The O-C diagram
what does it mean and how do we calculate it?

The term O-C stands for "Observed – Calculated" and it is used in many fields of research. As far as the ephemerides of transiting exoplanets are concerned, we use the term O-C to present the difference between the observed transit mid-time and the expected transit mid-time (this is the "calculated" part).

The ephemeris

For every transiting planet we have an ephemeris – an equation that is determined by current observations and connects the mid-times of different transit events in the past and in the future. This equation looks like this:

$$T = T_0 + N \times P$$

where:

T_0 is the zero-epoch transit mid-time –
the mid-time of a transit that we use as reference (it is up to us to choose which transit this will be)

P is the period –
the difference in time between two transit mid-times

T is the transit mid-time –
refers to the mid-time a transit

N is the transit epoch –
the number of periods that have elapsed since the reference transit

From the above parameters, T_0 and P are determined from existing transit observations. For example, the current ephemeris of WASP-10b is:

$$T = 2454664.038040(6) + N \times 3.0927295(3)\ BJD_{TDB}$$

This means that one transit – the one that we take as reference – happened at 2454664.03804 BJD_{TDB}, corresponding to the 16th of July 2008, 12:51:14.4 UTC, and other transits happen every 3.0927295 days.

Note: BJD_{TDB} is the Julian Date of the transit mid-time, corrected for the leap seconds, as if we were observing form the barycentre of the Solar System. This correction is important because as the Earth orbits around the Sun, the distance between us and the exoplanet-hosting system is changing, causing variations in the light travel-time. We will in more detail what BJD_{TDB} means and how we do the conversion from Julian Date in a future newsletter.

The "Calculated" part of O-C

Let's assume that we observed one transit of WASP-10b on the 10th of July 2016. At the UTC noon of that day, the BJD_{TDB} time was equal to 2457580.002037649. If we divide the difference between this time and T0, we can find how many cycles have elapsed since the T_0:

$$\frac{t - T_0}{P} = \frac{2457580.002037649 - 2454664.038040}{3.0927295} = 942.8448228818683$$

The transit we observed happened during the night, so a bit later. The next integer cycle is 943, which is the epoch, N, of the observed transit.

Hence, the predicted transit mid-time is:

$$T_{calc} = 2454664.038040 + 943 \times 3.0927295 = 2457580.4819585\ BJD_{TDB}$$

The uncertainty in the transit mid-time prediction can be calculated from the uncertainties on the T_0 and P parameters as follows:

$$\sigma_{T_{calc}} = \sqrt{\sigma_{T_0}^2 + N^2\sigma_P^2} = \sqrt{0.000006^2 + 943^2 \times 0.0000003^2} = 0.00029\ days = 0.4\ minutes$$

The "Observed" part of the O-C

This part comes from the transit model fitting on our data. On the ExoClock website, the data you upload are converted from any time format that you provide to BJD_{TDB}, and then your light curve is fitted using a transit model and an MCMC algorithm. Suppose that the result of this analysis is:

$$T_{obs} = 2457580.4802(8)\ BJD_{TDB}$$

The final O-C diagram

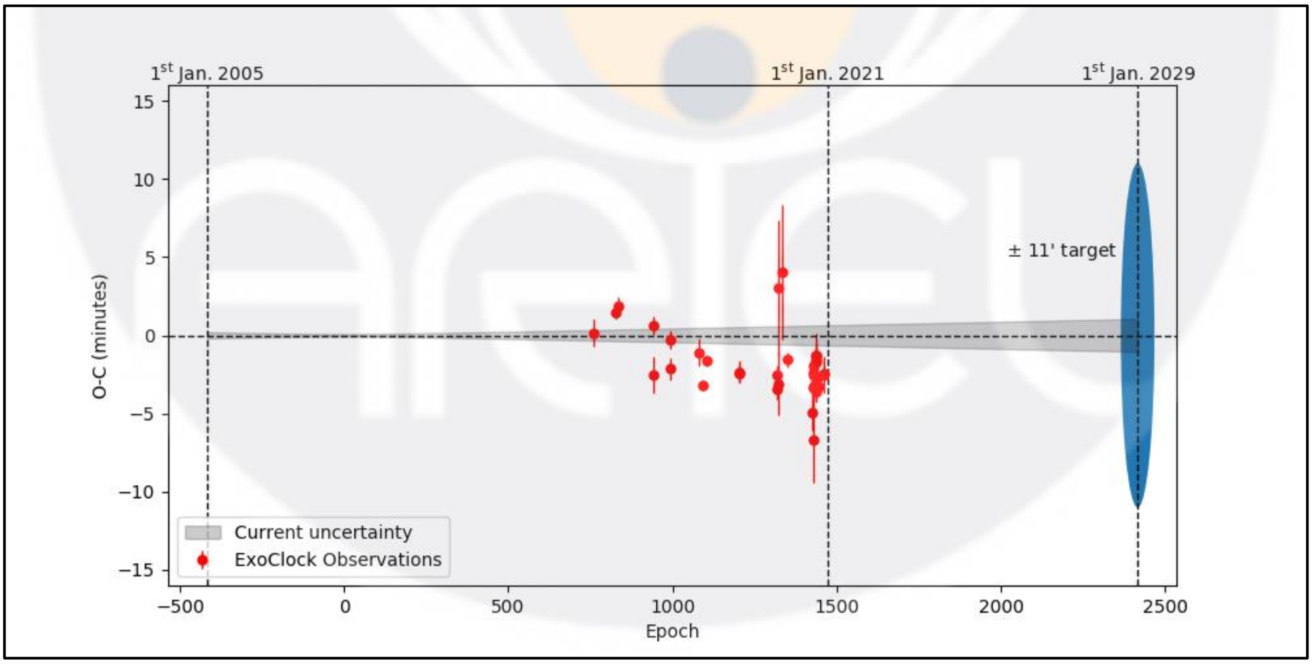
From the above values, the O-C is simply the difference between the T_{calc} and T_{obs}:

