Current state and prospects of development of passive radio engineering monitoring of storm activity

I I Kononov\textsuperscript{1}, E A Korovin\textsuperscript{2}, G G Shchukin \textsuperscript{2} and I E Yusupov\textsuperscript{1}

\textsuperscript{1}Saint-Petersburg State University, Ulyanovskaya 1, 198504 Saint-Petersburg, Russia
\textsuperscript{2}Mozhaisky Military Space Academy, Zhdanovskaya 13, 197198 Saint-Petersburg, Russia

E-mail: igor_kononov@mail.ru

Abstract. Passive radio engineering monitoring means of storm activity in VLF range are considered in the work. The comparative analysis of characteristics of modern Russian and foreign lightning location systems which have a broad practical application is carried out. Possibilities of improvement of precision and probabilistic characteristics of VLF methods and techniques for location of various types of lightning high current components are estimated.

Introduction

The actual beginning in development of thunderstorm radio engineering monitoring means is connected with the invention in the mid-twenties of the last century of the first loop Cathode-Ray Direction Finder (CRDF) with bearing displaying on the screen of electron beam tube [1]. One of the first successful examples of CRDF usage for registration of atmospherics and their sources location is described in work [2]. The possibility of two-point version of the direction finding (DF) system usage for location of atmospherics in the wide range of distances (500-4000 km) was shown in it. Results of data processing of registration of atmospherics in night propagation conditions allowed authors of the work to discuss for the first time the physical mechanism of their formation connected with existence of an ionosphere, to receive very reliable estimates of reflection heights and to propose the ”sky-hop” algorithm of a single station ranging which created prerequisites for construction in a combination with a direction finder of one of the first versions of a single station direction and range finder. All this was a good motivation for the subsequent development of passive radio engineering systems of storm activity monitoring.

The important factor which sharply raised the possibilities of deploying of new systems of lightning activity monitoring was starting at the end of the last century of the American GPS navigation system (and soon the Russian GLONASS) that allowed to solve a problem of high-precision (less than 1 microsecond) time synchronization of the distant registration points. Intensive development in the same years of telecommunication means and deployment of a set of local networks shortly united into a uniform global network removed a problem of high-speed data exchange between the distant observation points. Solution of the these problems, which many years slowed down a multi station lightning location systems deploying, allowed to start regeneration of the
park of technical means and creation of new generation of the systems which determined the modern level of passive radio engineering storm activity monitoring technique.

**Direction Finding Systems**

During almost a half-century period of their operation the CRDF direction finders, being undergone by numerous modernizations directed to increase the performance and improvement of ways of information display, were applied both in structures of single station direction and range finder and of multi station DF systems. However, the wide circulation of such a type systems was slowed down by serious shortcomings of the communication channels existing at that time (mainly telephone) used for synchronization of the distant registration points and transfer of registration data to the processing center. Low location accuracy of such a type systems was caused by the polarization errors. These errors caused by anisotropy of an ionosphere reached especially large values (up to 10-15°) in night propagation conditions. The set of the listed above shortcomings of these systems equipped with narrow-band CRDF direction finders or their subsequent numerous analogs did not satisfy the increasing requirements of most consumers, and gradually the usage of them in the scientific and utilitarian purposes was reduced.

However, the attempts for improvement of work quality of loop direction finders were not stopped. To avoid polarization errors caused by influence of anisotropy of an ionosphere, in [3] it was proposed to determine a bearing by the initial part of a signal formed by the "terrestrial" wave which is not undergone the influence of ionosphere reflections. At narrow-band receiving for a variety of reasons this way was inefficient. The radical solution published in [4] was the proposal to increase a receiver bandwidth to values of 1 kHz - 1 MHz and to use for bearing detection only a frontal part (before the first maximum) of "terrestrial" part of an atmospheric that allowed not only to exclude the ionosphere influence but also to essentially reduce the polarization error component caused by deviation of a source from a vertical.

