the deployment of detectors at more than three spatially separated locations. Data acquired within such a distributed basis allow for the reconstruction of synchronized, microsecond-scale dynamic images of lightning discharges across different spectral bands. A similar approach is used in meteor tracking systems, such as those operated by the Odessa Astronomical Observatory, to reconstruct trajectories of extraterrestrial objects entering the Earth's atmosphere. As in computed tomography, one component of the tomographic system is fixed (in this case, the detector array basis), while the second component—the object of study (lightning)—is dynamically evolving. The formation of instantaneous microsecond spectra has been analyzed using a binary detector for optical and hard radiation, as presented in Giant4-DNA versus [7]. Reconstruction of planar dynamic images of lightning must account for changes in the structure of the current-carrying channel. Thus, the problem involves reconstructing a sequence of images describing the evolution of lightning from its initiation to its termination.

Binary Detector–Spectrograph for Optical and Hard Radiation. The construction of lightning spectra has traditionally been performed in the optical and near-infrared ranges, i.e., within the atmospheric transparency windows. The parameters of such radiation are formed as a result of the radiative relaxation of excited molecules and atoms in the atmosphere. However, this information is often insufficient for describing the conversion of relativistic electron energy into radiation. The integration of a hard radiation spectrograph into such an instrument, operating within a unified time-synchronized electronic interface, was proposed in [4,5] and further elaborated in tabular form below. During a lightning discharge, hard radiation arises from interactions of relativistic electrons with atmospheric atoms. The characteristic interaction times can be divided into the time between pairwise electron–atom collisions, τ_{coll} , and the characteristic atomic de-excitation times, τ_a . Numerical estimates show that $\tau_a \ll \tau_{\text{coll}}$, $\frac{\tau_{\text{coll}}}{\tau_a} \sim 10^8$. This implies that the collision frequency $1/\tau_{\text{coll}}$ is proportional to the photon production rate. In quantum collision theory, the interaction of a relativistic electron with an atom is governed by the de Broglie wavelength $\lambda_D = \frac{h}{p_{\text{rel}}} \approx 10^{-11}\text{--}10^{-13}$ m, where p_{rel} is the momentum of the relativistic electron. These processes lead to sequential ionization and recombination involving K-shells of atmospheric atoms, sustaining a heterogeneous plasma state. Following K-shell ionization, allowed transitions such as $2p \rightarrow 1s$ occur in C, N, and O atoms. Hydrogen and helium atoms primarily undergo ionization followed by collisional relaxation or recombination. Recombination processes require less probable three-body collisions. In lightning observations, this radiation manifests as plume-like structures. In [5] using [7], it was shown that despite the presence of atmospheric transparency windows, soft X-ray and hard

ultraviolet radiation emitted by C, N, and O atoms are almost completely absorbed within and in the vicinity of the lightning channel. The characteristic times associated with mechanical energy transfer from electrons to atoms and molecules include the thermalization time τ_{heat} , radiative relaxation time τ_{rad} , and shock wave formation time τ_{shock} . It was also demonstrated that, together with optical radiation, hard X-ray and soft gamma radiation with energies $E_{\gamma} \gtrsim 60$ keV can reach the detectors. A comprehensive coverage and synchronization of processes related to the electrophysics of lightning discharges are only possible with a sufficiently large array of binary detector–spectrographs for gamma and optical radiation operating in photon-counting mode [4]. The photon fluxes incident on the detectors from lightning do not exceed 10^6 cm^{-2} , which allows operation without detector saturation.

Visualization of Atmospheric Plasma Configurations.

Physical Basis. The initial data are obtained from the detector systems presented in this work. Let the array of detector measurements be denoted by Y , and the data describing the shape and state of the lightning discharge by X . The application of computed tomography methods has proven effective for investigating plasma configurations under both laboratory and field conditions. Reconstruction of three-dimensional structures of such configurations requires a basis consisting of more than three fixed observation points with radius vectors $\mathbf{r}_i = (x_i, y_i, z_i)$. Each detector is mounted on a telescopic system and is described in angular coordinates (α_i, ϕ_i) , where $i = 1, 2, 3, \dots$. Thus, the detector system forms both a spatial and a physical basis. The integration of these two bases constitutes the main objective of this section.

