Stellar Spectroscopy Technique on Small- and Intermediate-Diameter Telescopes

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Abstract

We briefly present the history of technical solutions aimed at improving the efficiency of spectroscopy on small- and moderate-diameter telescopes. We assess the current state of spectroscopy techniques and some of the perspectives.

Keywords: technique: spectroscopic — telescopes.

1 Introduction

The interest in small- and moderate-diameter telescopes is due to the development of methods for the use of novel detectors. Thus the results of the first revolution of the technique of registration of weak signals (mind XX-century) served as the basis for the program of the 1956 symposium [1] (the Russian edition was also published [2], which was supplemented with papers considered to be promising). The next time the subject came to the focus at the level of an IAU symposium was in 1986 [3], when the results of the use of single-channel detectors were summarized and the prospects of the application of multichannel solid-state detectors already became apparent. Whereas in the mid-XX century instruments with diameters of 0.3 to 1-m were viewed as moderate-diameter telescopes, 30 years later telescopes with diameters up to 1 m were already classified as small instruments. A brief review of the types of equipment used on small- and moderate-diameter telescopes was presented by Panchuk et. al. [4], and in 2015 the international meeting “The Present and Future of Small and Medium Size Telescopes” [5] was held at the Special Astrophysical Observatory of the Russian Academy of Sciences.

We restrict the ensuing review of stellar spectroscopy techniques used on small- and moderate-diameter telescopes to the $D \sim [0.25; 1.22]$ m diameter interval. In exceptional cases when discussing new methodological achievements we mention studies carried out on $D \sim 1.5$ m telescopes. Unlike our review [4], we do not mention photometry techniques used on small-diameter telescopes. Such studies have since long become a separate field.

First, we provide some general considerations concerning small- and moderate-diameter telescopes, which we partly pointed out in our earlier paper [4]. The advantages and specificities of the operating of small- and moderate-diameter telescopes can be conveniently classified into technical, financial, organizational, scientific, and psychological types.
Technical:
• Practically all large telescopes are multiprogram instruments, which, unlike small telescopes, are difficult to optimize for addressing separate tasks. The DAO reflector \((D = 1.22 \text{ m})\) used for studies involving photographic spectroscopy in the coudé focus is a classical example of this type: the spectrograph of this telescope outperformed the coudé spectrograph of the Hale telescope \((D = 5 \text{ m})\) in terms of limiting magnitude.
• Because of the losses at the entrance slit, the advantage in the limiting magnitude in the case of high-resolution spectroscopy performed on intermediate-diameter and large telescopes is proportional to the first power of the mirror diameter rather than to the squared diameter as in the case of small telescopes.
• Small telescopes are easier to automate.

Financial:
• If a small telescope is equipped only with one kind of instruments, it is guaranteed to be operated at full capacity. The per-observation cost, which is determined not only by the operating costs but also by the cost of auxiliary instrumentation, is thereby reduced.
• If a small telescope is narrowly specialized (one type of equipment for dark nights and one type of equipment for darkless nights), then the expenses for switching the instruments are small.
• Overall technical maintenance of a small telescope is less expensive.
• The current dependence of the cost of a telescope on the diameter of its primary mirror shows a sharp increase at 1.2 m. Whereas the cost of “amateur-class” telescopes is proportional to its diameter, the cost of professional telescopes (starting from \(D \sim 1.2 \text{ m}\)) is proportional to the area of the mirror.

Organizational:
• With small telescopes it is easier to acquire time for repeating observations, which can be necessary for verifying some of the results.
• Equipment can remain longer on a small telescope during the checkout and preparation stage equipment than on a larger-diameter telescope.
• Observations on small telescopes are easier to organize because one observer is enough in most of the cases.
• Equipment breakdown on a small telescope is not viewed as a permanent loss of time, and the replacement of equipment is less formalized in most of the cases.

Scientific:
• Cloudy weather may simultaneously “switch off” and entire group of large telescopes located at the same site, whereas small telescopes better distributed across the Earth surface, have a better chance to detect a unique event (this does not apply to extremely faint and short-lived phenomena).
• A number of research tasks requires uninterrupted monitoring the object with telescopes located at different longitudes (such monitoring is practically impossible to organize with large multiprogram telescopes).
• Small telescopes offer more time for continued studies, which is important for studying spectral variability or when carrying out mass spectroscopic surveys. The efficiency of these instruments also increases as some of the telescopes mentioned above become
There is a view \[8\] that the time for fulfilling a single observational project on a 1-m telescope exceeds the corresponding time for a 4-m telescope, whereas one large telescope is equivalent to four half-diameter telescopes in terms of scientific efficiency. There are also other scientometric estimates \[9\].

A number of new phenomena were discovered just with small telescopes. The expansion of the Crab nebula was measured on a \(D = 0.91\) m telescope \[10\]. The same instrument was used in observations that resulted in the discovery of the rotation of the M31 nebula \[11\]. Circular polarization of white dwarfs, which was first measured with a \(D = 0.61\) m telescope \[12\], was later studied with larger instruments \[13\]. Mass photoelectric radial-velocity measurements, which, in particular, became the basis for compiling programs for Doppler-based searches for low-mass companions, were carried out with meter-class telescopes \[14, 15, 16\]. The first photometric studies of nonradial pulsations were performed on \(D = [0.6; 0.9]\) m telescopes \[17\]. The studies of optical effects accompanying short-wavelength flares are performed on even smaller telescopes. Some of the effects discovered with large telescopes were then studied in detail with small instruments. Linear polarization, which was discovered in four stars in observations carried out on a \(D = 2.08\) m telescope \[18\] was studied in detail in 175 stars with a \(D = 1.02\) m telescope \[19\]. This study was then followed by a high-precision photometric survey of 841 stars carried out over 1.5 years \[20\].

There is also one argument that concerns just spectroscopy on small telescopes. The fraction of high- and medium-resolution spectroscopic studies will increase because of the ever increasing light pollution in observatories founded in the XIX–XX centuries. Moving (mostly photometric) small telescopes to sites located far from large cities and operating them there is impractical. Whereas in the 1960–1970s the European Southern Observatory (ESO) was to a considerable extent equipped with such telescopes, by the end of the century these instruments, which became viewed as intermediate and small, were decommissioned by the international organization and are now again operated at the expense of their national owners. Such telescopes can prove to be of use for spectroscopic studies.

**Psychological:**

There are productive experts in any field of science and they view their creative research as largely colored by individualism. However, technically sophisticated experiments on large telescopes are collective work. The availability of small telescopes to a certain degree solves the psychological problems of the researchers who by no means view the individual nature of the process of astronomical observations as a secondary factor.

For many observing astronomers the priority of performing their own (sometimes the first) observation of a given object (or phenomenon) is an important factor compared to a study based on archival data.

Small telescopes are better suited for educational purposes. Here the major educational factor is the ability to influence the observing process (there are a lot of remotely controlled training telescopes). Small telescope do not develop separately from large telescopes because the progress in the use of small telescopes is entirely due to the progress in signal detection and the emergence of fundamentally novel optical methods. New technologies first appeared on large telescopes, although there are quite a few exceptions. What was considered large telescopes just fifty years ago are now viewed as moderate-diameter instruments. We will therefore consider the problem of the equipment of small
telescopes also in from historical perspective. There is a huge body of literature on the subject. Our aim was not to provide a full review, we limit ourselves to outlining the examples, which we considered to be either typical or of additional interest for us. We group the kinds of equipment and methods by the type of detectors employed, and within the same detector type, by the specificities of design solutions.

2 Spectrographs with photographic registration

Most of the technical solutions in the design of stellar spectrographs date back to the epoch of photographic registration of spectra. Some spectrographs were later reequipped with detectors of a new type. Moreover, some of the well-proven classical schemes can be revisited with increasing CCD format.

2.1 Prismatic spectrographs

The advantages of prismatic schemes include the concentration of the spectrum within a single strip, and its drawbacks, the temperature dependence of the acquired spectrum (which is stronger than in the case of diffraction spectrographs). Restricting factors also include the size of the glass block with high homogeneity and uniformity requirements to be met within its volume.

2.1.1 Slitless prismatic spectrographs

The role of the focal ratio of the spectrograph lens was demonstrated already during the establishment the Harvard classification: observations with the Bache telescope ($D = 0.2$ m, $1 : 5.6$) equipped with an objective prism (or a set of prisms) made it possible to acquire stellar spectra that were beyond the reach of slit prismatic spectrographs used with much larger telescopes with smaller focal ratios.

To classify spectra by their fragments near the Balmer limit, hot stars were observed on Jungfraujoch observatory (Switzerland) located at an altitude of 3457 m. A camera ($D = 0.4$ m, $1 : 1.5$) with a quartz objective prism was employed and the spectra were broadened via artificially produced astigmatism (the lens was inclined by $8^\circ$ with respect to the rear plane of Cornu prism).

The invention of Schmidt camera opened up, in particular, the possibility to photographically record spectra of extended objects. A two-prism nebular spectrograph with a Schmidt camera was attached to the lower part of the Yerkes refractor, whereas the entrance slit was placed in the upper part so that the telescope ($D = 1.03$ m) served both as a guide and support structure for the nebular spectrograph whose field of view was determined by the diameter of the Schmidt camera and the length of the refractor tube. This experiment was further developed in the design of the nebular spectrograph of McDonald Observatory, where terrain configuration made it possible to position the entrance “slit” far from the prismatic dispersing unit at a distance much greater than the length of the Yerkes refractor length. The idea of taking advantage of the terrain configuration was also implemented in the scheme of the nebular spectrograph of Crimea Astrophysical Observatory designed by D. D. Maksutov and B. K. Ioannisiani and installed at a mountainside near Simeiz (see Pikelnner). The main parts of the spectrograph were a meniscus camera ($D = 0.15$ m, $1 : 1$) and two flint glass prisms. Note that in the above design solutions spectra of stars located in the field of view of the nebular spectrograph were below the photographic registration threshold.
A slitless quartz spectrograph was used for spectrophotometry of hot stars near the Balmer discontinuity \cite{26}. An afocal $D = 0.25$ m telescope was used to do without expensive objective prism. The quartz spectrograph provided a reciprocal linear dispersion of $P = 150$ Å/mm near the H$\gamma$ line, and the spectrum of a $m_V = 7$th star could be acquired in a one-hour long exposure. The study investigated OB-stars in the CepII association.

The main shortcoming of prismatic slitless spectra is the lack of a comparison spectrum. An attempt to address the problem was undertaken long ago by Pickering \cite{27}, who proposed reversal of the objective prism. However, a comparison of two mutually reversed spectra does not yield pure Doppler shift because: (a) in the case of prism reversal the centers of the direct and reversed exposures have different declinations (the centers should coincide to within better than 0"05) and (b) prism distortion produces an extra shift of lines, which in the case of a two-degree field of view results in errors as large as several thousand km s$^{-1}$. The former problem restricts the application of the method to measuring relative radial velocities, and the latter was overcome by Fehrenbach \cite{28}. Fehrenbach prism is a plane-parallel plate consisting of two prisms made of different kinds of glass. The prisms have different dispersions but identical refractive indices for a certain wavelength. Between two consecutive exposures taken with the same plate the prism is reversed by 180° about the telescope axis and slightly shifted in right ascension.

