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Progress of Radar Observations of Meteors in Kazan (Russia) over the Last Sixty Years

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Abstract. This paper presents a brief survey on the history of radar observations of meteors in Kazan from 1950s to present days. Such achievements of Kazan researchers as development and further improvement of original measuring equipment and antenna systems, of observational data processing methods, their contribution to the theory of physics of meteor phenomena and theoretical interpretation of experimental data are highlighted. A particular progress in meteor astronomy has been achieved with a new discrete quasi-tomoghraphic method for faint meteor showers identification that uses goniometer data of meteor radio reflections detected on radar as input data. The current state and new horizons of meteor studies in Kazan are stated.

Keywords. Radar observations of meteors, Kazan meteor radar, meteor showers, meteor ionized trails.

1. Introduction: History and Development of Meteor Observations

Continuous radar observations of meteors have been carried out all over the world ever since 1947. Such eminent researchers as J. S. Hey and J. S. Stewart, A. C. B. Lovell, C. J. Banwell and J. A. Clegg, D. W. R. McKinley and P. M. Millman stand at the origins of radar studies of meteors (Hey & Stewart 1947; Lovell *et al.* 1947; McKinley & Millman 1948). However, they all used radio equipment that remained from World War II. In Russia, the very first radar observations of meteors were made in 1956 in Kazan Federal University under the direction of Professor K. V. Kostylev, also with the use of a former military radar. Accuracy and the amount of acquired observational data at these times were harshly limited by the unsatisfactory functional capabilities and the specified primary assignment of the equipment. Most of the limitations were caused by the inappropriate characteristics of antenna systems. It became evident quite soon that specialized radars are required for further progress in the study of meteors (Kostylev 1958). In 1957, under the supervision of Professor Kostylev, the Laboratory of Applied Radio Astronomy (LARA) was established at the Kazan University to deal with this challenging task. From the very beginning, study of influx of meteoric matter into the Earth's atmosphere became one of the leading research programmes of LARA. It took many years to acquire statistically reliable data, and many improvements were done to the radar observation equipment and data processing techniques throughout this time to ensure an acceptable accuracy of the data on meteor radiants and their activity.

In 1960, the first Russian meteor radar with an azimuth scanning antenna system able to observe meteor radiants over the entire celestial sphere (Kostylev *et al.* 1960) was put into operation in LARA by K. V. Kostylev, Yu. A. Pupyshev and V. V. Sidorov. The use of the azimuth scanning method developed by the Russian researchers allowed a more enhanced and simpler solution compared to commonly used techniques at these times by G. S. Hawkins (Hawkins 1956) that relied on joint observations from two independent radars. Using experimental data acquired with the new azimuth scanning method, Yu. A. Pupyshev obtained the very first rigorous mathematical solution to an inverse radio location problem. By concatenation of radar observations in different sectors of the celestial sphere, Pupyshev was able to construct a high-order system of linear equations, and by solving these it was possible to reconstruct a spatial distribution of meteor radiants over the celestial sphere, from simple detections of a number of meteor events in each hour of the day.

The first version of *Celestial Map of Meteor Radiants* (CMMR) was constructed from five years of data of continuous radar observations (Pupyshev 1964). Over the next decades, the radar data base was constantly supplemented with recent observations, and several new refined versions of the celestial map were released. This unique map contained reliable experimental data on the influx intensity of meteors from different regions of the celestial sphere, and had no analogues anywhere in the world. In the next two decades, the CMMR became an empirical basis both for fundamental astronomical and space studies (including an evaluation of the meteor danger for spacecraft) and for resolving applied problems such as the establishment of meteor burst communications (Pupyshev *et al.* 1980). A contribution of Kazan researchers and Yu. A. Pupyshev, personally, into applied meteor studies was noted, in particular, in the survey book by Robert Desourdis (Desourdis 1993).

