Transient Double-Beam Spectrograph for the 2.5-m Telescope of the Caucasus Mountain Observatory of SAI MSU

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Abstract—The Transient Double-beam Spectrograph (TDS) is designed for low-spectral-resolution optical observations of nonstationary and extragalactic sources at the 2.5-m telescope of the Caucasus Mountain Observatory (CMO) of SAI MSU. The spectra are recorded simultaneously in two channels, short-wavelength (360–577 nm, reciprocal dispersion 1.21 Å/pixel, resolution $R = 1300$ with a 1″-wide working slit) and long-wavelength (567–746 nm, 0.87 Å/pixel, $R = 2500$) ones, with the light between them being split by a dichroic mirror with a 50% transmittance at 574 nm. In the “blue” channel, it is possible to automatically replace the main grating by an additional one with a double resolving power. Two CCD cameras based on E2V 42-10 detectors cooled down to $-70^\circ$C with a readout noise of 3 electrons are used as detectors. The height of the entrance slit is 3 arcmin. The spectrograph incorporates a back-slit viewing camera and a calibration unit to record the line spectrum of a gas-discharge lamp and a continuum LED source (“flat field”) to take into account the vignetting and slit width nonuniformity. The transmittance of the entire optical path without losses on the slit at the zenith is 20 and 35% in the “blue” and “red” channels, respectively. Excluding the atmosphere and the telescope, the efficiency of the TDS itself reaches 47 and 65% at maximum, respectively. The spectrograph is permanently mounted at the Cassegrain focus of the 2.5-m CMO SAI MSU telescope together with a wide-field photometric CCD-camera; the light is fed into the spectrograph by a flat diagonal mirror inserted into the optical path. Regular observations of nonstationary stars and extragalactic sources to $\sim 20$th with a signal-to-noise ratio above 5 in 2 h of observations have been carried out with the TDS since November 2019.

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INTRODUCTION

Up-to-date astrophysical research, such as the search for and the classification of supernovae, optical afterglows of gamma-ray bursts, the study of nonstationary phenomena in close binary systems with relativistic components and the physics of pre-main-sequence objects, etc., require that optical spectra be promptly obtained and classified with medium-size telescopes in the follow-up and monitoring modes. The possibility of quickly setting a new task and a high light efficiency are most critical for the observations of such objects. Therefore, the effectiveness of such studies depends directly on the total transmittance of the optical system and the possibility of observations at any favorable time. Despite the abundance of medium- and large-size telescopes that have appeared in the last decades, a prompt characterization of transient phenomena remains a topical scientific task to be accomplished with large- and medium-size instruments (Onori et al. 2019; Copperwheat et al. 2015, 2016).

The telescope of the Caucasus Mountain Observatory (CMO) of SAI MSU with a 2.5-m primary mirror is a multitask instrument for scientific and educational purposes (Shatsky et al. 2020). The choice of observing programs is made in a wide range of research on a competitive basis to achieve maxi-
mum final effectiveness of the instrument, given its parameters and the peculiarities of its installation site. The astroclimate conditions for observations at CMO SAI (Kornilov et al. 2014) and the possibility of their prompt evaluation allow one to flexibly plan observations with various attached instruments based on the current situation and, thus, to use the observing time most efficiently. The telescope was installed in 2014 and is currently (October 2020) being prepared for acceptance tests after the replacement of the hardware and software of the control system.

To maintain the work on the characterization of new sources or the spectroscopic monitoring of non-stationary objects being carried out at SAI MSU (see, e.g., Lipunov et al. 2016; Volnova et al. 2017; Cherepashchuk et al. 2018; Balakina et al. 2020), the task to construct an efficient instrument for spectral classification and measuring the Doppler shifts and intensities of emission and absorption lines was set. A high transmittance of similar (in specialization) spectrographs for 1.5–2-m telescopes is key to their high productivity (for an overview of the FAST projects and references, see, e.g., Mink et al. 2020).

The relatively large telescope aperture and the arcsec seeing (Potanin et al. 2017) make it possible to use a narrow long working slit to perform measurements of both point and extended objects, for example, galaxies, with the possibility of accurately measuring the sky background spectrum. In this regard the instrument is aimed at having a higher resolution $R \sim 2000$ and a longer slit than, for example, the FLOYDS spectrographs of the 2-m telescopes at Las Cumbres observatory ($R < 1000$, $L_{\text{slit}} = 30''$; Brown et al. 2013) specially designed for observing purely transient objects. In slit parameters, range of scientific tasks being accomplished, and spectral resolution, the planned instrument more closely resembles the Intermediate Dispersion Spectrograph (IDS)\(^1\) of the 2.5-m INT telescope in the Canary Islands (see, e.g., Popescu et al. 2019), although the stability requirements are poorly combined with such a large set of dispersers and replaceable detectors as at IDS. Therefore, the TDS was designed from the very outset as an instrument with a minimal number of configurations.

**PARAMETER SELECTION CRITERIA**

Although the constructed 2.5–m CMO SAI telescope is highly mobile, its moderate aperture size requires a distinct specialization of the instrument to achieve high effectiveness for the main task, i.e., obtaining the spectra of transient sources and extragalactic objects to the 20th magnitude. Therefore, a maximum transmittance of the optics at a minimally needed spectral resolution and compromise wavelength coverage for the classification of objects was chosen to be the primary design optimization criterion. The modern line of optical glasses and the ubiquitous introduction of volume phase holographic (VPH) gratings (Barden et al. 2000) into astronomical practice allow this task to be accomplished with minimal losses of light in a dioptric system.

