The HATNet and HATSouth Exoplanet Surveys

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Abstract The Hungarian-made Automated Telescope Network (HATNet) has been in operation since 2003, with the key science goal being the discovery and accurate characterization of transiting extrasolar planets (TEPs) around bright stars. Using six small, 11 cm aperture, fully automated telescopes in Arizona and Hawaii, as of 2017 March, it has discovered and accurately characterized 67 such objects. The HATSouth network of telescopes has been in operation since 2009, using slightly larger, 18 cm diameter optical tubes. It was the first global network of telescopes using identical instrumentation. With three premier sites spread out in longitude (Chile, Namibia, Australia), the HATSouth network permits round-the-clock observations of a 128 square arcdegree swath of the sky at any given time, weather permitting. As of this writing, HATSouth has discovered 36 transiting exoplanets. Many of the altogether ~100 HAT and HATSouth exoplanets were the first of their kind. They have been important contributors to the rapidly developing field of exoplanets, motivating and influencing observational techniques, theoretical studies, and also actively shaping future instrumentation for the detection and characterization of such objects.

HATNet

In 1999 we started the development of a small robotic telescope mount with the goal of monitoring the sky for stellar variability. The design was inspired by the ASAS (Pojmański1997) project, and was encouraged by Bohdan Paczyński from Princeton University. The prototype horseshoe telescope mount and clam-shell dome were completed by July 2000, and first light was taken using a Nikon 180 mm, f/2.8 lens and Meade Pictor 768 × 512 CCD through a Bessel I-band filter from Agárd, Hungary. The telescope, named the Hungarian-made Automated Telescope (HAT-1),
was then installed on the roof of Konkoly Observatory, Budapest, and operated from September 2000 through December 2000.

We transported HAT-1 to Kitt Peak Observatory in January 2001, and operated it remotely with an Apogee AP10 2K × 2K CCD and Bessel I-band filter until its decommissioning in November 2002 (Bakos et al. 2002). This period of 1.5 years was very helpful in learning how to remotely operate a complex instrument, and how to reach robust autonomous operations with minimal supervision.

In 2001/2002 the science focus shifted to the detection of transiting extrasolar planets, and the telescope system was re-designed to improve tracking, to accommodate a larger lens, and to improve the photometric precision, as necessitated by the detection of <1% signals. We also embarked on building multiple units to increase sky and time-coverage. We tested the prototype of the new-generation mount (called HAT-5) at the Harvard-Smithsonian Center for Astrophysics (CfA/SAO) in December 2002, and the instrument began operations at the Fred Lawrence Whipple Observatory (FLWO) in February 2003. The network quickly expanded, with the installation of two more units, HAT-6 and HAT-7 at FLWO in May 2003, the Wise HAT (WHAT) telescope at Wise Observatory, Israel, in September 2003 (decommissioned in early 2010), and two more telescope units (HAT-8 and HAT-9) at the Submillimeter Array of SAO, atop Mauna Kea Observatory (MKO) in November 2003. Finally, the last unit (HAT-10) was installed at FLWO in November 2004.

The initial setup (2003–2006) used Canon 110 mm diameter f/1.8 lenses, Apogee AP10 2K × 2K CCDs and I-band filters on all telescopes, each yielding a 8.2° × 8.2° field-of-view (FOV). All CCDs were replaced with Apogee U16m 4K × 4K CCDs in September 2007, yielding a 10.6° × 10.6° field-of-view with 9′′pixel−1 resolution and ∼2 pixel wide stellar PSFs. At the same time, the I-band filters were replaced with Bessel R-band filters, and then, in September 2008, to Sloan r filters. Recently (October 2013) the CCD on HAT-7 at FLWO was upgraded to a back-illuminated, 2K × 2K FLI camera. We have also experimented with achieving high precision photometry with inexpensive, consumer grade digital single-lens reflex (DSLR) cameras, such as a Canon 60D. These cameras were piggy-backed on the HAT instruments in 2014–2017. We achieved the best DSLR-based precision so far (Zhang et al. 2016).

