The Princeton Variability Survey

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ABSTRACT

The Princeton Variability Survey (PVS) is a robotic survey which makes use of readily available, “off-the-shelf” type hardware products, in conjunction with a powerful set of commercial software products, in order to monitor and discover variable objects in the night sky. The main goal of the PVS has been to devise an automated telescope and data reduction system, requiring only moderate technical and financial resources to assemble, which may be easily replicated by the dedicated amateur, a student group, or a professional and used to study and discover a variety of variable objects, such as stars. This paper describes the hardware and software components of the PVS device, as well as observational results from the initial season of the PVS, including the discovery of a new bright variable star.

1. Introduction

Amateur astronomers have long been involved in the study of variable stars. Organizations like the AAVSO (http://www.aavso.org) and the Center for Backyard Astrophysics (http://www.astro.bio2.edu/cba) have promoted the study of a variety of phenomena by amateurs and overseen the collection of many years of high quality data. As technology, particularly the CCD, has become accessible to a wider range of enthusiasts, the opportunities for the amateur astronomer to conduct or lead scientific inquiry have grown tremendously. Recent projects such as TASS (http://stupendous.rit.edu/tass/tass.shtml), HCRT (http://www.mtco.com/~jgunn), have begun to make significant contributions along these lines. The importance of a comprehensive knowledge of variability across the entire sky has been outlined by Paczyński(2001) and explored experimentally through projects such as ASAS (Pojmanski 1997, 1998). Approximately 90% of all bright existing variable stars are thought to be yet undiscovered, with ASAS finding that approximately 3% of a set of 140,000 monitored stars turned out to be newly discovered variables with a wide range of periodicities, as discussed by Eyer & Blake (2001). The potential contribution from the study of a set of several thousand stars, even for just a few nights, is enormous. The
ultimate goal of the PVS has been to design a system to be utilized for just this purpose. In order for the desired scientific results to be achieved in as simple a manner as possible, a number of criteria must be met. Availability of components, ease of implementation, and reproducibility of results were all key concerns during the development of the PVS system. Today, a wide array of advanced devices are available to the savvy amateur, and when combined with powerful and inexpensive computational resources, the ability to survey the sky from a backyard is shown to be well within reach. Optical and electronic components of the PVS are easily available through mail order, or even a local retailer, and products already widely owned by amateurs were integrated whenever possible. Though the commercial hardware systems utilized in the PVS are shown to perform well, the power of the PVS design is derived from the software that controls all aspects of data collection and actively compensates for mechanical and electronic shortcomings in the hardware components. This collection of commercially available software products, all adhering to a set of inter-program cooperation guidelines called ASCOM (http://ascom-standards.org), work together on a PC, under Microsoft Windows, to control telescope, camera, and, if required, the telescope dome. These programs allow simple procedures to be controlled from a Graphical User Interface (GUI), and for complex observing sessions and data reductions to be scripted in Perl, Visual Basic Script, or C++ languages. This paper provides descriptions of the hardware and software utilized in the PVS such that a similar system may be constructed by interested parties. Examples are presented of the type and quality of results that may be expected.