The spectral range chosen for the subject of research—the near ultraviolet from the Balmer jump and the visible range—in combination with the requirement of a sufficiently long ($3'$) slit to ensure an accurate sky background subtraction and the possibility of observations of extended sources agree well with the format of available highly efficient spectral CCD detectors capable of operating for a long time in a near-cryogenic mode without significant maintenance costs for the system operating in a constant standby mode. A spectral resolution $\sim 1500–2500$ required for spectral classification and energy flux measurements in spectral lines turns out to be achievable in a double-beam design of the instrument with the separation of channels by a dichroic beam splitter in the wavelength range from 550 to 580 nm. Such a separation of the range obviates the need to apply blocking filters of nonoperating orders and allows one to use efficient antireflection coatings for the optics and CCDs and to achromatize the optics with a small number of elements. This solution is similar to the layout of the dispersive part of the last-generation SDSS BOSS spectrographs\(^2\) (Smee et al. 2013), but was scaled to more modest tasks with a long slit and a narrower spectral range in the red region. The latter allowed a common collimator of channels with minimal trade-offs in image quality to be used. This made the instrument more compact and containing fewer optical elements than the similar (in design) FRODOSpec spectrograph of the Liverpool 2-m telescope with two dioptric collimators (Morales-Rueda et al. 2004).

The final spectrograph multiplexing is determined by the almost complete coverage of the working surface of two $2048 \times 512$-pixel CCD detectors by the 350–750 nm spectrum with a 3-arcmin-high slit image at 3-pixel sampling for a 1-arcsec-wide slit image. These requirements are consistent with a median seeing at the observing site of 1.0'' and the image quality provided by the telescope optics (Potanin et al. 2017). Optimization of the scheme on a wide line of modern optical glasses allowed the required image quality to be obtained in the entire spectral and

\(^1\)http://www.ing.iac.es/Astronomy/instruments/ids/.

\(^2\)https://www.sdss.org/instruments/boss_spectrograph/.
Fig. 1. Optical layout of the TDS. (1) Slit in the focal plane of the telescope; (2) common collimator; (3) flat dichroic mirror; (4) replaceable blue-channel disperser (a $G$ grism and an additional wedge are shown); (5, 7) blue- and red-channel cameras, (6) red-channel disperser.
Table 1. Basic parameters of the elements and spectral characteristics of the channels

| Parameter                      | Value                        |
|-------------------------------|------------------------------|
| **Slits**                     |                              |
| Width                         | 1" and 10"                   |
| Height                        | 3′(18 mm)                    |
| **Collimator**                |                              |
| Focal length                  | 315 mm                       |
| Diameter                      | 64 mm                        |
| **Beam splitter**             |                              |
| Light incidence angle         | 35°                          |
| Dimensions                    | 65 × 90 mm                   |
| Short-wavelength boundary     | 350 nm                       |
| Average reflectance           | 98.2%                        |
| Transition wavelength         | 574 nm                       |
| Long-wavelength boundary      | 750 nm                       |
| Average transmittance         | 95.3%                        |
| **Dispersers**                |                              |
| Pupil diameter                | 39 mm                        |
| Light diameter                | 43 mm                        |
| Ruling density \(R, B, G\)    | 1200, 900, 1800 mm\(^{-1}\)   |
| Central wavelength            | 650, 460, 505 nm             |
| **Cameras**                   |                              |
| Focal length                  | 117 mm                       |
| Field of view, 2\(\Omega\)    | 13.9°                        |
| **Detectors**                 |                              |
| Model                         | E2V 42-10                    |
| Pixel size                    | 13.5 × 13.5 \(\mu\)m         |
| Quantum efficiency            | 90%                          |
| Readout rate                  | 50 kHz                       |
| Operating temperature         | −70° C                       |
| Readout noise \((R, B)\)      | 3.8, 3.1 e\(^{-}\)         |
| **Blue channel**              |                              |
| Reciprocal dispersion \((B, G)\) | 1.21, 0.55 Å/pix              |
| Wavelength range in \(B\)     | 3600–5770 Å                  |
| Wavelength range in \(G\)     | 4300–5434 Å                  |
| Resolution \(R(B, G)\)        | 1300, 2600                   |
| Max. efficiency \((B, G)\)    | 47, 50%                      |
| **Red channel**               |                              |
| Reciprocal dispersion         | 0.87 Å/pix                   |
| Wavelength range              | 5673–7460 Å                  |
| Resolution \(R\)             | 2500                         |
| Max. efficiency \(R\)         | 65%                          |

The efficiency of the TDS without the telescope and the atmosphere at the central disperser wavelength is given for the channels.

red and blue channels. With a minimum number of groups of elements (one in the collimator and two doublets plus a single lens in each of the cameras), an energy concentration in the images of 80% was achieved in a circle with a diameter of 24 \(\mu\)m approximately uniformly over the slit and along the dispersion. The computed images are shown in Fig. 2. The tolerances for the fabrication and alignment of the optics turned out to be moderately tight (0.1 mm in element displacement).

The main parameters and elements of the spectrograph are summarized in Table 1. The slits were laser cut from 200-μm-thick stainless steel on the robotic machine for cutting focal masks of the Binospec instrument and were kindly provided by the Smithsonian Astrophysical Observatory (D. Fabricant, USA; see Fabricant et al. 2019); their surface was not blackened. A working slit with a width of 0.1 mm (1"; the scale in the focal plane of the telescope is 10 arcsec/mm), a field diaphragm with a diameter of 18 mm for the identification and alignment of an object used for slitless spectroscopy of sources, and a wide spectrophotometric slit are installed in the wheel of focal apertures.

The key component of a two-channel spectrograph is a dichroic beam splitter. It is installed before the pupil of the system, because the pupil is occupied by the dispersive elements that determine the spectral characteristics of the channels. The main requirements imposed on the splitter are to provide a high average transmittance in the long-wavelength range and a high reflectance in the adjacent one. The steepness of the spectral response and as low as possible amplitude of spectral response oscillations (“waves”) against a background of the average level are also important. This determines the spectral profile of the light efficiency of the entire instrument and the possibility of correcting the spectrum reduction results for its variability with time to obtain accurate spectrophotometric characteristics of sources.

The initial (reference) computation of the dichroic beam splitter was kindly performed by Asahi Spectra\(^3\) and showed the theoretical possibility of providing average losses within 3% and a “wave” height less than 5–10%. However, for economic reasons, we could not order this splitter and searched for a domestic manufacturer.

Acceptable computed and then experimentally confirmed characteristics of the dichroic coating were obtained at the Ryazan production site of the “Alexander” limited liability company,\(^4\) which

\(^3\)www.asahi-spectra.com, the leading manufacturer of astronomical interference and glass filters.

