Simultaneous TESS and NGTS transit observations of WASP-166 b

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ABSTRACT

We observed a transit of WASP-166 b using nine Next Generation Transit Survey (NGTS) telescopes simultaneously with the Transiting Exoplanet Survey Satellite (TESS) observations of the same transit. We achieved a photometric precision of 152 ppm per 30 min with the nine NGTS telescopes combined, matching the precision reached by TESS for the transit event around this bright (T = 8.87) star. The individual NGTS light-curve noise is found to be dominated by scintillation noise and appears free from any time-correlated noise or any correlation between telescope systems. We fit the NGTS data for TC and Rp/R⊙. We find TC to be consistent to within 0.25σ of the result from the TESS data, and the difference between the TESS and NGTS measured Rp/R⊙ values is 0.9σ. This experiment shows that multitelescope NGTS photometry can match the precision of TESS for bright stars, and will be a valuable tool in refining the radii and ephemerides for bright TESS candidates and planets. The transit timing achieved will also enable NGTS to measure significant transit timing variations in multiplanet systems.

Key words: methods: observational – techniques: photometric – planets and satellites: detection.

1 INTRODUCTION

The Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) has been hunting for exoplanets transiting bright stars since July 2018. During its 2 yr nominal mission, TESS will monitor ~ 80 per cent of the sky, providing light curves at a 2 min cadence for > 200 000 stars and at a 30 min cadence for the full field of view. TESS has already made a number of notable discoveries of exoplanets transiting bright stars, including Pi Mensae c (Gandolfi et al. 2018; Huang et al. 2018), HD1397 b (Brahm et al. 2019; Nielsen et al. 2019), and the HR858 system (Vanderburg et al. 2019).

As part of this discovery process, ground-based transit photometry is used to improve spatial resolution, verify the transit is achromatic, check for transit timing variations, and improve the precision on transit parameters such as period, phase, and depth (e.g. Collins et al. 2018). However ground-based photometric observatories struggle to reach the precision of TESS for bright stars. The primary obstacle is that precise ground-based time-series photometry requires similar magnitude reference stars to the target star in order to adequately correct for photometric changes caused by the Earth’s atmosphere. However for a T ≈ 8.87 star the nearest similar magnitude reference star is, on average, separated by 1 deg.

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This is far outside the field of view of most photometric facilities (Collins et al. 2018).

The Next Generation Transit Survey (NGTS; Wheatley et al. 2018) is an exoplanet hunting facility situated at ESO’s Paranal Observatory in Chile. It consists of 12 robotic telescopes, each with a 20 cm diameter and a field of view of 8 deg$^2$. The wide field of view of NGTS places it in a unique position to obtain photometric follow-up from the ground of the brightest exoplanet host stars. One limitation is that the 20 cm telescope apertures do not collect as many photons we would wish for high-precision photometry. We mitigate this limitation with NGTS by observing a target star simultaneously with multiple telescopes. This increases the effective collecting area of the facility, allowing us to obtain a light curve equivalent to a larger aperture telescope while preserving the wide field of view.

One of the main sources of photometric noise for NGTS observations of bright stars is scintillation noise. Scintillation noise arises from light passing through regions of turbulence in the Earth’s atmosphere, resulting in changes in intensity (e.g. Osborn et al. 2015). Scintillation has been shown to behave as white noise on transit time-scales (Förhling et al. 2019). As such, simultaneous observations also reduce the noise present in the light curves due to atmospheric scintillation by a factor $\sqrt{N}$, where $N$ is the number of telescopes used. This is provided that scintillation noise does not correlate between the telescopes. This is especially important for bright stars ($I \leq 10$) as in this regime scintillation noise dominates all other noise sources (Wheatley et al. 2018).

An early experiment, using multiple NGTS telescopes was the observation of the K2 transiting planet HD 106315c in 2017 (Smith et al. 2020). This work demonstrated that by using multiple NGTS telescopes we could achieve the photometric precision needed to detect a shallow (0.1 per cent) transit from the ground.

