The colour of noise in SuperWASP data and the implications for finding extra-solar planets

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Abstract. A recent study demonstrated that there is significant covariance structure in the noise on data from ground-based photometric surveys designed to detect transiting extrasolar planets. Such correlation in the noise has often been overlooked, especially when predicting the number of planets a particular survey is likely to find. Indeed, the shortfall in the number of transiting extra-solar planets discovered by such surveys seems to be explained by co-variance in the noise. We analyse SuperWASP (Wide Angle Search for Planets) data and determine that there is a significant amount of correlated systematic noise present. After modelling the potential planet catch, we conclude that this noise places a significant limit on the number of planets that SuperWASP is likely to detect; and that the best way to boost the signal-to-noise ratio and limit the impact of co-variant noise is to increase the number of observed transits for each candidate transiting planet.

1. Introduction

Although a total of 14 transiting extra-solar planets have been discovered since the first, HD209458b (Charbonneau et al. 2000), the number of discoveries has
not lived up to early predictions (e.g. Horne, 2001). This observed shortfall in the number of transiting planets detected has recently been explained by the presence of correlated ‘red’ noise in the data from ground-based transit surveys (Pont, 2006). Previous forecasts of the planet ‘catch’ from ground-based surveys assumed that the noise in such data is entirely un-correlated or ‘white’ in nature. Pont showed that systematic red noise correlated on time-scales equivalent to a typical hot Jupiter (HJ) transit (≈ 2.5 hours) cannot be ignored and indeed tends to be the dominant type of noise for bright stars.

2. Observations

SuperWASP-N is a wide-field transit survey instrument that started observing in 2004 at the Isaac Newton Group on La Palma. The observations used in this work are those made by SuperWASP-N in the 2004 season, when the instrument comprised an array of five lenses, each with a CCD recording a 7.8° by 7.8° field. Up to eight sets of fields were observed at a time, with measurements made about 7 - 8 minutes apart. Further details of the SuperWASP project can be found in Pollacco et al. (2006). Prior to searching the data for transits, the SYSREM algorithm of Tamuz, Mazeh, & Zucker (2005) is applied to the data to reduce systematic errors. Four components of red noise are removed with SYSREM; it is thought that these are caused by variations in sky brightness, vignetting, focus and residual secondary extinction (Collier Cameron et al., 2006a).

3. How much red noise?

We follow closely the approach of Pont, Zucker, & Queloz (2006) in estimating the level of correlated noise present in SuperWASP data. We compute the running average of the data over the \( n(= 20) \) points contained in a transit-length time interval (2.5 hours). If the noise is purely random, the RMS scatter in the average of \( n \) data points should be \( \sigma_w = \sigma / \sqrt{n} \), where \( \sigma \) is the standard RMS of the whole lightcurve. If, however, there is a systematic component in the noise, the RMS scatter of the average of \( n \) points, \( \sigma_r \), will be greater than this.

The quantities \( \sigma \), \( \sigma_r \), and \( \sigma_w \) are calculated for each of the non-variable stars in one of the SuperWASP-N fields both prior to and after decorrelation with SYSREM. Fig. 1 shows that the SYSREM algorithm is highly effective at reducing the levels of systematic noise present in the data, but that not all correlation in the noise is removed. If that were the case, the \( \sigma_r \) curve would lie over the \( \sigma_w \) curve. Instead, the \( \sigma_r \) curve lies higher than \( \sigma_w \), and flattens out at about 3 mmag for bright \((V = 9.5)\) stars, indicating that systematic trends of this magnitude are present in the data on a 2.5 hour timescale.

4. Simulated planet catch

We model the objects in the 20 fields observed by one of the SuperWASP cameras in the 2004 season, by using the Besançon model of the Galaxy (Robin et al., 2003) to generate a catalogue of stars with \( 9.5 < V < 13.0 \) for each of the
Figure 1.: RMS scatter versus magnitude for the non-variable stars in one field both prior to (left hand panel), and after (right hand panel) decorrelation with SysREM. The upper curve shows the RMS scatter of the lightcurve of each object, $\sigma$. The middle curve shows the scatter, $\sigma_r$, after a moving average over a 2.5 hour time interval (20 data points) was calculated. The lower curve shows the RMS scatter divided by $\sqrt{20}$, $\sigma_w$.

Fields. Planets are then assigned to stars that are of spectral class F, G or K and luminosity class IV or V on the basis of their metallicity, using the planet-metallicity relation of [Fischer & Valenti 2005],

$$P(\text{planet}) = 0.03 \times 10^{2.0[\text{Fe/H}]}$$

where $P(\text{planet})$ is the probability that a star of metallicity $[\text{Fe/H}]$ is host to a planet. This probability, along with a semi-major axis drawn from a uniform log distribution [Smith et al. 2006], is used to determine whether or not each star hosts a transiting planet. 151 ±13 of the 154,156 stars generated by the Besançon model are allocated a transiting planet. It is assumed, for simplicity, that all planets have a radius, $R_p$, equal to that of Jupiter.

