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STARE operations experience and its data quality control

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Abstract. The STARE instrument was the first to detect the transits of an extrasolar planet in 1999. To date it has performed one of the longest running searches for transits, being in nearly continous operations since July 2001 at Teide Observatory, Tenerife. We describe the instrumental setup and the scheme that is used for data acquisition, handling and analysis. To this end, we first review the conditions under which we obtained data suggestive of transits, and we then follow a chain of verification and follow-up measures, progressing from fairly simple ones of low cost and effort towards more involved ones, which may be needed to positively verify the existence of a true planetary transit.

Key words: Instrumentation: photometers, Techniques: photometric, Methods: observational, Stars: indivudual: GSC 03136-01085

1. Introduction

The STARE (STellar Astrophysics and Research on Exoplanets) telescope is a 10.2 cm field-flattened Schmidt camera, with a focal length of 296 mm (Figure 1). It takes wide field images of several thousands of stars, in order to find exoplanets orbiting close to their host star (Hot Giant planets). This is possible when the planet crosses our line of sight, producing transits (Struve 1952). Indeed, STARE has been the discovery instrument for the first planetary transits, of the planet HD209458b (Charbonneau et al. 2000), and recently, of the planet TrES-1 (Alonso et al. 2004). After its commisioning period at the High Altitude Observatory (Boulder, Colorado), STARE was moved to its current location at the Observatorio del Teide (Spain) in 2001. The instrument uses a fork mount of a 12” telescope by Meade, Inc. The detector is a 2k × 2k front-illuminated CCD by Loral, with 15μm pixels. This provides a field size of $6.1^\circ \times 6.1^\circ$ with a scale of 10.8”/pix. A complete description of the instrument will be given by Brown et al. (in preparation). The system is controlled by two PCs under Windows 98, named ’Butch’ and ’Sundance’. Butch is responsible for the dome and mount control, and Sundance controls the CCD and the autoguiding system. The user interface consits of several programs written in Visual C++. These invoke scripts which are based on ”Orchestrate Scripting Software” for the telescope control, and ”AutomaDome” for the dome control; both are by Software Bisque. STARE’s operation is not fully autonomous however. It depends on an operator that decides to start the system if observing conditions are aceptable. The operator has to remove the telescope covers, open the dome manually, and start a telescope control script. This script will begin the observations at a specified hour, once a sample field reached a prescribed altitude or when the sky is dark enough. The telescope will then perform the entire observing programme autonomously. At the end of a night, or once a sample field moves too low, the telescope parks itself in a safe position (no direct sunlight on the telescope), and waits for the return of the operator. He will then close the dome and create copies of the aquired data. The operator is also required to monitor meteorological conditions and has to shut down the instrument in case of adverse conditions. These tasks are performed by an operator who is responsible for several instruments at Teide Observatory, avoiding the need for dedicated manpower.

The principal scientific purpose of the system is the detection of transiting extrasolar planets. For the detection of Hot Giant planets, high-cadence photometry with a precision of a few millimagnitudes rms (over time-scales of 5-15 minutes) for large numbers of stars is needed. Also, in order to obtain relevant detection probabilities ($> 80\%$) of

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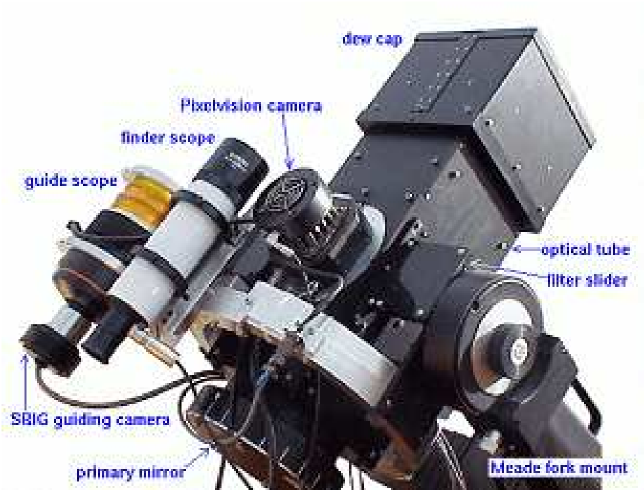

Fig. 1. The STARE telescope.

planets with orbital periods of more than four days, observational coverages of several hundred hours are needed (Deeg et al. 2004). To achieve this, the system undertakes continuous observations of the same field during spans of 2-3 months, and then continues with the next field. Only occasionally, two fields are observed in the same nights. Most sample fields have been observed simultaneously by two further teams with similar instruments, SLEUTH in Mt. Palomar, California (http://www.astro.caltech.edu/~ftod/tres/sleuth.html) and the PSST team at Lowell Observatory, Arizona (Dunham et al. 2004), thereby forming a network for planet detection (named TrES, after Transatlantic Exoplanet Survey). For an overview about the status of observations of sample fields, see Table 1.

