Chapter 4

The Acquisition and Guidance (A&G) System

The acquisition and guidance (A&G) system of an astronomical telescope essentially, serves two purposes. Firstly, it allows pointing of the telescope with sufficient accuracy so that the target of observation can be acquired without much time overhead. Secondly, it ensures that the telescope tracks the movement of the object across the sky with sufficient accuracy so that long exposures may be taken. The accuracy required in both these operations is determined by the particular application involved like imaging, spectroscopy, polarimetry etc.

The need for an A&G system for the imaging polarimeter has been emphasized in various contexts (see Sec. 2.1, Sec. 3.1.3, Sec. 5.1 etc.) in this thesis. This chapter discusses the design and implementation of such a system developed for the instrument. Though the particular application discussed is the imaging polarimeter, the device has the flexibility to cater to a wide range of applications, either as a part of the telescope control or built into a variety of back-end instruments. An added attraction of the device is that it is relatively inexpensive, being made of only standard optical and electronic components.

4.1 Design guidelines

Over the decades of the history of astronomical observations, several schemes have been devised to implement acquisition and guidance systems for telescopes. In the following discussion, we briefly consider the relative merits of three general approaches in vogue, at present. In section 4.1.2, we specify the performance accuracy for the A&G system demanded for its application to IMPOL.

4.1.1 Techniques for A&G systems

The earliest A&G systems used a smaller telescope, called the guide telescope, attached to the main one, for pointing and guiding. The guide telescope has a wider field of view, thus making it easier to locate the target or a suitable offset field for pointing the telescope. Tracking also may be done using the image in the guide telescope. The main limitation of such a scheme is its limited sensitivity due to the relatively smaller size of the guide telescope. Besides, relative flexures between the guide and the main telescopes also set limits to the tracking accuracy that can be achieved. An alternative is to devise a scheme, say, using partially transmitting mirrors or beam-splitters, in which the image formed by the main telescope itself is used for tracking. A difficulty with this scheme is that the objects which demand long exposures and good tracking are the faint and often extended targets. Good tracking accuracy, on the other hand, demands bright, isolated, point sources as the guide targets.

An off-axis A&G system, on the other hand, does not use the target of observation for pointing and guiding; instead a nearby, point source within the field of view of the main telescope itself is identified and used for the purpose. Thus, while the instrument collects light from the target of observation, an off-axis optics assembly collects light from a nearby guide star for tracking. This eliminates the problem due to differential flexure between the main and the guide telescope, while at the same time, the large collecting area of the main telescope allows fainter stars to be used for pointing and guiding.

4.1.2 Performance demands

(i) For the polarimeter, we need an acquisition system capable of bringing the telescope to bearing with an accuracy of 2-3 arcsec. assuming that the telescope on its own has a pointing accuracy of only about an arcminute. (ii) Often the targets of interest for polarimetry are at high Galactic latitudes and hence the A&G system should be sensitive enough to find stars in any part of the sky. (iii) If the guide stars are too far from the main field, difference in atmospheric refraction for the guide star and the main object can cause drift in the position of the image on the CCD surface. Therefore, we need a guidance scheme which can use stars within about a quarter of a degree of the main field.

(iv) A typical observation sequence consists of exposures taken at four positions of the half-wave plate, a few times repeatedly and the image position on the CCD has to remain fixed during the entire sequence. Since the image scale on the CCD is about one arcsec per pixel, we need the guiding to be accurate to within a fraction of an arcsecond. Also, it is necessary to have provision to rotate the half-wave plate without having to interrupt the tracking process. This requirement has to be met under the constraint that it is the same PC which controls both the tracking process and the motion of the half-wave plate.

