

An exposure time calculator for the Maunakea Spectroscopic Explorer

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ABSTRACT

The Maunakea Spectroscopic Explorer (MSE) will convert the 3.6-m Canada-France-Hawaii Telescope (CFHT) into an 11.25-m primary aperture telescope with a 1.5 square degrees field-of-view at the prime focus. It will produce multi-object spectroscopy with a suite of low ($R\sim 3,000$), moderate ($R\sim 6,000$), and high ($R\sim 40,000$) spectral resolution spectrographs in optical and near-infrared bands that are capable of detecting over 4,000 objects per pointing. Generally, an exposure time calculator (ETC) should simulate a system performance by computing a signal-to-noise ratio (SNR) and exposure time based on parameters such as a target magnitude, a total throughput of the system, and sky conditions, etc. The ETC that we have developed for MSE has individual computation modes for SNR, exposure time, SNR as a function of AB magnitude, and SNR as a function of wavelength. The code is based on an agile development methodology and allows for a variety of user input. Users must select either LR, MR, or HR spectral resolution settings in order to pull the associated MSE instrument parameters. Additionally, users must specify the target and background sky magnitudes (and have the ability to alter the default airmass and water vapor values). The software is developed with Python 3.7, and Tkinter graphical user interface is implemented to facilitate cross-platform use. In this paper, we present the logic structure and various functionalities of our MSE-ETC, including a software design and a demonstration.

Keywords: Maunakea Spectroscopic Explorer, multi-object, spectroscopy, survey, simulation

1. INTRODUCTION

Maunakea Spectroscopic Explorer (MSE) will provide multi-object spectroscopy for 4,332 objects simultaneously over a 1.52 square degree field of view. The primary telescope mirror (M1) will have an 11.25 m aperture and

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consist of sixty hexagonal segments, while necessitating very minimal structural change of the existing CFHT facility.¹ There will be two spectrograph units: a low/moderate resolution (LMR) instrument and a high resolution (HR) instrument. Regarding the multiplexing capability, 3,249 fibers lead to the LMR spectrograph and the other 1,083 fibers to the HR spectrograph. The LMR instrument will have a spectral resolution range from $R \sim 3,000$ to $R \sim 6,000$ over a wavelength range from 360 nm to 1800 nm and the HR instrument will have an approximate resolution of $R \sim 40,000$ and a wavelength coverage of about 360 nm to 900 nm.²

One purpose of an exposure time calculator (ETC) is to simulate the signal-to-noise ratio (SNR) according to exposure time during science operations, which in turn provides an overall (program) time estimate to users. Also, this tool can be used in the analysis of the instrument performance in the design phase as well as be employed in the evaluation of the scientific programs in the development of targeting strategy and survey design.

Our MSE-ETC provides four calculation modes for SNR, exposure time, target magnitude, and wavelength range. The software was written by Python 3.7.9 with a graphical user interface. In this paper, we present the development and simulation results of the MSE-ETC, including the calculation methods and software structure.

2. SIMULATION METHODS AND PARAMETERS

Currently, the MSE-ETC provides four calculation modes for low resolution (LR), moderate resolution (MR), and high resolution (HR) settings. These modes are described as follows: (a) S/N Calculation: provides the single SNR values for the central wavelength of the filter bands with the spectral resolutions; (b) ExpTime Calculation: provides the total exposure time for the central wavelength of filter bands with the spectral resolutions; (c) S/N vs. Magnitude: provides the plot and array data of correlation between the SNR and target magnitude (AB) about the full wavelength range of filter bands with the spectral resolutions; and (d) S/N vs. Wavelength: provides the plot and array data of correlation between the SNR and the full wavelength range of filter bands with the spectral resolutions.

2.1 Basic formulas for signal and noise

In the MSE-ETC, we use the formula of continuum signal for point source based on

$$S_{cont} = \frac{t_{exp} n_{exp} A_{tel} \tau_{atmo} \tau_{opt} \tau_{ie} f_{\nu}(m_{AB})}{hR} \quad (1)$$

where t_{exp} is exposure time for a single frame, n_{exp} is number of frames, A_{tel} is light collecting area of the M1, τ_{atmo} is atmospheric transmission, τ_{opt} is optical throughput of the MSE system, τ_{ie} is injection efficiency, $f_{\nu}(m_{AB})$ is spectral flux density for monochromatic AB magnitude, h is Plank constant, and R is spectral resolution. And we also use the formula of signal from the sky background