Altogether, the complete HAT Network (http://hatnet.org) has been fully operational in an autonomous fashion since 2004, for 13 years. It remained homogeneous, using close to identical instrumentation for all 6 telescopes currently in operation. Throughout these years, the design principle remained consistently the same: the only off-the-shelf components were the optics, CCDs and control computers. All remaining parts (dome, mount, electronics, software) were designed, built and assembled by our team. This led to a robust setup that we could maintain for over a decade. Running the HAT network necessitated on average one per mission per site per year, either for routine or preventative maintenance.

The search for the subtle signatures of transiting exoplanets motivated our team to develop novel observational methods, algorithms, and software solutions. One example is the box least-squares (BLS) fitting method by Kovács et al. (2002), a widely used algorithm for detecting periodic, box-shaped transits. We developed
The HATNet and HATSouth Exoplanet Surveys

The Trend-filtering Algorithm (Kovács et al. 2005) and External Parameter Decorrelation (EPD; Bakos et al. 2010) to remove systematic noise from the light curves, greatly improving the detection efficiency of transits. We also developed the PSF-broadening method (Bakos et al. 2004), whereby the telescope pointing is “drizzled” during the exposure, thus greatly reducing the photometric noise due to critical sampling of the stellar PSF by the front-illuminated pixels that have a non-trivial intra-pixel sensitivity. We developed a novel method for deriving the astrometric solutions for wide-field images (Pál and Bakos 2006), and the requirement of high precision wide-field photometry on HAT led to the development of the FITSH package (Pál 2012). The challenges of analyzing the time-series from HATNet and HATSouth also greatly motivated the development of the open-source software suite VARTOOLS (Hartman and Bakos 2016).

The HATNet observing strategy is to assign a primary field (i.e., one of 838 discrete pointings on the sky) to each instrument. The instrument continuously observes the primary field at 3 min cadence over the night so long as it is above 30° elevation and not too close to the Moon. Typically two of the instruments in Arizona are assigned the same fields as the instruments at Mauna Kea. The total time spent on a given field varies significantly, from a minimum of ~ 3 months, to several years in some cases, and with anywhere from 2,000 to 40,000 observations collected for a field (the median number of observations being 6000). A total of 145 fields, covering 34.6% of the Northern sky, have been observed and reduced to date.

Images from the HATNet instruments are transferred to Princeton University, where they are reduced to trend-filtered (EPD and TFA) light curves through a fully automated pipeline. This pipeline performs basic CCD calibrations, determines an astrometric solution for each image, performs aperture photometry at the fixed location of sources from the UCAC 4 catalog (Zacharias et al. 2013), performs an ensemble calibration of the light curves, allowing for a smooth overall flux scaling of the sources as a function of the color and image position, detrends each light curve against a set of instrumental parameters (EPD), and applies the Trend Filtering Algorithm in signal-detection mode (i.e., no attempt is made to preserve the shapes of large amplitude astrophysical variations). Light curves for a total of 6 million stars have been generated so far in the magnitude range of $r \approx 9.5$ (saturation) to $r = 14.5$. The photometric precision reaches ~3 mmag at the bright end at the 3-minute cadence. The trend-filtered light curves are searched for periodic transit signals using the BLS (Kovács et al. 2002) algorithm. A variety of cuts are applied to candidate signals to remove clear false positives (mostly pulsating stars, eclipsing binary systems, blends with neighboring eclipsing binaries, or cases where the detected “transit” is due to systematic errors in the photometry). Candidate transit signals are then visually inspected by multiple team members, and the selections are collated into a single list of transit candidates. More than 2400 candidates have been selected from HATNet observations to date.
Fig. 1 Two of the HATNet telescope units at Mauna Kea, on top of the Submillimeter Array hangar building. Each clamshell dome hosts a horseshoe mount, a 11 cm diameter lens, and a $4K \times 4K$ front-illuminated CCD. The systems are fully automated, and have been running since 2004. The Subaru (left), Keck (center) and IRTF (right) telescopes are in the background.

