AGREED UPON

Director of SAO RAS,

V.V.Vlasyuk

February __ 2020.

APPROVED

Chairman of the Russian Telescope Time Allocation Committee,

K.A.Postnov

February __ 2020 г.

Circular letter from the Russian Telescope Time Allocation Committee

The following observation methods are announced for use at the 6-m telescope of SAO RAS starting from the second half of 2020:

The circular letter gives a short description of the mentioned instruments and methods as of the beginning of 2020. Additional information can be found on the SAO home page http://www.sao.ru/Doc-k8/Telescopes/bta/instrum/

General use methods

BTA primary focus Universal spectrograph SCORPIO-1
Instrument status – general use
Responsible astronomer – D.V. Oparin (doparin2@gmail.com)

The universal spectrograph SCORPIO-1 is designed for observations of extended and star-like sources in three modes:

1. Direct imaging in the Johnson-Cousins (UBVRI) photometric system and in the midband (SED, ~100-250 A) interference filters;

2. Long-slit spectroscopy with a resolution of R=500-1000 in the 350-1000 nm range;

3. Multi-slit spectroscopy.

A 2048×2048 EEV 42-40 CCD array with a 13.5×13.5 micron element size is used as a light detector. The device is mounted on the BTA primary focus adapter, which is used for aligning and guiding, as well as spectral and photometric calibration of the spectrograph. Device control and data registration are performed remotely from the Lower scientific site of SAO RAS.

SCORPIO-1 Universal spectrograph parameters
1. DIRECT IMAGING
The field of view is 6.1×6.1 arcminutes, the image size is 0.357×0.357 arcseconds with a 2×2 binning and images size of 1024×1024 px. The spectral transmission curves of the broadband and interference filters included in the spectrograph are listed at https://www.sao.ru/hq/lsfvo/devices/scorpio/filters/filters.html#bvri, https://www.sao.ru/hq/lsfvo/devices/scorpio/filters/filters.html#sed.
2. LONG-SLIT SPECTROSCOPY
The maximal slit length is 6 arcminutes, and exchangeable slits of 1″.2 and 2″.3 widths are available for use. A mask can be used instead of the slit containing the 8-point test, as well as a mask for slitless spectroscopy. Two VPHG volume holographic gratings with direct view prisms (hereafter “grisms”) can be mounted simultaneously in the remote-controlled carriage of the spectrograph. Currently, grisms VPHG550G, VPHG550R, VPHG1200B, VPHG1200G and VPHG1200R are available for use. The grism parameters are listed at https://www.sao.ru/hq/lsfvo/devices/scorpio/grisms/grisms.html.
3. MULTI-SLIT UNIT SPECTROSCOPY
The multi-slit unit consists of 16 movable metal strips with slits that are moved remotely in a 2.′9×5.′9 size field. The height of the slits is about 18″, and the distance between the slit centers is about 22″. The position of each slit is fixed by two electromagnets. The total time of alignment of all the slits (with a required accuracy of 0.″2-0.″3) is approximately 10 minutes. At present, the unit is being modified and is unavailable for observations.

BTA primary focus adapter

Instrument status – general use

Responsible astronomer – R.I.Uklein (uklein@sao.ru)

The BTA primary focus adapter (hereafter “Adapter”) is designed for off-axis guiding and telecentric illumination of the input of the installed equipment by various calibration light sources. In addition to the focal reducers SCORPIO and SCORPIO-2, it can also host other spectrographs with a weight up to 150kg and a working section no longer than 40 mm. Two main modules are available:

1. GUIDING MODULE – correction of the position of the BTA telescope based on digital imaging, atmospheric transparency control, and control of the telescope focusing based on reference star photometry;
2. CALIBRATION MODULE – telecentric illumination of the CCD-arrays of the mounted instruments with discrete and continuous spectrum sources.

The Adapter is mounted on the rotary table in the BTA primary focus booth. Control of the Adapter is carried out remotely from the Lower scientific site of SAO RAS.

Parameters of the BTA primary focus adapter

1. GUIDING MODULE

An Atik Titan camera with a Sony ICX424 detector with a 7.4×7.4 micron element size and a 659×494 format is used as a guide. Depending on the position of the diagonal mirror of the Adapter, two main modes are available:

- FIELD (direct field of view). The diagonal mirror in the FIELD position transmits the image of the main field of view to the guide, which makes it possible to identify the field, including positioning bright sources on the slit. The FIELD size in the guide is 3′ × 2′.
- FIBERS (reference star images). In the FIBERS position, the light from the observed objects is received by the instruments mounted on the Adapter, and the guide receives the reference star images. The celestial sphere projected angular diameter of the fiber harness amounts to 54″, and the field size for moving it is 10′×4′.5. Guidance field centers are located at a distance of 12′ from the centers of the fields of view of the system.

In addition to visualization of the image from the guide, the guidance software allows one to superimpose digital crosses and marks on the image. The captured image shows either the position of the slit in the FIELD with the observed source, or two crosses in the FIBERS guidance fields, with stars captured in their centers.

A magnitude range of 10^m–15^m is optimal for guiding. Guiding by stars fainter than 15^m is possible only for good quality images and sufficient transparency. The limiting R-band magnitude for a signal-to-noise ratio of $S/N = 5$ is approximately 17^m. For guidance quality control, a plot can be viewed on the screen of the control computer showing the following parameters: the current extinction, reference star image size, and the azimuth and zenith correction values for the BTA telescope.

The input end of each of the guidance harnesses moves along the optical axis within 0-9.7 mm to focus the reference star, which allows one to correct the telescope focus during a long (more than one hour) series of spectral exposures if necessary. The presence of two calibration fields allows the focus control procedure to be performed on one of the stars while the other field is used to guide the telescope.

