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# The Transatlantic Exoplanet Survey (TrES): A Review

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**Abstract.**
The TrES project is designed to search for exoplanetary transits using three wide-field optical telescopes of 10-cm in diameter, in three different observatories. We describe the instruments and strategies used by the team, which has been working as a network since 2003. We summarize the major findings and difficulties faced during these years, which include the discovery of two transiting planets, a pair of eclipsing M stars, and many configurations of stars that mimic the signal of transiting planets.

## Introduction

When a planet orbits around a star, it produces a wobble in its parent star. This has allowed the detection of most of the exoplanets found to date. But the angle of inclination of the orbit $i$ remains unknown in most of the cases. The detection of an exoplanet (Mayor & Queloz 1995) with roughly half the mass of Jupiter, but an orbital period of 4.5 days, revived the idea that transits of exoplanets across their parent stars could be observable (Struve 1952), as with these Hot Jupiters the geometrical probability of a transit is on the order of 10 %. Since 1995 several groups developed photometric search programs (see for instance Charbonneau et al. 2007 and references therein), using different strategies and instrumentation. The transiting planets discovered with the transit method to date have used two different approaches: wide field photometry using small aperture telescopes or photographic lenses - with a diameter of less than 15-cm and target stars with $R$ magnitudes typically between 9 and 14 - or deep field transit searches using telescopes of more than 1-m in diameter and stars fainter than magnitude 14 in $R$ filter. In this paper, we discuss the wide-field survey strategy and summarize the instrumentation and findings of the TrES project.

**Pros and cons of a wide-field transit search**

The use of a wide-field surveying strategy involves the following advantages:

- It monitors relatively close stars. The total flux received at the detector of the instrument is proportional to $D^2/d^2$, where $D$ is the aperture of the telescope and $d$ is the distance to the source. Thus, to get the same flux from a source with a given absolute magnitude, $D \sim d$, or, in other words, the smallest telescopes will monitor the closest stars.

- Follow-up studies, due to the closeness and brightness of the stars, can be performed with modest instrumentation, or, in the case of using state-of-the-art instruments, the precision in the determined parameters is better than for candidates detected with a deep-field survey.

- There is useful catalogued information on the target stars, such as proper motions from the USNO-B or UCAC2 surveys, or magnitudes from the 2MASS catalogues. These are especially helpful to obtain some clues on their evolutionary state, and in some cases to recognize the main sequence stars.

- The project's cost is obviously lower than for bigger instruments.

- As a consequence, a dedicated instrument is more readily accessible, thereby fulfilling the requirement of several hundred hours of observing time at each target to maximize the visibility of an event.

On the other hand, there are several disadvantages to wide-field surveys, where deep surveys may be more effective:

- Precise photometry in wide-field surveys may be difficult. Within a wide field of view, the extinction may no longer be considered as constant throughout the field. The psf of the stars is undersampled, atmospheric refraction is important, and there is usually significant vignetting across the focal plane, resulting in uneven flat-field images.

- Small late main sequence stars are relatively rare in a wide-field sample, whereas these become increasingly frequent with observing depth. Smaller stars would allow the detection of smaller planets.

- False positives are more numerous, as noted by Brown (2003).

- The variety of stellar environments (such as open or globular clusters, or different regions in the galaxy) is limited by the closeness of the stars.

Table 1. The TrES telescopes

| | STARE | PSST | Sleuth |
|---|---|---|---|
| Diameter (cm) | 10.2 | 10.7 | 10 |
| Focal (mm) | 296 | 300 | 280 |
| f/ ratio | 2.9 | 2.8 | 2.8 |
| CCD+px size | 2k×2k×13$\mu$m | 2k×2k×15$\mu$m | 2k×2k×13.5$\mu$m |
| Camera type | back-illuminated | back-illuminated | back-illuminated |
| Scale (″/px) | 9.7 | 9.8 | 10.5 |
| FOV | 5.5°×5.5° | 5.6°×5.6° | 6°×6° |
| Mount | Mathis | Celestron | Meade |
| Filters | Johnson | Bessell | SDSS |
| Location | Tenerife (Spain) | Arizona (USA) | California (USA) |
| Reference | Alonso (2006) | Dunham et al. (2004) | O'Donovan et al. (2004) |

## The TrES Instruments

Motivated by the advantages and relative simplicity of wide-field searches, the STARE and PSST telescopes were set up in 1999 at HAO and Lowell respectively. STARE was moved to Teide in 2001 to improve its observing conditions and to provide observations at a different longitude. Sleuth came on line in 2003 and the TrES network was formed shortly after.