$$B_{sky} = \frac{t_{exp} n_{exp} A_{tel} \tau_{atmo} \tau_{opt} \Omega_{fiber} b_{\nu}(m_{AB})}{hR} \quad (2)$$

where Ω_{fiber} in units of $arcsec^2$, and $b_{\nu}(m_{AB})$ is sky brightness in units of $W m^{-2} Hz^{-1} arcsec^2$. Here we let the dark current of a detector to D_{dark} , the detector read noise to D_{read} , and the pixel resolution to N_{res} , the total noise is expressed by

$$N_{cont} = \sqrt{S_{cont} + B_{sky} + N_{res} n_{exp} [t_{exp} D_{dark} + D_{read}^2]} \quad (3)$$

then, the signal to noise ratio (SNR) is

$$SNR = \frac{S_{cont}}{N_{cont}} \quad (4)$$

Table 1. Spectral resolutions of the LR, MR, and HR spectrographs in the full wavelength range. The resolution is approximately the center of the band.

Low resolution (LR) spectroscopy				
Wavelength range (nm)	$360 \leq \lambda \leq 560$	$540 \leq \lambda \leq 740$	$715 \leq \lambda \leq 985$	$960 \leq \lambda \leq 1800$
Spectral resolution	2,550	3,650	3,600	3,600
Moderate resolution (MR) spectroscopy				
Wavelength range (nm)	$391 \leq \lambda \leq 510$	$576 \leq \lambda \leq 700$	$737 \leq \lambda \leq 900$	-
Spectral resolution	4,400	6,200	6,100	-
High resolution (HR) spectroscopy				
Wavelength range (nm)	$360 \leq \lambda \leq 460$	$440 \leq \lambda \leq 620$	$600 \leq \lambda \leq 900$	-
Spectral resolution	40,000	40,000	20,000	-

Table 2. Telescope, fiber and detector parameters.

Telescope		Fiber		Detector	
D_{tel}	10.14 m	D_{fiber}	1 arcsec	N_{dark}	0.02 electrons/s/pixel
A_{tel}	80.75 m ²	N_{res}	4×4 pixel	N_{read}	5 (R, G, B), 8 (NIR) electrons/pixel

2.2 Instrument parameters

The spectral resolutions for LR, MR, and HR spectrographs are shown in Table 1.³ And the parameters of the telescope, fiber, and detector of the MSE system are shown in Table 2, where D_{tel} is telescope effective aperture and D_{fiber} is slit size of fiber.

2.3 Sensitivity budget allocation

The factors influencing the determination of the optical throughput (τ_{opt}) for the MSE system are as follows: Enclosure (ENCL), Telescope mount structure (MSTR), Primary mirror (M1), Prime focus hexapod system (PFHS), Wide field corrector and atmospheric dispersion corrector (WFC/ADC), Fiber positioner system (PosS), Fiber transmission system (FiTS), and Spectrographs with low/moderate or high resolution (SIP). The estimates for these factors (over the full MSE wavelength range) as well as the injection efficiency (τ_{ie}) are taken from the MSE sensitivity budget allocation document.⁴

2.4 Telluric absorption spectra

In case of the telluric absorption spectra, we use the dataset of the ESO SkyCalc Sky Model Calculator*.^{5,6} The SkyCalc model data have a spectral resolution of R~50,000 and are generated for three values of precipitable water vapor (PWV) 1.0 mm, 2.5 mm, and 7.5 mm. The MSE-ETC will reads in the downloaded model data and then reconvolves them to match the spectral resolution of the MSE instruments. For given wavelength and PWV, the ETC will return the appropriate τ_{atmo} via three dimensional interpolation (see Figure. 1).

2.5 Background estimation

Currently, we have only considered the OH emission lines in the background estimation. The OH emission line data is generated by slightly modifying the OH sky line data for the H band of the IGRINS ETC (i.e., reconvolving the spectra to different resolutions).⁷ The wavelengths of the OH emission lines are from Rousselot et al. (2000)⁸ and the calibrated intensity values are from Oliva and Origlia (1992).⁹ The OH emission lines are as shown in Figure 2.