Observations on the GPO astrograph with $2 \times 30$ min exposures yielded radial velocities $V_r$ with errors between 4 and 9 km s$^{-1}$ for stars brighter than 9.7. A comparison with slit spectroscopy on a $D = 0.9$ m reflector showed the GPO to be five times more efficient in per star terms if the differences in the aperture are taken into account. There were a total of 35 program stars inside the field of view of the telescope and therefore the total gain of GPO was a factor of 150–200 compared to slit spectrography on a telescope of the same aperture provided the same, albeit rather low requirements in terms of the precision of $V_r$.

The average error of the Fehrenbach and Burnage \cite{31} catalog based on OHP observations is 4.2 km s$^{-1}$.

### 2.1.2 Prismatic slit spectrographs

Because of mechanical and temperature deformations prismatic spectrographs with high reciprocal linear dispersion $P$ have not become popular instruments for tasks involving Doppler measurements. Low $P$ ranging from 130 to 40 Å/mm were used for spectral classification. The foundations of two-dimensional MKK spectral classification \cite{32} were established based on observations made with Yerkes refractor ($D = 1.03$ m) equipped with a single-prism spectrograph (its slit-width factor is equal to 7) designed by G. Van Biesbroeck. The spectrograph recorded the wavelength interval 3920–4900 Å, with $P = 120$ Å/mm at H$\gamma$.

By mid-XX century prismatic slit spectrographs on telescopes with aperture diameters $D < 1$ m were used only in three cases. On Lick Observatory a three-prism spectrograph \cite{33} was used on the refractor ($D = 0.91$ m) and a two-prism spectrograph \cite{34}, on the Crossley reflector ($D = 0.91$ m). First, a single-prism spectrograph and then, since 1927, a Curtis spectrograph (collimator focal distance 1 : 18, $F_{\text{coll}} = 68$ cm, two 60-degree flint-glass prisms, interchangeable cameras with focal distances $F_{\text{cam}} = 7.5, 15, 30$, and 60 cm and a set of reciprocal linear dispersions $P = 140, 76, 38$, and 19 Å/mm, respectively, were used on the reflector ($D = 0.94$ m) of Ann Arbor Observatory (in the outskirts of Detroit). The spectrograph had been operated for more than 30 years. These spectrographs were also used
mostly for two-dimensional spectral classification [32, 35].

Simeiz reflector \((D = 1.0 \text{ m})\) was equipped with a single-prism spectrograph with an \(F_{\text{cam}} = 55 \text{ cm}\) camera (its wavelength range spanned from 3600 Å to H\(\alpha\), \(P = 36 \text{ Å/mm}\) at H\(\gamma\)) mounted in accordance with the scheme “folded Cassegrain” scheme with a plane diagonal mirror \((1 : 18.6)\) [36]. The prismatic spectrograph based on V. A. Albitzky’s design and used with the \(D = 1.22 \text{ m}\) reflector [37] had a collimator focal distance of \(F_{\text{coll}} = 99.5 \text{ cm}\) with a collimated-beam diameter of \(d = 5 \text{ cm}\), a 66°6 flint-glass prism, and three interchangeable lenses \((1 : 4, 1 : 8, 1 : 12)\) with the focal distances of \(F_{\text{cam}} = 23, 48,\) and 72 cm, respectively. These lenses provided the dispersion of \(P = 72, 36,\) and 23 Å/mm, respectively (at the H\(\gamma\) line). The two-prism quartz spectrograph, which was also used on the \(D = 1.22 \text{ m}\) telescope of Crimean Astrophysical Observatory, had the collimator focal distance of \(F_{\text{coll}} = 80 \text{ cm}\) with the collimated-beam diameter of \(d = 4 \text{ cm}\), and the camera focal distance of \(F_{\text{cam}} = 20 \text{ cm}\) \((1 : 4)\). The optics of the camera allowed the spectrograph to operate in the 3400–4300 Å wavelength interval with a dispersion of \(P = [65; 162] \text{ Å/mm}\), respectively.

A single- and four-prism spectrographs were used in the Newton focus of the telescope \((D = 1.2 \text{ m})\) of Saint-Michel Observatory. A total of more than 4500 spectra including 148 spectra of Be stars were acquired over 30 years since 1944 on the single-prism spectrograph \((F_{\text{coll}} = 400 \text{ mm}, d_{\text{coll}} = 70 \text{ mm}, F_{\text{cam}} = 215 \text{ mm})\) [38].

The spectral classification of hot stars by the fragment of the spectrum near the Balmer jump was based not only on spectra acquired with the prismatic camera [22], but also on spectra acquired with Chalonge’s two-prism slit quartz spectrograph [39], \(F_{\text{coll}} = 330 \text{ mm}\), and two Cornu prisms, \(F_{\text{cam}} = 118 \text{ mm}\). Spectroscopic observations on \(D = 0.25\) and 0.8 m telescopes recorded the wavelength interval from 3100 Å to H\(\alpha\). Nonstandard motion of the cassette was used to broaden spectra to 0.35 mm at 3100 Å and 1.5 mm near H\(\alpha\).

2.2 Diffraction spectrographs

Diffraction spectrographs became competitive after the development of ruled gratings with profiled grooves [40]. Further improvement of ruling machines [41, 42, 43] and manufacturing technologies for diffraction gratings [44], as well as the introduction of holographic techniques made it possible to efficiently use slit and slitless schemes for diffraction systems. Profiling the grooves of diffraction gratings increased substantially the angular dispersion of spectrographs with the size of the dispersing element remaining the same.

2.2.1 Slitless diffraction spectrographs

Epstein [45] proposed to combine a reflective Schmidt corrector plate with a diffraction grating \((D = 0.15 \text{ m}, F = 61 \text{ cm}, P = 150 \text{ Å/mm})\). This idea was further developed in the optical layouts of fast anastigmats [46] and slit spectrographs [47, 48] attached to telescopes of various diameters including instruments with \(D = 1.0\) and 1.2 m [49].

Hoag and Schroeder [50] used a transparent diffraction grating in the converging beam on the Kitt Peak Observatory reflector \((D = 1.0 \text{ m}, 1 : 7.5)\). In that case images of other spectral orders are located along a circle whose radius is equal to the distance from the grating to zero-order image. A 150 grooves/mm grating placed 5.1 sm from the focus provided a dispersion of 1260 Å/mm, with a working field of view having a 30’ size. A half-hour exposure allowed registering the spectra of objects as faint as \(m_B = 16''8\).

Linnik [51] proposed a solution to the problem of simultaneous acquisition of the standard and stellar spectra with a slitless spectrograph. A small part of the collimated beam passes through the plate that forms Talbot’s interference fringes located in the focal plane of the lens.
next to the spectrum of the star. The diffraction grating with a fixed diffraction angle has a reflecting prism mounted on it with a small angle deviating a small part of the collimated beam (without diffraction) to the camera field of view, where this undispersed radiation is deflected to the guide optics. Guiding is performed by rapidly moving the first lens of the collimator across its primary axis.

2.2.2 Slit diffraction spectrographs

The main advantage of slitless spectroscopy — the capability to simultaneously record several objects — goes along with a number of shortcomings with the most important being the influence of sky background and dependence of resolution of seeing and guiding quality. Therefore the main efforts were channeled to improve slit diffraction spectrographs.

The spectrograph of the first KPNO telescope ($D = 0.91$ m) was used for spectral classification [52]. A spectrograph with a “folded Schmidt” camera (1 : 2) [53] was designed for the $D = 0.91$ m telescope of Steward Observatory. It was equipped with a set of interchangeable gratings, which provided a $P = [22:800]$ Å/mm set of reciprocal linear dispersion values. A combination of a diffraction grating with a Schmidt camera changed the appearance of a slit spectrograph. The pursuance of universal capabilities gave rise to the development a set of photographic cameras often equipped with interchangeable diffraction gratings incorporated into a single structure. This resulted in the increase of the size and mass of equipment and that is why such devices were used on $D \geq 1.5$ m telescopes. As an example of such a solution we can mention the three-camera Cassegrain spectrograph of the Mount Wilson Observatory telescope ($D = 1.5$ m) equipped with three interchangeable gratings [54].

The focus of the $D = 1.2$ m Newton telescope of Saint Michel Observatory had three separate adapters, which allowed simultaneous observations to be performed using three techniques. One of the techniques was represented by diffraction spectrograph “E” [55] equipped with interchangeable 300 and 600 grooves/mm gratings and a $f/2.4$ ($P = 275$ Å/mm) dioptric camera. The spectrograph was also used with an image tube. Since 1959 the telescope has been equipped with “E’ spectrograph” [56] manufactured by REOSC and meant for operating in the near IR ($P = 230$ Å/mm, I-N) emulsion. The “E” spectrograph was refitted with gratings and camera (“semi-solid Schmidt camera”, $f/0.47$, $P = 290$ Å/mm and $f/2.5$, $P = 64$ Å/mm).

The large prismatic “glass” spectrograph of the $D = 1.22$ m reflector of Crimean Astrophysical Observatory was in 1961 replaced by the first domestic-made ASP-11 diffraction spectrograph. The spectrograph was equipped with two interchangeable diffraction gratings, making it possible to acquire spectra in two orders: in the 4800–6700 Å wavelength interval with a dispersion of 37 Å/mm in the first order and in the 3600–4800 Å wavelength interval with a dispersion of 15 Å/mm in the second order [55]. As a result of such replacement the accuracy of radial-velocity measurement degraded [56]. When operating in the near IR the spectrograph was equipped with a 300 grooves/mm grating and an FKT-1A image tube [57].