The three telescopes' characteristics and locations are summarized in Table 1, and in the references given therein. Their optical configurations provide fields of view of ∼6°×6°, and the images are taken by back-side illuminated CCDs of 2k×2k pixels. The scale in the focal plane is of the order of 10 arcsec/pixel. Each of the telescopes works in a semi-automatic way, requiring only minimal human contribution to decide whether the meteorological conditions are good enough to start an observation, or to stop an observation if the conditions are risky for the instrumentation. The observational coverage of a given field at each site is used to compute the visibility of planetary transits with different periods. For each period, the visibility is defined as the percentage of transit events that are recovered from a set of input transits with randomly distributed phases. For this purpose, a transit is considered to be recovered if at least half of a transit has been observed at the same site. The visibility function is regularly calculated, for the different assumptions of requiring two, three and four observed events to constitute a detection.

The same field of stars is observed until the visibility of planetary transits with periods on the order of 5 days is good enough (typically, above 80%). This requires between one to three months to be accomplished, the exact number of nights depending on the weather and instrumental conditions at each of the sites. The gain of using a longitude-distributed network is understood when these visibility plots are compared for a single site and the network (Fig. 1).

The data reduction of TrES has been described in detail in Dunham et al. (2004) and O'Donovan et al. (2006a). Basically, it employs the package DAOPHOT II/ALLSTAR (Stetson 1987, 1992) to compute the list of stars where the photometry is going to be extracted, and the routines *interp* and *subtract*

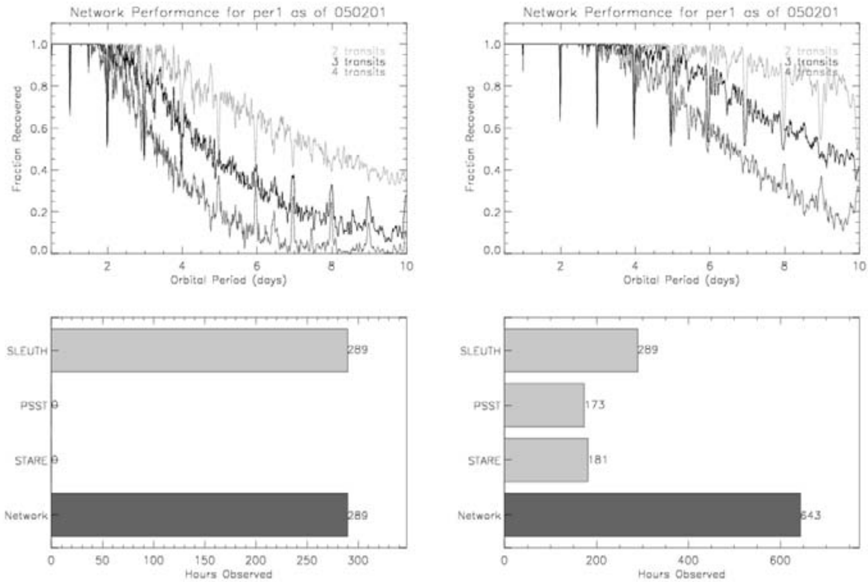


Figure 1. The transit visibility as a function of period, for a single-site observing run (left) and the whole network observing run (right).

from the ISIS code (Alard 2000), to subtract every observed image from the master image. This master image is the combination of several of the best images of the field (typically 10-20). Aperture photometry is performed on the subtracted images, and on the reference image to compute the variation in magnitude of each star at the time $i$, as:

$$\Delta m_i = -2.5log[(F_0 - \Delta F_i)/F_0] \tag{1}$$

where $F_0$ and $\Delta F_i$ are the aperture fluxes of the star in the master and in the $i$th difference image.

Our light curves are clearly affected by systematic effects, or red noise, an effect that has recently been brought to attention as a major factor limiting the performance of transit searches (Pont et al. 2006). We partially correct for these effects by computing, inside a set of light curves of stars with similar brightness and no obvious variability, the corrected magnitude for the star $i$, as the observed magnitude minus the least-squares fit of all the stars except the star $i$.

The transit search in the light curves is performed using the BLS algorithm (Kovács et al. 2002), and a visual inspection of the detected events is done to build an initial list of transit candidates. A careful analysis of the light curves of the candidates, searching for out-of-eclipse modulations (Sirko & Paczyński 2003), secondary eclipses, and measuring the transit's main parameters (e.g. Seager & Mallén-Ornelas, 2003) helps to prioritize and reduce the size of this list of candidates (see Alonso, 2006, for an application of all these techniques to the candidates of a TrES field).