2. Hardware

2.1. Telescope

The PVS optical system centers around the popular Meade LX200 Schmidt-Cassegrain telescope (http://www.meade.com). This telescope is well known for its low price and ease of use, and was found to be of more than adequate optical and mechanical quality for the purposes of the PVS. Here, the 12” aperture model was utilized, with the standard f/10 to f/6.3 focal reducer, yielding a working plate scale of 82”/mm. In practice, any of the Meade LX200 Schmidt-Cassegrain telescopes could be used. The PVS LX200 is permanently mounted on a pier in equatorial configuration. Care was taken to ensure that the telescope base was level and properly aligned with north celestial pole, following the instructions in the Meade manual. Although the instrument can be operated in an ALT/AZ configuration, field rotation would be problematic. The telescope comes standard with the ability to communicate with a nearby PC via an RS-232 to Serial port connector, facilitating the
development of a robotic system. This communications cable can be easily assembled
following instructions in the appendix of the Meade manual and requires a four wire RJ11
standard phone cable and an RJ11 to DB9 (9 pin serial) adapter. The voltages associated
with this RS232 signal are very low, so it was found necessary to utilize a high quality
shielded twisted pair phone cable, available at computer stores as a high speed modem
cable. With this connection, encoders on both axis can be read out to the computer and
dual axis motors actuated in response. The LX200 makes use of a large Right Ascension
gear of 180 teeth with a period of approximately 8 minutes. The periodic error of this gear
was found to prohibit unguided exposures of over 60 seconds in length, with peak to peak
deviations of approximately 20″ . The telescope does have the ability to actively compensate
by ”learning” these errors through a training process during which an observer manually
maintains the position of a guide star while the telescope’s small onboard computer records
these adjustments. The periodic error of the LX200 was not found to be reproducible
between pointing positions or nights, and random tracking errors of ≈ 10″ remain even
after training. An autoguider is utilized to compensate, at a rate of approximately 1Hz,
for these tracking errors during exposures, resulting in tracking accurate to the pixel level.
The necessity of an autoguider does impose a limit on the percentage of the entire sky that
is observable by PVS. Since a reasonably bright guide star is required, and in general a
rotation of the camera is not possible during observations, only fields a fixed distance away
from bright stars are observable. It was found that stars bright enough to guide by are
reasonably abundant such that something like 1/3 of all blind pointings will happen to
produce a usable guide star.

When permanently mounted in equatorial mode, the LX200 requires only one
alignment star in order to determine position. Once the instrument is aligned to a bright
star of known coordinates, the encoders will keep track of the telescope Right Ascension
and Declination with reasonable accuracy for the duration of the night’s observations.
Through the RS-232 connection, the controlling PC can slew the telescope toward any
set of coordinates. Pointings across the entire sky were found to be accurate to within 8′,
placing the desired object well within the field of view of the CCD camera used by PVS.
Locally, the pointings are further enhanced to much higher accuracy. With the assistance
of software, pointings to within an arcsecond are routinely achieved during the data
taking process. An important benefit resulting from the popularity of the Meade LX200
model is the Meade Advanced Products Users Group (http://www.mapug.com), an on-line
reference where hundreds of technically minded amateur astronomers have posted their
experiences and insights into LX200 usage, design, and enhancement. One major problem
with the LX200 optical design is the focusing mechanism. The focus is controlled through
movement of the primary mirror, resulting in perceptible image shift and very poor focus
repeatability. A new focuser, model NGF-2 manufactured by Jim’s Mobile Instruments (http://www.jimsmobile.com), was added to remedy this problem. This motorized focuser, with an analog focus micrometer, was found to be very rigid and reliable. This addition adds several centimeters to the optical path length, resulting in slight veining at a level > 10%. Optical filters, of the 50mm round variety, are inserted into the optical path inside the focuser, as opposed to closer to the CCD chip, in order to help reduce veining affects and ensure that any blemishes on the filter surface are well out of focus. Optical filters manufactured by Omega Optical (http://www.omegafilters.com) were utilized. The focuser is attached to the rear cell of the telescope using a special wide aperture adapter plate purchased from Jim’s Mobile Instruments. To the front of the focuser is attached the focal reducer, and finally the camera is affixed with a T-thread adapter to the focal reducer. Care is taken to ensure that the camera is aligned as closely as possible with the axis of the telescope in order to simplify guiding by aligning the rows and columns of the CCD chip with North, South, East, and West.

