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ABSTRACT

NGTS is a new ground-based transit survey aimed at detecting sub-Neptune sized exoplanets around bright stars. The instrument will be installed at the ESO Paranal observatory in order to benefit from the excellent observing conditions and follow-up synergy with the VLT and E-ELT. It will be a robotic facility composed of 12, 200 mm telescopes equipped with 2Kx2K NIR sensitive detectors. It is built on the legacy of the WASP experience.

1. INTRODUCTION

After the success of the WASP survey the next step is to build a ground based survey aiming at finding sub-Neptune size planets around bright stars, updating the WASP concept with larger apertures and more red sensitive detectors. The aim of the new facility is to provide a very wide angle photometry data with a millimagnitude (mmag) accuracy on V magnitude 13^{th} stars. The facility will be located in the southern hemisphere at the ESO Cerro Paranal observatory to benefit from the best weather possible and to allow an easy interaction with current and future follow-up instruments available at La Silla, Paranal and the ELT.

2. SCIENCE CASE

The prime objective of the survey is to search for transiting planets in the size range of Neptune and below, with diameters between 2 to 5 Earth size on bright stars. Recent results from the radial velocity surveys and transit search surveys[1–3] show that these planets are very common at short period.

NGTS survey will provide a statistical sample of planets which further characterisation will be possible thanks to the brightness of their host star, in contrast to the bulk of the transiting planets found by Kepler for example. The special geometry of the orbits of transiting planets severely constrains the orbital inclinations, allowing an accurate determination of their masses and radii. This information provides the key to determining the bulk composition of exoplanets, as well as their formation and evolution history.[4,5] Perhaps of even greater importance, the transit geometry offers a powerful means to probe the atmospheric composition of these planets. During secondary eclipse, the star occults the thermal emission from the planet, which can then be computed from comparison with the total out of transit flux. Thus the emission spectrum of the planet can be determined, despite the unfavourable luminosity contrast between planet and host star. Such observations have been successfully carried out in space with Spitzer and HST, and also from the ground with large telescope like the VLT using FORS or HAWK-I.

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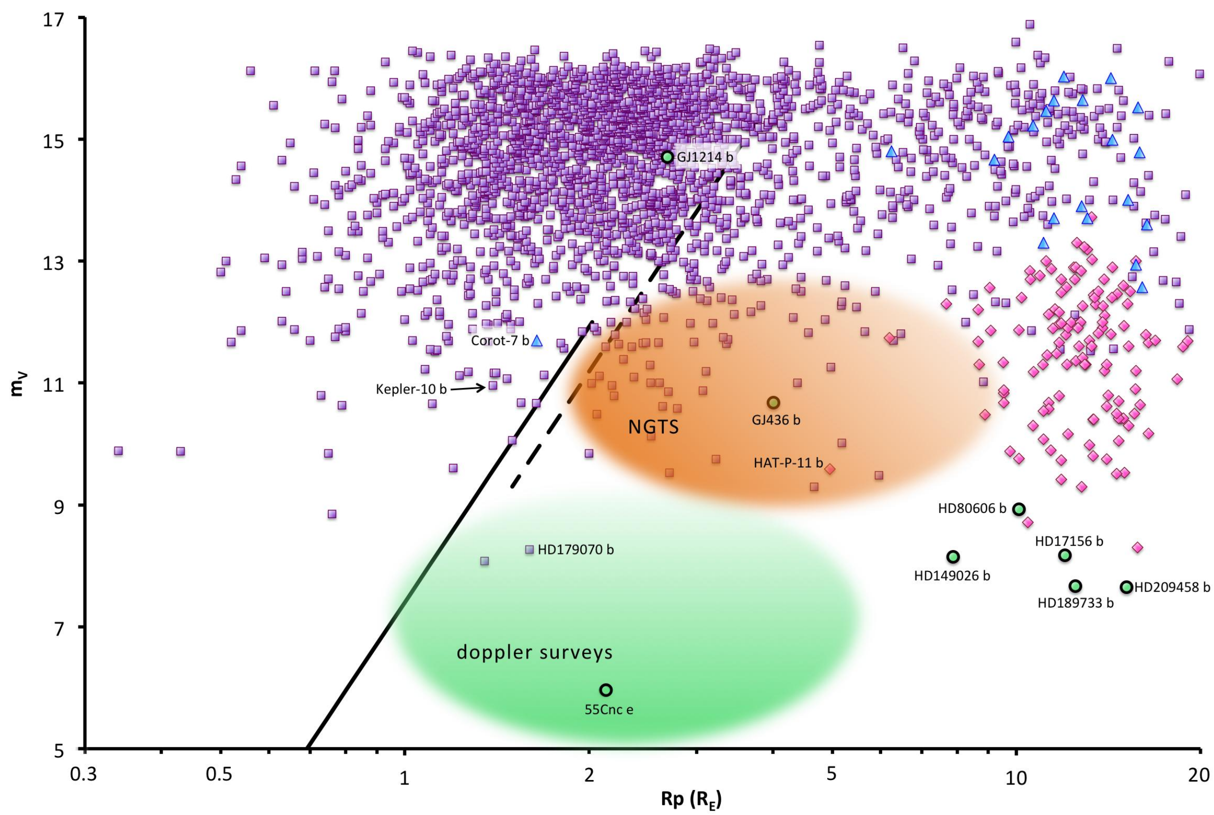