Mass instruments of the photographic epoch included Boller & Chivens (B&C) and Karl Zeiss Jena spectrographs operated in the Cassegrain focus. The B&C spectrograph has a collimated beam diameter $d = 9$ cm, interchangeable 102 × 128 mm$^2$ gratings, and a semi-solid Bowen-Schmidt-Cassegrain camera ($F = 14$ cm) with $6 \times 25$ mm$^2$ unvignetted field. UAGS spectrograph has similar parameters of the external-focus ($F = 15$ cm), two Schmidt cameras with internal focus ($F = 11$ cm and $F = 17$ cm), but a smaller collimated-beam diameter ($d = 7.5$ cm) and more optical elements. These instruments serves as a basis for transition of moderate-resolution spectroscopy to photoelectric detectors. Spectroscopists in our country

[http://www.obs-hp.fr/histoire/120/spectro_E.shtml](http://www.obs-hp.fr/histoire/120/spectro_E.shtml)  
[http://www.obs-hp.fr/histoire/120/spectro_Eprime.shtml](http://www.obs-hp.fr/histoire/120/spectro_Eprime.shtml)
Table 1: Some of the small- and medium-diameter telescopes used for spectroscopy and coudé spectroscopy

| Year | $D$, m | $D : F$ | Observatory            |
|------|--------|---------|-------------------------|
| 1922 | 0.91   | 1:36    | Steward                 |
| 1955 | 0.91   | 1:30    | Cambridge               |
| 1963 | 0.91   | 1:37    | KPNO coudé feed         |
| 1969 | 0.6    | 1:36    | Lick CAT                |
| 1970 | 1.0    |         | Canopus Hill            |
| 1970 | 0.61   | 1:28    | Fick, Iowa              |
| 1971 | 0.4    | 1:33    | Canopus Hill            |
| 1971 | 1.06   | 1:49    | Lowell                  |
| 1981 | 1.4    | 1:120   | ESO CAT                 |
| 1982 | 0.5    | 1:13    | Crimean AO              |
| 1990 | 1.0    | 1:36    | SAO RAS*                |

* – The effective diameter of the telescope was $D < 1.0$ m because of design errors in the coudé path optics.

used UAGS universal slit spectrograph commercially produced by Karl Zeiss Jena. In particular, the spectroscopy technique involving the use of image tube was tested on the $D = 0.6$ m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences and then used on the 6-m telescope as the main method for the study of galaxies. UAGS set up for photographic registration was used on the same telescope to monitor emission- and absorption-line spectra of Mira variables. Based on the results of observations on a $D = 0.6$ m telescope equipped with UAGS spectrograph ($P = 28$ Å/mm) Gulyaev et. al developed a system of Balmer-line indices tied to stellar model atmospheres.

Richardson and Brealey developed a small-sized photographic spectrograph with an off-axis camera and collimator for the Nasmyth focus of the $D = 0.9$ m reflector. This instrument was later equipped with a Reticon detector.

### 2.2.3 Diffraction spectrographs for coudé focus

Before the introduction of echelle spectrographs operating at high diffraction orders the primary way to increase the spectral resolution was to increase the focal distance of the spectrograph camera. Therefore the static coudé focus, which was introduced as early as XIX century for visual observations (Paris Observatory, 1882, the $D = 0.27$ m refractor), was also used in the XX century on small- and medium-diameter telescopes (Table 1). The parameters of the telescopes can be found in our earlier review.

### 2.2.4 Diffraction-based cross-dispersion slit spectrographs

The development of the technology of stepped-groove gratings made it possible to concentrate the flux within a narrow interval of diffraction angles. In the 1960s two-mirror schemes with coma compensation across a sufficiently large field of view of the camera were developed to operate in high diffraction orders. The parameters of the collimator should not have differed to much from those of the camera and therefore these solutions proved to be optimal just for small telescopes, where small slit width factor was quite acceptable. In the next 10 years the spectrographs listed in Table 2 were put into operation.
For over 20 years, until the beginning of the “fiber-optics era”, echelle spectrographs were used for stellar spectroscopy on small telescopes. This was because of the gain of spectral resolution, which is proportional to the tangent of the blaze angle, making it possible to achieve high and moderate spectral resolution using rather compact suspended systems. The development of these systems was hampered by problems with digitizing of photographic echelle spectra with microdensitometers (the use of a prism as a cross-dispersion element resulted in the curvature of spectral orders) and bright limiting magnitude (spectra of stars brighter than sixth magnitude were recorded). Some of the echelle spectrographs were later used with image tubes.

3 Spectrometers with single-channel photoelectric registration

Single and two-channel spectrometers have been the main detectors of small telescopes for about thirty years.

3.1 Slitless scanner with an objective prism

For spectrophotometric observations in the near IR a catadioptric telescope based on a design by P. P. Argunov \((D = 0.43 \text{ m}, 1 : 10)\) [76] was used with a four-degree objective prism and RCA-7102 photomultiplier. Dispersion was directed along declination and the spectra were scanned (4000–10 000 Å in 10 minutes) with a reversible motor [77].

3.2 Prismatic scanner on an afocal telescope

ASI-5 afocal Mersenne telescope \((D = 0.25 \text{ m})\) was used for photoelectric scanning of stellar spectra [78]. A parallel beam formed after the reflection from the parabolic secondary convex mirror of the telescope hit a 30-degree Littrow prism, and the dispersed beams were then

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Table 2: Cross-dispersion spectrographs in the Cassegrain focus

| Year | \(D, \text{ m}\) | \(d, \text{ cm}\) | \(\tan \theta_b\) | disp | \(R\) | Observatory |
|------|----------------|----------------|-----------------|------|------|-------------|
| 1971 | 0.9            | 5.5            | 2               | ech/gr | 16000 | Pine Bluff Obs. [69] |
| 1976 | 0.91           | 5              | 2               | pr/ech | 40000 | Goddard SFC [70] |
| 1977 | 0.61           | 9              | 2               | ech/gr | 43000 | Mt. John Obs. [71] |
| 1978 | 0.9            |                | 2               | pr/ech/pr | 40000 | Royal Greenwich [72] |
| 1978 | 1.0            | *              | 2               | ech/gr | 52000 | Ritter Obs. [73] |
| 1980 | 1.0            | *              | 2               | ech/gr | 52000 | Lowell Obs. [73] |
| 1980 | 1.0            |                | 2               | ech/gr | 30000 | Siding Spring Obs. |
| 1981 | 1.0            | 7.7            | 2               | ech/gr | 54000 | Vienna Obs. [74] |
| 1982 | 0.61           | *              | 2               | ech/gr |        | Las Campanas [73] |
| 1982 | 0.61           | 5              | 3.2             | filt/ech | 150000 | Whipple Obs. [75] |
| 1986 | 1.22           |                | 2               | ech/gr | 50000 | Rangapaur Obs. |

Designations: disp – sequence of dispersing elements along the ray path, ech – echelle, gr – grating, pr – prism, filt – filter; \(R\) – spectral resolution, \(D\) – diameter of the mirror, \(d\) – diameter of the collimated beam. * – copies of Harvard College Observatory spectrograph, used on the \(D = 1.52 \text{ m}\) telescope.
caught by a concave mirror, which provided a dispersion of 200 Å/mm at Hγ. The spectrum was scanned by turning the prism, and the 14 Å-wide measured spectral portion passed through the slit with a photoelectric photometer. The signal detection and scanner control system included 17 radio lamps. The device was highly efficient in the UV and allowed acquiring spectra of stars down to the seventh magnitude [79].

3.3 Scanning monochromators

To change the spectral resolution on a photographic spectrograph one has to change the focal distance of the camera. Jacquinot and Dufor [80] showed that spectral resolution achieved on monochromators depends on the slit width, i.e., monochromators are more flexible spectroscopic devices compared to photographic spectrographs. The main shortcoming of scanning monochromators is that seeing and transparency fluctuations at the spectrometer entrance show up in the details of the spectra. Hiltner and Code [81] proposed a method for compensating fluctuations by comparison with the signal from the reference channel, which records the fraction of the flux that passed through the entrance slit.

3.3.1 Prismatic slitless monochromators

A system for compensating fluctuations of the illumination of the entrance slit was used in the two-prism monochromator mounted on the $D = 1.2$ m reflector [82]. To achieve maximum resolution (0.5 Å) the slit width had to be reduced to 25 µm, whereas the size of the stellar image and the amplitude of image tremor were much greater. At the time, a complex system for fluctuation compensation was used: the photoelectric multiplier of the second channel recorded undispersed light reflected from the first face of the prism.

3.3.2 Scanners with a flat diffraction grating

Boyce et.al. [83] developed a scanner for coudé focus of the $D = 1.06$ m telescope of Lowell Observatory. The collimator used had a focal distance of $F_{coll} = 610$ cm, collimated-beam diameter $d = 12.7$ cm, 1200 grooves/mm grating, camera focal distance $F_{cam} = 305$ cm, reciprocal linear dispersion 2.67 Å/mm at 5000 Å, and a scanning step of 0.078 Å or more. The device was used to study axial rotation velocities of bright stars.

The scanner of the $D = 0.61$ m telescope of Bochum University is a good example of a device that was used efficiently to measure spectral energy distributions in stars of various types. In 1968 the telescope was moved to the European Southern Observatory where it was used to establish spectrophotometric standards for the Southern sky. The single-channel instrument was made according to the Czerny–Turner scheme, and scanning of the spectrum was achieved by moving the grating [84].

3.3.3 Scanners with a concave grating

Liller [85] showed that the transmission of a monocromator with a concave grating increases by a factor of three compared to a monochromator with a flat grating. The most popular among various monochromator schemes with concave gratings became the one proposed by Namioka [86], where the angle between the lines connecting the grating center and the slits, as well as the distance between the grating and the slits remain unchanged. The most productive spectrophotometer proved to be the device based on this scheme and made for the $D = 0.5$ m reflector [87]; with this device spectrophotometry of stars down to the seventh magnitude could be performed [88]. For observations on a $D = 0.37$ m telescope Beavers and
Eitter \cite{89} used a 1200 grooves/mm concave (1 : 4) holographic grating providing a reciprocal dispersion of 40 Å/mm.

### 3.4 Narrow-band spectrophotometers

The most obvious method for line spectrophotometry is to switch a system of slits centered on the measured line (group of lines) and onto the neighboring fragments of the continuum. Gustaffson and Nissen \cite{90} used an echelle spectrograph providing high dispersion ($P = 2$ Å/mm). In their program of the study of helium content \cite{91} used a 14 Å-wide slit centered onto the 4026 Å line and two 6 Å-wide slits serving to measure the continuum flux on both sides of the helium line. With up to 100000 counts per half-hour 10th magnitude stars could be observed on the 1-m telescope of European Southern Observatory \cite{92}. In the Northern Hemisphere the spectrophotometer was operated on the OHP telescope ($D = 1.93$ m).

The photomultiplier sizes made it impossible to use multichannel systems, which had proved to be a good choice for large (Oke \cite{93}, Rodgers et. al. \cite{94}, etc.) and moderate-diameter telescopes. The introduction of miniature photoelectric multipliers and optical-fiber technology allowed solving this problem \cite{95}. The object, comparison star, and sky background are projected simultaneously onto the three 400-micron entrance fibers of the multichannel spectrophotometer. The offset guide allows objects as faint as $16^m$ to be observed with a 1-m telescope. Optical fibers feed three identical prismatic spectrographs. The spectrum produced by each of the three spectrographs is projected onto the faces of 15 optical fibers whose output ends are connected to Peltier-cooled miniature photoelectric multipliers.

