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TOMOGRAPHY TECHNIQUE FOR GLOBAL LIGHTNING IMAGING FROM AMBIENT ELF ELECTROMAGNETIC NOISE

Introduction

Lightning discharges are the main source of natural electromagnetic interferences in the terrestrial environment. Electromagnetic emissions from lightning occupy very wide spectral range, but the bulk of energy is concentrated in the extremely low (ELF, 3 – 3000 Hz) and very low frequency ranges (VLF, 3 – 30 kHz).

Radio waves in the ELF-VLF bands, radiated by lightning discharges, are trapped between the conductive shells that are the earth's surface and the lower boundary of the ionosphere. Such a natural Earth-ionosphere waveguide provides round-the-world propagation at the lower part of the ELF band with very low attenuation that allows for a unique possibility for near the real time monitoring of the global lightning activity from one or a few receiving stations.

Analysis of the background ELF signals is usually performed by application of different models of lightning distribution elaborated on results of meteorological and space observations [7]. These solutions provide obtaining source intensities of the global thunderstorm centers associated with tropical continental regions in South America, Africa and South-East Asia (see [4] and references therein). But the problem of source redistribution within these centers remains unsolved with such an approach.

Observed in spectra of natural electromagnetic fields as resonant peaks at frequencies 8, 14, 20, 26, and 32 Hz, represent a global electromagnetic phenomenon known as Schumann resonances (SR) that are primarily connected with the worldwide lightning activity [1-3]. The amplitudes of the resonant peaks are modulated due to superposition between direct and antipodal waves, propagating toward to each other. This modulation results from arrival delay between them at an observation point and, in such a way, form a specific SR spectrum, determined by a source-to-observer distance.

The distance signatures in SR spectra and wave impedance [4] combined with direction finding technique provides single-site locating super power lightning discharges. In ELF band such signals exceed the background level on about of one order of amplitude and they can be analyzed as isolated in time events. In addition, multi-station observations, based on triangulation or/and the "time of arrival" method, are used to study the temporal and regional variation of lightning occurrences and their relation to sprite activity and climate variability [5-6]. However, due to essential overlapping between successive pulses that form natural ELF background, these techniques can be applied only to very strong events exceeding a background level in a few times that occur comparatively rarely and relate only to a small part of the total lightning activity.

To infer the global lightning from the background SR signal we proposed a technique of inversion of measured power field spectra into distribution of sources' intensity in refer to an observation station [8-9]. Application of the tomography procedure to a set of such distance profiles of lightning intensity related to a network of observation stations allows for obtaining source distribution over the earth's surface [10].

This paper is devoted to the further improvement of our newly developed technique for the global lightning mapping [10] to employ additional information on the azimuthal distribution of sources from separate use of signals received by orthogonal magnetic components.

Inversion of SR spectra to distance profiles of sources' intensity

We divide the whole distance range [0,π] between an observation point and its antipode to N = 40 intervals on the earth's surface. The distance interval is accepted to be approximately the distance resolution achieved in the point source location techniques [4]. The distance intervals correspond to narrow circular stripes around an observation point, which cover the entire sphere. The frequency responses $h(\omega,\nu,\theta)$ and $e(\omega,\nu,\theta)$ of the earth-ionosphere cavity at an observation point are defined by the distance θ to the middle of the stripe, a source belongs to. The power spectral densities of the field components formed by Poisson successions of lightning return strokes are expressed as expansions in series of distance dependant basis functions [8]:

$$\left\langle \left| H_{ew}(\omega) \right|^2 \right\rangle = \sum_{i=1}^{N} M_{ewi}(\omega) \left| h(\omega,\nu,\theta_i) \right|^2, \qquad (1)$$

$$\left\langle \left| H_{ns}(\omega) \right|^2 \right\rangle = \sum_{i=1}^{N} M_{nsi}(\omega) \left| h(\omega,\nu,\theta_i) \right|^2, \qquad (2)$$

where θ_i is the angular distance from an observer to the middle of the i^{th} stripe and triangle brackets denote averaging by an ensemble of the spectral densities of the field components. Expansion coefficients, $M_i(\omega) = x_i \overline{\left| Idl(\omega) \right|^2}$, represent power spectral density of lightning discharges with average occurrence rate x_i in the area on the earth's surface pertaining to a corresponding distance interval.

Coefficients M_{ewi} and M_{nsi} depend on azimuthal distribution of sources in refer to an observatory owing to directional selectivity of magnetic sensors, while their sum equals to the total source's intensity: $M_i = M_{nsi} + M_{ewi}$ [8].

