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What changes in multi-color sky survey will be required by the transition from the ISS to ROS

M. Prokhorov, A. Zakharov, N. Krusanova, V. Moshkalev, O. Stekolshchikov, and M. Tuchin

Sternberg Astronomical Institute of M. V. Lomonosov Moscow State University, 13 Universitetkiy Prospekt, Moscow, 119991 Russia

Abstract. The task of conducting a space-based multicolor photometric all-sky survey of high and moderate brightness stars with an emphasis on high accuracy and uniformity of measurements was formulated a long time ago, but remains in demand to this day. It was assumed that such survey would be carried out on board of the ISS (the Lyra-B experiment), but due to the end of the station's operation in 2028–2030 its preparation was stopped. An application has been submitted to conduct a similar survey on board of the Russian Orbital Station (ROS). However, ROS is noticeably different from the ISS; one of the main differences is the sun-synchronous orbit of the station. This article discusses in detail the changes that need to be made to the scientific equipment of the experiment and the methodology of a survey when transferring location of the experiment from the ISS to the ROS. The benefits and disadvantages of the new experimental location are considered.

Keywords: techniques: photometric; catalogs; surveys; space vehicles: instruments

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1 Modern large and high-precision photometric catalogues

The need for a highly accurate and uniform multi-color photometric all-sky catalogs of bright and moderate-luminous stars was recognized back in the 1980s. Such catalogs are required both for fundamental research in almost all areas of astronomy, and for applied astronomical work. The following requirements apply to such photometric catalogues:

1. high accuracy of photometric measurements;
2. large catalog size, i.e. large limiting stellar magnitude;
3. many photometric bands;
4. conducting a survey over the entire sky or a significant part of the sky;
5. the ability to detect stellar variability;
6. multiple observations of stars;
7. almost simultaneous measurements of stars in different photometric bands;
8. large dynamic range of star brightness;
9. the ground-based survey must contain the data necessary for the correct removal of photometric measurements beyond the Earth's atmosphere.

Let us explain this list of requirements. The accuracy of stellar photometry (item 1 of the list) can be considered high if the total photometry error does not exceed 0.001^m for bright stars and 0.01^m for stars of moderate brightness. The errors are indicated for non-variable stars; they are obtained by averaging all measurements over the survey duration. The limiting magnitude (item 2 of the list) may be ranked following the space experiment (SE) Gaia: bright ($m <$ 7–12), moderate ($m <$ 15–17), dim ($m <$ 20–21). For moderately bright stars Gaia gives the most accurate coordinates and photometry, while dim stars include all stars in Gaia survey. A large number of photometric bands (item 3 of the list) means that there should be at least 4–5 of them, preferably 10. The requirement for all-sky survey (item 4 of the list) seems almost obvious; we may need information about any star in the sky. However, for statistical studies one can limit oneself to viewing only part of the sky. An example of the latter situation is the SDSS survey (Almeida et al. 2023). The main purpose of its implementation was to study galaxies, therefore the observations did not include areas of low galactic latitudes; the survey covered only 2/3 of the sky.

Detection of stellar variability (item 5 of the list) is possible only with repeated measurements of stars (item 6 of the list). To correctly determine the characteristics of variable stars, measurements in all bands must be carried out within a short time interval (item 7 of the list).

Dynamic range (item 8 of the list) is important for photometric surveys: bright and dim stars must be measured simultaneously. Depending on the limiting magnitude, the typical dynamic range may be 12^m–14^m (flux ratio 60 000–400 000 times) or 17^m–18^m (flux ratio 6 –16 million times). An example of a solution to this problem can be the star registration system in the SE Gaia (Gaia Collaboration et al. 2016).

Unfortunately not a single present-day photometric catalog satisfies all listed requests. The most precise photometry are in the catalogs of Hipparcos and Gaia DR3 (Hipparcos 1997; Gaia Collaboration et al. 2021, 2023, 0.001^m), WBVR-catalog of SAI is slightly inferior to them (Kornilov et al. 1991; Cherepashchuk et al. 1994, 0.003^m). However, in the Hipparcos catalog there is only one photometric band Hp, in the Hipparcos and WBVR catalogs there are few stars (120 and 15 thousand). The Gaia DR3 catalog contains 1.8 billion stars, has a very high accuracy, but only three photometric bands. The next one in terms of accuracy is Tycho-2 catalog Hog et al. (2000). Its error is acceptable for many problems (0.008^m), but the number of stars is not very large ($2.5 \cdot 10^6$) and there are only two photometric bands B_{T} and V_{T}.

