Current status of the Permanent All Sky Survey (PASS) for the Detection of Transiting Planets

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Abstract. An overview is given over the Permanent All Sky Survey (PASS) experiment, currently being developed at the IAC. The primary goal of PASS is the detection of all transiting giant planets in the entire sky, with periods up to several weeks, and with a completeness magnitude of the central star of 10-11. The survey would also allow the pursuing a variety of work on temporal astronomical phenomena of any kind. Calculations of the instrument's noise sources and subsequent simulations indicate that the proposed design, based on an array of very small CCD cameras with wide-field optics, is able to achieve the main objective. As the next step, the installation of a prototype at Teide Observatory, Tenerife, is imminent. This will allow refinement of the observing strategies, and the start of a survey for transiting planets in a limited field.

Introduction. In this paper, an overview is given about the Permanent All Sky Survey (PASS) instrument, whose development has recently started at the Instituto de Astrofísica de Canarias. PASS is intended to perform a permanent all-sky survey, obtaining time-series photometry from *all* bright stars that are visible in one or more observing locations, with the major aim to detect all giant planets transiting bright stars, obtaining good coverage for periods on the order of months.

The detection of planets by PASS is based on the transit method, by detecting the small eclipse planets are causing in light-curves of their central star, when part of the star is occulted during the planet's crossing. Though the vast majority of currently known planets have been detected with the method of spectroscopic measurements of stellar radial velocity variation, interest in the transit method has strongly increased in recent years. This is mainly based on the much greater amount of information that can be gained from planets detected this way, as has been demonstrated for the planet of HD209458. This was the first transiting planet discovered (Charbonneau et al, 2000; Henry et al. 2000), and is by far the best studied planet. All its basic parameters like mass, radius, orbital distance, inclination, and indirectly, its temperature and density are known, and the first constituents of its atmosphere have recently been detected (Charbonneau et al. 2002). It should be noted, that many of these fairly detailed studies have only been possible because HD209458 is also a relatively nearby and bright, 7,6 mag star. In contrary, for planets detected only with radial velocities, only a lower limit of their mass and the period and eccentricity of their orbit is known.

The transit method requires of course that planet and central star are aligned in a way to cause observable 'transits'. For planets with periods of a few days to weeks, this probability ranges between 10% and 1%. Also, the light lost from the central star during a planetary transit is rather small, given by $\Delta L/L \approx (R_{pl}/R_*)$, where R_{pl} and R_* are radii of planet and star. For a Jupiter-sized planet crossing a solar-like star, transits cause a light-loss of about 1%. Lastly, transits occur only once for a few hours during every planetary orbit, and the observation of at least three transits is required to ascertain against confusion with brightness variations of different nature, with instrumental errors and atmospheric variations being of major preoccupation. Also, grazing eclipsing binaries, or faint eclipsing binaries in the background of a brighter star may mimic transit-like events. Strategies for a successful transit-detection instrument are therefore:

- Observations of many -at least *several thousand* - stars.
- High photometric precision. For giant-planet detection, about least 0.5% precision over integrations of 15minutes is needed.
- Observations of long duration, and with high duty cycle.
- Observations in several colours, or having the possibility for such observations as follow-up, to reject eclipsing binaries.

A wide variety of ground-based transit detection projects has sprung up in recent years (see Horne, 2002 for an overview). All of these employ large-format CCD cameras in order to observe well-populated stellar fields, and most of them operate on dedicated telescopes to obtain the observing time required. Consequently, these experiments tend to be performed on relatively small telescopes. This is not in contrary to the requirement of high photometric precision, if the targets are adequately bright stars. Also, the simultaneous observation of many stars on a CCD allows for the correction of many errors with sophisticated differential photometric techniques.

In the context of all current ground-based transit detection experiments, with telescope sizes ranging from a few centimetres to 4 meters, PASS is on the extreme end in two senses. For one it intends to employ the smallest telescopes, being really just photographic lenses. On the other hand, the field size being observed by PASS is the largest, with the entire visible sky at a given observing site -about 10 000deg^2 - being surveyed simultaneously. These parameters are driven by the goal of PASS to obtain a complete sample of *all transiting giant planets of bright stars in the sky.* This is the major difference of PASS to other instruments, which have the goal to detect *some* transits in some selected sample-fields. The underlying motivation for such an all-sky survey, concentrating thereby on the brightest stellar sample possible is the high suitability of all transiting planets detected this way for further detailed study. Such studies, like spectroscopy, tend to be critically limited by the achievable signal-to-noise ratio, which depends directly on the brightness of the system under study.

