

# XTcalc: MIRMOS Exposure Time Calculator

## v1

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## 1 Overview

XTcalc is an exposure time calculator for the Magellan Infrared Multi-Object Spectrograph (MIRMOS) concept. XTcalc uses an estimate of the instrument throughput, detector sensitivity, and noise, combined with estimates of the sky background, to calculate the signal to noise ratio (S/N) for a set of observations, or to estimate the exposure time required to reach a desired S/N. This code is based in large part off the Keck/MOSFIRE version of XTcalc, also written by G. Rudie.

## 2 Installation using IDL Virtual Machine

This is the default way to run the code. It does not require an IDL license.

### 2.1 Installation

First, the user should download and install the IDL virtual machine software. More information and a link to download is available at <https://www.harrisgeospatial.com/Support/Self-Help-Tools/Help-Articles/Help-Articles-Detail/ArtMID/10220/ArticleID/17309/The-IDL-Virtual-Machine>

Note that XTcalc was developed to be launched with `idl` from the command line. To run IDL from the command line, you must source the `'idl_setup'` file which is included in the `'bin'` directory of the IDL installation.

Once you have IDL set up, unpack the tarball and then set the environment variables with the location of the unpacked tarball:

- `'MIRMOS_XTCALC'` with the path where you put the code: REQUIRED. Note the directory will be `'[local_path]/XTcalc_dir'`
- `'MIRMOS_WD'` optional path for input and output files for MIRMOS. If not set, defaults to `'MIRMOS_XTCALC'`

### 2.2 Running the code

From the command line, in the directory `XTcalc_dir`, run the following line:

```
idl -vm=run_XTcalc_MIRMOS.sav
```

You can also supply the full path for `run_XTcalc_MIRMOS.sav`.

## 3 Installation with full IDL and license

If you already have a working IDL installation, the virtual machine is included. You can run the code as specified above. If you prefer, you can also compile the code and run it in the normal way with IDL as outlined below.

### 3.1 Installation

To run the code using a full IDL installation, XTcalc requires the astronomy idl library ‘ASTROLIB’. Note that when running the code outside the virtual machine, any settings in your IDL setup file as well as any previous code run in your IDL session may affect the performance of the code. If you run into issues, please attempt to use the code with the virtual machine, as outlined above.

The following code and directories are required to run XTcalc. In the bin directory in the packaged version of XTcalc, there are three .pro files which must be compiled prior to running the code.

- XTcalc\_MIRMOS.pro: This is the main program which does the actual S/N and exposure time calculations.
- run\_XTcalc\_MIRMOS.pro: This program creates and initializes the GUI.
- events\_XTcalc\_MIRMOS.pro: These programs handle the GUI actions and events.

In addition to the code, the following directories are also required:

- atmosphere: This directory contains the atmospheric transparency spectrum as well as night sky emission spectra.
- throughput: This directory contains spectra of the estimated throughput of MIRMOS.

The following environment variables should also be set:

- ‘MIRMOS\_XTCALC’ with the path where you put the code: REQUIRED. Note the directory will be ‘[local\_path]/XTcalc\_dir’
- ‘MIRMOS\_WD’ optional path for input and output files for MIRMOS. If not set, defaults to ‘MIRMOS\_XTCALC’

### 3.2 Running the code

- start IDL
- `.r run_XTcalc_MIRMOS`
- `.r XTcalc_MIRMOS`
- `.r events_XTcalc_MIRMOS`
- `run_XTcalc_MIRMOS`

## 4 Using XTcalc

XTcalc can be used in two principle modes: “Use Line Flux” or “Use Magnitude.” The line flux mode is useful for understanding the S/N within the FWHM of an individual emission line. The magnitude mode calculates the S/N over the full band of observations. In this mode, the default spectral shape is a flat  $f_\nu$  spectrum. However, users can also input their own ASCII spectrum to be considered. The program then scales the chosen spectral shape to match the input magnitude over the band pass considered.

