EXOplanet MOdeling Package (EXOMOP): Version 7.0

Jake Turner[1]
1. Department of Astronomy, University of Virginia, jt6an@virginia.edu

1. WHAT IT DOES:

1. Fits your transit data using a Levenberg-Marquardt (LM) least-squares techniques to a Mandel & Agol (2002) model
   (a) Finds robust errors on this fit using the Bootstrap Monte Carlo technique
2. Fits your transit data using a Differential Evolution Markov Chain Monte Carlo (MCMC) fit (ter Braak 2006) and finds errors.
   (a) Program stops when chains are well-defined using the Gelman-Rubin Statistic (Ford 2006)
3. Fits a linear or quadratic function to the OoT baseline simultaneously with the Mandel & Agol (2002) model for both the LM and MCMC methods
4. Accesses the influence of red noise for both the LM and MCMC methods (uses the residuals from the respective method):

   (a) Uses the Prayer Bead Method (Residual-Permutation Method) to access the influence of red noise on the transit and calculates new errors
      i. The method by Fernandez et al. 2009 but has updated to use the error bars from the residual (Like the Bootstrap Monte Carlo method). Assumes a Gaussian Distribution
      ii. The method in Todorov et al 2012 (APJ, 746,111). Does not assume a Gaussian Distribution.
   (b) Uses the Time-Averaging Method (Beta Method) (finds σ red Noise and σ white Noise) (Pont et al 2006, 373,231)
   (c) Uses the Wavelet Method (finds σ red noise and σ white noise) (Carter Winn 2009, APJ, 704, 51)

5. Finds the asymmetry of the transit about the calculated mid-transit time

2. HOW TO USE:

The only code that is called is EXOMOPv7.0.pro, all other included codes are called by this program or by programs called by this program.
The 11 programs (EXOMOPv7.0.pro,model_fit.pro,Useful_Values.pro, Detrend_linfit.pro, Detrend_quadfit.pro, bin.pro,beta_model.pro,exomop_chi2.pro,exomop_mcmcv2.pro, exomop_prayer.pro,exomop_wavelet.pro) used were developed by Jake Turner at the Lunar and Planetary Laboratory and University of Virginia for use in fitting planetary transit light curves.

All other programs referenced therein were developed by others and utilized in this code. All of these are included in the 'sub' folder. Any other codes required by this program that are not included are readily available on the Internet from a variety of sources. Most are available through the IDL Astronomy User's Library (http://idlastro.gsfc.nasa.gov/).

3. TO COMPILE:

Simply put these procedures in your IDL path
ex. !PATH = Expand_Path('+/home/jturner/data/EXOMOPv6.0:+/home/jturner/data/EXOMOPv6.0/sub') + ':' + !PATH

4. REQUIREMENTS:

IDL v 7.0 or later
May be compatible with earlier versions, but they have not been tested

5. INPUT REQUIREMENTS:

1. Your transit file. This file needs to contain: Time (HJD), Normalized Flux, Error
   (a) Program will not run unless you have error bars for each data point.
   (b) NOTE (limitation): Time of transit needs to be input with only the ones place and the decimals (e.g. change 2454218.90003 to 8.90003)
2. Input File (See Section 7.1 for more details)

6. RECOMMENDED PROCEDURE FOR EFFECTIVE RESULTS:

1. To check whether a linear or quadratic OoT fit is needed, check the Bayesian Information Criterion (BIC; Schwarz 1978).
   (a) whichever model minimizes the value of the BIC should be used (see discussion in Gibson et al, 2010, MNRAS, 404, L114-L118 about over-fitting and the use of the BIC)
2. Always check the Input_Values.dat file to make sure you fixed/fit the appropriate parameters and respective values
3. You will always fit R_p/R_* and Mid-Transit Time
4. Fit the following sets of parameters with ONLY the LM fit
   (a) Fit R_p/R_* and Mid-Transit time
   (b) Fit R_p/R_*, a/R_*,Mid-Transit Time
   (c) Fit R_p/R_*, Inclination, and Mid-Transit Time
   (d) Fit R_p/R_*,a/R_*, Inclination, Mid-Transit Time
5. After you ran all of these models check gauss.ps and gauss_prayer.ps to see if they are Gaussians A. If the parameters are not Gaussian then it is not recommended you fit those values
6. After you decide which parameters are the best to fit (See 2 above) run the full code with the MCMC fit

7. TO RUN:

In an IDL command window, navigate to the directory containing the above files. Then, type:

.r Useful_Values.pro
.r Detrend_linfit.pro
.r Detrend_quadfit.pro
.r exomop_prayer.pro
.r exomop_mcmcv2.pro
.r exomop_wavelet.pro
.r EXOMOPv7.0.pro
EXOMOP70,'Input_file.text'

7.1. Input File

An example Input File called input_file.text can be found with the download. Copy this file into your working directory and edit it.