An imager and photometer that obtains all-sky data with temporal resolution may also allow the pursuing of a variety of *additional objectives* related with temporal astronomical phenomena, such as:

- Detection and follow-up of any stellar variabilities with low amplitudes (up to 0.1%, depending on stellar brightness and frequency)
- Variable stars of any kind
- Flares
- Detection of supernovae
- Recording of frequency and direction of meteorites
- Detection of optical counterparts to gamma ray bursts and ‘optical flashes’
- Detection of asteroids, comets
- stellar occultations (e.g. by Kuiper-belt objects)

Additionally, sky-quality and meteorological studies are possible:

- Recording of sky brightness and extinction in all directions
- Percentage of clear sky, clouds
- Detection of satellites and airplays (intrusions into protected sky area over observatory)

It should be noted that the long-term follow up of precise eclipsing binary star’s minimum times may by itself constitute a method to detect planets (Deeg et al., 2000). In the following sections, the basic design, the temporal coverage by PASS, the expected planet sample, the instrument's noise characteristics, and simulations of images and photometry are introduced. Ultimate certainty on the instrument performance can however only be achieved by the acquisition of real data, for which a prototype is currently being installed.

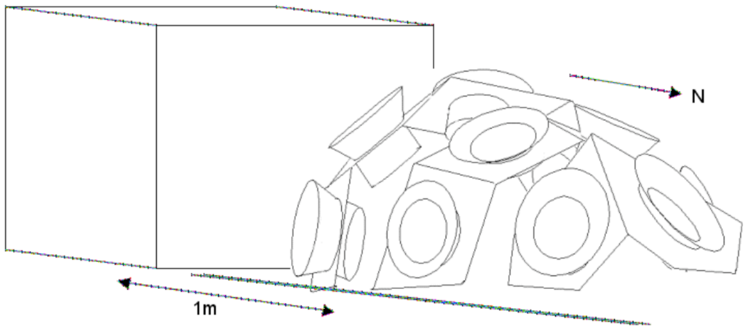

Fig 1. Drawing of PASS experiment (here with 10 cameras) in front of its enclosure, giving an approximate indication of the experiment's layout and size.

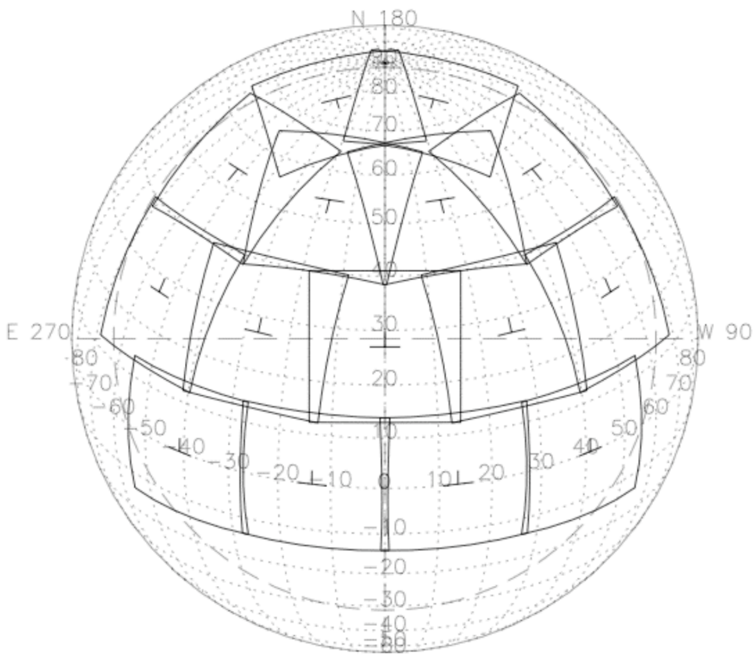

Fig2. Local all-sky view from a location at 28.5°N, showing camera positions (squares) for a system of 15 units (each with a field of view of 28°x28°), in orthogonal projection. Coordinate lines are declination and hour angle; also indicated is an altitude of 30° (long dashes around circumference). In this set-up, there is no coverage below declinations of -17.5°, as good temporal coverage of stars further south cannot be obtained (see Fig. 3a). Further north, the sky is completely covered for altitudes > 34°, with an average limit around 30°. The altitude limit is slightly lowered in the extreme north, to include the celestial North Pole. Other camera positionings have been evaluated, but for a view of 28° this is the most efficient one.