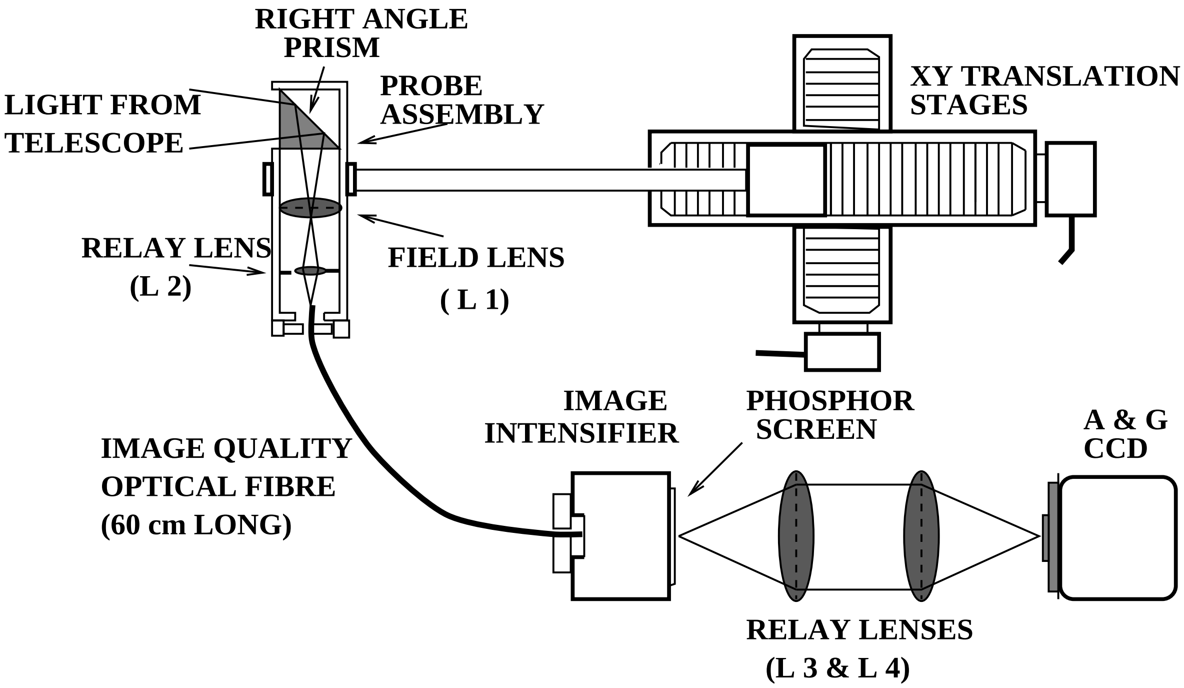

Figure 4.1: Block schematic of the acquisition and guidance system used in IMPOL.

4.2 Implementation of the A&G system

Fig. 4.1 shows the block schematic of an off-axis A&G system which has been designed with the above considerations in mind. The device has three parts, namely, the probe assembly, the XY linear translational stages, and the optics assembly consisting of the intensifier, the lenses (L3 and L4) and the CCD camera. Light collected by the probe assembly from the telescope is conveyed to the optics assembly through an image quality optical fibre bundle. The probe assembly is attached to the XY translational stage with an arm so that it can be positioned anywhere within a 40×100 mm^2 area, at the focal plane of the telescope, close to the main field of the instrument.

The probe assembly consists of a right-angle prism, a field lens (L1) and a relay lens (L2). The positioning of the assembly is such that the prism turns light from the telescope and brings the focus close to the field lens. The relay lens is at the focal plane of the field lens and it reimages the telescope focal plane onto the tip of the optical fibre. The other end of the optical fibre is coupled to the photocathode of the image intensifier. The phosphor screen of the image intensifier is imaged on to the CCD surface using two lenses, L3 and L4. The probe assembly is arranged in such a way that when the telescope focal plane coincides with the grid surface of the main field, the guide field will be in focus at the CCD surface of the A&G system.