### 3.5 Correlation spectrometers

Griffin \cite{14}, whose used the coudé focus of the $D = 0.91$ m telescope, was the first to practically demonstrate the efficiency of cross-correlation technique for measuring radial velocities. Griffin’s technique of radial-velocity measurements on small telescopes gave a three orders of magnitude gain compared to the photographic method \cite{96}. A description of the $D = 0.61$ m telescope of Fick Observatory dedicated for radial-velocity measurements can be found in Beavers and Eitter \cite{97}. A mirror with a diameter of $d = 41$ cm and a focal distance of $F = 305$ cm, which serves as a collimator and a camera, is mounted in the cylindrical camera of the coudé focus. The 1200 grooves/mm diffraction grating (with maximum concentration at 5000 Å and the size of the $135 \times 110$ mm$^2$ line area has its lines oriented parallel to the North–South direction. The reciprocal linear dispersion is 2.62 Å/mm, and the slit mask covers a wavelength 400 Å wavelength interval centered on 4600 Å. The 0.09 mm entrance slit corresponds to an image size of 1″ and resolution of 15 km s$^{-1}$ on the mask. The cylinder where the spectrometer is mounted must have its air pumped out. Wavelength calibration is based on the lines of the spectrum of a helium-neon laser.

Practically at the same time the first cross-correlation spectrometer with echelle — CORAVEL — was developed \cite{98}. The first such device operated since 1977 at the $D = 1.0$ m Swiss telescope of Observatoire de Haute Provence (OHP) \cite{99}. It allowed determining the radial velocity of a $m_B = 11^m$ K-type star with a standard deviation of 0.7 km s$^{-1}$ in 10 independent 0.5-min exposure measurements. The second CORAVEL device was since 1981 used at the $D = 1.54$ m Danish telescope of European Southern Observatory. Because of its compact size of the device ($F_{\text{cam}} = 57$ cm) the device was quite rigid and convenient to use in the Cassegrain focus. The 0.5 km s$^{-1}$ accuracy of radial-velocity measurements was achieved for $m_B < 15^m$ stars \cite{100}.  

An efficient photoelectric radial-velocity meter based on a coudé spectrograph \cite{5} was developed for the $D = 1.2$ m telescope of DAO \cite{15}. Its parameters are: a $F_{\text{coll}} = 757$ cm (1 : 30) collimator, mosaic 831 grooves/mm diffraction grating, $F_{\text{cam}} = 244$ cm camera, reciprocal linear dispersion $P = 2.4$ Å/mm, 0.08 mm slit projection width, a mask moved by a step motor, and a (1 : 1) plastic Fabry lens mounted in front of the photoelectric multiplier. With 10 counts per second made for a $m_B = 16$ star the final accuracy was better than 1 km s$^{-1}$.

It is interesting that the cross-correlation technique was also used to study dust particles in the F corona \cite{101}. A commercially produced Ebert monochromator (1 : 3.5) was equipped with a slit mask reproducing the locations of the specially chosen lines in the solar spectrum in the 4005–4352 Å wavelength interval. A $D = 0.15$ m (1 : 5) parabolic mirror combined with a flat coelostat mirror was used as feeding optics.

The small spectrograph mentioned above and designed for photographic observations \cite{62} was reequipped into the cross-correlation spectrometer of the $D = 0.4$ m DAO telescope. A special prism was mounted behind the slit and a mask (300 lines in the 415–485 nm wavelength interval) based on the spectrum of a K-type giant was installed in the focal plane of the camera. The accuracy of radial-velocity measurements (2 km s$^{-1}$) was limited by the insufficient rigidity of the small device.

Domestic correlation radial-velocity meter \cite{102}, which has been used with $D = 0.6, 0.7, 1.0, \text{ and } 1.25$ m telescopes since 1984 is currently one of the most long-lived devices based on this method.

### 3.6 Spectrum coding systems

The development of spectrum coding devices was sort of a crowning moment in the history of single-channel photoelectric systems. The method of spectrum coding consists in the registration by a single-channel detector of a sequence of signals produced as a result of the passage of light through a successfully changed slit masks. The sequence of slits and nontransparent parts of the mask, as well as the sequence of the replacement of such masks, can be made according to a certain pattern to make the digital processing of the set of signals a sufficiently simple process. For example, the replaced slits of the mask can be arranged in accordance with the algorithm of the construction of strings in the Hadamard matrix \cite{103}. The interest in experiments with Hadamard spectrometers is easy to explain: they offer the same multiplex gain as a Fourier spectrometer (i.e., the $S/N$ is proportional to the square root of the number of discrete elements of the spectrum), whereas the technology is much simpler: a diffraction spectrograph with mechanically changed masks is used. In the case of extended objects a combination of coding masks at the entrance to and exit from the spectrometer can be used \cite{104}. An Hadamard spectrometer allowing simultaneous acquisition of 15 IR spectra each consisting of 255 elements \cite{105} was used to study the latitudinal distribution of methane across the disk of Jupiter.

### 4 Spectrographs with multichannel photoelectric detection

The introduction of multichannel detectors into astronomical spectroscopy made it possible: (a) to extend the observed wavelength range; (b) to increase the spectral resolution, and (c) to gradually increase the photometric accuracy. Practically all types of multichannel detection came to be used on telescopes of diameters considered.
4.1 Spectrographs with image tubes

Most of the spectrographs with photographic registration whose design allowed the use of lens cameras or Schmidt–Cassegrain cameras served as a basis for testing observational techniques involving the use of image tubes with subsequent photographic registration. For example, the UAGS spectrograph equipped with an image tube \[58\], which was developed for the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences, was first tested on the \(D = 0.6\) m telescope. The use of an image tube with optical transfer to a photographic plate yielded no strong gain in terms of the “limiting magnitude for the given \(S/N\)”, and that is why at first the main reason for the use of an image tube was to explore the near IR part of the spectrum, which was inaccessible for direct photographic observations. For example, Wood \[106\] used the Cassegrain spectrograph of the \(D = 0.81\) m reflector to acquire Zeeman spectra of bright stars in the IR. Autocorrelation technique was adapted to search for lines that are asymmetric because of the Zeeman or other effects. Esipov \[107\] designed an efficient instrument of this kind. The spectrograph kit included lens cameras corrected for operating in the IR and providing the dispersions of 90 and 200˚A/mm with a 600 grooves/mm grating in the first order. The device was tested on the \(D = 0.33\) m reflector. The very first Cassegrain echelle spectrograph \[69\] was used on the \(D = 0.91\) m telescope including observations with an image tube.

4.2 Spectrographs with electronographic cameras

The first experiments with an electronographic camera \[108\] were carried out on “E” spectrograph in the Newton focus of the \(D = 1.2\) m telescope of Saint-Michel Observatory. Because electronographic cameras are difficult to operate in suspended arrangements (Newton and Cassegrain foci), the most efficient camera for spectroscopy on medium-diameter telescopes proved to be the one mounted in the coudé focus of the \(D = 1.52\) m telescope of European Southern Observatory. “ECHEL.E.C.” (echelle spectrograph with an electron camera) — the first universal white-pupil spectrograph — was mounted there in the early 1970s \[109\]. It had a Lallemand–Duchesne electron camera with electrostatic focusing and 30-mm S-11-type photocathode as a detector. When operating in the “echelle” mode it provides a dispersion of 4.5˚A/mm in the blue part of the spectrum. A spectrum of a \(m_B = 10^\text{th}\) star broadened to 0.2 mm was acquired in a 2.5-hour long exposure. When operated in the single-order mode with a dispersion of 74˚A/mm, the device achieved a limiting magnitude of \(m_B = 14^\text{m}\) in one-hour exposure \[110\]. Electronographic spectroscopy technique proved to be quite complex and that is why the spectrograph also used photographic registration including registration via an image tube. The white-pupil scheme was also used in the design of a nebular spectrograph with an image tube \[111\].

4.3 Spectrographs with dissectors

In the early 1970s an image dissector scanner (IDS) was used on the \(D = 1.0\) m telescope of Lick Observatory. It consisted of a three-stage image tube (with a 40-mm diameter S-20 photocathode), with a dissector scanning the spectrum during the phosphorus afterglow placed behind the third stage. Thus the phosphorescent screen was used as an intermediate memory device. The spectrograph had two apertures with the second one used for registration of the sky background. Aperture switching was used to more accurately take the sky background into account. The peak quantum efficiency of a dissector with 350 resolution elements was 20%. A shortcoming of dissector is the long afterglow of luminophor in the case of overillumination. In observations of the peculiar object SS 433 an IDS was used that mounted on
telescopes of various diameters including the \( D = 0.6 \) m reflector of Lick Observatory \[112\]. McNall et. al. \[113\] equipped echelle spectrograph \[69\] of the \( D = 0.91 \) m with an image tube with a dissector. The device registered 256 resolution elements in one of the orders of the echelle spectrum. However, the dissector was not a photon counter.

### 4.4 Spectrographs with diode arrays

The spectrograph of the \( D = 0.9 \) m telescope of Kitt Peak Observatory, which was operated since early 1980s, is a good example of an intensified Reticon scanner (IRS). The dissector after the image tube was replaced by two 820-element Reticon arrays. Readout was performed every 10 seconds and each image contained noise making up for four events per element. The accuracy of radial-velocity measurements on such a device was 3–5 km s\(^{-1}\).

A spectrograph for spectral classification in the near IR was designed for the \( D = 0.91 \) m, 1 : 10 telescope of MIRA observatory (\( h = 1520 \) m above sea level) \[114\]. This Cassegrain-focus spectrograph (\( F_{\text{coll}} = 380 \) mm, 600 grooves/mm grating, \( \lambda_{\text{max}} = 8400 \) Å, replaceable cameras with \( F_{\text{cam}} \) ranging from 55 to 600 mm) was used with a Reticon array whose high readout noise (no more than 1000 e\(^-\)) is not critical for spectrophotometry mode (\( 2 \times 10^7 \) e\(^-\) per diode).

### 4.5 Spectrographs with photon counters

Schechtman and Hiltner \[115\] described a multichannel spectrograph with a photon counter. The system includes two three-cascade image tubes connected by a fiber disk with optical transfer to the diode array. With a \( D = 1.3 \) m telescope one count per second per Angstrom was obtained for a \( m_V = 13 \) object. The “schectography” technique evolved into the 2D-Frutti system \[116\]. The device was developed for the \( D = 4.0 \) m CTIO telescope and then the same design was reproduced for a \( D = 1.0 \) m, 1 : 10 telescope with a Boller & Chivens spectrograph. It was a two-cascade image tube with a 40-mm S-20 cathode connected via optical transfer line to an electrostatically focused 40-mm image tube, which, in turn, was connected with a microchannel-plate image amplifier via a fiber disk. The image is then transferred to the CCD via a scale fiber transformer (phocton). The output \( 35 \times 28 \) mm\(^2\) output field of the spectrograph is then produced on the 11.3 \( \times 8.8 \) mm\(^2\) CCD. The total CCD readout time is 7 ms, however, one can read just a part of the CCD field. The total slit length, which has the size of 6'8, occupies only 32 rows on the CCD. Repeated event counts are struggled against at the stage of comparison with the preceding frame. Event coordinates are determined to within 1/8 of the pixel size. One thus obtains a 3040 \( \times 256 \) pixel frame at the output. The device is characterized by nonlinearity at large fluxes (more than 9 counts per resolution element per second). On a \( D = 1.0 \) m telescope this corresponds to registering a \( m_V = 12 \) object with a resolution of 4 Å. This system was more expensive than CCDs manufactured in the early 1980s. The photon counter developed by Mochnacki et. al. \[117\] for the \( D = 1.9 \) m telescope of DDO was tested on a \( D = 1.0 \) m telescope. Observations with a reciprocal linear dispersion of 16 Å/mm provided a radial-velocity measurement accuracy of 1 km s\(^{-1}\) for stars down to a limiting magnitude of \( m_V = 15 \). Thus the most complex systems of the registration of spectra successfully operated on meter-class telescopes.