The input file will ask you the following questions (Discovery values are encouraged and make sure your transit is normalized):

1. Object Name:
2. Folder name (EXOMOP will create this folder and everything will go in it):
3. Transit File:
4. Run the LM model fit:
5. Run the MCMC model fit:
6. Number of Monte Carlo Simulation to Run (10000 is a good number):
7. Maximum number of MCMC steps:
8. Number of Chains in MCMC fit:
9. Time in Phase? (0=YES,1=NO):
10. Initial Guess for R_p/R_*:
11. Initial Guess for a/R_*:
12. Initial Guess for Inclination (degrees):

13. Initial Guess for Mid-Transit Time (HJD):
14. Linear Limb Darkening Coefficient:
15. Quadratic Limb Darkening Coefficient:
16. Orbital Period (days):
17. Eccentricity:
18. Omega (Degrees):
19. Would you like to fit R_p/R_* (0=YES,1=NO):
20. Would you like to fit a/R_* (0=YES,1=NO):
21. Would you like to fit Inclination (0=YES,1=NO):
22. Would you like to fit the Mid-Transit Time (0=YES,1=NO):
23. Would you like to fit Linear Limb Darkening Coefficient (0=YES,1=NO):
24. Would you like to fit Quadratic Limb Darkening Coefficient (0=YES,1=NO)
25. Would you like to detrend the Out of Transit Baseline? (0=YES,1=NO):
26. Would you like to detrend the Out of Transit Baseline? (0=YES,1=NO):
27. Function of baseline fit (0=NO, 1=linear, 2=quadratic):
28. Data point (#) where ingress baseline ends:
29. Data point (#) where egress baseline starts:
30. Would you like to calculate the symmetry of the transit (0=YES,1=NO):
31. Renormalize the light curve (0=YES, 1=NO):

8. OUTPUTS:

8.1. IN MAIN FOLDER:

1. Input_file.text - Your input file.
2. Input_Value.dat - A file containing the input values and what values were fixed. This is what the program read from your input file

3. plot_LM.ps - Plot of the Best-fit model, data, and residuals from the Levenberg-Marquardt (LM) non-linear least-squares fit

4. plot_MCMC.ps - Plot of the Best-fit model, data, and residuals from the Differential Evolution Markov Chain Monte Carlo (MCMC) fit

5. Best-Fit_LM.dat - Time, Phase, original transit,detrended transit, error, best-fit model, and residuals from LM method

6. Best-Fit_MCMC.dat - Time, Phase, original transit,detrended transit, error, best-fit model, and residuals from MCMC method

7. FINAL_EVERYTHING.dat
   (a) Bayesian information Criterion
   (b) RMS of residuals from LM Method
   (c) RMS of residuals from MCMC Method
   (d) Differential Evolution Markov Chain Monte Carlo Parameter Values and Errors
      i. White noise red noise (both methods), Beta from Time-Averaging Method, Parameter Betas from Residual-Permutation Method (both methods)
   (e) Monte Carlo Levenberg-Marquardt Parameter Values and Errors
      i. White noise red noise (both methods), Beta from Time-Averaging Method, Parameter Betas from Residual-Permutation Method (both methods)
   (f) Other Useful Values
      i. Duration
      ii. Cadence
      iii. Out of Transit STDEV
      iv. Reduced Chi-Squared
      v. STDEV of Asymmetry
      vi. Version Number
      vii. Time and Date of Model

8.2. IN MCMC FOLDER:

1. Final_Parameters_MCMC.dat - Final parameters and errors from MCMC fit

2. beta_plot.ps - Plot of relative rms vs bin size (line is with no red noise Original_RMS/sqrt(bin size)) see Knutson et al 2012 (APJ, 754, 22)

3. gauss_prayer_mcmc.ps - Plot of the distribution of fitted parameters by the Prayer Bead Method from the Monte Carlo simulations

4. Final_parameters_prayer_mcmc.dat -

   (a) The fitted parameters of the planet with error bars derived from the Prayer Bead Red Noise method (rp/R_*,a/R_*,Inclination, Mid-Transit Time, Linear and Quadratic LD)

   (b) Beta Values of fitted parameters (Red noise error/white noise error)

5. Final_parameters_Beta_mcmc.dat

   (a) Sigma White Noise and error

   (b) Sigma Red Noise and errors

   (c) Beta Value calculated from the Time-Averaging Red Noise Technique

6. monte_value_prayer_mcmc.dat - Each Monte Carlo run from the Prayer Bead Method 1 (Best-fit model-monte carlo value)

7. probability_plot.ps -Plot of Probablity Distribution Functions (PDFs)

8. covar.ps -plot of covariances

9. monte_value_prayer_method2.dat - Each Monte Carlo run from the Prayer Bead Method 2 (Best-fit model-monte carlo value)

10. variablename_prayer_histogram.ps - histogram of monte_value_prayer_method2.dat for each parameter. Red-dashed lines are the error bars derived.