2. Data flow

A typical night of observation with STARE yields aproximately 2 Gbytes of data. Until recently, these were stored on DLT cartridges, which have now been replaced by DVD+RW devices. This change was due to lower cost and better reliability. The raw images are then taken to the IAC headquarters at La Laguna, where a program written in IDL performs a first quality control: It reads all the images and measures the signal and sky from a reasonably isolated star. If the difference between the signal and the sky is lower than a certain threshold, the image will not be further analyzed. The images that remain are then corrected of flat-field, bias, dark current and the (non negligible) shutter open-close time effects. Nine subimages of a reference image are used to obtain estimations on the quality of the night, the sky background, the guiding performance and the rotation and scaling trends of the field. Figure 2 gives an example of such quality assessment for a good night. All these plots are stored, and can later be accessed to evaluate the atmospheric conditions at times when an interesting event is found in the final light curves (transit candidates, variables, flares, etc). Photometry based on Image Subtraction techniques (Alard, 2000) is performed, and light curves of typically 10 000 stars per field are assembled. Finally, a transit search routine based on Box Least Squares fitting to the light curves (Kovács, Zucker, Mazeh 2002) is run, yielding a list of significant detection events. Visual inspection is then required to detect obvious false positives (stars close to the CCD edge, eclipsing binaries, pulsating stars).

Once a list of candidates is obtained, it is circulated among the members of the network. Since the other participants are in North-America, there is little overlap in nightly observations. However, transit candidates may allow the derivation of one or more possible orbital periods. In this case, the presence or absence of events at predictable dates in the others' data may strengthen – or reject – a candidate. In the positive case, these additional data will improve the signal to noise in the transit signal, which leads to better determinations of a candidate's parameters. In the near future, data from the three sites will be combined and the joint light curves will be searched for transits. This will improve the detectability of long period transits by typically 30%.

3. From transit candidates to transiting planets: The follow-up techniques

One clear result from all transit searches, is the neccesity to weed out lists of planet transit candidates that are several times larger than the expected number of transiting planets. A good example of this is the OGLE transit search (Udalski et al. 2002a, 2002b, 2002c, 2003), which has provided a list of 137 transit candidates, out of which 3 planets have been confirmed (Konacki et al. 2003a, Bouchy et al. 2004a, Konacki et al. 2004), and many more were rejected as false alarms. Out of the first announced 59 transit candidates, published follow-up work reports the rejection of at least 45 of them (Konacki et al. 2003b, Bouchy et al. 2004b)

A description of the estimated false alarm rates for transit searches is given by Brown (2003). He predicts that for wide field searches like STARE, there will be approximately six stellar systems detected for each planet. These stellar systems might be eclipsing binaries with large differences in the size of their components, or systems of three stars (physical triples or fortuite alignments within the instrument's spatial resolution) where two of them are eclipsing stars. The light from the third star dilutes the eclipses, making them appear like shallow transits.

A major effort needs to be put into the follow-up of transit candidates, and an organized chain of tests will minimize the resources employed, in terms of time, effort, coordination and cost. In particular, radial velocity measurements can be done only with a few state-of-the-art spectrographs and should be reserved for the most convincing candidates. Sorted from simple and cheap to expensive and sophisticated methods, every transit candidate should be verified as follows:

- Careful interpretation of the lightcurve. The data from different sites can be folded and smoothed, to search for out of eclipse modulations or secondary eclipses. These are proofs of stellar systems. Transit duration and shape can by itself reject false positives. Seager & Mallén-Ornelas (2003) provide a test to infer the stellar density of a planet's central star from basic transit parameters.

