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Development of a Three Channel Photometer for UPSO, Naini Tal

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Abstract. The design and performance of a portable three channel photometer installed at the Uttar Pradesh State Observatory (UPSO), NainiTal is described. The photometer is modular and the whole unit can be disassembled as individual channels such that the system can also be used as a single channel or two channel photometer. The system also has provision to monitor a guide star. The instrument was put into operation since November 1999 on the 1m Sampurnanand telescope at UPSO, Naini Tal. Since then, it is used extensively for the 'Survey of rapidly oscillating Ap (roAp) stars in the northern sky' from UPSO. Observational results using this new photometer in its initial phase of operation are discussed. The advantage of having continuous sky measurement is demonstrated.

Key words: Photometry-light curves-variable stars.

1. Introduction

Conventional photometers use a single channel to get the light curve of a program star. Variations in the observed light curve can be interpreted as variations in the star if the observations are made under ideal observing conditions. However in practice, even at some of the best sites, under normal observing conditions, the variations seen in the light curve of the star are often contaminated by the variations caused due to 1) thin clouds, transparency variations, changes in the sky background 2) telescope tracking problems 3) instrument related problems such as electronic noise, misalignment of components and mechanical flexure 4) human errors such as improper centering and guiding. Therefore, in order to detect and eliminate most of the above variations from the genuine variations in the light curve, a 2nd channel is added to the single channel photometer to simultaneously monitor a nearby field star. Genuine variations in the program star can be seen only in the 1st channel; any variations of terrestrial origin are included in both the channels. Thus, the two channel data enables distinguishing real and spurious variations in the time series data. If necessary, using the 2nd channel data, the 1st channel data can be corrected for cloud effects, transparency variations and extinction effects. It is also possible to make a good estimation of the extinction coefficient from the 2nd channel data for that night instead of using an average extinction coefficient. Thus, the addition of another channel to the single channel photometer results in a two-star photometer one of which we have developed (Venkata Rao *et al.* 1990) and have been using on telescopes at Vainu Bappu Observatory (VBO), Kavalur and UPSO, Naini Tal since 1988.

In a two star photometer, whenever sky measurements are needed, the stars have to be moved out of the diaphragm for a small interval of time in both the channels. This process has to be repeated several times during a night. This results in data breaks depending on the frequency and the length of the sky measurements needed. Such breaks in the data are in addition to those caused by inclement weather. The breaks in the data due to the above mentioned problems can cause aliases when we compute the discrete Fourier transform (DFT) of the data to search for periods. Also, in the two star photometer, the sky background is computed by interpolating the sky measurements made at different intervals assuming that the sky variations are always smooth. However, in practice, the sky background can abruptly vary due to changes in local conditions. A more serious problem arises during the times when the moon rises or sets. During this period the background varies nonlinearly making sky interpolation impossible. Even on dark nights, the sky background can vary non-uniformly from zenith to horizon. Sometimes zodiacal light can also cause considerable sky background variations. Therefore, it is clear that interpolating a few sky points in space and time to determine the sky background for the full night is inadequate. A solution is to have a 3rd channel attached to the two-star photometer to measure the sky background simultaneously. Thus, as a necessity, two star + sky, generally named as three channel photometers have evolved. In a three-channel photometer, sky measurements in all three channels are made only once at the beginning of the run and once more at the end if possible and rest of the time the sky is continuously recorded only in ch3. Using these sky measurements, the sky ratio of ch1/ch3 and ch2/ch3 is determined and using this ratio, the sky value at every point in the 1st and 2nd channel is determined using the corresponding 3rd channel sky data. Because the sky estimations are made for every data point, continuous sky variations are accounted for. Since the main channel data is not broken for sky measurements in between, we get continuous data on the program star. Using the three channel data, it is also possible to estimate, on each night, the limits of the scintillation noise and sky transparency noise which ultimately sets the limit on the range of frequencies which can be detected with a particular telescope at an observing site (Ashoka *et al.*2000).

Thus, in order to get reliable, continuous time- series data even under moderate sky conditions, a three-channel photometer is necessary. We have designed and developed a prototype three channel photometer in-house that is currently being used at UPSO, Naini Tal and VBO, Kavalur, for the study of intermediate polars, pulsating white dwarfs and other rapid variables.

Recently, we have been involved in a program titled 'NainiTal-Cape Survey for pulsating chemically peculiar stars' with UPSO, Naini Tal and South African Astronomical Observatory/University of Cape Town, S. Africa. The survey involves extensive photometric observations and hence a dedicated three-channel photometer was necessary at UPSO, Naini Tal. Using funds from the Department of Science and Technology (DST) to UPSO, we have built a three channel photometer at Technical Physics Division, ISRO Satellite Center, Bangalore jointly with UPSO.

2. Design considerations

The points discussed below are some of the important criteria which have gone into the design of our present three channel photometer. The photometer is designed to suit our scientific objectives and other logistical requirements. The instrument is designed primarily for use at the Cassegrain focus of the 1m telescope at UPSO, Naini Tal. It can also be used on other similar telescopes. The focal ratio of the telescope at Naini Tal is f/13 with maximum available backfocal length of 300mm. Therefore, the size of the photometer is optimised to suit these numbers.