\(^4\)https://macroptica.ru.
manufactured the working channel beam splitter. Its transmittance curves are illustrated in Fig. 3, which shows the computed transmittance curve of the Spectra dichroic coating for comparison.

The diffraction gratings of the spectrograph with a diameter of 2 inches were manufactured by Wasatch Photonics⁵ and operate in the first diffraction order; the main channel gratings have antireflection coatings optimized for their operating range.

A stationary VPH grating (R) on B270 glass substrates, which deflects the rays with central wavelength by 46°, is located in the pupil of the red channel. A block of two replaceable VPH gratings on fused silica substrates manufactured specially for our project is located in the pupil of the blue channel. The main B grating deflects the beam by 24° and is used without additional prisms. The auxiliary G grating with a double dispersion has 1800 lines per mm and a working wavelength of 505 nm and is used with prisms made of F1 flint glass to align the deflection angle with the B grating. To eliminate the emerging aberrations and the focus difference in the blue and green channels, the front prism is supplemented by a wedge made of KU-1 silica with a slightly convex front surface (R = 54 m).

Camera objectives of similar design optimized for their wavelength ranges are used in both channels. Both the glasses used in them⁶ and the antireflection coatings are different in the objectives in the red and blue channels. The five-lens objectives have a back focal distance of 30 mm, which allows a CCD camera of virtually any design, including an optical window and a shutter, to be used as a detector. By abandoning the use of fluorite in the spectrograph optics, we obviated the need for channel focusing; the images remain sharp in the temperature range from −15 to +25°C.

Andor Newton DU940P cameras⁷ with central shutters and plane-parallel fused silica optical windows are used in the TDS. The first-grade back-illuminated CCDs have BU- and BV-type antireflection coatings for the blue (as in the FLOYDS instruments) and red channels, respectively, and operate with 1.0 e−/ADU signal digitization at a constant operating temperature with thermoelectric air cooling all the year round. The contribution of the dark current to the data noise is minor, less than 0.005 e− s⁻¹.

**DESIGN**

The spectrograph was entirely designed and assembled at SAI MSU, where some of the parts were also made; the remaining ones were custom-made on CNC machines. The casing of the instrument is made of deformable aluminum alloys (AMG-6 and D16) to prevent warpage during treatment and consists of a 3-cm-thick load-bearing base plate with stiffening ribs, rectangular rigid props for the frames of the optical components and the flanges of the CCD cameras.

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⁵https://wasatchphotonics.com/.
⁶Schott, Ohara and LZOS glasses glued with a low-temperature OK-72FT5 glue transparent down to 350 nm are used in the TDS optics.
⁷https://andor.oxinst.com/products/newton-ccd-and-emccd-cameras/newton-940.
Fig. 3. Surface-averaged measured transmittance and reflectance curves of the working beam splitter (thin solid lines, the incidence angle is 35°) and reference curves of the dichroic splitter computed for the TDS in Asahi Spectra (dashed lines, for an incidence angle of 45°); the half-sum for the S- and P-polarizations is given. For clarity, the dashed–dotted lines indicate the quantum efficiency curves for the detectors and the thick lines show examples of the final output spectral response curve for the entire system corrected for the atmosphere.

and a 2-cm-thick cap of the instrument similar to the base. This design imparts the required rigidity to the instrument and is equipped with lateral light-proof caps. The spectrograph is fastened with screw pins through three axial holes of additional casing props to an aluminum-angle support truss screwed to the Cassegrain filters and shutter unit (FSU) of the wide-field telescope camera. The spectrograph design is shown in Fig. 4.

The block of replaceable slits and a slit viewer is mounted in a single tube fixed on the load-bearing collimator prop. The four-seated slit wheel is covered with a protective case (not shown in the figure) and rotates in precision bearings in such a way that it moves in the slit direction for wavelength calibration stability. Immediately behind the slits a folding flat mirror transfers the image of the entrance apertures with demagnification to a CMOS viewing camera 8 for object control and alignment before the exposure. The wheel and the mirror are driven by microservomotors.

The collimator and both camera objectives are focused manually when setting up the instrument and are clamped by locknuts; the objectives are mounted in sleeves with a sliding fit and do not rotate during focusing. The red-channel grating is installed on a rotating table to achieve a maximum efficiency in the first order. The carriage of replaceable blue-channel dispersers driven by a step motor and a precision zero-point sensor also has rotation angle adjustments relative to the beam. All dispersers are fine-tuned in the direction of the grooves by rotation around the optical axis.

The CCD camera in both channels is installed on an adjusting flange with a ball bearing with the center of curvature on the CCD surface, which allows the detector to be slightly rotated or tilted relative to the optical axis without defocusing in the central part.

The light transfer and calibration system is mounted separately from the spectrograph inside the FSU and is a linear guide with a ball-screw unit on the movable platform of which diagonal mirrors with a protected aluminum coating 9 are mounted. One mirror deflects the telescope light into the spectrograph; the other mirror is mounted in a pair with an achromatic lens (EO #49-286, \( F = 200 \) mm) that telecentrically transfers the image of the output port of the integrating sphere (IS) with calibration sources onto the slit. The carriage is moved by a step motor with an encoder, just as the FSU drives, and can also occupy the positions for light transmission into the broadband CCD camera and for the third diagonal feeding mirror of the high-resolution fiber spectrograph being designed.

The calibration sources are represented by a gas-discharge lamp for wavelength calibration and a composite continuum LED source ("flat field"). Light from the hollow-cathode lamp is fed into the IS via an optical fiber, while the LED source is mounted directly on the IS.

Before September 2020, a hollow-cathode lamp containing Ne + Kr + Pb + Na was used, which was

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8 Model BFLY-PGE-23S6M-C. https://www.flir.eu.