Figure 1: Outlook of all transiting planet for different surveys: planet radius vs the V-magnitude of the host star. Pink diamond: ground base transiting planet (mostly WASP and HAT), Green: the planet in radial velocity survey that have been found transiting their star; Blue triangles: Corot transiting planets, Violet square: Kepler transiting planet candidates (most of the not yet confirmed). The orange area indicates target search domain of NGTS the next generation ground transit search like NGTS. The green line indicates target regions of the precise Doppler search programs like HARPS. HARPS Radial velocity limits to characterize planet mass at 20% (when period and ephemerids is known, considering 20 measurement) is indicated by the solid black line for Earth density and dotted black using water mean density,

The observation of the planet during its transit at many different wavelengths allows us to obtain its transmission spectrum (stellar light going through the planet atmosphere). The transmission spectrum is measured by identifying the small differences in transit depth as a function of wavelength. This technique usually requires extremely high signal to noise data and has been successfully applied only on few planets orbiting bright stars, like for example HD189733. However it is a powerful technique to measure the distinct signature of chemical components in the atmosphere of a planet. This technique can be used to search for water on some planets, and even eventually for biomarkers on rocky planets. It has been recently[6] successfully carried out on GJ1214b a Neptune type planet with FORS observations. However, the discovery of additional bright targets is essential for this technique to be more widely applied to planets in the Neptune size range. NGTS will provide very interesting targets for the next space telescopes like JWST, ECHO or CHEOPS.

3. SURVEY DESIGN

NGTS is designed to reach 1mmag accuracy over a wide field, with the prime objective of detecting transiting Neptune size planets see figure 1 and 2. From the ground, assuming a precision of 1 mmag, for wide-field small-size telescopes, the most optimal targets are K and early M stars. For G stars the difficulty in reaching sub-mmag photometric accuracy arises from the ground limits. While in the visible there are insufficient numbers of bright later-type M stars.

The optical system is designed to observe with optimal sensitivity in the 600 to 900nm range, in order to match the peak

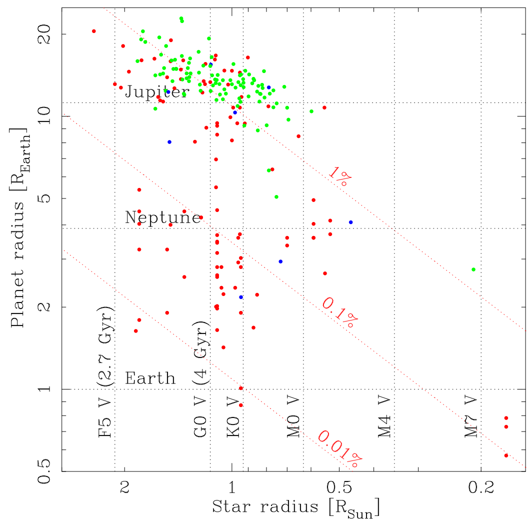


Figure 2: NGTS discovery space seen in planetary radius vs. host star radius. Red dotted lines are showing the transit depth. Green dots are planets discovered by ground based survey, Red dots are planets found by space based survey, blue one are the one discovered by radial velocity surveys.