The program star is always observed through the 1st channel (main channel). Unlike the 2nd and 3rd channels, the 1st channel is designed with minimum transmitting optics and without any reflecting optics in order to minimize light loss from the program star. Even the Fabry lens is made thin and planoconvex and fabricated using BK-7 material for best transmission. The 2nd channel is made identical to the 1st channel except for an additional reflection using a prism to pickup a star in the 2nd channel. The 1st and the 2nd channel photometers therefore, can be interchanged if necessary.

The photomultiplier tube (PMT) is placed inside a housing which contains a Fabry and a shutter. Identical PMT housings with PMTs are made for all the three channels. Therefore, the PMT housings can be interchanged among the channels if necessary, and out of the three, the best (high gain, low noise) PMT is used in the 1st channel, the next best in the 3rd channel.

A suitable field star has to be always picked up in the 2nd channel without moving the telescope but by moving only the 2nd channel X-Y table within the photometer. Therefore, provision for scanning a large area (15×10)sq. arc min is provided in the 2nd channel so that stars are always available in any field to be picked up in the 2nd channel. Hence, even in rarified fields, stars can be picked up in the 2nd channel.

During observations, the stars have to be guided such that they stay within the diaphragm throughout the observations. If the tracking of the telescope is good, minimum guiding is sufficient. Generally, the offset guiding is done manually on the guide telescope using either a high power eyepiece or an autoguider. Since we need to guide on the same star throughout the night, the flexures between the main and the guide telescope result in slow drift of the stars in the diaphragm. Perfect guiding is possible only if the guiding is done on a star in the main telescope. Provision is made on top of the photometer to pickup some arbitrary star in the field of view of the main telescope without disturbing the stars in other channels. Therefore, a guiding unit is attached to the photometer. In the guiding unit provision is made to scan large (50 × 50) sq. arc min to pick up any suitable bright star. The guiding is done using either a video CCD camera or a commercially available guiding CCD camera.

The photometer is designed to use Hamamatsu R647-04 photomultiplier tubes (PMTs) of half an inch diameter. They are blue sensitive tubes with quantum efficiency (QE) ~ 30% and do not need any cooling since the dark counts are only ~ 20 cps at room temperature. The tube response range (300–700 nm) and the region of the highest QE (400 nm) are optimal for observing blue stars such as A type stars, cataclysmic variables and white dwarfs. The usage of these tubes enabled us to make the unit compact and light weight.

All the three channels are made similar by using identical PMTs, filters and amplifier/discriminator. All electronics are powered by a single power supply and all PMTs are powered by the same high voltage (HV) source so that any electronics related variations should be reflected in all the three channels.

Since the optical observatories in India are situated throughout the country, a light weight, modular design is emphasised for transportation ease. All the three channels can be detached during transportation to fit in a suitcase and assembled easily at the telescope. The total weight of the photometer is ~15 kgs. The entire photometer can be carried as a check-in baggage in an aircraft.

3. Description of the instrument

The three-channel photometer in the lab before shipment to UPSO is as shown in Fig. 1 (The circular plate at the bottom is attached to the telescope/guiding unit at the observatory). The schematic diagram is shown in Fig. 2. We discuss below, the different parts of the present photometer. As in the case of any conventional photometer, a wide angle eyepiece of 2 inch size and 32 mm focal length is used to identify the star fields, center the program star and select the star for the 2nd channel. The eyepiece can cover a field of 8 arc min at the focal plane of the 1m UPSO telescope. The 1st channel photometer is attached below the wide angle unit. The photometer has all the parts of a conventional single channel photometer such as a diaphragm plate, a microscope to view the star within the diaphragm and a filter wheel. An easily detachable type of a photomultiplier housing is attached to the photometer which consists of a shutter, a Fabry lens and a PMT with wired base. At the end of the housing, there are two connectors; one for the High Voltage (HV) input and the other for the signal output. The 2nd channel has got all the components as in the 1st channel with the addition of a pick-up prism before the diaphragm. The entire 2nd channel photometer is mounted on an X-Y table. The 2-

D motion of the photometer is used to pick up a star for the 2nd channel in the same field other than the program star. The movement of the 2nd channel is such that 15 × 10 sq. arc min area can be scanned to pick up a suitable star. The 2nd channel is mounted perpendicular to the 1st channel as shown in the figure. There is a dead region of 75 arc sec from the 1st channel where stars cannot be picked up in the 2nd channel. This is purposely introduced to avoid obscuration of the 1st channel star beam by the 2nd channel pick-up prism. The 3rd channel is a fixed channel which is used only for the sky background measurement. Similar to the 2nd channel, the 3rd channel also has a pick-up prism. To make the design simple unlike in the 1st and 2nd channel, the 3rd channel has a fixed diaphragm and provision for one filter. Since the sky variations are non gray, most of the time the sky measurements are made without a filter. The 3rd channel is also mounted perpendicular to the first channel and diametrically opposite to the 2nd channel. This channel measures the sky region close to the 1st channel at a distance of 90 arc sec. from the 1st channel star.