2.2. CCD Camera

The advent of the low cost CCD camera has revolutionized amateur astronomy. Technology once available only at professional observatories is today within reach of many dedicated home observers. Several companies manufacture such CCD systems, but SBIG (http://www.sbig.com) was chosen as a result of experiences with cameras from a variety of makers, as well as a result of SBIG’s reputation for innovation, quality, and good customer service. The model ST-8E was selected as a reasonably priced, large format camera accessible to amateurs and schools. The 16-bit ST-8E uses a Kodak KAF-1602E CCD ship with an area of 1530 by 1020 pixels, each 9 µm². This chip reaches a peak quantum efficiency of ≈ 70% at a wavelength of 575 nm and slowly loses QE to 10% at 1 µm wavelength. Located adjacent to the imaging CCD, on the same focal plane, is a smaller TI TC-211 chip used for autoguiding. Both chips are cooled with a single stage thermoelectric device to approximately 25 degC below ambient. At a chip temperature of 0 degC, the dark current is reported at 1 e⁻/pixel/s. The camera is mechanically shuttered, so the full Kodak CCD is used for imaging at all times. The ST-8E comes with the option of antiblooming circuitry which helps to lessen the affects of bleeding caused by an overexposed stellar image. Many amateur astronomers choose this option since it is helpful in deep sky imaging. Unfortunately, the antiblooming reduces the full well capacity of the CCD from 100,000e⁻ to 50,000e⁻ and may also be responsible for non-linear effects that are seen to occur as a pixel nears full well capacity. For use with the PVS, a non-antiblooming version of the camera was chosen. The ST-8E reads out to the controlling PC via a
parallel port interface in approximately 52 seconds, with a read noise of $15e^{-}$ RMS. In conjunction with the previously described PVS optical system, the ST-8E yields a field of view of approximately $23'$ by $15.5'$ at a plate scale of $0.91''/\text{pixel}$ with the use of the 0.63x focal reducer. All electronics are integrated into the head of the camera unit, so its total dimension is approximately 12cm round with a total weight of 0.9Kg. This weight is held several centimeters from the rear of the optical tube, and must be balanced with a counterweight placed near the front of telescope.

3. Astronomy Common Object Model software

The computer control systems for the PVS instrument are all run and developed under Microsoft Windows 2000. Windows was chosen since it is far more accessible to the majority of amateur astronomers. The programs used by the PVS are all commercially available products that adhere to the guidelines of the Astronomy Common Object Model (ASCOM, Medkeff 2000). ASCOM is a new and extremely powerful software concept that utilizes Windows ActiveX objects, each representing an instrument component or mathematical manipulation, in order to integrate the functions of a variety of independent software packages and facilitate the automation of an observing system. With products that incorporate ASCOM, complex scripts can be written that may control an entire night of observations with data handling and control of the telescope, CCD, and dome. The ASCOM products also have the advantages of opensource, since scripts with differing functions can be easily written and traded between observers. It was felt that the ASCOM initiative represents a new direction in amateur astronomy and much of the PVS was designed around the usage of ASCOM compliant products. While ASCOM products are used here to control a Meade telescope and SBIG camera, the same programs and scripts can be used with a variety of different CCD cameras and telescope mounts. The telescope control software ACPv2.0 (http://acp.dc3.com) was chosen to oversee telescope motion and pointing, as well as coordinate and time transformations. The astrometric software PinPointv3.0 (http://pinpoint.dc3.com) was selected to manage all astrometric calculations. A wide variety of CCD camera control products are currently available, but MaximDL/CCDv2.12 (http://www.cyanogen.com) was found to be generally superior. MaximDL/CCD was used to control the camera, and manipulate FITS data. Since all three of these products are ASCOM compliant, scripts can be prepared that utilize functions from each in order to carry out observations or analysis. A variety of languages may be used to prepare such scripts, but Visual Basic Script was selected as the PVS language since it is relatively easy to learn and an integrated feature of Microsoft Windows. Scripts may be prepared as plain text documents in Notepad and executed with Microsoft Internet Explorer, or from
within the GUI of ACP. The data taking procedure is managed by a master script which incorporates elements from all three software components. ACP is used to send movement commands to the telescope, calculate topocentric coordinates for objects based on USNO calibrated UTC time and the telescope latitude, longitude, and elevation, and handle issues related to time, such as Julian date calculations. PinPoint creates full World Coordinate System (WCS, Calabretta 2000) astrometric solutions for CCD data images based on best guess center-of-frame coordinates from ACP and a CDROM version of the USNO SA2.0 star catalog. These fits have typical residuals of less than a pixel, and can be utilized to update the exact pointing of the telescope in near real time. Once the telescope is positioned close to a desired set of coordinates by ACP, an image can be taken, the exact pointing calculated by PinPoint, and then the telescope can be moved to compensate for the error (up to a several arcminutes) in the initial pointing. This entire process of point-image-solve-repoint takes approximately 20 seconds when a 3x3 binned image is used for the test pointing and the process is executed on a computer with an 800Mhz Celeron CPU. On this same computer, PinPoint solves a full resolution 1530 by 1020 image in 15 seconds.