Along with every polarimetric observation target, at least one guide star is identified, the image of which is formed by the telescope, within the scan area that can be covered by the probe. The right ascension and declination coordinates of the centre of the observation target as well as the guide star is given to the control computer, which

Table 4.1: Optical components used in the A&G system

Component	Source	Part number	Description
Lenses L1	Edmund Scientific		eff. FL 25 mm, f/2.0
L2			eff. FL 6 mm, f/2.0
Optical fibre	Dolan Jenner	ISO 636	6x6 mm, coherent glass fibre, 36 inch long, N.A. 0.66
Image intensifier	Philips	XX1500	14 mm dia., 36 lp/mm
Lenses L3 & L4	Nikon		eff. FL 50 mm, f/1.2

in turn calculates the corresponding offset needed for the probe, relative to the centre of the main field, and positions it accordingly. In order to acquire the target in the main field, it is sufficient to ensure that the guide star is centred in the field of view of the A&G system. Once the target is acquired, tracking is activated, which involves taking an exposure of the guide field, determining the shift in the centroid of the guide star image with respect to the centre of the field and generating signals which correct the telescope pointing so as to bring the guide star image to the centre of the field. The control computer repeats the above sequence of operations every three seconds or so, until the tracking is stopped.

Table 4.1 gives a list of the optical components which have been used in the A&G system and some information related to each of them. The prism faces are 12×12 mm, square while the field lens has a diameter of 12.5 mm and a focal length of 25 mm. Together, these give an unvignetted field of view of about 10 mm diameter at the telescope focus. The relay lens is just 3 mm in diameter with a focal length of 6 mm. The fibre bundle is made of 80 μm fibres, has a numerical aperture of 0.66 and has a square cross-section of about 6×6 mm^2. The image intensifier photocathode has an active area of 17.5 mm. Two fast Nikkon lenses (50 mm,f/1.2) are used to collect light from the phosphor screen of the image intensifier and their arrangement is such that the image scale is not changed. The array detector is the ST-6 CCD camera system from Santa Barbara Instrument Group which has a thermoelectrically cooled CCD with 375$\times$242 array of 23 $\mu m \times 27$ μm pixels.

4.3 Assembling and Testing

Considering the fact that a good tracking system is indispensable for imaging polarimetry, the development of the A&G system was undertaken as an integral part of the instrument, hardware wise as well as software wise. The actual arrangement of the XY translational stages and the probe assembly are shown in the cross-sectional view of the front end of IMPOL given in Fig. 4.2. The Cassegrain mounting plate of

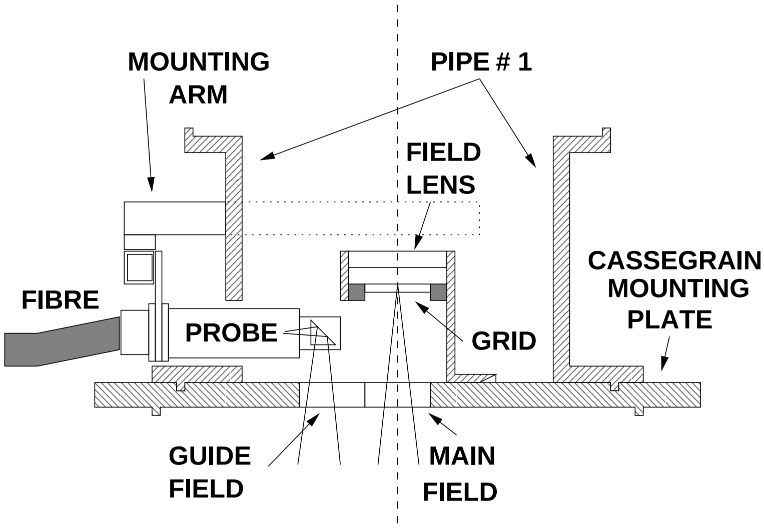

Figure 4.2: Cross-sectional view of the front end of IMPOL, showing the arrangement of the XY translational stage and the probe assembly relative to the main field of the instrument.

the instrument, described in Sec. 2.4, has an extension on which the XY translational stages are mounted. A large opening at the side of the main pipe (150 mm×38 mm), close to the Cassegrain plate, allows the probe to enter the pipe and cover a scan area of 40 mm×100 mm just adjacent to the main field. In the view shown in Fig. 4.2, the probe can move 40 mm in the plane of the page and 100 mm in or out of the plane (see also Fig. 2.9). The optics assembly which consists of the image intensifier, lenses L3 and L4 and the CCD camera head forms a single unit, which is clamped to one of the flanges of the main pipe.