9 38 × 54 mm Elliptical Mirror Protected Aluminum EO #30-258. https://www.edmundoptics.com.
Fig. 4. Model of the spectrograph mechanics: (1) wheel of replaceable slits, (2) tube with an image transfer system and a viewing camera, (3) collimator, (4) dichroic beam splitter, (5) red-channel grating, (6, 9) red- and blue-channel objectives, (7, 10) red- and blue-channel CCD cameras, (8) block of replaceable blue-channel dispersers.

then replaced with a Ne + Al + Si lamp. Both lamps were made and kindly provided by Yu.N. Bondarenko (Odessa) and show a number of single bright lines in the $R$ channel and a set of weak lines in the $B$ channel (Fig. 5). This slightly complicates the calibration process, because in the $B$ channel more time (about 15 min) is required to obtain a lamp spectrum with a signal-to-noise ratio enough to reconstruct the coefficients of the two-dimensional dispersion relation (in the red channel this is 3–5 min).

The continuum source incorporates a broadband super-bright LED with a “Sun-like” spectrum\textsuperscript{10} and 402, 380, and 365 nm LEDs whose flux is adjusted by variable resistors. The current and temperature of the substrate are stabilized by the source electronics and maintain the long-term relative spectral brightness of the LEDs within 0.02% after 1-min warm-up. The use of xenon lamps was abandoned, because their spectrum is a non-smooth (line) one.

The CCD cameras of the spectrograph channels are controlled and read out in the Linux operating system using the SDK library of version 2.102.30024 and the code written at SAI in C/C++ for operation with Andor cameras and to save the results with the metadata of observation conditions in FITS files. The TDS slit, viewer, and blue-channel disperser carriage drives are controlled by Arduino controllers, which also take readings from the digital temperature sensors of the optics frames. The TDS control computer is installed in the server room of the 2.5-m telescope tower and exchange data with the CCD cameras and controllers via a 4-channel fiber USB extension cable. The software for TDS control and data exchange with the telescope control system is written in Python.

DISPERSION RELATION AND DEFORMATIONS OF THE INSTRUMENT

Like many Cassegrain instruments, the TDS is not thermally stabilized and during observations changes its orientation in space in the course of pointing and tracking of objects and as the slit position angle changes. The emerging gravity and, as the external conditions change, thermal deformations affect its calibration (the dispersion relation of the detector coordinates and wavelengths in the channels), and an insufficient allowance for the corresponding

\textsuperscript{10} Model STW9C2PB-S Q54CY3, see http://www.seoulsemicon.com.
Fig. 5. Spectrum of the Ne + Al + Si calibration lamp with the labeled unblended lines used for wavelength calibration in the corresponding channels.

Displacements can lead to systematic errors in the measured Doppler shifts of lines in the spectra of objects. A calibration source with a line spectrum or night-sky emission lines is used to study the displacements.

Gratings and a grism are used as dispersers in the TDS and, therefore, the dispersion, to a first approximation, is linear in wavelength. A polynomial of the fifth—seventh order is used for calibration; a further increase in the polynomial order does not lead to a significant improvement in the quality of the fit. The nonlinear terms of the dispersion relation have a total relative amplitude of 2% in $B$, 1.4% in $R$, and 0.3% in $G$.

A distortion of up to 0.3% as well a bend and tilt of the slit images up to 5 pixels (in the red channel) with respect to the middle line of the spectrum image are
observed in the spatial direction. Cubic polynomials are used to correct the spatial distortions.

Although our simulations of the spectrograph mechanics by the finite-element method showed the stability of the mutual orientation of its optical components with displacements up to 5 μm for an arbitrary change in the orientation of the instrument, we performed a series of special measurements to independently determine the pattern and amplitude of gravity deformations. At different elevations of the telescope tube, we measured the shift of the wavelength scale as a function of the angle of the Cassegrain telescope port rotator on which the TDS is mounted (Fig. 6). It can be seen from the graphs that the elastic component of the shift has an amplitude of ±5 μm (0.3 Å or 20 km s\(^{-1}\) for the H\(_\alpha\) hydrogen line) and is the same in both channels. These shifts are obligatory for correction and are removed from the determined Doppler shifts by the wavelength calibration based on the hollow-cathode lamp or night-sky lines.

The hysteresis and non-reproducibility of gravity deformations are much less, below 0.5 μm. The reproducibility of the slit setting was studied separately; it is about 0.7 μm. On the whole, we can conclude that the total uncorrectable mechanical error in the measured line shifts in the spectrum does not exceed 1 μm (0.06 Å or 3 km s\(^{-1}\) for the H\(_\alpha\) hydrogen line). The measurement errors of the spectral line positions due to the variations in the positions of stellar images relative to the center of the spectrograph slit, as a rule, are noticeably higher than these mechanical errors.

In addition to gravity deformations, we also detected thermal deformations possibly related to temperature-dependent stresses in the spectrograph casing. Their value in the red channel is 0.05 Å/1°C in the red channel; in the blue channel the shift is much smaller, less than 0.01 Å/1°C.

Based on the presented data, we evaluate the reliability of Doppler line shift measurements during observations and implement the calibration approach described below.

The system deformations also include the variable displacement of the TDS casing as a whole due to the deflection of the support truss through which the instrument is fixed to the telescope. At different orientations of the instrument, the relative shift of the slit center toward the center of the detector of the wide-field CCD camera changes within ~0.1–0.2 mm (1″–2″). This makes the setting of faint sources invisible through the camera viewer on the slit more difficult and is an additional source of displacements of stars relative to the slit during long exposures. These effects have to be taken into account by the observing technique.
MEASUREMENT TECHNIQUE

The TDS control software includes the following blocks: the channel CCD camera control andor-daemons and the scripts for controlling the spectrograph actuator drives, starting the exposures and the operator GUI written in Python. Two copies of the andor-daemon operate continuously, because the interruption of communication with the Andor cameras causes the thermoelectric coolers of the detectors to stop; the start commands and detector configuration and state parameters are transmitted via a socket connection. All of the information about the state of the telescope control system, the target, and the observation conditions enters through the EPICS bus,11 through which the FSU and TDS units are also controlled.

The interface of the TDS operator is built around the GUI through which the observer controls the TDS viewing camera, perform corrections of the telescope pointing, the slit position angle and telescope focusing, chooses the working slit and the blue-channel disperser, and starts a series of spectral exposures (synchronously or separately in channels). Below we describe the observation and instrument calibration procedure.