The 1st channel has three diaphragms of size 15, 23.5 and 30 arc sec. The 2nd channel has the same number of diaphragms but their sizes are 10% less than the corresponding ones in the 1st channel. This is done so that while guiding, any drift of the stars within the diaphragm can be detected first in the 2nd channel so that the telescope is guided in time such that no drift occurs in the 1st channel. The filter wheel consists of four holes in which three holes are fitted with Johnson UBV filters and one is left blank for observations without a filter. A neutral density filter can be used in the blank hole while observing very bright stars. The PMT housing has a Fabry lens whose focal length is 65mm such that at f/13 focus, it produces an image of 5mm in size on the 10 mm photocathode of the PMT. The 3rd channel has a fixed diaphragm (15 arc sec) and provision for one filter only since this channel is always used only for sky measurements. All the three PMT housings are made alike so that they can be interchanged among the three channels. The 1st and 2nd channel photometers are made modular so that they can be moved independently to get them focused on the stars.

4. Detector, instrumentation and data storage

The detector and the other electronics which are used here are similar to the Whole Earth Telescope (WET) standard photometer (Kleinman *et al.* 1995).

The detector is used in photon counting mode. We are interested in the intensity measurement of the star which is proportional to the number of photons detected. Photons striking the photocathode will produce pulses and the intensity of the source is determined by pulse counting. The detector is a Hamamatsu R647-04 PMT made for photon counting applications at low light levels. The tube is blue sensitive with S-11 response. The photocathode has a size of 10 mm and is made of bialkali material. It is an end window tube with anti magnetic shield coating on the outer glass. The tube has a gain of 2.2 x 10^6. The quantum efficiency is 30%

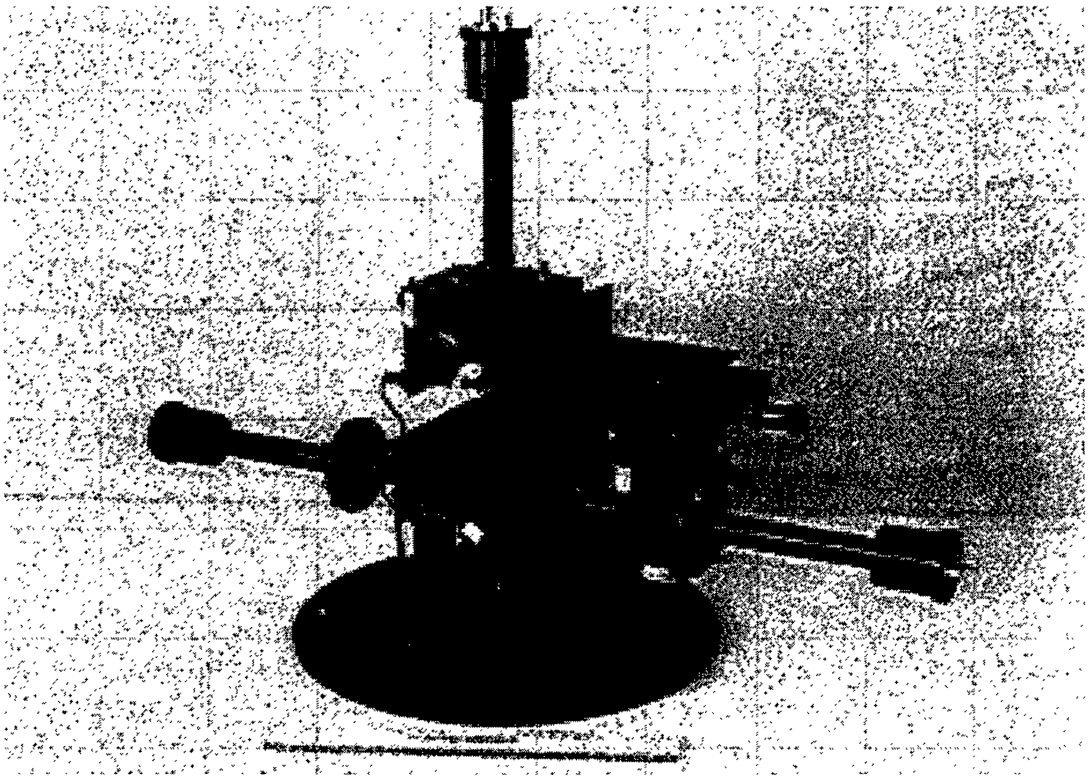

Figure 1. Three Channel Photometer.