The field power spectra (1), (2) can be written in a compact matrix form after discretizing by frequency:

$$\mathbf{b} = \mathbf{A} \cdot \mathbf{x}. \qquad (3)$$

In this equation **b** is the vector of a measured field's power spectrum, **A** is a matrix of model field spectra, produced by an elementary vertical dipole, calculated for a set of source-observer distances $A_{ij} = 2\left| I_0 \tau dl \right|^2 \cdot \left| h(\omega_j,\theta_i) \right|^2$, and **x** is the vector of distance distribution of an effective flash rate. The system (3) is solved by minimization in the least squares sense of the functional regularized by Tikhonov:

$$F(\mathbf{x},\alpha) = \left\| \mathbf{A}\mathbf{x} - \mathbf{b} \right\|^2 + \alpha \left\| \mathbf{x} \right\|^2; \quad \mathbf{x} \geq 0, \qquad (4)$$

where α is a small positive regularisation parameter that is determined empirically. It was shown [8,9] that serious errors in the reconstructed distance profiles are connected with "slow" trends in the experimental field spectra introduced by a source spectrum $Idl(\omega)$ or/and by uncorrected frequency response of the receiving channels.

Tomography reconstruction of source's intensity by partial projections

As modeling has shown, the lightning activity concentrated in the tropical continental regions can be mapped quite accurately by a network of seven stations. Our recent study [10] has demonstrated reconstruction by three-station network (Moshiri, Lekhta and West Greenwich) that allows tracking for diurnal redistribution of lightning activity in tropics. Experimental setup for tomographic reconstruction of global lightning activity by a network of SR observatories is shown in Fig.1.

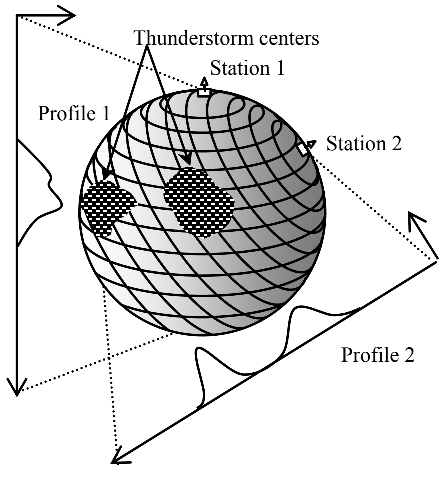

Fig.1. Experimental setup for the worldwide lightning tomography.

Further numerical study of the tomography procedure performed in the present work shows that the network of those three observation stations could reconstruct only relatively simple structures of source's distributions consisting of a few active areas on the Earth's surface. Complication of the spatial source structure can lead to appearance of lots of artefacts after tomographic reconstruction.

To facilitate determination of spatial distribution of sources with limited number of observation stations we implement additional information into the tomography procedure inferred based on the properties of directional sensitivity of two orthogonal magnetic antennas, used as a rule for SR measurements at most every observation station.

Advantages of this new approach are demonstrated by comparison between results of reconstruction of a complicated reference lightning distribution performed with omni-directional data [10] and reconstruction with separate use of the distance profiles resulted from inversion of spectra of the orthogonal magnetic components.

The problem of tomography reconstruction by partial projections in application to the global lightning study is as follows. A SR observation network consists of K stations each equipped by two orthogonal magnetic sensors, and. A net of ordered points $M(\phi_j,\gamma_j,s_j)$ with geographical latitudes ϕ_j and longitudes γ_j form an unknown L-vector $\mathbf{s}$ that determines spatial distribution of sources' intensity over the earth's surface. For the sake of simplicity, we use a net of cross points between meridians and parallels 5 degrees of latitude and longitude apart. N-vectors $\mathbf{x}_k^{ew}$ and $\mathbf{x}_k^{ns}$ represent intensity profiles of lightning, resulted respectively from inversion of SR spectra of H_{ew} and H_{ns} magnetic components ("*ew*"- and "*ns*"-profiles), measured at k^{th} station of the network. Vector $\mathbf{x}=\left[\mathbf{x}_1^{ew},\mathbf{x}_1^{ns},\mathbf{x}_2^{ew},\mathbf{x}_2^{ns}\ldots\mathbf{x}_K^{ew},\mathbf{x}_K^{ns}\right]^T$ is a concatenation of the distance profiles obtained at all observation stations. The following system of linear algebraic equations establishes connection between spatial sources' distribution $\mathbf{s}$ and the set of projections $\mathbf{x}$ as follows:

$$x_{(kni)}=\sum_{j=1}^{L}W_{(kni)j}s_j; \quad , \qquad (5)$$
$$k=1\ldots K, i=1\ldots N, j=1\ldots L, n=1,2$$

where the system matrix $\mathbf{W}$ has $2KN$ rows and L columns.