*<https://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=SKYCALC>

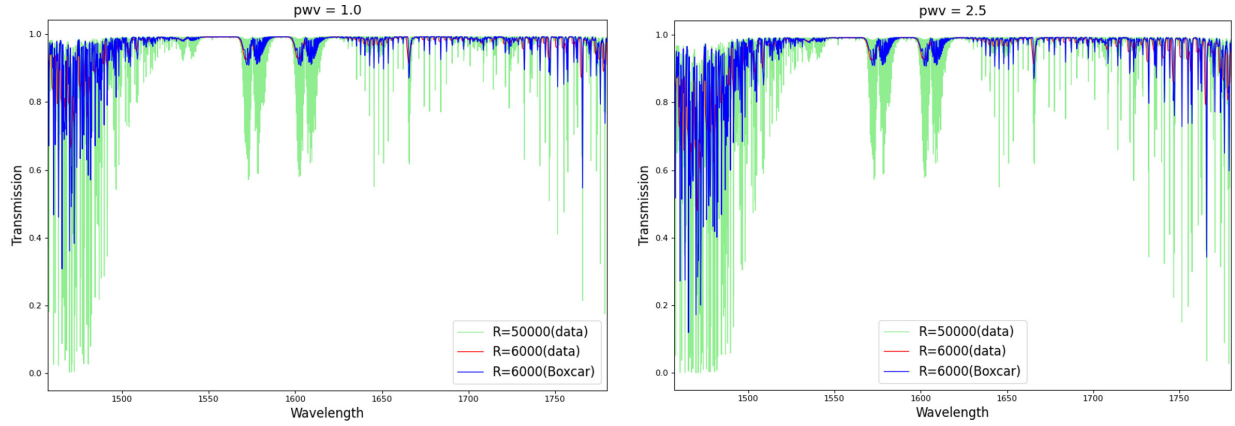


Figure 1. Sample data convolution in the red band (737~900 nm) of MR for the PWV 1.0 mm (left) and 2.5 mm (right). The green indicates the raw model data of $R \sim 50,000$ and the red is the convolution data of $R \sim 6,100$ that is gained from the ESO SkyCalc Sky Model Calculator. The blue is generated using boxcar method, which shows the same results compared with the red.

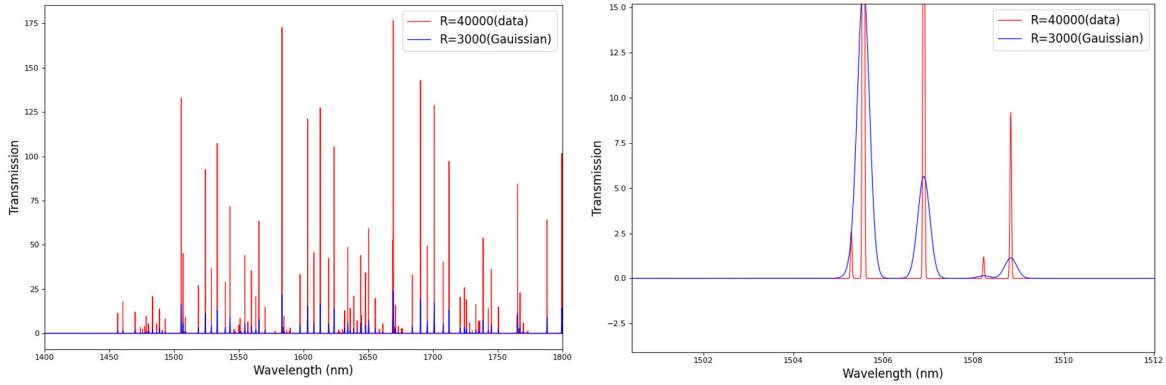


Figure 2. Plots of the reconvolution of the OH emission lines over the wavelength range of 1,400 to 1,800 nm (left) and the enlarged line profile (right). The red line indicates the original data and the blue line is the convolution spectra by the Gaussian method.

3. SOFTWARE

3.1 Development process

The software development process of the MSE-ETC is based on the Agile development methodology. The application will extend by units of feature in every iteration process from design to release phases. This model has the advantage of flexible reflection on the design change or user feedback. We use the Git repository for developer community to support sustainable development. Currently, the MSE-ETC code is available on GitHub (https://github.com/mse-cfht/etc_khu_group).