In this paper, we present a study into the photometric precision and noise properties of the NGTS multitelescope observations for a bright star hosting a transiting planet. WASP-166 is a $V = 9.351 \pm 0.002$ F-type dwarf star that hosts a $0.64 \pm 0.03 R_\odot$ transiting exoplanet that orbits the star on a period of 5.4435 d (Hellier et al. 2019). A summary of the main properties of WASP-166 is set out in Table 1. We were able to observe WASP-166 simultaneously with TESS, which provides a unique opportunity to rigorously compare the NGTS ground-based light curve with the TESS light curve.

We set out this study in the following manner. In Section 2, we outline both the NGTS and the TESS observations of WASP-166. In Section 3.1, we examine the noise properties of the multitelescope NGTS photometry. We model the NGTS data and examine the uncertainties on key system parameters in Sections 3.2 and 3.3. The comparison between the NGTS and TESS photometry is set out in Section 3.5. Finally, we provide a discussion of our results in Section 4.

## 2 Observations

### 2.1 NGTS Photometry

WASP-166 was observed with NGTS on the nights 2019 February 25 and 26. The observations were taken at airmass <2 and under photometric conditions. Across both nights, 9 of the 12 NGTS telescopes were available to be used to simultaneously observe WASP-166. Each telescope used the custom NGTS filter (520–890 nm). A total of 40,003 images were taken across the two nights, all with an exposure time of 10 s. The NGTS cameras have a readout time of approximately 3 s, and therefore the full cadence of these observations was 13 s. For all observations, due to the brightness of WASP-166 the telescopes were slightly defocussed, in order to avoid saturation. The NGTS telescope guiding is performed using the DONUTS autoguiding algorithm (McCormac et al. 2013); this extremely high-precision guiding resulted in a mean RMS of the location on the CCD of the target of 0.27 pixels (plate scale: 5 arcsec pixel$^{-1}$) across the two nights.

The reduction is carried out on the raw frames using a custom aperture photometry pipeline that utilizes SEP (Bertin & Arnouts 1996; Barby 2016). This pipeline computes the photometry for a set of circular apertures with a range of radii, and the final light curve is determined by finding the aperture with the minimum RMS scatter. Background subtraction is performed by creating and subtracting a global background map. This background map is created using SEP. After extensive testing, we find that bias, dark, and flat-field frame corrections do not improve the precision of the photometry. In some conditions these corrections decrease the precision. Therefore, we do not apply these corrections during the image reduction.

Comparison stars are ranked according to their colour, brightness, and position on the image, relative to the target star. This ranking is used to select the best non-saturated non-variable comparison stars. Any comparison stars with a significantly bright GAIA neighbour that would contaminate the photometric aperture are automatically discarded. The differential target star flux is computed by dividing the photometric counts from the target star by the total sum of the counts from all the comparison stars.

Despite WASP-166 being a bright star ($T = 8.87$), the wide field of view of NGTS allowed us to monitor 23 good quality comparison stars of similar magnitude to WASP-166, more than could be monitored by a 1 m telescope. The 23 comparison stars monitored were the same for each telescope. We combine and analyse these photometric data from each NGTS telescope in Section 3.

On the night of 2019 February 25, a transit of WASP-166b was observed, and we use these data to investigate the precision with which we can measure planetary system parameters with this