The design of PASS. Driven by the requirement to obtain an all-sky transit survey within a reasonable duration of operation, a single PASS instrument would consist of an array of 15 CCD cameras with short focal length. With their fields slightly overlapping, these would image the entire sky that is visible from an observing location. The CCD cameras would be mounted fixed, without any guiding (Figs. 1 and 2.). This way, an excellent mechanical and photometric stability of the instrument should be achieved. The instrument's 'base-line' design uses conventional read-out of the CCD chips, and stars will then appear as traces on the images. Alternatively, the celestial motion parallel to a CCD's columns may be compensated by a synchronous line-by-line reading of the CCD.

The current base-line consists of 15 cameras with lenses of f=50mm, as used for common high quality 36mm cameras, with a CCD of appropriate size, of about 25x25mm, which gives a field of view of about

28°x28°. Fig. 2 shows that 15 such cameras give complete coverage of the sky above 30°-34° altitude. The experiment would need to be mounted on a sturdy platform and be covered with a completely removable enclosure. The amount of data produced depends mainly on the size of the CCD chips (1k x 1k and 2k x 2k designs are being evaluated) and on the level of on-line processing that is being performed. If images are co-added (accounting for the stellar motion in the co-adding) and saved only every 500 seconds, about 800 images are generated every night, each with a size of 2 Mbytes (for a 1k x 1k chip). This would result in fairly manageable data volumes of 1.6 Gbytes per night. Precession will cause a constant shifting of the stellar tracks. This may be accounted for by an occasional recalibration of the tracks, or by a mechanical adjustment, turning the entire system slightly around the precession axis.