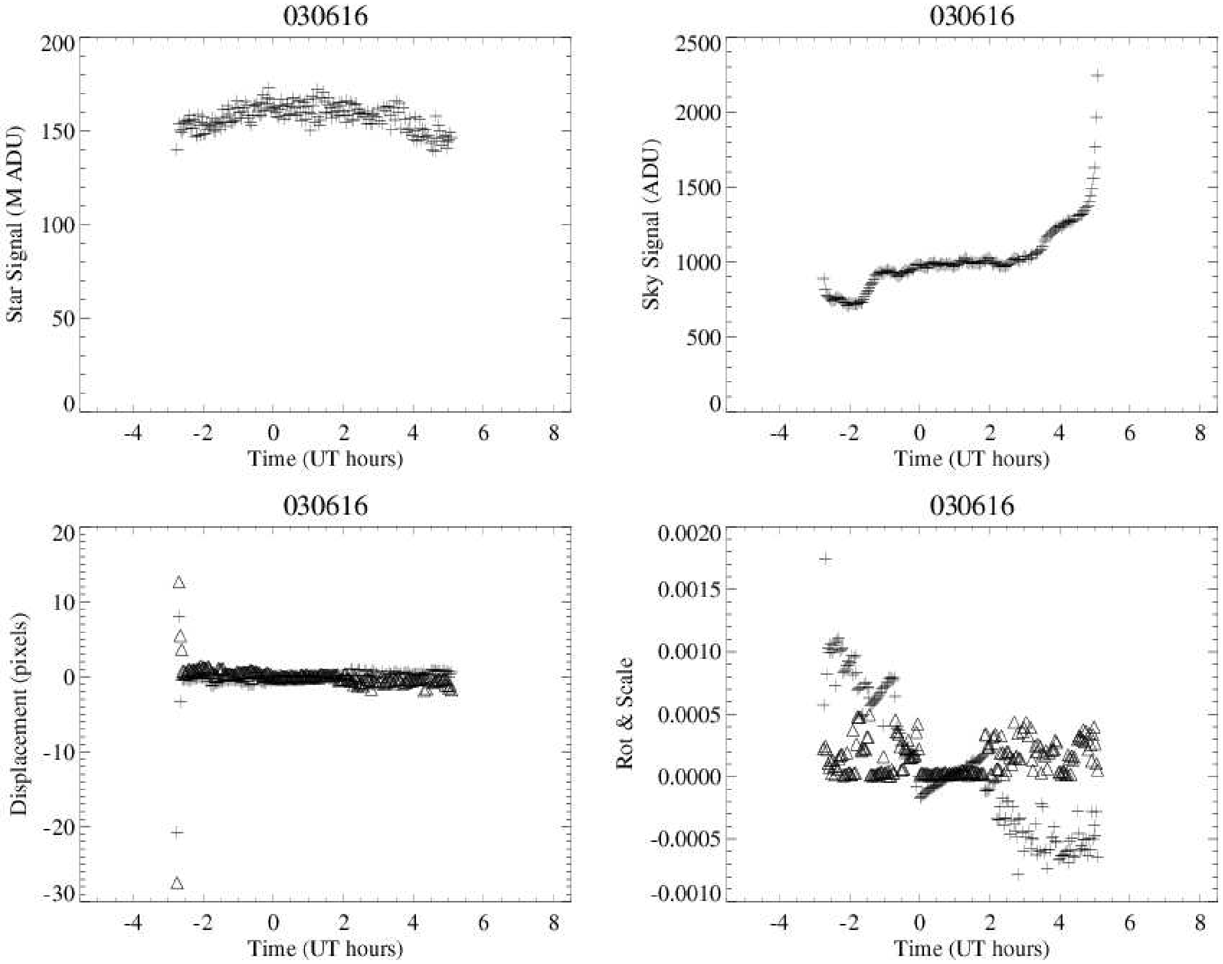

Fig. 2. Plots for quality evaluation in a good night of observation. Top left: The signal of a bright unsaturated star. Top right: The sky signal. Bottom left: The displacement of the image from a master image. Bottom right: The rotation and scaling trends during the night.

Comparison of this density with tabulated values for the star's spectral type (derived, for instance, from 2MASS colors) may detect false positives.