### Table 1. Stellar properties for WASP-166.

| Name | Value | Source |
|------|-------|--------|
| TIC ID | 408310006 | Hellier et al. (2019) |
| RA | 09°39′30.09″ | 2MASS |
| Dec. | −20° 58′ 56.9″ | 2MASS |
| $μ_R$ (mas yr$^{-1}$) | −55.082 ± 0.072 | GAIA DR2 |
| $μ_{dec}$ (mas yr$^{-1}$) | 10.927 ± 0.069 | GAIA DR2 |
| Parallax (mas) | 8.7301 ± 0.0448 | GAIA DR2 |
| $R_*$ (R$_\odot$) | 1.25 ± 0.06 | TIC v8 |
| $M_*$ (M$_\odot$) | 1.14 ± 0.15 | TIC v8 |
| TESS | 8.8685 ± 0.0062 | TIC v8 |
| GAIA | 9.257 ± 0.00031 | GAIA DR2 |
| $V$ | 9.351 ± 0.002 | |
| $B$ | 9.940 ± 0.034 | |
| $J$ | 8.350 ± 0.021 | 2MASS |
| $H$ | 8.135 ± 0.033 | 2MASS |
| $K$ | 8.032 ± 0.023 | 2MASS |
| WISE (3.4 μm) | 7.999 ± 0.025 | WISE |
| WISE (4.6 μm) | 8.054 ± 0.019 | WISE |

Notes. 2MASS (Skrutskie et al. 2006); WISE (Wright et al. 2010); GAIA DR2 (Gaia Collaboration et al. 2016); TIC v8 (Stassun et al. 2018).
Figure 1. The nine individual NGTS telescope light curves for the transit of WASP-166 b on 2019 February 25. The normalized flux data points are all shown binned to 2 min. The solid red lines give the individual transit models for each light curve (see Section 3 for details).

observing mode. We use the out-of-transit data from the night of 2019 February 26 to investigate the multitile telescope noise properties of NGTS, as it is independent of any transit modelling steps. The nine individual NGTS telescope light curves are displayed in Fig. 1, and the NGTS photometry is provided in Table 2.

2.2 TESS photometry

WASP-166 was observed by TESS (Ricker et al. 2015) at a cadence of 2 min from 2019 February 02 to 2019 February 27 during Sector 8 of the primary TESS mission. TESS observes over a wavelength range of 600–1100 nm. WASP-166 fell on TESS Camera 2/CCD 3 and data were reduced by the official SPOC pipeline (Jenkins et al. 2016). We accessed the data through the MAST portal1 and utilized the PDCSAP_FLUX, which has had any spacecraft systematics removed (see Jenkins et al. 2016, for details). The full TESS light curve of WASP-166 spans ~27.4 d and contains four full transits. However for this work we consider only the sections of the light curve which coincide with the NGTS observations; 2458540.51961711 ≤ BJD ≤ 2458540.8531236 for the transit night and 2458541.5199 ≤ BJD ≤ 2458541.84915 for the non-transit night. This allows for a more direct comparison of the light curve and parameter precision available from the two data sets.

1https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html
Table 2. Example table of the NGTS photometry of WASP-166. The full table is available online.

| BJD (TDB) (−2450000) | Flux   | Flux error | Cam |
|-----------------------|--------|------------|-----|
| 8540.51964025         | 0.99863 | 0.008012   | 1   |
| 8540.51979072         | 0.999378| 0.007995   | 1   |
| 8540.51994118         | 0.999461| 0.007972   | 1   |
| 8540.52009164         | 0.997650| 0.007938   | 1   |
| 8540.52024211         | 0.997247| 0.007918   | 1   |
| 8540.52039257         | 1.000107| 0.007918   | 1   |
| 8540.52054303         | 0.998085| 0.007882   | 1   |
| 8540.52068192         | 1.015229| 0.007980   | 1   |
| 8540.52083238         | 0.995757| 0.007831   | 1   |
| 8540.52098285         | 0.980196| 0.007706   | 1   |

3 ANALYSIS

3.1 NGTS noise properties

We used our NGTS observations of WASP-166 on the night of 2019 February 26 to investigate noise correlation between NGTS telescopes. We studied three main properties of the noise of the individual NGTS light curves.

