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THE NEXT GENERATION TRANSIT SURVEY PROTOTYPING PHASE

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RESUMEN

El Next Generation Transit Survey (NGTS) es un nuevo sondeo de exoplanetas transitantes de campo amplio que tiene como objetivo descubrir exoplanetas del tamaño de Neptuno y super-Tierras entorno a estrellas brillantes ($V < 13$) cercanas. NGTS consiste de un arreglo de 12 telescopios operados robóticamente observando en la banda de $600 - 900$ nm. NGTS sondeará más de cinco veces el número de estrellas, con $V < 13$, que Kepler y por lo tanto proveerá los objetivos más brillantes para ser caracterizados con instrumentación existente y futura (VLT, E-ELT y JWST). En 2009/10 un prototipo del NGTS fue probado en La Palma, comprobando que un sistema así puede alcanzar nuestros objetivos de fotometría estelar esencialmente limitada sólo por el ruido blanco. Los resultados son resumidos aquí. NGTS se alimenta de la experiencia del proyecto SuperWASP, que, por muchos años, ha liderado la detección terrestre de exoplanetas transitantes.

ABSTRACT

The Next Generation Transit Survey (NGTS) is a new wide-field transiting exoplanet survey aimed at discovering Neptune and super-Earth size exoplanets around bright ($V < 13$) nearby stars. NGTS consists of an array of 12 robotically operated telescopes observing in the $600 - 900$ nm band. NGTS will survey more than five times the number of stars with $V < 13$ than Kepler and will therefore provide the brightest targets for characterisation with existing and future instrumentation (VLT, E-ELT and JWST). In 2009/10, a prototype for NGTS was tested on La Palma, proving that such a system can meet our goals of essentially white noise limited photometry of bright stars, the results of which are summarised here. NGTS builds on the experience of the SuperWASP project, which, for many years, has lead the ground-based detection of transiting exoplanets.

Key Words: instrumentation: photometers — methods: data analysis — planetary systems — techniques: photometric — telescopes

1. INTRODUCTION

The Next Generation Transit Survey (NGTS[4]) is a wide-field photometric survey for transiting exoplanets currently under construction at ESO Paranal, Chile. The motivation behind NGTS is to understand planetary formation and evolution, as well as determining atmospheric and bulk compositions of Neptune and super-Earth sized exoplanets. The *Kepler* survey has shown there to be an abundance of Neptune sized objects in their field (Dong & Zhu 2013). While the results from *Kepler* are important in terms of statistics, the mean brightness of host stars of small planets observed by *Kepler* is too faint for efficient spectroscopic follow up from the ground. The NGTS project (Wheatley et al. 2013) was conceived to detect this population of Neptune-sized transiting exoplanets around bright (V≤13) K and early M-type stars accessible to the ESO telescopes.

Pont et al. (2006) showed that systematic (red) noise is non-negligible when searching for transiting exoplanets and hence limits the detection efficiency of most ground-based surveys. Initial predictions of transiting planet detection rates considered uncorrelated (white) noise only, overlooking the effects of red noise (e.g. Horne 2003). Pont et al. suggest that this may explain the inconsistency between transiting exoplanet detection rates compared to initial predictions. In order to meet the scientific goals of the NGTS project it is crucial we understand the type of noise in an NGTS-like system and identify any possible sources of systematic noise. A prototype telescope for NGTS (hereafter NGTS-P) was constructed at Queen's University Belfast in the winter of 2008/09 with the aim of determining the level of systematic noise in an NGTS-like system (described in §2) and to prove that millimagnitude photometry or better can be achieved on transit time scales.

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NGTS-P was tested at the Observatorio del Roque de los Muchachos on La Palma during 2009/10, conducting several experiments to determine the technical feasibility of the proposed NGTS project, the results of which are summarised here.