Mathematical Basis. Synchronization of spectrographs and data acquisition. To extend lightning diagnostics using a binary detector system, the following conditions must be satisfied:

- The format of the acquired and recorded data must be standardized to enable subsequent visualization. In this work, we adopt the DICOM format, widely used in tomographic imaging.
- A synchronization unit discretizes the spectrograph data in time with microsecond resolution.
- Data recording in DICOM format must include mandatory metadata fields specifying the time of measurement and the formation of each spectrum.

Radiative Transfer Equation for Intensity. The geometric configuration of a lightning discharge is formed by radiation emitted from a current-carrying cylindrical channel within a given region of space. For monochromatic X-ray radiation with energies $E \geq 30 \text{ keV}$ (typical for computed tomography), the radiative transfer equation in integro-differential form is given by:

$$\frac{dI(\mathbf{r}, \Omega)}{ds} = -\mu_t(E, \mathbf{r}) I(\mathbf{r}, \Omega) + \int_{4\pi} \mu_s(E, \mathbf{r}) p_{KN}(\Omega' \rightarrow \Omega) I(\mathbf{r}, \Omega') d\Omega' \quad (1)$$

Where

- $\mu_t = \mu_a + \mu_s$ – полный коэффициент ослабления,
- μ_s – коэффициент комптоновского либо Рэлеевского рассеяния,

- $p_{KN}(\Omega' \rightarrow \Omega)$ – индикатриса рассеяния Клейна–Нишины, нормированная по 4π .

Here we have:

- $\mu_t = \mu_a + \mu_s$ is the total attenuation coefficient,
- μ_s is the scattering coefficient (Compton or Rayleigh),
- $p_{KN}(\Omega' \rightarrow \Omega)$ is the Klein–Nishina scattering phase function, normalized over 4π .

$$I(\Omega_s) \approx I_0 e^{-\mu_t L} + \int_V I_0(\Omega_0) e^{-\mu_t s_1} \mu_s(\mathbf{r}) p_{KN}(\theta) e^{-\mu_t s_2} \frac{dV}{4\pi R_s^2} \quad (2)$$

Here:

- s_1 is the path from the source to the scattering point,
- s_2 is the path from the scattering point to the detector,
- θ is the scattering angle,
- dV is the volume element (within the hypoxic region).

In lightning discharges, the first exponential term $e^{-\mu_t s_1}$ can be approximated as unity, since the origin of scattering coincides with the current-carrying channel. If the lightning illuminates fragments of the surrounding atmosphere, the factor $e^{-\mu_t s_1}$ describes the attenuation of its radiation.

Klein–Nishina Compton Scattering Phase Function. For photon energy $E = 130\text{keV} (\approx 0.254 m_e c^2)$, the Klein–Nishina differential cross-section at scattering angle θ is given by:

$$p_{KN}(\theta) = \frac{1}{\sigma_{KN}} \frac{r_e^2}{2} \left(\frac{E'}{E}\right)^2 \left(\frac{E'}{E} + \frac{E}{E'} - \sin^2 \theta\right), \quad E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos \theta)} \quad (3)$$

Here, σ_{KN} is the total (integrated) Klein–Nishina cross-section for electrons. For detectors positioned at a scattering angle $\theta_s \approx 90^\circ$, the energy ratio is given by: $\frac{E'}{E} |_{\theta=90^\circ} = \frac{1}{1+\alpha}$, $\alpha = \frac{E}{m_e c^2} \approx 0.254$, which yields $\frac{E'}{E} \approx 0.797$. In [1-6], it was shown that in thundercloud aerosols, the contributions of scattering and photoabsorption to the structure of the detected spectra are significant for photons with energies above approximately 30 keV. Characteristic X-ray emission lines of atmospheric atoms are absent at any distance from the lightning channel, as they remain effectively “trapped” within the current-carrying cylinder due to strong photoabsorption.

