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Off-the-shelf Echelle Spectroscopy: Two Devices on the Test Block

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Abstract

Today, various Echelle spectrographs for small telescopes are available on the market. These instruments are ready-to-use, including professional data reduction chains. Manufacturers claim that their compact instruments can deliver professionally usable data for very low prices. This paper presents extensive tests of the two most popular small-scale Echelle spectrographs for telescopes in the 1 m domain with a focus on radial velocity accuracy.

Key words: instrumentation: spectrographs – methods: analytical – techniques: spectroscopic

Online material: color figures

1. Introduction

In recent years a number of astronomical long-slit spectrographs have been commercially developed and are available off-the-shelf. Many observing campaigns have been carried out using such instruments (e.g., Fahed et al. 2011). Observing campaigns have also been carried out using recently developed Echelle spectrographs (e.g., Miroshnichenko et al. 2013; Aldoretta et al. 2016). Unlike the more common long-slit spectrographs, which must be adjusted to each spectral region to be used, an Echelle can operate without moving parts if it is designed to have complete wavelength coverage. The best-known commercial systems are eShel from Shelyak Instruments,[1] BACHES from Baader Planetarium,[2] and SQUES from Eagleowloptics.[3] All devices can be used with small telescopes. Recently, professional tests have been carried out on eShel and BACHES, providing manufacturer-independent insight into their performance. Kozłowski et al. (2014) tested BACHES on the 50 cm Solaris-4 telescope at CASLEO in Argentina, whereas Pribulla et al. (2015) tested eShel on the 60 cm telescope of the Stara Lesna Observatory in Slovakia. Both tests were published in professional publications and provide information on different spectroscopic operating parameters, in particular, on mechanical influences on wavelength measurements. Thus, the data quality, stability, and user-value for professionals and amateurs in terms of their corresponding research objectives can be estimated with a focus on achieving high radial velocity accuracy. This is the baseline of the present comparison. For SQUES such a test has not been published yet. In the following we therefore only consider BACHES and eShel.

2. Similarities

BACHES and eShel are fundamentally different in their structure and in their applications. While BACHES works directly at the telescope focus, eShel light is fed through an optical fiber and the spectrograph operates on a stationary platform (photos can be found on the company websites). Although both units internally use Echelle gratings as the primary dispersion elements, they follow different configurations for the cross-dispersion of the diffracted light. One common feature is the wavelength calibration with thorium-argon (ThAr) lamps. Both devices have external calibration units that feed the ThAr and flat-field lamps through fiber optics into the spectrograph. Both can automatically track the target with these units. These units have not been tested but corresponding details can be found from the manufacturers. Both systems contain complete and easy-to-handle spectroscopic data reduction packages that are based on the professional software package ESO-MIDAS. They can be run on any Windows computer via the appropriate emulation.

2.1. BACHES

BACHES was developed by the Club of Aficionados in Optical Spectroscopy (CAOS)[4] a professional team at ESO and MPE and is distributed by Baader Planetarium in Germany. It operates directly at the telescope focus. The incident convergent telescope light is collimated via a doublet and is then guided onto an Echelle grating. The light then passes a grating

[1] http://www.shelyak.com
[2] http://baader-planetarium.de
[3] http://www.eagleowloptics.com
[4] https://spectroscopy.wordpress.com