2. THE PROTOTYPE TELESCOPE

NGTS-P consisted of an Andor Technologies iKon-M 934N BR DD-CCD camera and a Takahashi E-180 wide-field Newtonian telescope. The sensor was a back-illuminated, 1024×1024 pixels, deep depleted (to eliminate fringing) CCD made by e2v. It had a peak quantum efficiency $> 90\%$ at ≈ 800 nm. The camera was cooled to $-80°$C using a five-stage Peltier thermoelectric cooler resulting in a dark current of 2.46 e^- pixel^{-1} min^{-1}. A readout speed of 1 MHz was chosen resulting in a gain and read noise of 1.2 e^- ADU^{-1} and 7.1 e^-, respectively. NGTS-P had a field-of-view and plate scale of $1.^{\circ}56 \times 1.^{\circ}56$ and $5.''36$ pixel^{-1}, respectively. A single fixed filter was housed in the camera-to-telescope coupling. All of the observations described in §4 were obtained using the pseudo I-band filter ($650 - 950$ nm).

The telescope was mounted on a Paramount ME German Equatorial Mount (GEM) and autoguided using a separate refracting telescope and autoguider camera. To avoid the common pier flip problem on GEMs all of the tests described in §4 were conducted on one side of the meridian. NGTS-P was housed inside a 7 ft Astrohaven clamshell dome and weather information was obtained from SuperWASP-N (Pollacco et al. 2006), beside which NGTS-P was installed. The focus of each telescope was controlled using a Robofocus absolute stepper motor.

3. OBSERVATIONS AND DATA REDUCTION

Observations with NGTS-P were obtained between September 2009 and July 2010, collecting 100+ nights of data. Each night's data were reduced using the standard routines in IRAF. After some initial analysis it became evident that the flat fields contained significant scattered light content, the affects of which could not be removed via detrending (see below). As a result the data analysed here were reduced without flat fielding. Light curves were extracted from the series of images using the DAOPHOT package (Stetson 1987) in IRAF and passed through our implementation of the SysRem detrending algorithm (Tamuz et al. 2005). A full description of the detrending algorithm and its application to an OGLE data set is given by Tamuz et al. (2005) and Mazeh et al. (2007), respectively.

A stopping criterion must be defined for SysRem so that only the strongest trends are removed and

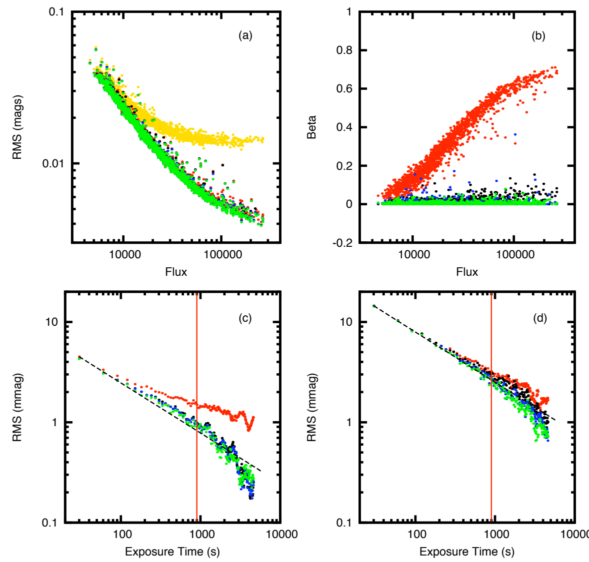

Fig. 1. Results from detrending NGTS-P data. The red, black, blue and green points represent the data after the removal of 1, 2, 3 and 4 trends with SysRem, respectively. The gold points represent the original data from 2009 September 19 uncorrected for airmass etc. The black dashed lines show the expected $\sqrt{n}$ decrease in RMS in the presence of Gaussian noise only, where n is the number of points per bin. Panel a shows the different RMS vs flux diagrams for each level of detrending. Panel b shows fractional improvement *Beta* in each light curve's RMS versus its average flux for each level of detrending. Panels c & d show the average RMS vs binned exposure time for the 9 brightest stars and 9 stars of medium brightness at each level of detrending, respectively. The solid red line highlights the proposed 900 s binned exposure time required to reach 1 mmag RMS in the brightest sources.