Fraction of Nights	La Silla	Paranal
< 2mm water vapour (winter only)	50%	70%
< 4 mm water vapour (yearly average)	50%	80%
Photometric nights (1983-2000)	60%	78%

Table 1: Site comparison. Data from Ardeberg et al. 1990, Paranal web page, GMT site testing report.

emission of the primary targets (K and early M). Large format (2kx2k) deep depleted CCD cameras have been developed by our industrial partners (Andor Technology*, Belfast, and e2v, Chelmesford) specifically for our requirements, and these have now been made commercially available in their product line (Ikon-L 936BR-DD).

When one considers the requirements for wide field and photometric precision, including the constraints from scintillation noise,[7] an optimal telescope aperture of 20cm is derived, achieving sub-mmag photometric accuracy in a few minutes of exposure time.

One can consider a conservative planet occurrence of typically 5% for Neptune size planets with periods shorter than 10 days[1–3] (corresponding to an average transit probability of about 5%). One then finds that a minimum sample of about 40,000 stars needs to be monitored to detect about 100 transiting planets of this kind. With the additional constraint to identify these planets on bright stars, to ensure an optimal capability for follow-up observations, we considered a V magnitude of 13^{th} as practical faint limit. For M stars a fainter V magnitude down to 15^{th} may be considered in view of the smaller mass of the star and the larger radial-velocity amplitude expected from the planet. An additional benefit of staying in this magnitude range is the limited crowding factor, less than 20% for our PSF, even for a field 30 degrees from the Galactic plane.

The use of the V-magnitude as reference instead of the I-band, which would be more naturally suited for K and M stars, arises from the need to conduct radial velocity follow-up with precise high-resolution spectrographs like HARPS or ESPRESSO.

The 600 to 900nm wavelength region includes strong water bands whose rapid variations obviously degrades the quality of the photometry by adding short-term variable colour effects. The quality of the site in this respect crucially affects the discovery potential of the survey. Another key parameter affecting the final planet catch is the number of clear nights per year. The site in Chile that is optimal regarding these two constraints, while providing good logistics, is Paranal. This site has been selected by the NGTS consortium, and ESO has accepted to host the facility. Table 1 provides comparisons between Paranal at La Silla on the key parameters affecting the efficiency of our survey.

*Andor Technology: www.andor.com

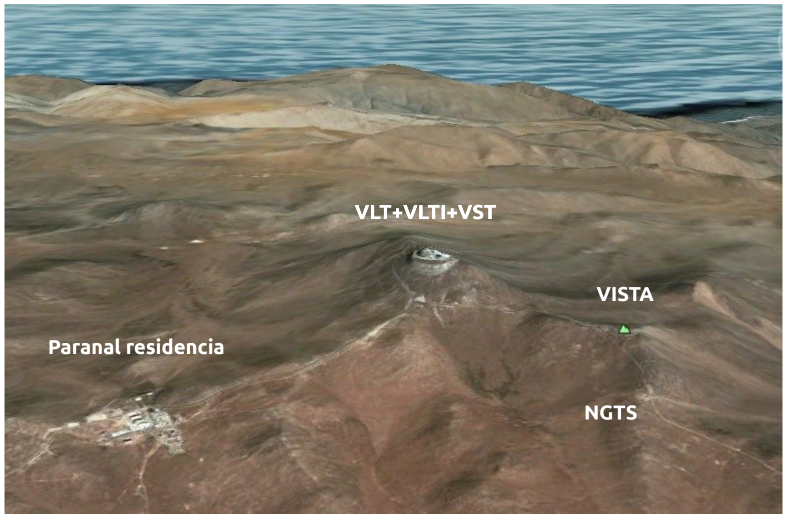


Figure 3: View of the selected site

The exact site selected for the facility is shown on figure 3, on an existing dirt road going downhill from the VISTA telescope. This site is providing good dark skies and allows to make the enclosure face the north in order to protect the facility from the dominant winds.