3.1.1 Noise properties of the individual telescopes

To investigate the noise properties of the individual NGTS telescopes, we computed the RMS precision over a range of time-scales, \( \tau \), from unbinned cadence (13 s) up to 45 min. We compare the RMS trend with time-scale to that expected from purely white (Gaussian) noise. Our results are plotted in Fig. 2. We find that the individual NGTS telescopes closely follow the predicted 1/\( \sqrt{\tau} \) white noise scaling. This suggests that the noise in the NGTS light curves is dominated by Gaussian noise, and that we do not have any significant systematic noise on these time-scales. In some telescopes, we see deviations from the predicted Gaussian noise scaling, especially at larger \( \tau \) values. This is a consequence of only having a small number of binned flux data points at large \( \tau \) values.

This result gives us confidence that systematic noise is not a major hindrance to the effectiveness of this multitelescope observing method.

3.1.2 Flux correlations between telescopes

We performed a pairwise correlation test of all the NGTS light curves of WASP-166 to search for any obvious correlation in the photometric noise between the NGTS telescopes. Since the NGTS telescopes all operate independently, the time-stamps for the nine individual light curves are not perfectly synchronous. We therefore create a set of time-stamps at 13 s intervals, between the start and end of the observations. Each telescope time series was then mapped to these new time-stamps before comparing to the other telescopes. This was done by assigning each flux data point to the new time-stamp that represents the smallest deviation in time from the actual mid-point of the exposure. This allows for a more accurate comparison between the fluxes from the pairs of telescopes.

We find no flux correlation between any pair of telescopes – see Fig. 3. We also note that the flux distribution for each telescope looks Gaussian. This again gives us confidence that the light curves are free from systematic noise.

3.1.3 Combining individual telescope data

Given individual NGTS light curves show uncorrelated Gaussian noise, by combining the light curves we expect a combined light curve with an RMS scatter, \( \sigma_m \), given by:

\[
\sigma_m = \sigma_s / \sqrt{N},
\]

where \( \sigma_s \) is the RMS scatter of a single telescope light curve, and \( N \) is the number of telescopes combined.

For each value of \( N \), we calculated \( \sigma_m \) at a time-scale of 30 min for each possible telescope combination. We then found the mean of the \( \sigma_m \) for each value of \( N \). The results are set out in Fig. 4, showing that...
the calculated $\sigma_m$ values are very close to the uncorrelated Gaussian-noise expectation of $\sigma_m$ given by equation (1). The deviation from the expected $\sigma_m$ for $N = 9$ is just 5 ppm.

3.1.4 Scintillation noise

As stated in Section 1, the NGTS light-curve noise for bright stars ($I \leq 10$) is expected to be dominated by scintillation noise (Wheatley et al. 2018). We tested this by analysing the variation in the flux RMS during the observation and comparing this variation to the predicted light-curve noise. We calculated the predicted scintillation noise using the modified Young’s approximation

$$\sigma_Y^2 = 10 \times 10^{-6} C_Y^2 D^{-4/3} t^{-1} (\sec z)^1 \exp(-2h_{\text{obs}}/H),$$

where $D$ is the diameter of the telescope aperture (m), $t$ is the exposure time used (s), $z$ is the zenith distance, $h_{\text{obs}}$ is the altitude of the observatory (2440 m for Paranal), and $H$ is the scale height of the atmospheric turbulence, which is taken to be 8000 m (Osborn et al. 2015). $C_Y$ (m$^{2/3}$s$^{1/2}$) is an empirical coefficient and $\sigma_Y$ is the dimensionless normalized scintillation noise (Young 1967; Osborn et al. 2015).
Using batman curves with respect to external parameters and fitted each transit simultaneously detrended the individual NGTS telescope light sky background, and time. We found that only detrending with parameters for detrending, including airmass, target pixel position, parameters: the time of the transit centre, the final model. P combination of curves co-added. The blue points give the mean precision for each possible number of individual telescope light curves (see the text for details). The errorbars give the standard error on this mean. The solid black line shows the Gaussian 1/√N improvement in σ_m for pure white noise, scaled from the N=1 data point. The dashed red line shows the calculated RMS precision of the TESS light curve for WASP-166.