not the signal from planetary transits etc. The stopping criterion for SysRem was set to remove effects that were stronger than 95% of all random effects ($\alpha = 0.95$). The detrending algorithm typically removed two trends, an airmass trend and a second, much less dominant trend, most likely due to colour-dependent atmospheric extinction. In the majority of cases the stopping criterion was almost satisfied after the removal of the airmass trend only, $\alpha \sim 90\%$. This meant that trends stronger than $\sim 90\%$ of all random effects had been corrected with the removal of a single trend, highlighting the absence of systematic noise in the system. An analysis of the prototype's systematic noise is given in §4.3.

4. NGTS-P PERFORMANCE

4.1. *Tracking and Autoguiding*

We observed several target fields with NGTS-P during September 2009 to investigate the tracking and autoguiding performance of the telescope. We monitored a drift of 3.79 pixels h^{-1} in the stellar positions on the CCD while autoguiding. After extensive investigation the source of the flexure remained illusive. It most likely stemmed from the significant (~ 30 cm) back focal distance required to focus the separate autoguiding telescope and camera. All of the data presented here therefore contained a slow drift in the stellar positions on the CCD. Our solution to the drifting problem is discussed in more detail in §5.

4.2. *Optical*

To characterise the optical performance of the telescope and camera we monitored the change in PSF with ambient air temperature and scattered light content in the flat fields. The PSF remained suitably constant with time and temperature, however we discovered a significant amount of scattered light in the twilight flats. This was traced to scattered light reflecting from the inside of the telescope and striking the CCD from outside the beam. We installed a light-weight baffle which reduced the effects of the scattered light but finally (as mentioned in §3) we decided not to flat field the prototype data due to the additional noise added during the flat fielding process. Our solution to the optical issues of NGTS-P are discussed in §5

4.3. *Photometry and Systematic Noise*

We characterised the photometric performance of NGTS-P on several different nights with sky brightnesses ranging from full to new moon conditions. We created an RMS vs magnitude and an RMS vs binned exposure time diagrams for each night (see Fig. 1). The RMS vs binned exposure time diagram was compared to the $1/\sqrt{n}$ decrease in RMS expected in the presence of Gaussian (white) noise only, where n is the number of points per bin.

We investigated the effects of systematic noise in the data by measuring the fractional improvement in the RMS of the light curves after the forced removal of up to 4 trends using SysRem. The results after the removal of 1, 2, 3 and 4 trends can be seen in Fig 1. It is clear that the largest fractional improvement comes from correcting the atmospheric extinction caused by the airmass (see Fig 1 panel b, red points) and that the removal of subsequent trends resulted in less significant improvements. The stopping criterion for SysRem was typically satisfied after the removal of 1 or 2 trends only (see Fig 1 red and black points, respectively) indicating that the system was relatively free from systematic trends.

4.4. *Known Transiting Planets*

Observations of several known transiting planets with a range of transit depths and host star brightnesses were made with NGTS-P. We present the results from observations of GJ 436b (Butler et al. 2004; Gillon et al. 2007) below. NGTS-P also aided in the discovery of two new transiting exoplanets from the SuperWASP survey; the joint discovery of HAT-P-14/WASP-27b (Torres et al. 2010; Simpson et al. 2011) and WASP-38b (Barros et al. 2011).

The hot-Neptune GJ 436b was originally discovered via the RV method (Butler et al. 2004) and was subsequently observed to transit (Gillon et al. 2007). With a host star brightness, planetary radius and transit depth of $V = 10.68$ (Torres 2007), $R_p = 1.06 \pm 0.06$ $R_{\rm Nep}$(Southworth 2010) and 9 mmag respectively, GJ 436b is a prime example of an NGTS-type target. Therefore, this object was observed during the prototyping phase to show the detection of such hot-Neptune sized exoplanets is possible with an NGTS-like system. Three transits of GJ 436b were observed with NGTS-P and are shown in Fig 2, each over plotted with the best fitting model using the formalism of Mandel & Agol (2002). The transits of GJ 436b are clearly visible in our data and at a sufficient level of photometric accuracy (RMS) to allow for initial characterisation of the planetary system.