The mass distribution of meteor particles is one of the most valuable bits of information obtained from radar observations. Specifically, in many tasks it is very important to know the expected number of meteors with masses greater than the least detected mass. Unfortunately, such data are not directly available from primary radar observations and can only be obtained by indirect calculations. To obtain these data, it was first necessary to develop a calculation method allowing transition from observed physical parameters of ionized meteor trails to desired characteristics of meteor particles. It should be noted here, that, unlike the optical range, in the radio range we observe no meteor bodies but only radio waves reflected from ionized trails left by these meteors. In this way, detected radio reflections present only data on physical properties of meteor trails. However, advances in the physics of meteor phenomena and in the theory of meteor ionization, in particular, provided reliable calculation of parameters of initial meteor bodies based on the characteristics of meteor trails.

The fundamentals of meteor phenomena physics were laid down by N. Herlofson in 1948 (Herlofson 1948). In the following 15 years, this classical theory of meteor phenomena was refined and completed in the works of J. S. Greenhow, T. R. Kaiser and R. L. Closs, D. W. R. McKinley, and P. M. Millman. The Kazan researchers O. I. Belkovich, K. V. Kostylev, and V. S. Tokhtas'ev also made a contribution (Belkovich *et al.* 1995; Andreev *et al.* 1976). Specifically, after an extensive analysis of the reasons for a sharp break in the middle of the integral distribution of durations of meteor bursts, Belkovich and Tokhtas'ev concluded that other processes, aside from the well-known ambipolar diffusion, proceed within the plasma of meteor trails that accelerate their dissipation. Tokhtas'ev's theory also allowed for the experimental determination of the density of some types of meteor bodies, and his estimates were quite accurate.

In the period from 1960 to 2000, five meteor radio observation setups starting from "KGU-M1" to "KGU-M5" were designed in LARA, each with new technology advancements. The most advanced meteor radar "KGU-M5" was equipped with a brand new detecting system operated as a phase goniometer consisting of five phased Yagi antennas synchronously rotated within the azimuth plane (see Figs. 1 and 2). This radar was put

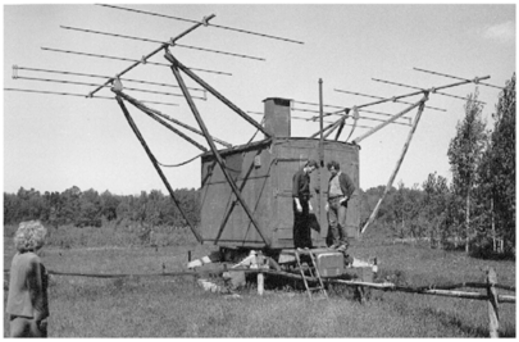

Figure 1. Transmitter of probing signals of the “KGU-M5” meteor radar (photo of 1983).

Figure 2. Phase interferometric goniometer of the “KGU-M5” radar for identification of angle of arrival of meteor radio reflections consisted of 5 Yagi antennas (photo of 1983).

into operation in 1980, and it worked over the next 25 years, providing high-precision data for studies of fine orbital structure of the meteor complex in the vicinity of the Earth’s orbit (Makarov *et al.* 1981).

Radar observations also provide valuable data for studies of the fine spatial structure of the main meteor showers, which may give a better understanding of the origins and evolution of meteor swarms and clusters in the Solar System. A method for identification of such fine spatial structure has been proposed by A. V. Karpov in (Karpov 2001). It is based on statistical analysis of grouping regularities in detection of meteor events both in space and time.

Along with an astronomical research campaign, applied studies of meteor phenomena, both in geophysics and radio communications, were also carried out in LARA. Specifically, the mesosphere investigation methods in the region of meteor phenomena heights (from 80 to 100 km) were actively developed (Fahrutdinova *et al.* 1997). The progress achieved made possible an inclusion of Kazan researchers into international scientific cooperation on studies of dynamic processes of the mesosphere (Jacobi *et al.* 1999). In the field of communications, the patterns of meteor activity revealed in LARA from radar observations were actively used for performance forecasting of the designed meteor burst communication links (Karpov 1995; Karpov & Naumov 2002).