At high airmass, differential refraction across the field of view will cause the comparison stars to move on the CCD relative to the target star. The slight differences in response of neighbouring pixels on the CCD will result in this movement causing an increase in the flux RMS at high airmass. Therefore, we expect the scintillation noise model (equation 2) to not perfectly describe the observed light curve noise at high airmass.

We modelled the noise in our data as a combination of scintillation noise and photon noise from both the target star and the sky background. We used only the data with airmass sec z < 1.2 and fit for the coefficient C_Y, finding a value of C_Y = 1.57 ± 0.06. This is in good agreement with the results from Osborn et al. (2015). They find a median value of C_Y = 1.56 for Paranal, with 1st and 3rd quartiles of 1.27 and 1.90.

The flux RMS and the noise model are displayed in Fig. 5, and we see that the noise in the NGTS light curve is dominated by the scintillation noise, as predicted. The variation in this noise during the night is well described by Young’s approximation for low airmass. The predicted deviation of the flux RMS values from the noise model at high airmass can also be clearly seen.

### 3.2 Fitting individual NGTS light curves

In order to determine the transit parameters of WASP-166 b from our NGTS data from the UT night of 2019 February 25, we simultaneously detrended the individual NGTS telescope light curves with respect to external parameters and fitted each transit using batman (Kreidberg 2015). We tested a number of external parameters for detrending, including airmass, target pixel position, sky background, and time. We found that only detrending with respect to time significantly improved the log likelihood, ln z, of the final model.

For the batman transit model, we used the following free parameters: the time of the transit centre, T_C, the orbital period, P, the planet-to-star radius ratio, R_p/R_*; the impact parameter, b, and the stellar density, ρ_. We used a quadratic limb-darkening law, and fitted the parametrized coefficients q1 and q2 from Kipping (2013). For these coefficients, we used uniform priors between 0 and 1, in order to ensure physically realistic limb-darkening profiles (Kipping 2013).

As the NGTS data cover just a single transit, they alone do not place any constraints on the period. However, Hellier et al. (2019) were able to very tightly constrain the period due to the very long time baseline afforded to them by the combination of WASP and TESS photometry, as well as their precise measurement of the Rossiter–McLaughlin effect for WASP-166. Therefore we place a 1σ Gaussian prior on the period, based on the period and uncertainty reported in Hellier et al. (2019). We also utilize the stellar parameters from version 8 of the TIC (Stassun et al. 2018) to place a Gaussian prior on ρ_*, with a mean and standard deviation of 0.58 ± 0.11ρ_⊙. In addition, we use a uniform prior to ensure that b ≥ 0. For the remaining parameters, we simply impose further uniform priors to ensure that they take physically realistic values. Hellier et al. (2019) find a 2σ upper limit of the eccentricity of e < 0.07, and so they adopt a circular orbit. Based on this, and the fact that our photometric data provide little information on the eccentricity of the orbit, we also adopt e = 0. The modelling was performed using an MCMC sampling method implemented using the emcee Ensemble Sampler (Foreman-Mackey et al. 2013). We ran 50 walkers for 15 000 steps as a burn-in process, and then a further 5000 draws were made to sample the posterior for each chain. The chains were inspected and found to be well mixed. We plot the best-fitting models for each individual light curve in Fig. 1.

In analysing these fits, we focus on the two main parameters which can be obtained from a single transit: the planet-to-star radius ratio, R_p/R_*, and the time of the transit centre, T_C. In Fig. 6, we compare the posterior parameter distributions (PPDs) for these two parameters from the modelling of the nine individual NGTS light curves.

In terms of the individual PPDs, we see good agreement between the obtained parameter values for the two parameters. For R_p/R_*, the PPDs behave as might be expected, with the single telescope PPDs being scattered around the ‘true’ value. The average single telescope uncertainty in R_p/R_* is ±0.0034. The weighted mean of the nine R_p/R_* measurements is 0.052 ± 0.001 10.