2. CALIBRATION MODULE

The calibration module consists of an integrating sphere (Ulbricht sphere), calibration illuminator optics and a control system integrated into the SCORPIO and SCORPIO-2 instrument control interfaces. The integrating sphere has two linear spectrum sources, a continuous spectrum source and 32 ports for installing LEDs as illuminators, which gives three calibration modes:

- NEON: a lamp with He-Ne-Ar filling for calibrating the wavelength scale.
- QUARTZ: quartz halogen continuous spectrum lamp for creating a flat field.
- LEDS: A LED system that provides a continuous spectrum for a flat field with approximately uniform brightness over a wide range of wavelengths. This allows an equidistant illumination of the flat field in different spectral ranges and reduces parasitic scattered light in the blue region.

The Adapter is described in detail in the work of V.L.Afanasiev, V.R.Amirkhanyan, A.V.Moiseev, R.I.Uklein, A.E.Perepelitsin, the Astrophysical Bulletin, 2017, volume 72, No.4, pp.497–507 https://www.sao.ru/Doc-k8/Science/Public/Bulletin/Vol72/N4/ASPB497.pdf. The current instructions for observers can be found on the website https://www.sao.ru/hq/lsfvo/adap/

Main Stellar Spectrograph (MSS)

Instrument status – general use

Responsible astronomer – D.O. Kudryavtsev (dkudr@sao.ru)

Method: spectroscopy and spectropolarimetry (circular polarization) of bright star-like astronomical objects with the MMS of the BTA in the 330-900 nm wavelength range with a spectral resolution of R=15000

General information

The Main stellar spectrograph (MSS) is designed to record spectra of stars and star-like objects with magnitudes m_V up to 14 in the spectroscopy mode and up to 12 in the spectropolarimetry mode (circular polarization) in an adjustable 3300-9000 AA wavelength interval with a moderate spectral resolution ($\lambda/\Delta\lambda$ = 2000-15000). The spectrograph can be used in tasks dedicated to the study of stellar magnetic fields, determining the chemical composition of stellar atmospheres and their physical parameters. The capabilities of the MSS in tasks related to measuring radial velocities are limited by its temperature and mechanical instability: the maximum accuracy of V_r measurements is about 1 km/s.

The MSS was manufactured by the Leningrad Optical and Mechanical Association simultaneously with the BTA and is stationary inside the left side frame of the telescope (Nasmyth-2 focus). Over the course of its use at the telescope, the spectrograph has been significantly upgraded (Panchuk et al., 2014), in particular, it was modified for CCD observations, partially automated, the pre-slit part was significantly reconstructed; several generations of circular polarization analyzers were manufactured.

Instrument kit

Pre-slit devices. The calibration lamp assembly (Th-Ar emission lines for wavelength calibration and a continuous spectrum halogen lamp), the local star position corrector on the spectrograph slit, and the field and slit cameras are common for the MSS and NES spectrographs.

Optics. The diameter of the collimated beam of the MSS is 258 mm, the light diameter of the collimator is 310 mm, and the focal distance is F = 7929 mm. The focal distance of the spectrograph camera (camera №2) is F = 604 мм, its optical scheme — Schmidt-Newton — contains a quartz correction plate which allows working in the 3300-10000 Å wavelength range. The focal plane curvature of the camera is corrected by a Piazzi-Smith lens.

The spectrograph is equipped with a set of exchangeable diffraction gratings with blaze angles of 8°, 15.5° and 24.7°, designed to operate in the first three orders of diffraction. The size of the grooved part of the grating is 320×360 mm with a groove density of 600 grooves/mm. The isolation of working orders is carried out by filters. The diffraction gratings are changed during the day time. A change of the observed part of the spectrum is possible within an observing night by changing the tilt angle of the grating.

Table. 1. Main parameters of the MSS optical scheme.

Angle of beam tilt to the *Z* axis	65°
Collimator	
Focal distance	7928.7 mm
Light diameter	310 mm
Axis inclination angle	3°
Angle between the collimator and camera axes	45°
Camera №2	
Focus	604 mm
Mirror diameter	700 mm
Corrector diameter	405 mm
Flat mirror diameter	120 mm

Табл. 2. Parameters of the MSS diffraction gratings.

Blaze angle	8.0°	15.5°	24.7°	24.7°
Working order	I	II	II	III
Recommended range, A	4300-6500	3100-5600	5600-9000	4000-4900
Average inverse dispersion (Å/mm)	26.1	13.2	13.2	8.8

Registration system. As a detector, the MSS uses a CCD array manufactured by the Advanced Design Laboratory of SAO, based on a 2050×4600 E2V CCD 42-90 (deep depletion) chip. The size of one element is 13.5×13.5 microns. In the case of a grating with a blaze angle of 24.7°, inverse linear dispersion in the third order with the mentioned CCD system in the 4000-5000 ÅÅ spectral range is 0.1215 A/pixel. The sky-projected slit width in this case is equal to 0.5″. One frame registers a 500 A wide portion of the spectrum.

Slit part and spectropolarimetry

The use of two slit units is possible for the spectrograph. The slit manufactured by LOMO has a height of 50 mm, and its width can vary. The spectrograph slit designed at SAO by G.A.Chuntonov is used in spectropolarimetric observations, as it is structurally combined with a synthetic two-beam refractive crystal and a double image slicer. A 5″ diameter diaphragm determines the slit height, and its width remains constant and equal to 0.5″ in projection. Together with this slit unit a λ/4 phase plate is used, which can assume two fixed positions (0 and 90°) relative to the crystal.

The set of calibration sources consists of a continuous spectrum lamp (filament lamp) and an emission spectrum source (Th-cathode lamp filled with Ar).

Storage and reduction of observed data

All spectral material acquired with the MSS is stored in the shared archive of SAO in FITS format. For frame reduction and extraction of one-dimensional spectra, standard procedures may be used from the packages of ESO-MIDAS, IRAF and others (DECH, Reduce, etc.).