To further increase the resolution of the Pupyshev’s CMMR (which was only 20° × 20° in the celestial coordinate system) and to account for additional grouping of meteoroids by heliocentric velocities, a new method for radiant identification was developed in the late 1980s that used all the recent advances of the new phased goniometer setup of the

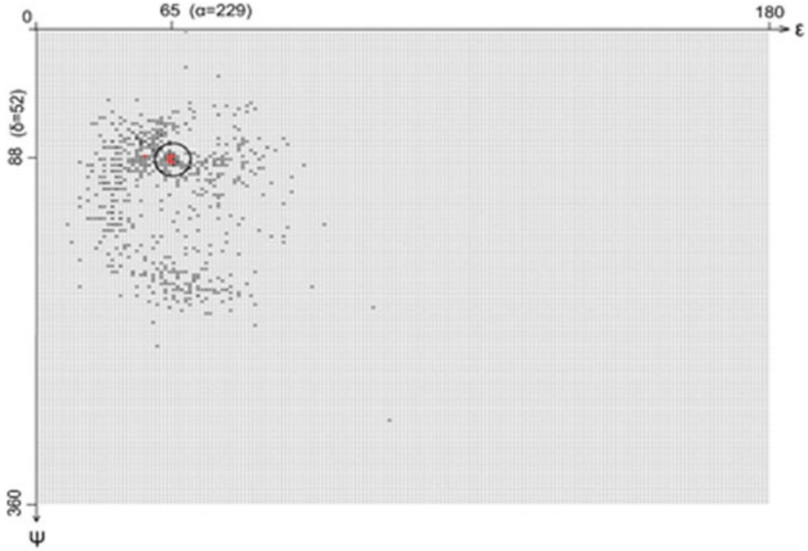

Figure 3. Celestial map of meteor radiants detected in January 2016 at the Kazan Meteor Radar with radiants of the Quadrantids shower encompassed by circle.

"KGU-M5" radar. As a result, the resolution of the CMMR was improved to 10° × 10° (Belkovich *et al.* 1991, 1997). These refined data were used to create a reference model of the celestial distribution of the influx intensity of meteors in the vicinity of the Earth's orbit, which was laid into the foundation of the National standard of USSR on meteoric matter. For many years, it became the basis for practical calculations of the functioning reliability of spacecraft and equipment in outer space under bombardment by meteoroids (GOST 1984).

2. Recent achievements, new methods and results

In the early 2000s, a new discrete quasi-tomographic approach (Sidorov *et al.* 2003) was developed by V. V. Sidorov and S. A. Kalabanov that allowed identification of meteor radiants with much better angular resolution, up to 2° × 2°, on the basis of radar observations with goniometric measurements. Such a precision made it possible for the first time in the world to reveal in the sporadic background the presence of very faint meteor clusters with intensities as low as only six events per day (Sidorov *et al.* 2004). Very simple but effective criteria for assigning a group of meteoroids to a single cluster were adopted. It was substantiated that their radiants all must lie within the same (2° × 2°)-celestial sector and their velocities must be collinear and differ only within the ~ 3 km/s range. Such clusters were named as "microshowers", because they are detected both regularly and reliably along with large meteor showers. As an example, Fig. 3 shows a celestial map of meteor radiants detected in January 2016. The map was constructed in the ecliptic coordinate system, and each cell has angular dimensions of 2° × 2°. We encompassed the radiants assigned with the well-known Quadrantids shower by the circle. In such a way, we can see that the large shower may be presented as a sum of a number of microshowers, which allows investigation of its fine spatial structure.

After identification of all probable microshowers, parameters of their astronomical orbits are determined. The obtained results are easier to interpret if one visualizes them as 4D-graphs of parameters of microshower orbits, where each microshower is displayed as a "bubble". Two dimensions are assigned for the angular coordinates of the orbits, the