Figure 4. 30 min RMS precision (σ_m) of the NGTS combined light curve for WASP-166 as a function of the number of individual telescope light curves co-added. The blue points give the mean precision for each possible number of individual light curves (see the text for details). The errorbars give the standard error on this mean. The solid black line shows the Gaussian 1/√N improvement in σ_m for pure white noise, scaled from the N=1 data point. The dashed red line shows the calculated RMS precision of the TESS light curve for WASP-166.

Figure 5. Variation of the flux RMS for the combined NGTS light curve. The total noise model (solid red) includes the scintillation noise (blue dashed) and the photon noise from the target star (green dashed) and the sky background (cyan dashed).
The combined NGTS light curve and the resultant transit model from this modelling process are displayed in Fig. 6. The system parameters obtained are given in Table 3, where the parameter values reported are the median values from the posterior distributions, with the corresponding 1σ uncertainties.

We compare this combined light-curve fit to the individual light-curve fits from Section 3.2. The PPD of the combined light-curve fit is plotted in Fig. 6. The average single telescope uncertainty in \( \frac{R_p}{R_*} \) is ±0.0034, while the uncertainty in \( \frac{R_p}{R_*} \) from the combined light curve is ±0.0012. Thus we see that the uncertainty in the measured value of \( \frac{R_p}{R_*} \) from the combined light curve is reduced by a third, as expected from the \( 1/\sqrt{N} \) scaling. In addition, the combined light-curve uncertainty is comparable to the error on the weighted mean of the nine individual light-curve measurements. We also find that the \( \frac{R_p}{R_*} \) value derived from the combined light curve is consistent with the nine light curve weighted mean at the 1σ level.

The uncertainty in \( T_C \) measured from the combined light curve is ±0.0007 d, which is a reduction from the average of the individual light-curve uncertainties found in Section 3.2 (±0.00318 d) of more than a third. The two individual light curves with the high \( T_C \) uncertainties inflate the average single telescope uncertainty. However, the fit to the combined light curve is less affected by the out-lying points that result in the higher single telescope uncertainties.

As with \( \frac{R_p}{R_*} \), the \( T_C \) value derived from the combined light curve is consistent with the nine light-curve weighted mean at the 1σ level. We note that the error on this weighted average is slightly higher than the combined light-curve \( T_C \) uncertainty. This is again likely a result of the out-lying individual \( T_C \) measurements having more of an effect on the weighted mean than it had by the out-lying data points in these light curves on the combined light-curve \( T_C \) measurement.

### 3.4 Fitting TESS data

In order to make a direct comparison to the results of modelling the NGTS data, we model the TESS data with a process identical to that for the combined NGTS light curve set in Section 3.3. We select just the portion of the TESS data obtained simultaneously with our NGTS data (2458540.1961711 ≤ BJD ≤ 2458540.531236). The TESS data and the resulting best-fitting transit model are displayed in Fig. 7, with the parameter values given in Table 3.

### 3.5 NGTS and TESS comparison

The main parameters of interest for this comparison are \( T_C \) and \( \frac{R_p}{R_*} \), as they both can be constrained by a single transit. We plot the PPDs for these parameters in Fig. 8.

We find the two values of \( T_C \) from NGTS and TESS to be consistent to within 0.25σ of each other. The value of \( \frac{R_p}{R_*} \) measured from the TESS transit is found to be a lower than the value measured from the NGTS data, with a difference of 0.9σ. The \( \frac{R_p}{R_*} \) values from NGTS and TESS are formally consistent to 1σ, but we note that a similar modelling of the first transit of WASP-166 b in the TESS light curve yields a value of \( \frac{R_p}{R_*} = 0.05235 ± 0.0005 \). This value represents a difference from the NGTS value of just 0.4σ.