More detailed information on the MSS spectrograph, its characteristics and instrumental capabilities can be found on the website

http://www.sao.ru/hq/lizm/mss/ru/

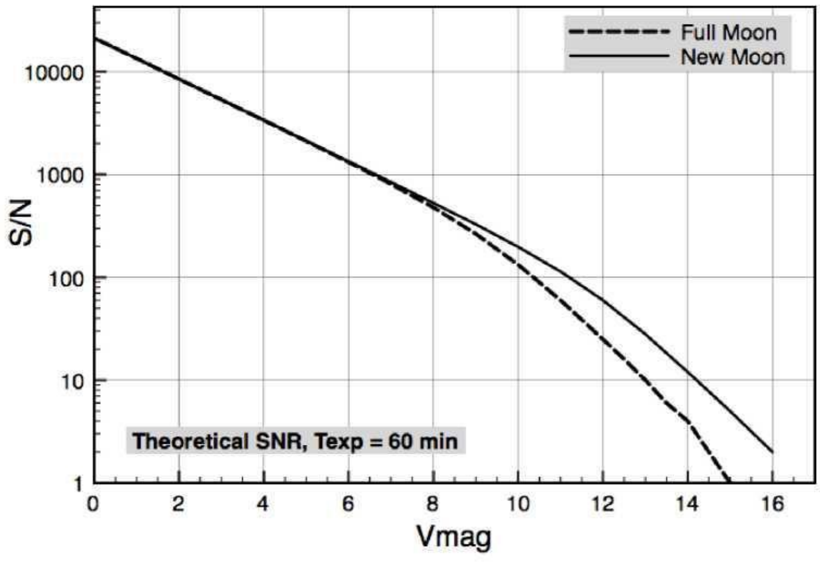

Fig. 7. Theoretical resolving power of the MSS as a function of lunar phase for typical conditions (the FWHM of the image is 1.2-1.5″, z = 20°, λ_c = 4550 Å, the circular polarization analyzer is combined with the image slicer, the inverse

linear dispersion is 9 A/mm (0.1215 A/pixel)).

LITERATURE

1. A.S. Vasiliev, A.M. Evzerov, M.V. Lobachev, I.V. Paysahson. Optical and Mechanical Industry, issue 2, p.31 (1977).
2. V.E. Panchuk. Spectral complex of the Nasmyth focus of the 6-m BTA telescope. VII. Main stellar spectrograph. SAO preprint No.154 (2001).
3. V.E. Panchuk, G.A. Chuntonov, I.D. Naidenov, Astrophysical Bulletin., V.69, p. 360 (2014).
4. BTA telescope. Technical description. Book 4. Main stellar spectrograph, Leningrad: LOMO (1974).

Methods with author's supervision

BTA primary focus Universal spectrograph SCORPIO-2

Instrument status – author's

Responsible astronomers – V.L.Afanasiev (vafan@sao.ru), A.V.Moiseev (moisav@sao.ru)

The SCORPIO-2 universal spectrograph is designed for observations of extended and star-like sources in six modes:

1. Direct imaging in the Johnson-Cousins (UBVRI), SDSS (ugriz) photometric systems and in the narrow-band (2.5-25 nm) interference filters;
2. Long slit spectroscopy with a resolution of R=500-4000 in the 350-950 nm spectral range;
3. Long slit spectropolarimetry (Stokes parameter measurements);
4. Image polarimetry in broad- and mid-band filters;
5. Panoramic spectroscopy with a Fabry-Perot scanning interferometer
6. Integral field spectroscopy with a lenticular screen.

A 4612×2048 EEV 42-90 CCD array with a 13.5×13.5 micron element size is used as a light detector. The device is mounted on the BTA primary focus adapter, which is used for aligning and guiding, as well as spectral and photometric calibration of the spectrograph. Device control and data registration are performed remotely from the Lower scientific site of SAO RAS.

SCORPIO-2 Universal spectrograph parameters

1. DIRECT IMAGING

The field of view is 6.1×6.1 arcminutes, the image size is 0.357×0.357 arcseconds with a 2×2 binning and images size of 1024×1024 px. The spectral transmission curves of the broadband and interference filters included in the spectrograph are listed at https://www.sao.ru/hq/lsfvo/devices/scorpio-2/filters_rus.html.

2. LONG-SLIT SPECTROSCOPY

The maximum slit length is 6 arcminutes, the slit width varies within 0.5-7 arcseconds. A mask can be installed before the slit, containing a 13-point test, as well as diaphragms restricting the slit height to 2 and 1 arcminutes, which is necessary in spectropolarimetric observations. The spectrograph has 9 VPHG volume holographic gratings with direct view prisms (hereafter "grisms") mounted on a turret which is switched remotely. The grism parameters are listed at https://www.sao.ru/hq/lsfvo/devices/scorpio-2/grisms_rus.html .

3. SPECTROPOLARIMETRY

For Stokes parameter measurements, the spectrograph uses two types of polarization analyzers mounted in the parallel beam – a single Wollaston prism in combination with achromatic phase plates ($\lambda/2$ and $\lambda/4$) and a double Wollaston prism consisting of two Wollaston prisms, isolating electric vector oscillation directions 0-90 and 45-135 degrees, respectively. In the first case, two long-slit spectra with height 2″ are recorded, in the second case – four spectra with height 1′. The instrumental polarization of the device does not exceed 0.1% in the linear polarization measuring mode (Stokes parameters *Q* and *U*) and 0.01% in the circular polarization measuring mode. The method of observations is described in the paper by Afanasiev and Amirkhanyan, 2012, Astrophysical Bulletin, V.67, p.455, https://www.sao.ru/Doc-k8/Science/Public/Bulletin/Vol67/N4/p455.pdf. Advice on observations should be sought from the responsible astronomer Afanasiev V.L. (vafan@sao.ru)

4. IMAGE POLARIMETRY

A rotating dichroic polarization analyzer is used in various filters to measure the linear polarization of extended and star-like images. The field of view is restricted by the size of the analyzer and has a diameter of 6 arcminutes. Observations are conducted by the standard Fesenkov method, where three fixed polarizer angles are registered: –60, 0 and 60 degrees. Advice on observations should be sought from the responsible astronomer Afanasiev V.L. (vafan@sao.ru)