cross-disperser and is then displayed by a camera lens, which is likely to be a simple achromat with low chromatic aberration. The maximum attainable resolving power is about 20,000 (averaged over all orders). The device is optimized for typical $f/10$ Schmidt–Cassegrain telescopes, which should provide a seeing disc of 25 μm. Hence, the internal 25 μm slit should be considered as the nominal slit width. Different seeing and telescope conditions can be taken into account by another slit width of 50 μm. This will naturally provide a lower resolving power due to the larger resolution element (slit width) projected onto the spectrum. The optical configuration is tuned to small telescopes. The resolving power when used on telescopes with a larger pupil diameter or larger F-number (leading to larger plate scales and necessitating larger slit widths) would be reduced. That is, BACHES cannot be well operated with telescopes larger than about 30 cm aperture and very good seeing conditions of 1 arcsec. Otherwise one suffers light loss and reduced resolving power. One might argue that a change to a smaller *f*-ratio would solve this problem. However, such a "faster" input would also require a "faster" and, hence, larger spectrograph collimator. Such a change is impossible for BACHES. If the telescope beam becomes faster (smaller *f*-ratio) the given and unchangeable $f/10$ collimator in BACHES could no longer be completely illuminated (the light cone from the telescope has then a bigger opening angle). Vignetting at the collimator would occur (larger beam), significantly reducing the spectrograph performance. For seeing conditions of 2 arcsec the respective maximum telescope aperture is reduced to about 25 cm. Thus, the manufacturer's information about the "average spectral resolving power" can be called into question. This average value of all spectral orders can only be achieved with perfect observing conditions and perfect instrument adjustment. Amazingly, the spectrograph has a welded housing and cannot be opened. Thus an evaluation of the individual components as well as any repairs and modifications by the user are excluded. Kozłowski et al. (2014) indicate that they used a prototype device for their tests corresponding to a later series. Considering the equipment geometry, however, it is likely that the transmission cross-disperser grating of the tested pre-series unit has been replaced by a prism grating (grism).

2.2. *eShel*

eShel was developed and is distributed by Shelyak Instruments in France. Shelyak follows an open design policy. Drawings and 3D plots are freely available. The internal design is thus well known. eShel is a device in which a fiber optic of 50 μm diameter at the telescope focus feeds the stationary spectrograph. Fiber optics only accept certain *f*-ratios (or acceptance angles) and reduce the *f*-ratio between input and output (Focal Ratio Degradation—FRD; Ramsey 1988). Therefore, the eShel fiber must be fed with $f/6$ and exits with $f/5$. After the light has passed through the fiber, the incident light is collimated by a respective doublet (here $f/5$) and is then guided onto an Echelle grating. In contrast to BACHES, the diffracted light is then cross-dispersed by a prism. The separated orders are then imaged by a commercial $f/1.8$ Canon camera onto the focal plane. The average resolving power of all orders is approximately 12,000. Since the eShel fiber acts as a virtual slit and only requires a fixed $f/6$ feed, this resolving power is always achieved. As long as the seeing disk in the telescope focus is 50 μm at most, the device can operate with larger telescopes of up to 10 m focal length and 1.5 m aperture without additional light loss as long as they feed the fiber with $f/6$ (possibly using a focal reducer or a Barlow lens). This means, with additional injection optics mounted on the fiber input side, one can adapt eShel to an even wider range of telescope focal lengths.

3. Comparison

The obvious difference between the two devices is their operation at the telescope. BACHES is subject to all movement and temperature effects at the telescope focus. This is a highly important point. An Echelle spectrograph can record the entire optical spectrum with one single shot. This makes it ideal for high-precision measurements of radial velocities and line profile analyses. The highest accuracy for exoplanet search and orbit determination of close binary stars requires as many accurate line radial velocities in as many Echelle orders as possible. This is done by averaging the wavelength position of many spectroscopic absorption lines. Echelle spectrographs with full order coverage of the respective wavelength domain are hence the first choice for such investigations. Of course, simultaneous line investigations in single orders might not necessarily need highest radial velocity accuracies. In this respect, both instruments work well. Even very small deviations of the CCD pixel positions with respect to the calibration spectra, introduced by mechanical and thermal variations, instantaneously degrade achievable measurement accuracies. Between individual calibration measurements, the pixel positions should therefore be as stable as possible. For professional observatories, Echelle spectrographs are therefore mechanically and thermally stabilized and either operate in the Coudé focus or are fiber-operated in another room.