Development of VLF pulse source location systems in the USSR was going in the similar directions. Originally the works were carried out in the interests of the Special Control Service for determination of nuclear explosions epicenters coordinates. Here the focus was on the development of long range systems. In the early seventies of last century the automated stationary complex (ASC) of nuclear explosions detection was created [5]. As an experiment this complex was used for storm activity observations. In 1985 the similar complex was sent to trial operation in the Asian part of the USSR. In 1987 in the European part of the USSR on the basis of several registration points equipped with new generation of the data-acquisition equipment made by scientific development and production center "Vector" the prototype of the modernized system was developed and was successfully tested by electromagnetic signals in 1989. Unfortunately, with the collapse of the USSR the complex stopped the existence because the majority of points appeared in the adjacent states. In 1995-1997 the works on reconstruction of ASC in the interests of different types of armed forces as a result of which the software was completely updated and outdated registration complexes were replaced with the hardware modules "Vereya" manufactured in scientific development and production center "Monitoring technologies". In the mid-nineties the conversion edition of this complex known under the name "Lightning discharges location system" was developed in Eastern Siberia on the basis of three registration points placed in the buildings of aviation service bases of forest protection in Tomsk, Krasnoyarsk and Irkutsk. This complex was a long range system of mixed type (different time of arrival - DTOA, DF). Results of complex operation by high current lightning discharges registration location in 1997 confirmed its rather high precision and probabilistic characteristics. So, according to the publication [6], the mean square error of a cloud to ground lightning location on the Krasnoyarsk region was 5 km and the probability (efficiency) of detection was 80%. In 2010 the "Vereya-MR" system, consisting of 26 registration points and being developed in the interests of Federal State Institution "Aviation forest protection", provided detection, determination of
coordinates and parameters the lightning discharges on the area of 11·10⁶ sq. km with an error of 3 km.

**Difference Time of Arrival Systems**

Let us illustrate a creation methodology of DTOA on the example of creation of the American National Lightning Detection Network (NLDN), being indicative in terms of structure of placement of the distant registration points, types of the used equipment, a technique and testing technology of characteristics. Creation of this network began in the late seventies of 20th century with deploying of several local DF systems in the western part of the USA on the border with Canada, and on Alaska, equipped with broadband direction finders, made by the American Lightning Location and Protection (LLP) firm on the technology offered in [4]. Originally the system was destined for Bureau of land management (BLM) of the USA and was used for operative detection of sources of the wildfires initiated by high current lightning discharges. Soon on the east coast of the USA one more local short base DF system (the distance between registration points did not exceed 50 km) also equipped with LLP direction finders was developed. Careful control and calibration of this system with an exception of the systematic errors of direction finding caused by influence of local irregularities allowed locating the lightning discharges in a system interior with an accuracy 0.5-1 km. Achievements in thunderstorm location have raised an interested in power engineering specialists. Deploying of a system in all territory of the USA with financial support of Electric Power Research Institute (EPRI) was begun in 1983.

Reached accuracy in short base DF systems in the scales of the whole country would require deployment of very large (several hundreds) number of registration points. Possible reduction of this number by increasing the base distances leads to the proportional growth of location errors. This fact induced the developers of national network to use DTOA systems characterized by potentially higher, in comparison with DF systems, the location accuracy which is not changing with base distances increase (provided that the accuracy of definition of times of arrival of signals to the distant registration points is preserved). By this time (1982) the commercial version of Lightning Positioning and Tracking System (LPATS), a type of DTOA system, was put into operation in Florida. The network of several similar systems covering a continental part of the USA integrated into the developing national system [7] was soon deployed.

In newly developed system it was supposed to choose the size of base distances within 300-350 km, and to carry out timing by the first half wave maximum of a \"ground\" component of the signal registered in a 1-400 kHz frequency band. It provides high precision of measurement of amplitude of an atmospheric and the subsequent reconstruction of discharge current value which is one of important system parameters. Within the internal zone of NLDN there are no problems with identification of the first half wave in the distant registration points and its high-precision timing providing a fixing accuracy of about 500 m. As the parameters of DTOA systems coincided practically with characteristics of the broadband LLP sensors used in earlier developed DF systems, all old equipment along with already existing infrastructure could be used in creation of a new system. Magnetic sensors in structure of the equipment allowed to solve a quite often arising problem of ambiguity of hyperbolic coordinate evaluation without additional expenses and to considerably increase a speed of the main location algorithm.

Since 1989 this mixed system equipped with the updated technologies of measurements and location techniques known under an abbreviation of IMPACT (Improved Accuracy from Combined Technology) having undergone by some more modifications [8], as a part of 114 registration points is functioning in the continuous mode so far and serving the all continental part of the USA territory.