$$O - C = T_{obs} - T_{calc} = 2457580.4802 - 2457580.4819585 = -0.00176(8)\ days$$

or

$$O - C = -2.5 \pm 1.2\ minutes$$

By repeating the process for all the observations that we have, we can construct the final O-C diagram that will tell us if we see any deviations from the current ephemeris – i.e. if the transits happen when expected, earlier or later. If the observations disagree with the predictions (large O-C values) this indicates that an ephemeris update is necessary. On the ExoClock website, you will find the following diagram for every planet (this is for WASP-10b):



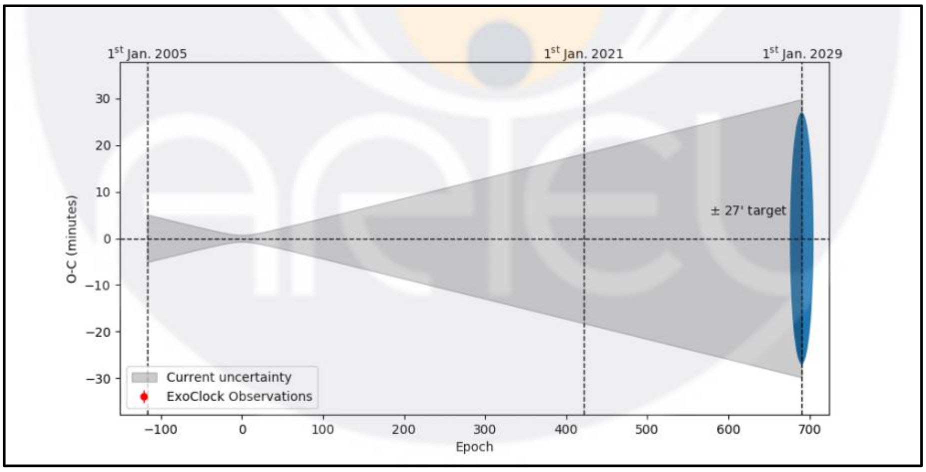
The horizontal axis represents the epochs (N) of all the transits that between the 1st of January 2005 and the 1st of January 2029, calculated in the same way as for the example transit on the 10th of July 2016. The vertical axis represents the O-C in minutes. Moreover:

- with red, we can see all the observations submitted to ExoClock and their respective uncertainties.
- with gay, we can see the uncertainty in the transit mid-time prediction (using the current ephemeris) for all the transits, calculated in the same way as for the example transit on the 10th of July 2016
- with blue, we can see the target uncertainty in the transit mid-time prediction that we have set for the ExoClock project – this is equal to the 1/12th of the transit duration (in this case 11 minutes) for transits that will happen at the end of 2028 / beginning of 2029.

We can see that for WASP-10b, using the current ephemeris, the uncertainty in the transit mid-time prediction for transits that will happen at the end of 2028 / beginning of 2029 is much lower than the target of 11 minutes. This is why the planet has a LOW priority. However, we can also see that the is a small deviation for the transit mid-time predictions of about -2.5 minutes, implying that we may need to update the ephemeris, although this is not crucial at the moment.

Note: The target uncertainty for the ExoClock project has been set to be equal to the 1/12th of the transit duration for transits that will happen at the end of 2028 / beginning of 2029. If this goal is achieved, we will be 99% sure that when Ariel observes, any O-C will be smaller than 1/4th of the transit duration (3 sigma).

HIGH priority planets usually have ephemerides that give predictions with uncertainties higher than the target uncertainty. For example, HAT-P-15 (the grey area is larger than the blue on the 1st of January 2029):



ALERT planets may have ephemerides that give predictions with uncertainties lower than the target uncertainty, however, there are observations with unexpectedly large O-C values. For example, XO-4b (the grey area is smaller than the blue on the 1st of January 2029, but the red points have O-C values of -20 minutes):