### 4.6 Spectrographs with linear and 2D CCDs

Reticon-type arrays had noise that was one order of magnitude fainter than the noise of CCDs of the mid-1980ies and that is why successful use of linear arrays was associated with the possibility of acquiring long exposures. Efficient use of a Reticon in the coudé focus of
the 1.2-m telescope of the University of West Ontario (UWO) made it possible to develop techniques for identifying the broadening components (rotation, macro- and microturbulence) of absorption-line profiles \[118, 119\]. A 316 grooves/mm R2-echelle was used with one of the orders \((m = [6; 15])\) separated via interference filters (with 85% transmission). The “folded Schmidt-type” camera \((F = 559 \text{ mm})\) provided a dispersion of 0.038 \(\text{Å/diode} \ (6250 \text{ Å, ninth order})\). With these parameters a one-hour exposure yielded \(S/N = 100\) for a sixth-magnitude star. Microscanning by shifting the detector unit position by half the width of the 15-micron diode before repeating the exposure was used to double the number of points on the spectral-line profile. Doubling the number of data points on the line profile formally facilitated the separation of broadening components in the Fourier domain. In such studies one has to take into account line broadening due to spectrograph flexibility. The coudé focus spectrograph of the UWO telescope \((D = 1.2 \text{ m})\) was known for its high stability (dome temperature variations did not exceed one degree per week). In the case of long exposures lines can also broaden because of the Earth’s diurnal rotation. For example, when a zero-declination star is observed from the equator diurnal rotation of the Earth broadens a line by 0.35 \(\text{km s}^{-1}\) near meridian, and the effect is stronger at other hour angles, whereas line broadening parameters have to be known to within 0.1 \(\text{km s}^{-1}\) in some cases \[120\].

Recall that the CES coudé echelle spectrograph of European Southern Observatory \[121\] was mostly used with the auxiliary \(D = 1.4 \text{ m}\) telescope \[122, 123\] of the coudé focus of the large \(D = 3.6 \text{ m}\) telescope. This spectrograph was used to perform many programs requiring high spectral resolution combined with low level of scattered light (as a result of preslit filtering and the use of the double-path system). The popularity of the device was also due to the fact that it allowed observations to be remote-controlled from Europe.

Furenlid \[124\] proposed a scheme of the telescope-spectrograph with only one optical element — a concave diffraction grating. Estimates showed that such a telescope with an equivalent diameter of \(D = 0.18 \text{ m}\), focal distance \(F = 3.3 \text{ m}\), line density 210 grooves/mm, and a dispersion of \(P = 14.3 \text{ Å/mm}\) provides spectra of a 10th-magnitude star to be acquired on a CCD with a signal-to-noise ratio \(S/N = 100\). The above authors pointed out, for comparison, that the limiting magnitude of the coudé-focus spectrograph with the same dispersion and \(S/N\) ratio operated on the \(D = 0.97 \text{ m}\) KPNO telescope has 1\text{m} brighter limiting magnitude. It goes without saying that a single-element spectrograph telescope retains all the shortcomings of slitless spectroscopy.

Further improvement of the CCD charge coupled device (CCD) technology substantially facilitated designing suspended spectrographs by reducing the lower limit for the diameters of spectroscopic telescopes. McDavid \[125\] developed a miniature \((0.3 \times 0.18 \times 0.13 \text{ m}^3)\) Cassegrain spectrometer for a \(D = 0.4 \ (1 : 12)\) telescope. Its detector consists of a 128-element CCD array (each element has the size of 13\(\times\)13 \(\mu\text{m}^2\)). The 60 mm diameter spherical mirror (with a focal distance of 200 mm) serves as both the camera and the collimator providing in the Littrow combination with a 600 grooves/mm grating (maximum concentration at 6500 Å, the size of the ruled domain 30\(\times\)30 mm\(^2\)) a reciprocal linear dispersion of 80 Å/mm. The single-pixel 13-\(\mu\) wide entrance slit corresponds to 0\(\text{\prime}\)5. The device is designed for spectroscopy in the H\(\alpha\) region; the main problem was to accurately center the star along the slit height. Denby et. al. \[126\] developed a compact spectrograph for a \(D = 0.6 \text{ m}\) telescope with the following parameters: a folded lenses collimator with \(F = 485 \text{ mm} \ (1 : 9)\), a 300 grooves/mm grating, an \(F = 85 \text{ mm} \ (1 : 2)\) camera with a dispersion of 4 Å per 13-micron pixel. The guide view is achieved through a \(F = 75 \text{ mm} \ (1 : 3.5)\) lens.

The main difficulty during the first years of working with 1-D and 2-D CCD arrays was due to the low transfer efficiency, which resulted in residual effects in sky background line subtraction. One of the methods used to address this problem was by preillumination of the detector surface, which increased the readout noise. In the case of low relative contribution
from readout noise the $S/N$ ratio is proportional to the square root of the number of counts, $\sqrt{n}$. Or, simply, the principal characteristic of the detector in the case of low and high $S/N$ is readout noise and quantum efficiency, respectively. To measure integrated colors of galaxies, Rakos et. al. [127] developed an ultra-low-resolution spectrophotometer (140 Å in the 3200–7600 Å interval. Two (“object” and “background”) focal lens reducers (1 : 15 to 1 : 2) feeding fiber bundles are mounted at the device entrance. The bundle outputs are located at the focus of the 108-mm diameter (1 : 2) 225 grooves/mm concave holographic grating providing a dispersion of 200 Å/mm. The spectrum is recorded by a CCD and the device is equipped with an offset guide. On $D = 1.1$ and 1.3 m telescopes the spectrum of a bright galaxy ($m_V = 12^m$) with a signal-to-noise ratio of up to $S/N = 10$ could be acquired in four 10-minute long exposures during full Moon.

Mass redshift measurement, which with the introduction of photon counters came to be used on moderate-diameter telescopes, was further supported by the construction of an efficient Cassegrain spectrograph of the 1.5-m telescope [128]. With a collimated beam diameter of 100 mm, a slit width of 1′′5, and a 300 grooves/mm grating the spectral resolution is 3 Å, and the simultaneously registered wavelength interval spans 4000 Å. The slit length is 3′, its efficiency 26%, and the number of spectra acquired in a year exceeded 10 000, i.e., the spectrograph replaced the famous Z machine [129] with a 1th gain in terms of limiting magnitude. The main shortcoming of suspended Cassegrain spectrographs is their mechanical flexibility, which in each particular case makes it difficult to construct a system of radial velocities measured with the given device. Munari and Lattanzi [130] studied flextures of two Cassegrain spectrographs of Asiago Observatory. Shifts were found that corresponded to an error of 10–40 km s$^{-1}$, whereas the error of cross-correlation technique was just 0.8 km s$^{-1}$.

A numerical model was constructed, which made it possible to improve the accuracy of radial-velocity measurements, with night-to-night errors reduced by one order of magnitude, i.e., down to 1–3 km s$^{-1}$.

ANS consortium developed three models of suspended spectrographs for $D = 0.61$ m, 0.70 m, and 0.84 m telescopes [131]. Two of these models (Mark II and Mark III) can be transformed into cross-dispersion devices without unmounting the spectrograph from the Cassegrain focus.

Panchuk et. al. [132] reported the development of a cross-dispersion spectrograph for 0.6–1.0 m-diameter telescopes. The two-pixel spectral resolution is $R \sim 40000$. The simultaneously recorded wavelength interval (350–800 nm) is determined by the spectral response curve of the detector and not by the format of the frame. There is complete overlap of neighboring spectral orders. A mirror collimator ($d_{\text{coll}} = 50$ mm) is used with a lens camera ($F_{\text{cam}} = 300$ mm, 1 : 3.5). The spectrograph slit width ratio is 2.2 with no magnification at the echelle ($\alpha = \beta$). The angular width of the normal slit matched to the resolution element is 1″6 and 1″ on 0.6 and 1.0 m telescopes, respectively. The mathematical apparatus for extracting one-dimensional spectra from two-dimensional echelle images used for the Nasmyth Echelle Spectrograph (NES) of the 6-telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences [133] was refined to be operated with a prism as the cross-dispersion element.

The low-resolution spectrograph ADAM developed for AZT-33IK telescope ($D = 1.6$ m) [134] underwent initial tests on the Zeiss-1000 ($D = 1$ m) telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences. A lens converter was used for matching with the 1-m mirror. When observed with 1′′5 wide slit $S/N = [6; 7]$ could be achieved for the spectrum of a $m_R = 20^m$ object with a 30-minute long exposure. Observations with a 1.6-m telescope produced spectra of such an object with a signal-to-noise ratio of $S/N = [10; 15]$. The spectrograph operates in the 3600–10 000 Å wavelength interval with a spectral resolution of 6–15 Å ($R = [1320; 270]$). As a dispersion element three volume-phased holographic
gratings (VPHG) are used, which are mounted on a turret: one 300 grooves/mm grating (for the entire working wavelength range) and two 600 grooves/mm gratings (3588–7251 Å and 6430–10 031 Å).

4.6.1 Single order fiber-fed spectrographs

The first successful experiment involving fiber matching of a spectrograph and a \( D = 0.91 \) m telescope \[135\] was carried out within the framework of FLOAT project (an array of telescopes connected with optical fibers \[136\]). To assess the efficiency of optical fiber matching on a \( D = 0.91 \) m telescope the same spectrograph with an image tube was used as in the Cassegrain focus of the \( D = 2.28 \) m telescope. Optical fiber was found to have appreciable loss in the ground-based ultraviolet. Furthermore, fiber matching was also shown to have advantages over the coudé focus where one has to maintain high reflectivity of the mirrors in the optical path.

Another solution of fiber-optics spectrographs operating in low diffraction orders worth noting is the Ebert-Fastie design and its Newton modification \[137, 138\] developed within the framework of the promising Multi-Telescope Telescope (MTT) concept. The primary focus of each of the nine mirrors \((D = 0.33 \) m) of such telescope \[139\] is connected to the spectrograph via a fiber. The effective aperture of MTT is equivalent to that of a telescope with a \( D = 1.3 \) m diameter mirror.