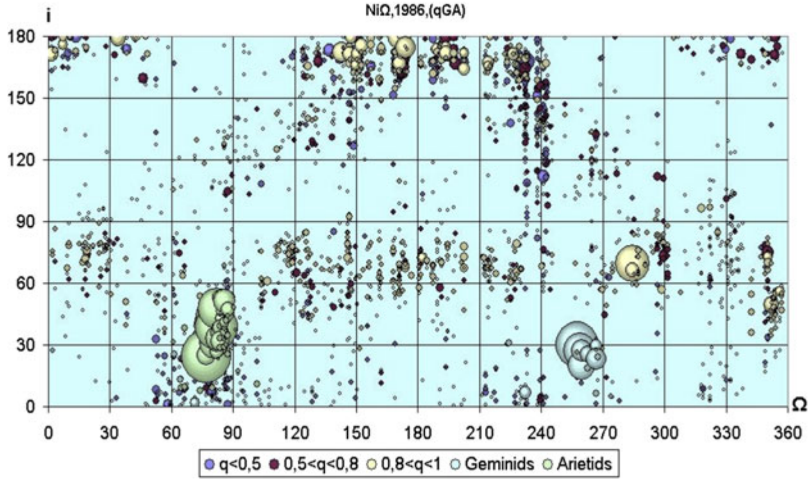

Figure 4. Summary one-year orbital structure of meteor complex observed in 1986.

radius of the bubble expresses the number of detected meteors within the microshower, and the last dimension (the colour of the bubble) expresses the elongation of the orbits, which is defined by their eccentricity. Such a presentation allows for the simultaneous depiction of large and faint meteor showers in one graph (Sidorov *et al.* 2008).

Figure 4 shows an example of the resultant 4D-graph that presents the spatial distribution of the orbital structure of the meteor complex. The ordinate axis shows values of inclination angle i of microshower orbits to the ecliptic plane, whereas the abscissa axis depicts values of longitude of the ascending node Ω. The radius of the bubbles is proportional to the detected number N of meteors in a shower. The colour of the bubbles expresses the type of orbit in terms of its perihelion distance q. Fig. 4 shows a summary of the one-year distribution of all orbits, both with direct and inverse inclination of i observed in 1986.

A complete software package for data processing of the “KGU-M5” radar was developed in the period of 2004–2010. The software takes a primary data in form of angular coordinates of meteor radio reflections and entry velocities of meteoroids into the Earth’s atmosphere and gives estimated orbital parameters of meteor showers at the output. Along with high-sensitivity radio equipment, this software turns the Kazan meteor radar into a very capable tool for astronomical and applied studies of the structure of meteoric matter in the vicinity of the Earth’s orbit (Kalabanov *et al.* 2018).

3. New era in meteor observations

In 2015, Kazan Federal University deployed a new modern multifunctional meteor radar of the SKiYMET system produced by the Genesis Software Co. (Australia) (Genesis Software 2018). Figs. 5 and 6 show its principal components.

Currently, the new radar provides continuous radio observation of meteors with the purpose of monitoring of meteoric matter influx in the vicinity of the Earth’s orbit. Unfortunately, standard in-house radar software by the Genesis Software Co. could not meet all the traditionally plural interests of researchers of LARA. In the first three years of exploitation of the radar, new original data processing algorithms and substituting software were developed under the leadership of D.V. Korotyshkin. After the original programs were entered into the radar, both quality and quantity of observational data significantly increased. Just for one year of observations in 2017, it became possible to register over 8.7 million meteor radio reflections with measured angular coordinates of arrival, of

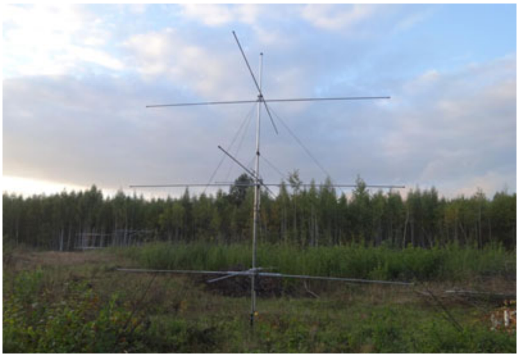

Figure 5. Transmitter antenna of the SKiYMET Meteor Radar operating in Kazan.

Figure 6. Transmitter of sounding pulses of the SKiYMET Meteor Radar in Kazan.

which 5.9 million radio reflections allowed measurement of meteoroid entry velocities. In comparison, the standard in-house software by Genesis Software Co. detected in the same year only 3.2 million meteor radio reflections, and only 186 thousand detections allowed velocity measurements. It means that the efficiency of the standard radar system was less than 6%.

The recent achievements give hope that the modern radar with continuously collected up-to-date data on meteor phenomena is able to provide a long-term experimental basis for a new era in meteor observations in Kazan.

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