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Challenges of high-resolution spectroscopy in the Nasmyth focuses of the BTA

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Abstract. The article discusses the challenges and solutions associated with high-resolution spectroscopy on alt-azimuth mount telescopes, particularly focusing on the 6-meter BTA (Big Telescope Alt-Azimutal) and its Nasmyth focus. The main attention is given to the instability of spectra caused by the design features of the telescope and the equipment used. Special attention is paid to the issues of temperature non-uniformity and its impact on observation quality. Various stages of equipment development and testing are described along with the results of applying new technologies and methods to achieve high spectral resolution.

Keywords: instrumentation: spectrographs; telescopes

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1 Investigation of the regular spectral equipment

The alt-azimuth design of the 6-meter telescope hinders the performance of the high spectral resolution equipment on the BTA moving part. Efforts to deel with the problem have focused on finding the observing programs that can be performed regardless of spectral instability and the methods for achieving high spectral resolution with varying equipment. Here are the main stages of the work.

During the commissioning of the BTA complex, the primary objective for the first generation of the Special Astrophysical Observatory (SAO) astronomers was to investigate the spectral equipment created by the optomechanical industry. This equipment was developed in accordance with specific technical requirements formulated by astronomers and was formally accepted following rigorous testing both in the workshop and in the observatory, but some difficulties arose because the technical specifications for the telescope and its spectral equipment were prepared at another observatory, and the acceptance was conducted by SAO astronomers.

The idea of the combination of a telescope with a fiber-fed stationary spectrograph appeared only after the BTA had been put into operation, and was optimal for the telescopes of moderate size, see the review of Panchuk et al. (2011). For 4-meter class telescopes, echelle systems placed at the coudé focus were still being developed in the 1980s (Walker & Diego 1985). For the BTA, an idea of the horizontal placement of the spectrograph in a uniform temperature layer was realized (Gusev et al. 1976; Zandin et al. 1977), where spectral resolution was limited by the dimensions of the mounted structure. An investigation of the spectral equipment mounted near the support of the BTA alt-azimuth construction revealed positional instability of high-resolution spectra. As a result, the typical spectral resolution for long photographic exposures was lower. The variety of observing programs had been limited, priority was given to the studies of relative characteristics, either measured relative to the continuum (equivalent widths) or the components of different kinds of circular polarization (measurements of the longitudinal component of the magnetic field). The search for the causes of the positional instability did not allow them to be identified either by linear scales or by characteristic times. Work was performed on the reconstruction of the optical scheme of the Main Stellar Spectrograph (MSS) long-focus camera (Gazhur et al. 1986), light and heat insulation of its volume, change of the oil supply mode at the BTA "Z"-axis drive, and methods for operating with the MSS were selected (Klochkova et al. 2008), but the main problem, the temperature non-uniformity in the volume of the vertical mount of spectrograph elements, remained.

2 Television-type photon counters

The transition to television-type photon counters in high-resolution spectroscopy was connected with matching the characteristic format of the light detector cathode with the scale of the spectrograph camera focal plane while maintaining high spectral resolution. The optimal solution was the use of a diffraction grating in high orders. As a first step, the SP161 spectrograph was reconstructed, where a medium-resolution spectrum was formed on a centimeter focal plane of the camera. The camera design made it possible to use an electron-optical converter with electromagnetic focusing, providing a record throughput (for the BTA Nasmyth-2 focus) $F_{\rm coll}/F_{\rm cam} = 3684/182 = 20$ (Gazhur et al. 1990). The positional stability of the echelle spectrum was limited by the varying orientation of the image intensifier tube focusing system due to its movement in Earth's magnetic field. The transition to solid-state small-format CCDs (charge-coupled devices) was performed on the ESPAK autocollimation echelle spectrograph developed for using both two-dimensional photon counters and CCDs (Klochkova et al. 1991).

3 CCD echelle spectrographs with small apertures

Investigation of the stability of the stellar spectra obtained with the BTA MSS were complicated by the lack of digital recording methods that would allow collecting measurement statistics remotely, without visiting the spectrograph volume. In 1989, a conference of BTA applicants was held in Odessa jointly with the BTA Program Committee (KT6T). At this conference we put forward an initiative to reconstruct the MSS for the full use of the collimated beam (by that time, a set of diffraction gratings intercepting the entire beam at any working angles had been manufactured) with spectrum recording on first CCDs. This initiative was not supported by any of the parties. Thus, we were guaranteed to lag behind the spectroscopists of the Crimean Astrophysical Observatory, where a domestic CCD camera had already been used in 1989 at the spectrograph ASP-14 in the coudé focus of the 2.6-meter telescope. At the BTA MSS, observations were continued with photographic plates with a high level of fogging. In this situation, we began work on creating an echelle spectrograph with a small-diameter collimated beam, LYNX (Panchuk et al. 1993). The format of the CCD chip used limited the size of the simultaneously recorded wavelength range, and we did not have the ability to deal with the problems of remote monitoring and control. Therefore, one of the subsequent modifications of the LYNX echelle spectrograph was built as a combination containing a set of three cross-dispersion gratings (with a density of 150, 300, and 600 gr/mm), operating in the first diffraction order, and two R2 echelles ($\tan\theta_{\rm b} = 2$). This spectrograph design can be found in Panchuk et al. (2016), Fig. 3. The units with the dispersing elements are movable across the collimator axis ($d_{\rm coll} = 100$ mm), which provides six possible "cross-dispersion grating – echelle" combinations, optimal for operation in different wavelength ranges with required separation of the adjacent orders in the echelle spectrum. In addition to the modifications of the LYNX echelle spectrograph, other cross-dispersion designs were also constructed (Gazhur et al. 1990; Klochkova et al. 1991). The variety of the parameters of these devices made it possible to implement most of the research programs of the SAO RAS Laboratory of Astrospectroscopy (Klochkova 2012). Thus, in the late 80s – early 90s the foundations were created for designing a cross-dispersion system corresponding to the MSS investigation results and the scientific interests of the 6-meter telescope staff.