In the energy range from 30 keV to 90 keV, scattered radiation dominates, analogous to continuous optical spectra. X-ray spectra depend primarily on the electron density along the photon path, i.e., on the matter density or variations in chemical composition along the line of sight. Differences between the densities of atmospheric gas and aerosols along the propagation path enable the measurement of the relative mass fraction of the condensed phase.

The detection of gamma quanta during lightning discharges by satellites and later by gamma detectors at the Fukushima nuclear facility, as well as by the Compton Gamma Ray Observatory and INTEGRAL satellites, indicates that the energy distribution of hard radiation shifts toward higher energies at sufficiently high discharge power. Therefore, local plasma characteristics generated by lightning can be recorded by sensitive detectors. The binary detector proposed in [4] is particularly effective for

lightning diagnostics. Uncertainty in the position, geometry, and boundary parameters of lightning leads to a large number of unknown variables. Therefore, it is essential to choose reconstruction and visualization methods that minimize the number of parameters. We aim to reconstruct quantities such as the integral luminosity of hard radiation within the atmospheric transparency window, coupled with the temporal dynamics of the growth and decay of energy-related parameters.

Main Reconstruction Approach. The lightning channel is discretized into a set of small elementary segments $\mathbf{r}_k(t_k)$. Each event corresponds to a short segment of the channel emitting an electromagnetic pulse at time t_k . Detector i registers this signal at time: $t_{i,k} = t_k + \frac{|\mathbf{r}_k - \mathbf{r}_i|}{c}$, where c is the speed of light. The differences in arrival times between detectors are given by:

$$\Delta t_{ij,k} = t_{i,k} - t_{j,k} = \frac{|\mathbf{r}_k - \mathbf{r}_i| - |\mathbf{r}_k - \mathbf{r}_j|}{c}. \quad (4)$$

This fundamental equation is referred to as the Time Difference of Arrival (TDOA) formulation and is presented in Table 1 of this work. For two-dimensional (2D) reconstruction, a minimum of three detectors can be used. For full three-dimensional (3D) reconstruction, at least four detectors are required, since the following quantities are unknown: x_k, y_k, z_k, t_k , i.e., four parameters – three spatial coordinates and the emission time. In practice, it is preferable to use $N \geq 5$ or 6, since lightning has a complex structure, involves noise, reflections, non-simultaneous emission, and multiple branching channels.

Geometric Reconstruction from Emitting Points. For each short pulse, the coordinates \mathbf{r}_k are determined by minimizing the functional: $\chi^2(\mathbf{r}_k, t_k) = \sum_{i=1}^N \left[t_{i,k}^{\text{obs}} - t_k - \frac{|\mathbf{r}_k - \mathbf{r}_i|}{c} \right]^2$, or, in the TDOA formulation:

The minimum of this functional yields the position of the elementary emission source.

$$\chi^2(\mathbf{r}_k) = \sum_{i < j} \left[\Delta t_{ij,k}^{\text{obs}} - \frac{|\mathbf{r}_k - \mathbf{r}_i| - |\mathbf{r}_k - \mathbf{r}_j|}{c} \right]^2 \quad (5)$$

Reconstruction of Lightning Geometry. After processing a large number of pulses, a cloud of points is obtained: $\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_M$ set. This is no longer a single point, but a spatio-temporal structure of the lightning channel: $\mathbf{r} = \mathbf{r}(t)$. The following steps are then performed:

- filtering of noise points;
- clustering in time and space;
- extraction of the main branch;
- identification of secondary branches;
- construction of a 3D lightning curve;
- smoothing using splines or a graph-based model.

As a result, lightning is represented as an irregular graph: $G = (V, E)$, where vertices V correspond to reconstructed emission points, and edges E represent connections between consecutive segments of the channel. The operation of visualizing physical processes together with their geometric structure is referred to as reconstruction. Reconstruction itself constitutes the fundamental inverse problem of recovering spatial objects, or their cross-sections, from data acquired by the detectors described above.