The next three subsections describe the important considerations while assembling the A&G unit and incorporating it as part of the imaging polarimeter.

4.3.1 Opto-mechanical hardware

One of the requirements while assembling the optical elements within the probe is to ensure that, when the target of observation comes to focus at the correct grid surface, the guide field should be in focus at the fibre tip within the probe. This is accomplished in the laboratory with the setup shown in Fig. 4.3. The instrument along with the XY translational stages carrying the probe, is mounted on the test setup in the laboratory optical bench. A pinhole is imaged on the grid surface so that it is focussed on the main CCD surface. Then the probe assembly is moved using the XY translational stage so that the pinhole comes into its field of view. Now the position of lens L2 within the probe is adjusted so that the pinhole is reimaged properly on the fibre tip within the probe. This is verified by checking the FWHM of the image at the other end of the fibre through a suitable magnifying arrangement with a reticle scale. Once focusing is done, L2 is fixed at the position by locking screws.

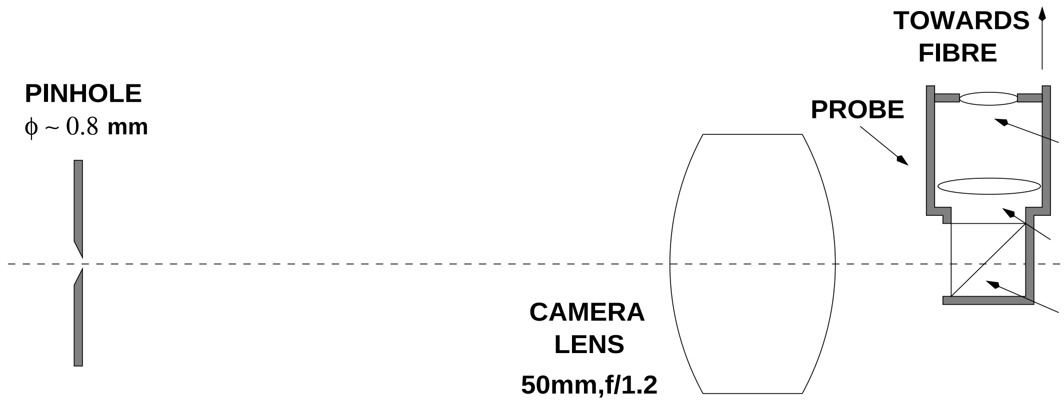

Figure 4.3: The setup used to determine the focal scale reduction of the probe assembly optics.

All the required image scale reduction is achieved in the optics of the guide probe. The optical magnification of this assembly also may be determined by the above setup. When the pinhole (0.8 mm) image is focussed properly on the main CCD at the beginning of the above experiment, a note is made of the image size. After moving the probe in, so that the pinhole comes into its field of view, the image size at the end of the fibre tip is again measured. By a comparison of these two, the gain of the probe optics was determined to be about 0.36.

The other end of the fibre is pressed against the photocathode of the image intensifier by a spring-loaded mechanism. In order to ensure proper coupling of light from the fibre tip to the image intensifier, a thin layer of oil is spread on the fibre tip, before it is pressed against the photocathode. This is a one-time operation, carefully carried out in the laboratory and once accomplished, the fibre is left attached to the image intensifier. Proper mechanical support is provided to the fibre, as part of the coupling mechanism, so as to avoid mechanical stresses due to bending of fibre, tension under gravity etc.

