

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

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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 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

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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 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 there exists a linear proportional relationship between the total PMT counts and the CCD exposure flux. Second, using historical observations of different spectral types, we determined the corresponding conversion factors separately for each type. Third, we validated the method using actual observation data, which showed that all coefficient of determination values exceeded 0.92. Finally, we developed software that displays PMT counts and estimated CCD exposure flux in real time during observations, providing a visual reference for optimizing exposure time control.

Keywords: telescopes: Lijiang 2.4-m Telescope; instrumentation: Fiber-fed High Resolution Spectrograph; instrumentation: Exposure Meter

1 INTRODUCTION

The signal-to-noise ratio (S/N) is a key parameter for evaluating the data quality of high-resolution spectra. During observations, since CCD exposure flux information cannot be obtained directly, exposure time is generally estimated based on weather conditions, observing conditions, and stellar characteristics, which introduces large uncertainties. Blindly increasing exposure time to achieve high S/N wastes observation time and may contaminate data through CCD saturation. Conversely, if the S/N fails to meet requirements, repeated observations reduce efficiency. Two methods typically address this problem. The first uses Exposure Time Calculators (ETC), which require accurate simulation of target, weather, and instrument information before observations. Most instruments use ETC to estimate exposure time, though with some uncertainties. For IGRINS, the simulated S/N from ETC is overestimated by 40-50% (Le et al. 2015), while for HARPS it is within 10% (ESO 2021). The second method employs an Exposure Meter (EM) installed as part of the instrument. The EM can monitor flux in real time to optimize exposure time by terminating exposure when desired counts are acquired. The EM can also calculate the photon-weighted mean time of each exposure, which is critical for precise radial velocity (RV) measurements (Telting et al. 2014; Tokovinin et al. 2013). For precise RV measurements with long exposures, an EM becomes a necessity (Raskin 2011). Many high-resolution spectrographs have been equipped with EMs using photomultiplier tubes (PMT) or CCDs as detectors (Gibson 2013; de Cuyper et al. 2007; Tokovinin et al. 2013; Landoni et al. 2014; Ben-Ami et al. 2016; Blackman et al. 2020; Kibrick et al. 2006; Gupta et al. 2022). EMs typically pick up 1% to

8% of the light from behind the slit or grating. Count rates vary according to different spectrographs. For a $V=5$ mag star, 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 $V=16$ mag star, the count rate is 19 s^{-1} with mean exposure time error within 165 s for the EM of HARPS (Chile 2010).

In this paper, we propose a method to estimate CCD exposure flux in real time using PMT counts from the Fiber-fed High-Resolution Spectrograph (HiRES) of the Lijiang 2.4 m telescope. Through flat-field lamp observations, we determined that the signals between the two detectors are linearly proportional and obtained relationship conversion coefficients for six different spectral types using historical observation data. Validation results from observed data show that estimated CCD exposure flux values agree well with actual observed values. Additionally, we developed application software to realize real-time display of estimated CCD exposure during observation. Section 2 describes the method's principle, Section 3 presents validation results, Section 4 describes the software working principle and user interface, and Section 5 summarizes the results and discusses error factors.

2.1 Optics of HiRES and Exposure Meter

HiRES on the Lijiang 2.4 m telescope has 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 the sky) at 550 nm, respectively. The orders of an observed spectrum range from 61 to 156, with wavelength coverage from 380 nm to 990 nm. The spectrograph's long-term temperature and pressure stability are controlled within $26 \pm 0.25^\circ\text{C}$ and $30 \pm 1 \text{ Pa}$, 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 spectrometer via scientific fiber. [Figure 1: see original paper] shows the optical layout of HiRES for the 2.4 m telescope.

An EM (red box in [Figure 1: see original paper]) was installed in the spectrograph optical path to monitor starlight coupling into the science fiber during observation, picking up 3% of starlight by a small folding mirror to the EM. Its main component is a wide dynamic range PMT. [Figure 2: see original paper] shows the quantum efficiency curves of the two detectors (CCD and PMT), which have high detection efficiency in the wavelength range from 500 nm to 800 nm, with peak quantum efficiencies at 400 nm for PMT and 550 nm for CCD. We used observed 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 set differ-

ent exposure times (0.5 s, 0.6 s, 0.7 s, 0.8 s due to the sufficiently bright flat-field lamp) for group observations, obtaining four sets of CCD spectral images and corresponding total PMT counts. First, we corrected the background signals of the spectral images and PMT counts. Second, we extracted the 2000th column of pixels with the strongest signal in the spectral image and summed the ADU values of pixels covered by the 96 orders individually to obtain exposure fluxes at wavelength points corresponding to different orders. [Figure 3: see original paper] shows the relationship between exposure fluxes of 10 orders and 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.