For lightning studies, it is essential to select spectral data that encode physical information about local properties of the medium. Detector measurements enable the reconstruction of integral energy parameters and the localization of emission regions. In particular, one can estimate the total energy released during atmospheric discharges and its partition into plasma formation, radiative bursts, and acoustic shock waves.

Matrix Formulation of the Inverse Problem. Using the notation introduced in Section I, we construct a matrix equation to recover the distribution of an unknown quantity. In the present case, this corresponds to the emission activity of lightning radiation. Let:

- $x = \{x_j\}_{j=1}^{N_{\text{vox}}}$ be the unknown parameters (voxelized emission intensities),
- $y = \{y_i\}_{i=1}^{N_{\text{meas}}}$ be the measured data.

They are related through a discretized forward model of the radiative transfer equation:

$$y_i \sim F\left(\sum_j A_{ij} x_j\right) \tag{6}$$

Here:

- A_{ij} is the system matrix encoding both the geometry and physics of the lightning discharge and the detector configuration,
- F is the statistical measurement model (likelihood function).

Using MLEM reconstruction for solving the problems with a large number of contributing stochastic parameters, an iterative scheme known as Maximum Likelihood Expectation Maximization (MLEM) is used. The likelihood function is given by: Maximization of $\ln L(x)$ leads to the MLEM iterative update rule:

$$L(x) = \prod_i \frac{\left(\sum_j A_{ij} x_j\right)^{y_i} e^{-\left(\sum_j A_{ij} x_j\right)}}{y_i!} \tag{7}$$

$$x_j^{(k+1)} = x_j^{(k)} \cdot \frac{\sum_i A_{ij} \frac{y_i}{(Ax^{(k)})_i}}{\sum_i A_{ij}} \tag{8}$$

After specific features of the Lightning Reconstruction Problem, we proposed using of the conventional computed tomography. In contrast with this in present work we approach employs a relatively small number of detectors ($i = 3-4$), supplemented by a time series of measurements. The limited number of detectors necessitates the use of a Poisson statistical model during data processing. The binary detector design incorporates a short-focus mirror for recording the optical spectrum. The hard radiation detector is positioned as close as possible to the entrance aperture, along the direct optical

axis of the telescope system. This configuration ensures maximal coverage of the spatial region occupied by the thundercloud.

Dynamic Reconstruction. Lightning evolves over time; therefore, its three-dimensional structure is reconstructed using a sequence of components of the form $\mathbf{r}(t_1), \mathbf{r}(t_2), \dots, \mathbf{r}(t_M)$, which allows recovery of the leader velocity, propagation direction, branching events, return strokes, repeated discharges, and the temporal evolution of brightness/power. The velocity of the local front is given by: $v_k = \frac{|\mathbf{r}_{k+1} - \mathbf{r}_k|}{t_{k+1} - t_k}$.

In case of the dynamic spectrum estimation, each detector records a time-domain signal $s_i(t)$. From this signal, a spectrogram is constructed: $S_i(f, t) = |\int s_i(\tau) w(\tau - t) e^{-2\pi i f \tau} d\tau|^2$, where $w(\tau - t)$ is a short-time window function. Here we consider using of corresponds to the Short-Time Fourier Transform (STFT). In practice, this yields a two-dimensional map of frequency \times time, i.e., the dynamic spectrum of lightning.

Spatially Dependent Dynamic Spectrum. Rather than considering only the spectrum at each detector, we associate the spectrum with reconstructed points along the lightning channel: $S(\mathbf{r}_k, f, t_k)$. Thus, for each segment of the lightning channel, it becomes possible to determine:

- the spatial location of the channel,
- the emission time,
- the frequency range,
- the emitted power,
- the temporal and spatial evolution of the spectrum.

This corresponds to a four-dimensional reconstruction: $(x, y, z, t) + f$, or, equivalently: $S(x, y, z, t, f)$. A practical implementation of the reconstruction algorithm is described below in the form of Table 1.