3.2 Software architecture

The MSE-ETC code consists of six modules except for *main.py* (see Figure. 3). The GUI and initial parameter settings are found in the *gui.py* and *initial_values.py* routines. And *functions.py* contains the functions for each of the calculation modes. The MSE instrument parameters as well as physical constants are defined in *parameters.py*. Throughput and atmospheric transmission information are calculated by *interpolate.py*. These parameters are transferred to *functions.py* during the calculation process. Finally, the results are displayed via *output.py*. The detailed data flow of the MSE-ETC is shown in Figure 4.

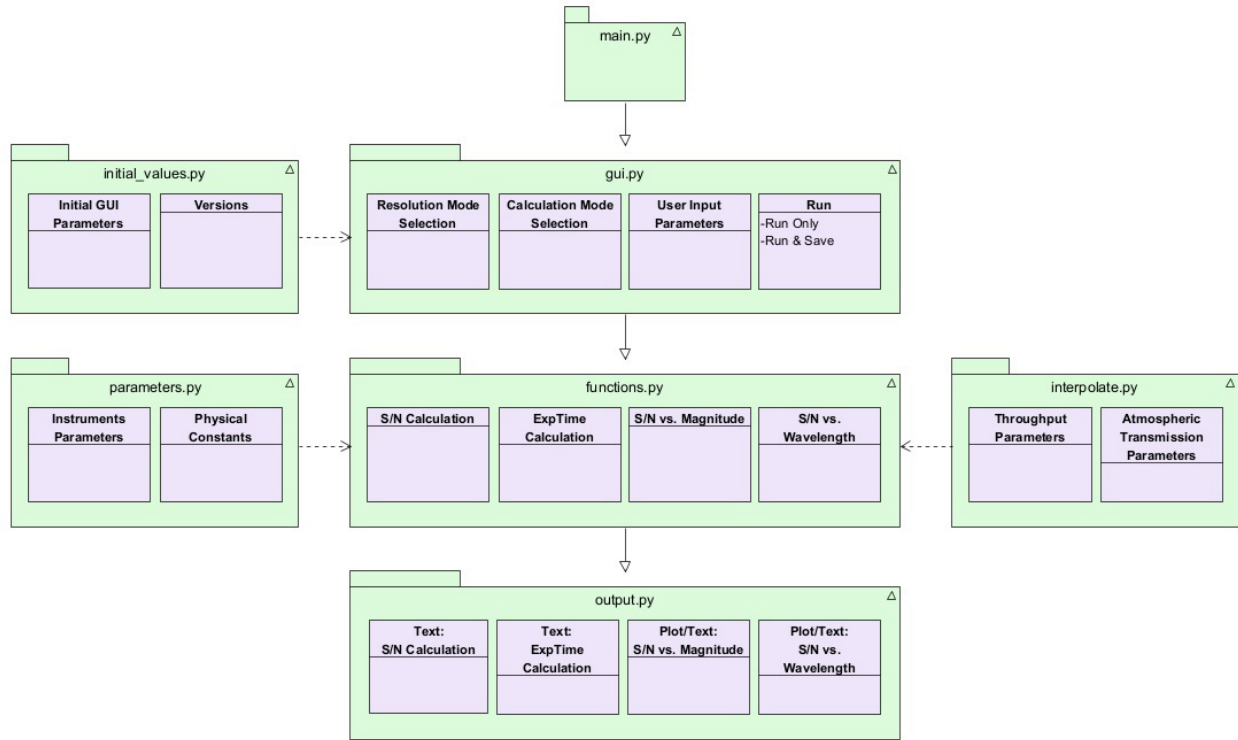


Figure 3. The software architecture of the MSE-ETC. It shows the connection between the Python module files, and the dashed line represents the importing.