The complete set of the equipment and location methodology used in NLDN has found an application in the majority of other systems developed in the different countries. From the largest systems of this kind both on the number of points and by the sizes of the served territory it is possible to highlight the Canadian CLDN system (83 points) [9] which subsequently merged with NLDN and
formed the North American Lightning Detection Network (NALLDN) serving all the continental part of North America [10].

Similar on equipment, structure of placement, work characteristics (detection efficiency, accuracy) and the sizes of the served territory is the Brazilian RINDAT [11] system. In 2001 the EUCLID project (European Cooperation for Lightning Detection) which originally has united into a uniform network the local storm location systems of six European countries (Austria, France, Germany, Italy, Norway and Slovenia) started. Now the system contains 164 sensors placed in 27 EU countries. EUCLID provides lightning location data within Europe in real time (with a delay in several seconds) by visualization of lightning activity on the map.

The system of DTOA type known as "Alwes" is developed in Russia. The system is intended for monitoring of storm activity in real time, providing potential consumers with information on current state of storm activity and also on its territorial distribution corresponding to various intervals of averaging (daily, seasonal, annual). The system incorporates about 80 registration points with operational service zone covering all the European part of Russia and some regions from the Urals to the Far East [12].

Since the beginning of this century considerable efforts on creation of passive means of storm activity monitoring in global scale were made. Here first of all it should be noted a large base DTOA system WWLLN (World Wide Lightning Location Network). Unlike all the systems of DTOA type considered above there is another method of measurement of the moments of arrival of signals offered in the work [13]. Time of arrival is defined by means of measurement of the time of group arrival (TOGA) of a signal estimated by the value of a derivative of linear component of a total phase characteristic, registered in a 6-22 kHz frequency band. Group velocity is calculated at the central frequency of operating range in an assumption of justice of single-mode representation of the field (vertical electric component). To cover all the territory of the globe it is necessary to develop an uniform network of 50-60 points arranged by distance of about 3000 km. Testing of a system with use of NLDN location data showed that the efficiency of detection is about 10% for currents more than 25 kA and 35% for currents over 130 kA [14]. So far the formation of WWLLN is not completed yet. According to developers of the network a full covering of the globe will require 2-3 years more.

At the end of 2009 the corporation Vaisala began formation of long range Global lightning detection (GLD360) network. In it a priori unstable number of the sensors placed worldwide is used. The location of lightning discharges is estimated by the technique used in NLDN with that difference that the moments of arrival of signals are determined not by the first half wave of a broadband atmospheric but by the time counts corresponding to its absolute maximum or the next to it to zero crossings. On the latest data the detection efficiency of cloud-to-ground type discharges is about 70%, and the location accuracy is 2-5 km. Operation of GLD360 network showed that it is capable to display the storm activity with high resolution on large distances both in real time and on various intervals of averaging (hour, daily, seasonal) with rather accurate display of the specific situations arising in various synoptic conditions [15]. Now this network provides a possibility of a lighting location in those zones of the globe where there are no means of meteorological observations. Data of GLD360 are supposed to be used at observation of mesoscale cyclonic formations, in research of convective structures of hurricanes and typhoons.

Summary
Passive radio engineering storm activity monitoring means in the process of the improvement of a technical part and algorithms of processing caused by the increasing requirements of consumers to information on thunderstorms have reached the level allowing to carry out lightning location on a global scale with rather high precision. Now the most effective lightning location method is difference time of arrival one allowing with a bigger accuracy than goniometric or goniometric and ranging to realize the location of coordinates. At the same time the deployment of DTOA systems is not always realizable or economically inexpedient. The lack of strict approaches to justification of the choice of
the means meeting requirements of consumers of information on thunderstorms often leads to realization of expensive and inefficient systems.

Further improvement of storm activity monitoring means is directed on increasing of probability of detection of all lightning types and the accuracy of location of their coordinates. Improvement of accuracy is reached by optimization of structure of a system and introduction of the amendments on propagation considering distinction in routes extents and their electric parameters. In the absence of control systems a confirmation of high characteristics of the existing and new storm activity monitoring means is difficult. Control of precision characteristics requires creation of the control devices realized on the basis of the systems of artificial lightning initiation (trigger lightnings), or the systems similar to the Cascade simulator operated in the Soviet Union till 1980, both representing the power store of big power and the radiating system in the form of the cable lifted by an aerostat on height up to 3 km.