- Multi-color time-series. Time-series photometry and imaging (see next item) of a STARE transit candidate may easily be obtained in several colors with $1m$-class telescopes. Comparison of lightcurves in different colors may then show color signatures that are incompatible with a planetary transit (which is achromatic in first order), and indicate an eclipsing binary system.
- Imaging with higher resolution. STARE's scale is 10.8 arcsec/pixel. In crowded fields this causes several faint stars to fall within its PSF. Digitized surveys (DSS, 2MASS), or mid-sized telescopes may indicate close faint stars that need to be checked for eclipses. Stars that are too faint can not provide enough light to the diluted system, and their eclipses will not explain $\approx$ 1% depths in the blended lightcurve. For main sequence eclipsing stars, the faintest system that would cause diluted eclipses of relative depth δ would be $\Delta mag \approx -2.5 log_{10}(1/2\delta - 1)$ fainter than the main light contributor. If there is a star within Δmag, it must be checked for eclipses, with better spatial resolution telescopes. Adaptative Optics or Speckle interferometry techniques might show very close (<1") companions. An example of one candidate showing companions of this kind is plotted in Figure 3. In that case, however, none of the close companions could have eclipses that, after being diluted by the brightest star, could explain the eclipses with $\approx$ 5% depths that were observed by STARE.
- Low resolution radial velocities. In many cases, just two spectra might show radial velocity variations of several km/s, which can not be produced by planetary mass companions and indicate eclipsing binaries instead. The spectra might also be double-lined, which constitutes a quick detection of a false positive.
- High resolution radial velocities and bisector analysis. As a final stage of the follow-up chain, these are the only measurements that can give an independent verification of a planet candidate. In the positive case, they allow the derivation of the planet's mass, and consequently provide a solution of its orbit.

4. Results and conclusions

The STARE telescope has been performing routinary transit search observations since July 2001. It has collected data on

Table 1. Observations by STARE at Teide Observatory.

Field	Observing dates	Observing nights (Teide)	Observing time from Teide (h)	Collaborating telescopes
Cyg0	Jul-Oct 01	38 of 91	195	2
Boo1	Apr-Jul 02	39 of 118	238	2
Cyg1	Jul.Oct 02	16 of 78	67	2
Per2	Oct-Nov 02	30 of 58	193	2
Cnc0	Feb-May 03	16 of 89	127	2
Her0	May-Jun 03	44 of 54	291	2
Lyr0	Jul-Sep 03	50 of 68	367	2
And0	Sep-Jan 04	40 of 118	243	3
Lyn0	Jan-Mar 04	29 of 61	103	3

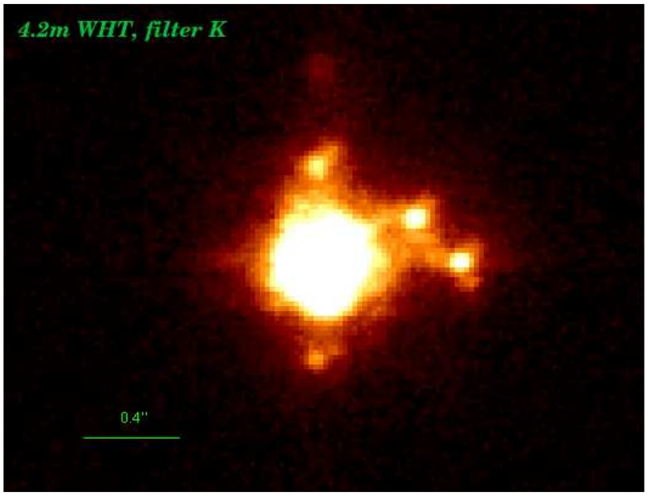

Fig. 3. GSC-03136-01085, one of STARE's transit candidates, showing faint close companions when observed with NAOMI/INGRID at the 4.2 m William Herschel Telescope (Roque de los Muchachos Observatory, La Palma).

8 different fields with more than 100 h of observations each, and obtained photometry with precisions better than 1% for several tens of thousands of stars. An improvement in precision will be obtained from a planned upgrade of the current front-illuminated CCD to a back-illuminated one. Most of the technical problems detected in these years of operation were caused by the telescope mount, which will be replaced by a more robust one. The second major source of problems has been the uninterruptable power supply (UPS), which has the particularity to also provide a conversion from 220V to the 110V that are used by the instrument's components. The operation of STARE and the other sites of the network (PSST, Sleuth) will continue in a coordinated way for at least 3 more years. A combined analysis of the lightcurves coming from the three sites is currently being implemented, which will result in a more sensitive transit detection. This network is also coordinating follow-up observations of the transit candidates, both photometrical and spectroscopical ones, which are essential for a reliable detection of the false positives, and the true transiting planets.

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