Discussion. The results presented in Tables 1–7, obtained from testing reconstruction methods for fast-evolving physical processes, have for the first time enabled new possibilities for determining the fractional mass of the solid phase in thundercloud aerosols. Conventional approaches—such as estimating the integral energy of a discharge using radiometers, magnetic field sensors, and optical and infrared spectrographs—have long demonstrated limited capability in resolving the local characteristics of plasma within lightning discharges. The high-speed hard-radiation spectrograph design proposed by Mark Doikov [4] has made it possible to identify the compact spatial region of hard radiation formation in atmospheric lightning. The inhomogeneities revealed through X-ray and gamma-ray mapping of lightning are associated with the presence of impurities in liquid or solid phases [4,5]. Electron density is linearly dependent on matter density and contributes additively to the Compton scattering coefficient $\mu_s(\mathbf{r})$. Beyond lightning diagnostics, the discussed instrumentation has broad applications, particularly in the design of monitoring and control systems for fast processes in non-equilibrium thermodynamic plasma with a condensed dispersed phase (LTP with CDP).

Table 1. Structure and Description of the Lightning Reconstruction Algorithm

Step No.	Name	Description
1	Geometry	Define detector coordinates: $\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3, \mathbf{r}_4$. It is preferable that they are not collinear or confined to a small region. A good configuration is a triangle/polygon on the ground plus a fourth detector located at height h above the plane formed by the first three detectors.
2	Synchronization	Detectors must have precise timing: GPS PPS; atomic clocks; PTP synchronization; common clock generator. Spatial accuracy is related to timing by $\Delta r \approx c\Delta t$. For lightning shape reconstruction, synchronization on the order of tens of nanoseconds is desirable. In practice, timing accuracy typically exceeds the interface response time and does not significantly affect the physical reconstruction at the characteristic timescales of lightning processes.
3	Pulse Detection	Peaks are identified in each signal: $t_{i,1}, t_{i,2}, \dots, t_{i,M}$. Methods include amplitude thresholding, matched filtering, wavelet detection, cross-correlation, and peak clustering.
4	Pulse Matching Across Detectors	Determine which peaks correspond to the same lightning segment. Criterion:
5	TDOA Reconstruction	For each matched group of peaks, solve: $\min_{\mathbf{r}, t_0} \sum_i \left[t_i - t_0 - \frac{ \mathbf{r} - \mathbf{r}_i }{c} \right]^2, \text{ yielding } \mathbf{r}_k = (x_k, y_k, z_k), t_k.$
6	Channel Construction	Construct a graph of the lightning channel: $G = (V, E)$. Methods include nearest-neighbor linking, minimum spanning tree, time-ordered graph, DBSCAN/HDBSCAN for branch detection, and Kalman or particle filtering for leader dynamics
7	Dynamic Spectra.	For each detector, compute: $S_i(f, t)$. After correcting for propagation delay: $s_i^{\text{corr}}(t) = s_i\left(t + \frac{ \mathbf{r}_k - \mathbf{r}_i }{c}\right)$, the local source spectrum can be obtained: $S_k(f, t_k)$.
8	Spatially Dependent Dynamic Spectrum	Instead of considering only detector-based spectra, associate spectra with reconstructed channel points: $S(\mathbf{r}_k, f, t_k)$. Thus, for each lightning segment, one can determine: <ul style="list-style-type: none"> • spatial location of the channel • emission time • frequency range • emitted power • spectral evolution along the channel This corresponds to a 4D reconstruction: $(x, y, z, t) + f$, or equivalently: $S(x, y, z, t, f)$.
Step No.	Name	Description
9	Timing accuracy	Distance error
	1 μs	~ 300 m
	100 ns	~ 30 m
	10 ns	~ 3 m
	1 ns	~ 0.3 m

Table 2. Final Data Structure for a Reconstructed Lightning Element

No.	Parameter	Description
1	x, y, z	Spatial coordinates of the channel segment
2	t	Emission time
3	A	Signal amplitude
4	f_{peak}	Dominant frequency
5	$S(f)$	Local spectrum
6	v	Propagation velocity
7	branch_id	Branch identifier
8	uncertainty	Reconstruction error