The CCD camera itself is controlled through the program MaximDL/CCD. This program sends commands to the camera, such as open or close shutter, and writes out standard 16-bit FITS files with headers containing the usual information, as well as the WCS astrometric structures reported by PinPoint. MaximDL/CCD also controls the autoguiding by downloading images of a bright (> 10m_I) star placed on the secondary CCD chip, located adjacent to the main chip, and sends small positioning corrections directly to the telescope mount at rates up to a few times per second. These corrections are adequate to alleviate most of the periodic error in the Right Ascension gear of the telescope. The coordinates of guide stars are provided in the PVS scripts, and with the known offset from the center of the main CCD to the center of the guide CCD, ACP and PinPoint are used to place the guide star in the center of the guide CCD. At the beginning of the night the script incorporates a guider calibration, whereby the exact alignment of the CCD pixels with the directions of movement of the telescope, and the speeds of those movements, are determined. As long as the camera is not moved, this calibration will suffice for the night with small adjustments, as a function of Declination, being automatically calculated by MaximDL/CCD. Lastly, MaximDL is used, in conjunction with ACP, to estimate and control focus values. This is done by taking series of short exposures of a bright star, while ACP slowly changes focus, and attempting to minimize the stellar FWHM. The focus values were found to be well correlated to dome temperature, and thus a reasonable guess at focus value can be ventured prior to taking any images.
4. PVS Implementation

4.1. Site Description

The PVS data is taken from a dome located on top of Peyton Hall, Princeton University, Princeton, New Jersey. This suburban locale provides less than ideal observing conditions, but conditions typical of those endured by many amateur astronomers. Although the sky is seldom, if ever, photometric, and seeing averages approximately $5''$, the conditions are conducive to relatively accurate differential photometry. The most significant limitation to the observations is sky brightness combined with poor seeing. Since the sky above Princeton is quite light polluted, observations are taken in the Bessel I band. This NIR bandpass is red enough to be free from much of the light produced by nearby academic buildings and major metropolitan centers, as well as much of the light from the moon, and falls on area of high CCD efficiency.