We obtained dark counts for the CCD and PMT before observations. In the no-exposure state, the effective signals of both detectors are zero. The relationship can be expressed by Equation 1:

$$F_{\text{CCD}} - d_T = G(C_{\text{PMT}} - b_T)$$

where F_{CCD} is 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 of 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 is the sum of exposure fluxes across all detected bands. Since energy distributions differ among stars of different spectral types, combined with HiRES's inconsistent response across bands and actual atmospheric absorption, it is difficult to obtain accurate spectral response curves using the standard blackbody radiation formula. [Figure 5: see original paper] shows actual observed energy distributions for stars of six spectral types, with observed energies normalized. Additionally, actual observed stellar spectra differ from flat-field lamp spectra, as shown in [Figure 4: see original paper]. Stellar spectra contain many absorption lines, with darker regions in the right image showing these features. Based on these HiRES spectral characteristics, we need to determine respective conversion factor G matrices for different spectral types.

Using Equation 1, we determined six types of conversion factors (Type B, A, F, G, K, and M) from historical observations including CCD spectral images, total PMT counts, CCD dark current, and PMT dark counts. [Figure 6: see original paper] shows the conversion coefficient matrix for a spectral 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 July 16-20, 2022. provides information on the observed targets, with CCD dark current and PMT dark

counts 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 using Equations 2-4:

$$R^2 = 1 - \frac{SS_{\text{estimated}}}{SS_{\text{total}}}$$

$$SS_{\text{total}} = \sum (y_i - y_{\text{mean}})^2$$

$$SS_{\text{estimated}} = \sum (y_i - y_{\text{estimated}})^2$$

where R^2 is the coefficient of determination, y_i is the observed CCD flux, $y_{\text{estimated}}$ is the estimated CCD flux, and y_{mean} is the average of observed fluxes. Perfect agreement between estimate and observation yields $R^2 = 1$. The third column of shows all R^2 values exceed 0.92, indicating high agreement.

[Figure 7: see original paper] plots estimated versus observed CCD exposure flux values, with blue curves representing observed values and orange curves representing estimated values. For clarity, absorption lines and inter-order regions in estimated values are ignored. Comparing these results demonstrates that our method can reliably estimate CCD exposure flux using real-time PMT counts during observation.

4 SOFTWARE

We developed Python-based software using the Qt Designer IDE on Windows 10 to estimate exposure time using the EM. [Figure 8: see original paper] shows the software workflow. The mechanism operates primarily through communication among three threads: the main thread, data acquisition thread, and spectra thread. The main thread receives 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, and subtracts background counts. The main thread receives photon counts, computes statistics (sample value, mean value, total value, and number of samples), and dynamically updates statistical results. The spectra thread estimates current exposure flux at 0.2 Hz frequency and updates in real time.

[Figure 9: see original paper] shows the software user interface. Observers can select or input stellar information according to scientific requirements before observation. During observation, the interface displays PMT counts and estimated exposure flux in real time, providing visual and reliable reference for observation.

5 CONCLUSIONS AND DISCUSSION

We have presented a method for estimating CCD exposure flux in real time using PMT counts from an exposure meter and validated it using observational data. Validation results show that estimates obtained using this method agree well with 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. We determined transformation coefficient templates for six spectral types from historical observations. Validation using data from July 16-20, 2022 shows that coefficient of determination values between estimated and observed CCD exposure fluxes all exceed 0.92, demonstrating that the method can reliably estimate CCD exposure flux using real-time PMT counts. Additionally, we presented the working mechanism and user interface of the application software, which displays real-time PMT counts and estimated CCD exposure flux values, providing visual reference for optimizing exposure time control.

In Section 2, we determined model transformation coefficient templates for different spectral types using historical observations, with key considerations in data selection. First, data were chosen to cover as many subtypes of each spectral type as possible, though limited by precious observing time preventing observation of all subtypes. Second, we selected higher quality observations, such as those with high signal-to-noise ratios under stable conditions. PMT observation distributions can determine whether conditions were stable and unaffected by cloudiness. Considering these factors, the actual selected observation amount is small. 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-end wavelength region, due to atmospheric window and spectrometer efficiency effects. Therefore, we must perform separate model transformation coefficient determinations for particularly bright standard stars or particularly faint special targets of the same spectral type.

Additionally, this paper does not consider effects from sky background light and atmospheric absorption lines. According to long-term monitoring statistics from Lijiang Observatory, sky background light ranges between 16.5-21 mag/arcsec² (Xin et al. 2020), which may introduce uncertainties in estimating faint stars observed with long exposures. This factor must be considered if high accuracy is required. For example, sky background observations in the target region could be made as background correction before observation, though this reduces observation efficiency by losing additional time. Furthermore, atmospheric absorption line intensity at Lijiang Observatory varies seasonally (Lu et al. 2021), affecting flux at covered wavelengths, and observers can avoid referring to pixel areas covering these wavelengths.

Future plans include increasing observation sample size to optimize model trans-

formation coefficients and improve estimation accuracy, and enhancing software functionality based on observation requirements. This research provides valuable insights for applying the method to other similar spectrometers. Note that current implementation is limited to bands with wavelength coverage less than 10,000 Å in HiRES for the 2.4 m telescope, though with appropriate detector selection, this method can be extended to other wavelength spectrometers.

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