In order to estimate the intrinsic accuracies, a number of measurement series were analyzed for both spectrographs. First, it is striking that Kozłowski et al. (2014) did not adapt BACHES with its $f/10$ collimator sufficiently to the $f/15$ telescope. At CASLEO one can assume excellent average seeing conditions of 1 arcsec or better, so that the telescope seeing disc has a diameter of 36 μm in the telescope focus. However, the smallest slit width of BACHES is 25 μm. Therefore, the spectrograph loses approximately 30% of the light at both the Echelle grating and the slit. The telescope

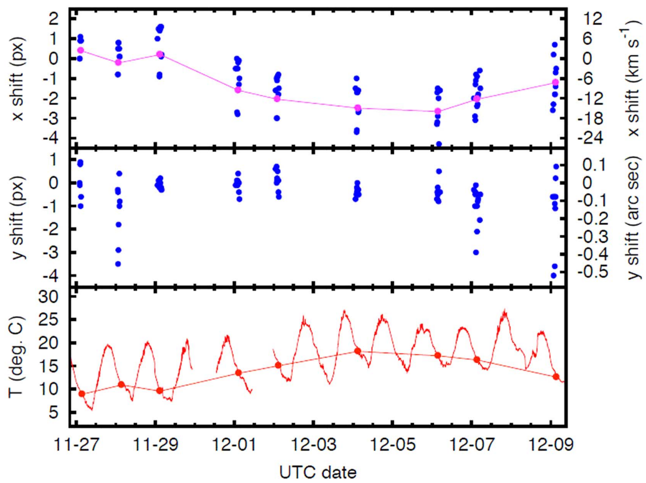

Figure 1. Differences between all BACHES-ThAr calibration spectra from the first nightly calibration spectrum on 26 November (11–26) in the *x*-direction (top) and in the *y*-direction (center). The values are in pixels (left). For the *x*-direction in the upper graph, the displacement is also expressed in kilometers per second, and for the *y*-direction analog, in arcsec. In the upper graph the solid curve shows the average displacement in the *x*-direction. The respective deviation with respect to the ambient temperature is shown in the lower graph. 1 pixel corresponds to 6 km s^{-1} radial velocity (Kozłowski et al. 2014).
(A color version of this figure is available in the online journal.)

aperture at CASLEO was thus virtually reduced by approximately 50% in total. This is basically no problem as long as one measures sufficiently bright stars. However, the optimal utilization of a spectrograph in terms of the achievable signal-to-noise ratio is not possible at CASLEO without a focal reducer. For the test, every night several calibration exposures were collected at different telescope positions over the course of 14 days. The nightly spectra were averaged and their mean deviations in the *x* and *y* pixel positions on the CCD chip with respect to the first night were estimated. Figure 1 shows the corresponding results.

There is a noticeable scattering of up to 3 pixels for all spectral line positions during one night, which corresponds to 18 km s^{-1}. Over the entire two-week CASLEO campaign at Solaris-4, Kozłowski et al. (2014) also found a variable trend in the corresponding averages with a maximum value of 18 km s^{-1}. That means one has to deal with a maximum of 25 km s^{-1} if both effects occur independently and are necessarily quadratically added. While short-term shifts are caused by mechanical effects, the long-term behavior of the spectrograph is caused by the temperature trend, as displayed by the correlated long-term behavior of pixel displacement and temperature. The authors have also analyzed the instrumental behavior during individual nights. For this purpose, they recorded various calibration spectra before and after the corresponding object spectrum and determined their position shift on the chip (Figure 2).

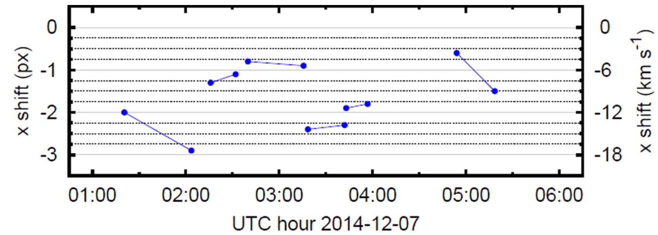

Figure 2. Example position differences of calibration spectra. The pairs of points indicate ThAr measurements before and after target data recording. The maximum velocity difference is 15 km s^{-1} (Kozłowski et al. 2014).
(A color version of this figure is available in the online journal.)