4 Increasing the aperture and spectral resolution

In 1993, we proposed a program for transition to collimated beams of large diameters (at least 250 mm). The program mainly included: (a) reconstruction of the MSS, proposed in 1989; (b) development of an echelle spectrograph installed on the Nasmyth-2 focus platform, with a horizontal arrangement of the optical scheme. The administrative decision to build the Nasmyth echelle spectrograph (NES) was made in the fall of 1996, the manufacture and assembly of the spectrograph continued throughout 1997, and first light was obtained in December 1997 (Panchuk et al. 1999). The optical scheme of the spectrograph was oriented in the plane of the Nasmyth focus platform, with all units and elements of the scheme in a uniform temperature layer; the corresponding mechanical unloading of the BTA turned out to be successful. The positional characteristics of the spectrograph were studied in Klochkova et al. (1999). It was found that the accuracy of processing individual orders allows detecting even the subtle manifestations of instability of the light detector at the beginning of cryostat freezing. After several years of NES operation, the stability of the spectrum position was checked during three days when the observations were not carried out due to weather conditions and the temperature difference between the outside air and the in-dome space was record-breaking (Panchuk et al. 2006). It was found that the shifts of the comparison spectrum lines correlated neither with the variations of meteorological parameters (temperature, atmospheric pressure, velocity) nor with the temperature variations of the NES mechanical structure. However, noticeable shifts in the positions of spectral lines were observed. An analysis of the experiments conducted at NES with other detectors revealed the effect of line shift for four different detectors, one of which (with a CCD of 2048×2048 elements) was manufactured in accordance with the European Southern Observatory standards (Sørensen 2001)

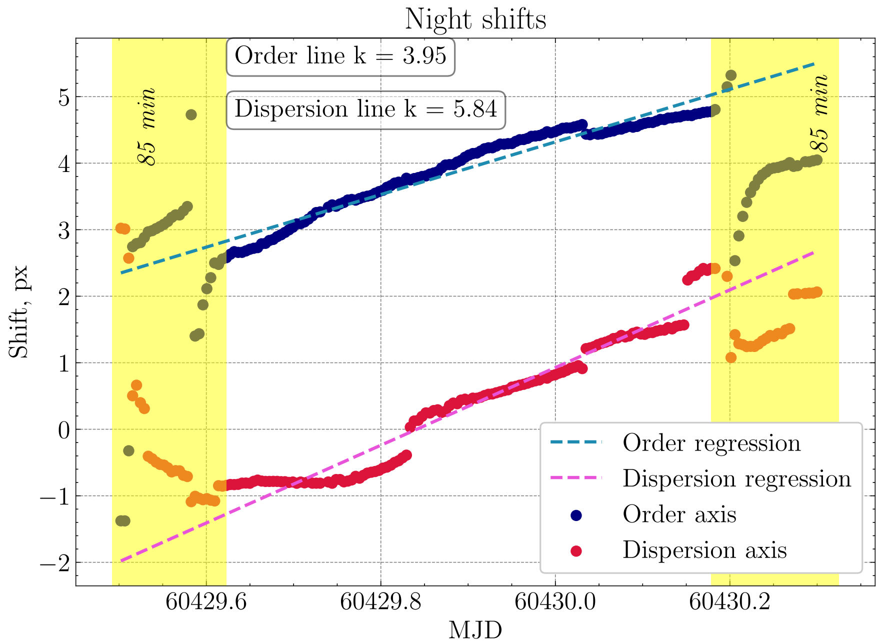

Fig. 1. Dependence of line position on time. The yellow sectors show the moments of significant instability during the filling of the cryostat with coolant. The ”linear“ section is approximated by a straight line, the coefficients k are shown in the figure.

and had been used on NES for 10 years. At present, NES is equipped with a system based on the 4.6k × 2k E2V CCD42-90-1-G01 chip, the system has been designed and manufactured at SAO RAS (Vlasyuk et al. 2024). The actual state of NES is described in Panchuk et al. (2017).

Subsequent investigation into the causes of image shifts on the CCD chip was conducted using the MIDAS software suite. Initially, cross-correlation algorithms were applied, which, at that time, yielded results along just one axis of the chip. For a higher precision measurement of these shifts, a specialized algorithm was required, the one that would be less universal but more focused on this specific task. Therefore, a two-dimensional optimization method has been utilized in the current study of NES stability. An analyzed image was randomly shifted relative to the reference image, then the difference image between them was calculated, a cost function was created and subsequently minimized (Powell 1964; Press et al. 1986). To prevent falling into a local minimum, the sequential Gaussian pyramid technique and a hopping algorithm (Wales & Doye 1997) were applied. This allowed the shifts along the x and y axes to be determined, the resulting combination was used to calculate image rotation. The results are presented in Fig. 1. Sharp coordinate changes coincide with the addition of coolant into the cryostat. The nature of the coordinate variation is complex and requires further study in the laboratory conditions. For details, see technical report Zhuklevich & Panchuk (2024).

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