In the regime where red noise dominates, the signal-to-noise ratio, $S_{\text{red}}$, is given by

$$S_{\text{red}} = \frac{\Delta m \sqrt{n_{\text{trans}}}}{\sigma_r(V)}$$

where $n_{\text{trans}}$ is the number of transits observed and $\Delta m$ is the transit depth, determined using equation (9) of [Tingley & Sackett 2005]. The red noise as a function of magnitude, $\sigma_r(V)$, is determined by fitting a line to the middle curve of the right hand panel of Fig. 1. Using SuperWASP observation times enables us to calculate $n_{\text{trans}}$ and hence $S_{\text{red}}$ [Smith et al. 2006].

The value of $S_{\text{red}}$ that one chooses as a threshold for planetary detection is a compromise between allowing too many false positive detections and rejecting large numbers of genuine transiting planets; in this work we use the (perhaps slightly conservative) requirement that $S_{\text{red}} \geq 10$ for a planet to be ‘detected’.

The signal-to-noise ratio for each simulated planet is calculated for each of three different observing baselines; the results are plotted in Fig. 2. Also shown is the detection efficiency as a function of period for the requirement that 2, 4, and 6 transits are observed. Increasing the number of transits required for
a detection causes the detection efficiency to fall dramatically at most periods. If one requires a larger number (6 or more) of transits for detection, then the detection efficiency is much lower, except for several pathological periods where the detection fraction is such that finding planets with that period is particularly favourable. Increasing the number of observing nights has the effect of increasing the detection efficiency at nearly all periods (Fig. 2).

Figure 2.: Left hand panels: Signal-to-noise ratio versus magnitude for 151 simulated transiting extra-solar planets, with the $S_{\text{red}} = 10$ threshold indicated. Top-to-bottom: 51, 80, 130 nights of observations result in 1, 2, and 12 ‘detections’ respectively. Right hand panels: the corresponding transit detection efficiency as a function of period. In each case the solid, upper curve is for the requirement that at least 2 transits are observed for a detection; the dashed, middle curve for 4 transits; and the dotted, lower curve for 6.
A notable property of many of the current SuperWASP transit candidates (e.g. Christian et al. 2006) is their large value of $n_{\text{trans}}$. Also, many of the candidate periods coincide with the narrow pathological period ranges where there is a much greater chance of detecting a large number of transits. The effects of red noise can be reduced by increasing the signal-to-noise of the data by requiring that a larger number of transits ($\approx 10$) are observed. In order to have a reasonable chance of observing this many transits, especially for planets with periods that are not pathologically favourable, longer time-base observations are required.

A further simulation of the 20 SuperWASP-N fields, this time using the observing baseline of each field, yields a total of $3.72 \pm 1.60$ detected planets (see Smith et al. 2006 for the complete results of this simulation). The detection rate was found to increase linearly with observing baseline (Fig. 3).

![Figure 3. Detection rate of transiting extra-solar planets versus length of observing baseline. The squares correspond to all 20 fields modelled using the same observing baseline, while the triangles represent an additional 130 nights of observations in a second season. The 20 fields, modelled using their own observing baselines, are represented by the open circles.](image)

Given that SuperWASP-N observed with five cameras in 2004, our predicted planet yield can be scaled up to $18.6 \pm 8.0$ planets, which we compare to the number of planets discovered by SuperWASP-N from the 2004 data set. Two new transiting systems, WASP-1 and WASP-2, were discovered (Street et al. 2006; Collier Cameron et al. 2006b) and a third, known system, XO-1 (McCullough et al. 2006) was also detected.

There are several reasons for the apparent discrepancy between the number of predicted planets and the number detected. Probably most significant is that only the best candidates brighter than $V = 12$ were selected for the initial radial velocity follow up. Analysis of our model reveals that $\approx 25$ per cent of our predicted detections lie in the magnitude range $12 < V < 13$, and further undetected planets may lie among the remaining brighter candidates. Additionally, the distribution of semi-major axis used in our model (Smith et al. 2006) may tend to slightly over-predict the number of very short-period planets, to which the transit method is most sensitive.
5. Conclusions

We conclude that there is a significant component of systematic, red noise present in data from SuperWASP-N. The SysRem algorithm of Tamuz et al. (2005) appears highly effective at reducing the level of red noise, but fails to eliminate it entirely. The remaining 3 mmag of red noise present in the data on transit duration time-scales has a significant impact on planet detection.

Modelling the objects in the fields of one SuperWASP-N camera reveals that in order to improve the \( S_{\text{red}} \), and thus increase the number of detectable planets, a greater number of transits must be observed in the data set of a particular object. This requires observations to be made over a longer time period.

On the basis of our predicted transit detection rates, the SuperWASP consortium have decided to continue observing for a further season all the fields that were monitored during 2004. We expect that this will enhance greatly the number of planetary transit events detected at non-pathological periods.

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