Photometry of the 2MASS (Almeida et al. 2023) and SDSS (Cutri et al. 2003) are most often used by astronomers. The 2MASS catalog has three bands JHK, SDSS has five bands $ugriz$. These catalogs contain ∼500 million stars each. The rest of their characteristics as photometric catalogs should be attributed to disadvantages: lower photometric accuracy, almost complete absence of repeated observations, lack of data for removal of measurements beyond the atmosphere.

The USNO A2.0 and USNO B1.0 catalogs contain a lot of stars, but they were obtained from scanning photographic plates of the Palomar POSS-I survey. The photometric accuracy of these catalogs is completely unacceptable.

In the next decades, the final version of the Gaia catalog and the optical survey of the China Space Station Telescope (CSST), can appear.

Stellar photometry in Gaia is obtained by two ultra-low resolution spectrometers, creating spectra with about 30 pixels in blue and red channels (Jordi & Carrasco 2007). Based on them, 14-band photometric system Gaia C1M was introduced, which has now been forgotten. The Gaia DR3 catalog published the brightness of stars in the Bp and Rp bands, which are complete integrals of blue and red microspectra. These quantities have high accuracy ($\sim 0.001^m$). It is unknown whether photometry in the C1M system will be presented in the final version of the Gaia catalogue or if it will remain 3-colored (G, Bp, Rp).

Another possible source of high-precision stellar photometry in the near future is a 2-m Chinese Space Station Telescope (CSST). The telescope is expected to be launched into orbit in 2025–2026. Information about the characteristics of CSST is inconsistent. The telescope will be equipped with a 6 or 7-band photometer operating at $\lambda = 255$–1000 nm, the limiting magnitude in g band will be 26^m. It is expected that over 7–10 years, CSST will conduct photometry of stars over an area of 17 500 square degrees. Other characteristics of this possible survey are unclear.

2 Space experiment proposed by SAI MSU

Due to the need need for a high-precision photometric survey of stars, the SAI MSU proposed the SE Lyra-B, which maximally satisfies the above requirements. The Lyra-B project was included in the long-term program of scientific research on ISS. More detailed information about the SE Lyra-B can be found in Zakharov et al. 2013, 2018; Zhmailov & Prokhorov 2020.

The project was implemented with long interruptions. In 2008–2010 preliminary design was developed, in 2018–2019 the design documentation was made. From 2019 SE was suspended. In 2021 it became clear that even with the maximum extension of ISS life, there would not be enough time to complete the Lyra-B SE. At the same time, the scientific task of the research remains relevant (Prokhorov et al. 2022).

In 2023 SAI provided an application to Nebosvod SE onboard Russian Orbital Station (ROS), similar in goals and objectives of Lyra-B SE.

During the development of scientific equipment for Nebosvod SE, many of Lyra-B solutions will be used, however, despite maintaining the basic principles of Lyra-B, transferring its location to ROS will require significant changes in the scientific equipment.

3 Changes in the project due to the transfer to the ROS

There are several reasons to change the design of scientific equipment developed for Lyra-B on ISS due its transfer to the ROS. The main one is the sun-synchronous orbit of ROS, changes in the construction of ROS and the progress of matrix photosensors.

The ROS will revolve around the Earth in a sun-synchronous orbit, such an orbit precesses around the Earth with a period of 1 year. In the coordinate system associated with the station's orbit, the Sun shifts to $\pm 23^\circ\ 26'$ in north–south direction and by several degrees in east–west during the year (in an asynchronous orbit, like the ISS, the Sun may be in almost any position relative to station and telescope). Such movement of the Sun allows the use of a motionless oblique hood at the telescope. In this case, the total length of a lens hood for ROS may be less than an axisymmetric telescope hood for ISS. An issue that requires additional consideration is the use of stationary anti-solar screens at the ROS. This was impossible on the ISS.

On the ISS, the telescope was going to be placed on a high mount and strongly shifted in the horizontal direction. This was because the star trackers of ISS attitude control were located near the telescope installation place. On ROS there will be no such problem (we hope), which will make the mount much shorter and stronger.

Another important change in ROS design is a planned increase of docking hatches. On the ISS, they were ∅800 mm, which allowed the telescope to have a body of ∅600 mm and the main mirror ∅500 mm. It is assumed that a new hatch will be ∅1000 mm (this is not yet known exactly). With the new hatch the main mirror may be increased to ∅700 mm, which will lead to an increase of the area by 96 % and the limiting magnitude by 0.73^m.