4.6.2 Fiber-fed echelle spectrographs

The increase of the accuracy of radial-velocity measurements is limited by the fundamental property of slit spectrographs. Because of atmospheric dispersion positions of monochromatic star images differ and the filling pattern of the collimator optics depends on the orientation of the telescope due of residual nonadjustments and mechanical flexures. Whereas the former problem can be solved by installing an atmospheric dispersion compensator, to address the latter, one has to feed the spectrograph input a flux with constant angular aperture, unchanging intensity distribution along the angle independent of seeing and object tracking accuracy. That is why the progress of fiber-optics technology has soon been put to use in astronomical spectroscopy. In the case of small telescope the possibility of mounting the spectrograph outside the telescope was of no small importance (the sizes of Cassegrain echelle spectrographs are comparable to those of the \( D \sim [0.5; 0.9] \) m telescopes).

One of the first attempts to achieve high position accuracy on a fiber-fed echelle spectrograph was the study of Kershaw and Hearnsheaw \[140\] who used a suspended echelle spectrograph \[11\] combined with the MacLellan telescope \((D = 1.0 \) m) of Mt John Observatory. The above authors used a liquid-nitrogen-cooled Reticon diode array and then a CCD as a detector. Cross-correlation techniques made it possible to achieve an accuracy of 50 m s\(^{-1}\) (with \( R \sim 35 000 \)) for \( m_V \leq 7 \) stars \[141\]. Long-term efforts of New Zealand spectroscopists culminated in the construction of the large HERCULES spectrograph \[142\]. The increase of the collimated-beam diameter from 45 to 210 mm, stabilization of conditions inside the spectrograph volume as a result of the use of highly efficient optical coatings combined with the use of efficient optical technologies made it possible to achieve an accuracy of \( \sigma_V = [4; 14] \) m s\(^{-1}\) with a peak efficiency of 18% under 1" seeing conditions on a \( D = 1 \) m telescope. The collimated beam overfills the echelle \((R2, 40 0 \times 200 \) mm), and a “folded Schmidt” type camera \((F_{\text{cam}} = 973 \) mm, \( D_{\text{cam}} = 525 \) mm) is used. The spectral resolution is determined by the fiber-and-slit combination \((R = 41 000, 70 000, 82 000)\).

In the Flash spectrograph \((d_{\text{coll}} = 80 \) mm) tested on the \( D = 0.75 \) m Heidelberg telescope the echelle \((R2, 31.6 \) grooves/mm) operates in the principal plane, and this layout reduces
the projected diameter of the fiber core on the CCD [143]. The spectrograph was moved to the $D = 0.5$ m telescope of European Southern Observatory [144] to monitor hot southern-sky supergiants. The Heidelberg Extended Range Optical Spectrograph (HEROS) [438] with the “blue” and “red” branches was constructed. Splitting the dispersed beam into two branches (3450–5600 Å and 5800–8650 Å) made it possible to optimize the echelle order packing density in each branch (by using cross-dispersion gratings with different groove densities). In each branch CCDs were used that were optimized in terms of format and quantum efficiency. The spectrograph was mounted at European Southern Observatory, where it was also used in the program of the monitoring of hot southern-sky supergiants over 120 days during six months. Observations with HEROS spectrograph were also conducted on the $D = 0.9$ m Dutch telescope transferred to ESO from Southern Africa [145]. The accuracy of radial-velocity measurements was $\sigma_v < 1 \text{ km s}^{-1}$, which was considered sufficient for the program of the monitoring of hot stars. HEROS was later moved to the $D = 2$ m telescope of Ondřejov Observatory [146]. In 2005 the $D = 0.5$ m ESO telescope was moved to the University Observatory near Santiago (Chile), where it is now operated with PUCHEROS fiber-fed spectrograph [147]. The parameters of the spectrograph are: fiber-core diameter 0.05 mm, $d_{\text{coll}} = 33$ mm, 44.4 grooves/mm echelle, blaze angle 70°, cross-dispersion unit consisting of two 48° prisms, a (F$ = 355$ mm) lens doublet camera with a meniscus field corrector, $R = 17800$.

Baudrand and Bohm [148] developed a fiber-fed spectrograph designed for observations within the framework of MUSICOS program. This inexpensive device for $D \sim 2$ m telescopes distributed along the longitude was also suitable for observations on small telescopes.

Some of the suspended echelle spectrographs pointed out in Table 2 were later equipped with modern detectors combined with fiber feed. Thus one of the copies of the spectrograph based on the successful design of the Harvard College spectrograph [73] was mounted on the $D = 1.0$ m telescope of Toledo University Observatory and has been operated for several decades in the fiber-fed mode with a CCD (see, e.g., Morrison [149]).

There are also well-known echelle spectrographs that were not manufactured at observatories. REOSC company developed a universal spectrograph operated both in the single-order version ($R = 1000$) and in the cross-dispersion layout ($R = 21000$, 3800–8000 Å wavelength interval). One of such spectrographs, which was earlier operated in the F/15 Cassegrain focus of the $D = 0.91$ m telescope mounted on a slope of Etna volcano is currently operated in the fiber-fed mode [5] [150]. Note that this assembly provides a radial-velocity measurement accuracy of $\sigma_v < 0.3 \text{ km s}^{-1}$, which is sufficient for most of the tasks involving spectroscopic monitoring of variable stars. It has a commercial CANON EF300 lens installed instead of the Schmidt camera, allowing the entire collimated beam to be used in the fiber-fed mode.

The fiber-fed CORALIE echelle spectrograph [151], which is an improved twin of ELODIE spectrograph [152], is installed at ESO in the Nasmyth focus of Euler Swiss telescope ($D = 1.2$ m) and serves to search for extrasolar planets via measuring the Doppler shifts of the spectrum of the central star. The combination of Euler telescope with CORALIE spectrograph is fully automated [153].

In addition to telescopes dedicated for a specific class of tasks, robotic telescope facilities, e.g., STELLA [154, 155], are developed. The parameters of this spectroscopic and photometric facility are optimized for the study of the structure and dynamics of the activity at the surfaces of stellar photospheres. The facility incorporates STELLA-I ($D = 1.2$ m) — the first fully robotic telescope equipped with SES high-resolution echelle spectrograph ($d = 130$ mm, 390–860 nm, R2, 31 grooves/mm). It is operated with two fibers, providing a resolution of

http://www.lsw.uni-heidelberg.de/projects/instrumentation/Heros/

http://w3c.ct.astro.it/sln/strumenti.html
$R = 50,000$ and $R = 25,000$ for the entrance aperture of $1''7$ and $3''4$, respectively.

For Mercator telescope ($D = 1.2$ m) HERMES spectrograph was developed [154], which is highlighted by its record combination of quantum efficiency (25% at the peak) and spectroscopic resolution ($R = 85,000$).

Most of the fiber-fed echelle spectrographs of the 1990s are used with 1.5–3.6 m telescopes [157], but it should be borne in mind that methods of radial-velocity measurements based on echelle spectra with minimum $S/N < 1$ were also developed [158]. Thus radial-velocity measurements with fiber-fed echelle spectrographs can also be performed on $D = [0.5; 0.9]$ m telescopes.

For Russian meter-class telescopes EFES spectrograph [159] was developed whose prototype [157] has been operated since 2010 on the $D = 1.2$ m telescope of Kourovka Observatory of Ural Federal University [160].

An array of $D = 0.7$ m telescopes [17] has been designed for the spectroscopy of candidate exoplanet system stars. The facility also performs photometric observations and that is why central screening covers almost half the diameter of the primary mirror. The promising KiwiSpec model [161, 162] based on the asymmetric white pupil scheme ($R = 80,000$, 5000–6300 Å) serves as a spectrograph. Such a limited wavelength range is caused by the need to display each of the 26 spectral orders six times (four “science” and two calibrating spectra) on the $2K \times 2K$ CCD. Calibration can be performed not only in the classical way (via a hollow-cathode lamp), but also via a Fabry–Perot standard.

Besides the errors mentioned in [163], the main factor that limits the positional and photometric accuracy of high-resolution fiber-fed spectrographs is modal noise, which results in nonidentical signal correction at the calibration stage. Simply speaking, fiber input illumination variations and flexures of the multimode optical fiber in the process of signal accumulation prevent achieving high $S/N$ whatever the calibration method. For example, it was shown in laboratory experiments with $R \sim 150,000$ [164] that $S/N \sim 500$ can only be achieved in simplified arithmetic estimates. A comprehensive solution is provided by the transition to a single-mode fiber where the aperture of the emerging beam is always Gaussian. The size of an operating (diffraction-limited) spectrograph will also be smaller. For example, in the case of the study of Schwab et. al. [165] the spectrograph with R4 echelle and $d_{col} = 25$ mm provides a spectral resolution of $R \sim 100,000$. However, the core diameter of a single-mode fiber is several times (or by one order of magnitude) smaller than that of a multimode fiber and the solution of the problem of matching at the input to the optical fiber depends on the adaptive optics tools employed.

### 4.7 Spectropolarimeters

Examples of spectropolarimetric methods including the cases where they were used on moderate-diameter telescopes can be found in Klochkova et. al. [166]. Fine spectropolarimetric effects, which show up in the profiles of spectral lines, are apparent only at high $S/N$, i.e., they can be studied with large telescopes. In the case of small telescopes low-resolution spectropolarimetry is an option when effects in the continuum, e.g., specificities of stellar and circumstellar polarization, can be studied. For this reason here we mention one of the devices that occupies a “niche” between narrow-band photopolarimeters and moderate-resolution spectropolarimeters, — the HBS spectropolarimeter [167] developed for the $D = 0.9$ m telescope. In front of the lens diffraction spectrograph a classical polarimeter is installed with phase-shifting plates and a Wollaston prism operating in the converging beam. The spectroscopic resolution is 40–200. Let us point out some of the tasks that can be solved with such a facility. Wavelength dependence of interstellar polarization differs from that of circumstellar polarization [168]. The task of their separation is based in the relation.
between the wavelength of maximum polarization and the total-to-selective extinction ratio ($R = 5.5\lambda$). If extra local effects show in the vicinity of stars then $R > 3$, i.e., $\lambda_{\text{max}} > 0.55$. Hence low-resolution mass spectropolarimetry of stars can be used to find circumstellar envelopes. Another kind of tasks involves monitoring of circumstellar polarization. It is known that variable broadband polarization in T Tauri and Be stars can amount to 10% and 1%, respectively. In the case of observations with medium spectral resolution polarization effects can be referred to separate spectral fragments or features. For example, Be stars have smaller polarization degree of the emission spectrum [169]. The proper variable polarization of M-type supergiants (up to 2%) caused by giant convective cells is also better to study with low spectral resolution.

The famous spectropolarimeter of Washington State University based on the Boller and Chivens spectrograph ($R \approx 800$) was used on the $D = 0.91$ and 1.0 m telescopes of Pine Bluff and Ritter Observatories, respectively [170].

4.8 Interference spectroscopic devices

The application of interference spectrometers in astronomy is based on two factors. First, Fellgett [171] pointed out that if the proper noise of the detector dominates then a two-beam interferometer is more efficient than a monochromator. Second, Jacquinot [172] considered multibeam interferometer with a Fabry–Perot etalon as a high-resolution monochromator. In the era of single-channel detectors the main task was to separate one of the orders of the etalon.