8.3. IN LM FOLDER:

1. Final_parameters_prayer.dat

   (a) The fitted parameters of the planet with error bars derived from the Prayer Bead Red Noise method (R_p/R_*,a/R_*,Inclination, Mid-Transit Time, Linear and Quadratic LD)

   (b) Beta Values of fitted parameters (Red noise error/white noise error), Both methods

2. Final_parameters_Beta.dat

   (a) Sigma White Noise and error

   (b) Sigma Red Noise and errors

   (c) Beta Value calculated from the Time-Averaging Red Noise Technique

3. Final_parameters.dat

(a) The fitted parameters of the planet with error bars from the Levenberg-Marquardt Monte Carlo method (R_p/R_*,a/R_*,Inclination, Mid-Transit Time, Linear and Quadratic Limb Darkening)

(b) Duration of transit in days and mins (with errors)

(c) Cadence of observations (days and secs)

(d) Out of Transit RMS

(e) RMS of residuals

(f) Reduced Chi-Squared from best fit-model

(g) Lowest Monte Carlo Reduced Chi-Squared

(h) STDEV of the transit subtracted by the mirror image of itself (from transitsymmetry.pro)

(i) Baseline Intercept calculated from Detrend_linfit.pro

(j) Baseline slope calculated from Detrend_linfit.pro

4. Best-Fit_LM.dat - Time, Phase, original transit,detrended transit, error, best-fit model, and residuals

5. plot_LM.ps - Plot of the Best-fit model, data, and residuals

6. monte_value2.dat - Each Monte-Carlo run (Best-fit model-Monte Carlo value)

7. monte_value.dat - Each Monte-Carlo run (Monte Carlo values and Chi-Squared)

8. gauss.ps - Plot of the distribution of fitted parameters from the Monte Carlo simulations

9. Asymmetry_Plot.ps - 4 Plots showing the asymmetry process (the 4th plot shows the subtraction)

10. symmetry_test - time and flux used for the asymmetry test

11. monte_value_prayer.dat - Each Monte Carlo run from the Prayer Bead Method (Best-fit model-monte carlo value)

12. gauss_prayer.ps - Plot of the distribution of fitted parameters by the Prayer Bead Method from the Monte Carlo simulations

13. beta_plot.ps - Plot of relative rms vs bin size (line is with no red noise Original_RMS/sqrt(bin size)) see Knutson et al 2012 (APJ, 754, 22)

14. beta_value.dat - The Values plotted beta_plot.ps (Bin size,Relative RMS,Original_RMS/sqrt(bin size))

15. monte_value_prayer_method2_LM.dat - Each Monte Carlo run from the Prayer Bead Method 2 (Best-fit model-monte carlo value)
16. variablename_prayer_histogram.ps - histogram of monte_value_prayer_method2_mcmc.dat for each parameter. Red-dashed lines are the error bars derived.

9. LIMITATIONS:

1. Does not fit for period
2. Time of transit needs to be inputed with only the ones place and the decimals (e.g. change 245551.90003 to 1.90003)

10. ENSURING YOU HAVE RELIABLE VALUES AND ERROR BARS:

1. Pay attention to the Bayesian information criterion value (lower values are usually better).
2. Check to make sure that the gauss.ps and gauss_prayer.ps plots are Gaussian. If they are not, run your model with more/less fixed parameters
3. The file FINAL_EVERYTHING.dat includes all parameter fits, respective errors, both red noise calculation results and residuals.
4. It is recommend that you choose the method (LM or MCMC) that have the highest error bars (ONLY if they are within error of each other).
5. Multiple your error bars from FINAL_EVERYTHING.dat for each parameter by the largest beta (either the global value or individual parameter betas)
6. To get your final error bars multiple the error bars from step 3 by $\sqrt{\chi^2}$, where χ^2 is the Reduced Chi-Squared in FINAL_EVERYTHING.dat file. Only do this if the Reduced Chi-Squared is greater than one.

11. IMPROVEMENTS TO MAKE:

1. Double precision time input

12. OTHER PROGRAMS:

1. bin.pro: Bin a set of inputted data to the bin size inputed- Outputs both the weighted mean and the median value of the data points binned

13. Citations

If you use this program please cite:

Main Paper: Pearson K. A., Turner J.D., Sagan T.G. 2013. Photometric observation of HAT-P-16b in the near-UV. New Astronomy. arXiv.1310.5397.

Turner J.D., et al., 2015, MNRAS, In press
Mandel K., Agol E., 2002, ApJ, 580, L171
Eastman, J., Gaudi, B.S., Agol, E., 2013. Pasp 125, 83, 1206.5798

14. CONTACT INFO:

If you find a bug please let me know:
Jake Turner
University of Virginia
Department of Astronomy
530 McCormick Rd
Charlottesville, VA 22904
astrojaketurner@gmail.com
https://sites.google.com/site/astrojaketurner/
http://www.linkedin.com/pub/jake-turner/4b/278/4aav