Sky brightness in I band is found to be related to atmospheric glow rather than man made light pollution. In I band, the sky brightness above the PVS observing sites was found to average $17.7 \text{mag/arcsecond}^2$. Teare (2000) compiles sky brightness for a number of site. For comparison, the measured brightness at Mt.Wilson, California, located above the Los Angeles basin and its millions of inhabitants, is reported to be $18.8 \text{mag/arcsecond}^2$ in the direction of the city. The sky brightness at CTIO, Chile, is reported at $19.9 \text{mag/arcsecond}^2$ in I band. The I band sky brightness for Princeton, Mt.Wilson, and CTIO are found to be somewhat comparable, thus independent of man made light pollution, while the sky brightness in V band vary by as many as 5 magnitudes. The Princeton site is brighter in I band than Mt.Wilson probably as a result of the differences in altitude and atmospheric moisture between the two sites. Figure 1 presents a histogram of sky brightness at the PVS site over the month of observations. With exposure durations reasonable for a survey, up to a few minutes in length, the limiting magnitude with the PVS 12” telescope at Peyton Hall was found to be approximately 16 in I band. The atmospheric conditions in Princeton were also observed and found to be notably poor. Probably as a result of inherent seeing and local turbulence, compounded by guiding errors, the image FWHM was found to routinely be greater than $6''$. Figure 2 presents a histogram of image FWHM values for month of PVS observations. Scintillation affects were severe, and caused large amplitude (up to 30%) variations in image FWHM on frequency scales to above 5Hz. These seeing affects might be assumed to be caused by heat rising up into and around the telescope dome from Peyton Hall below, but similarly bad seeing conditions are reported from other observatories in the area. To this end, great care was taken to ensure that the dome was adequately ventilated, and temperature equalized with the outside, using large fans activated several hours prior to the start of observations. The performance of the PVS system as tested in Princeton is
certainly limited by poor conditions, and thus in a better climate the capabilities of this instrument may be considerably extended.

4.2. Data Collection

With the objective of monitoring several hundreds of stars, an area of the sky was chosen near the galactic equator, in the constellation Auriga, which would be visible for many hours during the period of the PVS observations. Sections of sky near the Milky Way should in theory yield the highest number of stars per image, but any area of the sky could in principle be studied. A strip of 5 pointings, amounting to a total field of view of $0.5 \text{deg}^2$, was selected near the intersection of the galactic plane and the ecliptic. One of these pointings contained the open star cluster NGC 1912. This rich cluster, with $\approx 300$ members, has an HR diagram from the observations of Subramaniam (1999) which indicates that it may contain lower instability strip variable stars at magnitudes accessible to the PVS instrument. A nearby open cluster of similar age and metallicity, NGC 2516, was studied by Zerbi (1998) and was found to have several short period intrinsic variable stars. The other four fields, all within a few tens of arcminutes, were picked visually from digitized sky survey plates to be fields with many stars. An analysis by Eyer & Blake (2001) of the variable star catalog produced by ASAS, indicates that the histogram of periods below 50 days, the type of variable star likely to be found with PVS, peaks at periods a bit longer than 1d. As a result, it is not critical that the PVS data be time sampled at rates even as high as hourly. For example, 15 data points per night, over several nights, would yield frequency sampling perfectly adequate for accurate determinations of the periods of many intrinsic (Cepheid, RR Lyrae, dwarf Cepheid, Gamma Doradus) and extrinsic (contact binaries, eclipsing binaries) variable stars.

Based on the conditions in Princeton, each of the five fields observed by PVS is allotted 240 seconds per observation. This amounts to 150 seconds of integration, 50 seconds for image read out, and 40 seconds for various overhead associated with astrometric analysis and pointing. The 150 seconds of integration time was found to balance well the faint limit imposed by sky brightness and the saturation of bright ($m_I < 8$) stars. The telescope is parked at the end of the evening at a prescribed Altitude and Azimuth so that the next night, with accurate local time and telescope latitude and longitude, a reasonable estimate of initial RightAscension and Declination when the telescope is first turned on may be ventured based on the known Altitude and Azimuth. The night’s initial alignment of the telescope with a bright star is therefore automated. From the time the power is turned on, a script may be executed, and the remainder of the night’s observations completed
robotically. Images of the five fields are taken in series for a prescribed number of hours. A master script initializes the camera, begins the camera cool down, executes the initial telescope alignment, moves the telescope with high accuracy to sets of pre-determined coordinates, begins guiding, and takes data exposures. Unfortunately, this script does not include dome automation for the results presented here. The cost of automating the pre-existing dome at Peyton Hall was found to be prohibitive, and so the dome was moved by hand every hour or so. There are several commercially available robotic dome systems that utilize ASCOM compliant software, and as a result dome control may be integrated seamlessly into PVS scripts in the future. Sets of five dark frames are taken each night and used during data reduction to subtract both the dark current and bias from the data images. Sets of 10 flat field exposure are taken from the evening sky following sunset, or from an evenly illuminated flat screen inside the dome, and used to compensate for pixel to pixel variations in system light sensitivity. Exposure times for the flat fields are set so that the CCD chip is filled to approximately half of full well capacity.