Table 3. Determination of the 3D Shape of Lightning

No	Name	Description
1	Source Signal Model	Lightning is modeled as a distributed current $J(\mathbf{r}, t)$ along the channel. Detector records: $s_i(t) = \int G_i(\mathbf{r}) \frac{\partial J(\mathbf{r}, t - \mathbf{r} - \mathbf{r}_i /c)}{\partial t} d^3\mathbf{r} + n_i(t),$ where $G_i(\mathbf{r})$ is the detector directivity/sensitivity, the time derivative reflects radiation generated by rapid current variations, and $n_i(t)$ is noise. In practice, the signal is approximated by discrete “radiation events” (impulse sources)
2	Event picking	Instead of simple peak detection, use multi-band detection (VLF, LF, VHF), cross-correlation between detectors, and wavelet-based detectors for short bursts. The result is a set of timestamps $\{t_{i,k}\}$ for each detector.
3	Event Association and Uncertainty	Signals from the same channel segment are detected by all sensors, but may include reflections, multiple branches, and overlapping pulses. Methods include time-window matching $ t_i - t_j < D_{\text{max}}/c$, Hungarian or greedy matching (HGM), and probabilistic data association (PDA).
4	3D Localization (TDOA / TOA)	Solve the minimization problem: $\min_{\mathbf{r}, t_0} \sum_i \left(t_{i,k} - t_0 - \frac{ \mathbf{r} - \mathbf{r}_i }{c} \right)^2$. Enhancements include robust loss functions (Huber / soft-L1), weighting by timing variance σ_i , and spatial regularization. The result is: $(\mathbf{r}_k, t_k, \Sigma_k)$, where Σ_k is the covariance matrix (uncertainty estimate).
5	Point Cloud → Lightning Channel	After localization, a point cloud $\{\mathbf{r}_k, t_k\}$ is obtained and transformed into a structured representation of the lightning channel.
6	Temporal Ordering and Linking	Sort points by t_k . Connect points if: $ t_{k+1} - t_k < \Delta t_{\text{max}}, \mathbf{r}_{k+1} - \mathbf{r}_k < v_{\text{max}} \cdot \Delta t$, where $v_{\text{max}} \sim 10^7$ m/s (typical leader velocity).
7	Graph Model Construction	Construct a graph: $G = (V, E)$, where V are nodes (points \mathbf{r}_k), and E are edges defined by temporal and spatial proximity.
8	Branch Extraction	Apply clustering and graph-based methods: DBSCAN/HDBSCAN (in x, y, z, t), minimum spanning tree (MST) with pruning, or directed graph approaches (time-oriented).
9	Result	Identification of the main channel, side branches, and branching regions.
10	Anti-aliasing and final geometry	Apply smoothing techniques such as B-splines, Kalman smoothing, or Gaussian process regression. Final representation: $\mathbf{r} = \mathbf{r}(s, t)$, where s is the parameter along the channel

Table 4. Dynamics of Lightning Channel Development

No.	Name	Description
1	Leader velocity	$(v_k = \frac{dL}{dt})$
2	Lightning phases	Stepped leader; branching; return stroke; subsequent strokes
3	Temporal topology	$G = G(t)$; branching times; channel length $L(t)$; growth rate $\frac{dL}{dt}$
4	Energetics	$P_k \propto A_k^2$; power distribution along the channel; regions of maximum discharge

Table 5. Dynamic Spectra of Individual Lightning Segments

No.	Name	Description
1	Spectrogram (STFT)	For each detector: $S_i(f, t)$; this represents a mixed signal from the entire lightning channel
2	Back-projection to source	For point \mathbf{r}_k : $(\tau_{i,k}) = \frac{d}{c} \ \mathbf{r}_i - \mathbf{r}_k\ $
3	Local signal formation	Sum over detectors: $s_k(t) = \sum_i w_i s_i^{(k)}(t)$, where w_i are weights (SNR, geometry); analogous to beamforming
4	Local spectrum	$S_k(f, t_k) = \text{STFT}(s_k(t))$; alternatively wavelet transform: $W_k(f, t_k)$

