An Exposure Meter of Lijiang Fiber-fed High-Resolution Spectrograph (Postprint)

Authors: Xiao-Guang Yu, Kai-Fan Ji, Xi-Liang Zhang, Liang Chang, Yun-Fang Cai, Ying Qin and Zhen-Hong Shang

Date: 2023-12-15T00:00:00+00:00

Abstract

In 2016, an exposure meter was installed on the Lijiang Fiber-fed High-Resolution Spectrograph to monitor the coupling of starlight to the science fiber during observations. Based on it, we investigated a method to estimate the exposure flux of the CCD in real time by using the counts of the photomultiplier tubes (PMT) of the exposure meter, and developed a piece of software to optimize the control of the exposure time. First, by using flat-field lamp observations, we determined that there is a linear and proportional relationship between the total counts of the PMT and the exposure flux of the CCD. Second, using historical observations of different spectral types, the corresponding relational conversion factors were determined and obtained separately. Third, the method was validated using actual observation data, which showed that all values of the coefficient of determination were greater than 0.92. Finally, software was developed to display the counts of the PMT and the estimated exposure flux of the CCD in real-time during the observation, providing a visual reference for optimizing the exposure time control.

Full Text

Preamble

An Exposure Meter for the Lijiang Fiber-fed High-Resolution Spectrograph

Xiao-Guang Yu[1],[2],[3], Kai-Fan Ji[1],[2], Xi-Liang Zhang[1],[2], Liang Chang[1],[2],[3], Yun-Fang Cai[1],[2], Ying Qin[1],[2],[3], and Zhen-Hong Shang[4]

[1] Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China; yuxiaoguang@ynao.ac.cn, changliang@ynao.ac.cn
[2] Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650216, China

[3] University of Chinese Academy of Sciences, Beijing 100049, China
[4] Faculty of Information Engineering and Automation, Kunming University of Science and Technology, Kunming 650500, China

Received 2023 March 8; revised 2023 August 10; accepted 2023 August 24; published 2023 October 10

Abstract

In 2016, an exposure meter was installed on the Lijiang Fiber-fed High-Resolution Spectrograph to monitor the coupling of starlight to the science fiber during observations. Building upon this system, we investigated a method to estimate the CCD exposure flux in real time using the counts from the exposure meter's photomultiplier tubes (PMT), and developed software to optimize exposure time control. First, through flat-field lamp observations, we determined that a linear and proportional relationship exists between the total PMT counts and the CCD exposure flux. Second, we determined separate relational conversion factors for different spectral types using historical observations. Third, we validated the method using actual observation data, which showed that all coefficient of determination values exceeded 0.92. Finally, we developed software to display the PMT counts and estimated CCD exposure flux in real time during observations, providing a visual reference for optimizing exposure time control.

Key words: telescopes – instrumentation: spectrographs – instrumentation: photometers

1. Introduction

The signal-to-noise ratio (S/N) is a key parameter for evaluating the quality of high-resolution spectral data. During observations, since CCD exposure flux information cannot be obtained directly, exposure time is typically estimated based on weather conditions, observing conditions, and stellar characteristics, which introduces large uncertainties. Blindly increasing exposure time to achieve high S/N wastes valuable observation time and risks saturating the CCD, which would contaminate the data. Conversely, if the S/N fails to meet requirements, repeated observations reduce overall efficiency. Two primary methods address this problem.

The first approach uses an Exposure Time Calculator (ETC), which requires accurate simulation of target, weather, and instrument parameters before observations. While most instruments employ ETCs for exposure time estimation, uncertainties remain. For instance, the simulated S/N from the ETC is overestimated by 40%–50% for IGRINS (Le et al. 2015), whereas it remains within 10% for HARPS (ESO 2021).