4.3. Data Reduction

As a result of the limiting magnitude at the PVS test site, the data images are not considered crowded. Typically, average star densities on the CCD frames are on the order of 3,000 pixels per star. In this regime, a number of different photometry techniques are applicable (Alard 2000, Alard & Lupton 1998). Though simple aperture photometry could be utilized, the technique of differential image analysis is applied in order to gain experience with this method for the time when a better observing site might produce CCD images sufficiently dense to warrant this advanced treatment of the data. This method has several other advantages, including high accuracy, a lack of comparison stars which might induce significant noise if they themselves were variable, and deals well with the highly variable PSFs found in the PVS data. Image subtraction has been shown by Wozniak (2000) to produce photon noise limited photometry, and thus could be expected to yield the best possible results for the PVS data. Data reduction tasks such as flat fielding, dark subtraction, and cosmic ray removal are carried out within the Interactive Data Language (IDL) environment.

There are numerous publicly available IDL codes to manage FITS file I/O (http://idlastro.gsfc.nasa.gov/homepage.html), as well as a wide variety of mathematical and image analysis routines. Each night’s flat fields are read into an image cube, individually normalized by dividing by the sigma-clipped image mean, and then the normalized images are averaged, with sigma clipping, to produce a robust nightly flat field. The flat fields
themselves were found to be of acceptable quality, but were a potential source of significant noise. Fortunately, star centroids remain quite close to the same pixels throughout each night, so large scale, high amplitude, gradients and inconsistencies in the flat fields are effectively rendered null for differential photometry. The dark frames are also read into a data cube and averaged, in order to help eliminate cosmic ray hits, and a nightly dark frame is created. The dark current of the CCD camera is a function of chip temperature, so it is important to prepare a separate dark frame for each night’s observations. Similarly, changes in the optical surfaces and focus require that a separate flat field be prepared for each night. The dark frame is subtracted from the image frame, and the result divided by the flat field. Finally, cosmic ray hits are removed from the data images. There are several available IDL codes to do this, but LACOSMIC.pro (van Dokkum 2001) was found to be most effective. New FITS files with with the reduced data and full header, including WCS information, are written out. A file, called dates, containing the image names, Julian date times of observations, and seeing values was also written out to be later referenced during the photometry. The seeing, or image FWHM, is calculated by determining the average parameters of a three term bi-variate gaussian least squares fit to a set of 40 stars of near mean brightness in each image. The reduced image FITS files, and the dates file, may now be fed to the image subtraction code to produce photometric data.

