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Coordinate support system of the automated control system of the antenna feed type 3 on RATAN-600: results of applying the coordinate search algorithm

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ABSTRACT

In 2019, a new automatic control system (ACS) of the antenna feed type 3 was put into experimental and then into regular operation on the RATAN-600 radio telescope, which provided new opportunities for controlling the motion parameters of the antenna feed elements and, in general, allowed starting a series of methodological work on the implementation of a new observation mode with tracking of objects. To improve the quality of the tracking mode and implement the new automated observation modes, it is necessary to integrate a coordinate support system into the ACS of the antenna feed. The paper investigates approaches to solving the problem of automated coordinate support for the operation of the antenna feed type 3 on the RATAN-600 radio telescope.

Key words: automation, Hough transform, localization problem, image analysis methods

1 Introduction

The coordinate support of the antenna feed type 3 of the RATAN-600 radio telescope belongs to the well-known class of coordinate support problems (Savinykh, 2015), which are reduced to establishing relationships between the geodetic and astronomical coordinate systems. An observer located on the ground establishes these relationships using geodetic systems (Maksimova, 2013). While observing astronomical objects, it is required to restore astronomical coordinates based on the previously known relationships between the radiation pattern of the RATAN-600 radio telescope and the geodetic coordinate of the center of the secondary (receiving) mirror. A research problem is the increased accuracy of finding the current geodetic coordinate, which follows from these relationships, and requirements for iterative observations. In the process of observing and tracking space objects (the Sun), a problem arises due to the contradiction between the required operational calculation of the current geodetic coordinate when moving the feed cabin and the transit (stationary) nature of the antenna feed operation, initially determined by the telescope developers. In particular, Storozhenko et al. (2021) defined tasks both for closing the feedback of the automated control system (ACS) of the antenna feed movement (feed position) and for the ACS subsystem for ensuring observations (clarifying the true track angle, which is the angular displacement of the feed cabin location). In this work, we investigate possible approaches and find an acceptable solution to these problems. The work aims to create a prototype of the coordinate support system for the antenna feed type 3.

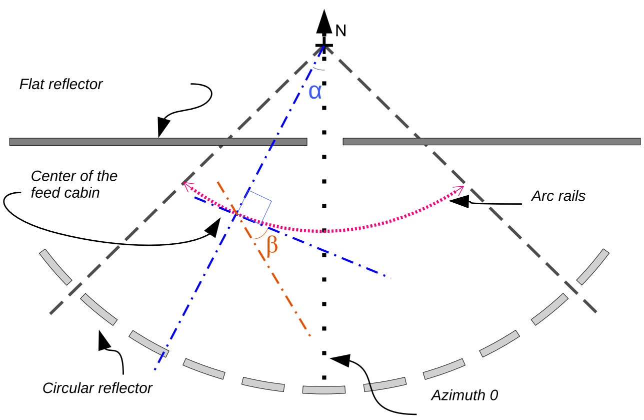

Fig. 1. Coordinate system of the feed cabin No. 3 in the antenna system “South+Flat”; α is the track angle (coordinate of the feed center on the arc path), and β is the relative angle of the cabin rotation.

The problem of determining geodetic coordinates can be reduced to the problem of calculating local coordinates (spatial, rectangular) on the section of the arc path of the feed cabin No. 3 (Maksimova, 2013). The required error of setting to a given azimuth in the transit mode is defined as 1 mm (Fig. 1). The local coordinate problem can be formulated as the calculation of relative coordinates or the calculation of absolute coordinates (Berka, 1983).

2 Solution of the coordinate problem, localization of the coordinate mark

The coordinate support problem can be solved by finding the absolute coordinate of a machine-readable mark (localization problem) in the control zone on the path of the feed cabin along the arc rails (Atali et al., 2018). Additional conditions are the presence of a sufficient amount of information that such a mark can contain (several hundred identifiers), noise immunity of reading this information, and a fast heuristic algorithm for finding the mark on a raster image. A QR mark satisfies these conditions (Zhang et al., 2015), and noise immunity was investigated in Karrach et al. (2020). The disadvantages of this approach include the limitations in the accuracy of detecting QR coordinates, which is a modern research problem. In particular, in Teoh et al. (2022), the error in model calculations is ≈ 0.4 mm, whereas in Karrach et al. (2020), it ranges from 6 to 10 mm. In our case, the pixel-by-pixel method for restoring the projective transformation matrix (Teoh et al., 2022) is not applicable due to the complex interference situation and possible blurring of the mark boundaries, as well as lens dusting under real operating conditions. The solution to this problem would be to use group pixel statistics and, in the best case, transition to the subpixel measurement range. Nevertheless, in this work, the accuracy of coordinate restoration was assessed depending on the distance to the mark for an f2.8 lens. Of the modes listed, the most promising, from our point of view, is the use of a distance of 40 cm and 30 cm from the lens for a mark with a width of 5 cm. To bring the recognition accuracy of the technical mark to the required level, the applied technique of two-stage detection (Brinkmann, 1999) was used, as well as the identification of the supposed object boundaries.