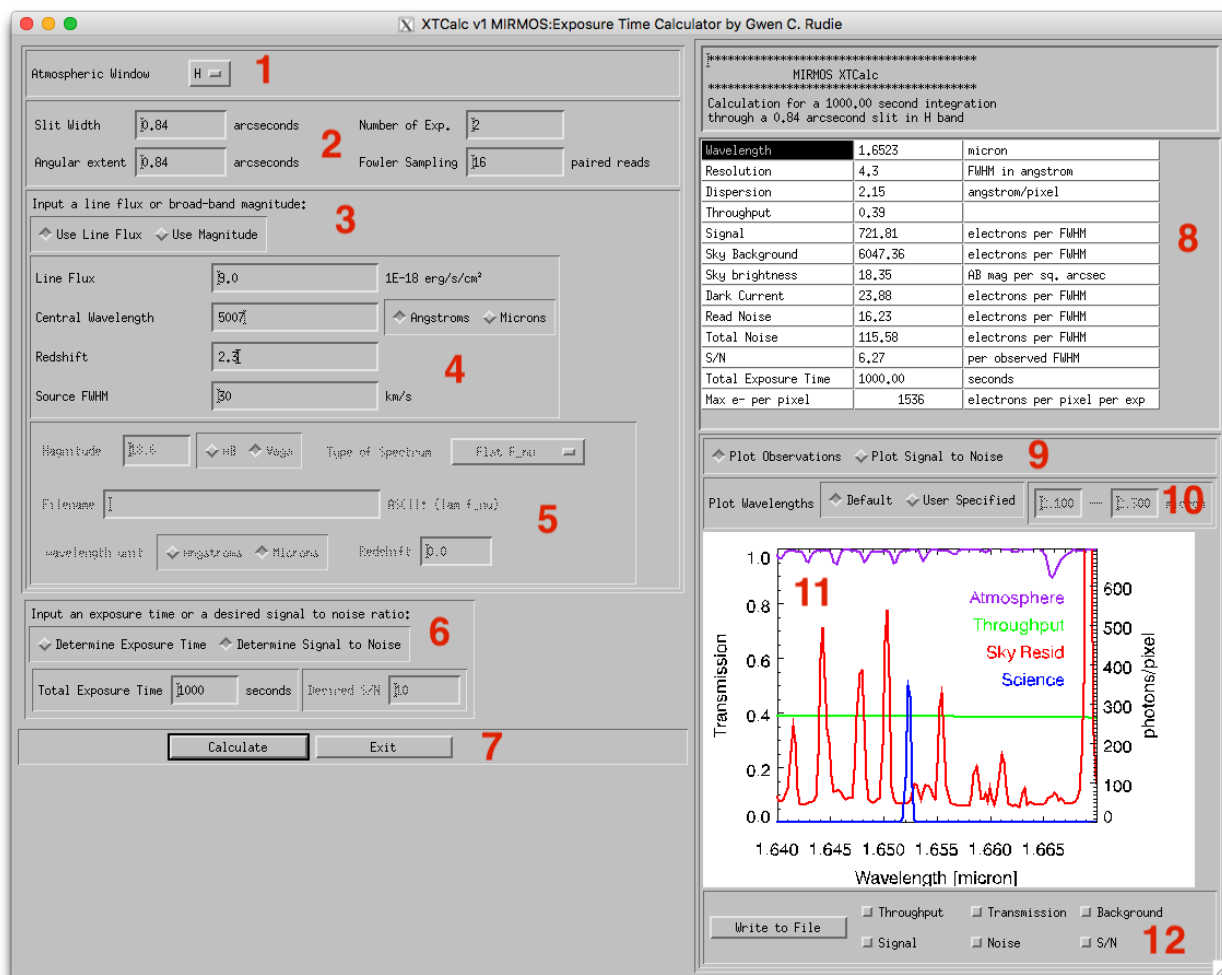


Figure 1 The XTcalc GUI. The red numerals mark the positions of various features as outlined in the text.

## 4.1 Input

Please refer to Figure 1 in the following section where the features of XTcalc are described. Sections 1-7 of the GUI allow users to input the properties of their objects. Sections 8-12 pertain to the output of the code.

- The atmospheric band (Y, J, H, or K) of the observations can be chosen with a pull down menu at position 1. While MIRMOS can observe all 4 atmospheric bands simultaneously, XTcalc currently performs signal to noise calculations for a single band at a time.
- At position 2, the slit width, angular extent of the object, number of exposures, and number of reads (fowler sampling) can be input.
- Position 3 allows users to choose either the line flux or continuum mode.
- Section 4 of the GUI pertains to the “Use line flux” mode. Within this section, the line flux, central wavelength, redshift, and FWHM of the line can be input.
- Section 5 pertains to the “Use Magnitude” function. Here the magnitude in AB or Vega can be specified. The spectral shape can be selected using the pull down menu at the top right-hand corner of the box. If the user would like to import their own spectra, choose “My Own Spectrum” from the pull down menu. You will be prompted to select a file with the input ASCII spectrum with a format ( $\lambda f_\nu$ ). The wavelengths can be provided in micron or Å. The spectrum can also be a rest wavelength spectrum, and the observed redshift can be entered. The program will scale the chosen spectral shape to match the input magnitude over the band pass considered. If you do not wish to rescale the spectrum, enter 0 as the magnitude.
- The box labeled “6” is where the user chooses to calculate the S/N given the exposure time or vice versa.
- Position 7 marks the location of the “Calculate” button which runs XTcalc with the specified parameters and the “Exit” button which closes the GUI.