It was assumed that CCD matrices would be used as photodetectors on the ISS (Zakharov et al. 2013). Their development and production was to be entrusted to e2v Ltd., now Teledyne e2v (UK). Unfortunately, today this is no longer possible. There are several possible ways to solve this problem:

– Use of ready-made or custom-made CCD matrices from other manufacturers

  Unfortunately, there are no other manufacturers of CCD ready to carry out the necessary development for Russia. There are also no commercially produced matrices with required characteristics. The latter is related to the overall decline of CCD production, which are replaced everywhere by cheaper and faster CMOS matrices.

– CCD-in-CMOS TDI (Mahato et al. 2021)

  This is a recent development in which, based on CMOS technology, the light-sensitive structure of CCD-matrix is reproduced to operate exclusively in the TDI-mode. The readable part of the chip is a conventional CMOS, the data output is in a digital form. The main disadvantage of CCD-in-CMOS produced today is a high level of electron thermal emission, which either makes it impossible to use them for recording weak astronomical signals, or requires very strong cooling.

– Using a swinging mirror to implement frame mode

  A light flat mirror rotating around an axis perpendicular to the station's orbit is installed in the telescope's optical system. The mirror rotates uniformly for some time at a speed equal to the half of station's orbital angular velocity. At this time, the images of stars in the focal plane are motionless. Then the mirror quickly returns to the initial position, and the frame is read from the matrix. After the cycle of exposure and reading is repeated, the neighboring section of the starry sky is recorded.

  This approach can be used for any type of a matrix. A similar approach was successfully used in 2MASS survey and WISE SE.

– CMOS matrices with fast readout

  The CMOS matrix is located in the focal plane of a telescope so that images of stars move along its rows or columns. The exposure lasts for a time equal to the movement of star images by one pixel (on a telescope for the ISS this is ~1/300 s). The resulting frames are added with a shift of one pixel. CMOS matrices with the frame frequency of 300 Hz and higher, up to 1000–2000 Hz, are now mass-produced.

4 Conclusion

The creation of a multicolor, high-precision photometric catalog of stars remains an urgent astronomical task. The SE Lyra-B onboard of the ISS has been in preparation for this task during several years at the SAI MSU. Due to the end of ISS operation, it has been proposed to conduct a similar SE Nebosvod on ROS.

The transfer of SE from the ISS to the ROS, while maintaining the tasks and principles of sky survey, requires serious reworking of the scientific equipment. The main reasons for this are the changes in the type of the orbit and the construction of the orbital station, as well as the progress of matrix photodetectors. In the preparation of SE Nebosvod it is necessary to repeat the stages of Preliminary design and Development of design documentation, which have already been carried out for SE Lyra-B. Some issues of the SE Nebosvod require additional research.

The ROS station is proving to be a "more convenient" place for photometric sky survey than the ISS.

References

Almeida A., Anderson S., Argudo-Fernandez M., et al., 2023, Astrophysical Journal Supplement Series, 2023, 267, id. 44

Cherepashchuk A., Khaliullin Kh., Kornilov V., and Mironov A., 1994, Astrophysics and Space Science, 217, p. 83

Cutri R., Skrutskie M., van Dyk S., et al., 2003, The IRSA "2MASS All-Sky Point Source Catalog"

Gaia Collaboration, Brown A., Vallenari A., et al., 2021, Astronomy and Astrophysics, 649, id. A1

Gaia Collaboration, Prusti T., de Bruijne J., et al., 2016, Astronomy and Astrophysics, 595, id. A1

Gaia Collaboration, Vallenari A., Brown A., et al., 2023, Astronomy and Astrophysics, 674, id. A1

Hog E., Fabricius C., Makarov V., et al., 2000, Astronomy and Astrophysics, 355, p. L27

Jordi C. and Carrasco J., 2007, ASP Conference Series, 364, p. 215

Kornilov V., Volkov I., Zakharov A., et al., 1991, Trudy Sternberg Astr. Inst., 63, p. 4

Mahato S., Thijs S., Bentell J., et al., 2021, arXiv:2109.14532

Prokhorov M., Zakharov A., Stekolshchikov O., and Tuchin M., 2022, in Proceedings of VAK–2021 conference "Astronomy at the epoch od multimessenger studies", p. 69

The Hipparcos and Tycho catalogues. Astrometric and photometric star catalogues derived from the ESA Hipparcos Space Astrometry Mission, 1997, ESA SP Series, 1200

Zakharov A., Mironov A., Prokhorov M., et al., 2013, Astronomy Reports, 57, p. 195

Zakharov A., Zhukov A., Mironov A., et al., 2018, in Proceedings of "Modern Star Astronomy. Astronomy–2018", 1, p. 174

Zhmailov S. and Prokhorov M., 2020, Astronomy Reports, 64, p. 34