4. PROTOTYPE

The concept has been validated through the realization of a prototype that was tested in 2009 and 2010 in La Palma. This prototype was built with 2 Takahashi E180 telescope on a single German mount. The prototype allowed us to test the detector that has been chosen for the survey (in a 1Kx1K version): thermoelectrically cooled deeply depleted e2v CCDs packaged by the Andor company. It has proved that outstanding photometry could be obtained with a system such as NGTS. It has also taught some interesting lessons:

- The Deeply depleted CCDs behave as expected and have very low fringing. They are excellent detectors for our purpose.
- It is difficult to obtain good enough flat fields; there is not enough time to gather enough photons before the system changes. It is much better to stay as much as possible on the same pixel. This constraint has had a major impact on the design of the facility.
- Auto-guiding with a separate optical device is not enough to keep stars on a single pixel, one need to implement a guiding system based on the image itself. This method has already been implemented on Euler Cam the camera of the Swiss telescope with success.[8] Even at a frame rate of 1 image per minute it is possible to compensate for the tracking errors. A similar technique will be implemented for NGTS.
- We can reach the one mmag precision expected, the noise are mostly white see figure 5 and 4.

5. FACILITY DESIGN

The facility design is mostly driven by the required field of view and the aim at having a very precise photometry.

The telescopes have been changed from the prototype to have a design tweaked to the specific needs of the survey. This also made sense economically as the telescope price is small compared to the price of the detector. The new telescopes (made by the ASA[†] company, based on a standard product) have a 200mm aperture at F/2.8. It gives an 8 square degree Field of