4.8.1 Scanning Fabry–Perot interferometer with a photomultiplier

Geake and Wilcock [173] implemented the method where lines in stellar spectra were studied by tilting the Fabry–Perot interferometer (FPI). They used a two-prism monochromator (25 Å/mm at H$\gamma$) mounted in the Newton focus of the 120-cm telescope of Asiago Observatory. The beam emerging from the monochromator was collimated ($F_{\text{coll}} = 90$ mm) and passed through the etalon. The role of the monochromator reduces to suppressing all transmission bands of the etalon except one. The wavelength transmitted by the etalon must vary at a constant rate and to this end the etalon was tilted via a camshaft mechanism (the cosine of the tilt angle varied linearly with scanning time). The wavelength at the monochromator output simultaneously varied so that the transmission band of the etalon would remain at the center of the monochromator transmission band. The 0.09-mm thick separator of the plates of the Fabry–Perot standard ensured 11 Å gap between the orders of the standard, and the transmission of the standard was equal to 60%. A factor-of-three gain was achieved in this first experiment compared to a monochromator without a etalon.

4.8.2 Polarization interferometers

The use of interference spectrometers to study point objects with small telescopes is not restricted to methods involving crossing with prismatic or diffraction devices. The idea of a polarization interferometer incorporating two crystal wedges placed between two polarizers and moving in opposite directions toward each other was first implemented by Bakhshiev in 1956 [174]. Mertz [175] then tested a similar scheme of multichannel stellar spectrometer with a single-channel detector, which was also based on the interference of rays with different polarization. First, the only main element of the scheme was a Soleil compensator placed between the two polarizers. The first polarizer consists of a Wollaston prism and a half-wave plate covering only one image and turning its polarization plane. This solution makes it possible to use both polarizations. It involves measuring the difference between the halfwave
shifted systems of bands. Scintillation proved to be the main source of noise. Then a potassium dihydrophosphate plate was added to the scheme. When subject to a longitudinal electric field, this plate changes the path difference as a result of double refraction. Lock-in detection was performed with a frequency of 3 kHz. The polarization interferometer was tested in the Cassegrain focus (1 : 18) focus of the $D = 0.6$ m telescope. With low-resolution observations it was planned to use interferograms directly for the classification of spectra (observations were made in the pre-computer era). Serkowski [176] proposed a method for studying the distribution of radial velocities in extended objects with emission-line spectra. The line studied is separated by an interference filter and then light passes through the polarization interferometer and is then registered by a field detector. Exposures are made for different turn angles of the phase-shifting plate of the interferometer. The polarization position angle at each point of the nebula can be calibrated in terms of radial velocities. The method provides higher angular resolution compared to FPI.

4.8.3 Multichannel spectrographs with a FPI

We illustrate the use of multichannel systems in interferometric devices with two examples. Serkowski [177] mounted a FPI at the entrance of the echelle spectrograph in the Cassegrain focus (1 : 13.5) of a 1.54-m telescope. The light in the 4100–4400 Å part of the spectrum was separated by a preliminary dispersion grism unit (70 Å/mm), and then arrived to the spectrometer where eight echelle orders were registered by a brightness amplifier and a 342 × 42 diode array (Digicon). A quartz plate is placed behind the entrance diaphragm. This plate can take two positions in terms of tilt angle. These tilt angles ensure shifting the FPI order on the diode array to the location of the neighboring order. To compensate the wavelength dependence of the free spectral interval of the FPI the thickness of the quartz plate varies along the grism dispersion direction. The FPI transmission bands have the width of 0.06 Å, and the separation between neighboring orders is 0.62 Å at 4250 Å, which for the reciprocal linear dispersion 3.4 Å/mm corresponds to five-pixel separation between neighboring FPI orders whose images have two-pixel-sized diameters. The vacuum camera with the FPI is tilted by a precision device within ±1°, and the total observing run consists of 20 exposures with recording the points of the spectrum 0.03 Å apart. Interferometer tilt angle and wavelength calibration is performed by recording the comparison spectrum of a hollow-cathode lamp and photodiode registration of the pair of He-Xe laser beams separated by 6°. The observing technique prevents any effect of the atmospheric transparency, photocathode sensitivity, and seeing variations. The accuracy achieved with 20 FPI tilt positions for a sixth-magnitude star corresponds to a radial-velocity error of 10 m s$^{-1}$.

The second attempt to use interferometry technique for measuring the Doppler shift was also made by the staff of the University of Arizona Observatory. McMillan et. al. [178] developed a fiber-fed echelle spectrograph with a CCD where the FPI operated in the inner installation, i.e., it was placed in the collimated beam. A total of 350 FPI orders were recorded simultaneously in the spectral orders of the echelle spectrum covering the 4250–4600 Å wavelength interval. The width of a FPI order at 4300 Å is 47 mÅ and the neighboring orders are 0.64 Å apart. Doppler shifts in the stellar spectrum change the order intensity ratios. For the sake of simplicity, only velocity variations were recorded, i.e., the device operated as an accelerometer. The argon-glow lamp calibration provided an accuracy reaching two one-hundred millionth, which corresponds to a velocity error of ±6 m s$^{-1}$. Instrumental variations within ±27 m s$^{-1}$ were found on a time scale of several months. The device was used on a $D = 0.9$ m telescope.
4.8.4 Spectrographs with an external interferometer

To analyze spectra of extended sources, Panchuk [179] proposed the method of twice crossed dispersion whose idea consists in measuring a single-sided fringe system of the FPI mounted in front of the echelle spectrograph. However, a high-Q-factor Fabry–Perot interferometer does not produce sine waves like the Michelson interferometer, and hence the advantages of Fourier analysis cannot be used for precision determination of the phase shift. Furthermore, the FPI transmits less light than the Michelson interferometer at the peaks of the instrumental function. Erskine [180] proposed a scheme where the Michelson interferometer is crossed with a diffraction spectrograph, and demonstrated its efficiency in measuring radial velocities with an accuracy that allows recording the displacement of the Earth–Moon barycenter (the variation amplitude is $12 \text{ m s}^{-1}$). Compared to heterodyne holographic spectrograph [181], the working wavelength range of the device is broader by tens of times.

Externally dispersed interferometry (EDI) deserves a separate consideration as a promising development. Here we only point out that the first Doppler-based detection of an exoplanet using this method was performed on a $D = 0.9 \text{ m}$ telescope and then confirmed on large telescopes [182]. The half-amplitude of radial-velocity variations of a $m_V = 8^{m}05$ star was $63.4 \pm 2.0 \text{ m s}^{-1}$ with a period of 4.11 days. This is how a companion with a minimum mass $m \sin i$ equal to 0.49 Jupiter masses was discovered.

4.9 Small-telescope spectrographs

In this section we mention spectrographs meant for the use on small telescopes ($D = [0.25; 0.4] \text{ m}$) with various detectors and in various combinations with the telescope.

In Canopus Hill Observatory (University of Tasmania) a $D = 0.4 \text{ m}$ reflector equipped with coudé focus (1 : 33) came into operation in 1977 [183]. The parameters of the spectrograph are: $F_{\text{coll}} = 330 \text{ cm}$, $d = 100 \text{ mm}$, two diffraction gratings with a $152 \times 102 \text{ mm}^2$ ruled area, 600 grooves/mm (used in the first order) and 1200 grooves/mm (in the second order), and two cameras, $F_{\text{cam}} = 122$ and 182 cm with the 76 cm camera mirror diameter. The reciprocal linear dispersion values were $P = 2.4, 3.6, 9, \text{ and } 14 \text{ Å/mm}$. Note that the diameter of camera mirrors is greater than the diameter of the primary mirror of the telescope, so that the cost of the spectrograph is comparable to the cost of the telescope. The results of photographic spectroscopy of bright F-type supergiants can be found in Castley and Watson [184]. Research work at Canopus Hill were discontinued in 2013 because of ever increasing light pollution.

A stigmatic echelle spectrograph ($R = 40\,000$) with an image tube (electrostatic focusing, S-25 cathode) was used to search for water bands ($8200 \text{ Å}$) in the atmosphere of Venus [185]. To reduce the contribution from the spectrum of tropospheric water vapor, observations were made from onboard an aircraft at a height of 14.6 km during the period of the elongation of Venus (April, 1972), when the radial-velocity difference between the atmosphere of Venus and telluric absorptions was maximal. A $D = 0.25 \text{ m}$ telescope was used as feeding optics. The parameters of the spectrograph are: Newton collimator, $d_{\text{coll}} = 150 \text{ mm}$; 79 grooves/mm, $\tan \theta_b = 2$ echelle with the $150 \times 300 \text{ mm}^2$ ruled area, operating in the primary plane ($2 \theta = 12^\circ$); a 300 grooves/mm cross-dispersion grating with a $200 \times 250 \text{ mm}^2$ ruled area. In this case the spectrograph is even more expensive that the telescope optics.

Currently, the manufacturers offer spectrographs oriented toward both professional and amateur astronomers. These devices, which can be mounted on $D = [0.2; 0.4] \text{ m}$ telescopes, are also used in programs of spectroscopic monitoring of bright stars [186].

BACHES Cassegrain echelle spectrograph equipped with a CCD [187] appears to be of
commercial interest and the parameters of the device are not fully disclosed: it has a 1 : 10 collimator; 79 grooves/mm, \( \tan \theta_b = 2 \) echelle; a cross-dispersion grating, and a lens camera. The 1530 × 1020 CCD with a pixel size of 9×9 \( \mu \)m\(^2\) simultaneously records 29 spectral orders in the 3900–7500 Å wavelength interval. The entrance slit projection onto the detector has a size of 2.4 pixels and the spectral resolution is \( R = 19000 \). On a \( D = 0.25 \) m telescope the spectrum of a fifth-magnitude star is acquired with \( S/N = 50 \) in a 900-second exposure under 1′′.7 seeing conditions. The spectrograph transmission is equal to 27% at 5040 Å. The quantum efficiency of the system (the atmosphere, telescope, spectrograph, and detector) is equal to 11%. Recall that under the same conditions UVES VLT spectrograph has a quantum efficiency of 17%. Before starting serial production of the spectrograph it was field tested on a \( D = 0.25 \) m telescope \[188\], and short-scale radial-velocity errors (\( \sigma_V = [1.5; 1.7] \) km s\(^{-1}\)) were shown to be determined by the flexibility of the standard adaptor and can therefore be reduced. BACHES spectrograph is equipped with two slits and is optimized for a \( D = 0.25 \) m (1 : 10) telescope.