We fitted the limb darkening coefficients during the modelling, therefore any differences in measured \( \frac{R_p}{R_*} \) values will not be due to any depth difference caused by the differences between the TESS and NGTS pass bands. Helloc et al. (2019) measure a value of \( \frac{R_p}{R_*} = 0.0530 ± 0.0007 \), which is consistent with the value measured from the NGTS transit and the first TESS transit.
NGTS simultaneous observations

Figure 7. Light curves showing the 2019 February 25 transit of WASP-166 b. **Left:** Combined light curve obtained with a simultaneous observation using nine NGTS telescopes. The black circles show the data binned to 2 min, for visual comparison with the 2 min cadence TESS data. The solid red line gives the best-fitting transit model from the modelling process (Section 3.3). **Right:** Black circles show the unbinned 2 min cadence TESS data. The solid red line again gives the transit model from the modelling process (Section 3.4).

### Table 3. Planetary system properties for WASP-166.

| Planetary parameters | Value (NGTS) | Value (TESS) |
|----------------------|--------------|--------------|
| **Fitted parameters** |              |              |
| $T_C$ (BJD)          | 2458540.739646 $^{+0.000715}_{-0.000726}$ | 2458540.739389 $^{+0.000721}_{-0.000670}$ |
| Orbital period (d)   | 5.4435399 ± 0.0000028 | 5.4435402 $^{+0.0000027}_{-0.0000030}$ |
| $R_p/R_*$            | 0.05298 $^{+0.00010}_{-0.000123}$ | 0.0515 $^{+0.00011}_{-0.00011}$ |
| $b$                  | 0.423 ± 0.090 | 0.398 ± 0.111 |
| $\rho_*$ ($\rho_\odot$) | 0.593 $^{+0.082}_{-0.080}$ | 0.627 $^{+0.074}_{-0.081}$ |
| $q_1$                | 0.26 $^{+0.015}_{-0.015}$ | 0.33 $^{+0.020}_{-0.017}$ |
| $q_2$                | 0.16 $^{+0.012}_{-0.012}$ | 0.16 $^{+0.012}_{-0.012}$ |
| **Derived parameters** |              |              |
| $a$ ($R_*$)          | 11.00 $^{+0.47}_{-0.51}$ | 11.14 $^{+0.42}_{-0.50}$ |
| $a$ (au)             | 0.064 ± 0.003 | 0.065 ± 0.003 |
| $inc$ (°)            | 87.80 $^{+0.67}_{-0.59}$ | 87.95 $^{+0.62}_{-0.59}$ |
| **Fixed parameters** |              |              |
| $e$                  | 0.            | 0.            |
| $\omega$ (°)        | 90.           | 90.           |

but is discrepant with the value from the TESS transit on 2020 February 25.

During Sector 8 of the TESS mission, a few days prior to the 2020 February 25 transit, an instrument anomaly caused the heaters to switch on.\(^2\) The resulting temperature increase affected both the camera focal plane scale and the individual CCD mean black levels.

\(^2\)https://archive.stsci.edu/missions/tess/doc/tess_drm/tess_sector_08_drm10_v02.pdf

It is probable that this resulted in a problem with the systematic error corrections in SPOC pipeline, which could have induced the slightly shallower transit depth observed for this transit.

### 4 DISCUSSION

The NGTS photometric noise for bright stars is dominated by atmospheric scintillation (Wheatley et al. 2018). Scintillation behaves as white noise on the time-scales of exoplanet transits (Fohring et al. 2019), and indeed the NGTS light curves in this study confirm...
et al. 2019). These stars are 2–3 mag fainter than WASP-166, and

systems of this type, such as TOI-175 (Cloutier et al. 2019; Kostov

host stars. The TESS mission has already revealed many candidate

multitelescope observations to measure

Figure 8. Same as Fig. 6 but comparing the PPDs from the fit to the
combined NGTS light curve (solid, blue online) and the fit to the TESS
transit on 2020 February 25 (dashed, red online).

this: see Section 3.1. We also find that there is no correlation
between the photometric noise from individual NGTS telescopes – see Figs 3 and 4. This indicates that the spacing between the
telescopes (approximately 2 m) is enough to ensure that the light
paths through the atmosphere are separated enough to ensure that
they do not result in correlated scintillation noise. The fact that
the NGTS telescopes are well spaced is critical for the success of these
observations.