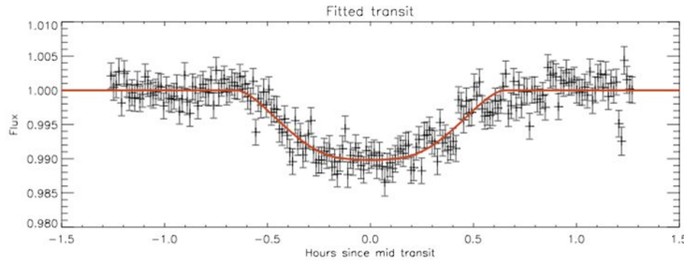


Figure 4: Transit of GJ436 recorded with the NGTS prototype

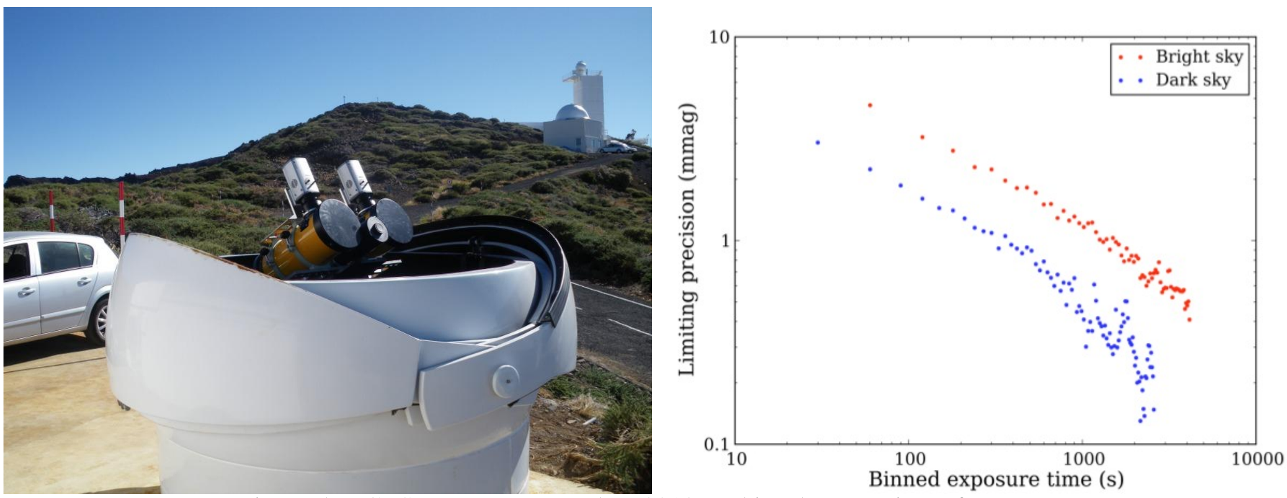
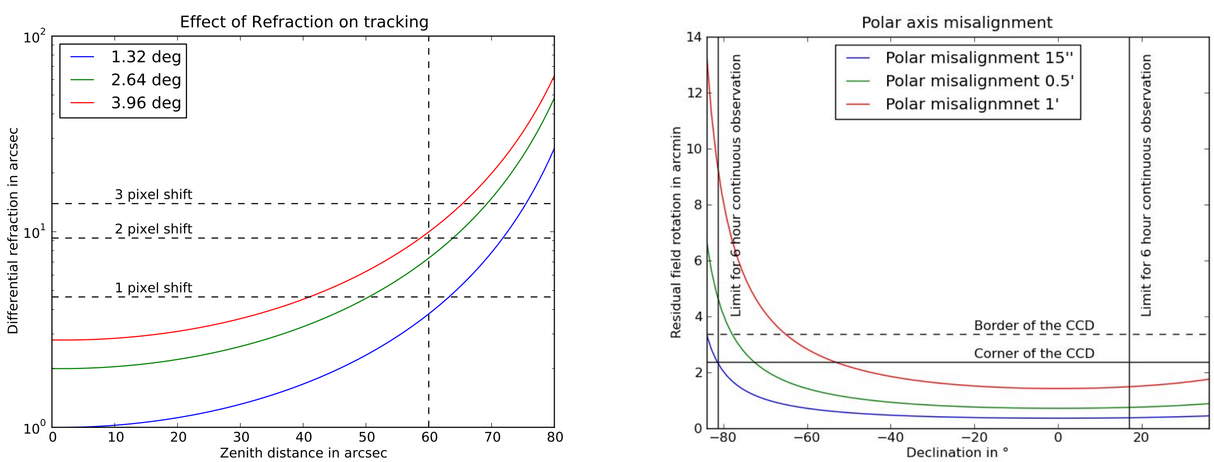


Figure 5: NGTS prototype, La Palma 2010, and its photometric performances



(a) (b)

Figure 6: (a) Effect of refraction on the plate scale as a function of the zenith distance. To keep all stars of the FoV on the same pixel during observation one cannot have a FoV Larger than $2 \times 1.4°$(b) Polar alignment effect on tracking. Polar axis misalignment produces residual field rotation. The tolerance on the polar alignment to keep all stars on the same pixel for a 6h continuous observation is approximately 30 arcseconds

Figure 7: View of the NGTS telescopes and their mount

View (FoV) with the selected detector. To reach a large enough number of star surveyed, 12 telescopes are necessary. In order to simplify the system, equatorial mounts have been chosen. It avoids using a derotator.

As seen with the prototype in order to get the best photometry possible it is necessary to maintain the stars on the same pixel on the detector along the observations. This will minimize the flat-field errors and make it possible to detrend the photometry data during the reduction. To achieve this goal, two issues have to be addressed:

- Atmospheric refraction: particularly at high airmass the atmospheric refraction has a differential plate scale. Using standard model, found in Slalib[9] one can determine the maximum FoV of an instrument to allow observation up to 60° from the zenith (see figure 6). The consequence of this analysis is that contrary to the WASP design each telescope will have its own mount.
- Mounts polar alignment: As there is no derotator, an inaccurate polar alignment will give residual field rotation. In the case of NGTS (see figure 6) to allow for 6h continuous observation of the same field it is necessary to have a polar alignment better than 30 arcseconds.

The telescopes are hyperbolic astrographs with a corrector. They have been optimized to get a constant PSF FWHM of approximately 12 micron across the field of view (a 40 mm image circle) and over the spectrum of interest. The mirrors have a standard aluminium protected coating. The corrector has optimized anti-reflection coatings for the range 500-1000 nm. Thus the expected throughput of the telescope is of the order of $\geq 75\%$ on the full NGTS band.