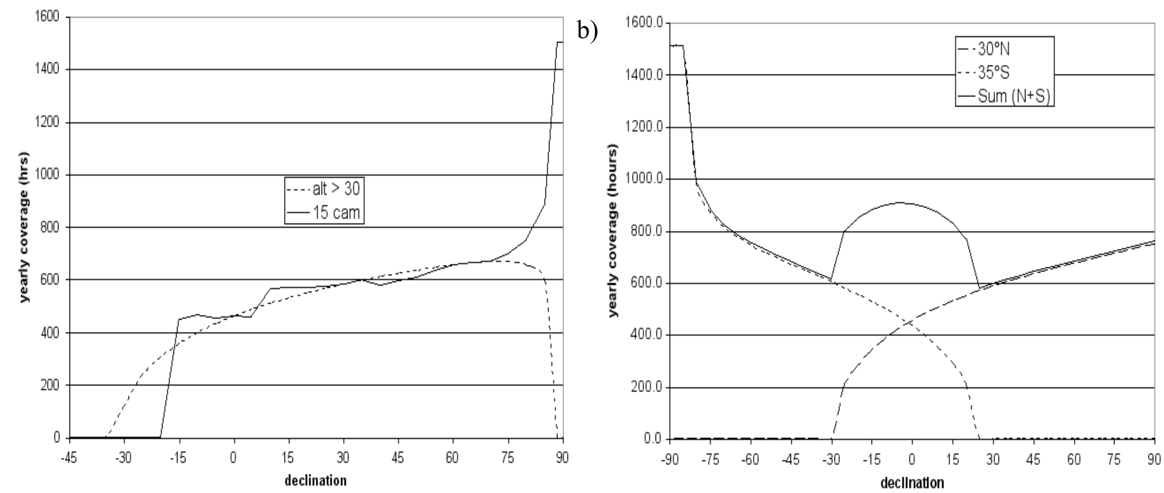

Fig. 3. a) . Yearly observational coverage in dependence of stellar declination, assuming a yearly total of 1500 hours of clear observing conditions (200 nights of 7.5 hours), for a site at 28.5°N (Teide Observatory). The coverage shown here is the average for stars at any right ascension. Dashed line: Coverage if entire sky above 30° altitude is surveyed. The North Pole, at an elevation of 28.5°, is not covered. Solid line: coverage by the 15 camera system shown in Fig. 2. A small region around the celestial North Pole is now circumpolar by lowering the altitude limit to 27° at very high northern declinations. **b)** As before, now showing temporal coverage from a northern (30°N) and southern (35°S) site, assuming simple 30° altitude limits for both. If night-hours do *not* overlap among the sites, coverage near the celestial equator will be the sum from both sites, and a relatively uniform coverage (solid line) of over 600 hr/year is achieved over the entire sky.

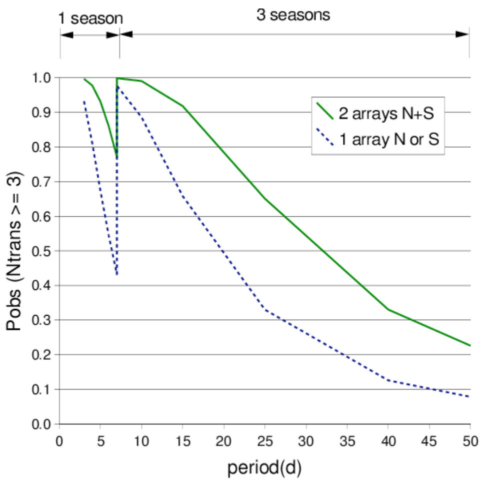

Fig. 4. Probability *Pobs* that transiting planets will be detected, in dependence of their orbital period. This probability is based on the requirement to observe at least 3 transits. The left side, for periods up to 7 days, is based on observations from one season (or one year), whereas for periods of 7-50 days, observations spanning 3 years were assumed. The dashed line is for a single array, with 400 hours of coverage per year, whereas the solid line is for a configuration of two arrays, with 650 hours per year (compare to Fig. 4).

Temporal Coverage: The celestial sphere above 30° altitude has a spatial angle of 1π rad^2. Hence, anytime a quarter of the entire sky will be observed. The amount of time that a star can be observed during the course of a year depends primarily on its declination and on the observatory's geographical latitude. Coverage at high northern latitudes depends critically on the altitude limit; stars at the stellar equator would be visible about 1/3 of the yearly night-time, and coverage declines rapidly towards southern declinations (Fig. 3a). Coverage of southern declinations would be achieved from a similar observatory located at 30-40°S, that should be located at a very different longitude to avoid overlapping night-hours. For stars near the celestial equator, the coverage with two observatories in antipodal position would then be doubled (Fig. 3b).

Numbers of stars surveyed and expected planet detections: From a single northern location with a southern declination limit of –17.5°, about 65% of the entire sky would be observable with a coverage of better then 400hrs/yr. With 3 years of observations, coverages of at least 1200 hours should be achieved, which will allow high (larger than 50%) detection probabilities for planets with orbital periods of up to 15 days (if observations of 3 transit events is required, see Fig. 4). Longer observing spans would increase the detectable orbital periods, increase the confidence in detections, and lower to some extent the detectable planet sizes due to the observation of more transits. A single array in a mid northern or mid-southern (25-40° latitude) could survey about 250 000 stars to magnitudes of V~10.5 with sufficient precision for the detection of giant planet transits (photometry of better then 0.7%). Assuming 45% Main-Sequence stars, of which 1% have short-orbital giant planets, with a probability for transits of 5%, about 60 planets may be detected. For the final goal of PASS to establish an All-Sky Survey, with instruments in both hemispheres, about 400 000 stars will be accessible for surveying, giving on the order of 100 detections. It should be emphasised, that the major goal of PASS is not the detection of large numbers of planets, but the complete detection of planets transiting bright stars with some well-established and consistent completeness limit.