3 Algorithm for recognizing the coordinates of a machine-readable mark

To provide the observation process with data on the feed coordinates α and β (Fig. 1), two-coordinate extraction of a machine-readable mark from a raster image is required. Various approaches to solving this problem are known, as presented particularly in Zhong et al. (2017). Since the proposed machine-readable mark has a black-and-white raster, we used the Hough transform, which is an algorithm used for parametric identification of geometric elements of a raster image (Hough, 1962; Ershov, 2018). The search results pass through a filter for a given heuristic, for example, the location of intersections in a given square relative to the elements of the QR mark. Ershov (2018) showed that for a 512 × 512 image, the restoration of the true parameters of a discrete line by the Hough method has an error of less than a pixel. In this work, for pairwise lines, the localization error σR is defined as for dyadic lines and is limited by the relation

$$\left(\frac{\log_2 n}{\sqrt{22}}\right) \le \sigma R \le \frac{\sqrt{2}\cdot\log_2 n}{6}, \qquad (1)$$

where $n = 2 \cdot k$ is the side of the image.

In the case of detecting more than one line intersection, it is possible to use other algorithms, for example, those averaging the geometric locus for a more accurate search for the line intersection coordinate and selection of the best point based on a selected heuristic (Vinogradov et al., 1977). It is proposed to combine the QR mark detection algorithm with finding the coordinates of line intersections (Fig. 2).

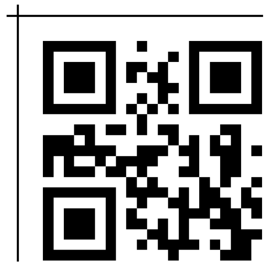

Fig. 2. Image of a machine-readable mark, which contains a QR marker and coordinate lines, used to restore the coordinate of the mark setting position.

4 Approbation of the algorithm for recognizing the coordinates of a machine-readable mark

A prototype of the technical mark recognition system was required to ascertain the step of the obtained measurement scale and to determine the optimal lens settings. It consists of a lifting table with a micrometric screw on which the mark was fixed, as well as a camera fixed motionlessly, horizontally, with the sighting axis directed toward the lifting table. A Panasonic WV-SP306 1 MP camera with a Fujinon YV10x5HR4A-SA2L 1:1.6/5–50 mm 1/3 CS lens was used. The estimated characteristic of the sensitivity threshold of the scale was 120–150 μm at the center of the sighting axis, and 200–220 μm is the scale division value (expected movement accuracy) on the stand in noise-free conditions inside the room. Based on the same prototype, the calculation of the lens distortion matrices was carried out (Penate-Sanchez et al., 2013). Such estimates are in good agreement with the calculated ones (Ershov, 2018), according to which, for ROI of 256 × 256, the lower error estimate is 0.57 pixels, and the upper one is 0.6361 pixels; for ROI of 100 × 100, it is 0.49058–0.5423 pixels. For a lens field of view of 300 mm, the scale step for a small mark should be 114.66 μm and 126.89 μm, respectively. For full-scale tests, a Panasonic WV-SP306 camera with a Fujinon YV10x5HR4A-SA2L lens was used, adjusted to a field of view of 300 × 300 mm and a focus distance of 300 mm to the machine-readable mark. The tests were carried out on a camera fixed motionlessly on feed cabin No. 3, with marks placed along the northern rail of the arc path. The testing methodology included repeated movements of the feed cabin as accurately as possible to the initial (starting) coordinate. The feed coordinates were measured by the developed coordinate support system, as well as by using an external (reference) Leica measuring complex. Testing showed that the coordinates derived by both complexes are within the limits allowed by technical specifications. After removing the lens distortion, the values of the discrete resolving power of the system reached 0.34 mm in units of the traversed path of the feed cabin No. 3.

5 Prototype of the coordinate support system

The software package that implements the functionality is developed in Python programming language (Rossum et al., 2001) using OpenCV libraries (Bradski, 2000). To ensure the output of coordinates to external systems, a REST interface was implemented through HTTP requests. The estimated frame processing rate was 400 ms. A mode of operation with two cameras for calculating the track angle was also implemented. For integration into the ACS subsystem, it is further planned to expand the software functionality by supporting the Modbus TCP protocol. For the target task of coordinate support, automatic tracking, and calculation of the track angle, various camera placement schemes were considered: diagonally north-southwest; above the southern rail; under the supporting bosses of the secondary mirror. The variant under the supporting bosses of the secondary mirror of feed cabin No. 3 allows determining local coordinates with minimal influence of feed leveling and bending deformations of the feed frame. However, taking into account the technical and economic features of the considered schemes, the placement above the southern arc rail with the possibility of installing an additional camera above the northern arc rail was chosen.

6 Problems and discussion

Approbation of several methods for solving the coordinate problem showed high complexity in finding an acceptable solution. Despite the good results obtained on the research stand, tests on the antenna feed showed that for some coordinate axes, achieving an accuracy of 340 μm is possible only after removing the distortions introduced by the optical system (lens distortion), which means that the full accuracy of the algorithm under operating conditions depends on the design, manufacturing quality of a particular lens and its settings. Tests of the prototype system in April 2023 showed that the recognition of the combined mark occurs steadily under precipitation conditions. However, under conditions of solar illumination in the middle of the day, shading of the camera with the lens and the camera's field of view is required. It is possible to solve this problem by applying binary gradient search algorithms on raster images with a shift of the binarization boundary in relation to the Hough algorithm (Nikolaev, 2023).

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