The elements of the system matrix are determined as follows:

$$W_{(kni)j}=\begin{cases}\cos^2\alpha_{kj}; & M_j\in\Delta_i, \quad n=1\\ \sin^2\alpha_{kj}; & M_j\in\Delta_i, \quad n=2\\ 0; & M_j\notin\Delta_i\end{cases}. \qquad (6)$$

α_{kj} is azimuth (clockwise from the north direction) of M_j^{th} point as it is seen from k^{th} observation point. The cosine and sine squared of corresponding azimuthal angle determine directional sensitivities of magnetic antennas to a source at point M_j with geographical coordinates ϕ_j, γ_j. Triple indexation for the elements of vector $\mathbf{x}$ indicates their belonging to sub-vectors $\mathbf{x}_k^{ew}$ and $\mathbf{x}_k^{ns}$ that correspond to "*ew*"-profile (n = 1) and "*ns*"-profile (n = 2) from k^{th} observation station.

Reducing of dimension of the system can be reached by bounding the set of points on the surface by areas formed by intersections between circular stripes with nonzero intensities, drawn for each observation point. Zero elements in $\mathbf{s}$ allows removing corresponding columns in $\mathbf{W}$ in (5). To facilitate calculations we also rejected sub-polar regions with latitudes higher than 75°, we a priori do not expect noticeable lightning activity.

Solution of the above system uses the nonnegative least squares algorithm; it minimizes the following functional:

$$F(\mathbf{s})=\left\|\mathbf{W}\mathbf{s}-\mathbf{x}\right\|^2 \qquad (7)$$

Modeling reveals that a network of the three stations allows for reliable quality of reconstruction for only simple configuration of active areas. It could consist of one to three compact regions filled with sources. More complicated distribution can seriously affect results of reconstruction. As is demonstrated below, the application of partial distance profiles essentially improves the quality of reconstruction.

Comparison of the "full" and "partial" projections techniques

Lightning distribution evaluated from space observations by OTD and LIS instruments (http://thunder.msfc.nasa.gov/) in 1995 – 2002 shown in Fig.2a served as a reference map. Reconstructions of the reference sources both with use of the full and partial distance profiles are shown in Fig.2b and Fig2c respectively. We use convolution with five-point Hamming window by rows and columns of resulted source distributions for regularization.

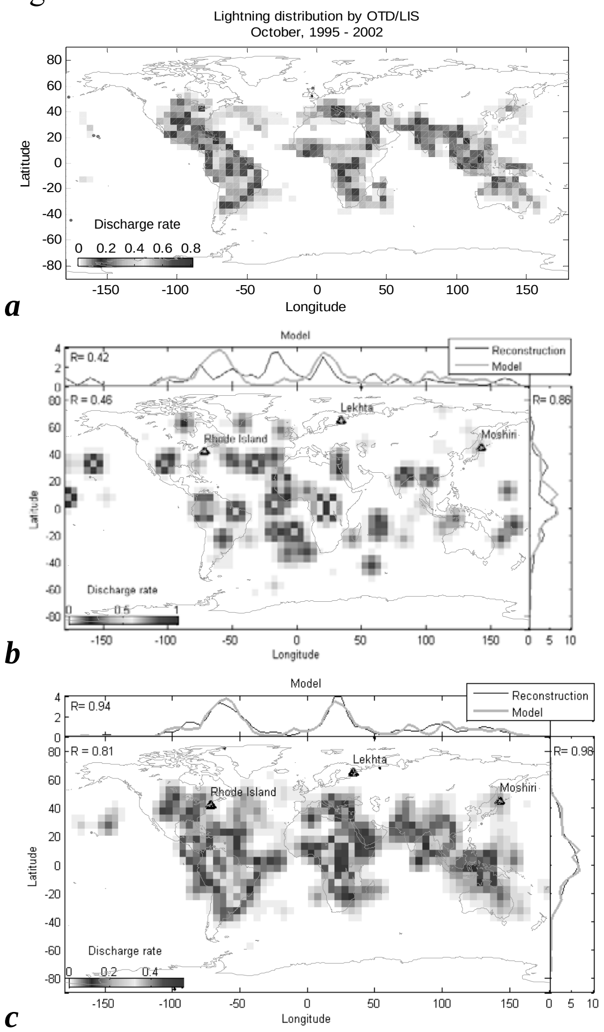

Fig. 2. Reference distribution of lightning (*a*), and three-station reconstructions by partial (*b*) and full (*c*) distance profiles

Bold triangles designate observation stations. The color bars show the scale of the source's intensities. Latitudinal and longitudinal integral distributions of lightning intensity in 5-degrees bands are shown in the graphs docked to the maps at right and top sides respectively.