5. SCANNING FABRY-PEROT INTERFEROMETER (IFP)

IFP observations consist of consecutive acquisition of several tens of images of interference rings from the studied object (or the interferometer calibration lamp). The ring radius is a function of wavelength and the optical distance between the interferometer plates. A complete set of such images filling the free spectral range of the interferometer (interfringe) is called a “scan cycle”. After reduction the images may be presented in the form of a “data cube”. Control of the scanning (change of distance between the plane parallel mirror plates) is carried out via a CS100 controller manufactured by IC Optical Systems Ltd., controlled from a PC. SCORPIO-2 has four IFPs, realizing the spectral resolution *R* from 250 to 16000 in the 480-700 nm spectral range (https://www.sao.ru/hq/lsfvo/devices/scorpio-2/ifp_rus.html). The field of view in this mode is limited by the filter size and has a diameter of 6 arcminutes. The spectrograph is equipped with a set of filters isolating narrow spectral regions around the *H*-alpha, [OIII]5007, [NII]6548,6583, [SII]6717,6731 emission lines. A description of the process of observations and reduction of data obtained with the scanning IFP with the 6-m telescope is presented in the following papers: Moiseev A.V. 2002, Bull. SAO, 54, 77 , Moiseev A.V., Egorov O.V., 2008, Astrophy. Bull., 63, 181, Moiseev A.V., 2015, Astrophy. Bull., 70, 494; Advice on observations should be sought from the responsible astronomer Moiseev A.V. (moisav@sao.ru).

6. INTEGRAL FIELD SPECTROSCOPY WITH A LENTICULAR SCREEN

SCORPIO-2 has an integral spectroscopy unit (IFU) consisting of a 22×22 microlens lenticular screen with a size of 2×2 mm, onto which an image of an extended source is projected. Each lens of the raster forms an image of the main mirror of the BTA. The matrix of micropupils obtained in such a way is reformed by optical fibers into two pseudo-slits, the image of which is fed to the spectrograph input. The optical scheme (https://www.sao.ru/hq/lsfvo/devices/scorpio-2/ifu_rus.html) of the spectrograph is then rearranged - a microlens unit is installed instead of the slit which projects the object image onto the lens raster and another collimator is introduced in place of the standard luminous intensity reducer collimator. The image size at the IFU input is 0.75"/lens in a 16.5"×16.5" field of view. In addition to the main ones, the lens raster uses 14 micropupils at the top and at the bottom, which facilitate a simultaneous acquisition of a sky background spectrum together with the object spectrum, at a distance of ±3′ from the image center. The set of volume phase holographic gratings for SCORPIO-2 facilitates a spectral range of 460-730 nm and a resolution $\lambda/\delta\lambda$ from 1040 to 2800 in the IFU mode. The working spectral range for each grating is isolated by bandpass filters from the spectrograph kit. A detailed description of the IFU unit, observation method, the obtained data and their reduction can be found in the following paper: Afanasiev V.L., Egorov O.V., Perepelitsyn A.E., 2018, Astrophysical Bulletin, 2018, 73, 373 (Russian PDF). Advice on observations should be sought from the responsible astronomer Afanasiev V.L. (vafan@sao.ru)

In accordance with the "DIRECTIVE ON USE OF USI BTA EQUIPMENT" dated 21.10.2019, the studies carried out with SCORPIO-2 are conducted in cooperation with the staff of the Laboratory of Spectroscopy and Photometry of Extragalactic Objects of SAO RAS, and the applications submitted to RTTAC must be approved by the supervisor, *V.L. Afanasiev*.

BTA primary focus speckle-interferometer

Instrument status – author's
Responsible astronomer – Maksimov A.F. (max@sao.ru)

The speckle-interferometer (SI) of the BTA primary focus is mainly designed for the study of compact object structure (isolated stars, binary and multiple stellar systems, asteroids, etc.) with a diffraction resolution close to the resolution of the telescope's optics in the visible spectral range. Objects with a complex structure, such as asymmetric stellar envelopes, emission regions in galactic nuclei, etc., are also available for observations, however, they require simultaneous registration of a point reference source. The SI registers momentary speckle-images of objects in the spectral range from 500 to 900 nm with exposures not exceeding the "freezing" time of atmospheric turbulence (5-30 ms). The method of observations also includes obtaining calibration images of dark and flat fields. Currently, the limiting magnitude that can be registered is 15^m. The attainable accuracy of resolving binary stars with a small magnitude difference based on a single measurement is 0.02". The maximum magnitude difference between the components is – 6^m.

The SI kit includes:

- A unit of exchangeable microlenses for image enlargement in order to coordinate the spot diameter on the speckle-interferogram (2 microns in the BTA primary focus) with the size of the detector element (16 microns). Microlenses with magnifying factors 2.5, 10 and 16 facilitate scales of 0.055, 0.014 and 0.008 "/element in the camera focal plane, respectively. The sizes of the fields of view (the side of a square raster) are 28.2, 7.1 and 4.4″. The rear working section of the microlenses is equal to 160 mm.
- A compensator of atmospheric chromatic aberration. Designed to correct the distortions in the registered speckle-interferograms caused by atmospheric dispersion. The image is blurred along the dispersion vector and the resolution in that direction decreases. In order to avoid this effect, an element with dispersion of the opposite sign must be present in the optical path. The compensator is constructed based on two direct view prisms rotating about the optical axis of the instrument in opposite directions. Each prism has the form of two wedges (crown + flint) at the optical contact and provides a dispersion of 330″/20 nm and the direct view wavelength 550 nm. The mechanism of rotation of both prisms is dependant, and assumes a turn of prisms by equal

angles with respect to the optical axis. The compensation is carried out within the zenith distance limits of 0 to 60 degrees.