Table 6. Physical Interpretation of Lightning Spectra

No.	Segment	Spectral Characteristics
1	Leader	VHF, broadband emission
2	Return stroke	LF/VLF, high-power emission
3	Branching	Noise-like spectrum
4	Channel interruptions	High-frequency peaks
3	Leader	VHF, broadband

Table 7. Unified Model and Constraints

No.	Name	Description
1	Unified model	Discrete representation: $(\mathbf{r}_k, t_k, S_k(f), v_k, G(t))$; continuous form: $S(x, y, z, t, f)$
2	Key practical constraints	(1) Timing accuracy — dominant factor; nanosecond synchronization required. (2) Detector geometry — wider baseline improves reconstruction; 3D configuration preferred. (3) Multipath effects — reflections from ground/clouds; require consistency filtering. (4) Event density — too sparse leads to poor reconstruction; too dense complicates event association.
3	Analogy with tomography	CT vs Lightning: rays \rightarrow signals; detectors \rightarrow detectors + antennas; attenuation \rightarrow time delay; reconstruction \rightarrow TDOA inversion; 3D image \rightarrow lightning channel [8]

Conclusion. The visualization and diagnostics of local processes in lightning plasma using high-speed hard-radiation detectors open new opportunities for:

1. Development of advanced instrumentation for monitoring and control of fast-evolving physical processes.
2. Adaptation of new testing methodologies and mathematical approaches for solving inverse problems in aerosol physics.
3. Control and suppression of unstable modes in non-equilibrium thermodynamic plasma with a condensed dispersed phase using AI and neural network methods.
4. Simultaneous reconstruction of instantaneous spectra and spatial images of the investigated object, demonstrated in this work using lightning as an example.

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Візуалізація блискавки в запиленій атмосферній плазмі

Анотація

У даній роботі розглянуто методи візуалізації процесів в атмосферній запиленій плазмі під час виникнення грозових розрядів. Проведено аналіз характерних часів релаксації основних кінетичних процесів, що визначають формування радіаційної та візуальної картини розвитку блискавки в неоднорідному середовищі. Запропоновано алгоритм реконструкції швидкоплинних спектральних зображень грозових розрядів, який базується на поєднанні часово-роздільної спектроскопії та методів обробки сигналів. Особливу увагу приділено задачам відновлення просторової структури плазмових каналів у запиленій атмосфері з урахуванням розсіяння, поглинання та спектральної селективності випромінювання. Здійснено спробу створення нових інструментальних методів аналізу та керування процесами реконструкції при розв'язанні обернених задач відновлення геометричних зображень досліджуваних фізичних об'єктів. Показано перспективність використання бінарних детекторів на основі напівпровідникових матеріалів типу CsPbBr₃ для реєстрації широкосмугового випромінювання блискавок, а також можливість їх застосування в умовах нерівноважної термодинамічної плазми з конденсованою дисперсною фазою. Представлені в таблицях результати тестування методів реконструкції швидкоплинних фізичних процесів уперше продемонстрували нові можливості для визначення часткової маси твердої фази аерозолів у грозових хмарах. Отримані дані свідчать про підвищення чутливості до локальних параметрів плазми, що формуються під час розвитку грозового розряду. Традиційні підходи, засновані на вимірюванні інтегральної енергії розряду за допомогою радіометрів, датчиків магнітного поля, а також оптичних та інфрачервоних спектрографів, протягом тривалого часу демонстрували обмежену здатність до відновлення локальних характеристик плазми. Зокрема, ці методи забезпечують переважно інтегральні або усереднені оцінки параметрів, що ускладнює визначення просторово-часової структури плазмових каналів і розподілу аерозольної компоненти. Запропоновані методи реконструкції дозволяють подолати зазначені обмеження шляхом використання спектрально-часової інформації та розв'язання обернених задач, що забезпечує відновлення локальних фізичних характеристик середовища з підвищеною просторовою та часовою роздільною здатністю.

Ключові слова: *спектроскопія блискавок, реконструкція та візуалізація плазмових конфігурацій, бінарні детектори, CsPbBr₃ напівпровідники, нерівноважна термодинамічна плазма з конденсованою дисперсною фазою.*