HATSouth

Planning of the HATSouth network [http://hatsouth.org] began in late 2007. The prototype was fully built by the summer of 2008 at Pécel, Hungary. Altogether six “HS$_4$” telescope mounts were installed at the respective sites of Las Campanas Observatory (LCO), Chile, the High Energy Spectroscopic Survey (HESS) in Namibia, and Siding Spring Observatory (SSO) in Australia by November 2009. The three sites are close to equally spread in longitude, permitting round-the-clock observations. Each of the HS$_4$ units (see Fig. 2), holds four 0.18 m diameter f/2.8 focal ratio telescope tubes on a common mount producing an $8.2^\circ \times 8.2^\circ$ FOV on the sky, imaged using four front-side-illuminated $4K \times 4K$ CCD cameras and Sloan $r'$ filters, to give a pixel scale of $3.7''/\text{pixel}$. The full HATSouth network, with altogether 24 optical tube assemblies, was commissioned in 2010. In periods of good weather we have realized stretches of up to 130 hours of non-stop observations, enabling the discovery of many more long period transiting exoplanet candidates than can be found by any other ground-based transit survey. What distinguishes HATSouth from other wide-field ground-based surveys is the fine pixel scale, greater
sensitivity to K and M dwarf host stars, and sensitivity to long period and small radius planets.

As of March, 2017, the telescopes have opened on \(\sim 2300\), \(\sim 2070\), and \(\sim 1780\) nights from LCO, HESS, and SSO, respectively. Based on weather statistics through 2017, the sites have averaged 7.99 hrs, 7.50 hrs, and 5.48 hrs of useful dark hours per 24 hr time period (here dark refers to the Sun elevation below \(-12^\circ\)). HATSouth has taken 3.35 million science frames at 4-minute cadence, covering 17\% of the Southern sky, yielding light curves for 10 million individual sources with \(r < 16\), and \(\sim 4\) million light curves suitable for searching for transit signals. Data reduction is broadly similar to that of HATNet. To date we have identified 1800 transiting planet candidates from the HATSouth data, including approximately 300 with \(P > 10\) days, and 60 with the size of Neptune or smaller.

![One of the HATSouth telescope units at Las Campanas Observatory, Chile. The diameter of the yellow optical tubes is 18 cm. Each optics is coupled with a 4K \(\times \) 4K front-illuminated CCD. The twin Magellan telescopes are in the background.](image)

**Fig. 2** One of the HATSouth telescope units at Las Campanas Observatory, Chile. The diameter of the yellow optical tubes is 18 cm. Each optics is coupled with a 4K \(\times \) 4K front-illuminated CCD. The twin Magellan telescopes are in the background.

### From Transit Candidates to Fully Confirmed Planets

Candidate TEPs from both HATNet and HATSouth undergo spectroscopic and photometric follow-up observations to rule out false positives, confirm those that are
planets, and characterize their properties. This is a massive effort, using a plethora of facilities in a coordinated manner.

Our first follow-up step is to obtain reconnaissance moderate- to high-resolution optical spectra for all candidates. The spectra are used to determine bulk properties of the star, including its radial velocity (RV), effective temperature \((T_{\text{eff}})\), surface gravity \((\log g)\), metallicity and projected equatorial rotation velocity \((v_{\sin i})\). These are used to identify many false positives, such as F stars transited by M dwarf stars, giants that are blended with fainter eclipsing binary stars, or other stellar triple systems. If the star is not excluded by the reconnaissance spectroscopy, it is subject to further follow-up observations. Often the RV precision of the reconnaissance measurements is sufficient to detect the wobble of the star due to the orbital motion of a massive planet. If no RV variation is detected, then additional RV monitoring may be done using a higher precision facility. More than 3000 candidates have been subject to spectroscopic follow-up, using 16 instruments altogether. (These numbers are for HATNet and HATSouth combined).