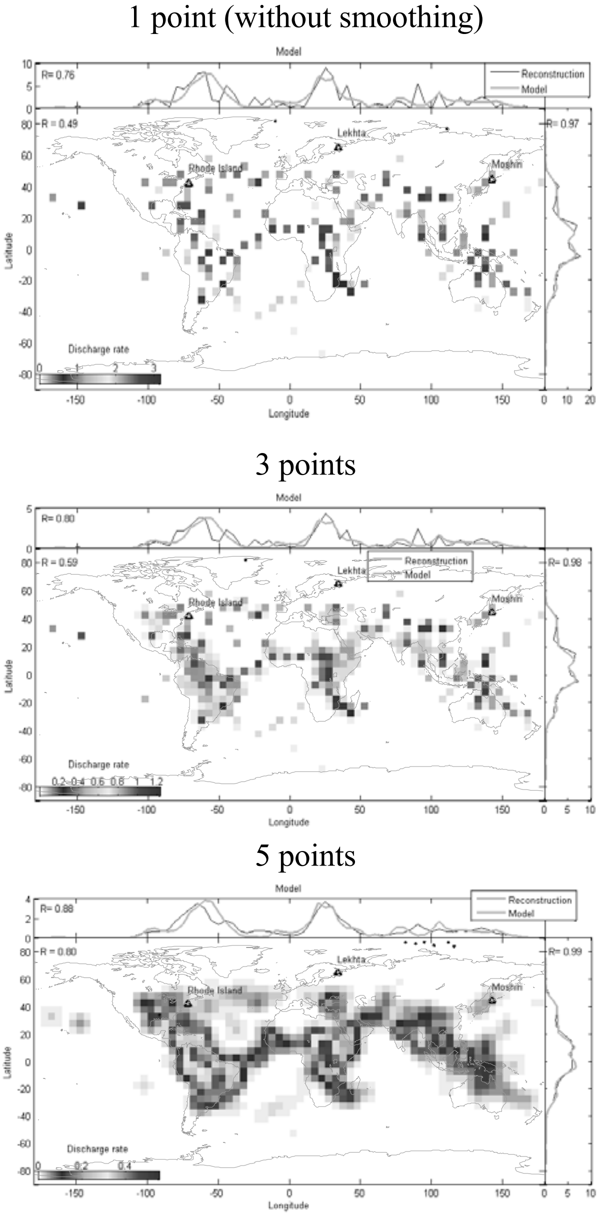

Fig. 3. Smoothing of reconstructed distributions with Hamming windows of different length

Correlation coefficients between the reference and reconstructed two-dimensional distributions and between corresponding latitudinal and longitudinal profiles are shown in the left upper corners of the graphs. We can observe essential improvement in the case of using information on the azimuthal distribution provided by partial distance profiles. In particular, correlation coefficients between the model and reconstructed source distributions, longitudinal and latitudinal sources' distributions grow from 0.45, 0.42 and 0.86 to 0.81, 0.94 and 0.98 respectively.

For regularization of results of tomography reconstruction we use smoothing by convolution of rows and columns in the matrix of the solution with Hamming window. Maps in Fig.3. demonstrate the best correlation coefficients for the 5-points Hamming window.

Conclusion

Numerical modeling shows that the number of stations enough for accurate reconstruction of complicated global lightning distributions obtained from OTD/LIS space observations can be reduced to three stations in the world with application of our newly developed technique. We have suggested using of source distance profiles obtained from spectra of outputs of two orthogonal magnetic antennas, operating at each observatory, as separate tomographic projections. Implementation of additional information on azimuthal distribution of sources to the tomography reconstruction procedure improved sufficiently the quality of global lightning mapping under condition of a limited number of observation stations. We consider such approach is a universal way to improve the accuracy of reconstruction as much as possible in the inverse problem.

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Ключові слова: світова грозова активність, Шуманівський резонанс, локація блискавок, томографічна реконструкція.

Ключевые слова: мировая грозовая активность, Шумановский резонанс, локия молний, томографическая реконструкция.

Key words: worldwide lightning activity, Schumann resonance, lightning location, tomography reconstruction.

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