# A Guide to TTV Target Observing for the EXPLORE Project

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**by**

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## 1. Introduction

This document provides guidance on observing confirmed exoplanets that may be exhibiting transit timing variations (TTVs). Guidance herein supplements the best practices for general exoplanet observing described in Sections 1-6 of “A Practical Guide to Exoplanet Observing” (https://astrodennis.com/Guide.pdf), hereafter referred to as the Guide. TTVs are defined here to occur when there is a difference between the observed mid-point of an exoplanet’s transit and its predicted transit mid-point time. Exoplanets exhibiting TTVs are herein referred to as “TTV targets.”

The guidelines below are intended for TTV targets that are part of the EXPLORE project and, hence, lend themselves to observations by amateur astronomers.

## 2. Background

TTVs can be caused by a number of factors, including:

1. The orbital decay of an exoplanet.
2. The influence of a secondary star in the exoplanet system.
3. The influence of another, unknown exoplanet.

Multiple observations of a given TTV target, as well as radial velocity measurements, help inform the cause of TTVs, as well as the mass of any secondary planet.

In addition to TTVs, changes in the eccentricity of a TTV target could be indicative of the influence of an unknown body.

To suitably analyze and characterize TTVs, a number of observations at different epochs are required. Additionally, simultaneous observations are also beneficial in order to confirm the TTV of a given epoch.

The following describes the high-level process flow for observers participating in the EXPLORE project:

1. Users are provided with a list of TTV targets. The target list may be updated from time to time.
2. Users schedule observations of TTV targets that are observable from their location and are appropriate for their telescope aperture size.
3. Photometry programs such as AstroImageJ (AIJ) and HOPS are used to conduct differential photometry of a TTV target.
4. The photometry text file output from AIJ/HOPS are input to the ExoClock modelling software.

For observations that are of high enough quality that they are accepted by ExoClock, the user will then submit the corresponding photometry files from 3. above to the AAVSO Exoplanet Database. Observations of TTV targets in the AAVSO Database will then be "scraped" by the EXPLORE analysis team to detect, analyze, and confirm TTVs and their cause.

## 3. Observing Requirements

### 3.1 Unique TTV observing requirements

When observing for TTVs, the two most critical parts of the light curve are the midpoint and duration of the transit, and therefore the need to observe full and not partial transit. Changes in the transit midpoint, especially cyclical ones, from observation to observation can help identify a secondary body influencing the TTV target. Likewise, changes in the duration of the transit, which may may relate to changes in the eccentricity of the TTV target's orbit, may also be indicative of the influence of another influencing body. Determining precise transit depth is, therefore, not as critical. This implies that limb darkening, and therefore the influence of the wavelength being used to conduct the observation, is not as critical as in the normal exoplanet observation.

As seen below, the need for accurate timing of the transit midpoint and duration over transit depth have a bearing on observation filter choices, scheduling, image time stamping, exposure time, and cadence.

### 3.2 Instrumentation

The targets selected for the EXPLORE project will be chosen such that they are suitable for observations by amateur telescopes with 10" or greater apertures.

Guidelines on the selection of mount, imaging camera, and auto guiding technique for TTV target observing follow the same guidance as for normal exoplanet observing outlined in the Guide.

### 3.3 Filter Choice

Because of the unique TTV observing requirements described earlier, a filter, or even a clear filter, should be chosen that maximizes the SNR of the TTV target signal.

### 3.4 Observation scheduling

Because of the need to get a reliable transit duration and midpoint, targets should be chosen only if their full transit, plus at least a 30-minute (ideally 60-minute) pre-ingress and post-egress baseline, are observable on a given night.

Two facilities are useful for determining the TTV targets that are observable at a given location for a given night or series of nights: the Swarthmore Transit Finder and the ExoWorlds Spies

Transit Scheduler. Appendix A contains instructions on using the Swarthmore finder for EXPLORE TTV targets and the webpage containing the user dialogue for use of the ExoWorlds Spies Transit Scheduler can be found at https://www.exoworldsspies.com/en/scheduler/.

Participants in the EXPLORE project will periodically be given updated TTV targets both as a comma-separated list (e.g., HAT-P-7 b, HAT-P-13 b, …) and as a Perl expression (e.g., HAT-P-7 b|HAT-P-13 b|…). Users of the Swarthmore finder should enter the Perl expression in the Name field to restrict the finder from only finding transits related to the TTV target list (see Appendix A). Users of the ExoWorlds Spies would need to select the TTV targets of interest in the "Planet selection…subset" section each time it is used. An advantage of the Swarthmore finder is that the target list remains in its Name field from observation-to-observation so the user does not have to enter the TTV targets each time.

### 3.5 Image time stamping

Because of the need for accurate transit mid-point estimation, the clock of the image capture computer should be accurately updated prior to the observation by being synchronized with an Internet time server or a GPS-connected device.

### 3.6 Binning

As described in Section 6.2.1 of the Guide, binning may be necessary to spread the target star's FWHM over 3-5 pixels.

### 3.7 Camera operating temperature

The imaging camera should be operated at the lowest temperature possible in order to reduce thermal noise.

### 3.8 Exposure time and cadence

Exposure times should be set so as to maximize the SNR of the TTV target signal, while not reaching the non-linearity or saturation limits of the imaging camera. In order to get the maximum number of observational data points, there should be no delay between exposures, except that needed by the image camera to download its images – i.e.., the cadence should be as fast as possible.