In parallel to and coordinated with spectroscopy, we also perform photometric follow-up to have a higher precision light curve for determining the system parameters, and to rule out some blended eclipsing binary false positives through higher spatial resolution observations. A total of 18 facilities have been used for this effort to gather follow-up light curves for more than 1100 candidates. We also regularly perform high-spatial resolution imaging for candidates (using AO systems, speckle imaging, and lucky imaging) to search for close stellar companions at separations less than an arcsecond.

Occasionally, additional types of follow-up are performed. This may include spectroscopic observations taken through transit to measure the Rossiter-McLaughlin effect (e.g., Zhou et al. 2015), or in the case of very rapidly rotating stars, to confirm the planet via Doppler tomography (e.g., Hartman et al. 2015a; Zhou et al. 2017).

For HAT and HATSouth, altogether, we have obtained at least some follow-up observations for \(~3200\) of the \(4200\) candidates, confirmed \(~140\) as substellar objects, and concluded that \(~2300\) are false positives or false alarms. The remaining candidates require more follow-up observations.

**Highlights**

We have been fortunate to contribute some of the exciting discoveries to the booming field of extrasolar planets. The physical parameters of these exoplanets span a very wide range, as shown in e.g. Fig. 3, exhibiting the mass–radius diagram of those \(~435\) exoplanets with well measured masses and radii, and with contributions from selected projects color-coded. Some of the highlights from the HATNet and HATSouth surveys include:

**HAT-P-2b:** the first super-massive hot Jupiter with both mass \((9.09 \pm 0.24 M_J)\) and radius \((1.16 \pm 0.073 R_J)\) measured accurately (Bakos et al. 2007).
The mass-radius diagram of transiting extrasolar planets, as of 2017 March, color-coded by the projects. HATNet and HATSouth have contributed exoplanets spanning a wide range of masses and radii, along with other physical properties.

**HAT-P-7b:** a short period hot Jupiter, discovered before the launch of the *Kepler* mission, falling in the field of *Kepler*, and later becoming one of the best studied exoplanets (Pál et al. 2008). It was the first planet found on a retrograde orbit (Winn et al. 2009; Narita et al. 2009).

**HAT-P-11b:** the first transiting Neptune discovered by a ground-based survey (Bakos et al. 2010). It is also the first Neptune with an orbital tilt measurement (Winn et al. 2010) and water vapor detection (F Matte et al. 2014).

**HAT-P-13b:** the first transiting planet in a double-planet system with a closed orbit for the outer planet (Bakos et al. 2009). This system proved to be a rich dynamical laboratory, constraining the interior structure of the inner planet (Batygin et al. 2009; Buhler et al. 2016).

**HAT-P-15b:** with $P = 10.3$ days, was the first TEP with $P > 10$ days found by a ground-based survey (Kovács et al. 2010). Along with HAT-P-17b (Howard et al. 2012), these planets were important in realizing that the inflation of hot Jupiters is related to the infalling flux from their host star.

**HAT-P-26b:** was the second transiting Neptune-sized planet found by a wide field ground-based survey (Hartman et al. 2011a). It remains one of the few Neptune-sized bodies for which transmission spectroscopy was carried out, hinting at some properties of its atmosphere (Stevenson et al. 2016).

**HAT-P-32b and -33b:** with $R \approx 2R_J$ are amongst the largest radius planets ever found (Hartman et al. 2011b).
**HAT-P-44b, -45b, and -46b:** are rare multi-planet transiting hot Jupiter systems \cite{Hartman2014}.

**HAT-P-47b and -48b:** are two of the lowest density planets ever found ($\bar{\rho} \approx 0.1 \text{g cm}^{-3}$), and are members of the very rare class of short-period planets with masses intermediate between Neptune and Saturn \cite{Bakos2016}.