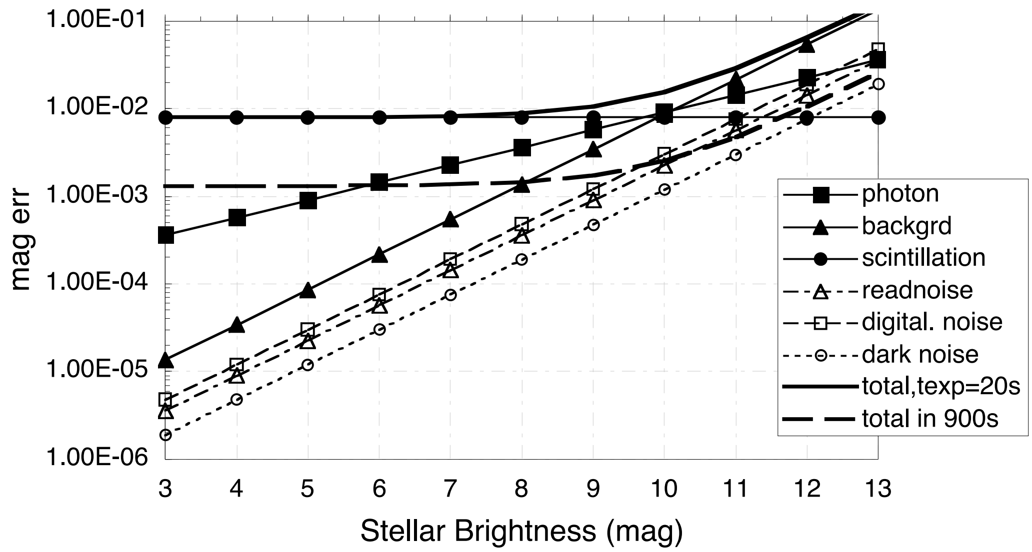

Fig. 5. Noises of the PASS instrument against stellar magnitude, as expected in star-trail images. The fat dashed line is the total noise for 900 seconds of integration, whereas all other lines indicate noises in a single 20 second exposure of a field at the celestial equator with the 'base-line' set-up (see text). Photometric precision suitable for transit-detection can be expected up to 10.5–11*mag*.

Instrumental performance. Fig. 5 shows the contribution from various noise sources that have been calculated for a 'base-line' set-up of PASS. Currently this consists of a front-illuminated CCD (1k x 1k size, 24micron pixels, quantum efficiency of 0.45 against light from solar-type stars and 0.23 against light from sky-background with a red cut-off filter at 725*nm*), an *f*=50*mm* lens operated at aperture *f*/2.0, and exposure time of 20*s*, and moonless sky at a dark site. Scintillation is calculated for 1.4 airmasses at an altitude of 2400*m*, using the equation by Young (1974). The three major noise sources are scintillation, photon noise from stellar sources, and photon noise from sky-background. Other noises, all related to the CCD chip (read, dark and digitalisation noise) are without impact. With stellar photon noise being the major noise source around 10th magnitude, the instrument may be considered optimised for that magnitude range, with no significant improvements possible from the suppression of other noises. The baseline design presented here should be capable of achieving a precision of 2*mmag* for stars brighter than 9.4*mag* and 10*mmag* precision for stars brighter than 11.7*mag* (in 900 second integrations in dark nights). Setting the requirement to detect transits with at least 1% brightness variation, and with transits lasting several hours, for magnitudes brighter than about 10.5 each transit will generate a brightness variation that is at least 3 times larger than the noise, and lasts over tens of data-points (of 900 seconds integrations). Such a signal should readily be classifiable as a transit candidate. The signal-to-noise calculations give therefore confidence that the goal of the experiment can be reached with the base-line design. It should be noted that the base-line set-up is for typical good observing conditions, and sky-brightness, declination of the stellar fields and airmass are further factors that influence in one way or the other.