The data reduction is performed independently at each of the sites. In a second step, the individual light curves are combined and searched for events that might have not been visible in the individual sets.

## Learning how to deal with impostors

Both theory (Brown 2003) and practice (e.g. Bouchy et al. 2005) have demonstrated that the number of events that mimic the signal of a transiting planet (at least with the precision attained by ground-based instruments) clearly outnumber real transiting planets.

These false positives can be of instrumental or of astronomical origin. A description of the different astronomical false positives is given in the chapter by F. Bouchy in these proceedings.

In order to recognize these configurations in the candidates detected by the network, we use, or have used in several occasions:

- Low signal to noise spectra, obtained with the CfA Digital Speedometers (Latham 1992), installed either on the Tillinghast 1.5 m reflector at the Whipple Observatory in Arizona or on the 1.5 m Wyeth Reflector at the Oak Ridge Observatory in Harvard. A detailed description of the observations, procedures and statistics on the nature of 456 candidates coming from three different surveys is given in the chapter by D.W. Latham in these proceedings. Most of the candidates are quickly characterized using this instrument.

- Photometry with color and/or high precision and better angular resolution. We have used the KeplerCam on the 1.2 m telescope at the Whipple Observatory, the IAC-80 cm and OGS-1 m telescopes at the Teide Observatory, the University of Colorado SBO 61 cm telescope and the Lowell Observatory 105 cm telescope in several occasions to observe the color dependency of a transit event. If this color signal is bigger than that expected from the limb darkening variation with wavelength, then the most plausible scenario becomes that of at least a triple system. One case of TrES where the color information was essential to determine the nature of the system was that of GSC-03885-00829, described in detail in O'Donovan et al. (2006a). Another case, where two nearby stars could be resolved with the telescopes mentioned above, is plotted in Figures 2. If the stars had not been resolved, the color signature of the eclipse would have shown that the system appears redder while in transit (Fig. 3).

  This is the opposite effect as the limb-darkening wavelength dependence of planetary transits; in this case, the limb-darkening effect is more noticeable at shorter wavelengths. The transit shape would thus be flatter at longer wavelengths. This would leave a colored signal that would make the star appear slightly redder in the ingress and egress phases, and bluer in the central parts of it. The observed contrary effect means that *i*) the companion cannot be a transiting planet, and *ii*) the "third" star (i.e., the one that is providing most of the flux to the system, component A in our case) is redder than the brightest star in the eclipsing system (component

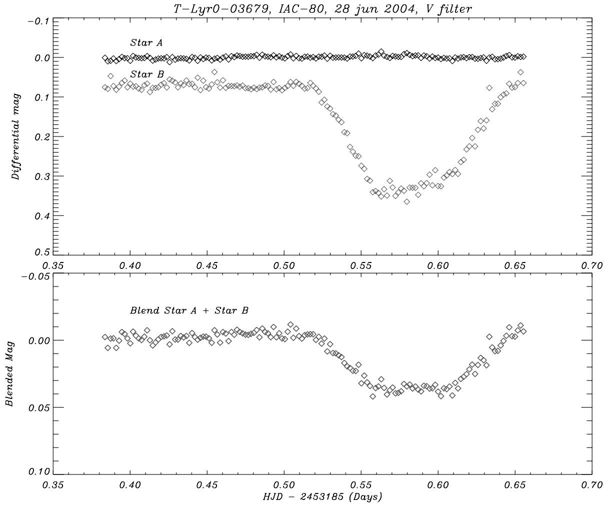


Figure 2. $V$-filter differential light curves of the system T-Lyr0-03679, obtained at the IAC80 telescope. Top: the two individual light curves of each of the components, revealing a flat-bottomed eclipse in the faintest star. Bottom: the light curve of the unresolved system, with a transit-like depth.

B). This is confirmed with the 2MASS colors ($(J-K)_A = 0.614$, $(J-K)_B = 0.510$) of the resolved system. Thus, in this case, even if the stars had not been resolved, the color signature of the eclipse would have revealed this false positive.