- A unit with a set of interference filters for work in spectral bands with centers from 550 to 850 nm and with different passband widths from 40 to 100 nm. The interference filters are designed to facilitate the condition of coherence when recording speckle-interferograms. The SI hosts 5 interference filters on the turret, which are introduced into the optical path by the rotation mechanism. All filters have an external diameter of 25 mm (the light diameter is 21 mm) and a thickness of 6 mm. The filters in the kit may change depending on the purpose of object registration. Currently, the set installed in the SI includes the following filters: (center/half-width) 550/20 nm, 676/10 nm, 694/10 nm, 700/50 nm, 800/100 nm. The turret window free from filters, meant for operating in polychromatic light, hosts a grism that is used in observations in lunar occultation mode. Simultaneous recording of photometric curves in different spectral channels is necessary for comparing different regions of stellar atmospheres. For binary and multiple systems, this allows one to measure the relative fluxes in various spectral regions and refine the spectral types of the component stars.
- TMCM-310 stepper motor drive controller manufactured by Trinamic for controlling the optical elements of the SI. This controller is used to turn on and off the registering EMCCD camera. The controller is connected to a COM-port of the controlling computer via a standard RS-232 serial communication interface. The microlenses are moved by an LM-160-type linear positioning mechanism manufactured by OWIS. The installation accuracy amounts to 2 microns per 50 mm length of the movable part. The dispersion compensation prisms are rotated by a differential mechanism driven by two independent motors via a 10:1 ratio gear. The turret with the interference filters is mounted directly on the shaft of the FL39ST stepper motor.
- The iXon Ultra DU-897-CS0 electron multiplication charge-coupled device (EMCCD) manufactured by Andor has a format of 512×512 elements with a resolution of 16×16 microns each. The camera uses a CCD97 (E2V)-type backlit matrix with a light sensitivity area of 8.2×8.2 mm and a quantum efficiency of 96% (550 nm). In order to decrease dark current, the matrix has a highly efficient cooling system based on a four-stage cooler with Peltier elements. The minimum achievable temperature for air cooling is –70 ºC. The dark current decreases in this case to values less than 0.01 electrons per second per resolution element. The output node is made in the form of two independent reading registers. One is used for readout as in normal CCD arrays, the other operates in electron amplification mode. Correspondingly, the camera has two independent data output channels. The input data are represented by a 16-bit code and determine the dynamic camera range. At a 10 MHz readout rate of the output register with electric amplification, the frame rate is 18-25 Hz depending on exposure time. The root-mean-square of readout noise for a single amplification amounts to about 40 electrons. When working with maximum amplification, the readout noise effectively decreases to values less than 1 electron. The gain can be set to values from 1 to 1000.
- Control computer. Due to the use of an industrial computer version with an extended range of operating temperatures it was possible to combine all components of the speckle-interferometer directly in the telescope primary focus booth. It is no longer necessary to place part of the equipment in the control room of the telescope, connecting this equipment through fiber-optic lines, as well as for personnel to be present at the telescope during observations. Additionally, the presence of a 256GB SSD with a USB-3 interface near the computer allowed data to be written to the drive bypassing the computer's RAM, which in turn significantly reduced the process of

overwriting data during observations. Until recently, the SI used a NISE-2100 computer with an Intel Atom D525 processor from Nexcom. In 2018, the control computer was replaced by a more high-performance industrial computer eBOX700-891-FL based on an Intel Core i7-6700TE processor with 8 GB of RAM and a 1 TB hard drive. An external drive was no longer needed, as the internal drive has enough capacity to record data throughout the entire set of observations. Replacing the computer also made it possible to eliminate interruptions in the transmission of frames transmitted over the network via the VNC protocol due to a better performance. It is also planned, in the future, to automate some of the tasks currently performed manually during the observations, as well as to assign the computer the primary data reduction.

During observations, all SI nodes are located on a flange, which in turn is attached to the SPF turntable. The module is controlled through a Gigabit Ethernet communication line via VNC access protocol from a public computer in the control room (room 505).
The reduction of the obtained images includes geometric and photometric correction, averaging instant images, accumulation of correction functions of the second and third orders and reconstructing images with diffraction resolution.
A complete reconstruction of an image of an arbitrary structure is possible when computing both the module and the image phase. The corresponding recursive calculations are very time consuming and require significant computer capacity. For this purpose, a high-performance workstation based on the Server ASUS ESC4000 G3 platform is used.

The instrument is described in the following paper:
A.F. Maksimov, Yu.Yu. Balega, V.V. Dyachenko, E.V. Malogolovets, D.A. Rastegaev, E.A. Semernikov. Speckle-interferometer of the 6-m telescope of SAO RAS based on EMCCD: characteristics and first results. // Astrophysical Bulletin, 2009, Volume 64, № 3, pages 308-321.

MPPP Fast variability study complex

Instrument status – author's
Responsible astronomer – V.L.Plokhotnichenko (pvl@sao.ru)

The method of studying optical variability of astrophysical objects with high temporal resolution is designed for the search for and investigation of rapidly variable processes and events in astrophysical objects: periodic, irregular, flare, with typical timescales ranging from minutes to microseconds. It allows one to conduct synchronous observations with a precise reference to UT, provided by the used navigation systems.

The objects for study are stellar mass “black hole” candidates, pulsars, flaring stars and any other rapidly varying objects. The principle of registering individual quanta with a set of spatial, spectral and polarimetric characteristics, with a following analysis of their combination, is the basis of the methods of searching for and studying variations of their emission.

The method uses the Multicolor Panoramic Photometer-Polarimeter (MPPP), see [1,2], which generates the so-called photon sheets at the output – rows of registration moments of individual light quanta with their spatial, energetic, and also polarimetric characteristics, accumulated in the long-term computer memory. These data may be reduced using various programs, in particular, for a statistical analysis of the distributions of intervals between quanta, a study of light curves with any given window, starting with microsecond, for phased light curves, correlation functions, power spectrum.

The structure consists of:

- a focal platform with a mirror-slit unit for viewing the working field and forming parallel beams of light from the sky region with the object under study;
- a node of optical units with a linear polarization analyzer at the input of the optical beam and a device for remote installation of the units into the operating position;
- two photo-receiving devices based on coordinate-sensitive detectors with a system of registering multidimensional stochastic quantum fluxes based on two Kvantokhron 4-48 chronometric devices [6], with a 30 ns time resolution and a reference to UT, facilitated by a time server;
- EMCCD-cameras with a registration system that makes it possible to receive up to 14 frames/s.

The instrument is designed for installation in the BTA primary focus.