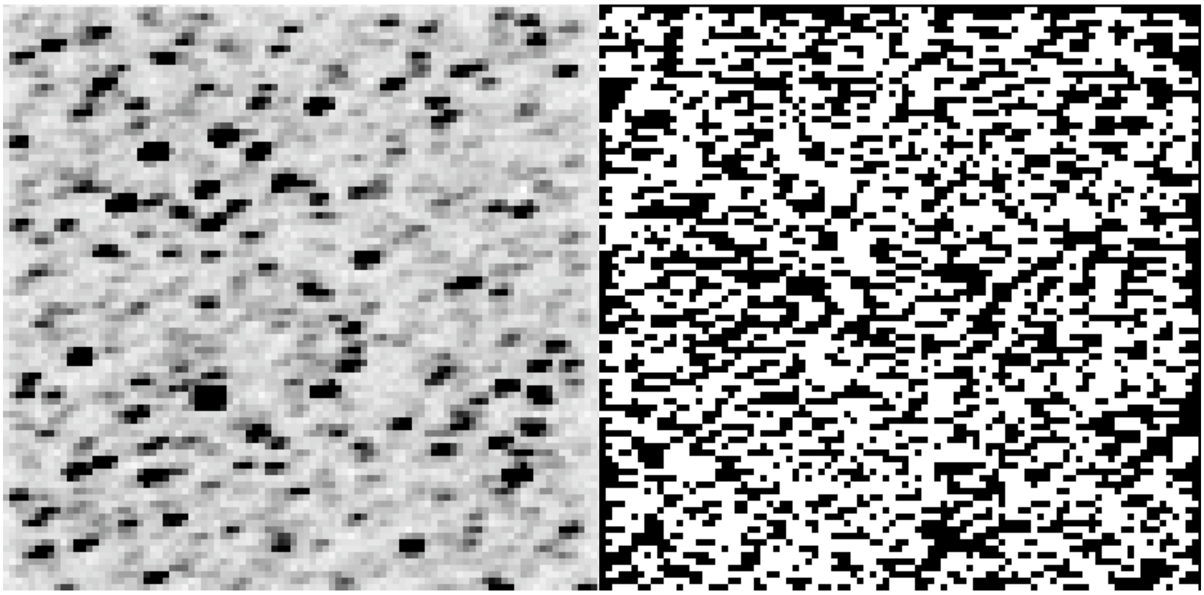

Fig. 6. a) *Left*: simulated PASS image (with stellar density typical for 10° galactic latitude), with an exposure of 20 seconds and the 'base-line' set-up. The size of the field is about 2 x 2 degree. The brightest star has 5,7*mag*, several have 6-9*mag*, and the faintest ones are 14-15*mag*
b) *Right*: Final aperture mask. Starting from the brightest stars, the maximum number of *non-overlapping* traces has been fitted in (here extracting apertures for 1155 stars), so that each aperture-pixel (white) is assigned to just *one* star.

Simulated images and photometry. To evaluate if the noises predicted in the previous section can be recovered by photometry done on realistic images, a simulator for CCD images taken by PASS has been developed. Besides the noises described previously, the simulations also represent stellar crowding, and the variations in inter-pixel quantum efficiency expected in front-illuminated CCDs (as described by Kavaldjiev & Ninkov, 1998). Fig. 6*a* shows a simulated field that represents a small section of a field observed by one of PASS's cameras. In current simulations, sequences of such images have been generated, regenerating the appropriate noises every time, and optionally accounting for the motion of the stars from field to field. On these image sequences, stellar photometry is being performed with a program 'tracephot'. In its first analysis step, an aperture mask is being build up on the first image, using the known stellar positions and brightnesses: The program starts with the brightest star, and assigns any pixels under its track to that star's aperture. This process is being continued for fainter and fainter stars, but stars where parts of their tracks are already assigned to brighter stars are rejected. With this algorithm, the maximum number of the brightest stars is being sampled in the field, resulting in very dense final aperture masks similar to those shown in Fig. 6*b*. In the second step, 'tracephot' applies this aperture mask to the first image and then, with appropriate shifts, to the following ones. Simple aperture photometry through these masks is then being performed, resulting in a time-series for each star. Fig. 7 shows the rms error of such a time-series from the base-line set-up, against the known input-brightness of the stars. Comparison with the theoretical noise figures (solid line in Fig. 5) shows that the photometry on stellar traces is able to extract stellar brightnesses close to the noises that are intrinsic to the images. The major factor that is degrading the precision against the theoretical one, especially among the fainter stars, is probably the crowding that many of these stars are suffering.