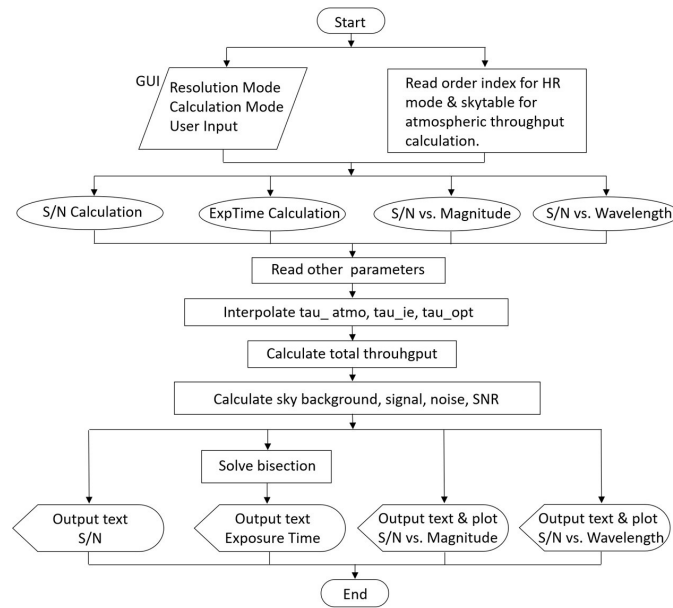


Figure 4. Entire diagram of data flow for the MSE-ETC. The functions, parameters, and outputs are determined by a user's selection on the GUI.

3.3 Graphical user interface (GUI)

The GUI of the MSE-ETC is designed with the Tkinter library for cross-platform use, and it runs on Windows, Linux, and Mac OS. The instrument parameters are applied automatically when the user selects the resolution and calculation mode. The simulation results are displayed on a separate window, such as a terminal and a figure plot (See Figure. 5).

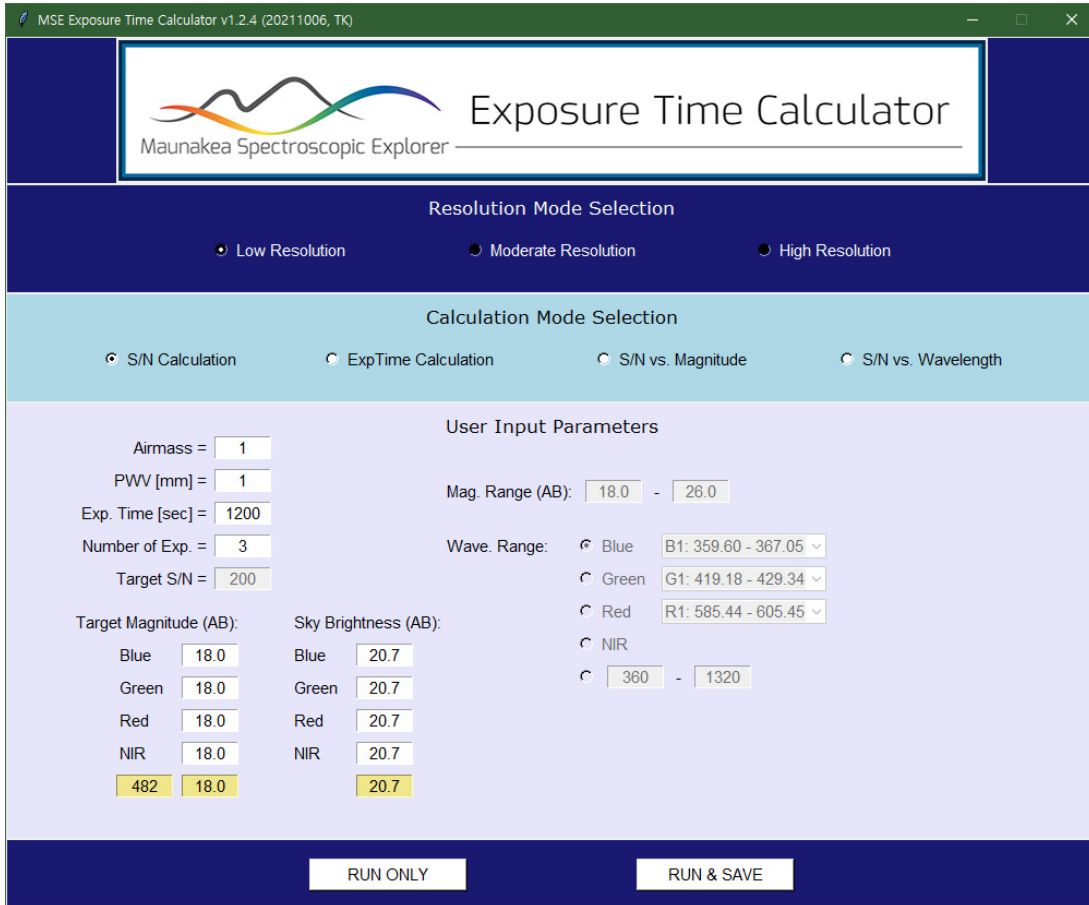


Figure 5. The GUI of the MSE-ETC. It is designed with pop-up application, which is written by Tkinter library on Python 3.