The telescopes have a 600 mm long baffle in front of their tube. It is necessary to minimize the straylight from when it points at 30°from the moon. If during the first tests the current baffling is proved not to be good enough it is possible to add additional baffling internally.

The mechanical interfaces to the mount and to the detector have also been customized to our needs by the ASA Company: on the side the detector, space for shims has been added to be able to adjust the CCD plane to the optical image plane. The telescope/mount interface has been designed to allow telescope provider and mount provider to work independently and to minimize the necessary mechanical adjustment at the installation of each telescope.

The electric focuser is provided with a thermal sensor and a regulation mechanism that will maintain the focus as a function of temperature. If necessary a slow control loop on the focus will be implemented with the self-guiding image algorithm.

The camera chosen for the experiment are 2Kx2K deeply depleted CCD from e2v. The pixel size is 13.5 μm, and the quantum efficiency is shown on figure 8. These devices have a very low fringing in the infrared as they very thick and thanks to e2v proprietary anti-fringing technology. They are packaged in a thermoelectrically cooled camera build by the Andor Company. They can be run at temperature as low as -75°C with air cooling.

NGTS filters are shown on the figure 8. The red end of the filter is 927 nm corresponding to the beginning of strong water bands that would add significant red noise in the photometry. The blue end has been chosen as a compromise to avoid the

[†] ASA: www.astrosysteme.at

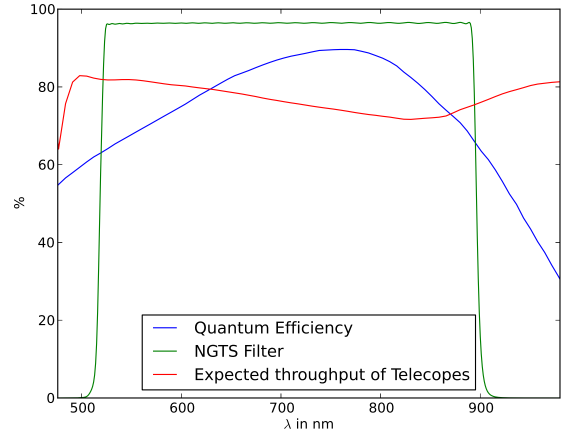


Figure 8: Different figure of merit of the NGTS Detector, telescopes and filter.

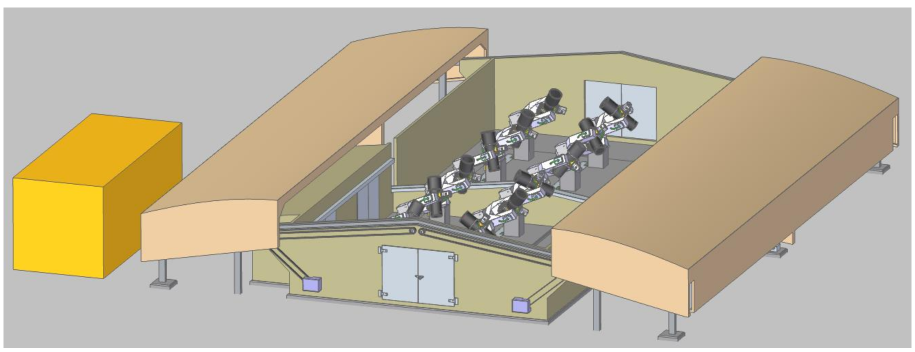


Figure 9: NGTS enclosure

flat-field structure induced by the laser annealing process step in the fabrication CCD and to keep as much stellar flux as possible.

The mounts are robotic mounts (see figure 7) built by the OMI‡ Company. They have proved to be very reliable for WASP. A special model is being built for this experiment adapted to the small size of the telescope.

The enclosure (see figure 9) has been designed in order to allow independent pointing for all the telescopes. The roof opening is done with a chain mechanism. The design has also been inherited from the WASP experiment. The orientation of the building is such as that the open roof will provide an additional protection from the winds from the north that are the dominant winds. An independent weather station will put the enclosure in security in case of bad weather conditions.

