Extreme Precision Doppler Spectrometer Exposure Time Calculator
Documentation
Daniel Q Nagasawa

Department of Physics and Astronomy, Texas A&M University, College Station, Texas, USA 77840
dnagasawa@physics.tamu.edu

ABSTRACT

This document is a brief description of the underlying assumptions and equations of the exposure time calculator written for the Extreme Precision Doppler Spectrometer (EPDS) project proposed by the Department of Physics and Astronomy at Texas A&M University, in partnership with scientists at the University of Texas at Austin, Johns Hopkins University, Indiana University, NOAO, and the Johns Hopkins University Applied Physics Laboratory. For more information about the project itself, please see the instrument website at http://instrumentation.tamu.edu/epds.html.

I. Description

I.a. S/N Calculator Mode

In S/N Calculator Mode, the calculator takes a given exposure time and generates a graph of S/N as a function of wavelength for a star of a particular spectral type and V magnitude. For this mode, the parameter “Calculator Input” should set to the exposure time in seconds that the user would like to calculate S/N for. For convenience, the program will output an S/N at a particular wavelength, set as parameter “Wavelength of Interest” in Å.

I.b. Exposure Time Calculator Mode

In Exposure Time Calculator Mode, the calculator takes a given required S/N and generates a graph of exposure time in seconds required to achieve that S/N as function of wavelength; it can do this for a variety of spectral types and V magnitude. For this mode, the parameter “Calculator Input” should set to the required S/N that the user would like to calculate the exposure time for. For convenience, the program will output an exposure time at a particular wavelength, set as parameter “Wavelength of Interest” in Å.

II. Telescope and Spectrograph Parameters

The Extreme Precision Doppler Spectrometer (EPDS) is a proposed echelle spectrograph of resolution $R = \lambda / \Delta \lambda \sim 70,000$ being proposed for the WIYN 3.5m telescope. It will be fed by a 70µm fiber, corresponding to 0.66 arcseconds in the sky. Light entering the telescope will reflect off 3 aluminum coated mirror before interacting with the spectrograph with one additional aluminum coated mirror in the spectrograph itself. Other components of the spectrograph accounted for in the throughput calculation of EPDS are the echelle and the cross-dispersal gratings.
III. Exposure Time Calculator

III.a. Template Spectra of Various Spectral Types

The calculator utilizes the Pickles Atlas of Stellar Spectra Flux (Pickles 1998). Fluxes in the Pickles atlas are provided in ergs/s/cm²/Å for a 0 magnitude star in Vega V magnitudes. It should be noted that the Pickles atlas provides flux for wavelengths 1150Å to 25000Å in increments of 5Å. EPDS is limited to 3800Å to 6800Å and provides a dispersion of 0.017Å/pixel.

A target flux relative to Vega is calculated using the target Vega system V magnitude \( V_{\text{target}} \), the airmass of the target \( X \), and the Vega system V magnitude of the template spectrum (\( V_{\text{std}} = 0 \)) in Equation 1.

\[
F_{\text{rel}}(\lambda) = 10^{-0.4\left(V_{\text{target}} + (X \times E(\lambda)) - V_{\text{std}}\right)}
\]

In Equation 1, \( E(\lambda) \) represents the extinction of the atmosphere for Kitts Peak National Observatory in units of magnitudes/airmass (obtained from the onedstds folder in the onedspec package of IRAF). Equation 1 is used to calculate a flux relative to a magnitude 0 star for all wavelengths of interest; by multiplying this by the flux of the template spectra, a flux of an appropriate spectral type with an appropriate magnitude is determined for all wavelengths of interest, \( F_{\text{target}}(\lambda) \). At each wavelength, we calculate the photon energy and, using this flux, calculate the number of photon flux of the target star \( C_{\text{target}} \) in photons/s/cm²/Å; this is shown in Equation 2.

\[
C_{\text{target}}(\lambda) = \frac{\lambda F_{\text{target}}(\lambda)}{hc}
\]

In Equation 2, \( h \) represents Planck’s constant and \( c \) represents the speed of light in a vacuum.