around 400 nm. The operating HV is 1000V DC. Positive high voltage is used so that the cathode will be at ground potential and the magnetic shield is also kept at ground potential which reduces the noise. All the three PMTs are powered by single modular HV unit C4710-51 from Hamamatsu. It has an HV output adjustable in the range 200–1500V with maximum current of 0.1mA. It has a ripple of 0.005% (p-p) at maximum rating and voltage stability of 0.01% for 1V change in the input voltage. The output of the PMT goes to the amplifier/discriminator (PAD) EG&G PARC 1182 . The PAD amplifies the pulses coming from the PMT, discriminates the photon pulses from the dark noise pulses using a lower level threshold and then shapes the pulses suitable for counting. The pulse pair resolution is 20ns. The output is TTL pulse of width 10–75 nano secs. The PAD is well shielded and is free from EMI pickups. The output of the PAD is fed to an interface card. The present one we are using is CCLA three-channel interface card modified and marketed by the Vilnius team at Lithuania for all the WET participants as per the WET specified standards (Kalytis *et al.* 1995). The interface card is designed to operate as a computer interface to the photometer. It has timing circuits to ensure an accurate clock and integration times. The hardware of the card consists of a micro controller, counters, oscillator and EPROM. The interface card communicates with PC through a serial port.

The software which communicates between the PC and the interface card is the data acquisition software "Quilt-9" developed by the Texas group for the WET

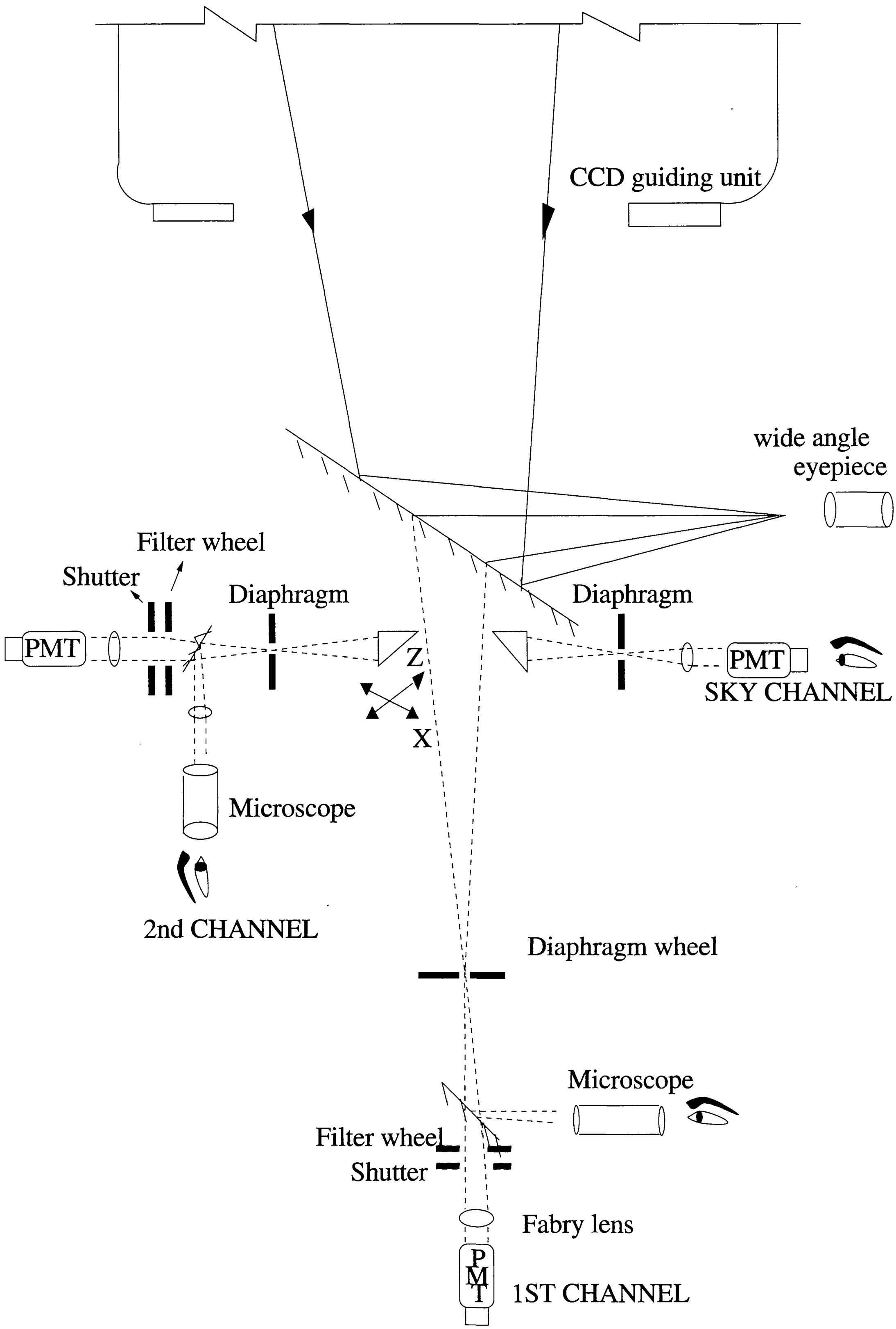

Figure 2. Schematic diagram of the three channel photometer.

program and distributed to all the "WET" participants (Nather *et al.* 1990). The software along with the interface card can acquire the data simultaneously from three channels. The software has provision for real time display of the data and its storage on hard disk and floppy. The data are stored as an ASCII file which contains header information and data. The header information includes relevant details such as the file name, name of the object, date of observation, start time of the run, integration time, filter used and the observatory name. After this the data follows. The data file can directly be read for further analysis.