For these bright stars, the noise will be dominated by scintillation
and photon noise, which will both result in the precision increasing
by \( \sqrt{N} \) when combining telescopes. However, from Wheatley et al. (2018), CCD readout and sky background become significant noise
sources for \( I > 13 \). This suggests that combining NGTS telescopes
would be less advantageous for fainter targets.

We find that we can achieve a precision for \( T_C \) on a single transit
of 1 min for a transit of this bright star. This will allow NGTS
multitelescope observations to measure \( T_C \) with a precision of a
few minutes for systems of multiple rocky planets, orbiting bright
host stars. The TESS mission has already revealed many candidate
systems of this type, such as TOI-175 (Cloutier et al. 2019; Kostov
et al. 2019), TOI-178 (Leleu et al. 2019), and TOI-270 (Günther
et al. 2019). These stars are 2–3 mag fainter than WASP-166, and
so we expect lower photometric precision than we achieved for
WASP-166. A lower photometric precision is likely to result in a
higher uncertainty on the transit timing (Carter et al. 2008).

We also find in Section 3.3 that the measured value of \( T_C \) from a
single telescope light curve can be biased by out-lying data points
during ingress or egress. This in turn affects the \( T_C \) value that is
derived from a weighted mean of the individual \( T_C \) measurements.
By modelling all the data together as a combined light curve, we
find that the measured \( T_C \) value and uncertainty is more resistant to
these flux outliers.

Observing simultaneously with multiple telescopes also grants
some protection against technical faults with individual telescope
systems. This is especially of importance for high priority can-
didates with not many opportunities for observations, such as long
period candidates (e.g. TOI-222, Lendl et al. 2020; TIC-238855958,
Gill et al. 2020).

The TESS mission has recently been extended for two more
years. As such, the Southern sky will be re-observed by TESS
between July 2020 and June 2021. TESS observes in the anti-Sun
direction, and so this extended mission will provide many more
opportunities for simultaneous ground and space observations for
bright planet hosting stars.

5 CONCLUSION

Our data have shown that the noise in NGTS bright star light curves
is dominated by scintillation noise. We have shown that this noise is
Gaussian, and is uncorrelated between the telescopes. This allows
us to combine simultaneous observations with multiple telescopes
to obtain ultra-high precision light curves of individual exoplanet
transits. We can combine this technique with the wide field of view
of the NGTS cameras to achieve some of the highest precisions
from the ground for the brightest stars.

We can use this technique to achieve transit timing on order
of minutes for planets orbiting bright stars, with transit depths
on the order \( \sim 1000 \) ppm. As a result, this technique will enable
NGTS to measure any significant transit timing variations in
multiplanet systems with similarly bright host stars. The precise
transit ephemerides achievable with this observing method will
also allow NGTS to monitor the transit timing variations of short-
period Jupiter-like planets to search for signs of orbital decay (e.g.
Balucnev et al. 2019; Patra et al. 2020; Yee et al. 2020). In addition
to measuring transit timing variations, the precise ephemerides
achievable with NGTS multitelescope observations will also be
of use for the scheduling of future transmission spectroscopic
measurements, and other characterization efforts.

Over the next few years, hundreds of rocky planet candidates
orbiting bright stars will be detected by TESS. The confirmation
of these planets and the measurement of their masses will contribute
to the TESS Level 1 Science goal of measuring the mass of 50
planets with a radius \( \leq 4 R_\oplus \). We have demonstrated that NGTS
can achieve the same precision as space-based photometry from the
ground through simultaneous multitelescope observations. As such,
NGTS will contribute significantly to the confirmation of these and
other rocky planets around bright stars, both by confirming the
transit signal and by measuring the mass by detecting any TTV
signals.

3https://heasarc.gsfc.nasa.gov/docs/tess/announcement-of-the-tess-exten-
ded-mission.html
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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

wasp166b_supp.zip

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