**HAT-P-49b:** orbits one of the highest mass ($M_\star \approx 1.54M_\odot$) host stars found to date \cite{Bieryla2014}.

**HAT-P-54b:** was the first ground-based transiting planet detection confirmed by *Kepler/K2* \cite{Bakos2015a}.

**HAT-P-57b:** the fastest spinning host star ($v \sin i = 100 \text{km s}^{-1}$) with a transiting planet \cite{Hartman2015a}. This was confirmed via Doppler tomography.

**HAT-P-67b:** is an ultra low-density planet ($R \approx 2.1R_J$, $M < 0.59M_J$) around a rapidly rotating F subgiant, confirmed via Doppler tomography \cite{Zhou2017}.

**HATS-6b:** one of only two transiting giant planets confirmed around an M dwarf star \cite{Hartman2015b}.

**HATS-7b and HATS-8b:** were, respectively, the third and fourth transiting Super-Neptunes found by a ground-based survey \cite{Bakos2015b, Bayliss2015}.

**HATS-9b:** \cite{Brahm2015}, at $t = 10.8 \pm 1.5 \text{Gyr}$, is the oldest well characterized hot Jupiter, where the age of the host star is known to better than 20% precision.

**HATS-14b:** a hot Jupiter transiting a late G dwarf star \cite{Mancini2015}, which, unlike the other such objects known, has a high obliquity \cite{Zhou2015}.

**HATS-17b:** with $P = 16.3 \text{days}$, is the longest period TEP discovered by a ground-based transit survey to date \cite{Brahm2016}.

**HATS-18b:** an extremely short period ($P = 0.84 \text{day}$) transiting Super-Jupiter which has tidally spun up its host star, enabling a strong constraint on the tidal quality factor of the star \cite{Penev2016}.

**Future Prospects**

Both HATNet and HATSouth are currently running with full force. They are providing high-precision high-cadence photometric measurements for millions of stars, which can shed light on the long term variability of objects, such as, for example, peculiar stars \cite{Boyajian2016}, or the secular variations of eclipsing binaries with period changes \cite[e.g.][]{Tylenda2011}. They are yielding thousands of transiting planet candidates, which are actively followed up by an arsenal of telescopes and instruments. Finally, they are yielding transiting planets at a high rate.

Once the Transiting Extrasolar Survey Satellite (TESS) is in operation (est. 2018), all these data components (light curves, transiting exoplanet candidates, and confirmed exoplanets) from HATNet and HATSouth will prove extremely useful. TESS
The HATNet and HATSouth Exoplanet Surveys

will produce a high precision light curve for most bright stars on the sky, with a typical time-span of 27 days and cadence of 30 minutes. The spatial resolution of TESS will be twice as coarse as HATNet, and five times worse than HATSouth. Data from HATNet and HATSouth will be instrumental in revealing blends; systems that mimick transiting exoplanets, but are blends of eclipsing binaries with brighter stars. Archival and follow-up data from the HAT surveys will offer further synergies with TESS: the combined data-stream will enable the detection and characterization of transiting planets that would otherwise be undetected in the individual survey data, and additional astrophysics offered by the knowledge on the long term variability of the sources. Many of the TESS planet candidates will already have follow-up observations through the HAT follow-up efforts. Finally, experience from these wide-field ground based surveys will be directly carried over into scientific investigations with TESS.

In parallel to TESS, we anticipate that a new ground-based survey, called HATPI, will come online. HATPI will ultimately use an array of 63 lenses and CCDs to image the entire sky above 30 degrees (1 π steradian) on a mosaic, every 30 seconds, whenever conditions permit, yielding better than 3 mmag photometric precision at 30 s cadence for stars at $r \approx 10$. Construction of HATPI at Las Campanas Observatory is under way. The massive, high-precision data from HATPI will complement TESS, and will also offer remarkable synergies with the Gaia space mission.

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