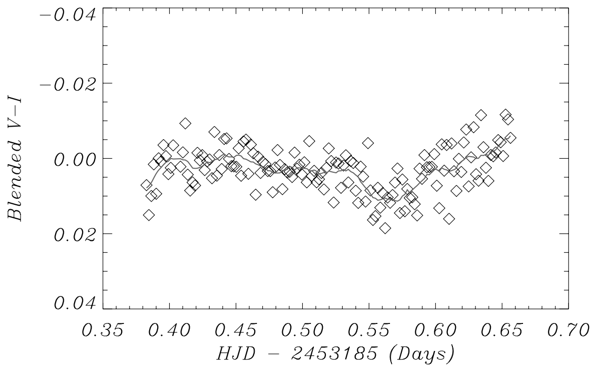


Figure 3. $V-I$ color signature of the same system as in Figure 2, as would have resulted if the system had not been resolved. The color pattern of the eclipse is the opposite as expected for a transiting planet (see the text for details).

- High angular resolution photometry. The NAOMI Adaptative Optics system (Myers et al. 2003) on the 4.2 m WHT telescope has been used to investigate the close neighborhood of several of the TrES candidates. In a few cases, this instrument has allowed the detection of stellar companions at distances from the target of less than one arcsec.

- High signal to noise spectra are needed to have the definitive confirmation by radial velocity of a transiting planet, and a measurement of its mass. There are only a few state-of-the-art instruments capable of achieving a few m $s^{-1}$ velocity precision. For this purpose, the team has used the HIRES spectrograph on the Keck telescope (Vogt et al. 1994).

**The TrES top false alarm**

Several cases in the literature have proved to be difficult to be recognized as false positives (e.g. Torres et al. 2004). In our network, the most difficult case that we have been able to disentangle to date has been GSC 01944-02289 (Mandushev et al. 2005), in the Cancer constellation. Both multicolor photometry and radial velocity observations (Fig. 4) appeared at a first sight consistent with an interpretation of the system as a substellar object in orbit around an F-type star.

If the observed sinusoidal velocity variation for the primary star (with an amplitude of $\sim$3 km $s^{-1}$ and matching the 3.35 days photometric period) was interpreted as an orbital companion, the corresponding mass of $\sim$32 $M_{\rm J}$ would have placed the object in the brown dwarf regime, and thus would have constituted the first observations of transits of this type. Merely the detection of such an object in a tight orbit would have been of great interest, because of its location in the so-called “brown-dwarf desert”. The fact that it transited its host star would allow measurements of the sizes and densities of the brown dwarf companion, something that has never been done. Thus, special care was needed in the follow-up of this system.

The presence of a faint spectrum due to the primary in an eclipsing binary in the system was revealed by an analysis using the two-dimensional correlation technique TODCOR (Zucker & Mazeh 1994). Although the rotationally-broadened lines were not apparent to the eye in the original observed spectra or in the one-dimensional correlation functions, the velocity amplitude was large enough to distort and pull the lines of the bright star in a sympathetic motion, but with a much smaller amplitude (Fig. 5).

A model consisting of three blended stars, in which two are eclipsing and the third is providing light to the system (thus diluting the eclipses), served to derive the properties of the three components. The photometric and spectroscopic observations could be explained by a hierarchical triple, in which a slightly evolved F5 primary (with $v \sin i$=34 km $s^{-1}$, providing 89% of the total flux) dilutes the eclipses of an M3V star passing in front of a G0V star. This TrES candidate has proved our most difficult case in disentangling a false positive, a cautionary tale to be remembered when a transiting planet (or brown dwarf) candidate is detected around an F star.

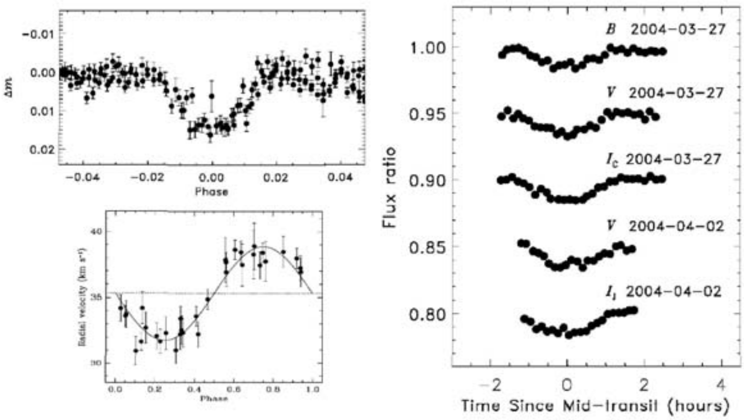


Figure 4. Top left: The PSST binned phased light curve of the star GSC 01944-02289 (with a period of 3.35 d), showing a 1.4% eclipse with a total duration of 2.7 h. Right: Multicolor photometry of transits of the same star. Bottom left: The CfA radial velocity curve, with an amplitude consistent with a brown dwarf companion. From Mandushev et al. (2005).