Features:

1. **Viewing the working field** is carried out with the mirror-slit unit which directs the light arriving from the telescope mirror to the final image objective. The size of the working field is 2′.5×3.5′ with the TVCCD-camera now in use. The unit allows one to set the slit width in the 0-10″ range, and by moving it along the slit, select its size as 10″ or 60″. This function is used when conducting polarimetric and spectral measurements to minimize the contribution of background emission (especially in dusk or bright Moon conditions). Additionally, the slit unit has a window with an installed 1′ field lens, which is used during its insertion into the telescope axis in order to search for and observe faint objects in a wide field. Behind the slit unit an achromatic collimator lens is located, transparent in the UV range, that forms the parallel beam from the axial source.
2. **The determination of three Stokes parameters** is carried out with a linear polarization analyzer in the form of a double Wollaston prism [3] inserted into the parallel beam of the axial source flux. It is divided into two components along the gluing boundary of the prisms and allows one to simultaneously measure the emission intensity with the main polarization planes, oriented at the angles of 0 and 90 degrees in one half of the beam and 45, 135 degrees in the other.
3. **The determination of spectral (photometric) characteristics** of the registered emission is carried out with dichroic mirrors (in the optical units) in combination with UBVR-filters, as well as spectral units (Abbe prism and diffraction grating).

The light detectors consist of two coordinate-sensitive quantum detectors: “blue” with a c multi alkaline cathode [4,9] and “red” with a GaAs cathode [5,7,8,10], with quantum efficiency maxima 10% and 30% at the wavelengths 400 nm and 500 nm, respectively. These detectors are devices with external photo effect and micro channel multiplication of electron avalanches. The latter are transferred to the multi-element collectors connected to the charge-sensitive amplifiers and analogue-to-digital converters, which code the centroid coordinates of these avalanches. The working field of the “blue” detector is 15 mm, and that of the “red” is 14 mm (over 60" in the selected scale of image transfer), the spatial resolution in the field center is 0.05 mm, the temporal resolution (dead time) is 1 microsecond. The allowed limiting registration rate at each CSD is 100000 counts/s for the entire field and 30000 for a star-like source.

The quantum sequences recorded by both CSDs are multiplexed by a mixer of multi-bit stochastic signals and fed as a combined flux into the data acquisition system, see below.

An EMCCD-camera is used as an additional detector in the MPPP, placed together with the *BVR* optic filters at the end of the device. The video sequences from it are accumulated by a separate computer. Each frame has a size of ~250 Kb. The limiting frequency of readout without gaps between them is 14 frames/s . The sky background is detectable with a moonless sky camera in direct focus and in integral light above the thermal noise level up to a frequency of 10 frames/s .

The **MPPP** allows the use in observations of any of the five remotely controlled modes, specifically,

> a — broadband mode, where the input emission is divided into two fluxes in the ~450 nm region, after which the “blue” and “red” components are transmitted to the corresponding photo detectors (i.e., the “blue” and “red” CSD).
>
> b — high-sensitivity mode with the EMCCD camera [4], where sequences of frames are accumulated in integral color or in *BVR* bands with a temporal resolution of up to 0.1s, with simultaneous registration of the *U*-band quantum fluxes reflected by the dichroic mirror in the “blue” CSD.
>
> c — photometric mode with registration of quantum fluxes in one of the *U* or *B* bands, and simultaneously in two bands, *V* and *R*;
>
> d — spectral mode with an Abbe prism, which in the slitless mode forms a spectrum with 5 resolution elements (for second images) registered by the “red” CSD, with a simultaneous recording of emission in the *U*-band by the “blue” CSD;
>
> e — spectral mode with a diffraction grating that forms a spectrum with 50 resolution elements, with similar use of the 2 CSDs.

These modes can be used both by the field lens and the fields formed by the mirror-slit unit. A polarization analyzer (double Wollaston prism) can be inserted into the parallel beam of emission of the studied object. When observing bright sources, the slit width can be decreased with a consequent slight increase in spectral resolution.

To provide the optimal ratio of the intensities of registered fluxes and for protection from overloads dangerous for the detectors, a perforated attenuator with remotely variable transmission from 100 to 3% (for a factor of 2) or a full shut-off of the beams is installed in front of each CSD.

The total transmission of the MPPP in the blue, green and red spectral bands is about 60%.

The system of data collection stores in the computer memory sequences of encoded moments of quantum registration (photon sheets). It consists of two identical computers with installed PCI plates of chronometric “Kvantakhron-4/48” devices [6] that record and store 64-bit codes of photons in internal FIFO-type RAM, and also a third computer used to control the process of collecting and storing the obtained data in the long-term memory. The first two computers, alternating in second intervals, receive and store the multiplexed by the mixer stochastic floxes of photon coordinate codes and add to them moment codes of their registration (time measurement accuracy is 30 ns), linked to Universal Time (by GPS). The acquisition of data occurs over any period of time, limited only by the capacity of the computer disk drives. The allowed data collection rate is 10^6 counts/s.

Control of the MPPP is carried out in interactive mode, where the stepper motor controller is used to move the device units into operating positions; the electric component parameters are selected using a graphic interface. This interface demonstrates the scheme of the optical unit mounted on the optical axis of the instrument, the keyboard symbols for controlling its operating mechanisms, the parameters of its condition, the total light curve of the emission fluxes received by the CSD with a temporal resolution of seconds, and the zenith angle of the telescope. The “tracking” signal is used when the telescope is operational to register the information on its condition. All the received counts are fixed every second in the device operation log.

Remote setting of the device operation modes allows to flexibly reconfigure it according to the purpose of observations and to carry them out in a complex and multidimensional manner.

Control of the data collection computer cluster is also managed interactively through a graphic interface containing two image panels of the working fields recorded by the detectors. A separate screen is used to monitor the second temporal resolution quantum registration rates in several multiangular areas selected in these fields.

“Photon sheets” - collected data on the quanta registered in all light beams formed in the MPPP can be reduced in combination, as synchronous time series corresponding to fluxes with different color or spectral characteristics, or spectral characteristics and in different polarizations.