4. TEST AND RESULTS

The results of the S/N calculation and the exposure time calculation mode are displayed as shown in Figure 6. In this test, we set to resolution mode as LR, airmass to 1.0, PWV to 2.5 mm, and the number of exposures to a single frame. The target magnitude and sky brightness values are 18.00 and 20.70, respectively. They are also indicated by text in the output terminal.

S/N vs. magnitude and S/N vs. wavelength results are displayed by figures and stored in an array of data. The results of these two modes are displayed as shown in Figure 7. In this test, we set the airmass to 1.0, PWV to 1.0 mm, exposure time to 1200 seconds, and the number of exposure to 3 frames. The target magnitude and sky brightness input are 18.00 and 20.70, respectively.

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The calculation Signal-to-Noise from single magnitude input
Resolution Mode = Low Resolution
Airmass        = 1.0
PWV [mm]      = 2.5
Exposure Time [s] = 1200
Exposure Number = 1

Band  Mag.  Sky  S/N
[Blue] 18.00 20.70 130.586203
[Green] 18.00 20.70 118.995047
[Red] 18.00 20.70 135.685177
[NIR] 18.00 20.70 122.438872
[482.0] 18.00 20.70 130.586203 (Band = Blue)

=====
The calculation exposure time for target S/N
Resolution Mode = Low Resolution
Airmass        = 1.0
PWV [mm]      = 2.5
Exposure Number = 1
Target S/N    = 200

Band  Mag.  Sky  ExpTime [s]
[Blue] 18.00 20.70 2784.179688
[Green] 18.00 20.70 3346.679688
[Red] 18.00 20.70 2590.820312
[NIR] 18.00 20.70 3100.585938
[482.0] 18.00 20.70 2784.179688 (Band = Blue)
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Figure 6. Results of the S/N calculation mode (left) and the exposure time calculation mode (right) for single target magnitude input in the LR spectrograph. Blue, Green, Red, and NIR indicate the central wavelength of the filter bands.