## A pair of eclipsing M-stars

The TrES transit search has served to detect one of the few known pairs of eclipsing M stars. The work by Creevey et al. (2005) describes the follow-up observations on the system TrES-Her0-07621, which consists on two M3e stars with almost identical masses of 0.49 $M_{\odot}$ orbiting each other with a period of 1.12079±0.00001 days. The light curve fit provides sizes for both components of 0.45 $R_{\odot}$.

## The TrES planets

To date, the TrES efforts have led to the discovery of two transiting planets: the first transiting planet to be detected by a wide-field survey, TrES-1 (Alonso et al. 2004), and the first planet detected in the Kepler field of view, TrES-2 (O'Donovan et al. 2006b). They are both Hot Jupiters, with periods of 3.03 and 2.47 days respectively, and masses of 0.61 and 1.28 $M_{\rm J}$. The host stars are of spectral types K0V and G0V, and the measured radii of the planets are 1.08 and 1.24 $R_{\rm J}$, both consistent with current theories of planetary evolution.

The brightness of the TrES-1 star was well suited for the use of the IRAC camera on board the Spitzer telescope to detect the thermal emission from the planet in 4.5$\mu$m and 8$\mu$m (Charbonneau et al. 2005) during secondary eclipses, opening a new path for the study of the atmospheres of these objects. The observed timing of the transits have been used by Steffen & Agol (2005) to provide limits on third bodies in the system, and exquisite ground-based photometry (Winn, Holman & Roussanova 2006) has allowed to refine the orbital and physical parameters of the star and planet, positioning it as one of the best

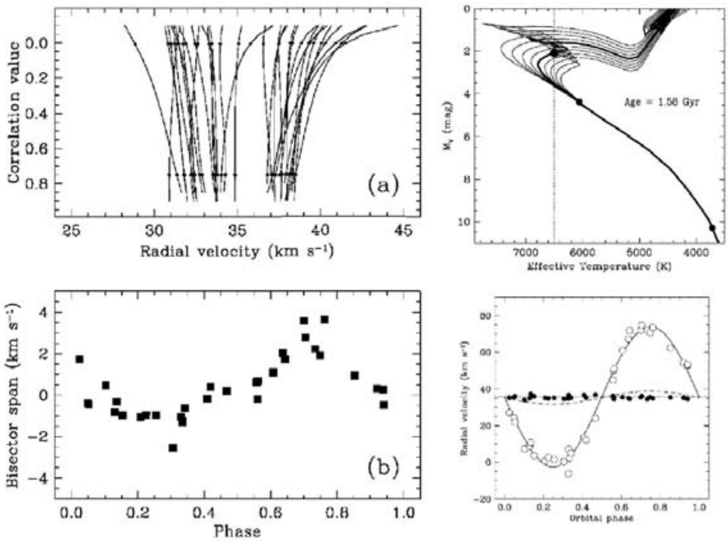


Figure 5. Top left: The line bisectors of the CfA spectra, showing a wider velocity range in the wings of the lines than in the cores. Bottom left: The bisector span, defined as the velocity difference between the top and the bottom of the spectral lines. Top right: The location in the H-R diagram of the three stars that best explain the data. Bottom right: The extracted radial velocity curve of one of the stars in the eclipsing system (the G0V star, open circles) and the star providing most of the light to the system (the evolved F5 star, filled circles). The dashed line is the apparent radial velocity of the blended system, which could have been confused with a transiting brown dwarf. From Mandushev et al. (2005).

known exoplanets to date. The prospects for the TrES-2 follow-up observations are strongly encouraging, both due to its high impact parameter and the many transit observations that will be obtained with the Kepler telescope (O'Donovan, these proceedings).

## Current status and future prospects

About 22 fields have been surveyed with TrES, with 400-700 observing hours per field, and containing between 1,000 and 5,000 stars with photometry with a rms lower than 1%. A total of ~170 candidates have been extracted from these data, and almost 90% of these have already been identified as false positives.

PSST and Sleuth continue to operate routinely and the STARE system has recently been upgraded (see Rabus et al., these proceedings). We hope to add a fourth system this year and look forward to the discovery of TrES-3!

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