The image subtraction algorithms were implemented with the ISIS2.1 package prepared by Christophe Alard (http://www.iap.fr/users/alard/package.html). The first step in the analysis is the sub-pixel image alignment which is required prior to image convolution. Since the CCD camera is occasionally removed and re-attached to the telescope, it was necessary to use the 2nd degree image interpolation option so that translations, as well as small rotations, could be corrected for. The image to which all others are aligned, called REFERENCE in the ISIS configuration file, was chosen to be the image with the best seeing. It is important that this fiducial image be of high quality so that the alignment will be sufficiently accurate. ISIS creates a file called loginterp which tabulates the average residuals for each alignment and thus the sub-pixel residuals may be verified. Any image that fails to align to the reference image will be flagged in the log file and should therefore be removed from list of data images to be analyzed, as stored in the dates file. Once the images are well aligned, a new reference image of high signal to noise is created. To do this the 10 best images are combined using the Simpleref procedure. The 2nd degree spatial kernel variation option, along with 1st degree background variation fitting, in order to help, compensate for the visually obvious variations in PSF and background across the frames. The images are not sub-divided prior to analysis as has been done by some users of the image subtraction method. The reference image will be convolved to match the PSF within each data image and then the two are subtracted to determine differences in flux. The
subtraction is carried out by the *Subtract* script and produces subtracted images which should be nearly devoid of stars. The entire process is computationally intensive, and may take several hours, depending on the number of data images. Using the ISIS package under Linux on a PC, the production of fluxes from approximately 100 images required just less than 1 hour of computational time on a 1.0GHz Pentium III work station with 1GB of RAM. The errors in the subtraction photometry are found to be small and well behaved. Strictly speaking, variance in the subtracted images should be the sum of the Poisson deviations in the reference and data images. In practice, it is found that bright, but not saturated, stars often have convolution residuals several times those expected from photon noise. The effect, due to seeing variations, is explained by Alrad and Lupton (1998). The image subtraction methods are found to work extremely well for the PVS data. Figure 3 shows the histogram of the residuals of a subtracted image normalized by the Poisson errors expected from the reference and data image. The idealized distribution of the residuals, $N[0,1]$, is overplotted with the dashed line. The actual residuals fall into a $N[0.005,0.98]$ distribution, indicating that the image subtraction techniques are working quite well and that accuracies at the limit of the sky noise should be achieved.

In order to detect variability, the subtracted images, normalized by the gain adjusted sums of the Poisson deviations of the reference and data images, may be squared and coadded. The resulting variance image makes variable objects easily identifiable visually and by a simple detection script. Variable sources, which have variance well above that expected from just photon noise, may be photometered with basic aperture photometry on the individual subtracted images in order to determine how stellar flux changes with time. False detections are found to occur for bright and nearly saturated stars, as well as for stars near the edges of the frames where drift in the image centroid during a night may cause stars to come in and out of the field of view. The errant bright star detections, in this case for stars brighter than about 8th magnitude, are generally disregarded. In practice, this amounts to very few stars, and when considering that many of the stars this bright would have been previously studied by other programs, the loss is considered negligible. The photometric errors are found to be quite small for all stars. Figure 4 shows average errors, in magnitudes, for a star of a given I band magnitude. Overplotted on these points is the line indicating the magnitude errors from sky noise that would be expected in the aperture photometry of a subtracted image with average seeing and sky brightness. For stars fainter than approximately $m_I = 11$, the photometric accuracy is clearly sky limited. The increased errors in the brightest stars has been noted by other users of the image subtraction techniques, and is thought to be due to centering errors caused by atmospheric induced seeing fluctuations on scales comparable to the size of the bright stars’ PSFs.

A master list of stars for each frame is prepared, from the averaged reference image,
using the DAOPHOT FIND routine with detection thresholds determined by Poisson statistics, as outlined in appendix B of the DAOPHOT II manual. The fluxes, as measured from the subtracted images, of all of the stars in the master lists are searched for periodic signal using the Lomb Periodogram algorithm. This algorithm produces a probability statistic that the fluctuations of a given star are due to noise or periodic signal, and a list of the 10 most likely variables in each field is prepared so that these stars can be inspected visually. Fluxes are converted to magnitudes by choosing one star of known I band magnitude in each frame in order to set a frame zero point. The comparison star for each frame is chosen by searching the SIMBAD database (http://simbad.u-strasbg.fr/sim-fid.pl) for stars in each frame with known spectral type and magnitude. A set of stars including HD 281143, HD 281144, HD 281142 were used. This process does indeed introduce errors in the zero point magnitudes of all the stars, but in no way affects the differential photometry. Since it is change in flux, and not average flux, that is being studied here, these errors are considered acceptable.