Object alignment. The 2.5-m CMO SAI telescope has a random pointing error of about 2′′, but, for several reasons, the uncompensated systematic deviations of the object position relative to the slit after pointing can reach 5′′–10′′. Therefore, alignment is required before starting the exposures in the slit mode.

Stars to $V \sim 19^m$ are visible through the TDS viewing camera, fainter stars are set on the slit in the following ways:

1) using a brighter star also placed on the slit with the calculated position angle;

2) using the calculated relative pointing displacements in declination and right ascension after slit alignment based on a star at a small (<1°) distance from the object;

3) alignment to the specified detector coordinates in the wide-field CCD camera of the Cassegrain port. The latter method is advantageous in that photometric information about the object under study can be obtained, for example, the magnitudes in the SDSS bands, can be obtained simultaneously. The coordinates of the “slit” on the 4K CCD detector slightly depend on the Cassegrain rotator elevation and orientation due to flexures in the spectrograph suspension and, therefore, are calibrated using brighter stars each time after the removal and installation of the spectrograph or the wide-field camera on the telescope.

Taking exposures of the object. Immediately after the target setting on the slit, an automatic guiding with the offset guide of the telescope Cassegrain port is started, which is performed with an accuracy $\sigma \sim 0.1′′$ during the entire measuring session; the guiding star is chosen in a ring of radius 10′–15′ around the target. The TDS viewing mirror is flipped back, the working or wide slit is set, and the exposures are started. A series of 3–5 exposures up to 20 min each is commonly used for the spectra; longer exposures are disadvantageous because of the accumulation of cosmic-ray particle hits.

Because of flexures in the spectrograph suspension, during long-term observations (monitoring) the object position on the slit is controlled between exposures. For this purpose, the TDS viewing mirror is introduced into the path, while for objects invisible through the viewer the FSU mirror, which deflects the light into the TDS, is brought out from the telescope axis and short exposures are taken with the wide-field camera. It takes 16 s to insert or remove the FSU mirror; the TDS viewing mirror and the slit wheel moves to the target position in 1–2 s.

The exposure execution script saves all of the relevant parameters of the target and observation conditions in the FITS files of spectra and in the database of observation results: the detector settings and exposure start times, the object identifiers and programs (requests for observations), the object catalog coordinates and current mounting coordinates (the parallactic and position angles of the Cassegrain rotator as well as the object elevation are recorded at the exposure start and end times), the positions of the TDS and FSU drives, the meteorological parameters and temperatures of the telescope optics and spectrograph elements. It takes about 25 s to read out and save the frame.

Wavelength calibration. It will suffice to obtain spectra of the line lamp with a high signal-to-noise ratio once a month or after interference in the optical system. The corrections to the wavelength scale related to TDS deformations for faint objects can be calculated from sky lines. When it is needed to obtain a reliable wavelength scale for bright objects, when the exposures are insufficient for a manifestation of sky lines, it is appropriate to obtain lamp spectra before and after the spectra of the object under study have been taken. Exposures ∼100 s are sufficient for this purpose.

Spectrophotometric standards are measured before or after the main objects at a close airmass. Stars from the list of the European Southern Observatory12 are commonly used for this purpose, among

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11https://epics.anl.gov/.
12https://www.eso.org/sci/observing/tools/standards/spec-tras/stanlis.html.
which there are white dwarfs with smooth and well-studied spectra; other catalogs can also be used. Any stars of spectral type A0V without peculiarities in the spectrum and with interstellar extinction $A_V < 0.2^{\text{m}}$ can be used for the telluric correction (the removal of absorption lines in the Earth’s atmosphere).

**Flat field calibration** is performed using the continuum LED source once a day. In clear evenings the twilight segment is measured approximately once a week to refine the shape of the slit function (see the next section).

**Dark frames** are taken approximately once in a season for the detector working modes and settings on overcast nights. Since the increase in the counts in hot pixels is nonlinear and reaches saturation, we use a series of the most commonly used exposures $T_{\text{exp}} = 0, 300, 600, 1200$ s, 10 frames with each of them.

The described procedure is performed by the operator; in future we plan to automate the object alignment and calibration measurements.

**SPECTROSCOPIC DATA REDUCTION**

The measured output characteristics of the range and the resolution of the spectrograph (the efficiency is discussed in the next section) are shown at the bottom of Table 1. The TDS focusing using a calibration lamp provided a spectral resolution lower than that determined from the geometrical width of the $1^{\text{st}}$ slit image only by 10–20%. Similar values of the resolution were obtained by fitting the day-sky spectra to the synthetic ones obtained by convolving the library spectrum of the Sun\(^{13}\) with the model of a variable-width instrumental profile. The images are nearly symmetric in the entire wavelength range.

To reduce the observations, we wrote a software package in Python operating in automatic and interactive modes and based on the keywords in the headers of the input FITS files. The package includes the following procedures.

**Combining dark frames** by median averaging.

**Dark frame subtraction** with a linear interpolation of the combined dark frames to the required exposure time.

**Cosmic-ray particle hit removal**, if necessary, with the LAcosmic package (van Dokkum 2001).

**Wavelength and curvature calibration** of the slit image based on the spectrum of a hollow-cathode lamp. For calibration we compiled a list of the least blended lines uniformly distributed over the spectral range. The line positions in each CCD row are determined by Gaussian fitting, whereupon these positions for each line are fitted by a parabola that simulates the observed curvature of the slit image. For convenience, the dispersion curves are constructed for each CCD row using these averaged positions and are fitted by a polynomial of the fifth degree for the $B$ and $G$ channels and of the seventh degree for the $R$ channel. The typical residual scatter is 0.20 Å in $B$, 0.07 Å in $G$, and 0.01 Å in $R$. The low calibration accuracy in the blue channel is due to the weaker spectrum, fewer unblended lines, and a lower spectral resolution.

**Data rebinning** onto a uniform wavelength grid by a linear interpolation of the frames based on the individual dispersion curve for each CCD row, which simultaneously corrects the curvature of the slit image.