Lenses L3 and L4 are identical; their back-focal length is determined in the laboratory and they are mounted within a pipe so that the output of the image intensifier is coupled to the ST-6 CCD without any change in the image scale. As shown in Fig. 4.4, the mount carrying the image intensifier is attached to a flange at one end of the pipe and the ST-6 CCD camera head to one at the other end. Provision is also made to fine adjust the focus setting of the lenses. The image intensifier–CCD assembly along with the lenses L3 and L4 make a single mechanical unit (see Fig. 4.4).

From the point of view of easiness of executing the acquisition and guidance operation, as well as implementing the tracker software, it is advantageous to arrange things in such a way that any motion of the telescope along one of its axes will result in the motion of images along the rows/columns on the ST-6 CCD. This requirement may be satisfied in two steps – firstly, by ensuring in the laboratory that there is one to one correspondence between the instrument axes and the rows/columns of the ST-6 CCD and secondly by ensuring that the instrument axes are aligned with the telescope axes

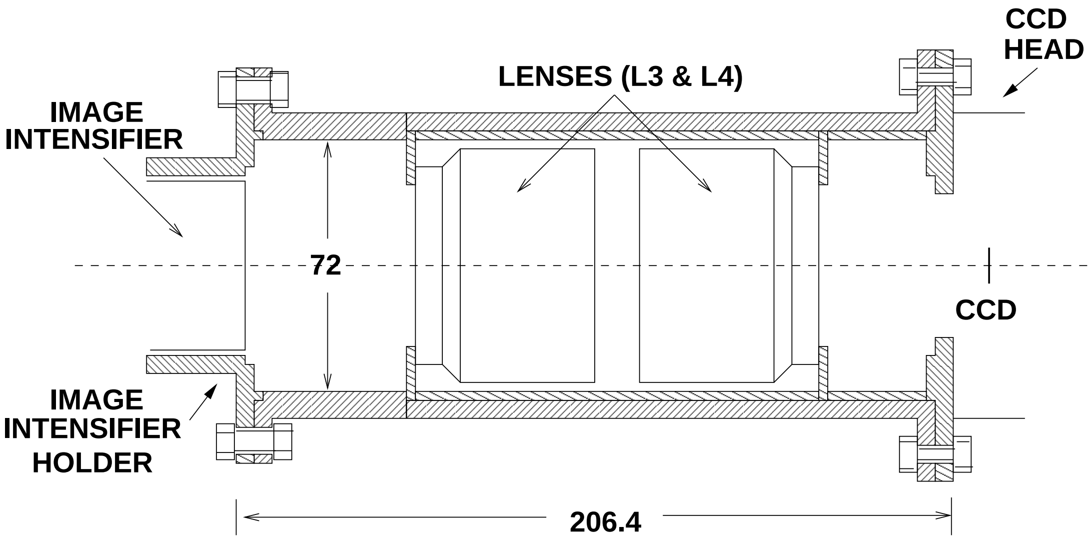

Figure 4.4: The mount for the optics assembly consisting of the image intensifier, the lenses and the CCD camera head.

when the instrument is mounted. The first step can be easily done in the laboratory by moving a pinhole source along one of the instrument axes and rotating the fibre tip within the probe until the motion of the pinhole image is along the rows/columns of the ST-6 CCD. Once the correct orientation of the fibre tip is determined, alignment markers are made so that the fibre may be inserted at the correct orientation subsequently. Markers are also provided on the Cassegrain mounting plate of the instrument, which indicates the required alignment, while mounting, of the instrument axes with respect to the telescope axes.

4.3.2 Electronics

The ST-6 CCD camera system, essentially has two parts, the camera head and the controller. The camera head, which is part of the optics assembly, contains the CCD detector mounted on a peltier device for cooling, an electromechanical vane and some electronics which control the exposure and image-acquisition - these are contained in a metallic enclosure provided with cooling fins.

The ST-6 controller mainly consists of a microcontroller which executes various operations as per the commands received form the control computer. These operations include shutter control, timing of exposures, reading out the pixel data, transferring to the computer etc. among other things. Four relay connections are provided in the controller, each of which can be activated individually for durations specified through commands issued from the control computer. These relays are connected to the telescope control and are activated suitably, to keep the telescope tracked onto the target (see Sec. 4.3.3).