The alternative method employs an Exposure Meter (EM) integrated into the instrument. An EM can monitor flux in real time to optimize exposure time by terminating the exposure once the desired counts are acquired. Additionally, EMs can calculate the photon-weighted mean time of each exposure, which is critical for precise radial velocity (RV) measurements (Tokovinin et al. 2013; Telting et al. 2014). For precise RV measurements with long exposures, an EM becomes essential (Raskin 2011). Many high-resolution spectrographs are equipped with EMs using either photomultiplier tubes (PMT) or CCDs as detectors (Kibrick et al. 2006; de Cuyper et al. 2007; Gibson 2013; Tokovinin et al. 2013; Landoni et al. 2014; Ben-Ami et al. 2016; Blackman et al. 2020; Gupta et al. 2022). EMs typically pick off 1% to 8% of the light from behind the slit or grating.

EM count rates vary depending on the spectrograph. For a star of V = 5 mag, the typical count rate is 10^3 s^{-1} in the EM of CHIRON (Tokovinin et al. 2013), with a maximum count rate of 456 s^{-1} and mean exposure time error within 1 s. However, for a star of V = 16 mag, the count rate is 19 s^{-1} in the EM of HARPS, with mean exposure time error within 165 s (Chile 2010).

In this paper, we present a method for real-time estimation of CCD exposure flux using PMT counts from the Exposure Meter of the Fiber-fed High-Resolution Spectrograph (HiRES) on the Lijiang 2.4 m telescope. Through flat-field lamp observations, we determined that the signals from the two detectors are linearly proportional, and we obtained transformation relationship coefficients for six different spectral types using historical observation data. Validation with observed data demonstrates excellent agreement between estimated and actual CCD exposure flux values. Simultaneously, we developed application software to enable real-time display of the estimated CCD exposure during observations.

2.1. Optics of HiRES and Exposure Meter

HiRES on the Lijiang 2.4 m telescope features two science fibers with spectral resolutions ($R = \lambda/\Delta\lambda$) of 32,000 and 49,000 for the 2.0” and 1.2” diameter fibers (on-sky) at 550 nm, respectively. The observed spectral orders range from 61 to 156, covering wavelengths from 380 to 990 nm. The spectrograph’s long-term temperature and pressure stability is maintained within 26 ± 0.25°C and 30 ± 1 Pa, respectively (Wang et al. 2019). A starlight coupling device installed on a side port in the AG-box unit (Fan et al. 2015) at the Cassegrain focus guides light from the telescope or calibration lamps to the spectrograph via the science fiber. Figure 1 shows the optical layout of HiRES for the 2.4 m telescope.

An EM (red box in Figure 1) was installed in the spectrograph optical path to monitor starlight coupling into the science fiber during observations, picking off 3% of the starlight via a small folding mirror. Its main component is a wide dynamic range PMT. Figure 2 shows the quantum efficiency curves for both detectors (CCD and PMT). Both exhibit high detection efficiency from 500 nm to 800 nm, with peak quantum efficiencies at 400 nm for the PMT and 550 nm for the CCD. We used observational data to study the relationship between

EM counts and spectrograph CCD flux, and developed software to improve observation efficiency.

2.2. Mathematical Model

We first investigated the relationship between signals from the two detectors (CCD and PMT) using flat-field lamp observations. Specifically, we performed group observations with different exposure times (0.5 s, 0.6 s, 0.7 s, 0.8 s, sufficient for the bright flat-field lamp) and obtained four sets of CCD spectral images with corresponding total PMT counts. After correcting for background signals in both the spectral images and PMT counts, we selected the 2000th column of pixels containing the strongest signal in the spectral image. We then summed the ADU values of pixels covered by the 96 orders in this column to obtain exposure fluxes at wavelength points corresponding to different orders. Figure 3 shows the relationship between exposure fluxes for 10 orders and the corresponding total PMT counts, with horizontal coordinates representing total PMT counts and vertical coordinates representing exposure fluxes at different wavelength points in the CCD image column.

Dark counts for both CCD and PMT were obtained before observations. In the no-exposure state, the effective signals of both detectors are zero. The relationship can be expressed by Equation (1). Here, F_{CCD} represents the observed flux at the corresponding wavelength point for each CCD pixel, C_{PMT} is the sum of PMT counts during exposure time T, G is the scale factor matrix for the corresponding pixel on the CCD image, d_T is the CCD dark current during exposure time T, and b_T is the sum of PMT dark counts during exposure time T.