‡OMI: www.opticalmechanics.com

Number of Telescope	12
Telescope	ASA custom 8" hyperbolic design
Telescope focal ratio	f/2.8
CCD	e2v 2kx2k DD chip, Ikon-L by Andor
Pixel size (μm)	13.5
Pixel size (arcsec)	4.97
FoV per telescope	8 square degrees
total FoV	87 square degrees
Mount type	OMI robotic mounts

Table 2: NGTS Facility description summary

	F & G	K	Early M	Late M	Total
10 mmag	4187	2671	411	56	7325
3 mmag	1840	640	69	8	2557
1 mmag	531	115	10	1	657

Table 3: Number of stars per type and achieved photometric accuracy in 8 square degrees FoV (l=227, b=-30)

mag	$R < R_{Jupiter}$	$R < R_{Neptune}$	$R < 2R_{Earth}$
Vmag<13	733	309	23
Vmag<15	3547	672	34
Imag<15	6288	823	55

Table 4: Number of stars for each limiting magnitude and planet size upper limit in 8 square degrees FoV (l=227, b=-30)

One key of the success of this experience is the fully robotic operation linked to the automatic reduction of the data. The facility will produce data at a rate of 200 to 300 GB of data per night. This data will be shipped to Europe on hard drives and will be processed in Leicester. The data reduction pipeline is being developed and will draw from the experience to the system that has been in use with success for WASP. It is designed to be very quick, use at best the multi-core architectures, so as to allow several successive complete reductions over a complete season. This will give the possibility to optimize the detrending of the data and thus give the best possible photometry for exoplanet detection. Another important part of the experiment is the user interface to the results of this pipeline. The last step of the detection process, nicknamed "Eyeballing", is a collaborative human assessment based on different indicators coming out of the pipeline of the best target for follow-up. This interface is also very useful for the follow-up operations.

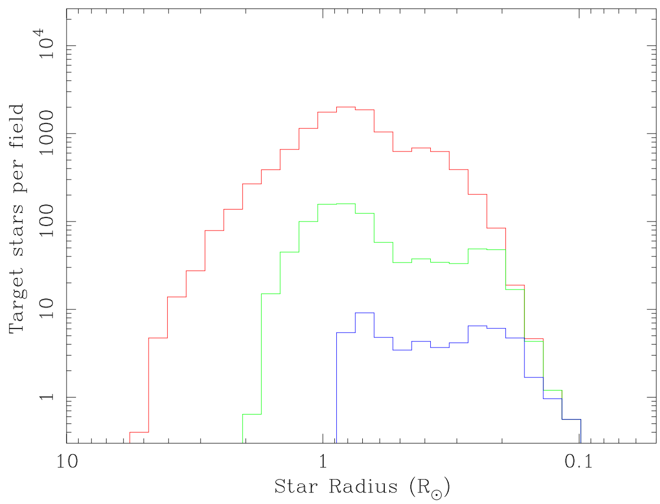
6. SURVEY PERFORMANCES

To assess the survey performance we considered an observation scenario assuming a typical exposure of 10 minutes per field (computed from a series of shorter exposure) and four different fields observed each year. This practically corresponds to a continuous observation of a given field until moving to the next field when the airmass becomes too large. In addition to the telescope and CCD characteristics, the filter response is assumed to be constant at 95 per cent from 550–927 nm and for simplicity we assumed a sky background as measured in average on the prototype at La Palma and a 3 pixel radius. We considered as well a 300ppm systematics (red-noise) threshold in all our data (upper value measured with our prototype). Using the Besancon model,[10,11] a total of about 2500 stars (at l=227 and b=-30 galactic longitude) would be measured with an accuracy better than 3 mmag in a field of view (FoV) of 8 square degrees, corresponding to the FoV of one telescope unit (see Table 3). In terms of magnitude in this FoV we will achieve the accuracy required to detect a Neptune size planet on about 250 stars brighter than V magnitude 13^{th}. We will reach the precision required to detect planets of 2 times Earth size on about 20 targets. A typical detection threshold of 6 times the transit signal-to-noise as practically experienced with WASP was used considering the equivalent observations of a total of 3 full transits.