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Nasmyth Echelle Spectrograph (NES)

Instrument status – author's
Responsible astronomers – Panchuk V.E.(panchuk@ya.ru), Yushkin M.V. (maks@sao.ru)

The Nasmyth Echelle Spectrograph (NES) is fixed on the Nasmyth-2 focus platform of the BTA telescope and is designed for spectrography of star-like objects with high spectral resolution in the entire optical wavelength range. The spectral resolution of NES can vary from $R = 30\,000$ to $R = 90\,000$, and the spectral region, from λ = 3050 Å to λ = 10000 Å, depending on the selected mode of observations.

NES is equipped with a light detector based on the E2V CCD42-90 CCD array with 2048·4612 elements and a 13.5·13.5 micron element size (https://www.sao.ru/hq/adlab/cam4290-3.html). The detector is manufactured using the technology of deep silicon depletion and has an Astro Multi-2 antireflection coating , which provides a high quantum efficiency in the entire working range of NES. The format of the light detector makes it possible to simultaneously register in one frame a spectral band 3000 Å wide. The detector is fixed on the spectrograph and is equipped with a cryostat filled with liquid nitrogen. The time of achieving working mode after turning on the photo detection device is 40 minutes for the spectrograph.

NES is equipped with two changeable cross-dispersion elements, designed to operate in two spectral sub-regions: ground-level visible UV, with a working band of 3050 – 7800 Å (the so-called “blue” range), and visible near-IR, with a 4800 – 10000 Å working band (the so-called “red” range). A change of the cross-dispersion elements (framed dispersion gratings) requires a long time and is done during the day, between the observing sets. A change of the spectral band registered with the light detector within the working range of the used cross-dispersion element can be done during the set of observations, however, such a change is best carried out at night, since this procedure requires an additional calibration of both the wavelength scale and the inhomogeneity of the light detector sensitivity.

NES has a set of input deckers, including: a "classical" slit with a size of 0.6"·2.5" as projected onto the celestial sphere, a three-slice image slicer with a size of 0.6"·2.0" each and a total size of the input diaphragm of 1.8"·2.0", a three-slice image slicer with a size of 0.4"·2.0" each and a total size of 1.2"·2.0", and a regulated slit of changeable width from 0.2" to 2.0" and a height from 0.2" to 40.0". The choice of the input decker is made depending on the purpose of observations; the spectral resolution of NES is determined from the relation $R \cdot s'' = 30\,000$, where s'' is the width of the entrance slit in arcseconds.

The pre-slit part of NES hosts a wavefront tilt corrector, which facilitates the automatic guiding mode, and also compensates the oscillations of the optical and mechanical structure of the telescope, both at intrinsic frequencies, and those resulting from wind gusts.

The unit of spectral lamps contains a hollow-cathode lamp covered with thorium salts, with an argon filled flask (Th-Ar), designed for wavelength scale calibration, and two halogen lamps with an equalizing filter for "flat field" effect calibration.

During work in the television mode of frame readout, the entrance slit camera facilitates the registration of sources up to 15^m in the *V* band for ideal weather conditions (i.e., when the size of the turbulent disk of a star is about 1" and the transparency is perfect). For observations of extremely faint sources under bad weather conditions, the camera is used in frame summation mode.

Currently, six modes of observations are available for NES:

1. Spectroscopy of star-like sources in the visible range with a 3·0.6"·2.0" image slicer.
2. Spectroscopy of star-like sources in the visible range with a 3·0.4"·2.0" image slicer.
3. Spectroscopy of star-like sources in ground-level UV range with a normal 0.6"·2.5" slit .
4. Spectroscopy of star-like sources in the near-IR range with a 3·0.6"·2.0" image slicer.
5. Spectroscopy of star-like sources in the near-IR range with a 3·0.4"·2.0" image slicer.
6. Spectroscopy of star-like and extended sources with a regulated slit.

NES parameters in different observation modes

1. SPECTROSCOPY OF STAR-LIKE SOURCES IN THE VISIBLE RANGE WITH A 3·0.6"·2.0" IMAGE SLICER.

Spectral resolution: $R = 50\,000$.
Working wavelength range: 3900 – 7800 Å.
Limiting magnitude: $m_V = 15.0^m$ (S/N = 10, Exp = 1^h).

A large-scale grooved diffraction grating is used as a cross-dispersion element, working in the first order of diffraction, with a density of 300 grooves/mm. A three-slice image slicer with a size of 0.6"·2.0" per slice is installed at the spectrograph input. Dark gaps are present between the slices with a height of 2.0", and the total height of an image of one spectral order corresponds to 10" with the slicer.

The spectral range in the short wave region is limited by the height of the monochromatic slit image. At wavelengths greater than 6000 Å, gaps appear between neighboring working orders. In case of a necessity to register individual spectral lines (that are outside of the standard frame), a shift of the spectrum along the diffraction orders is carried out by tilting the echelle-grating in the main plane.

This observation mode, along with a similar version in the near-IR range, has the maximal resolving power. Hereinafter, the limiting magnitude corresponds to the magnitude of a star-like object whose spectrum is registered with maximum signal-to-noise ratio S/N=10 with a 1^h exposure time, image quality of 1.0" and ideal atmospheric transparency. It should be noted that in all the NES observation modes, a single frame registers the spectrum simultaneously in two or three photometric bands, and therefore the precise signal-to-noise ratio for a specific object with a certain *V*-band magnitude will depend on the spectral type of this object.

2. SPECTROSCOPY OF STAR-LIKE SOURCES IN THE VISIBLE RANGE WITH A 3·0.4"·2.0" IMAGE SLICER.

Spectral resolution: *R* = 75 000.
Working wavelength range: 3900 – 7800 Å.
Limiting magnitude: $m_V = 14.5^m$ (S/N = 10, Exp = 1^h).

This mode is similar in everything to the previous one, with the exception of the image slicer installed at the spectrograph entrance. This version uses a slicer with the size of each slice of 0.4"·2.0". This makes it possible to increase the spectral resolution by a factor of 1.5. The amount of light entering the spectrograph decreases proportionally.

Observations in this mode are carried out under ideal weather conditions and/or in the case of a necessity to obtain spectra with a higher spectral resolution.