For a telescope of the same diameter an echelle spectrograph was developed that is oriented toward the study of \( m_V < 6^m \) stars \[189\]. Its 1 : 4 lens collimator forms a \( d = 30 \) mm beam and the device is equipped with a 75 grooves/mm, \( \tan \theta_b = 2 \) echelle and a 1 : 2 lens camera. The two-pixel spectral resolution is \( R = 16000 \) for the normal slit width \( s = 4^\prime 4 \). Echelle operates in the autocollimation mode (\( \alpha = \beta = \theta_b \), outside the primary plane, i.e., \( \gamma \neq 0 \)). In this case the dependence of energy concentration along the order varies more steeply and at maximum it is 20–30% greater than in the case \( \alpha > \theta_b > \beta \) and \( \gamma = 0 \), i.e., in the primary plane. The device’s cross-dispersion unit is a 300 grooves/mm grating operating in the first order. The latter circumstance made it possible to make design provisions for the change of \( \gamma \) (half of the 2\( \gamma \) angle between the collimator axis and the “echelle center–cross-dispersion grating center” line) to place the selected line to the maximum of the energy concentration curve in the echelle order. For example, varying \( \gamma \) from 6° to 8° changes the central wavelength in the \( m = 36 \) order from \( \lambda_c = 6593 \) Å to \( \lambda_c = 6564 \) Å. In the case of such a design the optimum choice is an R2 echelle with a line density of 37.5 grooves/mm, where the length of the order is twice shorter and the range of \( \gamma \) is twice smaller. A Meade LXD55 telescope, \( (D = 254 \) mm, \( F = 1016 \) mm) is used as feeding optics. The spectrograph used in the Newton focus is fixed parallel to the telescope tube.

Eagleowloptics company (Switzerland) developed compact SQUES spectrograph (\( R = 20000 \)).

Suspended single-order DADOS spectrograph is not intended for achieving maximum spectral resolution (its grating operates with the right angle between the incident and diffracted beams). It is operated with two — 200 and 900 grooves/mm — gratings, \( F_{\text{coll}} = 80 \) mm (1 : 10), and \( F_{\text{cam}} = 96 \) mm. When operated with the 900 grooves/mm grating the reciprocal dispersion and slit width are \( P = 106 \) Å/mm and 0.025 mm, respectively. When mounted on a \( D = 0.3 \) m telescope this spectrograph acquires \( S/N = 50 \) spectrum for a \( m_V = 6^m \) star in 20 minutes.

LHIIRES III suspended single-order high-resolution spectrograph is designed in accordance with autocollimation scheme: the same doublet serves as both the collimator and the camera, \( F = 200 \) mm. Provision is made for the use of replaceable diffraction gratings with line densities spanning from 150 to 2400 grooves/mm. The spectrograph is optimized for a \( D = 0.2 \) m (1 : 10) telescope. When equipped with a 2400 grooves/mm grating and a detector with a 9-\( \mu \)m-sized pixel, the spectrograph provides a resolution of \( R = 17000 \). The signal-to-noise ratio for a fifth-magnitude star observed with one-hour long exposure is \( S/N = 100 \). The spectrograph was used extensively in programs of monitoring of hot stars with H\( \alpha \) emission.

In the 1990s SBIG started selling SGS model where two replaceable gratings operate in
In accordance with the Ebert scheme with a small spherical mirror. In DSS7 model lens optics is used for both the camera and the collimator, $P = 600 \text{ Å/mm}$. The company equips its spectrographs with its own-manufactured detectors, which allowed it to use digital image stabilization.

Astro Spectroscopy Instruments EU (Potsdam) developed miniature MiniSpec spectrograph for 1:5 and 1:10 telescopes. Options (combination of the slit width and grating line density) are provided that allow the spectrograph to be operated on a detector with 9-µm pixel size and a reciprocal linear dispersion of $P = [0.2; 3.3] \text{ Å/pixel}$.

An autocollimation spectrograph was developed for Celestron CPC 1100 telescope ($D = 279 \text{ mm}$, $F = 2800 \text{ mm}$, Schmidt–Cassegrain) [190]. The collimator/camera has a mirror lens with $D = 45 \text{ mm}$, $F = 275 \text{ mm}$. The 1800 grooves/mm grating with a $50 \times 50 \text{ mm}^2$ ruled area operates in the first diffraction order. The reciprocal linear dispersion in the neighborhood of yellow mercury doublet is $P \sim 10 \text{ Å/mm}$. The maximum (theoretical) two-pixel (20 µm) spectral resolution is $R = 28900$, which corresponds to the $1''4$ slit width. The spectrograph is meant for monitoring selected lines the spectra of bright ($m_V < 6 \text{m}$) variable stars of various types with the resolution typical for the Main Stellar Spectrograph the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences [191], $R = 14000$.

The spectrographs for small-diameter telescopes are so far dominated by suspended devices because of their small size and mass. However, there also fiber-fed systems, which are usually adopted for financial reasons. First, where there is a laboratory spectrograph it can also be used with the telescope. For example, the $D = 0.51 \text{ m}$ telescope at the University of Illinois (Springfield [3] is equipped with SE200 Echelette spectrograph ($R \sim 20000$), manufactured by Catalina Scientific Instruments for laboratory works (it has fiber-fed input). Its dispersing unit (echelle and prism) operates in accordance with the Ebert scheme ($F = 200 \text{ mm}$, 1:10). The telescope is also used with an Optomechanics 10C spectrograph (developed by Optomechanics Research of Vail, AZ.) whose layout includes an $F = 225 \text{ mm}$ (1:9) spherical mirror collimator, replaceable gratings (with line densities spanning from 300 to 1200 grooves/mm), and an $F = 135 \text{ mm}$ (1:2.8) camera. Second, a commercial fiber-fed spectrograph is easier to adapt for small telescopes given the great variety of their mounting types and size restrictions. eShel fiber-fed spectrograph [192] is based on the cross-dispersion scheme. Its $F_{\text{coll}} = 125$ (1:5) mirror collimator is fed through an optical fiber (0.05 mm). The collimated $d_{\text{coll}} = 25 \text{ mm}$ beam is directed to the R2 echelle whose cross-dispersion unit is a prism. The camera has an $F_{\text{cam}} = 85 \text{ mm}$ (1:1.8) lens. The $13 \times 9 \text{ mm}^2$ detector records only the visible part of the spectrum (4500–7000 Å), $R = 10000$. Under $3''$ seeing conditions a $D = 0.2 \text{ m}$ (1:5.9) telescope achieves $S/N = 100$ during one-hour exposure of an $m_V = 7\text{m}$ star.

A fiber-fed single-order Czerny–Turner spectrograph was used on a $D = 0.4 \text{ m}$ telescope to study τ Boötis system [193]. The device has the following parameters — $F_{\text{coll}} = 762 \text{ mm}$; $F_{\text{cam}} = 240 \text{ mm}$; 1800 grooves/mm, 0.17 Å/pix grating, and simultaneously records a 88 Å wide spectral fragment. The projected size of the fiber core is 4 pixels (0.68 Å), $R = 7500$. Despite such spectral resolution, which is by no means optimum for the discovery of exoplanets, observations made with this device confirmed the parameters of the system distinguished by its large radial-velocity amplitude ($K = 471 \pm 10 \text{ m/s}$). The position of the star image was corrected eight times a second using standard SBIG tools.

6https://www.uis.edu/
5 Prospects

An analysis of various technical solutions and personal practical experience allow us to highlight some promising solutions in the technique and organization of spectroscopy on medium- and small-diameter telescopes.

First of all, this is the further specialization of instruments. It goes without saying that equipping a medium or small telescope with one instrument results in significant economy in terms of the maintenance costs of the telescope–spectrograph system and facilitate the transition to the remote control mode. The review \cite{194} proposed to develop a dedicated spectroscopic telescope with $D \sim 1.2$ m.

In fiber-fed spectroscopy, lens cameras are preferred, and Schmidt systems are underestimated due to losses in the case of center shielding. However, the cameras of efficient spectrographs — SOPHIE \cite{195}, STELLA and HERCULES — are made according to the “folded Schmidt” scheme, and the losses on central shielding are compensated for by other advantages (overfilling of the echelle, achromaticity of the camera, reduced vignetting, and reduced cost for a given $d_{\text{coll}}$). Recall that the replacement of the spectrograph with an ELODIE lens camera by SOPHIE has increased the quantum efficiency of the system tenfold.

It is necessary to develop a combination of different functions on one optical element. For example, the asphericity of reflective gratings makes it possible to build mirror schemes whose range is limited only by the parameters of the detector and optical coatings. In echelle systems, an aspherical reflective grating can operate as a cross-dispersion element. In the EMILIE fiber-fed echelle spectrograph, one of the surfaces of the double-path prism is made aspherical \cite{196}.

A dedicated spectroscopic telescope does not necessarily need to have a large field of good images. In that case it is enough to use a light-collecting telescope (similar to the Dutch Light Collector \cite{145}). A segmented mirror is planned to be used to correct aberrations in the spectroscopic telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences.

It seems to a promising solution for medium and small telescopes with quality optics to use a diffraction-limited spectrograph with a single-mode optical fiber. However, it should be assessed in which tasks addressable with such telescopes, the modal noise is a limiting factor.

Medium-resolution external-postdispersion (EDI) spectrograph schemes are used both with fiber-fed optics and in a suspended version.

In the class of suspended systems:

1. Mirror schemes with low slit-width ratios and astigmatism compensation are undeservedly forgotten \cite{68}. With then increasing CCD format, there will be a return to these schemes on $D \sim 1$ m telescopes. For operation in the ground-based ultraviolet, a purely mirror system with an image combiner can be built.

2. The scheme of the spectrograph using an echelle with a variable line density \cite{197, 198} has not become popular among the astronomers. Based on this solution, a compact high-resolution suspended spectrograph with maximum efficiency can be built for a medium-diameter telescope.

3. The designs of the Mark series suspended slit spectrographs proved to be a successful solution \cite{131}.

A common problem is the need to reduce the contribution of scattered light and ghost images. A new spectroscopic device, which prepares the comparison spectrum, is proposed for the two fiber spectrograph scheme \cite{199}.
Conclusions

We review the main types of spectroscopic equipment for small- and moderate-diameter telescopes indicating the principal parameters of the selected design solutions. We also provide a list of references to allow a more in-depth understanding of the problem.

Some prospects for the development of this instrumental and methodological direction are assessed.

In the era of the construction of large telescopes, interest in instrumental equipment for small — (less than 0.4 m) and moderate — (0.4–1.2 m) diameter telescopes may seem irrelevant. However, even a superficial assessment of the capabilities of modern instruments of the diameters just mentioned indicates unremitting attention to their equipment. The efficiency of these tools even increases as some of the small diameter tools move into the single-program category.

Small telescopes play a crucial role in the practical training of young astronomers. The technological gap that is observed in our country between the equipment of professional and training telescopes seriously affects the level of training of astronomers and physicists at universities. The aim of this publication is to review the spectroscopic equipment of small- and moderate-diameter telescopes and provide a brief description of the specificities of the operation of this equipment or provide references to the relevant literature. Despite the fact that some of the techniques and methods described here look archaic, one should know their strengths and weaknesses, which in the era of highly efficient multichannel detectors can lead to the rebirth of certain methods. Hence the published information may prove to be useful when reequipping domestic telescopes with new astrophysical equipment.

We believe that the instrumentation of such telescopes has large reserves, including a combination of well-known solutions with new technological capabilities.

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