The ST-6 controller has a communication port through which it can receive com-

Table 4.2: Pinout details of the control signals for the XY stages

X			Y		
Signal	Port	Pin number	Signal	Port	Pin number
Pulse	P1	3	Pulse	P1	6
Direction	P1	4	Direction	P1	7
Enable/Disable	C003H	1	Enable/Disable	C003H	4

mands from and send responses to the control computer, using an asynchronous serial communication protocol called RS 232C. This is the sole communication link between the instrument mounted on the telescope and the control computer usually placed in the control room of the observatory. In addition to this, the ST-6 controller can also act as a gateway through which communication between the control computer and another device with an asynchronous serial communication port, can be routed. We have exploited this facility for routing the communication between the control computer and the IMPOL control box (see Sec 2.5.1), which is mounted close to the instrument on the telescope.

The translator and driver circuits which activate the two stepper motors (one for each direction) of the XY translational stages are identical to the one which is used to rotate the HWP. However, these motors draw an average current of about 0.85 A per phase for a supply voltage of 12 V. The 8051-based embedded controller within the IMPOL control box, generates the enable/disable, pulse and direction signals required by these circuits, again according to the commands received from the control computer (see Sec 2.5.1). The ports and the pin numbers which correspond to these signals for the X and Y directions are given in Tab. 4.2

The translational stages are provided with signals which indicate when the limits of motion is reached in either direction, for each stage. Whenever a limit signal becomes active, a logic circuit ensures that further pulses from the microcontroller do not reach the corresponding translator, unless the direction of motion is reversed.

4.3.3 Software

The instrument control software may be switched to the acquisition and guidance mode by selecting the *Tracker* option in the main menu. All operations related to acquiring the target and locking the telescope on to it are done in this mode.

There are two ways, in which the software allows to position the probe. One is motion relative to the current position, in which the probe may be moved by a selected number of steps along any of the four directions, +X, -X, +Y or -Y. This option is useful in cases where the telescope has already been pointed correctly and one wants to look for a suitable guide star within the scan area of the probe. The second method for probe positioning offers relative motion with respect to the centre of the main field. Since the instrument axes are aligned with respect to the celestial coordinates, the position to which the probe is to be moved, may be specified in terms of the right ascension and declination values of the centre of the main field and the guide star. One way of specifying these coordinates is by directly typing them in after selecting the appropriate menu option of the software (see IMPOL User's manual for more details). A more convenient way is to create a disk file in which the right ascension and declination values corresponding to all the planned observations, are saved in a specific format. At the time of observation, by selecting the appropriate observation number, the corresponding coordinates are read from the file by the software and the probe positioned accordingly.

If the instrument is mounted on the telescope, with its axes properly aligned, as described previously, the range of right ascension and declination values which the guide star may have relative to the centre of the main field, are given by

$$(RA_{\text{target}} + \frac{24.7\ \text{s}}{\cos \text{DEC}}) < RA_{\text{guide}} < (RA_{\text{target}} + \frac{52.9\ \text{s}}{\cos \text{DEC}}) \tag{4.1}$$

$$(DEC_{\text{target}} - 9'15'') < DEC_{\text{guide}} < (DEC_{\text{target}} + 9'15'')\ , \tag{4.2}$$

where (RA_{target},DEC_{target}) are the coordinates of the centre of the main field and (RA_{guide},DEC_{guide}) are the corresponding quantities of the guide star. This range corresponds to the scan area which can be covered by the probe. The position of the probe at any time, in number of steps from zero position, is displayed on the screen of the control PC.