## 4.2 Output

- Section 8 outputs the calculated values for the signal, various sources of noise, the S/N and the exposure time. The bottom line of the table is useful for checking the saturation level of the data. If the box turns yellow, the exposure time and number of exposures suggest that some of the pixels will pass the 1% linearity. Orange represents the 5% linearity. And red means some of the pixels are saturated.
- Section 11 provides graphical information regarding the science observations.
- Section 9 controls what is plotted in the graphical output at position 11. One can choose to plot the Signal and sky residual spectra. Alternatively, users can view the signal, noise and S/N of the spectra.
- Section 10 allows users to change the plotted range in section 11.
- Section 12 allows users to print out ASCII spectra of the throughput, transmission, background, signal, noise, and S/N for their proposed observations.

## 5 Throughput

An estimated throughput of the instrument is implemented in XTcalc. Estimated throughput spectra are found in the “throughput” directory distributed with this code. These spectra include estimates for the transmission of the atmospheric dispersion corrector, collimator, camera, dichroics, and VPH gratings. Also included in the spectra is the reflectivity of the telescope’s three mirrors, the expected QE of the detectors, and the estimated aperture loss due to stops. We include an additional margin of 10% to account for unanticipated loss of light in the final spectrograph.

## 6 Sky Background

The background sky spectrum assumed by XTcalc was taken with Keck/MOSFIRE. At the blue end of the Y band shortward of the wavelength coverage of Keck/MOSFIRE, we use the sky emission spectrum available from the Gemini Observatory website.<sup>1</sup> The K-band spectrum includes additional thermal continuum to account for the somewhat higher ambient temperature at LCO.

The spectrum is integrated over the angular extent of the object  $\theta$  and is scaled considering the slit width selected. **Note that when the calculator is used with a broad band magnitude, the angular size of the object is assumed to be the same as (or less than) the slit width. Slit losses are not currently calculated.** We will refer to the spectrum of the sky background in units of photons  $\text{sec}^{-1}$  (spectral pixel)<sup>-1</sup> as  $\beta_{\text{sky}}$ .

## 7 Atmospheric Transparency

The atmospheric transparency used in the calculator are the transparency spectra from Gemini Observatory: Lord, S. D., 1992, NASA Technical Memorandum 103957. We assume 3.0 mm precipitable water vapor column and a 30 degree zenith angle.

## 8 The Source Spectrum

### 8.1 Line Flux

The quantity calculated is the signal to noise ratio in the line. If you input a S/N and ask for an exposure time, the program assumes you have input the desired S/N *per FWHM* of the line. Note that this quantity depends on both the spectral resolution and the entered intrinsic line width.

### 8.2 Broad Band Magnitude

The quantity calculated is the signal to noise ratio per spectral pixel. If you input a S/N and ask for an exposure time, the program assumes you have input the desired S/N *per spectral pixel*.

If you are using the broad band magnitude calculator, the spectrum chosen is read in. The default is a spectrum that is flat in  $f_{\nu}$ . The spectrum is convolved with the MOSFIRE resolution and resampled onto the MOSFIRE pixel scale. It is multiplied by the filter transmission spectrum, and then the spectrum is normalized such that the flux in the band pass matches the specified broad band magnitude. Note that if you do not wish for the spectrum to be rescaled, enter 0 in the magnitude box. The spectrum is then multiplied by the atmospheric transparency spectrum and the instrument+telescope throughput spectrum. The resulting spectrum has units of photons  $\text{sec}^{-1}$  (spectral pixel)<sup>-1</sup> and will hence forth be refereed to as  $S$ .

## 9 Noise Calculation

The number of pixels over which the source is spread in the spatial and spectral dimension will factor into the calculation of the noise. The number of pixels along the spatial dimension,  $N_{\text{Spatial}}$ , is taken to be the spatial extent of the object  $\theta$ , divided by the spatial pixel scale, 0.38 arcseconds pixel<sup>-1</sup>.

Here, we produce a spectrum of the noise. The units will be photons per spectral pixel. The increase in noise from spreading the light over the spatial direction will have already been factored in. The contributions to the noise,  $\eta_{\text{tot}}$ , considered are the read noise and the Poisson noise from the background, dark current (assumed to be 0.005 electrons  $\text{s}^{-1}$  pixel<sup>-1</sup>), and source.