The total PMT count represents the sum of exposure fluxes across all detected bands. Since energy distributions differ among stars of various spectral types, and considering HiRES's inconsistent response across different bands plus actual atmospheric absorption, obtaining accurate spectral response curves using the standard blackbody radiation formula is difficult. Actual observed stellar spectra differ from flat-field lamp spectra, as shown in Figure 4. Additionally, Figure 5 shows normalized observed energy distributions for six spectral types, revealing numerous absorption lines in stellar spectra (darker discontinuous regions). Based on these HiRES spectral characteristics, we determined respective conversion factor G matrices for different spectral types.

Using Equation (1), we determined six sets of conversion factors (for spectral types B, A, F, G, K, and M) from historical observations, which included CCD spectral images, total PMT counts, CCD dark frames, and PMT dark counts. Figure 6 shows the conversion coefficient matrix for a type A star. With this method, we can estimate target spectrum exposure flux using real-time PMT counts and obtain a simulated CCD spectral image.

3. Validation

We validated the method using observations from 2022 July 16 to 2022 July 20. Table 1 provides information on the observed targets, while CCD dark and PMT dark counts were obtained from same-day observations. We selected the conversion factor (G) corresponding to the target's spectral type and estimated CCD flux (F_{CCD}) using Equation (1) with PMT counts from observations. We evaluated results using the coefficient of determination between estimated and actual observed CCD exposure flux values, calculated via Equations (2), (3), and (4).

The coefficient of determination R^2 is defined such that if estimates and observations agree perfectly, R^2 equals 1. Table 1 shows all R^2 values exceed 0.92, indicating high agreement. Figure 7 compares estimated and observed exposure flux values for CCD pixels, with blue curves representing observations and orange curves representing estimates (absorption lines and inter-order regions are omitted for clarity). These results demonstrate that our method can reliably estimate CCD exposure flux using real-time PMT counts during observations.

4. Software

We developed Python-based software using the Qt Designer IDE on Windows 10 to utilize the EM for exposure time estimation. Figure 8 illustrates the software workflow, which operates primarily through communication among three threads: the main thread, data acquisition thread, and spectral estimation thread. The main thread receives user operations and sends commands to the PMT counter via serial port. The PMT counter executes commands and returns data to the software. The data acquisition thread receives counts, verifies data integrity, and subtracts background counts. The main thread receives photon counts, computes statistics (sample value, mean, total, and sample count), and dynamically updates results. The spectral estimation thread calculates current exposure flux at 0.2 Hz frequency and updates estimates in real time.

Figure 9 shows the software user interface. Observers can select or enter stellar information based on scientific requirements before observation. During observation, the interface displays real-time PMT counts and estimated CCD exposure flux, providing visual and reliable reference for optimizing exposure time control.

5. Conclusions and Discussion

We have presented a method for real-time CCD exposure flux estimation using PMT counts from an exposure meter and validated it with observational data. Validation results show excellent agreement between estimated and actual observations. Flat-field lamp observations established a linear proportional relationship between total PMT counts and CCD spectral image pixel fluxes at different wavelength points, with the transformation equation provided. Six spectral type transformation coefficient templates were determined from historical observations. Validation data from 2022 July 16–20 show all coefficient of determination values between estimated and observed CCD exposure flux exceed 0.92, confirming the method's reliability for real-time estimation using PMT counts.

The software implementation and user interface display real-time PMT counts and estimated CCD exposure flux, providing visual reference for optimizing exposure time control. In Section 2, we determined transformation coefficient templates for different spectral types from historical observations, with key considerations in data selection. First, data were chosen to cover as many subtypes per spectral type as possible, though observing time limitations prevented coverage of all subtypes. Second, we selected higher quality observations with high S/N under stable conditions. PMT observation distributions help determine whether conditions were stable and unaffected by clouds. Given these constraints, the actual number of selected observations is limited. Third, stars of the same spectral type have different magnitudes. We found that spectral imaging response distribution on the CCD varies between targets with large magnitude differences, particularly in the blue wavelength region, due to atmospheric windows and spectrograph efficiency. Therefore, separate model transformation coefficient determinations are necessary for exceptionally bright standard stars or particularly faint special targets of the same spectral type.