5. DISCUSSION

The results presented in §4 were very promising and have subsequently led to the commencement of the full NGTS project. The prototyping phase uncovered several issues with our original design. These issues lead to a full review of the system design (CCD camera, sensor, telescope, mount etc). The problems revealed during NGTS-P have subsequently been addressed for the full NGTS facility. The issues and their solutions are described briefly below.

A steady drift of ~ 4 pixels h^{-1} was seen in all of the NGTS-P data, even when autoguiding. After exhaustive investigation the source of this drift was never found. However, it was expected to come from a mechanical flexure between the science and autoguiding cameras. Hence we deemed an NGTS-like system with an off axis guider as unsuitable. To meet our science goal of sub-mmag photometry we require sub-pixel spatial stability over long periods of time. To combat the sources of systematic noise we aim to fix stars to within 1 pixel over time periods of weeks/months and possibly even years. To do so we created the versatile science-frame autoguiding algorithm DONUTS (McCormac et al. 2013).

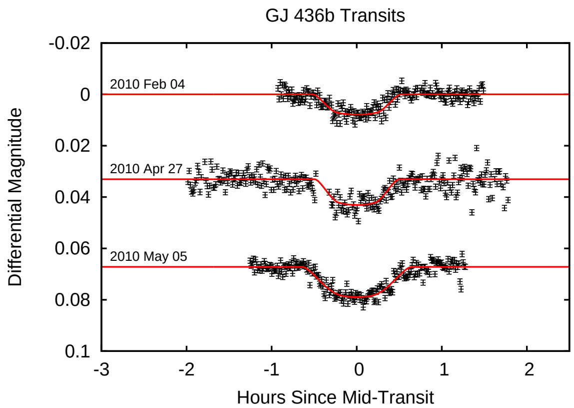

Fig. 2. Three transits of GJ 436b observed with NGTS-P during the 2010 prototyping phase. The transits are shifted vertically by integer numbers of 0.05 mag for clarity. The transits are over plotted with their best fitting transiting planet model using the formalism of Mandel & Agol (2002).

The algorithm has the added benefit of being able to guide on defocused PSFs so it can also be used at larger facilities to conduct even higher precision follow-up photometry after the initial discoveries by NGTS.

A significant systematic effect was seen the in RMS vs binned exposure time plots of the flat fielded data and the noise after flat fielding was found to be non-Gaussian. As the scattered light introduces noise in the data non-linearly SysRem is unable to remove its effect. Excluding the flat fielding process while maintaining all of the other reduction steps removed the systematic trend. A full optical design of the telescopes has been done for NGTS and significant internal and external baffling has been included to combat the effects of scattered light. Additionally, the theoretical throughput of the Takahashi E-180 was not optimised for the CCD QE ($< 70\%$ between $800 - 900$ nm) and confirmation of this was unavailable from the manufacturer. A red-optimised telescope from a different manufacturer has been included in the full NGTS facility.

6. CONCLUSION

We have designed, built and tested a prototype system (NGTS-P) for the new, wide-field, transiting exoplanet survey NGTS. The goal of NGTS-P was to determine the level of systematic noise in an NGTS-like system and prove that millimagnitude photometry or better could be achieved on transit time scales with an NGTS-like system. We have shown that millimagnitude photometry is possible using a modest aperture telescope and red-sensitive CCDs on transit timescales, and that the noise in our system is essentially free from systematic effects. We have demonstrated our sensitivity to hot-Neptune and super-Earth sized exoplanets and also highlighted several key areas of NGTS which required more consideration. NGTS is currently under construction at Cerro Paranal, Chile and we expect first light in 2014.

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