In order to acquire the target a view of the guide field is obtained by taking an exposure with the ST-6 CCD. If the telescope pointing is roughly correct, the guide star should appear in the displayed image. Now fine adjustments may be done to get the guide star close to the centre of the tracker field. Once this is done, the software allows a box to be fixed around the centre, the size of which may be one out of a set of allowed values. After taking an exposure of the tracker field, the control computer instructs the ST-6 controller to calculate the centroid of light within this box, using the formulae given in Eq. 2.5. Depending on the shift in the centroid relative to the centre of the field, the control PC determines which relays are to be activated and for what durations. The criterion for determining this is that, after activation of the relays, the guide star image centroid should coincide with the centre of the guide field. Three quantities which the software requires to calculate this, are the size of the ST-6 CCD pixels along each direction, the image scale at the CCD in space angle per mm and the rate of telescope motion along each direction, in arcsec. per unit relay activation time. The values for these parameters are provided in the configuration file for the software and may be modified, if need be, during observations. In order to avoid excessive jitter, particularly, if it is attempted to correct for very small errors in the pointing, the software allows to fix a threshold value of the shift in the centroid below which it will not attempt to correct the telescope pointing.

The image scale at the main CCD surface, when the instrument is used with the Gurushikhar telescope is about 1 arcsec. per pixel. Under typical seeing conditions this will lead to some undersampling of the images. In order to overcome this, the tracking software allows the telescope pointing to be dithered during tracking. The amount of dithering may be fixed by the observer before the tracking is started. Then the software, before calculating the relay activation time, adds a random number in the range *(-dither* to *dither)* to the centroid shifts actually observed. Thus, if it is ensured that the exposure period is much larger than the typical repeat time of the tracking operation, the point-spread function of the registered images will be broadened.

The software checks between successive pointing correction loops, whether a command has been given to reposition the half-wave plate and if so, instructs the IMPOL controller accordingly. It is essential that this is possible without interrupting the autoguiding process, since the image positions on the CCD need to be maintained within less than the size of a pixel.

After assembling the instrument along with the A&G system on the laboratory test bench, it was verified by suitable loading that the flexures of the arm carrying the probe assembly, are within tolerable limits. The accuracy and repeatability of the probe positioning also was verified.

4.4 Performance Estimate

In this section, we make estimates of the performance of the A&G system and compares with the specifications laid out at the outset, as described in Sec. 4.1.2.

The diameter of the field lens (L1) of the probe assembly is about 12.5 mm which corresponds to a field of view of over 2 arcmin. for the Gurushikhar telescope. Hence, if the initial pointing of the telescope can be done with an accuracy of about an arcminute, the guide star will appear in the field and further fine adjustments to the pointing may be done.

The scan area of 40×100 mm^2 at the focal plane of the above telescope corresponds to about 0.05 sq. degrees in the sky. Considering an average of about 185 stars brighter than $m_{\rm V}$=15, per sq. degree of the sky towards the Galactic poles, and assuming a Poissonian distribution for the probability of finding stars within any small region of the sky, there is better than 99% chance of finding at least three stars within the above scan area. Besides, this scan area is within about 15 arcmin. (see Eq. 4.1 and Eq. 4.2) of the main field, as required in Sec. 4.1.2.

For the above calculation to be applicable, one should also verify that the device is sensitive enough to track on stars as faint as $m_{\rm V}$=15, with sufficient accuracy. A crucial factor which will decide the accuracy of tracking is the ability of the system to collect sufficient number of photoelectrons from the guide star, within reasonable exposure times. This is because, to first order, the error (ΔX_c) in calculating the x-coordinate centroid of the guide star image is given by

$$(\Delta X_c)^2 = \frac{N_{\rm p} + N_{\rm Bp}}{N^2} \times hw^3 \tag{4.3}$$

where $N_{\rm p}$ and $N_{\rm Bp}$ are the photoelectron counts per pixel due to the star and the background respectively. N is the total photoelectron counts due to the star, within the image having average dimensions w and h along the x and y coordinate axes respectively. The above relation can be rewritten as

$$\begin{aligned}(\Delta X_c)^2 &= \frac{N + N_{\rm B}}{N^2} \times w^2 \\ \Delta X_c &= \frac{w}{\rm SNR} \,. \end{aligned} \tag{4.4}$$

where $N_{\rm B}$ is the total photoelectron counts due to the background, within the image and we have used $N_{\rm p} + N_{\rm Bp} \times hw = N + N_{\rm B}$. SNR is the total signal to noise ratio of the photoelectron counts within the image. If we put $h = w$, then Eq. 4.4 can also be written as

$$(\Delta X_c)^2 = \frac{N_{\rm p} + N_{\rm Bp}}{{N_{\rm p}}^2} \tag{4.5}$$

which is nothing but the inverse square of the signal to noise ratio per pixel, of the detected photoelectrons within the box used for calculating the centroid.