This paper does not consider sky background light or atmospheric absorption line effects. According to long-term monitoring at Lijiang Observatory, sky background ranges between 16.5 and 21 mag arcsec^{-2} (Xin et al. 2020), which may introduce uncertainties in faint star observations with long exposures. This factor must be accounted for when high accuracy is required. For example, sky background observations in the target region could be obtained before observation for background correction, though this sacrifices additional observing time and reduces efficiency. Additionally, atmospheric absorption lines at Lijiang Observatory vary seasonally (Lu et al. 2021), affecting flux at covered wavelengths; observers can avoid referencing pixel areas covering these wavelengths.

Future plans include increasing the observation sample size to optimize model transformation coefficients and improve estimation accuracy, while enhancing software functionality based on observational requirements. This research provides valuable insights for applying the method to other similar spectrographs. Current implementation is limited to HiRES bands with wavelength coverage below 10,000 Å for the 2.4 m telescope, but the method can be extended to other wavelength spectrographs with appropriate detector selection.

Acknowledgments

We thank the referee for constructive suggestions that improved this manuscript and acknowledge the support of Lijiang 2.4 m telescope staff. This work was funded by the National Natural Science Foundation of China (NSFC, Nos. 11803088, 12003068 and 12063002), Civil Aerospace pre-research project D020302, the science research grants from the China Manned Space Project (No. CMS-CSST-2021-B10), Yunnan Science Foundation of China (202001AU070077), and the Sino-German Scientist Mobility Programme M-0086.

ORCID iDs

Xiao-Guang Yu https://orcid.org/0009-0007-3650-6715
Kai-Fan Ji https://orcid.org/0000-0001-8950-3875
Zhen-Hong Shang https://orcid.org/0000-0003-1280-5255

References

Ben-Ami, S., Epps, H., Evans, I., et al. 2016, Proc. SPIE, 9908, 9908A0
Blackman, R. T., Fischer, D. A., Jurgenson, C. A., et al. 2020, AJ, 159, 238
Chile, L. O. E. 2010, HARPS User Manual (Garching: ESO)
de Cuyper, J. P., Hensberge, H., Raskin, G., et al. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 653
ESO, E. S. O 2021, HARPS Efficiency Monitoring (Garching: ESO)
Fan, Y.-F., Bai, J.-M., Zhang, J.-J., et al. 2015, RAA, 15, 918
Gibson, S. R. 2013, PhD thesis, University of Canterbury, New Zealand
Gupta, A. F., Bender, C. F., Ninan, J. P., et al. 2022, Proc. SPIE, 12189,
Kibrick, R. I., Clarke, D. A., Deich, W. T. S., & Tucker, D. 2006, Proc. SPIE, 6274, 62741U
Landoni, M., Riva, M., Pepe, F., et al. 2014, Proc. SPIE, 9147, 91478K
Le, H. A. N., Pak, S., Jaffe, D. T., et al. 2015, AdSpR, 55, 2509
Lu, K.-X., Zhang, Z.-X., Huang, Y.-K., et al. 2021, RAA, 21, 183
Raskin, G. 2011, PhD thesis, Katholieke University of Leuven, Astronomical Institute
Telting, J. H., Avila, G., Buchhave, L., et al. 2014, AN, 335, 41
Tokovinin, A., Fischer, D. A., Bonati, M., et al. 2013, PASP, 125, 1336
Wang, C.-J., Bai, J.-M., Fan, Y.-F., et al. 2019, RAA, 19, 149
Xin, Y.-X., Bai, J.-M., Lun, B.-L., et al. 2020, RAA, 20, 149

Note: Figure translations are in progress. See original paper for figures.