A compact power supply unit is built to power the high voltage module, amplifier–discriminators, interface card and diaphragm illuminating lights. The power supply along with the interface card, HV unit, amp/disc. are mounted along with the photometer.

5. Calibration of the photometer

After assembling the photometer the following checks and measurements were made on it by attaching it to the telescope.

5.1 *Focusing of the three channels*

The instrument is designed such that when a star is focused in the diaphragm of the 1st channel, it will be almost focused at the diaphragm of the 2nd channel, diaphragm of the 3rd channel and at the wide angle eyepiece. Due to small mechanical errors, the focusing need not be perfect. Therefore, the 1st channel photometer is independently moved such that the star is focused perfectly in the 1st channel. Focusing in the wide angle eyepiece is made by moving the wide angle eyepiece itself. Focusing in the 3rd channel is nearly perfect and here the focus is not so critical since it measures only the sky. When the guiding unit is attached, the guide star is exactly focused on the detector plane of the guiding camera.

5.2 *Knife edge test*

The so called "knife edge test" is a method to ensure perfect focusing of the stars in the respective diaphragms of the photometer so that the beam width will be minimum at the diaphragm. Therefore, the star within the diaphragm could drift till the edge without the light being cut. The focussing is done as follows. The microscope eyepiece from the eyepiece holder is removed and a star image is put in the diaphragm such that part of the image is cut by the diaphragm edge. On changing the telescope focus, when the star is exactly focused at the diaphragm, the edge of the diaphragm shines like a knife edge. If the focus is before or after the diaphragm, this will not happen. Thus, the best focus is determined. After this, the eyepiece is replaced and focused on the star. This test has to be conducted once at the beginning of the observing run or whenever the telescope focus is changed. This test may not be needed in ch3 because it measures only the sky.

5.3 *High voltage setting*

As the high voltage is changed the gain of the PMT also changes. Generally the high voltage is fixed at the plateau region of the gain versus high voltage curve. The more effective way is to select the high voltage within the plateau region where the signal to noise is also maximum. This is done as follows. First only the dark signal at different high voltage values are measured. Next, the diaphragm is illuminated with a steady light source and the signal is measured at various voltages. The voltage in the plateau where the S/N is maximum is taken as the optimum high voltage for that tube. For the tube R647-04, the high voltage is thus fixed at 990V. Thus the high voltage is fixed at 990V. Since we are using similar tubes in 2nd and 3rd channel and the same HV unit has to be used for powering all the three channels, we fixed optimum value of HV as 990V for all the channels.

5.4 *Fabry check*

Fabry lens is used before the PMT to image the telescope primary mirror on the photocathode of the PMT. Since the Fabry focal length is much smaller compared to the telescope focal length, the drift of star due to improper tracking of the telescope will produce negligibly small drift on the photocathode. Fabry check is a method to check the optical alignment of Fabry lens and the PMT. Due to the presence of the Fabry even if the star drifts in the diaphragm from one end to the other, there should be no variations in the light curve. If there is some misalignment of Fabry lens, or any other obscuration in the path of the light or dust or finger prints on Fabry or on the filter, their presence can be seen as a variation in the output signal when the star is put at different places within the diaphragm. Such variations can be mistaken for actual star light variations and produce spurious results. Even in a best telescope it is practically impossible to make the tracking so perfect as to avoid trailing of the star within the diaphragm. Therefore, Fabry lens is made to image the primary mirror to half the area of the photocathode. Next, the Fabry should be perfectly aligned to the PMT. In order to check the perfectness, we conduct a test on the telescope using a star in the 1st channel. First, the star is moved across the diaphragm in one direction (in right ascension) from one end to the other with a very slow speed available on the telescope. During this, the star signal is recorded at a fast integration time of about 200ms. Next, this process is repeated in the perpendicular direction (declination). Each time the resulting light curve should produce a square wave pattern indicating that the star any where within the diaphragm will produce the same signal and the alignment is perfect at the diaphragm. Fabry check is the ultimate test for the perfect optical and mechanical alignment of all the components in the photometer.

5.5 *Dead time correction*

Since the experiment is basically a photon counting system, the brightness of the star is proportional to the number of photons detected. Due to their random arrival, all the photons reaching the detector may not be counted if the count rate is high, resulting in dead time loss. This problem is obvious when bright stars are observed. Therefore, we have to estimate the dead time loss due to the overall system and correct for the loss. The dead time correction is determined by the aperture method (Clemens.J.C, private communications) as follows. Two apertures one small and another large are selected. Let S_1 and L_1 be the counts measured for a certain illumination in small and large apertures respectively. Let S_2 and L_2 be the respective measured counts for an increased illumination. From the four counting rates,

$$a = S_2 \times L_1, b = S_1 \times L_2, c = S_1 + L_2, d = S_2 + L_1$$

then the dead time is computed as (a-b)/(ac-bd). Using this method, the estimated dead time for the present system is 23 nano seconds.