While estimating the signal to noise ratio, it should be noted that the first detection of photons occur at the image intensifier and any noise which is introduced at this stage will also pass through the subsequent gain stages, along with the signal. Before the detection at the image intensifier, account has to be made for losses in the atmosphere, telescope, probe optics and the optical fibre and the quantum efficiency of the intensifier. Besides, the image is formed on an area of about 10 pixels on the CCD and hence each pixel collects only about 10% of the total light. Together, this results in transmission (η_1) of about 0.01. The gain of the image intensifier can be varied from 2000 to 50000 in six steps. The lenses L3 and L4 have an f-ratio of 1.2 and only about 10% of the light output from the image intensifier is collected and delivered by them to the ST-6 CCD, which in turn has a quantum efficiency of about 30%. We denote the product of these three factors by (η_2). From a point source of V-band magnitude $m_{\rm V}$, $F_{\rm V} = 10^{3-0.4 m_{\rm V}}$ photons arrive per cm^2 above the atmosphere in every second within a bandwidth of 1Å. Therefore, the total number of photoelectrons collected per pixel from a star of apparent magnitude $m_{\rm V}$(star), above the atmosphere, during an exposure of $t_{\rm exp}$ s is given by

$$S = F_{\rm V}(star) \times A(\Delta\lambda)\eta_1\eta_2 t_{\rm exp} \,, \tag{4.6}$$

where A is the light collecting area of the telescope and $\Delta\lambda$ is the optical bandwidth of the system. The total photon shot noise associated with the detection of this signal is given by

$$\begin{aligned}\sigma_S^2 &= F_{\rm V}(star) \times A(\Delta\lambda)t_{\rm exp}\eta_1\eta_2 + F_{\rm V}(star) \times A(\Delta\lambda)t_{\rm exp}\eta_1\eta_2^2 \\ &= F_{\rm V}(star) \times A(\Delta\lambda)t_{\rm exp}\eta_1\eta_2(\eta_2 + 1) \,, \end{aligned} \tag{4.7}$$

where the two terms correspond to the noise introduced at the two detection stages – first at the image intensifier and then at the CCD. If we assume that the background contributes to photoelectron counts within the stellar image, equivalent to that of a star of apparent magnitude $m_{\rm V}$(sky), which produces a photon flux of $F_{\rm V}$(sky) above the atmosphere, this will also add to the photon noise. Then $F_{\rm V}$(star) in the above equation is to be replaced by $F_{\rm V}$(star) + $F_{\rm V}$(sky). Besides, the readnoise of the CCD also contribute to the noise and adds an additional term to Eq. 4.7. However, if the gain of the image intensifier is large enough, the readnoise contribution will become negligible and the expression for the signal to noise ratio will become

$$SNR = \frac{F_{\rm V}(star) \times \sqrt{A(\Delta\lambda)\eta_1\eta_2 t_{\rm exp}}}{\sqrt{(F_{\rm V}(star) + F_{\rm V}(sky))(\eta_2 + 1)}}\,, \tag{4.8}$$

An exposure of 1s for a star with $m_{\rm V}$(star)=15 and a background with $m_{\rm V}(\text{sky}) = 20$ gives a signal to noise ratio per pixel of about 20. This is sufficient to obtain an auto-guiding accuracy of better than 0.1 arcsec. In the next chapter we discuss the results of the commissioning tests of the instrument, both in the laboratory and on the telescope and find that the performance estimates made above are realistic.