III.b. Efficiency of EPDS

The total number of photons collected \( P_{\text{target}}(\lambda) \) can be calculated using \( C_{\text{target}} \) through Equation 3

\[
P_{\text{target}} = C_{\text{target}}(\lambda) A_T \prod_{i=1} O_i
\]

The collecting area of the telescope \( A_T \) can be calculated as:

\[
A_T = \pi(D/2)^2 \times (1 - R_O^2)
\]

where \( D \) represents the diameter of the telescope and \( R_O \) represents the radial obscuration ratio (for the specific case of the WIYN 3.5m telescope, \( R_O = 0.33 \)); Equation 4 yields a total collecting area of \( A_T = 8.57 \times 10^4 \) cm².

The remaining efficiency terms \( O_i \) are the efficiencies of the various optical components. We use efficiencies for similar components in our sample calculation. Included in this efficiency calculation are (for version 1.1):
Fig. 1.— Total efficiency of the combined optical components that make up EPDS, including 4 Al-coated mirrors, 1 70μm fiber, 1 echelle grating, and 1 VPH grating.

- 4 aluminum coated mirrors
- 1 70μm, 25m long FBP-type polymicro fiber
- 1 echelle grating
- 1 volume phase holographic grating

The total efficiency of the system can be seen in Figure 1.

### III.c. Spectrograph and Pixel Calculations

The dispersion per slit width $D_{\text{slit}}$ and the dispersion per pixel $D_{\text{pix}}$ are calculated using the following equations:

$$D_{\text{slit}} = \frac{\lambda_c W_{\text{slit}}}{R} \quad (5)$$

$$D_{\text{pix}} = D_{\text{slit}} / (\text{pixels per resolution element}) \quad (6)$$

The calculator assumes that EPDS will allocate 3 pixels per resolution element. This yields $D_{\text{pix}} = 0.017$ Å/pixel. We can then calculate the number of target photons per pixel per second. We do this in Equation 7.
\[ P_{\text{pix}} = P_{\text{target}} \times D_{\text{pix}} \quad (7) \]

### III.d. Sky Background Counts

The calculator performs a similar computation for sky-sourced photons. We assume that at V magnitude of 0, the sky produces 100 photons/s/cm\(^2\)/Å/arcsecond\(^2\) across all wavelengths; the calculation for the number of photons produced by the sky is represented in Equation 8

\[ C_{\text{target}} = 100 \times 10^{-0.4V_{\text{sky}}} \quad (8) \]

Sky photons are treated similarly to target photons eventually yielding a number of collected sky photons per second in photons/s/Å/arcsecond\(^2\), \(P_{\text{sky}}\). In calculating the number of sky photons per pixel per second \(P_{\text{sky pix}}\), we also multiply this collected sky photons per second by the area of the sky covered by our 70\(\mu\)m target fiber, \(A_F\). This is seen in Equation 9

\[ P_{\text{sky pix}} = P_{\text{sky target}} \times D_{\text{pix}} \times A_F \quad (9) \]

### III.e. S/N Calculator

The signal is calculated using \(t_{\text{exp}}\), the exposure time in seconds. This is seen in Equation 10. Our noise is taken to be the square root of the counts per pixel, seen in Equation 11.

\[ \text{Signal} = P_{\text{pix}} \times t_{\text{exp}} \quad (10) \]

\[ \text{Noise} = \sqrt{t_{\text{exp}} \left( P_{\text{sky pix}} + P_{\text{pix}} \right)} \quad (11) \]

We take the ratio of these two to determine the signal-to-noise at every wavelength.

### III.f. Exposure Time Calculator

Given a required S/N ratio \(R\), we can calculate the necessary exposure time to achieve that S/N. This can be seen in Equation 12.

\[ t_{\text{exp}} = \left( \frac{R \sqrt{P_{\text{sky pix}} + P_{\text{pix}}}}{P_{\text{pix}}} \right)^2 \quad (12) \]

We can therefore calculate the required exposure time to achieve a certain S/N as a function of wavelength.
I would like to acknowledge all my professors and all my colleagues, especially Ting Li who assisted with the website and coding of the program.

REFERENCES