**Correcting the nonuniformity of sensitivity along the slit** by calculating a “flat field” from the twilight-sky spectrum and the spectrum of the continuum LED source. The flat fields with the LED lamp are recorded faster and more uniformly in noise, because they do not have strong absorption lines that are present in the sky spectrum. The nonuniformity of slit illumination by the LED source is seen as an illumination gradient of 10% in slit height. To eliminate this nonuniformity, a low-frequency correction is calculated using the calibration obtained from the twilight sky. The flat fields not only correct the shadows from specks of dust and slit imperfection, but also efficiently eliminate the fringes observed in the red channel.

**Extraction of spectra** in a graphical user interface by two methods.

1. A standard (linear) extraction by summing the counts within a given aperture with the subtraction of the background determined from areas far from the source.

2. An optimal extraction using the algorithm described by Horne (1986), which consists in calculating the spatial profile of the spectrum and then summing the counts with the weights of this profile.

Using an optimal extraction makes it possible to remove the cosmic-ray particle hits and is appropriate for relatively faint objects, for which it is possible to achieve signal-to-noise ratios higher than those with a linear extraction by 20–30%. For bright objects standard and optimal extractions lead to virtually identical results.

**Wavelength correction.** Simultaneously with the spectrum extraction, the wavelength correction can be calculated and taken into account using night-sky lines. In the blue channel the 5577 Å line and the Hg I 4046.57, 4358.34, 5460.75 Å lines from

\(^{13}\)https://noirlab.edu/public/images/noao-sun/.
light pollution are used for this purpose. In the $R$ channel a lot of oxygen lines and the sodium doublet are available for calculating the correction.

Calculating the response curve of the system using the spectra of standard stars with known spectral energy distributions close in time and airmass. The system’s response curve is computed using the calculated ratio of the extracted spectra for the standards to the published spectral energy distributions. The derived ratio reflects the spectral efficiency of the instrument for the entire measurement path from the upper boundary of the atmosphere to the received detector signal photoelectrons. The system’s response depends on the variable losses of light in the atmosphere and on the spectrograph slit; the next section is devoted to its discussion.

Calculating the flux by dividing the instrumental flux measured in counts per second by the response curve. The final values have the dimensions erg/(cm$^2$ s Å).

The entire data reduction history and parameters, the control information, and the barycentric wavelength and measurement time corrections are saved in the headers of the output FITS files containing the calibrated image of the spectrum. The spectrum extraction parameters and results are written into additional FITS extensions. The results of different channels are merged into a single spectrum, if necessary, separately from the standard data reduction described above.

Apart from the software package described above, an alternative version of the TDS data reduction system operating in the environment of Interactive Data Language (IDL, a commercial software package) or its free analogue, GNU Data Language (GDL), is available. This package is freeware licensed under the GPLv3$^{14}$ license and is based on algorithms from the automatic data reduction systems of the MMIRS and Binospec spectrographs (Chilingarian et al. 2015; Kansky et al. 2019) installed at the 6.5-m MMT telescope. It is a universal system for the reduction of long-slit spectra to which a block with a configuration for the TDS was added. In general, the algorithms used in it are similar to those described above, but there are a number of differences: (a) to construct the wavelength calibration, the positions of lines from the lamp of a comparison spectrum over the entire frame are fitted by a two-dimensional polynomial; (b) a cosmic-ray particle hit removal algorithm based on a simultaneous statistical analysis of several spectra at once (if available) is implemented; (c) any star of spectral type A0V without noticeable extinction on the line of sight (up to $E(B-V) = 0.05^{15}$) and strong chemical anomalies can be used as a spectrophotometric standard, which provides additional flexibility in choosing a star near the object, because such stars are often encountered in the sky; (d) the night-sky subtraction procedure is optimized for faint objects and is applied before the linearization and correction of the geometry of a two-dimensional spectrum (Katkov and Chilingarian 2011); (e) the final spectrum is optionally corrected for telluric absorptions.

LIGHT EFFICIENCY

Observations with a wide slit allow spectrophotometry to be carried out at the cost of reducing the spectral resolution. These observations performed quasi-simultaneously at different airmasses make it possible to separately reconstruct the current atmospheric transmission curve and the response function of the instrument. To achieve a high resolution and a photometric accuracy, it is necessary to carry out two measurements, with wide and narrow slits.

The thick lines in Fig. 3 indicate an example of reconstructing the response curve of the system corrected for the atmosphere by the above-mentioned method. The reconstruction was performed using the standards BD+75d325 and BD+28d4211 observed with a 10$''$ slit at airmasses $M = 2.0$ and 1.03, respectively. The presence of narrow features in the response curve, which are located in the region of the H$\gamma$–H$\delta$ lines, places increased requirements on the quality and resolution of the standard spectra. An insufficient spectral resolution of the data causes the shapes of these narrow features to be smoothed in the reconstructed curve.

The measured efficiency uncorrected for the atmosphere at the object’s elevation of 75° reaches 35, 22, and 20% in the red, green, and blue channels, respectively. Similar values and response curves were also obtained with other standards.

The reduced sensitivity of the blue channel compared to the red one prompted us to independently calculate the expected transmittance of the system near the central wavelengths of the channels for an object near the zenith. The median extinction at CMO (0.13 in $R$ and 0.25 in $B$; Kornilov et al. 2016) was taken for the atmospheric extinction; for the telescope mirrors M1 and M2 we took the surface-averaged reflection coefficients reduced by 8 and 5% to take into account the aging of the coatings. For the remaining elements we took the transmission and reflection coefficients and the quantum efficiency of the detectors from the manufacturers.

$^{14}$https://bitbucket.org/chil_sai/mosiu-pipeline.

$^{15}$The reflectivity of the mirrors of the 2.5-m telescope in a relative scale is monitored at CMO.
The final theoretical transmittance of the entire path near the zenith in the \( R \) channel is 37%, which is close to the measured one. At the same time, the above measured transmittance in \( B \) (blue channel) is only 73% of the expected 27.6%. The transmittance in \( G \) at the wavelength of the maximum grating efficiency (505 nm) turned out to be higher than that in \( B \) by 10%, although it does not exceed the latter theoretically. The causes of these inconsistencies are yet to be clarified.