5. Results

Observations totaling about 30 hours were carried out during the month of December, 2001. Data was taken under a variety of conditions, including partial cloud, since differential magnitudes are known to be relatively robust to poor observational conditions. Even during the best hours of atmospheric transparency and stability, the conditions were found to be relatively poor. Seeing, either local or intrinsic, and sky brightness combined to produce a limiting magnitude, at which expected photometric errors due to sky noise just exceed 10%, to approximately 15.5 in I-band. The poor conditions also caused occasional high amplitude scintillation affects that, when combined with residual mechanical guiding errors, caused jumps in the guide star centroid which were unrecoverable by the autoguider. As a result, approximately 10% of data image were smeared and not useful. These images were rejected by the astrometric fitting routines, but a second visual check was found to be helpful in identifying any remaining low level jumps in stellar centroids across frames resulting from guider failure. The total number of stars observed was approximately 3,000 over the five fields, with approximately 1000 of these stars being bright enough to have S/N such that photometric errors are < 10%. With a baseline of 30 days, and data sampled at a rate of 3 measurements per hour over portions of 10 separate nights, many types of variable stars may be detected when enough stars are measured with sufficient accuracy. Experience with ASAS has shown that the rate of short period eclipsing binaries is high enough that several may have been expected in the PVS fields. As a results of sky brightness and seeing, the data images are unfortunately not deep enough, or of high enough signal to noise, to
produce these results. With the data characteristics what they were, only one new variable star could be positively identified at the several sigma level. This new variable, previously designated $BD + 35.1114$, is a 9.5 magnitude O or B star in the constellation Auriga, with J2000 coordinates $05^h 28^m 09.6^s + 35^\circ 16' 56''$. The period is found to be 0.81d and the amplitude 0.34 mag. The phased light curve is shown in figure 5.

6. Conclusions

The design of a robotic photometric telescope, built out of commercially available and inexpensive components, is outlined. Results from one month of observations with the PVS instrument are presented, and it is demonstrated that the instrument produces high quality photometric results, even from a location with extremely bad atmospheric conditions. The discovery of a new short period variable star is presented. Though the system performs as well as could be expected given the atmospheric conditions at the Princeton, New Jersey, site, the full potential of the PVS design can not be determined until it is tested at a site with better conditions. A decrease in sky brightness by 1 magnitude, an improvement of mean seeing to 3”, and a higher percentage of clear nights would result in a tremendous increase in the number of variable stars that could be discovered by the PVS system. Many such sites exists, including ones, such as Mt.Wilson, within easy reach of major metropolitan areas of the American South West. The instrumental and computational techniques are developed and tested here so that a system at such a site could be efficiently and economically installed and operated.

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Fig. 1.— A histogram of the I band sky brightness from the PVS site in Princeton, NJ for the month of December, 2001. For comparison, the mean sky brightness, in mag/arcsecond$^2$, at CTIO is 19.9
Fig. 2.— A histogram of image FWHM at the PVS site in Princeton, NJ, for the month of December, 2001. Seeing is clearly quite bad, but the intrinsically poor atmospheric seeing is almost certainly compounded by local convection and guiding errors to produce these large PSFs.
Fig. 3.— The histogram of residuals from a single subtracted image normalized by the sum of the Poisson errors from the reference image and data image. Overplotted in a dashed line is the idealized result, a gaussian of variance 1 and mean 0. The variance of the subtracted image is shown to be approximately photon noise.
Fig. 4.— Typical errors in magnitudes for stars of a given I band magnitude. The errors are determined by calculating the ratio of the standard deviation of stellar flux to average stellar flux, for each star. The overplotted line represents errors that would be expected from the sum of the sky background Poisson errors in the reference and data image. Photometric errors are clearly sky limited for all but the brightest stars. The outlying point marked with a box is a bright variable star with light curve shown in figure 5.
Fig. 5.— The phased light curve of the newly discovered variable star BD+35 114. The period is found to be 0.81d with an I band amplitude of 0.34 magnitude. Errors in the magnitudes are approximately equal to the size of the data points.