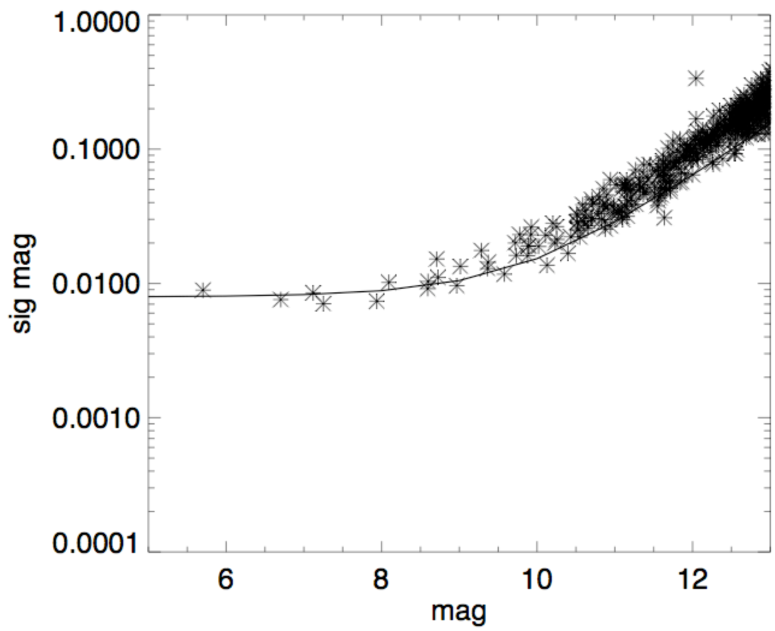

Fig. 7. Crosses indicate the rms error found in teim-series photometry on the artificial stars in 15 simulated images similar to those shown in Fig. 6*a*. The solid line is identical to the solid line in Fig. 5 and indicates the total expected noise for from S/N calculations. Some stars have photometric errors 'better' than the theoretical value; this is a result of the small sample of only 15 images.

Current status. Current activities on PASS center for one on a detailed exploration of parameters based on the simulations, studying the impact of stellar densities, exposure times, the camera optics, and technical parameters of potential CCD cameras. On the other hand, funding has recently been obtained for the purchase and installation of a prototype of the PASS experiment at Teide Observatory on Izaña, Tenerife. The prototype's major aim is a feasibility study, outlining the capabilities of the instrument in all aspects. The prototype will also serve to generate real data that are needed to develop and optimise the data acquisition strategies and the reduction pipeline. First images were taken in January 2004 with a system consisting of an Apogee 2k x 2k AP-10 CCD camera, and coupled to 50mm lenses. The images indicated good agreement with the simulated ones, but showed that strong vignetting is present if the lens' aperture is opened fully (two Nikon lenses, with f/1.2 and f/1.4 were tested). This vignetting already led to a revision use f/2.0 for the 'base-line', as presented here. An enclosure for the prototype, essential for tests of photometric stability across several nights, is currently under construction. In the near future, it is expected to supplement the loaned CCD with a second one specific to this project. Besides refining the observing strategies for PASS, and allowing the testing of the rather complicated issues involved in the tracking of stars across different cameras, a 2-camera prototype should already be able to deliver data useful for planet searches. With the region above 65° northern declination being fully covered by 2 cameras (see Fig. 2), start of a permanent sky survey for planet detection may not be that far away.

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References:

Charbonneau D., Brown T.M.,Latham D.W., Mayor, M. 2000, ApJ 529, L45

Charbonneau, D, Brown, T., Noyes, R.; Gilliland, R. 2002, 2002ApJ...568..377C

Deeg, H. J.; Doyle, L. R.; Kozhevnikov, V. P.; Blue, J. E.; Martín, E. L.; Schneider, J. 2000, A&A, 358, L5

Henry G.W., Marcy G.W., Butler R.P., Vogt, S.S. 2000, ApJ, 529, L41

Horne, K. 2002, in Scientific Frontiers in Research on Extrasolar Planets, Eds. D. Deming, S. Seager. ASP Conference Series, Vol 294, 361.

Kavaldjiev, D. & Ninkov, Z. 1998, Optical Engineering 37(3), 948

Young, A.T. 1974, in Methods of Experimental Physics, Vol. 12, Astrophysics, Part A, Optical and Infrared, ed. N. Carleton (New York: Academic)