Given the estimated transmittance of the feeding optics of the spectrograph (the telescope and the introduced diagonal mirror), the quantum efficiency of the TDS itself (including the CCD detectors) reaches 65, 47, and 50% in the \( R \), \( B \), and \( G \) channels, respectively, near the central wavelengths of the dispersers. These characteristics of the spectrograph are given in Table 1.

In observations with a narrow slit the system’s response curve allows only the small-scale transmittance nonuniformities to be taken into account, while the total transmittance remains uncertain due to the losses on the slit, which can vary with wavelength because of the wavelength dependence of the stellar image profile and atmospheric dispersion. The latter effect is eliminated by setting the slit along the dispersion direction, if this is possible for the task being accomplished. However, the total loss in the atmosphere and on the slit can vary over a very wide range (Fig. 7).

To estimate the expected signal at the channel sensitivity maxima, we calculated the magnitudes of AOV-type stars, which, without a correction for the atmosphere, give a signal of 1 photoelectron per second per pixel of the extracted spectrum: \( \text{mag}_1(B) = 17.6^m \), \( \text{mag}_1(G) = 16.8^m \), and \( \text{mag}_1(R) = 17.2^m \). When calculating the exposure time, these magnitudes should be corrected for the expected extinction, airmass, and the estimated loss on the spectrograph slit loss due to the atmospheric seeing.

**OBSERVATIONS AND RESULTS**

Owing to the system’s good transmittance due to the simple and efficient design of the optical system and its medium spectral resolution, which exceeds the typical values for existing extensive spectroscopic surveys (SDSS, LAMOST) by a factor of 1.5–2, the TDS occupies a peculiar niche that it shares with typical low-resolution spectrographs at telescopes with a mirror size \( \sim 3 \)–\( 3.5 \) m (the Shane Telescope of the Lick Observatory, the NTT of the European Southern Observatory). The TDS allows one to study in detail astrophysical objects that are 2–3 magnitudes fainter than those included in the samples of present-day spectroscopic surveys (i.e., quasi-point objects to \( 21.5^m \)) or to obtain spectra with a high signal-to-noise ratio for objects for which spectra of only mediocre quality are available in surveys in a reasonable exposure time (2–4 h).

Point and extended sources of different nature are studied with the spectrograph: nonstationary stars, planetary nebula nuclei, active galactic nuclei and disks, quasars, supernovae, etc. Regular observations are carried out within the programs of monitoring the microquasar SS433, novae (Sokolovsky et al. 2020), spectroscopy for objects from the Spectrum-RG/eROSITA mission (Dodin et al. 2020), active galactic nuclei (Illic et al. 2020), symbiotic stars, white dwarfs (Pshirkov et al. 2020), and planetary nebulae (Arkhipova et al. 2020) as well as within the program of research on galaxies with intermediate-mass black holes (Chilingarian et al. 2018) and the
program of research on the environment of rare low-surface-brightness giant galaxies (Saburova et al. 2018; Onori et al. 2019) in which satellites of an even rarer type “compact elliptical galaxies” have recently been detected (Chilingarian et al. 2009; Chilingarian and Zolotukhin 2015).

Some of the results showing the TDS capabilities are presented below.

Monitoring of SS433

Several monitoring sessions have been carried out with the TDS to study the variability of the profiles and radial velocities of emission lines in the spectrum of microquasar SS433, a traditional object of research at SAI MSU (Cherepashchuk et al. 2018, 2020). Figure 8 presents the time evolution of the spectra obtained in August–October 2020 (Modified Julian Days (MJD) of observations are specified along the vertical axis). The spectra from two channels were joined, the continuum was subtracted, and the intensity scale is relative. The brightness of this object allows it to be monitored virtually every night under any observing conditions. These observations are important for revealing possible evolutionary changes in the parameters of this X-ray binary system, which is at a special stage of secondary mass transfer. In this case, no common envelope has been formed for some reasons, while the loss of mass and angular momentum from the system occurs from a precessing supercritical accretion disk around the relativistic object. Thus, SS433 is at a critical evolutionary stage and, therefore, the search for its evolutionary changes is an important observational task.

Study of Symbiotic Stars

Figure 9 presents the spectra of the symbiotic stars V407 Cyg, CSS 1102, and YY Her obtained at various stages of activity. V407 Cyg is currently in a passive state and exhibits a typical spectrum of an oxygen-rich Mira-type star, with a Balmer decrement characteristic of this class of objects (Hδ is the strongest emission line in the spectrum). The spectrum of the classical symbiotic star YY Her was obtained in a quiescent state. In addition to the bright emission lines of H I, He I, He II, etc., there is a prominent nebular continuum that weakens the molecular bands of the cool component in the blue region. The TDS allows one to obtain spectra near the Balmer jump, which is important for studying both the nebula and the accretion disk appearing at certain stages of evolution of outbursts in symbiotic stars.

The middle spectrum in Fig. 9 belongs to the poorly studied star CSS 1102. The object was discovered during the survey by MacConnell (1982) as
an S3-type star. A report on a possible symbiotic nature of this object\textsuperscript{16} appeared in August 2020. Our spectroscopic observations showed that apart from the TiO and ZrO molecular bands, bright hydrogen emission lines are present in the spectrum of the star, with the Balmer decrement having a value nontypical of Mira-type stars (see the spectrum of V407 Cyg in the same figure above). Neutral helium lines and even weak forbidden [Ne III] lines are also present in the spectrum of the object. This undoubtedly allows us to classify the object as a symbiotic star. Our photometric observations carried out on August 26, 2020, with the 60-cm CMO SAI telescope revealed a fast brightness variability in the system CSS 1102 with a characteristic time scale $\sim 30$ min and an amplitude of 0.1\textsuperscript{m} in the $B$ band (Tatarnikova et al., in preparation). This is a rare type of variability in symbiotic stars that is probably associated with the presence of accretion disks and jets in these systems. The vast majority of such objects belong to the very rare subclass of recurrent symbiotic novae.