5.6 *Selection of apertures*

Apertures in general are selected based on the telescope and observing conditions. As in the case of a single channel photometer, the 1st channel aperture is selected based on the telescope performance, sky brightness and the required S/N based on the brightness of the star. The aperture size should be such that star should not drift within a consecutive guiding interval. Otherwise frequent guiding will be required. In general, one prefers to use smallest aperture to reduce the background. However, if the star is bright, a bigger aperture is selected to allow the entire seeing disk to be well within the aperture. In a three star photometer, the 1st channel aperture is selected based on the above criteria. The 2nd channel aperture as a thumb rule, is kept 10% smaller than the corresponding 1st channel. The 3rd channel being a sky channel, its diaphragm size is kept same as the 1st channel.

The Fabry check and focusing checks have to be made every time before starting an observing run. The high voltage setting once made should remain unchanged.

6. Performance of the instrument

The photometer is installed on the 1m telescope at UPSO Naini Tal The photometer was used for the first time in three channel mode during a WET international campaign on a pulsating DAV white dwarf star HL Tau 76 (m_V=15.2) in November 1999. Excellent light curves from all the three channels were obtained. A sample light curve of one full night observation is shown in Fig. 3. The 1st channel light curve shows periodic variations of HL Tau 76. The dominant periods around 600s can be seen visually from the light curve of the star. A field star of comparable brightness to the program star is observed in the 2nd channel. The 2nd channel shows no other variations except for the extinction + sky variations which indicates that the variations seen in the 1st channel are real. The sky background is measured in the 3rd channel. We can notice from the figure that the sky variation is

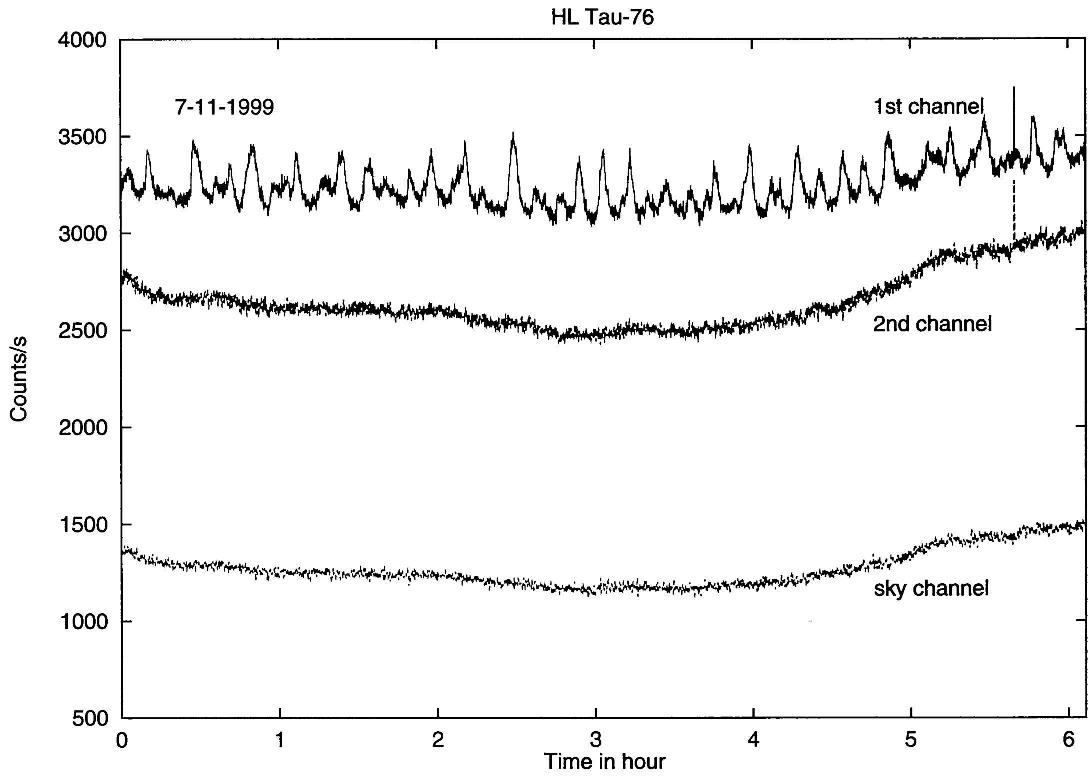

Figure 3. Three channel data on HL Tau 76.

not smooth throughout the night. In Fig. 4, the advantage of having continuous sky points instead of discrete sky measurements is demonstrated. The top panel in Fig. 4 shows the sky subtracted light curve of HL tau 76 with its DFT using the continuous sky background. The bottom panel in Fig. 4 shows the sky subtracted light curve and its DFT of the same data if we use only few sky points instead of continuous ch3 data. On comparing the two panels in Fig. 4, we can notice that the discrete sky points can introduce a long period trend in the light curve and thus few low frequency components in the DFT (bottom panel) which is not seen in the top panel. Therefore, it is clear that a continuous sky measurement is necessary whenever observations are made throughout the night. Thus, three channel photometer is a necessity for time series photometric studies.