## 4.0 Image Reduction

Bias, dark, and flat field calibration images should be taken in the normal way as described in Section 6.3 of the Guide. Likewise, image reduction using these calibration images should also be done in the normal way, with $BJD_{TDB}$ timestamps ideally created and included in the reduced files' FITS headers.

## 5.0 Image Alignment

One of the systematics that can potentially be detrended out by programs such as AIJ is image shift. If images are aligned before photometry takes place, the opportunity to use image shift in the X and/or Y axis of the image camera is lost. If image shift is to the point that the photometry software cannot reliably place its apertures on the selected target and comparisons stars from image to image, then image alignment may be necessary. Alternatively, a program such as AIJ that can use the RA and DEC coordinates of stars to place photometric apertures would be preferred so that image shift data can be maintained for possible later use as possible detrend parameters.

## 6.0 Photometry

When performing differential photometry on the reduced images, special consideration should be given to selection of comparison stars. Suggested comparison stars for each of the EXPLORE project's TTV targets will be provided. These will be chosen so that they are close in magnitude, color, and proximity to the TTV target. This also provides a means for all EXPLORE observations to be more uniformly compared.

## 7.0 ExoClock Model fitting

It is expected that photometry results will come from at least two sources: users using HOPS and users using AIJ. Use of Exotic/Exoplanet Watch photometry data may be indirectly included through scraping of the NASA Exoplanet Watch data, which itself is pulled from the AAVSO database. In the case of both HOPS and AIJ, the user's photometry data will be input into ExoClock as the .TXT file requested during the ExoClock upload process– see https://www.exoclock.space/upload/.

- For HOPS photometry, the input to ExoClock will be the "ExoClock_info.txt" file generated by HOPS.
- For AIJ photometry, the user should create a text file that contains the BJD_TDB time, relative normalized flux, relative normalized flux error, and detrend value for Airmass – see Section 7.12 of the Guide how to do this.

Although both HOPS and AIJ can do their own model fitting, the use of ExoClock to do a model fit provides a number of advantages:

1. Use of the same model fitting software provides uniformity across all EXPLORE users.

2. The vetting process of ExoClock provides higher quality submissions for the EXPLORE project.
3. ExoClock quality metrics such as residual standard deviation and SNR can be associated with a user's observation.

## 8.0 Submission to the AAVSO Exoplanet Database

If their submission is accepted by ExoClock, the user would next input to the AAVSO Exoplanet Database the photometry data that was originally input into ExoClock. This submission process is described below and uses the AAVSO WebObs dialogue page at https://apps.aavso.org/exosite/submit.

Before submitting their data to the AAVSO database for the first time, however, users would need to take the following one-time actions:

1. obtain an AAVSO observer code by going to https://www.aavso.org/you-need-observer-code-use-webobs;
2. define their site information by going to https://apps.aavso.org/site_equip/site;
3. define their equipment configuration by going to https://apps.aavso.org/site_equip/equipment.

An exoplanet observation submission to the AAVSO contains at least two parts: (1) the exoplanet database "report" – namely, photometry data along with some identifying metadata and (2) an image showing the field of comparison stars used for the observation. Additional information can be included in a .zip file. Part of the metadata will include the ExoClock quality metric of (TBD) associated with the observation.

1. For HOPS users, an intermediate step is needed to supplement the HOPS ExoClock_info.txt file with additional information before a suitable database report is created (NOTE: a Python program is being developed to support this.)

2. For AIJ users, the "Create AAVSO Exoplanet Database formatted data…" option on AIJ"s Multi-plot Main screen is used to create the appropriate database report.

# Appendix A:
# Swarthmore Transit Finder

The following describes the use of the Swarthmore transit finder to determine which targets on the EXPLORE TTV target list produce transits on a user-specified night or range of nights. The transit finder can be found at https://astro.swarthmore.edu/transits/transits.cgi. The following are recommended entries under each section of the transit finder's web page. Generally, only entries in item 3. need to change from night to night.

1. Target List: Choose NASA Exoplanet Archive.

2. Observatory. Select a known observatory in the list or choose "Manual coordinate entry" at the end of the list. If the latter, enter your latitude/longitude/timezone. Above the observatory location, select either UTC or local times to be displayed on the result page(s).

3. Date window. Select the beginning date of interest and the number of days following it, as well as the number of days prior to the beginning date.

4. Constraints. Select constraints on elevation values for ingress and egress. Since we are looking for full transits – i.e., that both the ingress and egress are viewable - select the AND constraint.

5. Hour angle: Enter -12 and 12.

6. Out-of-transit baseline: 1 hour is recommended, however, 0.5 hours may be needed to increase target opportunities for rare transit events. Check "Extend baseline…"

7. Depth: Enter 1.0 to get results for all of the candidates on the TTV Target List, otherwise enter the smallest depth that you believe your observatory is capable of detecting.

8. V magnitude. Enter 14, which should cover all targets in the TTV Target List.

9. Name: Copy and paste a plain text Perl expression containing the target names. For example:

   HAT-P-7 b|HAT-P-13 b|HAT-P-18 b|K2-19 b|Qatar-1 b|TOI-216.01|TOI-1130 c|TrES-3 b|WASP-4 b|WASP-12 b|WASP-19 b|WASP-43 b|WASP-148 b

   NOTE: the above Perl expression should be modified as TTV targets are added or removed.

10. Keep all other default entries.

Click on Submit.