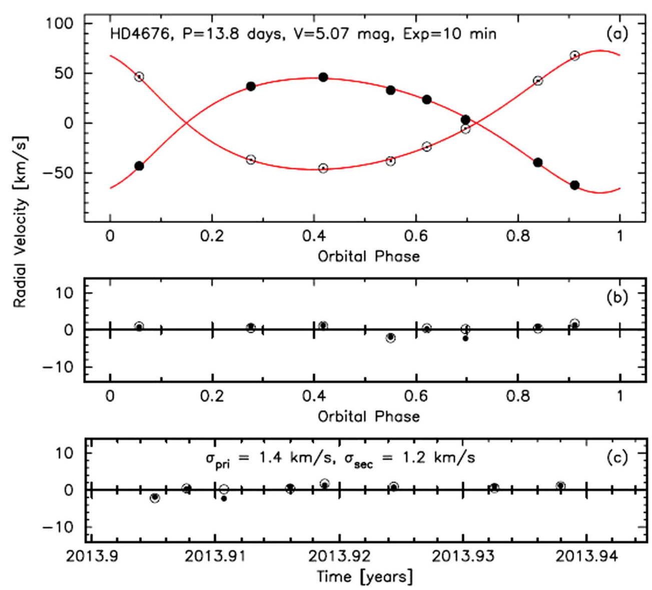

Figure 3. BACHES measurement results for the binary star HD 4676. (a) Radial velocities as a function of orbital phase as well as the best model fit. ((b) and (c)) Deviations from the best model fit and the corresponding standard deviations for the primary component (σ_{pri} = 1.4 km s^{-1}) and the secondary component (σ_{sec} = 1.2 km s^{-1}) (Kozłowski et al. 2014).
(A color version of this figure is available in the online journal.)

Relatively large shifts of up to one pixel (6 km s^{-1}) within just 30 minutes and about 15 km s^{-1} within the whole night are striking. Since the calibration light is fiber-fed directly into the spectrograph, these offsets are not introduced by the telescope optics. They must be caused by ambient conditions. There is a clear link between long-term shifts (several days) and the ambient temperature (Figure 3). Short-term shifts (one night) can be attributed to mechanical flexure of the spectrograph at the moving telescope. In this respect, the results considerably deviate from the manufacturer's description ("torsional rigidity better than 9 μm at a 180° swivel"). In principle, it is possible that the internal opto-mechanical components of the spectrograph also cause shifts. However, their behavior could

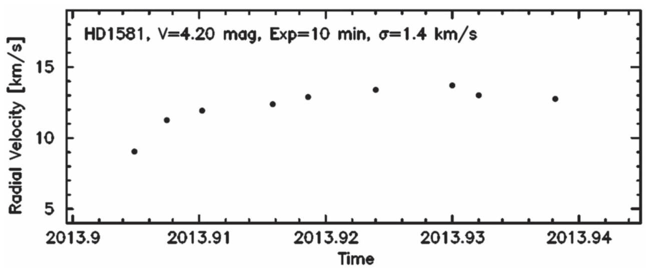

Figure 4. Radial velocities of the standard star HD 1581 during one night (Kozłowski et al. 2014).

not be tested because the production version cannot be opened. The spectroscopic 2D output of the instrument gives some information, though. The incoming light is first guided by a small prism onto a simple and small doublet and then dispersed by an off-the-shelf Echelle grating of unknown origin. The grating or grism cross-disperser works in transmission and the dispersed light is then imaged onto the CCD by a respective camera. Because of the unknown parts a detailed analysis or even modifications are therefore entirely impossible for astronomers. Kozłowski et al. (2014) note that most shifts may be compensated for by appropriate calibration. Unfortunately, they describe neither those shifts that can be compensated nor the corresponding procedure. However, they produce measurements of binary stars. Figure 3 shows an example for HD 4676. The deviation of the measurements from the appropriate data fit provides the accuracy of the whole system. For both components this is 1.3 km s^{-1} on average. This is the highest accuracy of all measurements. Despite adequate calibration, however, a global nocturnal trend was found for the measured radial velocities (Figure 4). The origin of this trend of no less than 5 km s^{-1}, which cannot be eliminated by a proper calibration, could not be explained. However, we can assume that the trend reflects the temperature response of the spectrograph to the changing ambient temperature during the night (the spectrograph cannot be thermally stabilized).