The instrument is now continuously in use at UPSO, Naini Tal for a recently initiated program titled ‘Naini Tal-Cape Survey for pulsating chemically peculiar stars’. The survey involves observing more than 300 potential stars in the northern hemisphere to discover new rapidly oscillating Ap stars and study them in detail. The survey was initiated on a trial basis in 1997. The program is taken up on a regular basis after having a three star photometer at the observatory. Since the survey involves observing many stars, initially each star is observed only for a duration of 1–2 hrs. Also, since these stars are bright (m_V=6-10), it is difficult to get an equally bright star for the 2nd channel. Therefore, the initial survey is

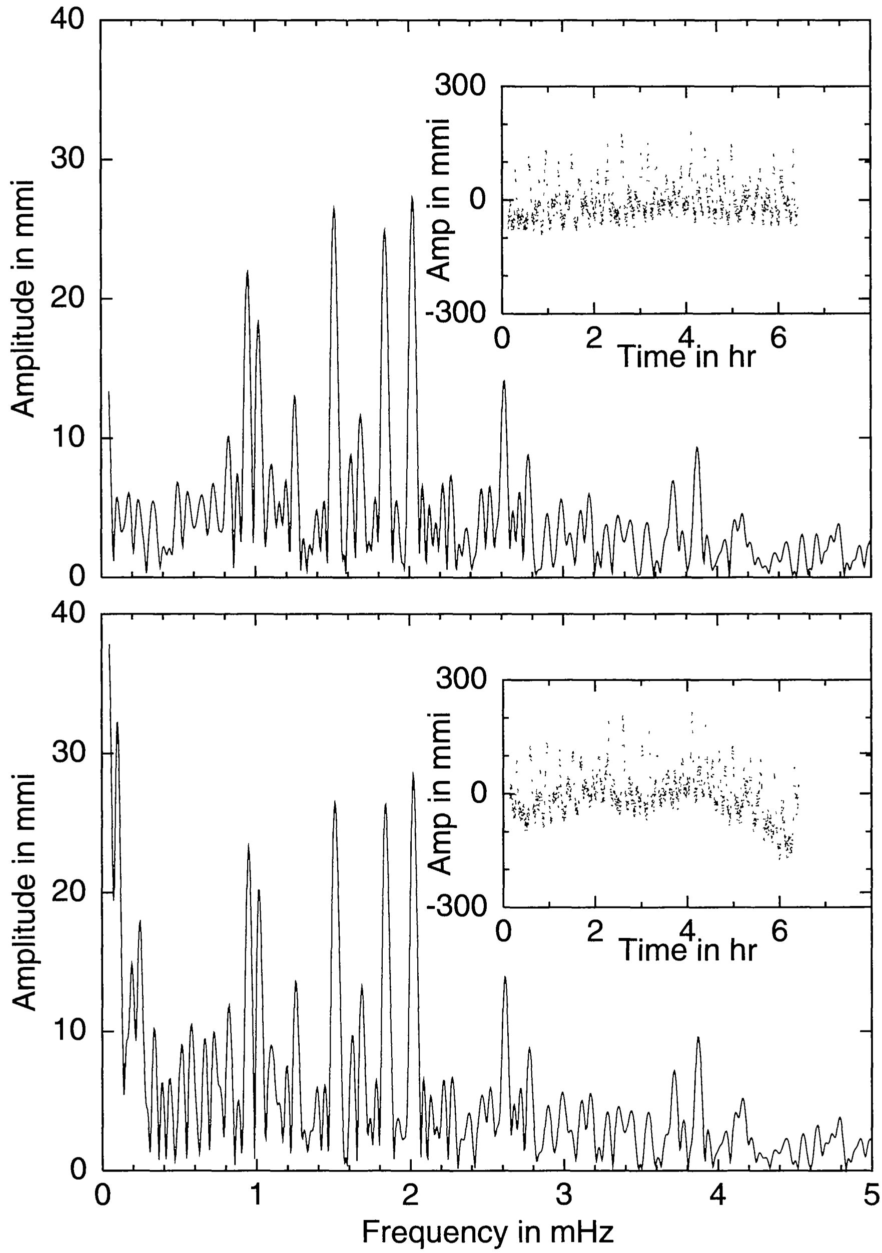

Figure 4. Amplitude spectrum of HL Tau 76.

made using a single channel mode. For a detailed study, the discovered variables are observed in three channel mode for long durations. The initial efforts resulted in the discovery of rapid oscillations in an Ap star HD12098. The initial analysis of the data indicated the presence of an oscillation at 7.61 min. with amplitude 1.5 mmag (Martinez *et al.* 2000) The light curve and its DFT are shown in Fig. 5 (top).