Transients and Flaring Stars

The dwarf nova SAI-V J004051.59+591429.7 was discovered\textsuperscript{17} at SAI MSU during the photometric monitoring of another variable star with the 60-cm CMO telescope. Two outbursts of the object were observed in 2019. Both outbursts correspond in characteristics to normal dwarf nova outbursts. The spectra of the variable ($R_c \sim 20$\textsuperscript{m}) obtained at the 2.5-m CMO telescope with the TDS are typical of dwarf novae at minimum light. Balmer hydrogen emission lines are clearly seen. The radial velocities determined from the H$\alpha$ emission show a regular variability associated with the orbital motion in the binary system (Fig. 10). The orbital period is more than 3.5 h; a further spectroscopic monitoring will allow it to be refined.

Absorption and Emission Spectra of Galaxies

The TDS allows a wide range of problems of research on both emission and absorption spectra of galaxies and active galactic nuclei to be solved. The medium-spectral-resolution mode with a grism in the blue channel covers almost all of the most commonly used absorption lines in the optical spectra of galaxies to measure the stellar kinematics and to estimate the properties of the stellar population (age, chemical composition). At the same time, the available spectral resolution makes it possible to measure the stellar velocity dispersions up to 35–40 km s$^{-1}$ in galaxies with an old stellar population at a signal-to-noise ratio of about 15 per pixel (or up to 70–80 km s$^{-1}$ when...
using the low-resolution mode; see Chilingarian and Grishin (2020), where the theoretical calculation of the quality of determining the parameters of the stellar kinematics from absorption spectra, which we used for our estimates, is discussed).

Thus, it becomes possible to study the internal dynamics of relatively low-mass dwarf galaxies that are inaccessible for study with other Russian telescopes, including BTA, due to the insufficient spectral resolution. At the same time, the red channel allows the Hα emission line profile to be well resolved, which makes the TDS an excellent instrument for studying active galactic nuclei, including those containing intermediate-mass black holes (Chilingarian et al. 2018), where the broad line component is rather weak and relatively narrow (150–250 km s$^{-1}$). The blue channel for such objects will be sufficient for measuring the relatively low stellar velocity dispersions (40–70 km s$^{-1}$).

Figure 11 presents the absorption and emission spectra of the giant low-surface-brightness galaxy Malin 1 (black line) and its compact elliptical companion (red line). Both galaxies contain faint active galactic nuclei. Despite the 20th magnitude of the companion in the SDSS $g$ filter, not only the emissions associated with the active nucleus, but also the absorptions from its stellar population are clearly seen in the spectrum.

CONCLUSIONS

The results of our pilot observing programs showed that the orientation toward a high transmittance of the instrument at a spectral resolution sufficient not only for estimating the integrated intensities, but also for studying the line profiles for nonstationary and extragalactic objects turned out to be correct. In the class of double-beam long-slit spectrographs for medium-size telescopes, whose brief overview is given in the Introduction, we failed to find an analog of the TDS (a completely dioptic system with a dichroic beam splitter and holographic dispersers). Therefore, direct comparisons of the spectrograph characteristics with those of related instruments are hardly possible.

Our tests of the spectrograph showed that the efficiency of the instrument in the red channel corresponds to the efficiency of the disperser and the detector claimed by the project and calculated from
the transmittance curves of the atmosphere, the telescope and spectrograph optics. By this parameter, the TDS expectedly acts as a high-“transparency” spectrograph according to the world-level criteria. At the same time, there remain a number of questions requiring a separate study. In particular, we need to clarify the source of a reduced efficiency of the $B$ channel with respect to the calculated value. Judging by the relative efficiency of the $G$ and $B$ channels, both the reduced response of the blue grating and the neglected losses in the optics of the blue spectrograph arm can be a cause. It is also necessary to investigate the “cutoff” of the system’s response toward 350 nm, which reduces the accuracy of spectrophotometric measurements near the Balmer jump in the objects under study.

The efficiency of the spectrograph can be improved further. For example, ordering the beam splitter from companies that for many years have specialized in complex dielectric coatings for astronomy will help to reduce the influence of “waves” in the reflection and transmission characteristics and to improve the reconstruction of the response curve, which is especially desirable near the hydrogen lines in the blue part of the working region. A noticeable reduction in scattered light and an additional $\sim 6\%$ efficiency can be achieved by replacing the standard detector windows with antireflection-coated ones for the ranges of TDS operation; replacing the coating of the diagonal mirror feeding light into the spectrograph with a multilayer one can give a similar gain in efficiency. Finally, an improvement in tracking the object under study with the telescope can reduce the losses on the slit, which can be significant for faint sources observed with long exposures.

The TDS has a great potential as an instrument for spectrophotometric research. The first results showed that the response curves reconstructed from various standard stars are consistent with an accuracy better than 2%. However, a separate study of the convergence of the estimates for standards on different photometric nights is required for a confident formulation of extensive programs of spectrophotometric studies.

Few spectra aimed at monitoring the Doppler shifts have been obtained with the TDS so far. Pshirkov et al. (2020) showed that the measurement technique gives reliable radial velocities within the range $10-20$ km s$^{-1}$ even for faint objects, but longer series of measurements of known spectroscopic binaries are required to improve this estimate.

The presented characteristics of the TDS at the 2.5-m telescope of CMO SAI MSU and the first results of its operation show that it is an optimal instrument for a prompt characterization and long-term monitoring of nonstationary and transient objects. The spectra of objects $\sim 20^m$ are taken by it with confidence in 1–2 h of observations with a signal-to-noise ratio higher than 5 per detector pixel and a resolution $R \sim 1500-2500$, depending on the wavelength.

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Fig. 11. Examples of the spectra for the central part of the low-surface-brightness galaxy Malin 1 with a total exposure time of 4 h, $g = 18.72^m$ (black line), and one of its compact elliptical companions, $g = 19.94^m$ (red line). The fluxes in the companion’s spectrum were tripled to improve the perception. The main absorption and emission lines are marked in the spectra. Both objects contain active galactic nuclei.
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