

ObsMap: Preparing observing maps with the best comparison stars for photometry

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Abstract. We present ObsMap, a Python framework that allows for the interactive creation of various alternative observation maps to maximize the potential of each observing night. The code requires the user to input the star’s name or equatorial coordinates, the passband of observation, field of view (FoV), and desired count level together with the minimum and maximum count limits in ADUs for the detector. ObsMap queries the stars in the Gaia DR3 archive within an area four times the size of the FoV, as the target star could be located anywhere within the FoV. It then generates a list of stars in that area, along with additional information about each star. Variable stars are eliminated from the list using Gaia’s variability flag. The total incoming light in the specified filter is calculated with the blackbody approach for the remaining stars, utilizing Gaia’s effective temperature, stellar radius, and parallax data. Using the filter-specific fluxes, the count levels of the stars are determined relative to that input by the user for the target. As a result, ObsMap creates three maps: a) A large map that is four times the size of the FoV, where the effective temperature and count levels of the stars are annotated. The user can manually select the appropriate FoV, based on this map. b) A suggested map that minimizes photon noise (scatter). c) A suggested map to maximize the number of comparison stars. In some cases, a single comparison star with a high count level could outperform a combination of dim comparison stars. However, if that bright comparison star is variable and not flagged as such in the Gaia archive, choosing dimmer comparison stars could be a better option.

Key words: observation maps

1. Introduction

Accurate and precise light curves are always desired in photometry, regardless of the observed object. These two elements depend not only on the brightness of the target object but also on the properties of comparison stars within the field of view (FoV). An ideal comparison star should not be a variable star, should be bright enough to increase the precision while staying within the limits of linear response of the detector and also its color should be as close as possible to that of the target star.

In order to minimize atmospheric effects such as airmass on the final light curve, the relative flux of the target is acquired using the differential photometry method. The relative flux can be measured using one or a combination of comparison stars (Collins et al., 2017). According to equation (9) in Collins et al. (2017), precision increases with the total integrated count of comparison stars. For the cases where only a single comparison star is used, this is limited by the saturation level or the linearity limit of the detector. In other cases where the combination of comparison stars is used, precision is limited by the total number of comparison stars.

As the target star can be placed anywhere on the detector, the observable sky region varies depending on the location of the target star. For rectangular-shaped FoV, the target star can be placed in close proximity to one of the four corners, making the potentially observable region including the target four times bigger than the FoV. This raises a problem: determining the optimal location of the target star on the detector to maximize the total count of comparison stars, and assessing whether they are suitable for use as comparison stars, for instance, checking if they are variable stars.

In the selection of suitable comparison stars, the data provided by Gaia can be very helpful. Gaia is a multi-purpose space telescope that can measure parallaxes, atmospheric parameters, radial velocities, positions of stars on the sky plane, and even perform photometry (Gaia Collaboration et al., 2016, 2018, 2023; Riello et al., 2021). Employing these measurements from Gaia, an observational map optimized for the best possible precision can be created.

2. Predetermination of comparison stars

2.1. Noise types

Final light curves have basically two types of noise sources, which are the so-called random scatter and correlated noise. Random scatter is also called photon noise, Poisson noise or white noise (e.g. Southworth et al. 2009), and is generally parameterized by the Photon Noise Rate (PNR, Fulton et al. 2011). White noise is dependent on the amount of light acquired in unit time by the detector. Since the light from the target and comparison stars is recorded by the same telescope and camera setup in the same exposure time, white noise will be dependent on the brightness of these stars. If a dim star is used as a comparison, then the relative fluxes will have a high scatter. It is possible to use a combination of dimmer stars to achieve better precision. Nevertheless, a better comparison star could be constituted with a combination of bright stars to reduce the white noise. The other noise type, correlated noise is due to the light variation correlated with astrophysical and/or observational variables, generally parameterized with β -factor (Winn et al., 2008). If a variable star is used as a comparison star, then the relative fluxes of the target will vary in the reverse direction as a result of the differential photometry technique. Consequently, one should have prior

knowledge of the variability, color and brightness of the stars within the specified passband to select them for comparison in differential photometry.