Pribulla et al. (2015) have carried out similar stability tests with eShel (Figures 5 and 6). They also converted the accuracy measurements to radial velocities. The telescope was equipped with a focal reducer to match the necessary fiber input *f*-ratio of $f/6$. The effective telescope focal length thus provided a 1 arcsec seeing disc of 18 μm. Hence, the spectrograph was well adapted to the telescope. Thus, the authors can achieve the maximum performance with their telescope-spectrograph configuration for the 50m fiber for a seeing of up to 3 arcsec. Several ThAr calibration spectra were recorded with eShel and their displacements during one night were determined. Figure 7 shows the result, which is analog to Figure 2. The quadratic fit to the data suggests a certain trend during the night. But considering the small number of data

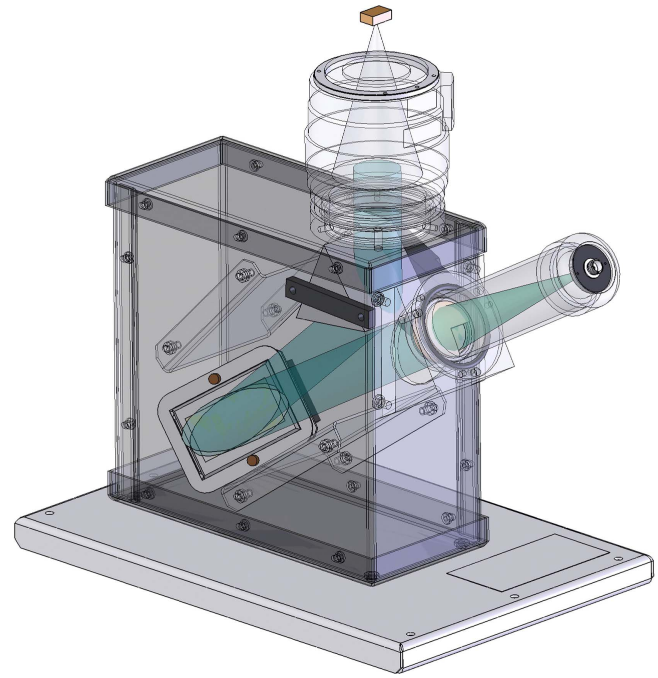

Figure 5. Transparent view of the eShel spectrograph (Shelyak Instruments). (A color version of this figure is available in the online journal.)

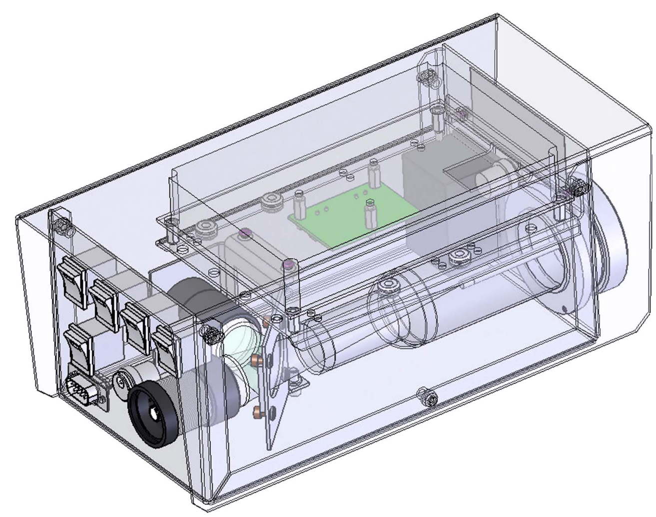

Figure 6. Transparent view of the eShel calibration unit (Shelyak Instruments). (A color version of this figure is available in the online journal.)

points this trend has only a limited value. In addition, the authors do not comment on the thermal environment where the spectrograph is positioned. Even if the spectrograph has probably been operated on a stationary platform, it remains unclear whether mechanical or thermal drift caused the deviations. The nightly scattering of the measured radial velocities is about 0.25 km s^{-1}. The authors have also