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<sup>1</sup><https://www.gemini.edu/observing/telescopes-and-sites/sites>

Table 1. Assumed MIRMOS Parameters

Name	Value	Units
Pixel Scale (spatial)	0.38	arcsec/pixel
Pixel Scale (dispersion)	0.42	arcsec/pixel
Detector Read Noise	21	electrons/pixel CDS
Dark Current	0.005	electrons/sec/pixel
K-band Dispersion	3.003	Å/pixel
H-band Dispersion	2.153	Å/pixel
J-band Dispersion	1.548	Å/pixel
Y-band Dispersion	1.478	Å/pixel
K-band $R\theta$ Product	3024	arcsec
H-band $R\theta$ Product	3192	arcsec
J-band $R\theta$ Product	3360	arcsec
Y-band $R\theta$ Product	2856	arcsec

### 9.1 Single Exposure

The read noise,  $\eta_{\text{read}}$ , is the detector read noise, RN, in electron  $\text{pixel}^{-1} \text{ read}^{-1}$  reduced by the Fowler sampling with  $N_{\text{reads}}$  and increased by the number of pixels.

$$\eta_{\text{read}} = \frac{\text{RN}}{\sqrt{N_{\text{reads}}}} \sqrt{N_{\text{spatial}}} \quad (1)$$

The noise resulting from the dark current is Poisson in nature:

$$\eta_{\text{dark}}(t) = \sqrt{N_{\text{Spatial}} D t} \quad (2)$$

Then the total noise per spectral pixel is:

$$\eta_{\text{tot}} = \sqrt{S t + \beta_{\text{sky}} t + \eta_{\text{dark}}^2(t) + \eta_{\text{read}}^2} \quad (3)$$

where  $D$  is the dark current in units of electron  $\text{sec}^{-1} \text{ pix}^{-1}$  (assumed to be 0.005). The source and sky Poisson noise is not multiplied by the number of spatial pixels in this expression because that has already been considered in the calculation of their spectrum in photon  $\text{sec}^{-1} (\text{spectral pixel})^{-1}$ .

The signal to noise ratio per spectral pixel is then:

$$S/N = \frac{S}{\eta} \quad (4)$$

### 9.2 Multiple Exposures with a Two Point Dither

If the number of exposures,  $N_{\text{exp}}$ , is  $> 1$ , then a two point dither pattern is assumed in the S/N calculation. The exposure time input is considered to be the *total* exposure time, and the exposure time of the individual frames is taken to be  $t/N_{\text{exp}}$ . The total noise per spectral pixel after the frames are differences and co-added is:

$$\eta_{\text{tot}} = \sqrt{N_{\text{exp}}} \sqrt{S \frac{t}{N_{\text{exp}}} + 2 \left( \beta_{\text{sky}} \frac{t}{N_{\text{exp}}} + \eta_{\text{dark}}^2(t/N_{\text{exp}}) + \eta_{\text{read}}^2 \right)} \quad (5)$$

The  $\sqrt{N_{\text{exp}}}$  results from the fact that the error in individual exposures is added in quadrature. And the 2 results from the additional contribution of read noise and Poisson noise from the background and dark current which occurs when using difference frames due to the noise in the estimate in the background.

This expression simplifies to:

$$\eta_{\text{tot}} = \sqrt{St + 2(\beta_{\text{sky}}t + \eta_{\text{dark}}^2(t) + N_{\text{exp}}\eta_{\text{read}}^2)} \quad (6)$$

The S/N per spectral pixel is then simply:

$$\text{S/N} = \frac{St}{\sqrt{St + 2(\beta_{\text{sky}}t + \eta_{\text{dark}}^2(t) + N_{\text{exp}}\eta_{\text{read}}^2)}} \quad (7)$$

### 9.3 S/N per resolution element or per FWHM

To instead have the S/N per resolution element or the S/N in a line, we multiply by the square root of the number of spectral pixels per resolution element or per FWHM,  $N_{\text{Spectral}}$ .

$$N_{\text{Spectral}} = \frac{\text{FWHM}}{\text{dispersion}}, \quad (8)$$

for the S/N in a line, or

$$N_{\text{Spectral}} = \frac{\text{Resolution Element}}{\text{dispersion}}, \quad (9)$$

for a continuum source.

The signal to noise reported for the "Use line flux" option is the signal to noise per FWHM within the line. The signal to noise reported for the "Use Magnitude" option is the median S/N per spectral pixel where the median is taken over the full band pass of the selected filter.

## 10 GUI Table

The max e- per pixel will turn yellow if the observations will have a pixel past the 1% linearity point of the detector. If the observations surpass the 5% linearity level, the row will turn orange. If the pixel would saturate, the row will turn red.