2.2. Predetermination of relative fluxes

An estimation of precision in photometric measurements requires predetermination of relative fluxes. In order to have an estimate on the relative fluxes of a target star prior to photometric measurements, we make use of the following equation inspired by Wong et al. (2021) based on blackbody radiation (B_λ):

$$Relative\ flux = \left(\frac{d_{comparison}}{d_{target}}\right)^2 \left(\frac{R_{target}}{R_{comparison}}\right)^2 \frac{\int B_\lambda(T_{target})t(\lambda)d(\lambda)}{\int B_\lambda(T_{comparison})t(\lambda)d(\lambda)} \quad (1)$$

where d is the distance, R is the radius, and T is the effective temperature of the stars, which can be assumed to be equal to Gaia values, while the transmission curve of the passband can be obtained from the Spanish Virtual Observatory's (SVO) filter profile service¹.

2.3. Creating observing maps

Assuming the FoV of the detector is a rectangle, the target star can be located on any of the four corners of the FoV, which makes the potential observable area four times bigger than the FoV. We have developed an open source code² in PYTHON that generates three maps. a) A large map that is four times the area of the FoV, where the effective temperature and count levels of the stars are annotated, allowing the user to adjust their real FoV with a visual inspection. b) a map that has the same size as the FoV and maximizes the total count of comparison stars to achieve optimum precision. c) a map that has the same size as the FoV and maximizes the number of acceptable comparison stars. This map can be useful in the case of a single bright star, which can induce more counts than a combination of dim comparison stars does on the detector. However, a single bright star can be an undetected variable. In that case, it should be ideal to choose the map that maximizes the number of comparison stars.

To create such maps, the code requires the target name (or its equatorial coordinates), detector's FoV in both axes in units of arcminutes, filter name, target's desired count level in units of Analog-to-Digital Units (ADU), maximum and minimum count levels for the comparison stars to be input. Then the code converts the FoV of the detector to the World Coordinate System (WCS) using ASTROPY's (Astropy Collaboration et al., 2013, 2018, 2022) WCS tool³ and queries the stars in a field four times bigger than the FoV around