The survey also resulted in the discovery of a new delta Scuti star HD98851. Periods are detected at 79.4 min and 167 min (Joshi *et al.* 2000). The complex

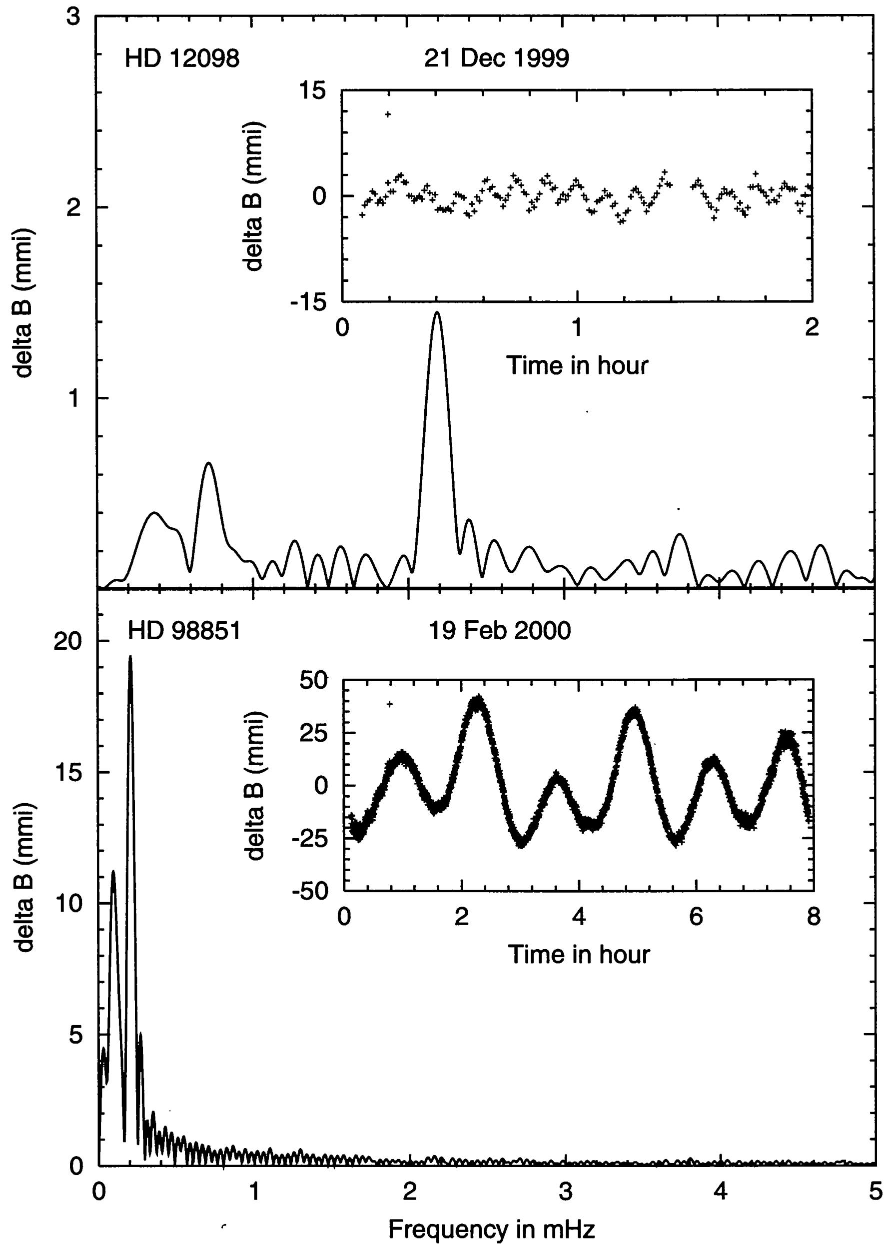

Figure 5. Fourier transform of the two variables HD 12098 (top) and HD 98851 (bottom). The respective light curves are shown in the inset.

light curve indicates the presence of multiple periods in this system. A sample light curve and its DFT is shown in Fig. 5 (bottom).

All the above results indicate the optimal functioning of the instrument during its operational phase.

7. Conclusion

The simultaneous monitoring of the program star, a field star and the sky background is essential to ascertain genuine variability during time series photometric studies. An instrument of this kind is also useful for the photometric study of the variables during a non photometric night where the variability can be retrieved from the 1st channel data using 2nd channel and 3rd channel data. Since the three channel photometer monitors the sky background continuously, the sky estimations could be made accurately even during moon-lit nights, dawn/dusk maximizing the utilization of telescope time. With this objective a 3 channel photometer was jointly built by the ISAC and the UPSO team. It has undergone all calibrations and its performance is excellent. It is at present being used at the 1meter telescope at UPSO Naini Tal.

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