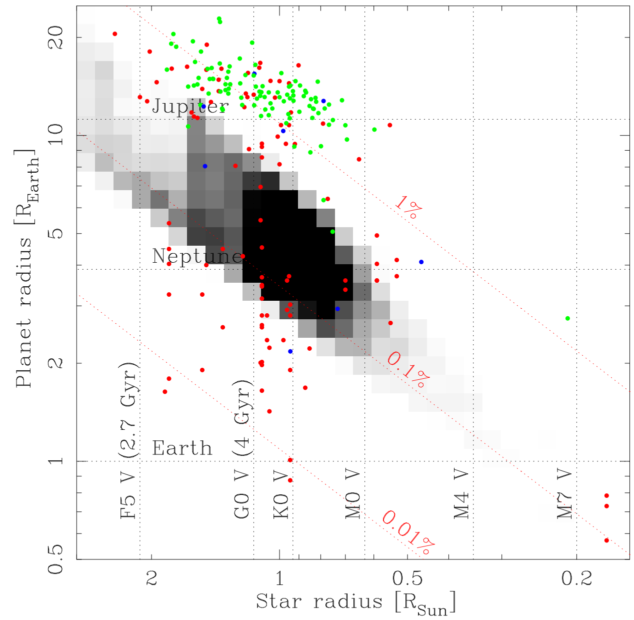
Considering that the facility is made of 12 unit telescopes and assuming that four different fields are observed each year by each camera, the target numbers expressed per unit FoV in Tables 3 and 4 multiplied by 48 lead to yearly yield numbers. This means that a total of around 20,000 stars will be observed every year with 1mmag photometry accuracy, and around 12,800 stars brighter than 13th V-magnitude where planets of Neptune size may be detected. After four years of operation, with different fields observed every year, more than 50,000 stars would then be observed with the required accuracy to detect Neptune-size transiting planets. This number can be favourably compared with the Kepler mission, with less than 10,000 late G, K and M stars brighter than 13th magnitude. About 3000 stars brighter than 13^{th} magnitude would be observed after four years of operations with the required accuracy to detect a transiting planet smaller than 2 times the Earth size. This may lead to the detection of a few of these small size planets. If one relaxes the limiting V-magnitude to 15^{th}, the potential number of Neptune and 2 Earth-size planets that may be discovered is multiplied by two. Our target numbers should be compared with the MEarth[12] survey, which recently discovered GJ1214b, which will be targeting 2000 late M stars when fully deployed, most of them fainter than 15th.

7. STATUS AND SCHEDULE

The project is now in its implementation phase: Half of the total number of detectors have been delivered. The first telescope and mount has been delivered. A complete mount-telescope-CCD system will undergo tests on the roof of the



(a)



(b)

Figure 10: (a) Histograms of the numbers of stars detected per unit telescope as a function of spectral type for different detection thresholds depending on planets size: Blue $R < 2R_{Earth}$; Green $R < R_{Neptune}$; red $R < R_{Jupiter}$ (l=227, b=-30) (b) Iso-density plot of our stellar sample expressed in planet discovery space. Only stars with V magnitude brighter than 15th have been considered. The red dotted line indicates the depth of the transit. Green dots are planets discovered by ground based survey, Red dots are planets found by space based survey, blue one are the one discovered by radial velocity surveys.

Geneva observatory during the summer 2012. The enclosure construction has started in Europe. The schedule is to have the first telescopes on sky at Paranal at the beginning of 2013 and the other units steadily being installed and commissioned to complete the whole facility by the end of 2013.

8. DATA ACCESS TO THE COMMUNITY

We anticipate that the observations made from this facility could have many other application aside exoplanet transit search, such as stellar physics using eclipsing binary radiuses or asterosismology, the study of the early evolution of star through the evolution of the rotation rates of stars or solar system science with the detection of near earth orbit objects.

The consortium, in agreement with ESO will provide an access to the photometric data after a proprietary period.

ACKNOWLEDGMENTS

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