The increased possibilities of modern lightning activity monitoring systems and considerable expansion of a circle of the tasks solved by them demanded changing the traditional approaches to the analysis of the storm phenomena, significant revision of requirements to technical characteristics at modernization existing and development of new generation of lightning location systems. Not less important tasks connected with development of methods and algorithms of secondary data processing of registration and location were added to problems solved earlier directed generally to increase the reliability of detection and location accuracy. These tasks allow:

- to carry out space-time grouping (clustering) of the data characterizing the place and time of separate impulses of electromagnetic radiation arising in development of storm activity; this procedure creates clusters corresponding to such physical objects as separate storm cell, storm center, mesoscale storm complex;
- to group the registered VLF-pulses of electromagnetic radiation corresponding to the allocated storm clusters into flashes with the subsequent their classification by types (cloud-to-ground or intra-cloud);
- to carry out the analysis of temporary changes of parameters of radiation from the allocated clusters for the purpose of determination of current state and evaluation of degree of danger of storm activity and also the short-term forecast of its future development with probabilistic evaluation of appearance of accompanying phenomena (intensive rainfall, squally wind, hail);
- to form storm location and registration databanks averaged in various space-time scales and formats adapted to various fields of research and production use (in power engineering, aircraft, hydrology, meteorology, climatology, etc.); in particular, the accumulated information on temporary and spatial distribution of lightning sources danger is important when planning construction of various production objects, laying power lines and communication, development of lightning protection means and quantitative evaluation of their efficiency.

References
[1] Watson-Watt R A, Herd J P 1926 An instantaneous direct-reading radiogoniometer (JIEE) 64 p. 611.
[2] Schonland B F J, Elder J S, Hodges D B, Phillips W E, van Wyk J W 1940 The wave form of atmospherics at night (Proc. R. Soc.) 176A 180–202.
[3] Adcock F, Clarke E 1947 The location of thunderstorms by radio direction finding (J. Inst. Electr. Eng.) 94B 118-125.
[4] Krider E P, Noggle R C, Uman M A 1976 A gated, wide-band magnetic direction finder for lightning return strokes (J. Appl. Meteorol) 15 301-306.
[5] Cherepanov S N 2002 Creation of automated stationary complex for nuclear explosion detection (Born by nuclear age, Moscow) 3 pp. 59-69 [in Russian].
[6] Moskovenko V M 1998 Usage of radio engineering method in the interests of national economy (Born by nuclear age, Moscow) 1 pp. 88-93 [in Russian].
[7] Lyons W A, Bent R B 1983 Evaluation of the time-of-arrival (TOA) technique for real-time ground strike measurements using the lightning position and tracking system (LPATS) (Proc. 13th Conf. Severe Local Storms, Tulsa, OK, Amer. Meteorol. Soc., 17-20 Oct.) 37–40.

[8] Cummins K L, Murphy M J 2009 An Overview of Lightning Location Systems: History, Techniques, and Data Uses (With an In-Depth Look at the US. NLDN, IEEE Transactions on Electromagnetic Compatibility) 51 (9).

[9] Burrows W R, King P, Lewis P J, Kochtubajda B, Snyder B, Turcotte V 2002 Lightning occurrence patterns over Canada and adjacent United States from lightning detection network observations (Atmos. Ocean) 40 59–81.

[10] Orville R E, Huffines G R, Burrows W R, Holle R L, Cummins K L 2002 The North-American Lightning Detection Network (NALDN) – First results: 1998–2000 (Mon. Weather Rev. 130) 8 2098–2109.

[11] Pinto I R C A, Abdo R F, de M Garcia S A, Filho A C 2006 Recent upgrades to the Brazilian Integrated Lightning Detection Network (Proc. 19th International Lightning Detection Conference (ILDC). Vaisala, Tucson, Arizona).

[12] Snegurov A V, Snegurov V S 2017 Storm location system (Proceedings of Main Geophysics Observatory) 586 117-140 [in Russian].

[13] Dowden R L, Brundell J B, Rodger C J 2002 VLF lightning location by time of group arrival (TOGA) at multiple sites (J. of Atm. and Solar-Terr. Physics) 64 (7) 817-830.

[14] Abarca S F, Corbosiero K L, Galarneau T J Jr 2010 An evaluation of the Worldwide Lightning Location Network (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth (J.Geophys. Res.) 115. D18206, doi:10.1029/2009JD013411.

[15] Holle R L 2012 Meteorological examples of GLD360 events (Proc.22 ILDC, 2-3 April 2012. Colorado, USA).