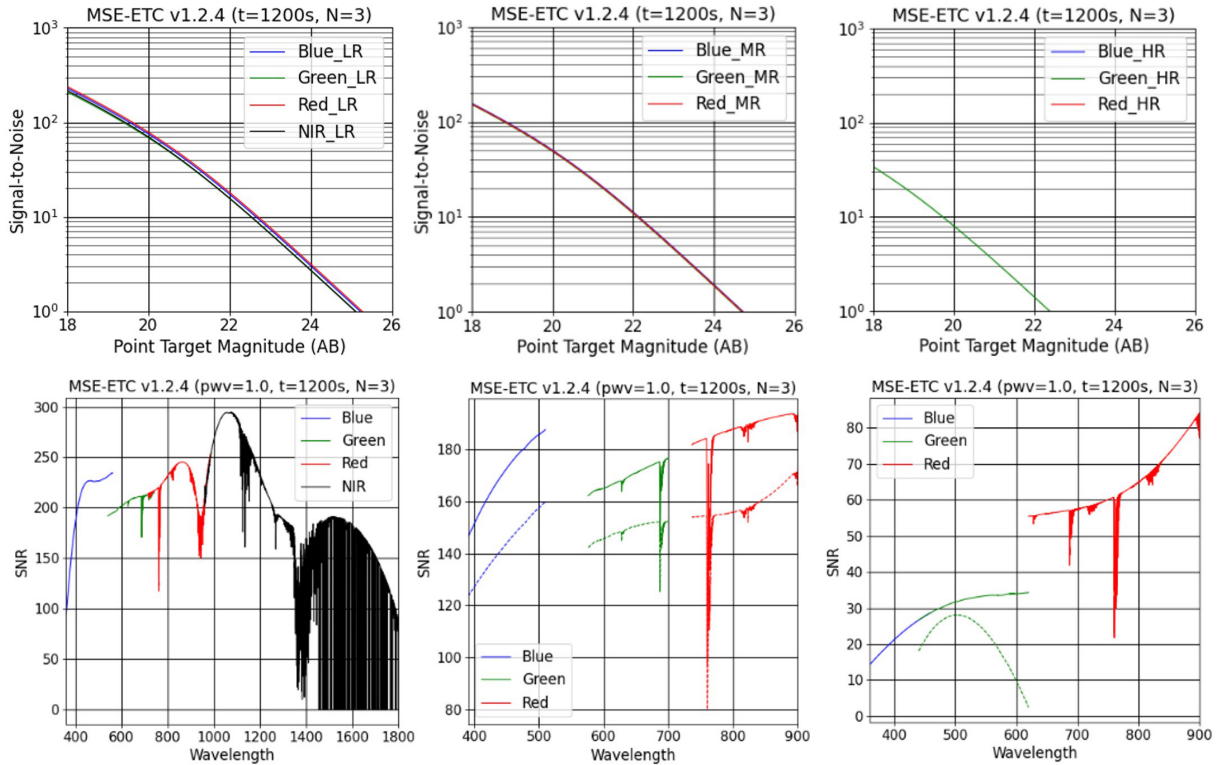


Figure 7. Plots of S/N vs. magnitude (top) and the S/N vs. wavelength (bottom) for LR (left), MR (middle), and HR (right) spectrographs. In the plots of the S/N vs. wavelength, the dashed lines in the MR and HR modes indicate the results including the grating efficiency.

5. SUMMARY

We are developing the MSE-ETC code to simulate the instrument performance of the MSE system, which has two instrument platforms of low/moderate resolution (LMR) and high resolution (HR). For a flexible development environment, we apply the agile process for software engineering. We also use a Git repository for code deployment and version tracking/management. In this paper, we have described the simulation methods and their parameters based on the calculation modes of the MSE-ETC. We have created a code architecture that allows for easy understanding of the data flow and structure of the code itself. We have also demonstrated the simulation results for each calculation mode of the ETC. In the future, we are planning for additional software upgrades (e.g., extended source consideration) and we will incorporate user feedback, which will be reflected in future code releases.

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REFERENCES

- [1] Szeto, K., Marshall, J. L., Flagey, N., Withington, K., and Surace, C., “Designing software for the science operations of Maunakea Spectroscopic Explorer,” in [*Software and Cyberinfrastructure for Astronomy VI*], Guzman, J. C. and Ibsen, J., eds., *Proc. SPIE* **11452**, 19–34 (2020).
- [2] Zhang, K., Shi, J., Wang, L., Zhu, Y., Tang, Z., Xin, Q., Szeto, K., Marshall, J., Flagey, N., Hill, A., Barden, S., and Gong, X., “Mauna Kea Spectrographic Explorer (MSE): new preliminary design for the multi-object high resolution spectrograph,” in [*Ground-based and Airborne Instrumentation for Astronomy VII*], Evans, C. J., Bryant, J. J., and Motohara, K., eds., *Proc. SPIE* **11447**, 1812–1822 (2020).
- [3] Hill, A., Flagey, N., McConnachie, A., and Szeto, K., [*The Maunakea Spectroscopic Explorer Book 2018*], MSE, CFHT Corp., MSE project document (2018).
- [4] Nicolas, F., [*MSE Sensitivity Budget Allocation Document*], MSE.PO.ENG.SYS-SYS-012-SensitivityBudgetAllocation, MSE project document (2018).
- [5] Noll, S., Kausch, W., Barden, M., Jones, A. M., Szyszka, C., Kimeswenger, S., and Vinther, J., “An atmospheric radiation model for Cerro Paranal - I. The optical spectral range,” *Astronomy and Astrophysics* **543**, A92 (2012).
- [6] Jones, A. M., Noll, S., Kausch, W., Szyszka, C., and Kimeswenger, S., “An advanced scattered moonlight model for Cerro Paranal,” *Astronomy and Astrophysics* **560**, A91 (2013).
- [7] Le, H. A. N., Pak, S., Daniel T. Jaffe, K. K., Jae-Joon Lee, M. I., and Seifahrt, A., “Exposure time calculator for Immersion Grating Infrared Spectrograph: IGRINS,” *Advances in Space Research* **55**, 2509–2518 (2015).
- [8] Rousselot, P., Lidman, C. E., Cuby, J.-G., Moreels, G., and Monnet, G. J., “Night-sky spectral atlas of OH emission lines in the near-infrared,” *Astronomy and Astrophysics* **354**, 1134–1150 (2000).
- [9] E., O. and L., O., “The OH airglow spectrum: a calibration source for infrared spectrometers,” *Astronomy and Astrophysics* **254**, 466–471 (1992).