¹<http://svo2.cab.inta-csic.es/theory/fps/>

²<https://github.com/selcukyalcinkaya>

³<https://docs.astropy.org/en/stable/wcs>

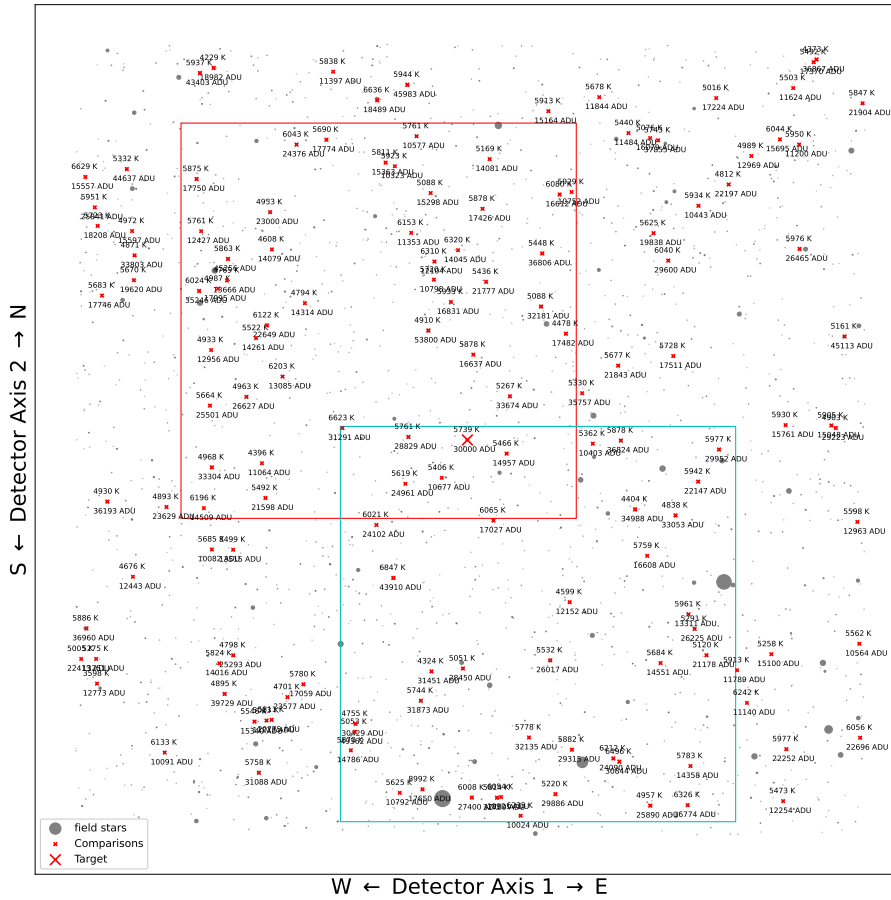


Figure 1. Example of the large map for Kepler-111. The red frame indicates the map that provides the maximum number of comparison stars, while the cyan frame offers the best comparisons in terms of maximum comparison counts. FoV is set at $12'' \times 12''$, target adu is 30000 ADU, linearity limits are between 10000 and 55000 ADU, scan-step is $3''$, and edge threshold is 5%. Declination increases upwards along the Y-axis, while right ascension decreases towards the right on the X-axis. The unused field stars are represented by gray circles, while comparison stars are depicted with a red cross. The target star is situated in the center of the large map and is marked with a prominent red cross.

the target star. We use ASTROQUERY's (Ginsburg et al., 2019) Gaia function⁴ for this purpose. Querying is performed by an SQL code that discards variable stars detected by Gaia and it is possible to put a magnitude offset between the target and the field stars to avoid very dim stars. The parallax, radius, equatorial coordinates, magnitudes in the g -band, and the T_{eff} parameters are retrieved. Then the transmission function of the filter is retrieved from SVO using the ASTROQUERY's relevant function⁵. The relative fluxes of the field stars are calculated using Eq-1 and the desired counts for the target as provided by the user. If the stars are out of the user-defined count limits (out of linearity limit or saturation), they are eliminated from the list. The code creates a "large map", centered on the target star by marking potential comparison stars and other stars (fig-1 as an example). The real observed area (FoV) is scanned with an arbitrary value of arcsecond-steps through the large map in each of which the number of comparison stars and the total counts from them are determined. Step size can be determined by the user depending on the proximity of the stars in the large map. We suggest small values such as seeing value for populated fields (e.g. galactic plane). When the scanning is complete, the maximum average distance of the target and comparison stars to the edges of the detector are selected for both optimum precision and a maximum number of comparisons stars maps because there can be more than one way to fit the stars inside FoV. The minimum distance of a star to the any edge of the detector is also an input parameter between 0 and 1, in units of related axis of detector. If the value is 0, then the target or comparison star can be placed on the edges and a value of 0.1 means the target or comparison star can be placed as close as 10% of the length of each axes from the edge.

3. Discussion

ObsMap interactively allows observers to prepare observing maps with an optimal set of available comparison stars to obtain high-quality light curves in terms of precision and accuracy. Knowing the exact location of comparison stars allows the user to observe Regions of Interest (RoI) by cutting out unused pixels, which significantly reduces the readout time and reduces the size of CCD images. OBSMAP is also very useful to avoid bad/hot pixel regions.