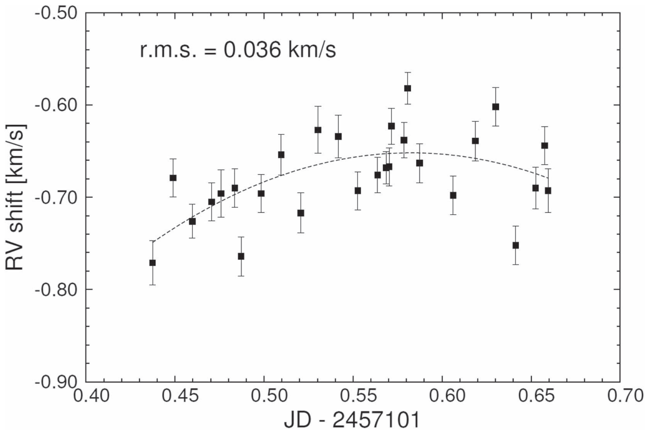

Figure 7. Shifting of the calibration spectra for one single night using the dispersion solution of 24 Echelle orders and a quadratic fit. The maximum shift is 0.25 km s^{-1} (Pribulla et al. 2015).

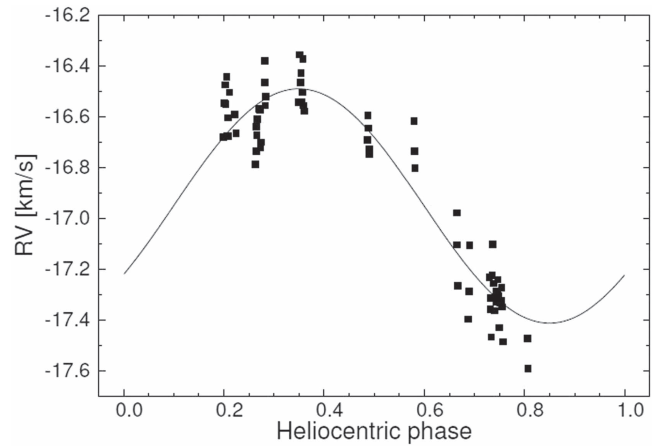

Figure 8. Radial velocities for the star τ Bootis (points) measured with eShel compared to the spectroscopic orbit by Butler et al. (2006) (solid line). The data scattering is about 0.4 km s^{-1} (Pribulla et al. 2015).

considered nocturnal linear trends and established a short-term stability of up to 0.05 km s^{-1}. This is a remarkable value for such a compact system, but they also fail to provide information about the exact time intervals for such a high stability. On the other hand, Csák et al. (2014) achieved precisely these accuracies at two telescopes of 0.5 and 1 m aperture. One can therefore assume that radial velocity accuracies of 0.25 km s^{-1} can be considered as a reliable output.

The accuracy of the eShel has been tested by measurements on τ Bootis. Figure 8 shows the results compared to the orbit solution of Butler et al. (2006), which has been determined with data from Lick, Keck, and AAT. The small periodic velocity variations in Bootis are caused by a hot Jupiter and can be clearly verified by eShel using a 60 cm telescope. The data point scatter is approximately 0.4 km s^{-1}. The short-term stability of up to 0.05 km s^{-1}, claimed by the authors, is not confirmed by these measurements.

Unfortunately, a comparison of the efficiencies of both instruments is not possible. Pribulla et al. (2015) only give limited information. Performing tests on standard stars they and other authors determine an overall system efficiency of around 1% in contrast to 7% specified by the manufacturer. Given the many optical surfaces in an Echelle system, values of around 10% are already very good. But 1% appears extremely low. The authors refer to light loss in the fiber and night-to-night efficiency variations by a factor of 2. According to our own experiences the manufacturer's fiber optics has only intermediate efficiencies of 50% maximum. This could be increased to around 80% with good fibers. It is also known that so-called fiber noise can dramatically reduce the fiber efficiency (Grupp 2003). Useful counter-measures (e.g. Avila et al. 2007) are not mentioned in the publication. In any case, fiber optics are optical elements that require attention and care for greatest accuracy. The measured low efficiency of eShel is certainly an ambiguous result that requires more detailed examination. Given the operation at the telescope focus one can assume that BACHES has a greater efficiency than eShel. In their recent paper Kozłowski et al. (2016) report an average $S/N \approx 22$ within 30 minutes exposure time for a $V = 10$ mag target (now operating at 50 cm Solaris-1 at SAAO). On the other hand BACHES uses a grating or grism cross-disperser in transmission with certainly lower overall efficiency than the prism cross-disperser of eShel. Moreover, the BACHES Echelle grating is unknown while eShel uses a high-efficiency Richardson grating. Since the BACHES components cannot be evaluated, all efficiency considerations essentially remain speculative.