3. SPECTROSCOPY OF STAR-LIKE SOURCES IN GROUND-LEVEL UV RANGE WITH A NORMAL 0.6"·2.5" SLIT.

Spectral resolution: *R* = 50 000.
Working wavelength range: 3050 – 6000 Å.
Limiting magnitude: $m_B = 12^m$ (S/N = 10, Exp = 1^h).

A “classical” entrance slit and a 300 groove/mm cross-dispersion diffraction grating are used. The mode is designed for obtaining spectra up to the short wavelength boundary of the Earth’s atmospheric transparency. The “blue” boundary of the working range, 3050 Å, is conditional, since it is limited by the concentration of ozone in the atmosphere, which is subject to strong variations, both seasonal and during the night; additionally, the distribution of ozone in the atmosphere is inhomogeneous, and the boundary of transparency can vary depending on azimuth and zenith distance of the object. NES optics makes it possible to obtain good quality spectra up to the region of anomalous fused quartz dispersion. The quantum efficiency of the detector at the “blue” boundary of the region is about 20%.

Due to the dense placement of high spectral orders, this NES configuration does not allow using an image slicer, and as a result, the resolving power of the instrument decreases. The limiting magnitude is also given conditionally, since the emission flux after the Balmer jump (at wavelengths shorter than 3646 Å) will depend on object type.

4. SPECTROSCOPY OF STAR-LIKE SOURCES IN THE VISIBLE AND NEAR-IR RANGES WITH A 3·0.6"·2.0" IMAGE SLICER.

Spectral resolution: R = 50 000.
Working wavelength range: 4800 – 10000 Å.
Limiting magnitude: $m_V = 15.0^m$ (S/N = 10, Exp = 1^h).

A grooved large-scale cross-dispersion diffraction grating is used with a density of 150 grooves/mm and a 3·0.6"·2.0" image slicer at the spectrograph entrance. The cross-dispersion diffraction grating has a maximum concentration of energy in the red and near-IR ranges. The groove density is decreased in comparison to the similar element in observation modes "1" and "2" in order to shorten the distance between neighboring spectral orders and, as a result, a more effective use of the useful area of the detector.

The free spectral interval of the diffraction orders of the echelle-grating increases sharply with wavelength, and therefore the detector in this mode of observations should be turned around the optical axis of the spectrograph camera, with the long side along the spectral orders. The spectrum is recorded without gaps up to a wavelength of 9000 Å, therefore, there is no need to shift the spectral image along the orders to select individual spectral lines. The echelle-grating is mounted in one position facilitating the maximum concentration of energy in the frame center.

Along with option "1", this mode provides the maximum resolving power of the spectrograph.

5. SPECTROSCOPY OF STAR-LIKE SOURCES IN THE VISIBLE AND NEAR-IR RANGES WITH A 3·0.4"·2.0" IMAGE SLICER.

Spectral resolution: R = 75 000.
Working wavelength range: 4800 – 10000 Å.
Limiting magnitude: $m_V = 14.5^m$ (S/N = 10, Exp = 1^h).

As in option "2", this mode of observation is totally similar to the previous one with the exception of the image slicer installed at the spectrograph entrance.

The observation mode with more narrow slices is used under ideal weather conditions and in the case of a necessity of obtaining images with higher spectral resolution.

6. SPECTROSCOPY OF STAR-LIKE AND EXTENDED SOURCES WITH A REGULATED SLIT.

Spectral resolution: up to 90 000.
Working wavelength range: 3050 – 10000 Å.

This mode of NES observations is used in special cases: when one needs to obtain super high (or super low) spectral resolution compared to the previous modes, and also for studying spectral emission lines in extended sources.

A regulated slit is installed at the spectrograph entrance, the width of which can vary from 0.2" to 2.0" which, according to the relation described above, formally corresponds to a spectral resolution from 150 000 to 15 000. However, as follows from the condition of agreement between the monochromatic image of the entrance slit and the detector resolution element size, the limiting spectral resolution of NES is 90 000. In order to achieve $R = 90\,000$, the width of the entrance slit must be 0.3". Only the brightest objects can be observed in this mode, with a *V* band magnitude of up to 10^m (12.5^m at the limit).

In this NES configuration, one can increase the entrance slit width and obtain a spectral image with a resolution of 20 000 – 30 000. A CCD array work mode with binning (increasing the effective area of the resolution element by combining the charges in neighboring detector elements) can also be used. This mode makes it possible to increase the limiting sensitivity of the spectrograph.

The height of the regulated entrance slit can be increased to 40". In this case, the images of neighboring spectral orders will overlap. In the case of extended emission source observations, whose continuous flux is several orders of magnitude lower than the flux in individual spectral lines (e.g., planetary nebulae), the overlapping neighboring orders can be ignored. In this case we obtain images of individual spectral lines with an angular resolution along the slit limited by atmospheric turbulence. The image size along the slit on the CCD array amounts to 0.197 "/pix.

ADDITIONAL INFORMATION

In accordance with the «DIRECTIVE ON USE OF USI BTA EQUIPMENT» dated 21.10.2019, studies conducted with NES are carried out for scientific programs in cooperation with the staff of the Laboratory of Astrospectroscopy of SAO RAS, and the applications submitted to RTTAC must be approved by the supervisor, V.E.Panchuk.

The description of the instrument, contact information and spectra examples can be found in the following publications:

- Panchuk, V.E.; Klochkova, V.G.; Yushkin, M.V.; Naĭdenov, I.D. The high-resolution spectrograph of the 6-m Large Azimuthal Telescope (BTA) // Journal of Optical Technology, Volume 76, Issue 2, pp. 87-97 (2009);
- Panchuk, V.E.; Klochkova, V.G.; Yushkin, M.V. The high-resolution Echelle Spectrograph of the 6-m telescope of the special astrophysical observatory // Astronomy Reports, Volume 61, Issue 9, pp. 820-831 (2017);

and also on the page of the Laboratory of Astrospectroscopy of SAO RAS https://www.sao.ru/hq/ssl/.