We would like to note that OBSMAP uses blackbody approximation for the estimation of relative fluxes. Therefore, photometric measurements in narrow-band filters around specific strong lines may not be accurate. In addition, interstellar extinction is not taken into account. Gaia is also not sensitive to short-period, low amplitude variations due to its poor timing resolution, which makes it difficult to detect every observed variable star, especially those that have such variations. In the presence of only a couple of good comparison stars, we

⁴<https://astroquery.readthedocs.io/en/latest/gaia/gaia.html>

⁵https://astroquery.readthedocs.io/en/latest/svo_fps/svo_fps.html

suggest checking these stars in other databases for variability. The light curves from Transiting Exoplanet Survey Satellite (TESS) (Ricker et al., 2015) can be employed to check variability.

OBSMAP is an open-source code, allowing the user to edit it at will. Users can upload a variable star database, specify a photometric filter by importing its transmission function, or improve the code further by using observed spectra from Gaia instead of the blackbody approach to eliminate stellar extinction.

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References

- Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al., The Astropy Project: Sustaining and Growing a Community-oriented Open-source Project and the Latest Major Release (v5.0) of the Core Package. 2022, *Astrophysical Journal*, **935**, 167, DOI: 10.3847/1538-4357/ac7c74
- Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al., The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package. 2018, *Astronomical Journal*, **156**, 123, DOI: 10.3847/1538-3881/aabc4f
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al., Astropy: A community Python package for astronomy. 2013, *Astronomy and Astrophysics*, **558**, A33, DOI: 10.1051/0004-6361/201322068
- Collins, K. A., Kielkopf, J. F., Stassun, K. G., & Hessman, F. V., AstroImageJ: Image Processing and Photometric Extraction for Ultra-precise Astronomical Light Curves. 2017, *Astronomical Journal*, **153**, 77, DOI: 10.3847/1538-3881/153/2/77
- Fulton, B. J., Shporer, A., Winn, J. N., et al., Long-term Transit Timing Monitoring and Refined Light Curve Parameters of HAT-P-13b. 2011, *Astronomical Journal*, **142**, 84, DOI: 10.1088/0004-6256/142/3/84
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al., Gaia Data Release 2. Summary of the contents and survey properties. 2018, *Astronomy and Astrophysics*, **616**, A1, DOI: 10.1051/0004-6361/201833051
- Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al., The Gaia mission. 2016, *Astronomy and Astrophysics*, **595**, A1, DOI: 10.1051/0004-6361/201629272
- Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al., Gaia Data Release 3. Summary of the content and survey properties. 2023, *Astronomy and Astrophysics*, **674**, A1, DOI: 10.1051/0004-6361/202243940
- Ginsburg, A., Sipőcz, B. M., Brasseur, C. E., et al., astroquery: An Astronomical Web-querying Package in Python. 2019, *Astronomical Journal*, **157**, 98, DOI: 10.3847/1538-3881/aafc33

- Ricker, G. R., Winn, J. N., Vanderspek, R., et al., Transiting Exoplanet Survey Satellite (TESS). 2015, *Journal of Astronomical Telescopes, Instruments, and Systems*, **1**, 014003, DOI: 10.1117/1.JATIS.1.1.014003
- Riello, M., De Angeli, F., Evans, D. W., et al., Gaia Early Data Release 3. Photometric content and validation. 2021, *Astronomy and Astrophysics*, **649**, A3, DOI: 10.1051/0004-6361/202039587
- Southworth, J., Hinse, T. C., Jørgensen, U. G., et al., High-precision photometry by telescope defocusing - I. The transiting planetary system WASP-5. 2009, *Monthly Notices of the RAS*, **396**, 1023, DOI: 10.1111/j.1365-2966.2009.14767.x
- Winn, J. N., Holman, M. J., Torres, G., et al., The Transit Light Curve Project. IX. Evidence for a Smaller Radius of the Exoplanet XO-3b. 2008, *Astrophysical Journal*, **683**, 1076, DOI: 10.1086/589737
- Wong, I., Kitzmann, D., Shporer, A., et al., Visible-light Phase Curves from the Second Year of the TESS Primary Mission. 2021, *Astronomical Journal*, **162**, 127, DOI: 10.3847/1538-3881/ac0c7d