Beside other optical elements (grating, camera optics, CCD pixel size) the achievable spectral resolving power depends on the given diameter of the spectrograph collimator and the telescope aperture. A resolution element (seeing disk or slit) in the telescope focus will introduce a geometric divergence of the collimated beam, which in turn deviates from Fraunhofer diffraction and, hence, degrades the spectral resolving power. One can show (Eversberg & Vollmann 2015) that the relation between the telescope aperture, the spectral resolving power and the seeing in the sky (slit matching the seeing disk in the telescope focal plane) is given by

$$D_{\max} = \frac{d_{\text{col}}}{R \cdot \tan\Theta \cdot \tan\omega}$$

with $D_{\max}$ the maximum telescope aperture, d_{col} the diameter of the spectrograph collimator, Θ the divergence angle behind the collimator and ω the seeing in the sky. The equation shows that bad seeing and high resolving power introduce problems for large telescopes. For instance, for 1 arcsec seeing and $\Theta = 5°$ (typical for most spectrographs) BACHES ($d_{col} \sim 10$ mm, $R \sim$ 20,000) is limited to telescopes of 118 cm aperture while this is about four times larger for eShel ($R \sim 12.000$, $d_{col} \sim 25$ mm). The limiting factors for BACHES is a very small collimator 2.5 times smaller than that used by eShel. However, BACHES and eShel are optimized for $f/10$ and $f/6$ telescopes respectively. Hence in reality such large telescope apertures would introduce significant light loss at the slit or fiber input due to a geometrically increasing seeing disk in the telescope focal plane. This limiting trade between telescope aperture and resolving power is mentioned neither by Kozłowski et al. (2014) and Pribulla et al. (2015), nor by the two manufacturers.

4. Conclusion

For measurements of radial velocities eShel delivers a radial velocity accuracy of approximately 0.25 km s^{-1}. This is about five times more accurate than BACHES with 1.3 km s^{-1}. If we also take the nightly shift of 5 km s^{-1} into account, this factor is increased to 20! The cause of this weakness of BACHES can be found in the lower stability and a lack of temperature stabilization. Higher efficiency (direct operation at the focus without fibers) is probably "paid for" by stability problems (lower wavelength accuracy). For maximum performance, BACHES relies on an accurate optical adaptation to the telescope. Its efficiency benefits are otherwise quickly dashed and the maximum resolving power is greatly reduced because of the required slit adjustment. For eShel, high stability is probably "paid for" by lower fiber efficiency. Better fiber optics for about 300 Euros would be useful.

Observers who wish to exploit the greatest strength of an Echelle, i.e., the measurement of radial velocities, rather opt for eShel. In terms of its performance parameters it can be flexibly applied and, in particular, is mechanically and thermally stable. In terms of efficiency the fiber optics are a weak optical element. They can be simply replaced by specially assembled fiber optics. Beyond that Pribulla et al. (2015) identify chromatic aberration in the Canon camera which can slightly reduce the resolving power at the order edges. They also address the problem of a slightly too small CCD chip for the entire optical spectrum. If necessary, the eShel camera optics can be changed, which is not possible for BACHES. For weaker target stars (by about 1 magnitude) one might opt for BACHES, while accepting lower radial velocity accuracies. Because of its low stability its professional use remains reduced, though.

However, the price speaks for BACHES. With almost 11,000 Euros for the complete system it is about 1/3 cheaper than eShel with almost 17,000 Euros (prices for 2016). In this price range, however, a relatively low mechanical stability and an unknown internal structure (BACHES) and fibers of intermediate efficiency (eShel) are avoidable issues.

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